Transverse Spin Physics at COMPASS

C. Schill (Universität Freiburg)

on behalf of the COMPASS collaboration

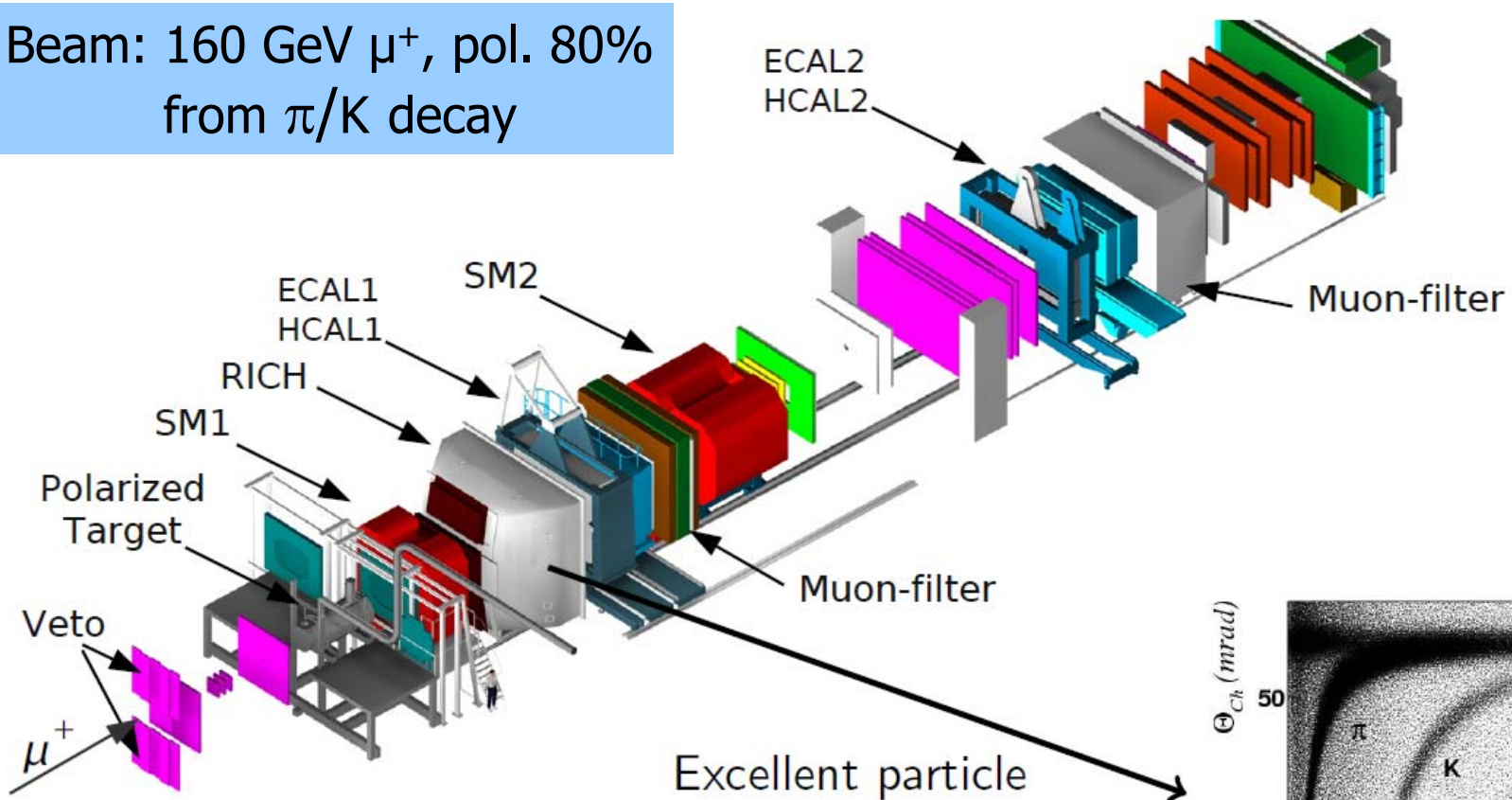
- **Transversity:**
  - **single hadrons, hadron pairs, Λ hyperons**
- **TMDs:**
  - **measured with transversely and unpolarized nucleons**

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

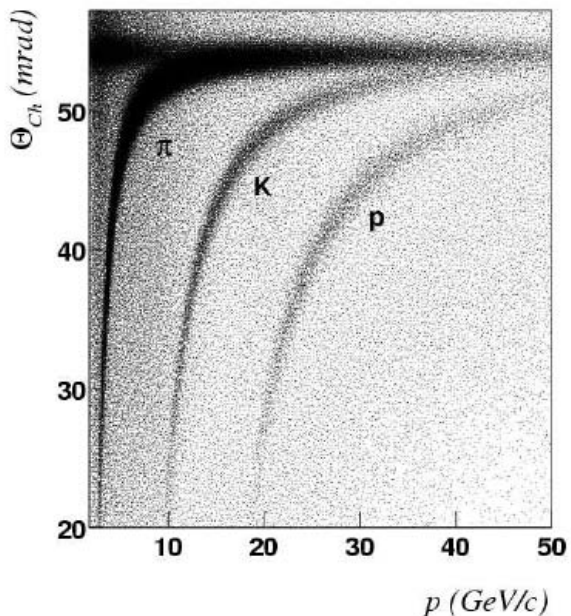

Jura mountains
Lac Léman
COMPASS
LHC
SPS
N
CERN

COMPASS

Beam: 160 GeV μ^+, pol. 80%
from π/K decay



longitudinally or
transversely polarized
fixed target

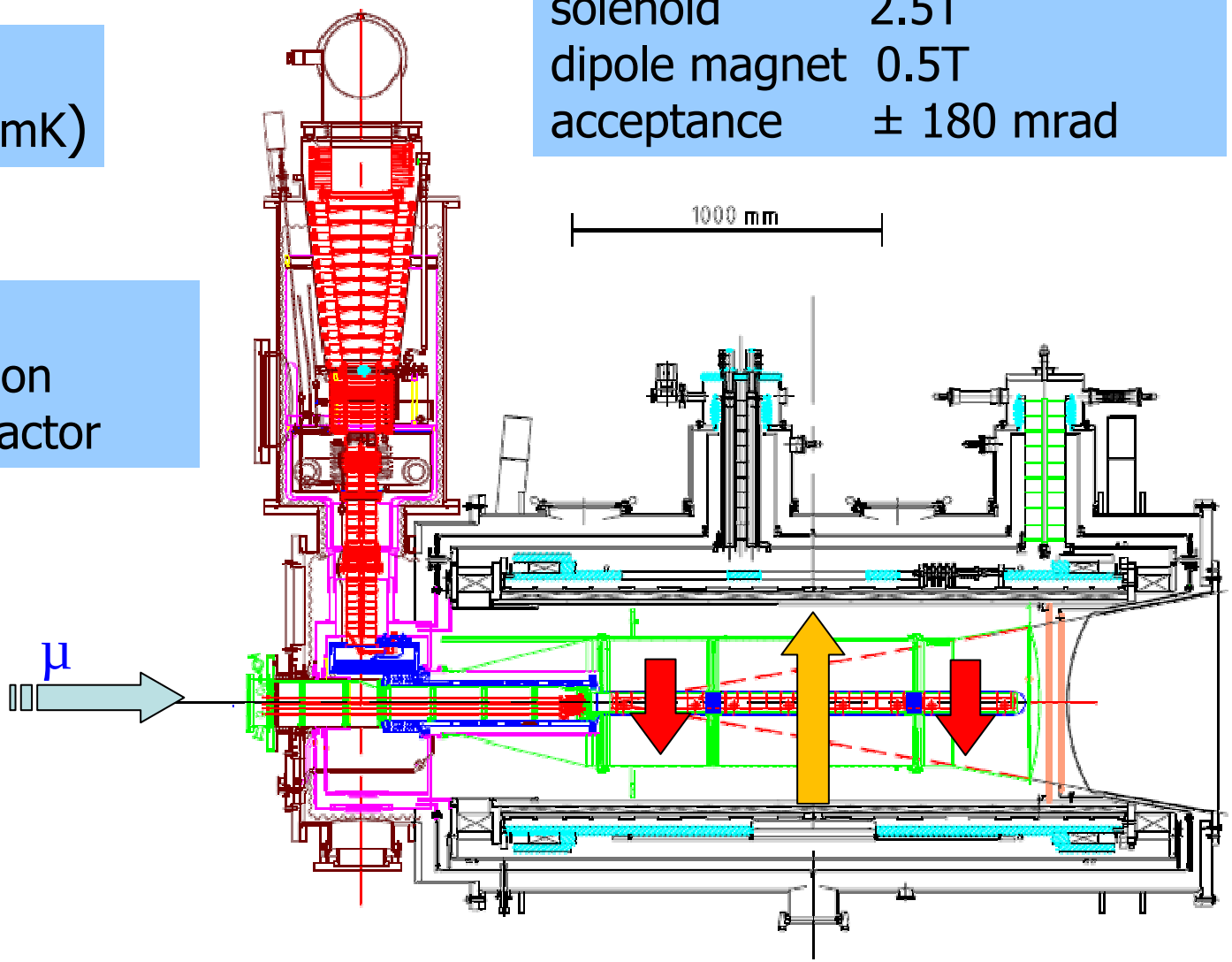


COMPASS target system

^{3}He – ^{4}He dilution refrigerator (T~50mK)

^{6}LiD or NH_3
50/90% polarization
40/16% dilution factor

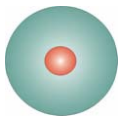
solenoid 2.5T
dipole magnet 0.5T
acceptance ± 180 mrad



Transverse Spin Physics

3 distribution functions are necessary to describe the spin structure of the nucleon at LO:

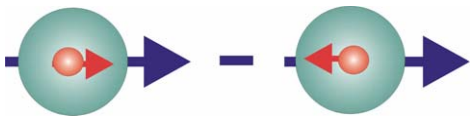
$q(x)$



quark distribution

in unpolarized DIS
l N →l' X

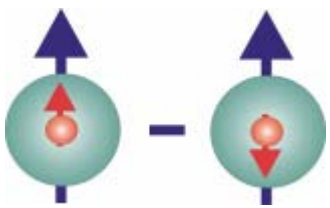
$\Delta q(x)$



helicity distribution

in polarized DIS
$\vec{l}\,\vec{N} \rightarrow l' X$

$\Delta_T q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$



transversity distribution

in polarized SIDIS

$l N^{\uparrow} \rightarrow l' h X$	**Collins FF**
$l N^{\uparrow} \rightarrow l' h h X$	**Interference FF**
$l N^{\uparrow} \rightarrow l' \Lambda X$	**FF of $q^{\uparrow} \rightarrow \Lambda^{\uparrow}$**

Transversity $\Delta_T q$

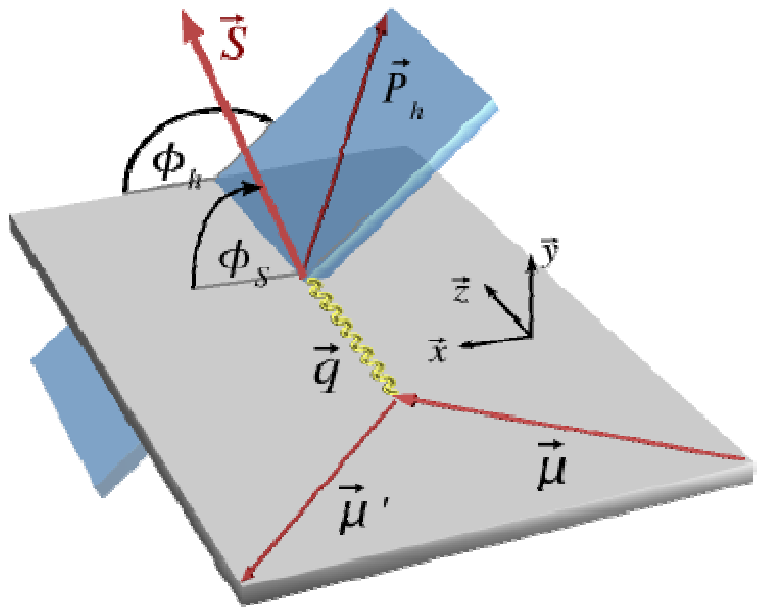
- Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Azimuthal cross-section asymmetry:

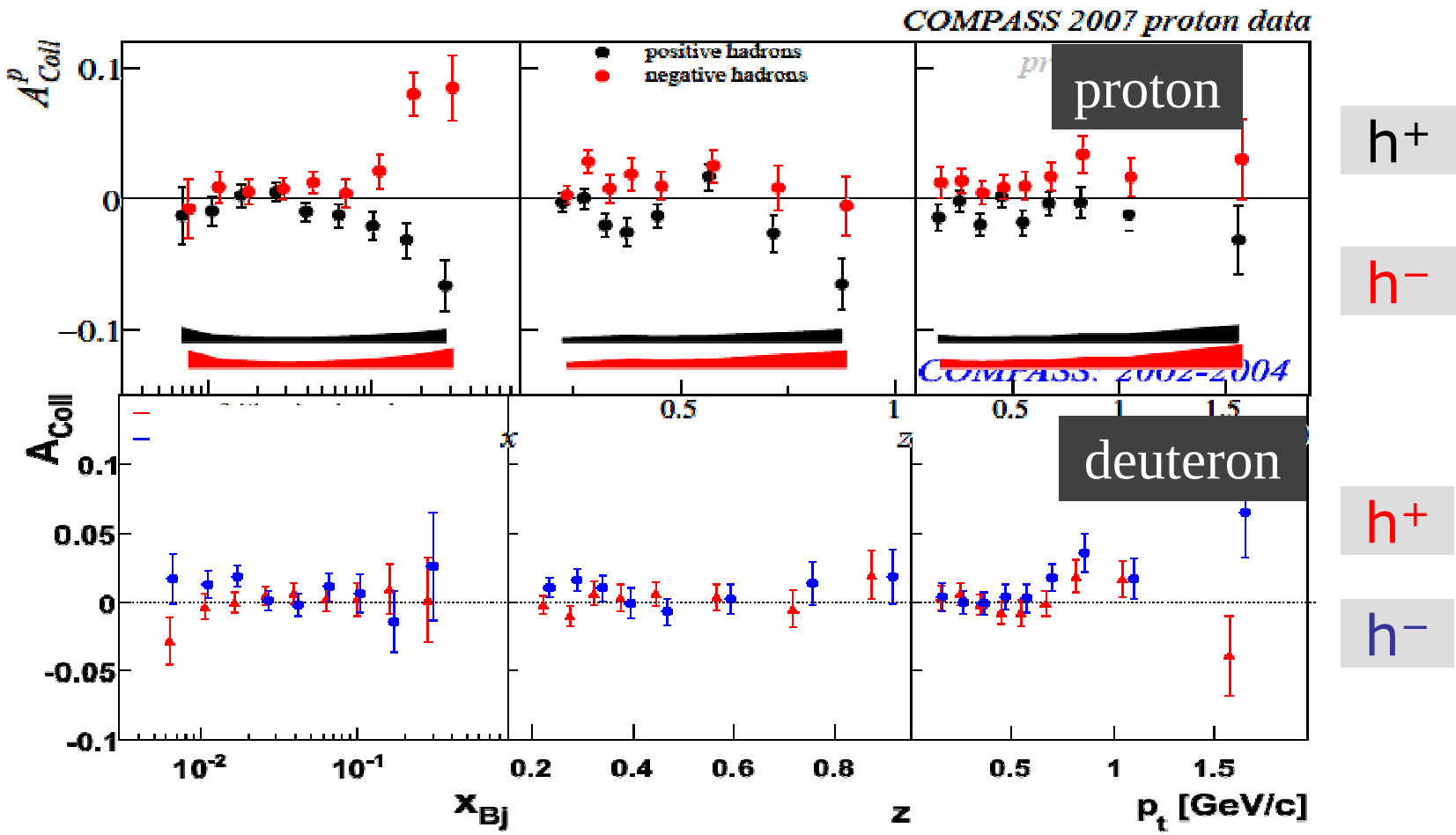
$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

$$\Phi_C = \phi_h - \phi_s - \pi$$



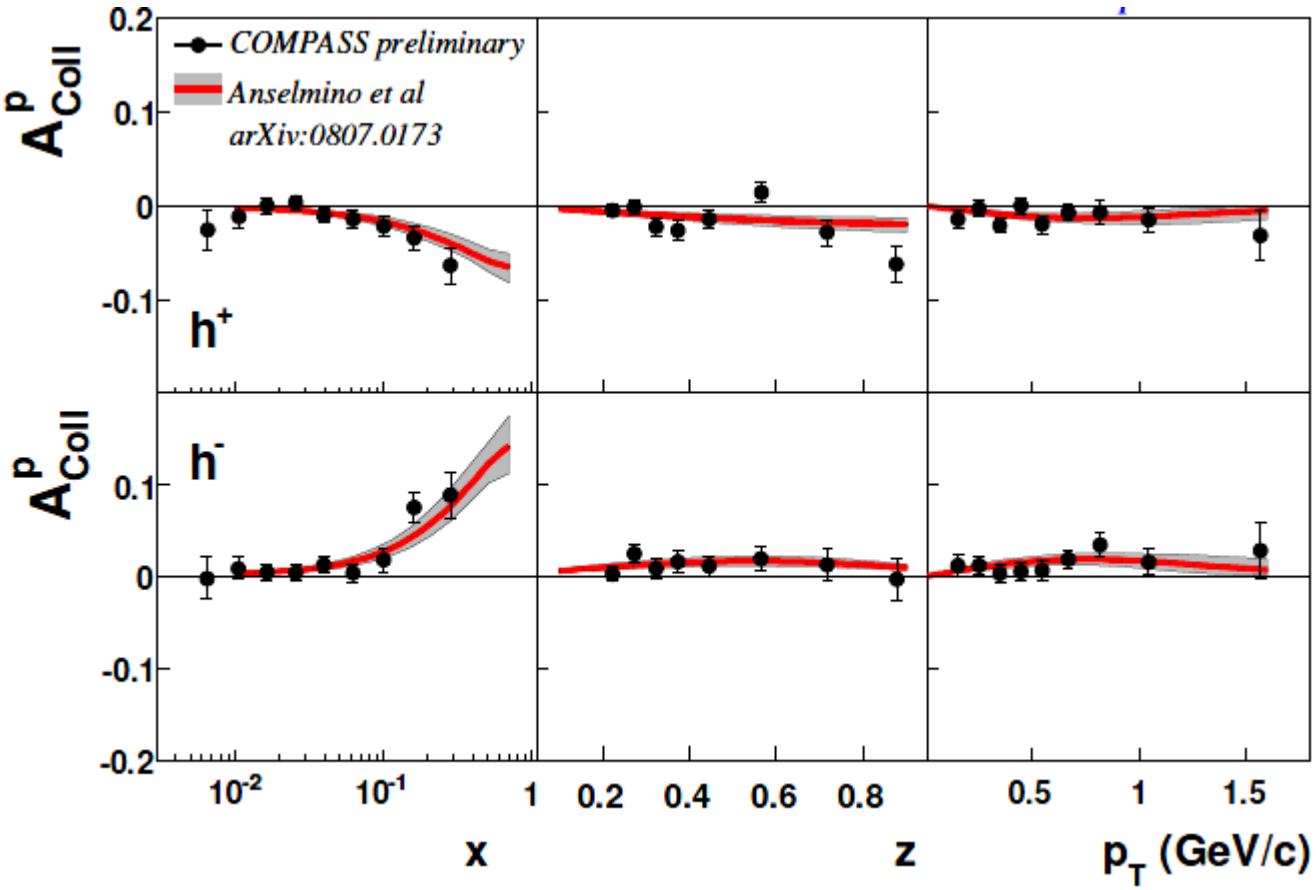
Transversity: Collins Asymmetries

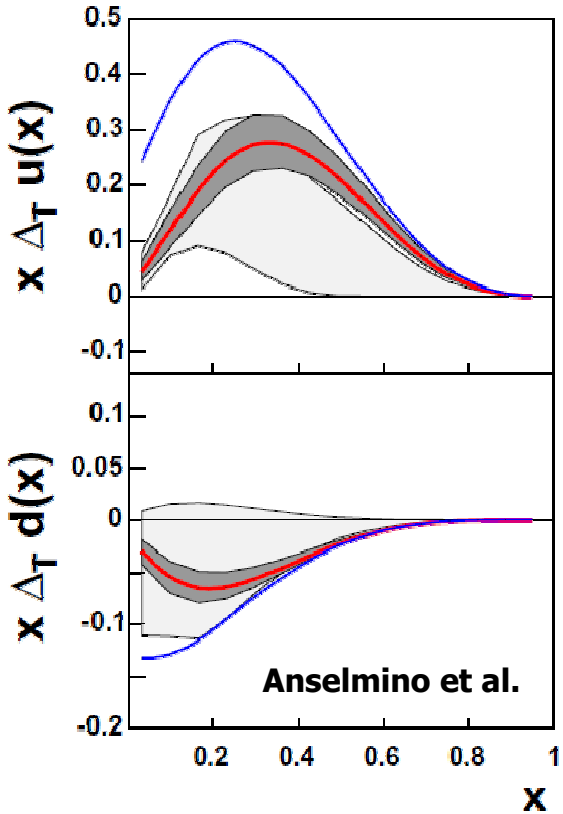
- large asymmetry for proton ~10%
- zero deuteron result important ⇒ opposite sign of u and d



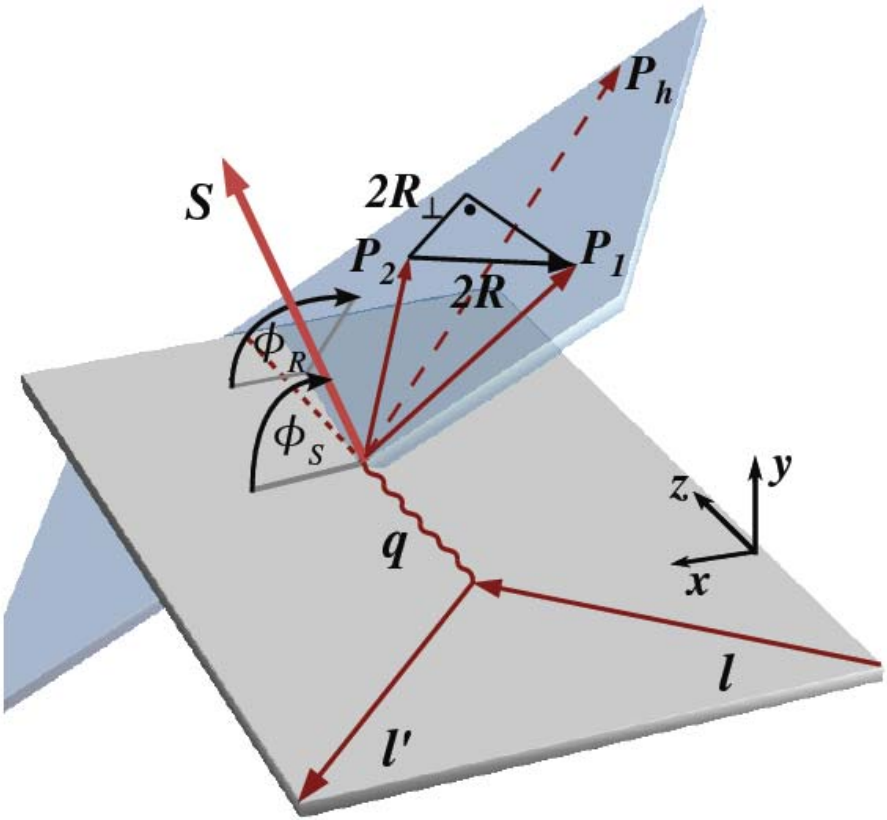
Transversity: Global Fit

- Fit to COMPASS *d*, HERMES, BELLE (Collins FF, e^+e^-)
- in good agreement with new proton data





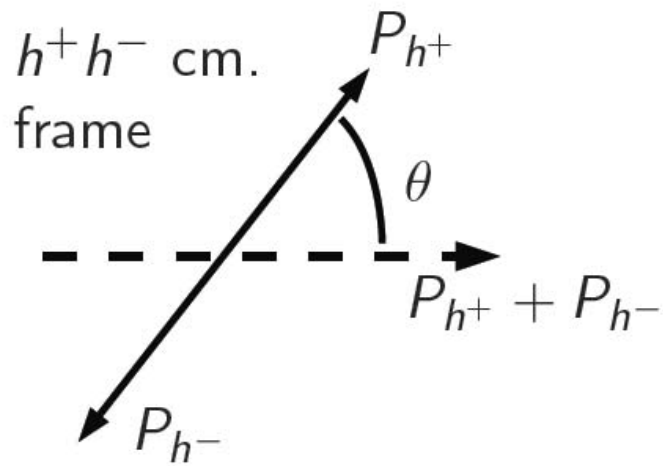
Transversity: Dihadron-Interference



$\rightsquigarrow$ azimuthal asymmetry:

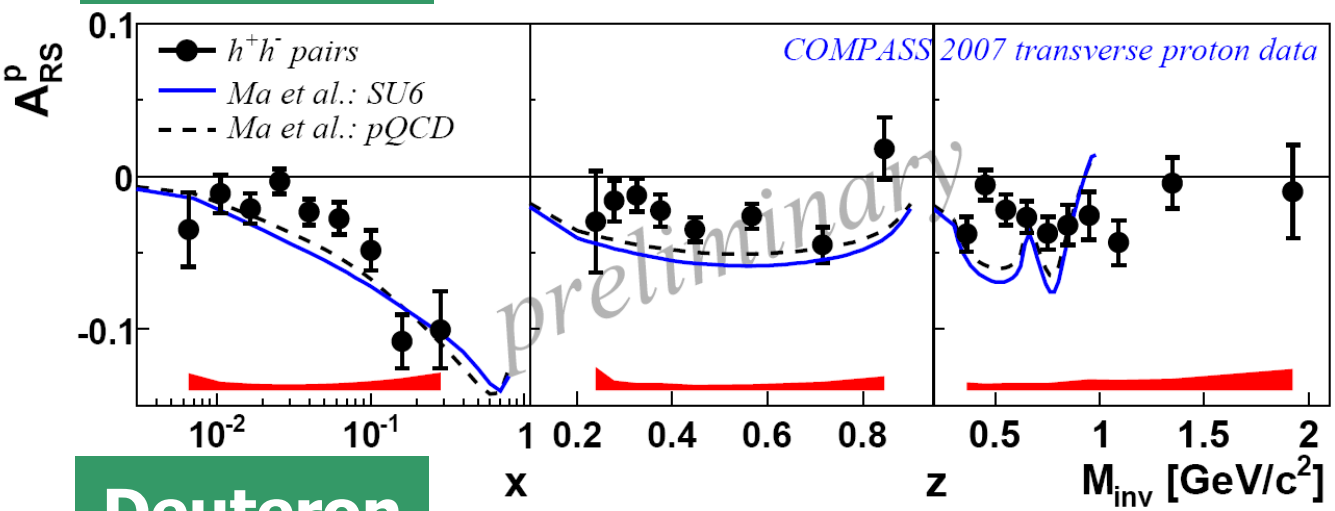
$$N_{h^+h^-} \propto 1 \pm A \cdot \sin\phi_{RS} \cdot \sin\theta$$

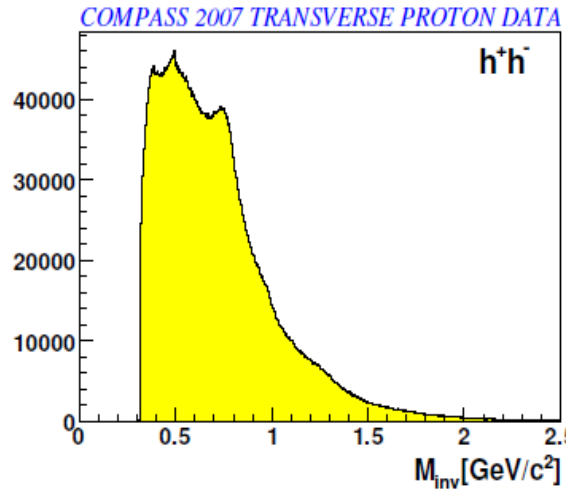
$$\boxed{\phi_{RS} = \phi_R + \phi_S - \pi}$$



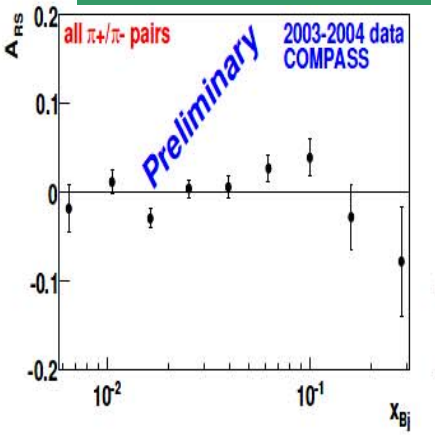
Transversity: Dihadron interference

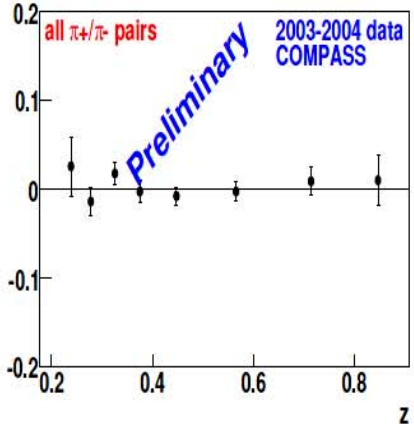
Proton

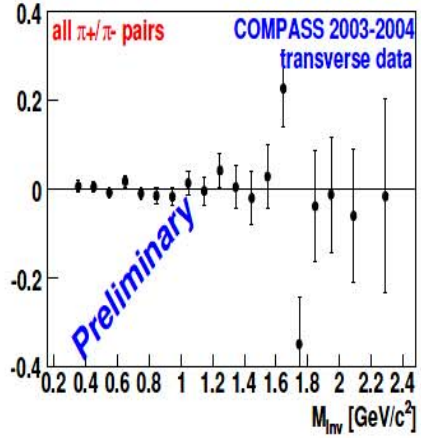


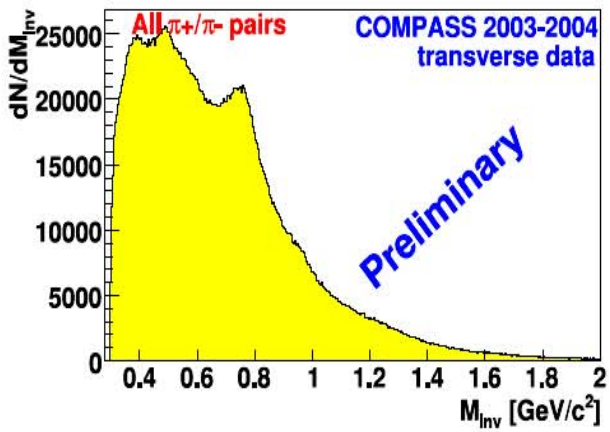


Deuteron







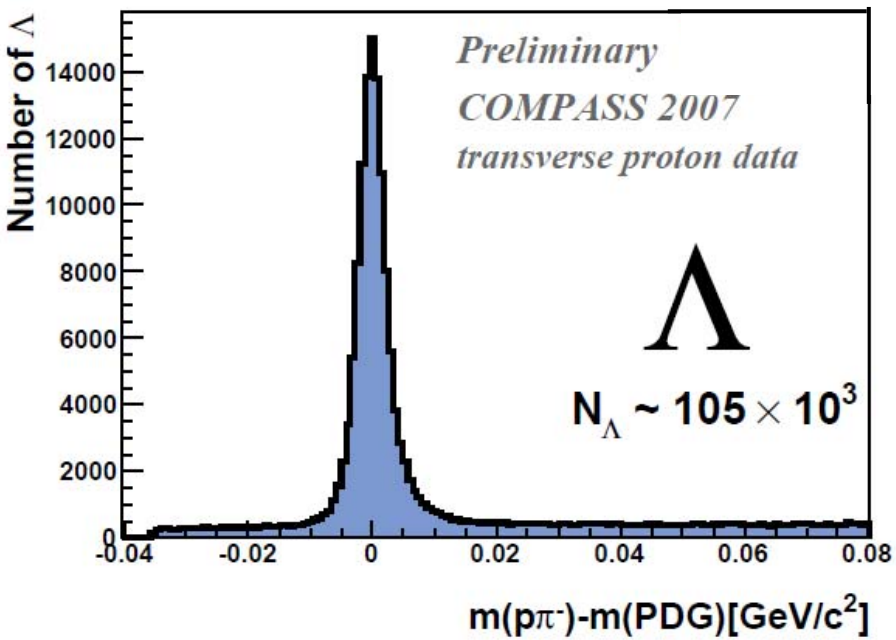


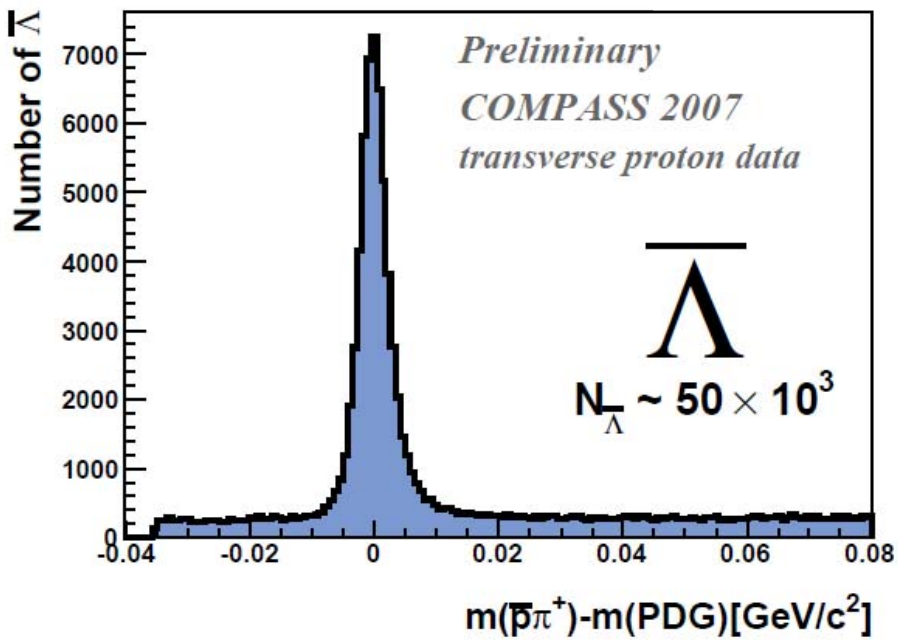
- large asymmetries on the proton
- with IFF from Belle: Global fit possible

Transverse Λ Polarization

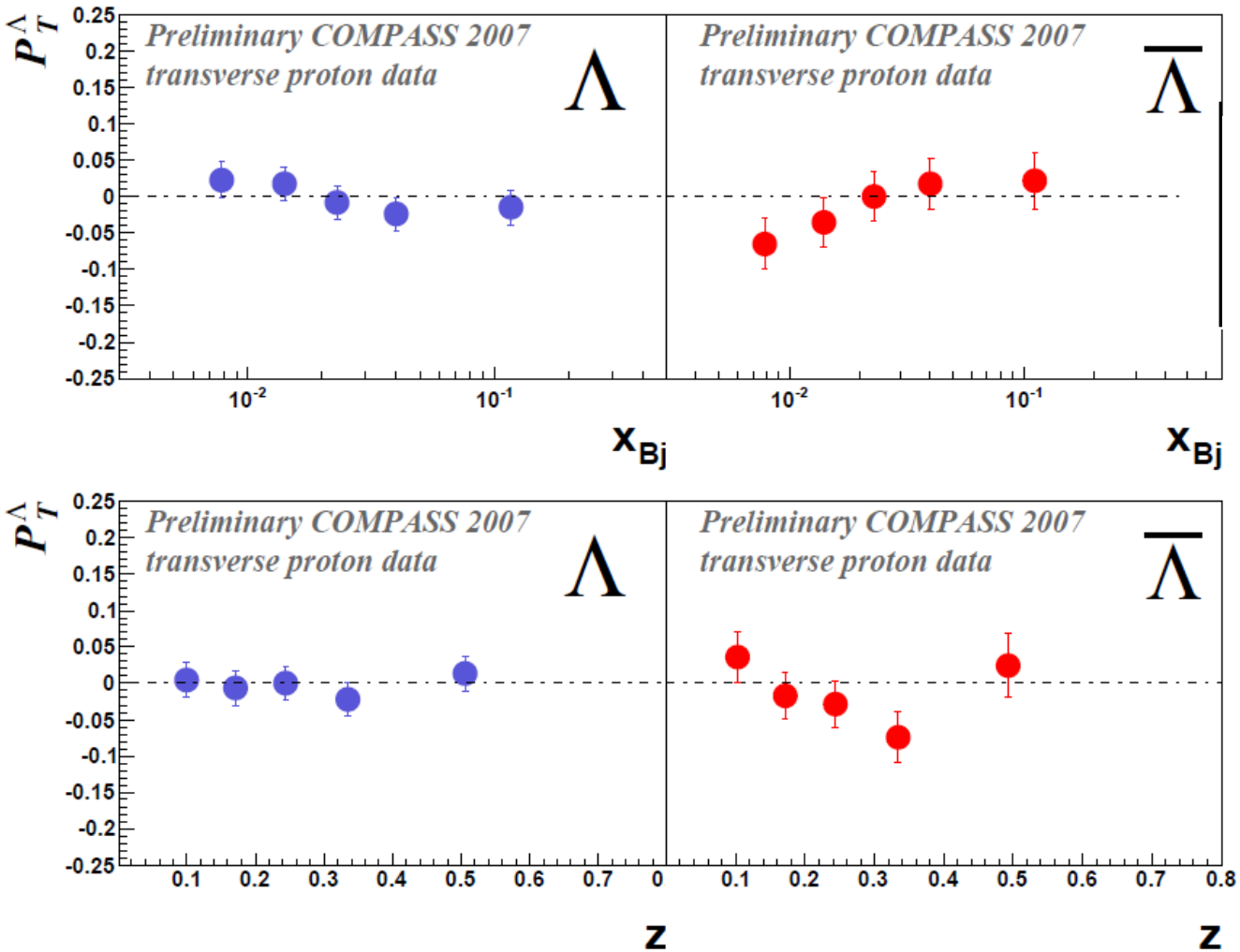
Λ-Polarization: $P_\Lambda \propto f\, P_T D_{nn} \sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T D_q^\Lambda$

measured via parity violating decay





Transverse Λ Polarization



P_T^{Λ}, $P_T^{\overline{\Lambda}}$ small, compatible with zero $\rightsquigarrow$ small analyzing power of $\Delta_T D_q^{\Lambda}$

Polarized SIDIS cross section

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

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

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

unpolarized target

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

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

longitudinally polarized target

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

Collins ✓

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

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

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

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

transversely polarized target

A.Bacchetta et al

JHEP 0702:093,2007

E-print number: hep-ph/0611265

Polarized SIDIS cross section

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

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

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

unpolarized target

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

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

longitudinally polarized target

Sivers

Collins ✓

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

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

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

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

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

transversely polarized target

A.Bacchetta et al

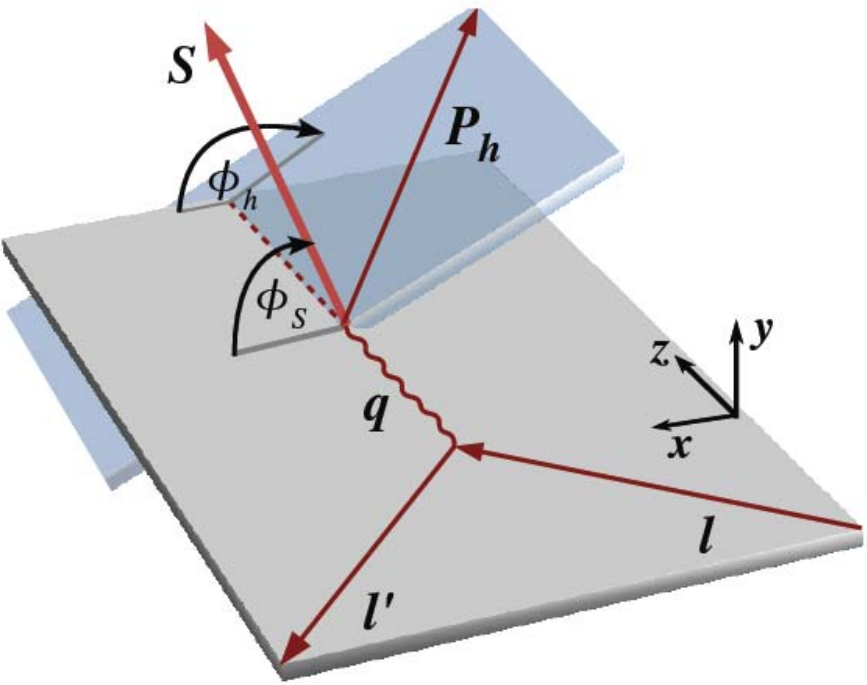
JHEP 0702:093,2007

E-print number: hep-ph/0611265

Sivers Effect

Sivers PDF $\Delta_0^T q$:

correlation between intrinsic transverse momentum
of the quarks and the transverse polarization of the nucleon



$\rightsquigarrow$ azimuthal asymmetry:

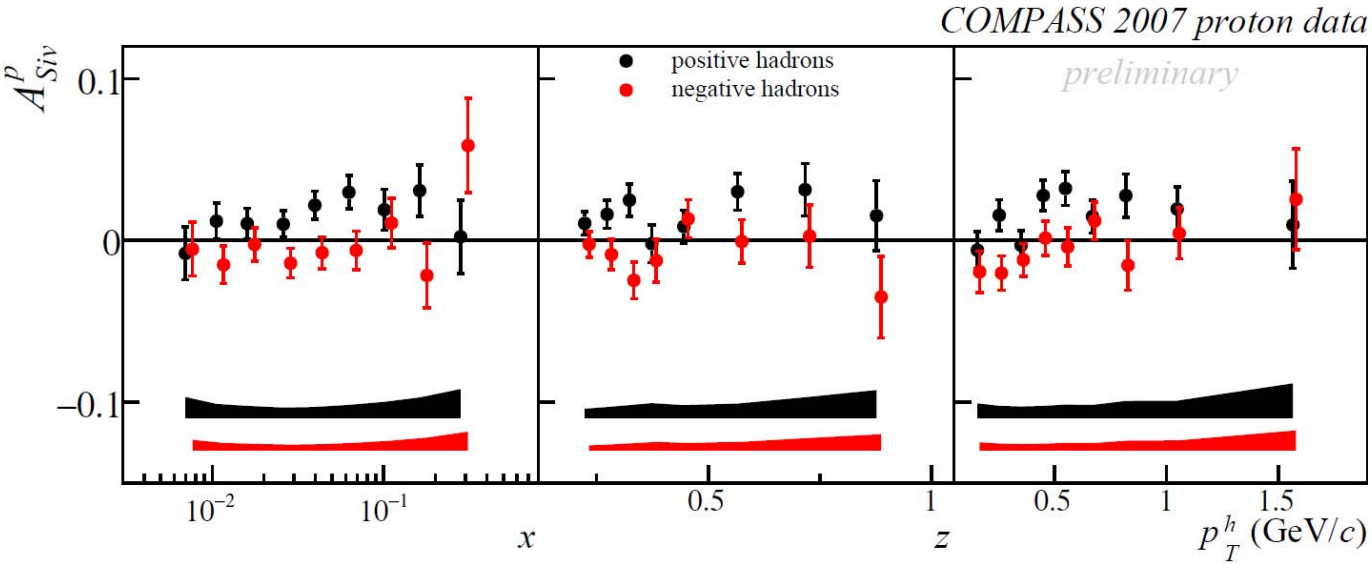
$$N_h \propto 1 \pm A \cdot \sin(\phi_h - \phi_S)$$

ϕ_h: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin of initial quark

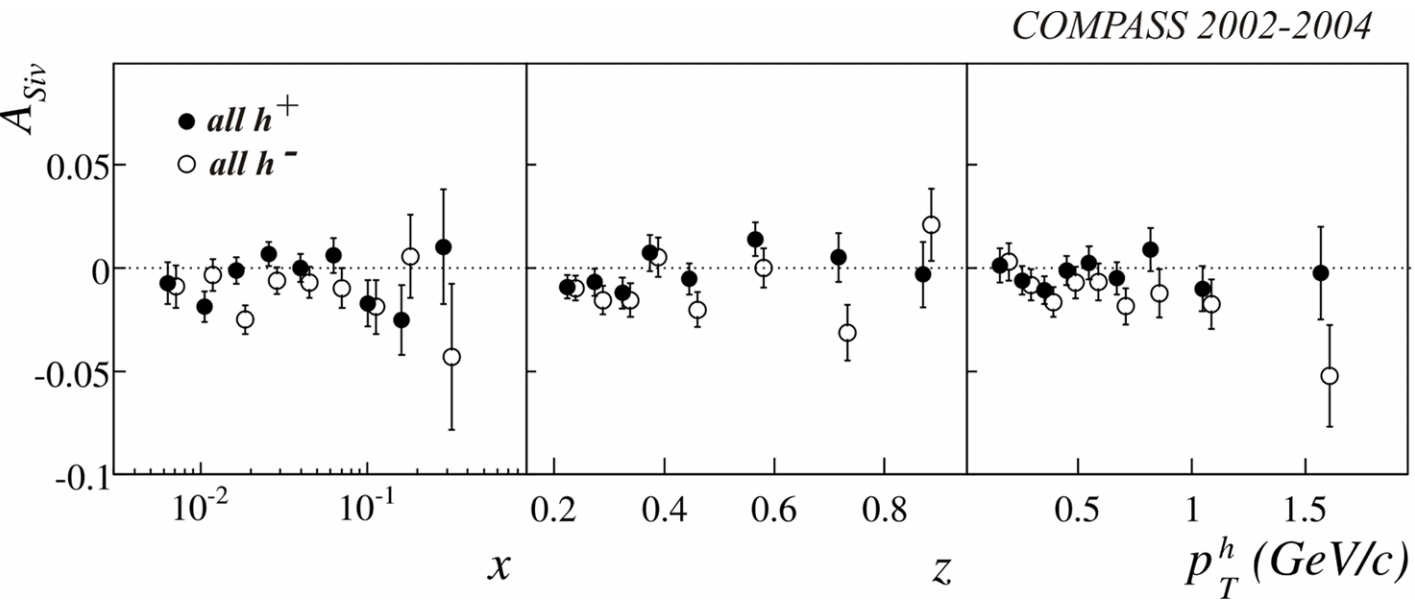
$$A_{Siv} = \frac{A}{f\ P_T} \propto \sum_q e_q^2 \cdot \Delta_0^T q \otimes D_q^h$$

Sivers Asymmetries



Proton

non-zero asymmetry for pos. hadrons

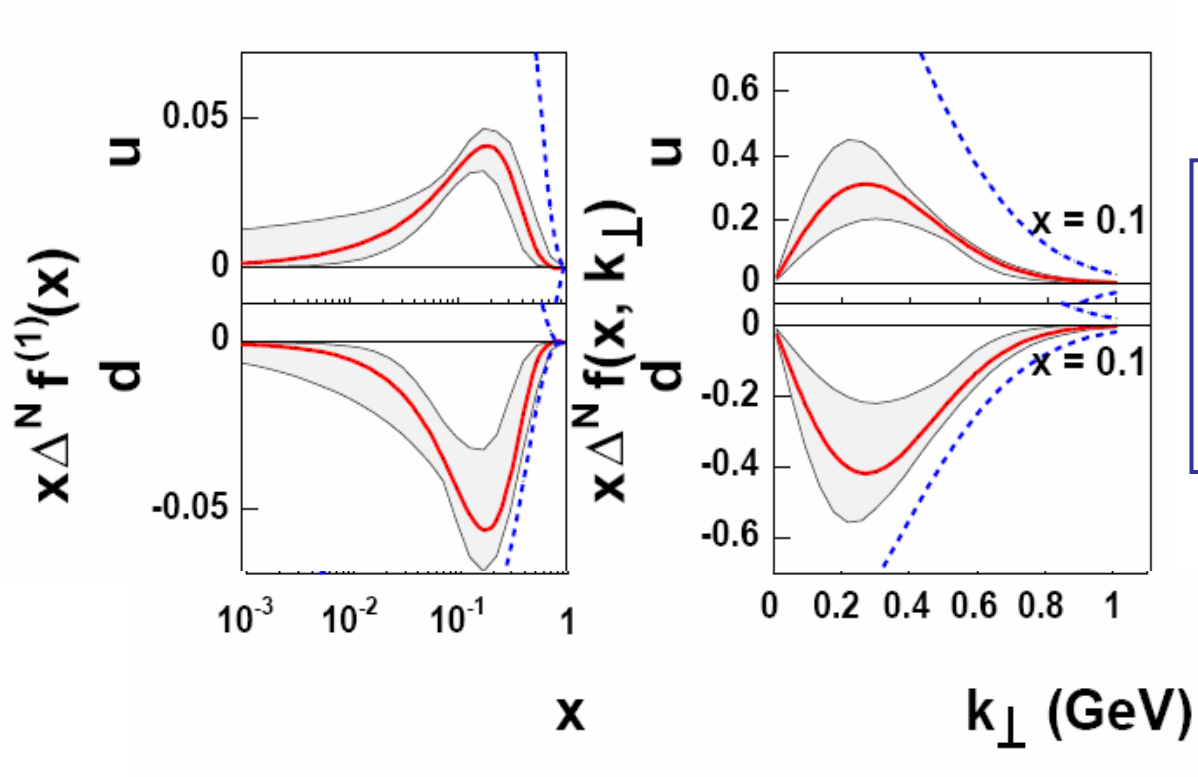


Deuteron

compatible with zero

Sivers Distribution Function

using COMPASS pion and kaon data on deuteron and HERMES proton data (but not COMPASS proton)



M. Boglione
in collaboration with
M. Anselmino, U. D'Alesio,
A. Kotzinian, S. Melis,
F. Murgia, A. Prokudin, C. Turk

Polarized SIDIS cross section

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

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

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

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

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

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

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

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

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

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

Cahn & Boer-Mulders

unpolarized target

longitudinally polarized target

Sivers ✓

Collins ✓

transversely polarized target

A.Bacchetta et al

JHEP 0702:093,2007

E-print number: hep-ph/0611265

Cahn effect

The unpolarized SIDIS cross section:

$$d\sigma^{lp\to l'hX} = \sum_q f_q\left(x,Q^2\right)\otimes d\sigma^{lp\to l'q}\otimes D_q^h\left(z,Q^2\right)$$

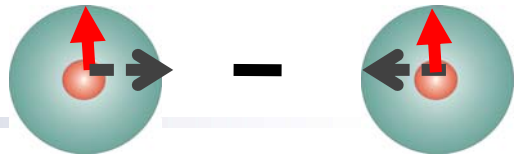
The elementary Cross-Section:

$$d\sigma^{lp\to l'q} \propto \hat{s}^2 + \hat{u}^2$$

Taking into account the quark transverse momentum:

$$\hat{s} = sx\left[1 - \frac{2k_T}{Q}\sqrt{1-y}\cdot\cos\phi\right] + O\left(\frac{k_T^2}{Q}\right)$$

Boer-Mulders Effect



$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \propto h_1^{\perp} \otimes H_1^{\perp}$$

Side view

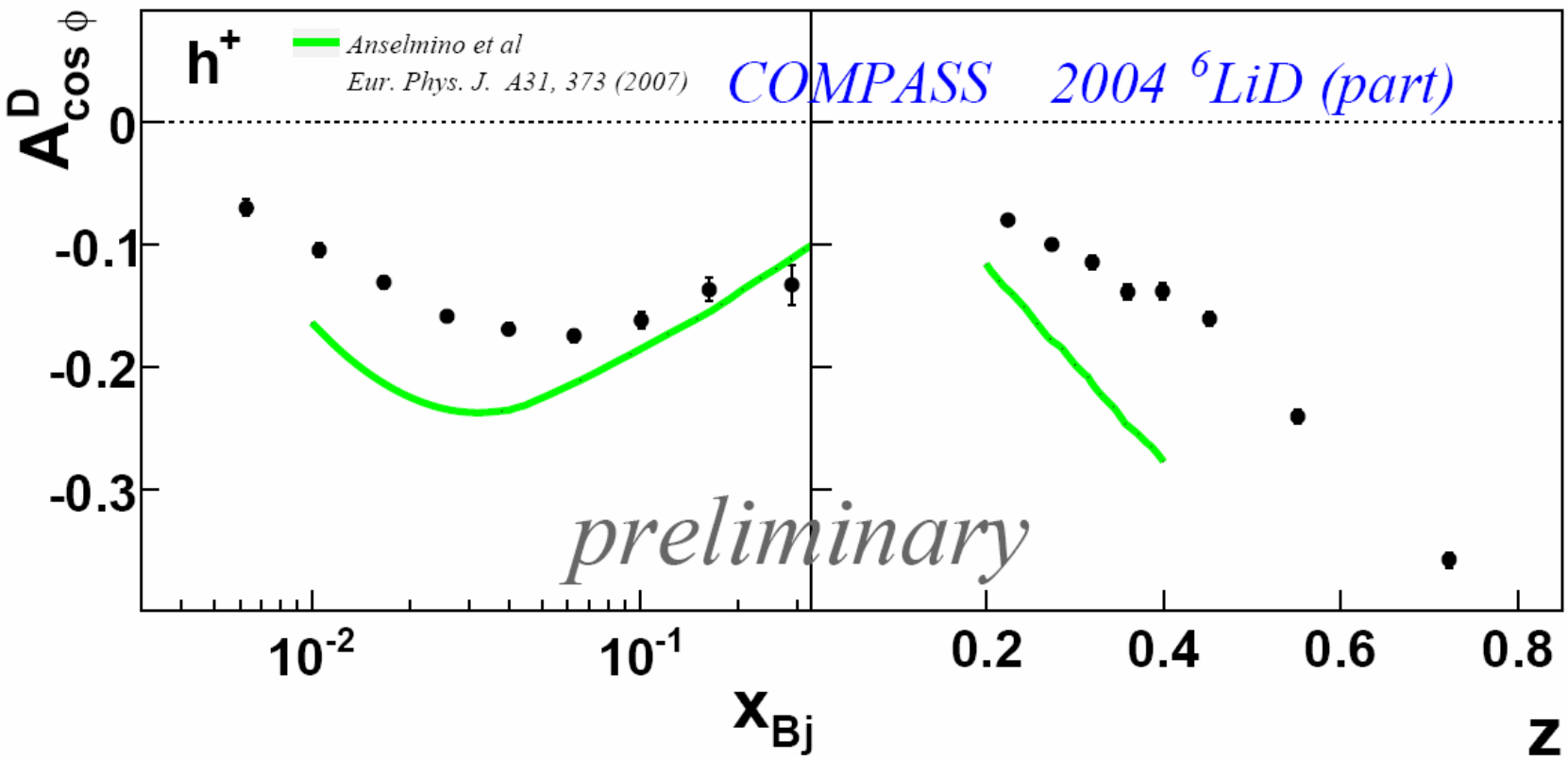
Front view

Convoluted with Collins function

Contributes to cos ϕ_h and cos $2\phi_h$ moments

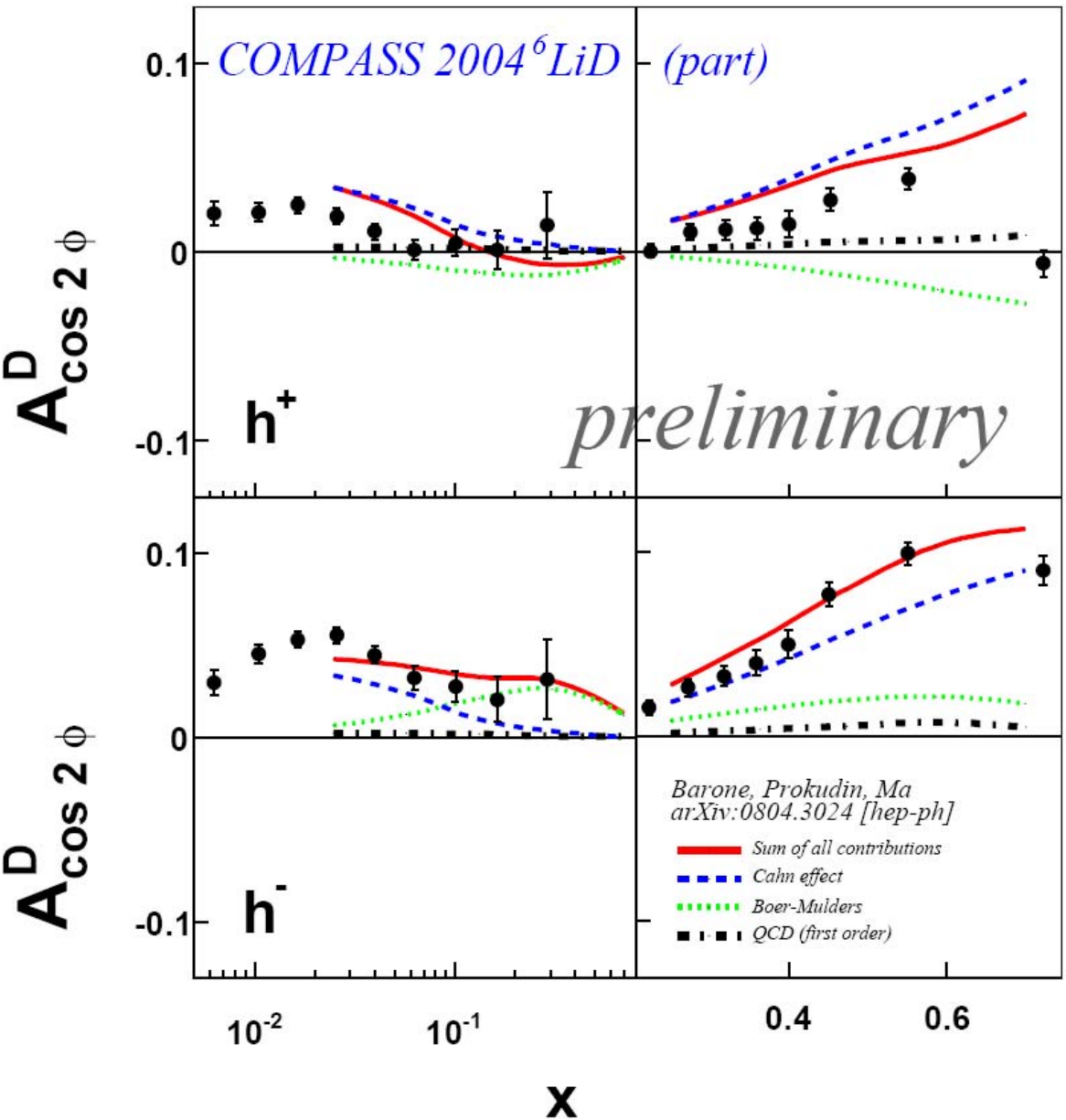
Results: cosϕ Modulation

comparison with theory



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

Results: cos 2ϕ Modulation



Barone, Prokudin, Ma
arXiv:0804.3024 [hep-ph]

- *Sum of all contributions*
- *Cahn effect*
- *Boer-Mulders*
- *QCD (first order)*

Polarized SIDIS cross section

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

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

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

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

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

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

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

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

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

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

Cahn & Boer-Mulders ✓

unpolarized target

longitudinally polarized target

Sivers ✓

Collins ✓

Pretzelosity

Worm Gear

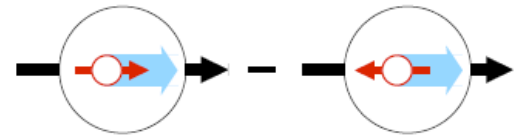
A.Bacchetta et al

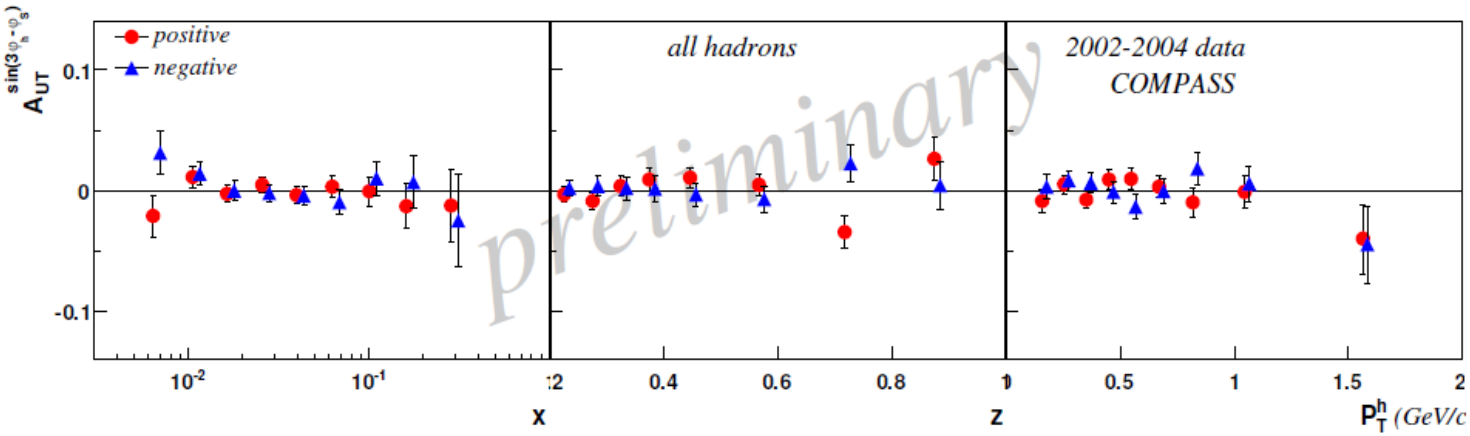
JHEP 0702:093,2007

E-print number: hep-ph/0611265

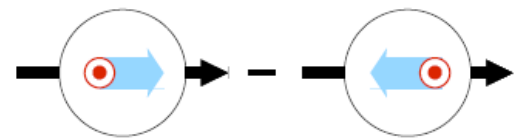
Pretzelosity and Worm Gear

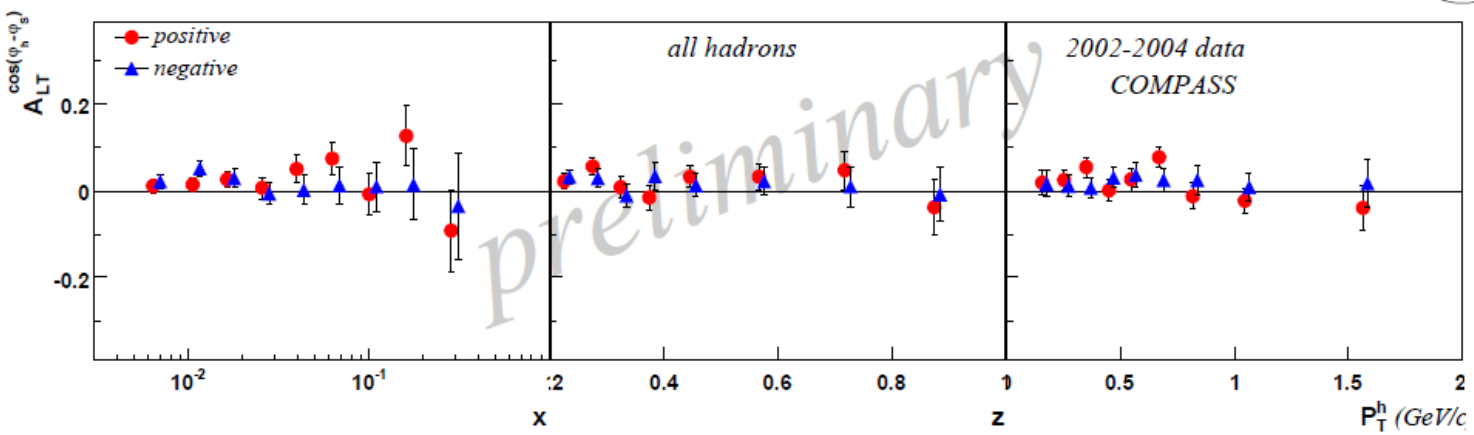
$F_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp,q} \otimes \Delta_T^0 D_q^h,$ Pretzelosity PDF $h_{1T}^{\perp,q}$:





$F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_q^h,$ Worm Gear PDF g_{1T}^q:





Conclusions

interesting COMPASS results for:

- **large unpolarized hadron asymmetries on deuteron for positive and negative hadrons**
- **Collins and Sivers asymmetries on protons and deuterons**
- **Two hadron asymmetries**
- **Transverse Λ polarization small, compatible with 0**
- **all 8 TMDs on the deuteron**

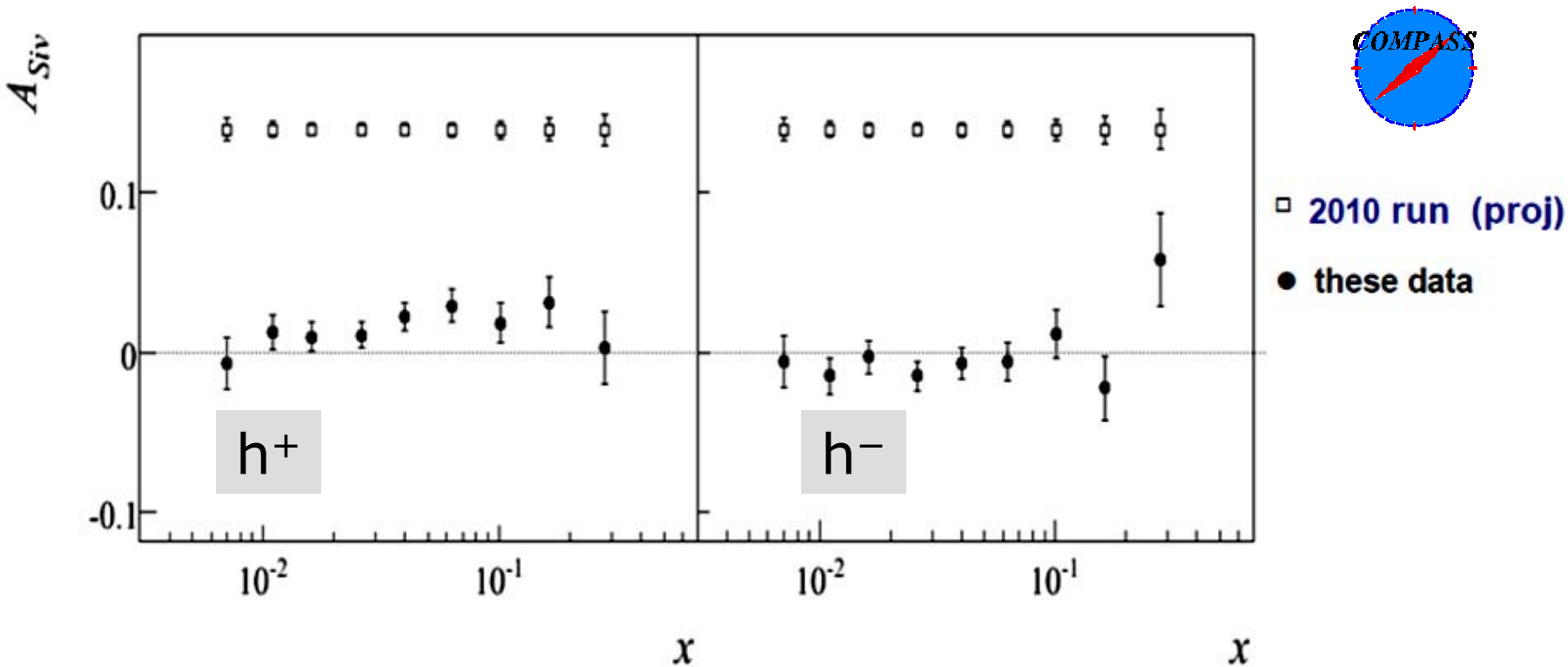
near future:

- **identified hadron asymmetries on proton**
- **all TMD asymmetries on the proton**

Outlook

one full year of transverse data taking has started

CERN-SPSC-2009-003
SPSC-I-238
21 January 2009



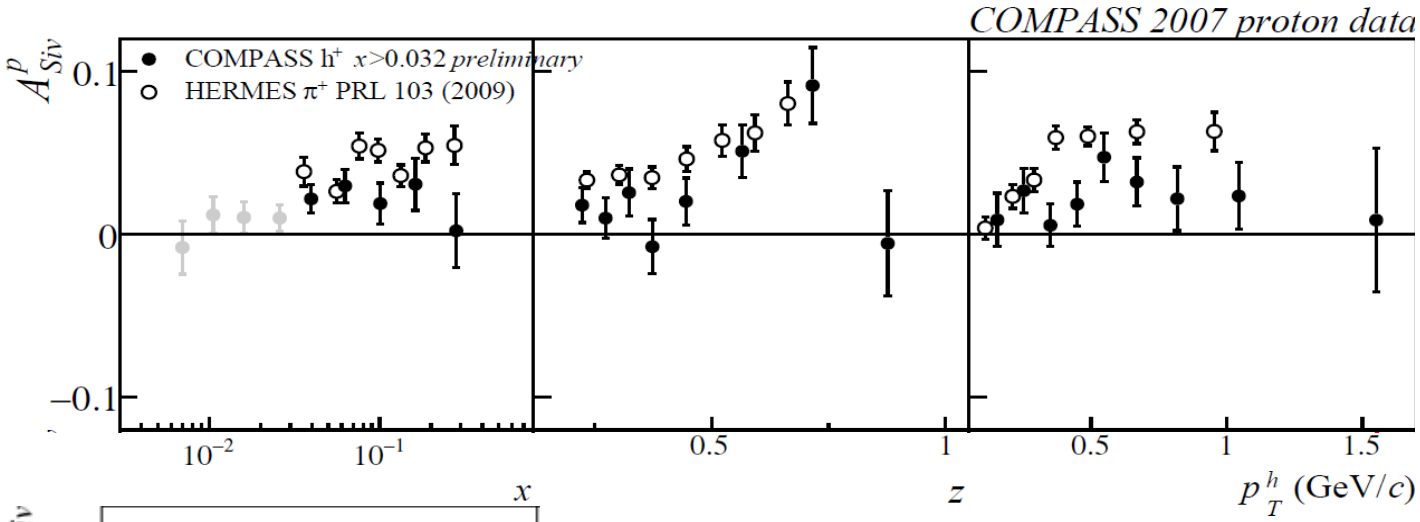
the study of transverse spin effects needs further precise measurements and COMPASS is the only place where SIDIS can be measured at high energy

Thank you!

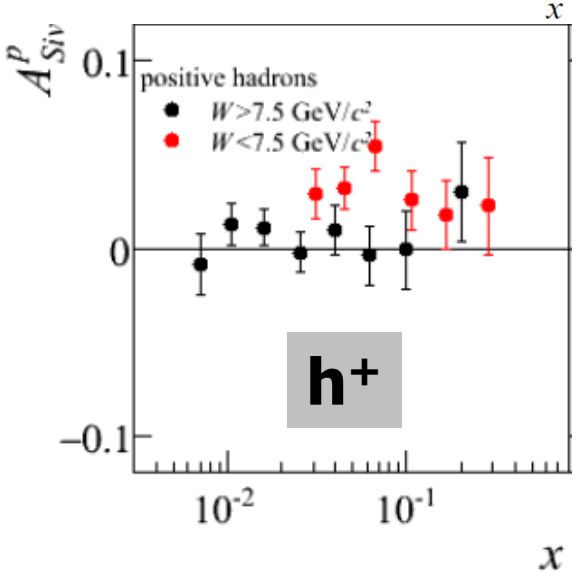
Sivers: Comparison with HERMES

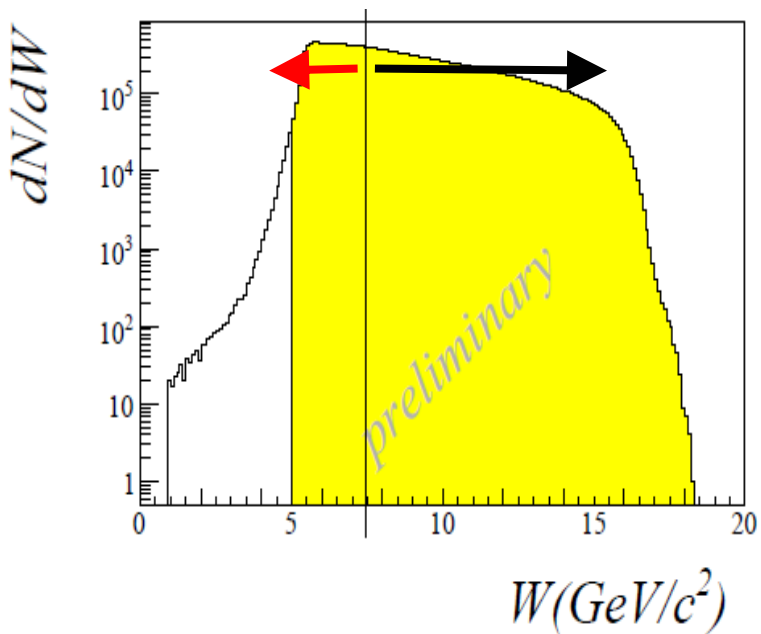
Compass data somewhat smaller for h⁺

Proton



h⁺



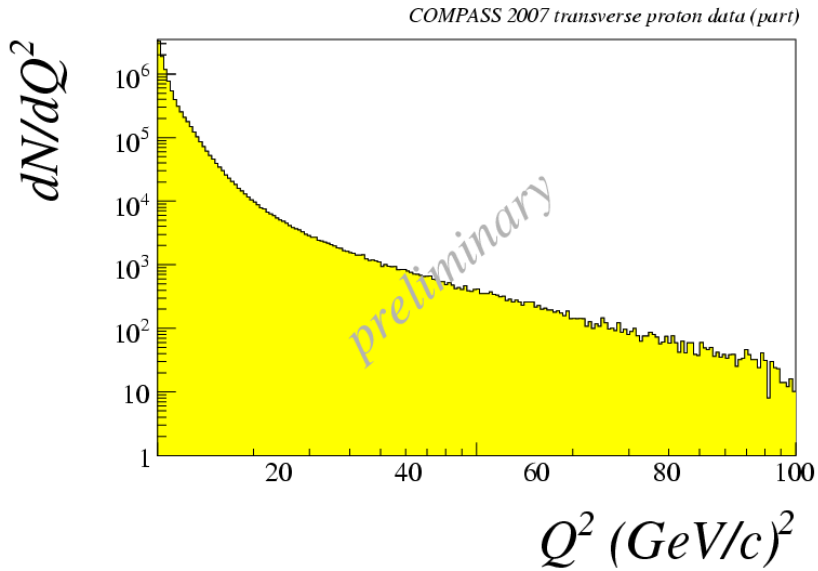


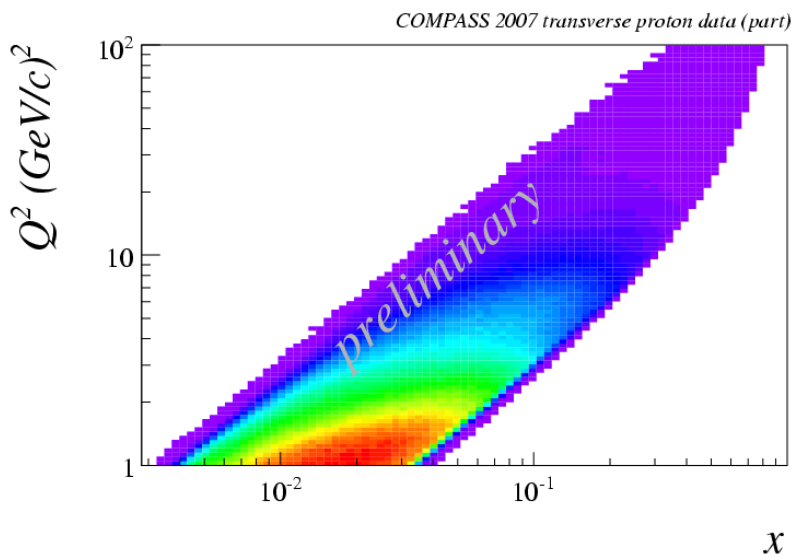
possible W dependence

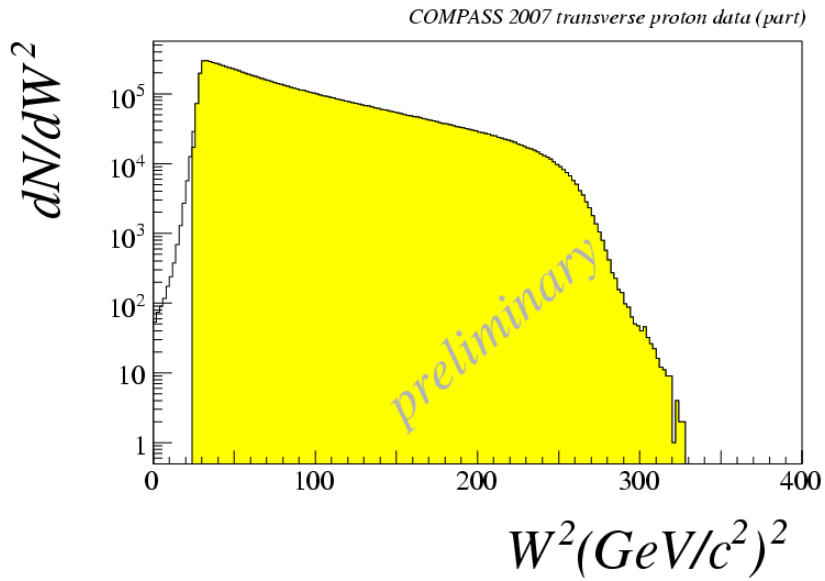
SIDIS Event Selection and Kinematics

DIS event selection:

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



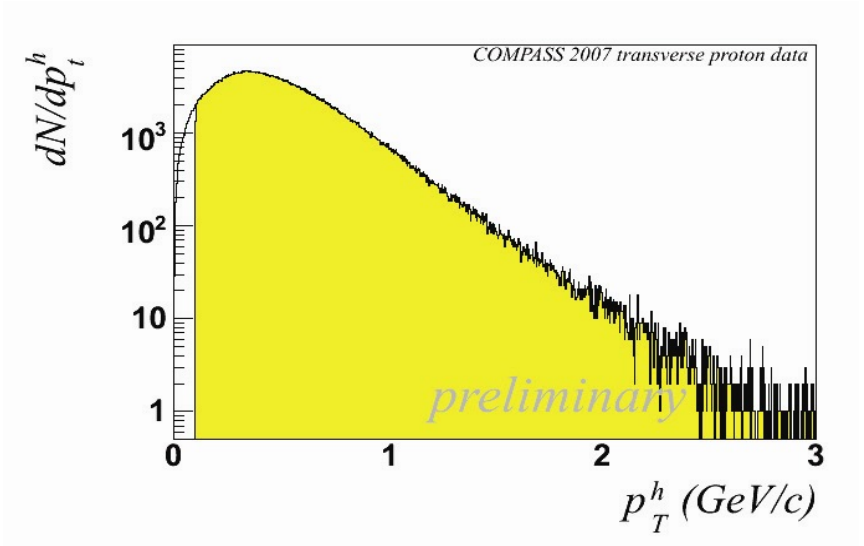




SIDIS Event Selection and Kinematics

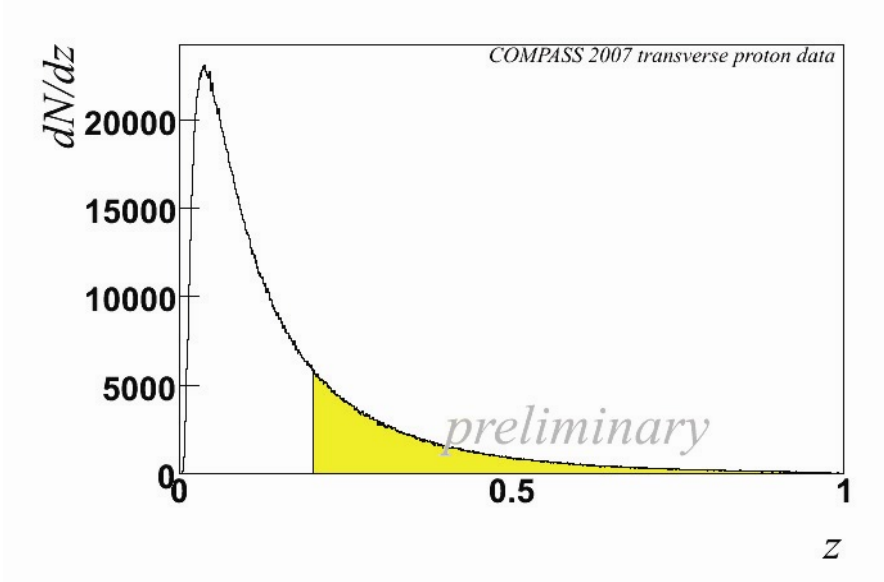
DIS event selection:

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



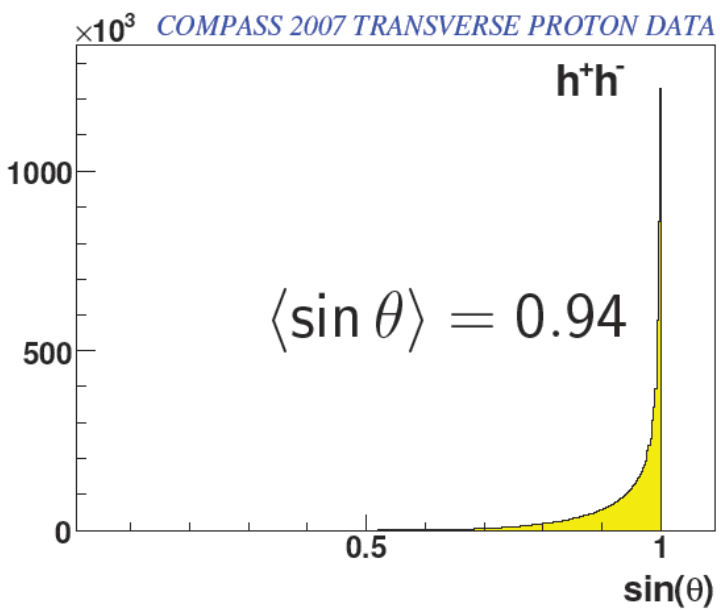
Hadron selection:

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



Dihadron-Interference

Measuring transversity with Dihadron-Interference-FF $H_1^{\sphericalangle}$:



$\rightsquigarrow$ azimuthal asymmetry:

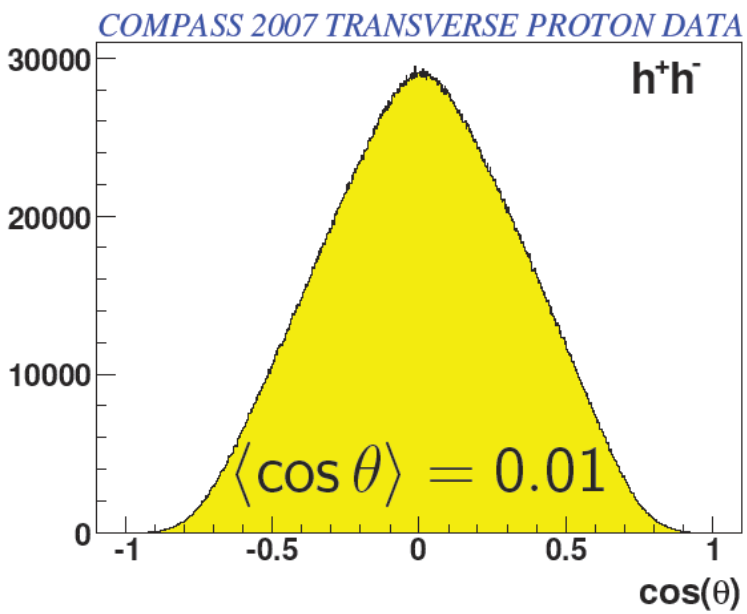
$$N_{h^+h^-} \propto 1 \pm A \cdot \sin\phi_{RS} \cdot \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

For this analysis:
$\sin\theta$ can be neglected

Dihadron-Interference

Measuring transversity with Dihadron-Interference-FF $H_1^{\sphericalangle}$:



$\rightsquigarrow$ azimuthal asymmetry:

$$N_{h^+h^-} \propto 1 \pm A \cdot \sin\phi_{RS} \cdot \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

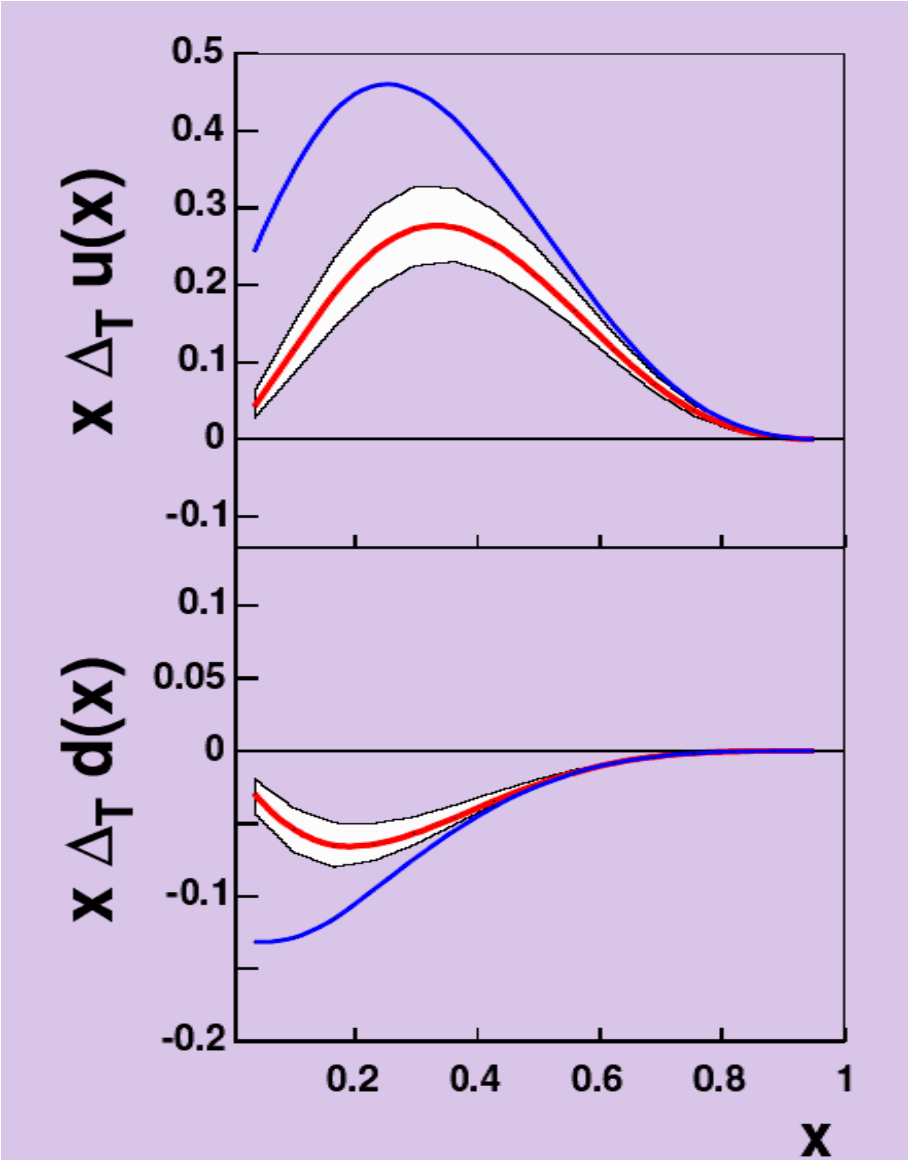
$$A_{RS} = \frac{A}{f\ P_T D_{nn}} \propto \sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\sphericalangle}$$

$$H_1^{\sphericalangle} = H_1^{\sphericalangle,sp} + \cos\theta H_1^{\sphericalangle,pp}$$

$\rightsquigarrow$ only sensitive to $H_1^{\sphericalangle,sp}$

Transversity – Fits to Data

new results using HERMES (p) and COMPASS (d) pion data, and BELLE data



A. Prokudin et al. Ferrara ´08

Collins Fragmentation function – Fits to Data

new results

using

HERMES (p)

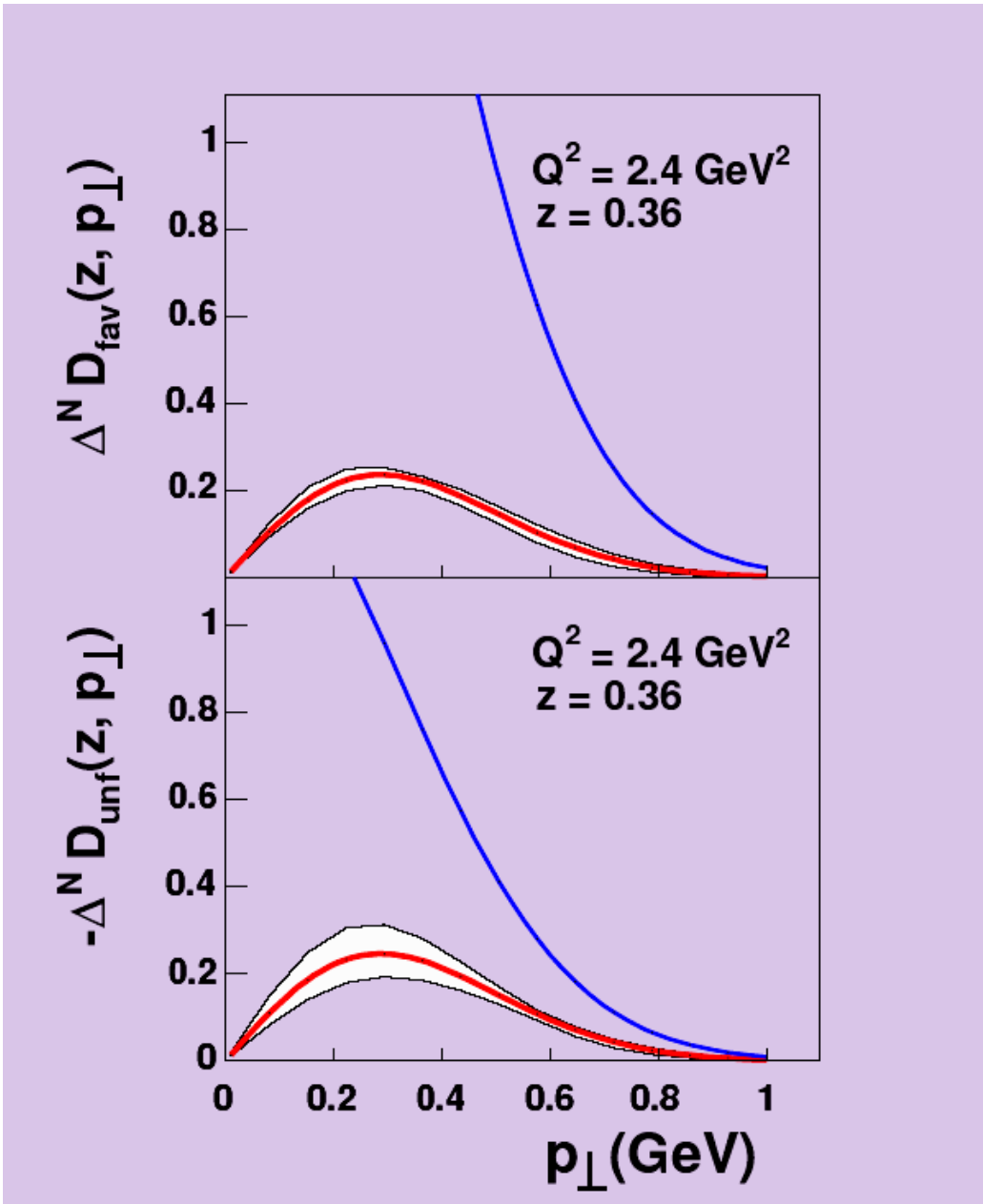
and

COMPASS (d)

pion data,

and

BELLE data

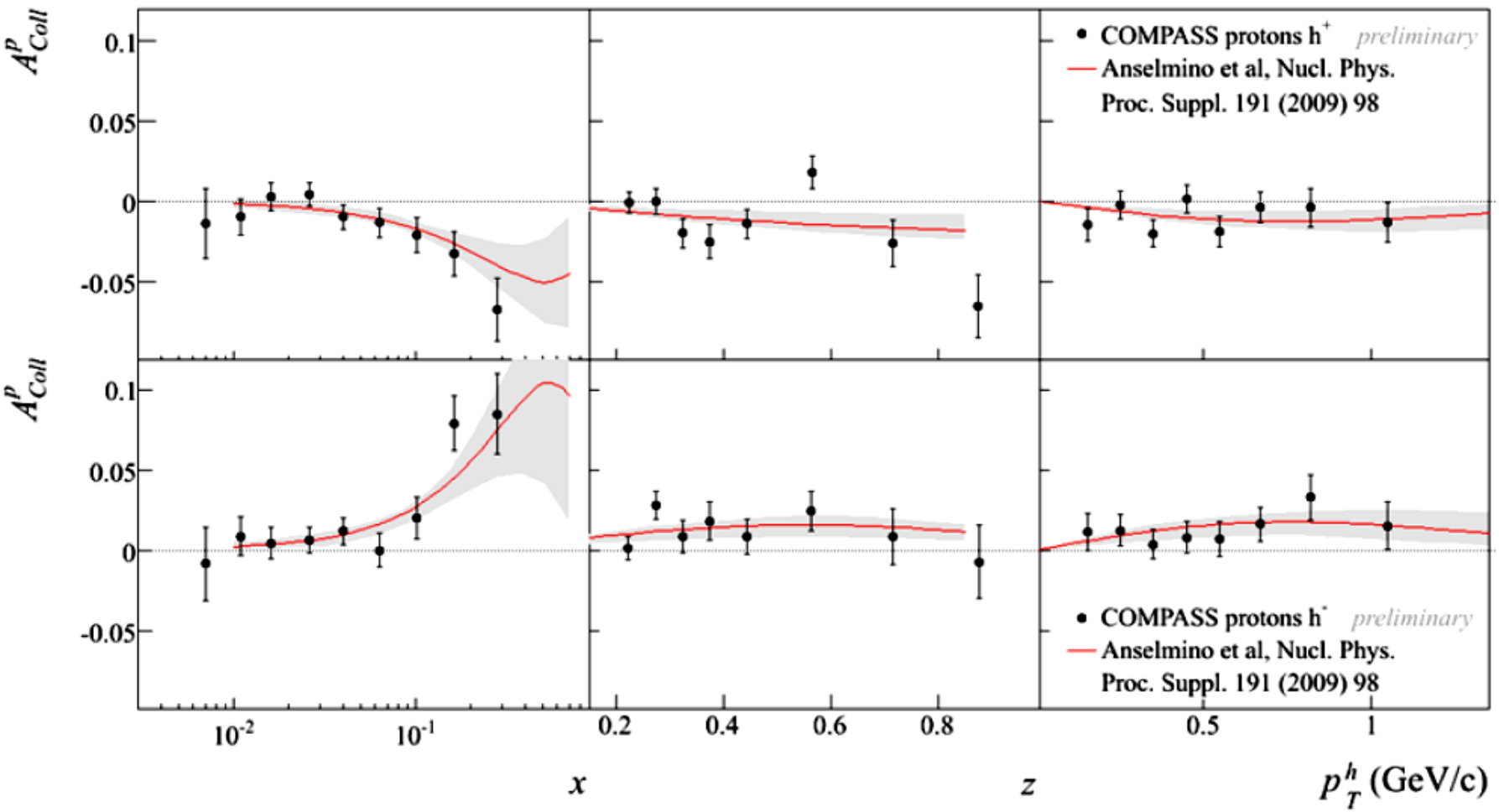


A. Prokudin et al.,
Transversity ´08
Ferrara, Mai ´08

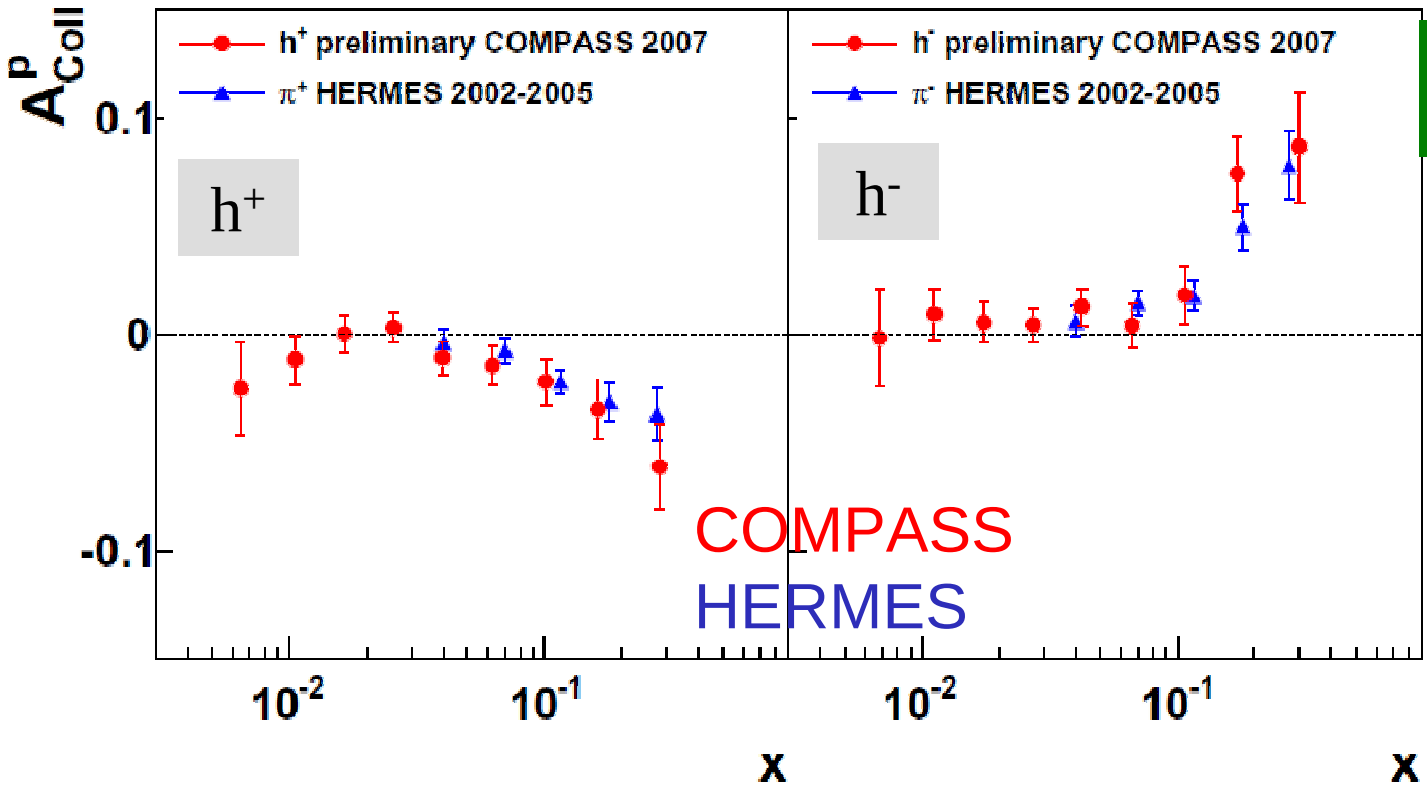
Comparison with predictions

Fit to HERMES proton, COMPASS deuteron, BELLE data

Proton



Comparison COMPASS-HERMES

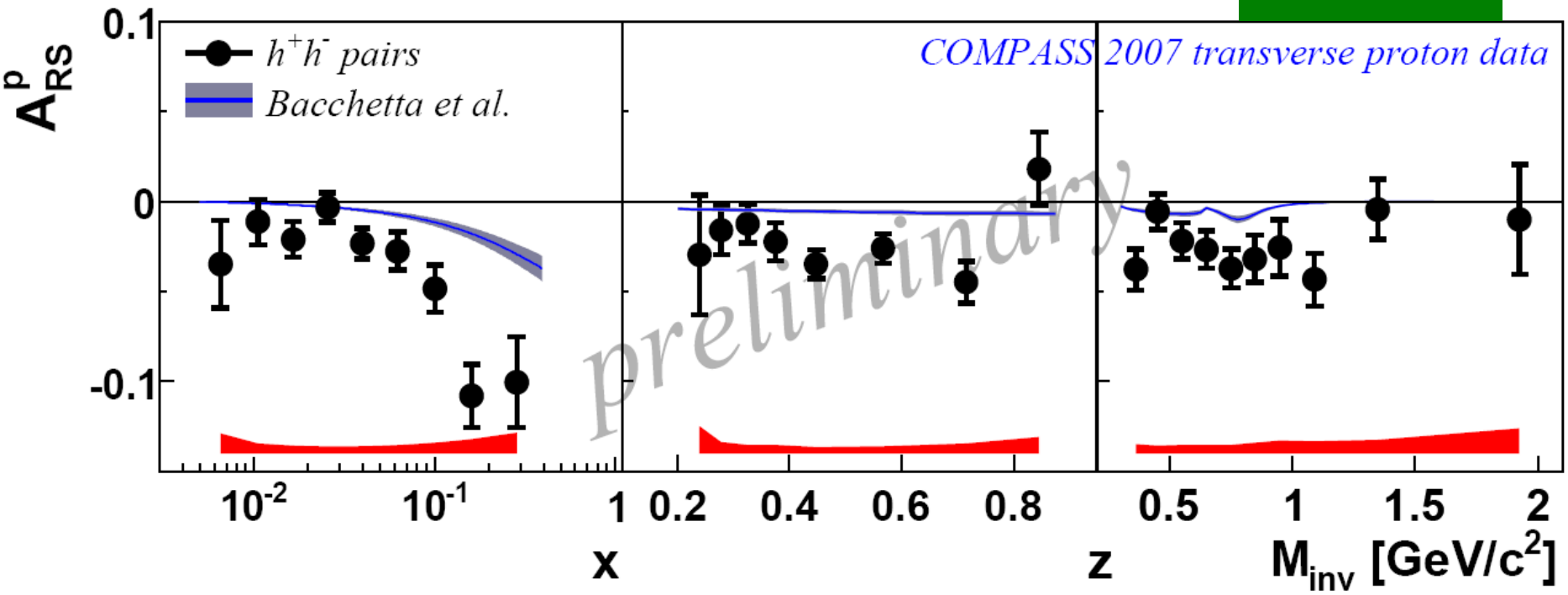


Proton

- large asymmetry ~10%
- good agreement in common *x* range
- zero deuteron result important ⇒ opposite sign of u and d quark transversity PDF

Dihadron-Interference

Proton

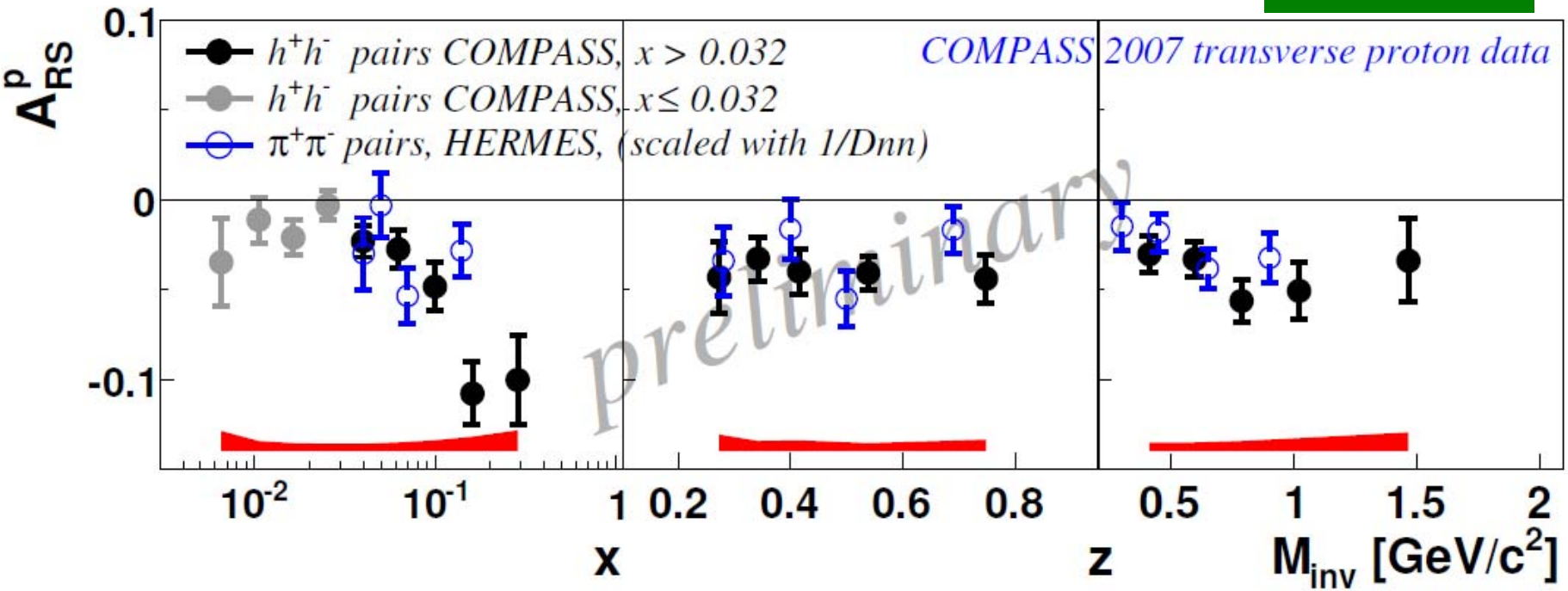


Prediction by Bacchetta, Radici, hep-ph/0608037
(Interference Fragmentation function scaled down to fit HERMES data)

still waiting for extraction of Interference FF by BELLE

Comparison COMPASS-HERMES

Proton



HERMES values scaled with $1/D_{nn}$

COMPASS covers much larger range in x