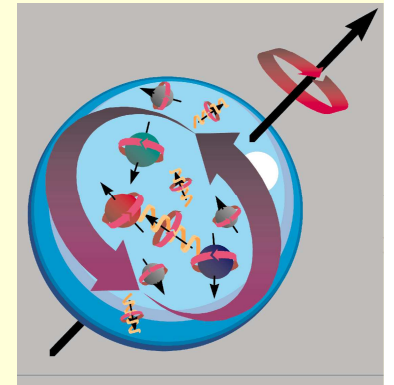


# Longitudinal and Transverse Spin Structure of the Nucleon from DIS

F.Kunne - CEA Saclay, France

- Quark and Gluon Helicity Distributions
  - Collins and Sivers Asymmetries
- HERMES & COMPASS results**



*GHP2009, Denver, USA, April 28-30 2009*

$$\text{Nucleon spin } \frac{1}{2} = \underbrace{\frac{1}{2} \Delta\Sigma}_{\text{Quark}} + \underbrace{\Delta G}_{\text{Gluon}} + \underbrace{L_z}_{\text{Orbital Momentum}}$$

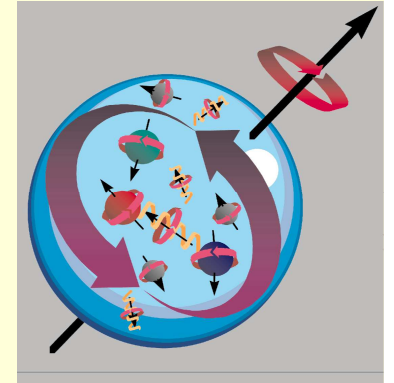
Quark spin contribution  $\Delta\Sigma$ :

Theory: QCD, Ellis-Jaffe with  $\Delta s=0$ :  $\Delta\Sigma=0.6$

Experiment:  $g_1$  spin structure function, SU(3) :

Spin crisis with EMC measurement of  $a_0 \approx \Delta\Sigma$  compatible with 0

Now:  $a_0=0.3$



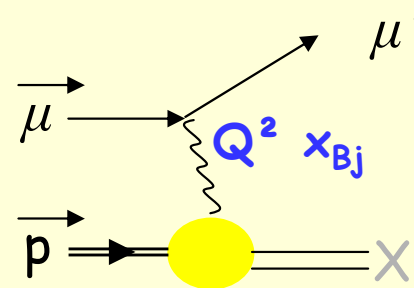
Quark model, QCD  $\overline{MS}$  scheme,  $a_0 = \Delta\Sigma$   
 QCD AB scheme  $a_0 = \Delta\Sigma - n_f (\alpha_s/2\pi) \Delta G$

- For  $a_0 \sim 0.3$ , need  $\Delta G \sim 2.5$  ( $L_z \sim -2.3$ ) to restore  $\Delta\Sigma \sim 0.6$
- $\Delta G$  enters also in the spin  $\frac{1}{2}$  sum rule

# Quark spin contribution $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

$\mu N$  Deep Inelastic Scattering DIS

$$F_1(x) \rightarrow 1/2 \sum_{u,d,s} e^2 q(x)$$

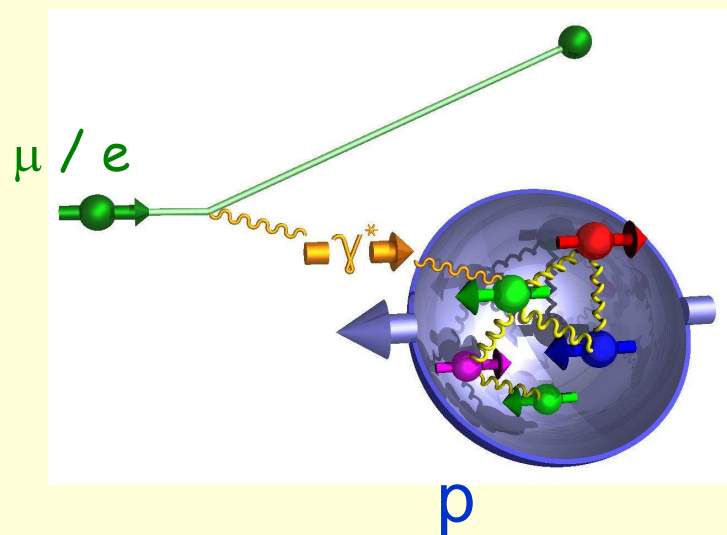


$$Q^2 > 1 \text{ (GeV/c)}^2$$

$x_{Bj}$  parton momentum fraction

$\vec{\mu} \vec{N}$  Polarized DIS

Virtual  $\gamma$  couples to opposite helicity quark  
 $\rightarrow$  measure one helicity distribution  $\vec{q}(x)$



By reversing nucleon polarization  $\rightarrow$   
 measure other helicity distribution  $\overleftarrow{q}(x)$

$$\Delta q = \overleftarrow{q} - \vec{q}$$

$$g_1(x) \rightarrow 1/2 \sum_{u,d,s} e_q^2 \Delta q(x)$$

Spin asymmetry

$$A = \frac{\vec{N} - \overleftarrow{N}}{\vec{N} + \overleftarrow{N}} = \frac{g_1}{F_1}$$

$$\xrightarrow{\text{QPM}} \frac{\sum_{u,d,s} e_q^2 \Delta q(x)}{\sum_{u,d,s} e_q^2 q(x)}$$

# $g_1$ and quark spin contribution $\Delta\Sigma$

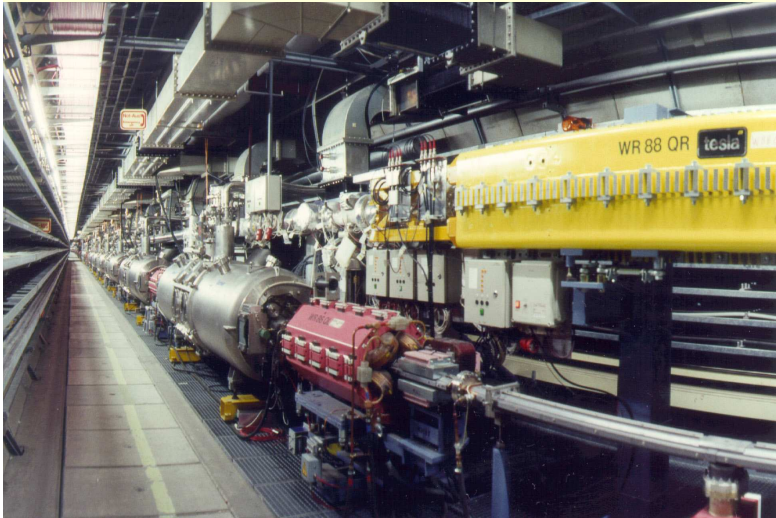
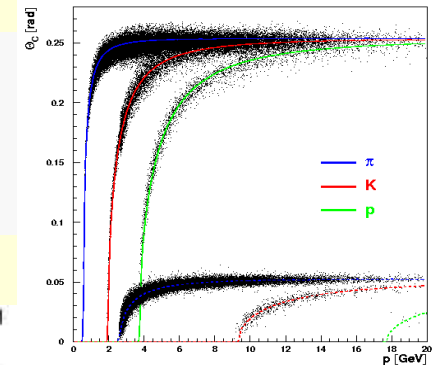
- measure  $\int_0^1 g_1^P dx \longrightarrow 4\Delta u + \Delta d + \Delta s$
- neutron decay constant  $a_3 = \Delta u - \Delta d = g_A = 1.257$
- hyperon  $\beta$  decay +SU(3)  $a_8 = \Delta u + \Delta d - 2\Delta s = 0.585 \pm 0.025$

$$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s$$

# HERMES at DESY

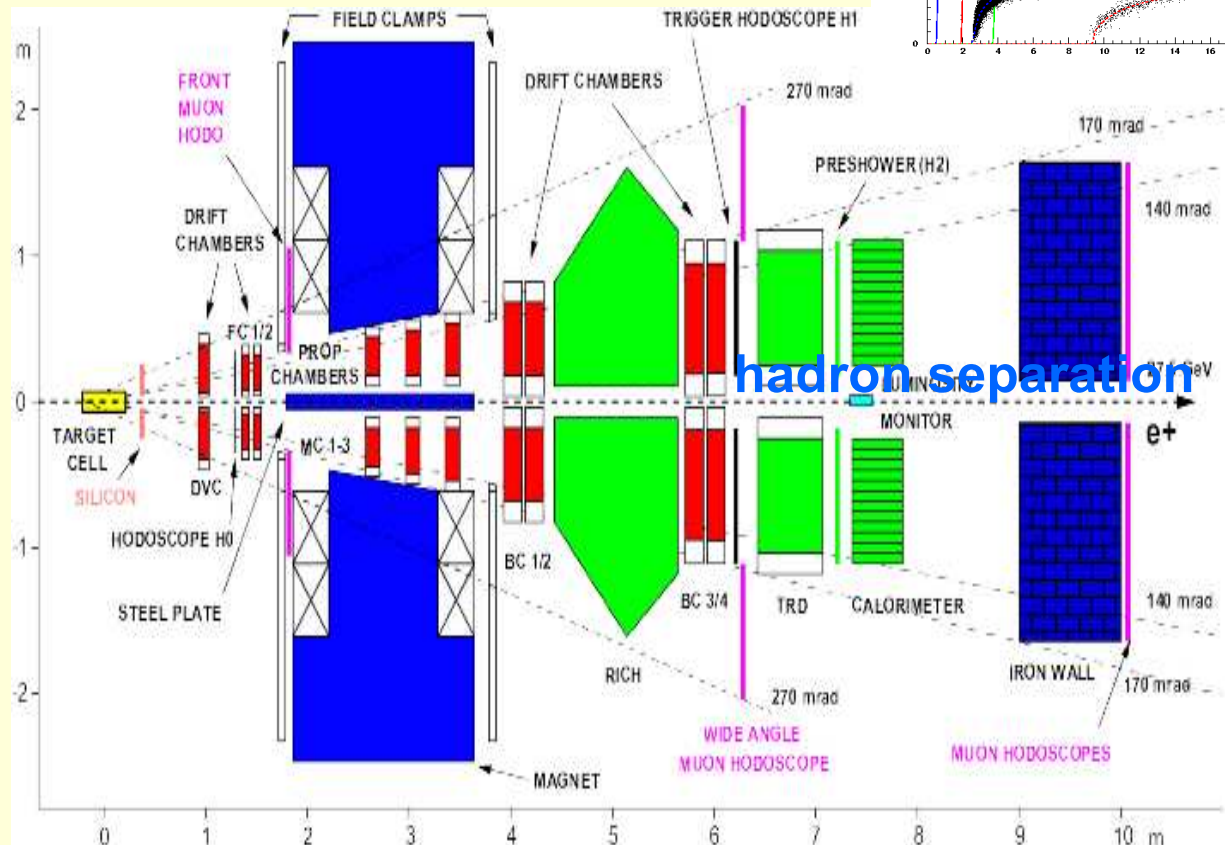
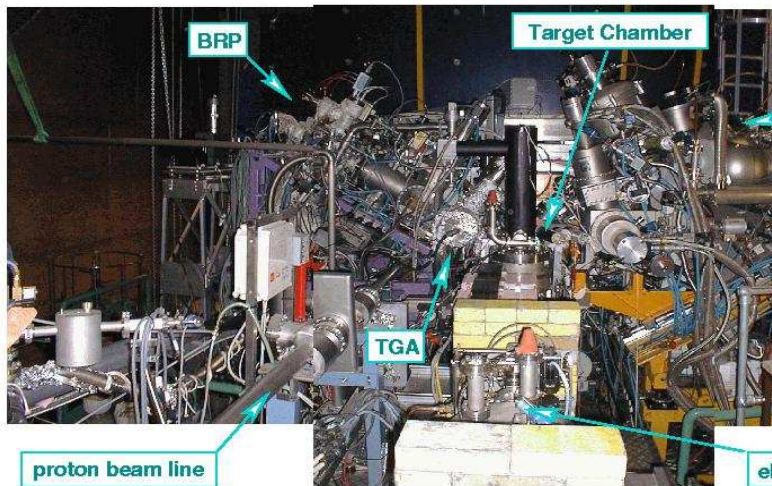
Data taking: from 1995 to 2007

Hermes spectrometer  
 $\Delta p/p \sim 2\%$ ,  $\Delta\theta < 1$  mrad  
 Excellent separation of  $\pi$ , K, p



HERA ring  $e^+$  and  $e^-$  27.6 GeV  
 longitudinally polarized  $\sim 54\%$

Gaseous internal target  
 Longit. Polar. 85% H, D, He  
 Transv. Polar H  
 Unpol H, D, Ne, Kr



Muon setup :

$160 \text{ GeV } \vec{\mu}$ ,  $P_B=80\%$

${}^6\text{LiD}$   $P_T=50\%$  2002-2006

$\text{NH}_3$   $P_T=80\%$  2007

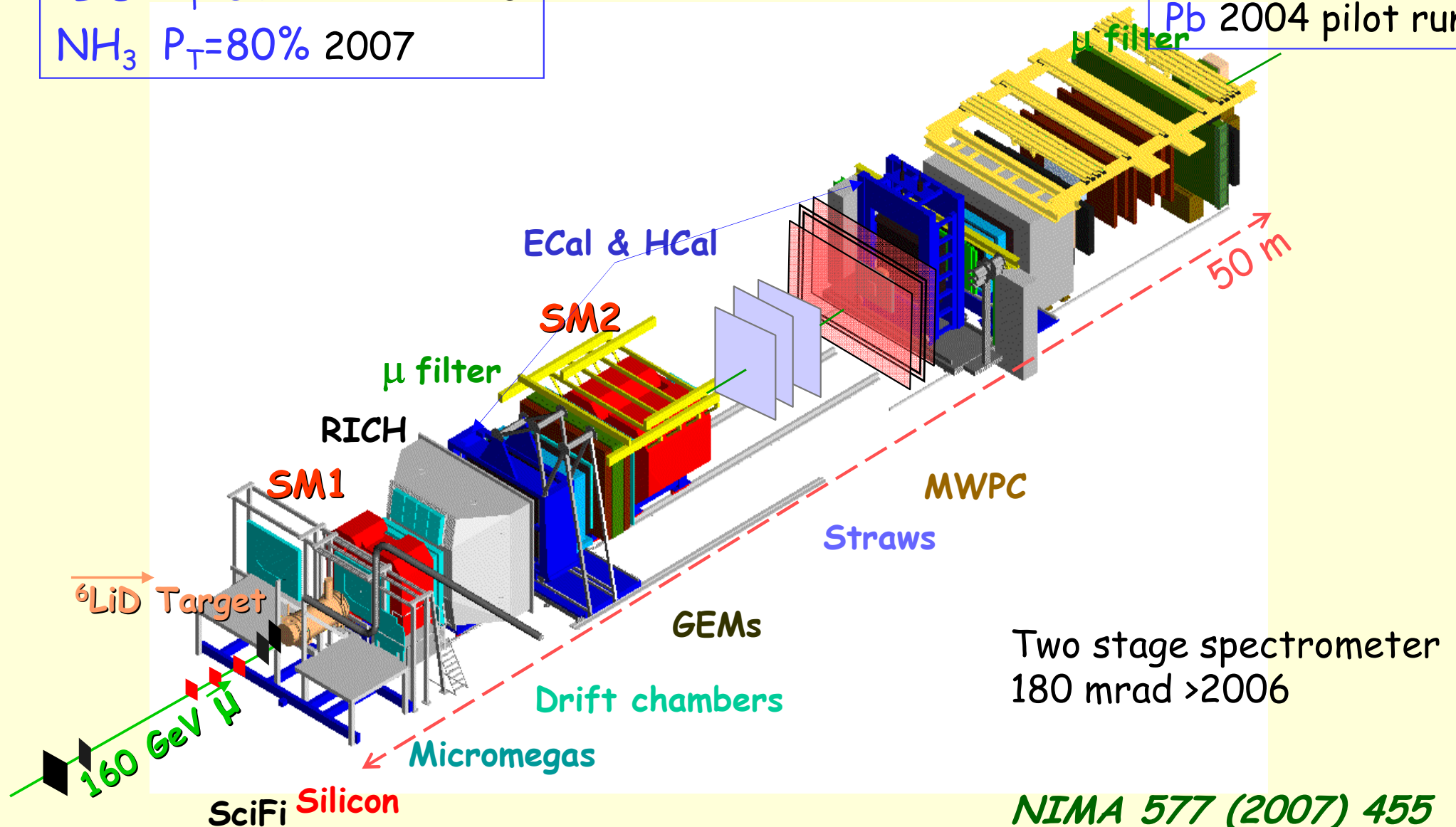
# COMPASS at CERN

Hadron setup :

$190 \text{ GeV } \pi / p$

$\text{LH}_2$  2008-2009

$\text{Pb}$  2004 pilot run



# $\Delta\Sigma$ from Spin structure function $g_1$

## COMPASS

$$\Delta\Sigma = 0.30 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (evol)}$$

COMPASS fit to  $g_1^{p,n,d}$  world data,  $\overline{MS}$  scheme,  $Q^2=3 \text{ (GeV/c)}^2$   
PLB 647 (2007) 8

$$\Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (evol)} \text{ COMPASS data only}$$

## HERMES

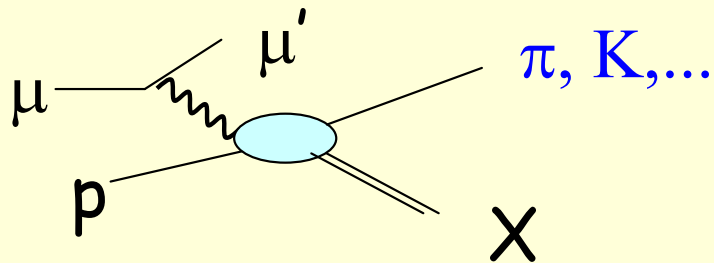
$$\Delta\Sigma = 0.33 \pm 0.011 \text{ (stat)} \pm 0.025 \text{ (theo)} \pm 0.028 \text{ (evol)}$$

HERMES from  $g_1^d$  data,  $\overline{MS}$  scheme,  $Q^2=5 \text{ (GeV/c)}^2$ ,  
neglecting  $x < 0.02$  contrib., PRD75 (2007)012007

$$\Delta s + \Delta \bar{s} = -0.085 \pm 0.013 \text{ (th)} \pm 0.008 \text{ (exp)} \pm 0.009 \text{ (evol)}$$

# Flavor dependent quark helicity distributions

Semi-inclusive DIS measurements



- Outgoing hadron tags quark flavour
- Need to know fragmentation functions of quark  $q$  into hadron  $h$ :  $D_q^h(z)$

$$z = E_h / (E_\mu - E_{\mu'})$$

$$A_1^{h(p/d)} = \frac{\sum_q e_q^2 D_q^h \Delta q}{\sum_q e_q^2 D_q^h q}$$

With **deuteron** data alone, can extract at LO:

$$\Delta u_v + \Delta d_v, \quad \Delta \bar{u} + \Delta \bar{d}, \quad \Delta s = \Delta \bar{s}$$

COMPASS

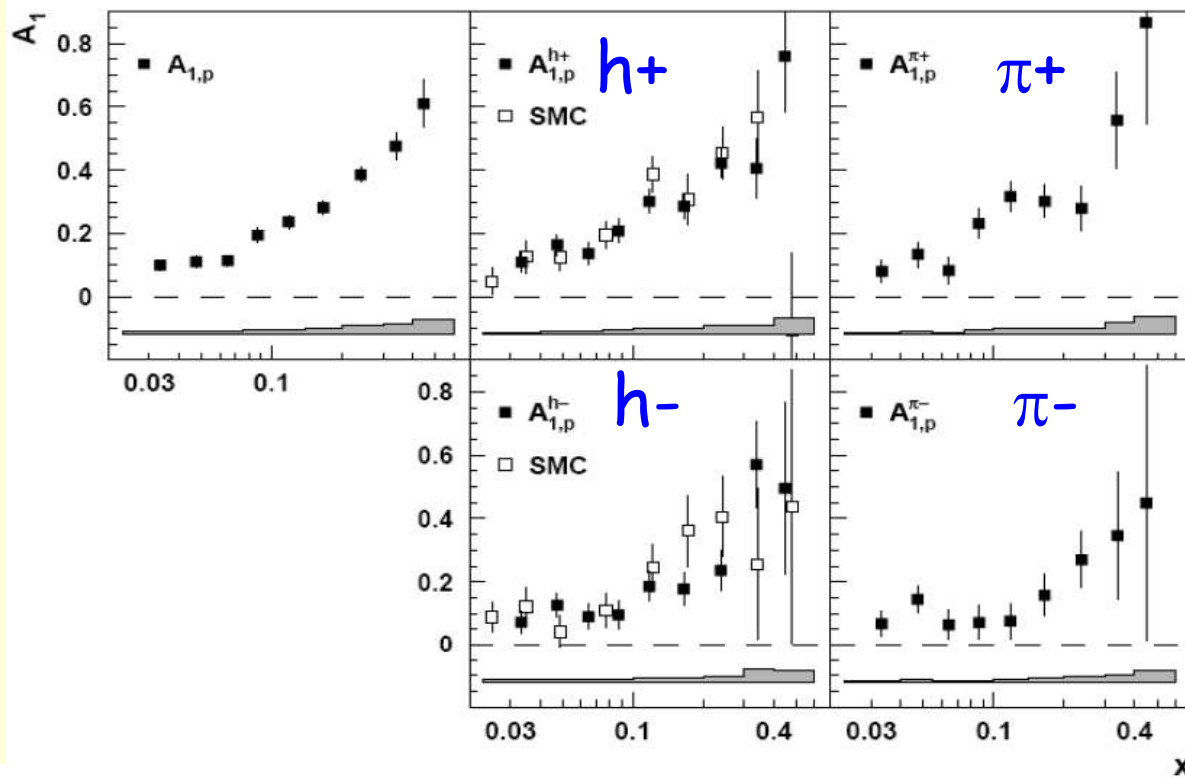
With **deuteron + proton** data, can extract at LO:

$$\Delta u_v, \quad \Delta d_v, \quad \Delta \bar{u}, \quad \Delta \bar{d} \text{ and } \Delta s = \Delta \bar{s} \text{ separately}$$

HERMES



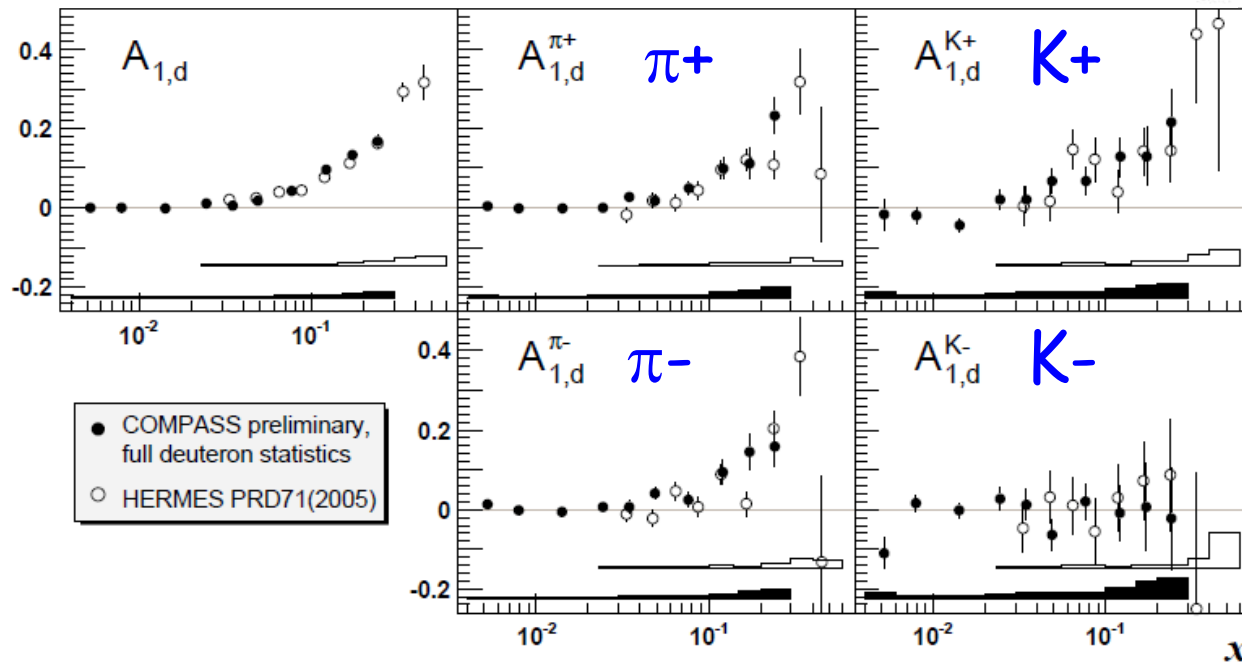
# Inclusive & Semi-inclusive Spin Asymmetries



Proton

SMC, HERMES

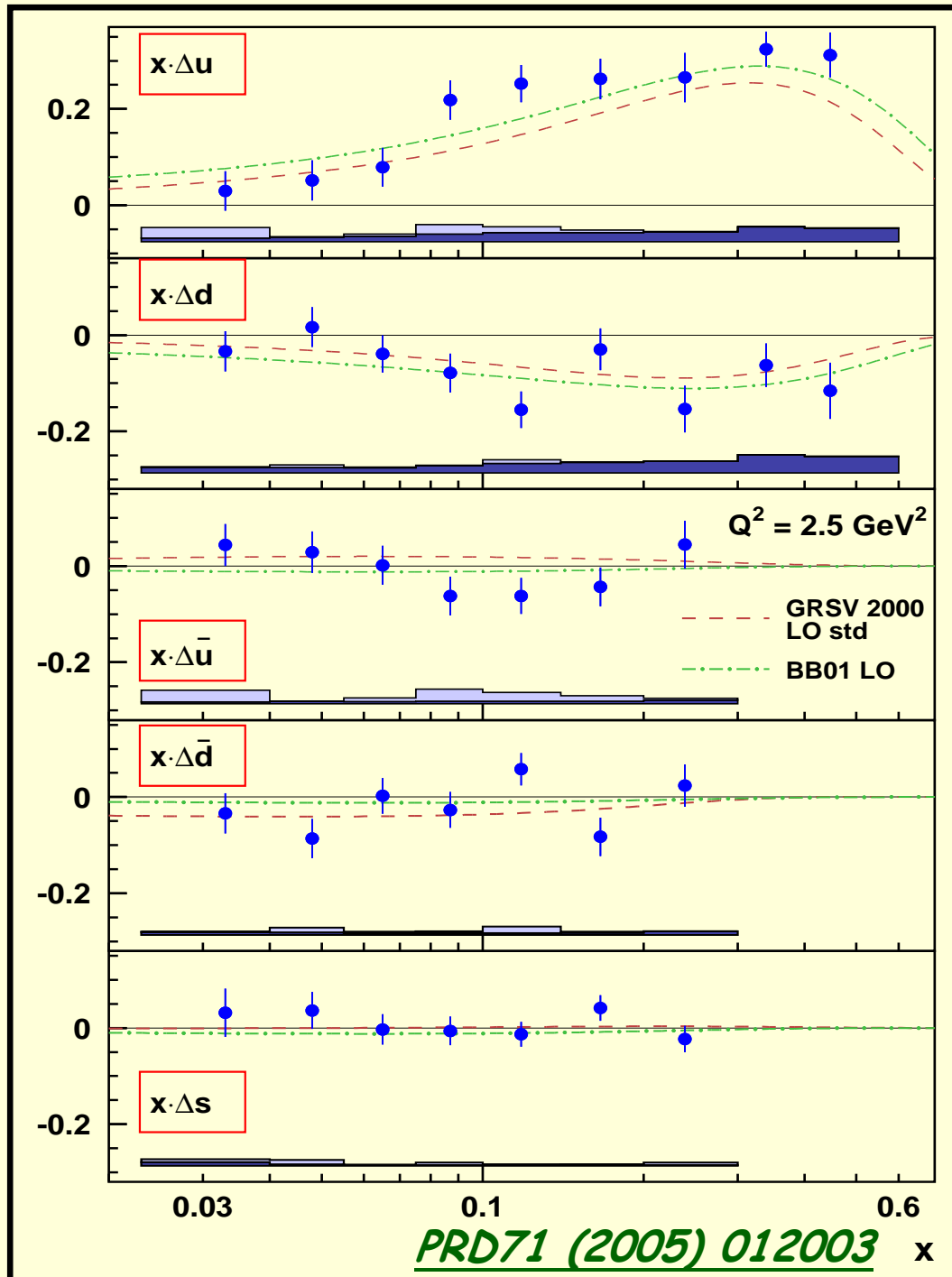
(2007 COMPASS proton data still to come...)



Deuteron

HERMES, COMPASS

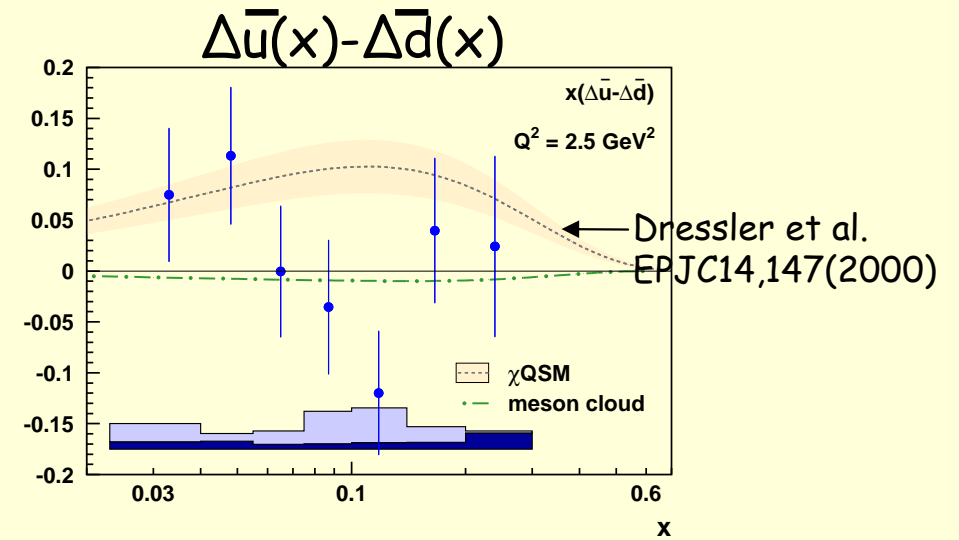
# HERMES - Helicity quark distributions



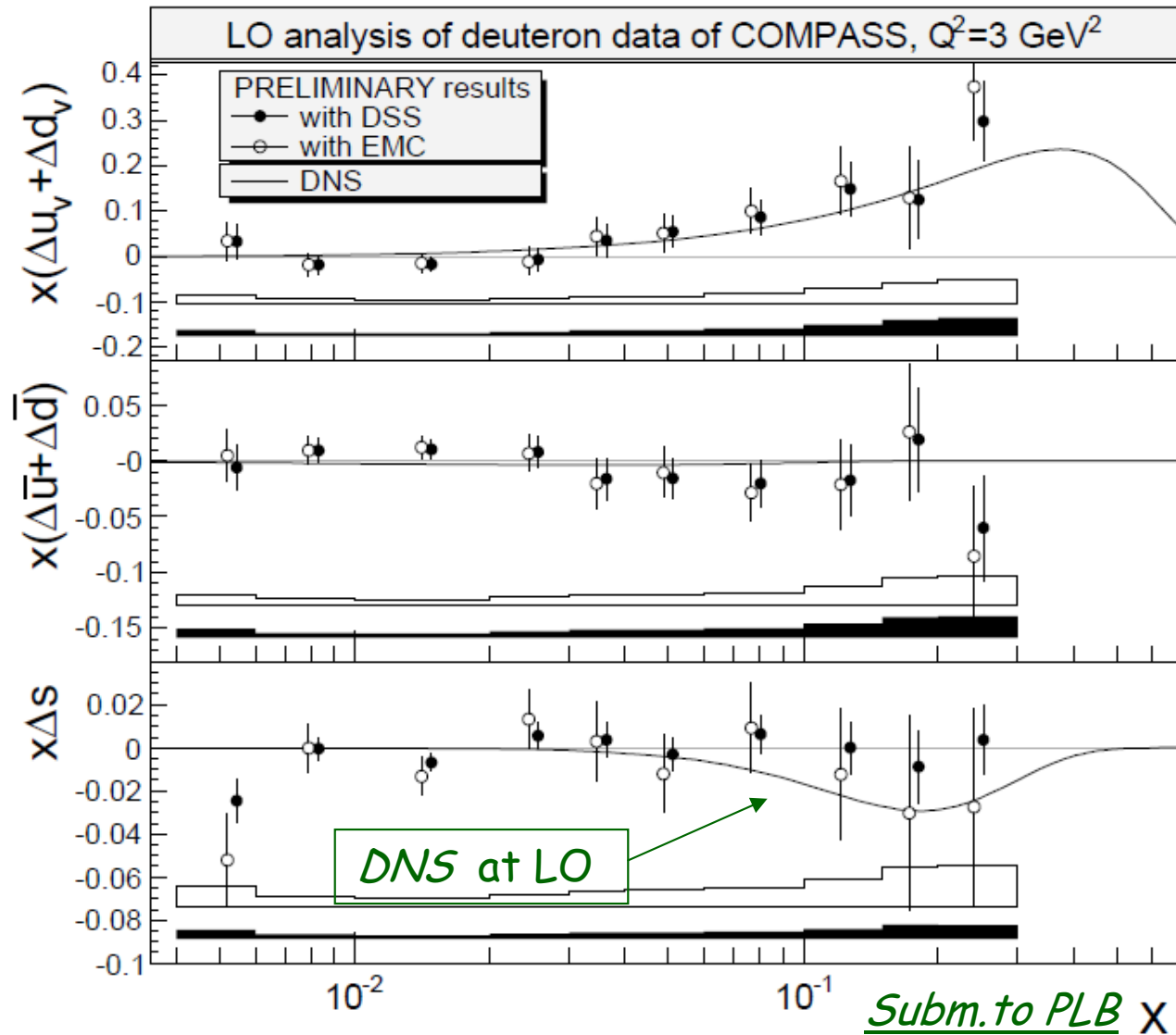
No assumption on sea polarization

$\Delta u(x)$  and  $\Delta d(x)$  good agreement with LO-QCD fit to inclusive data

Sea quark polarizations  $\Delta \bar{u}(x)$ ,  $\Delta \bar{d}(x)$  and  $\Delta s(x)$  ~ zero in measured region  $0.02 < x < 0.3$



# COMPASS - Helicity quark distributions



from deuteron alone

$\Delta u_v + \Delta d_v$  in agreement with results from  $A^{h^+ - h^-}$

$\Delta \bar{u} + \Delta \bar{d} \sim 0$   
asymmetric sea

$\Delta s$  value and error 2-3x larger with EMC than DSS frag. fct.

Strong dependence on  $s \rightarrow K$  frag. function

→ First moment  $\Delta s = \Delta \bar{s} = -0.1 \pm 0.1 \pm 0.1$  in  $0.004 < x < 0.3$

Need more statistics. Fragmentation functions? Low  $x$  contribution?

(to be compared to  $\Delta s = -0.045 \pm 0.005 \pm 0.010$  from inclusive data  $\Gamma_1^N$ ,  $0 < x < 1$  using F and D).

# Isoscalar extraction of $s(x)$ and $\Delta s(x)$

HERMES & COMPASS

- Use kaon multiplicities ( $K^+ + K^-$ ) from deuteron data only

$$K^+ = u\bar{s} \quad K^- = \bar{u}s \quad \text{high sensitivity to } s(x)$$

- From spin asymmetries  $A_1^d$  and  $A_1^d (K^+ + K^-)$   
extract  $\Delta Q = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d}$  and  $\Delta S = \Delta s + \Delta \bar{s}$

Assume : isospin symmetry p & n

charge conjugation invariance in fragmentation

$$D_q^{K^+ + K^-}(z) = D_{\bar{q}}^{K^+ + K^-}(z)$$

# Isoscalar extraction of $s(x)$ and $\Delta s(x)$

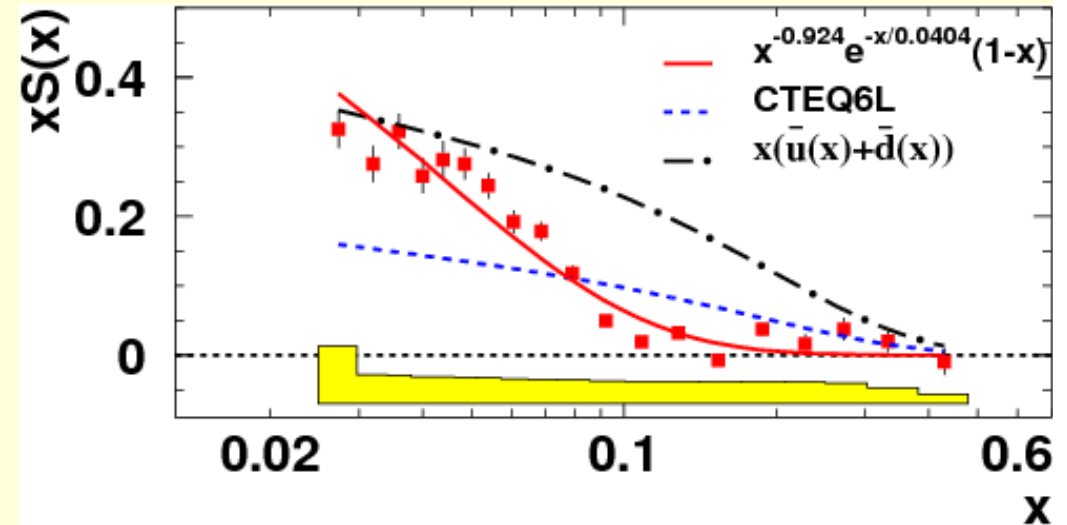
HERMES

- Unpolarized distributions

$$S(x) = s(x) + \bar{s}(x)$$

from Kaon multiplicities  
& frag. function from DSS.

→ Shape incompatible with CTEQ6L



- Helicity distributions

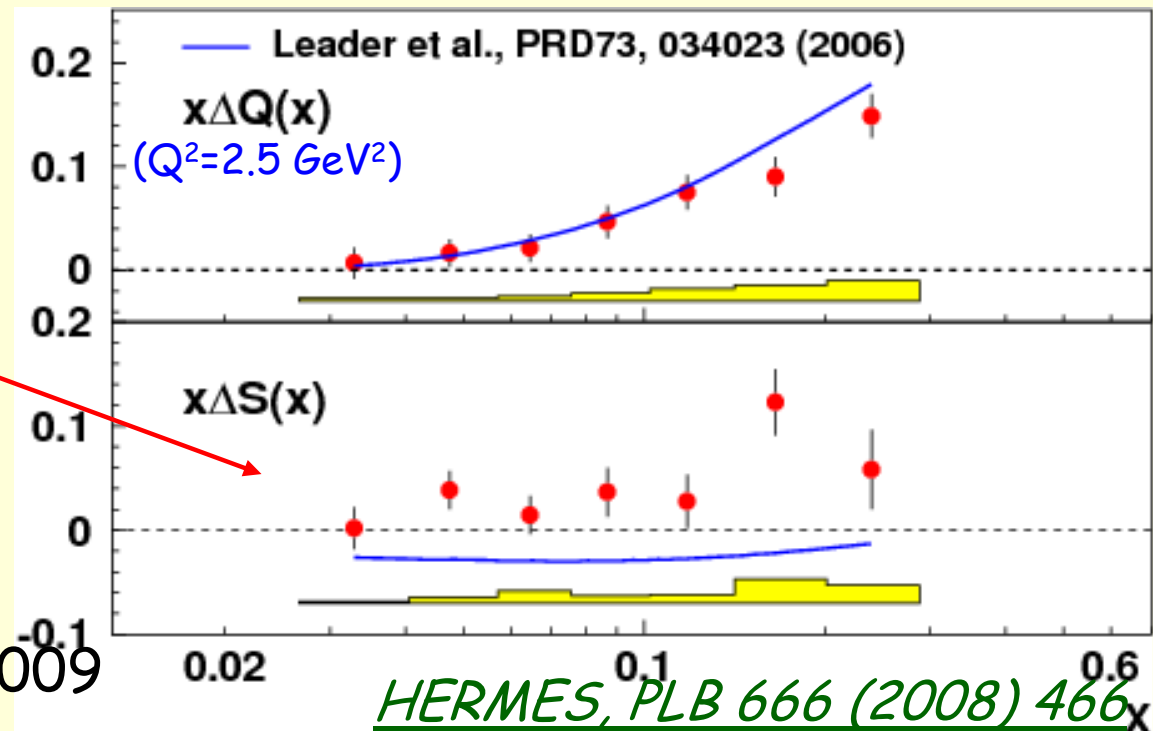
First moment in measured  
range  $0.2 < x < 0.8$ :

$$\Delta s + \Delta \bar{s} = 0.037 \pm 0.019 \pm 0.027$$

~zero or slightly  $> 0$

To be compared to result  
from inclusive data  $0 < x < 1$

$$\Delta s + \Delta \bar{s} = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$$



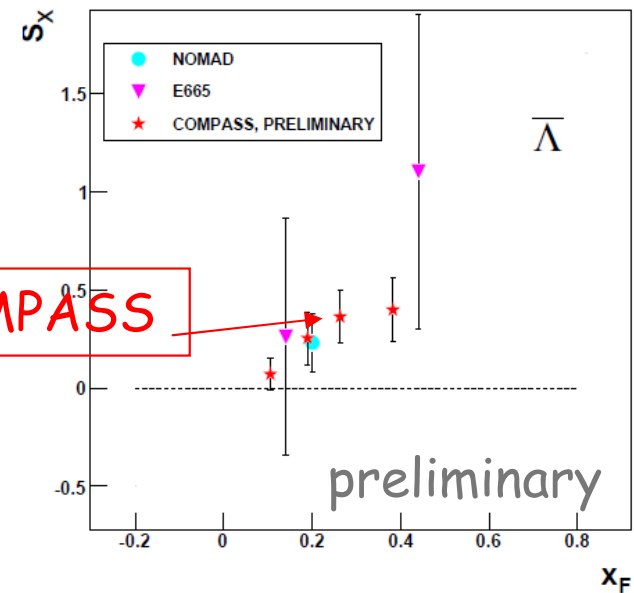
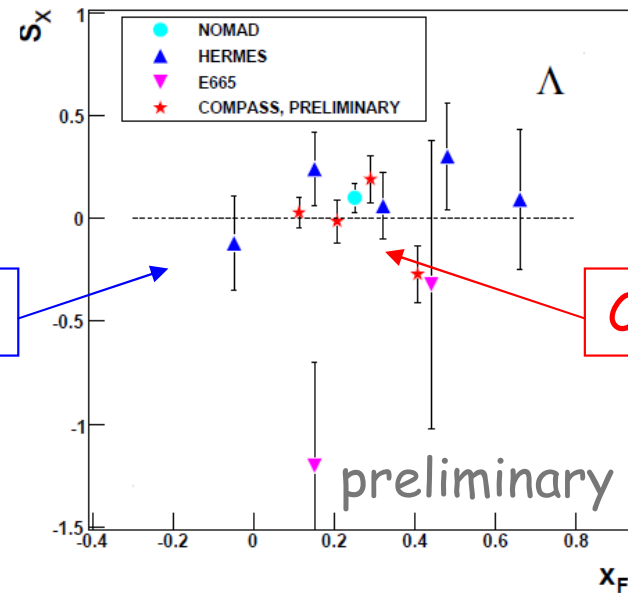
HERMES, PLB 666 (2008) 466  
arXiv:0803.2993

# Longitudinal spin transfer to $\Lambda$ & $\bar{\Lambda}$

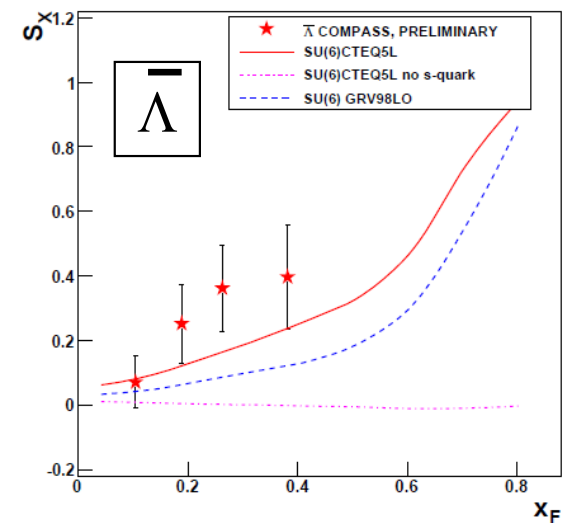
$$\vec{\gamma}^* N \rightarrow \vec{\Lambda} X$$

Polarized beam  
Unpolarized target

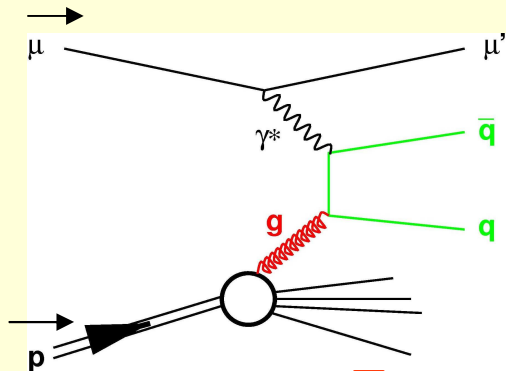
HERMES



- Spin transfer for anti- $\Lambda$  is large and positive
- Alternate way to access  $s$  distribution and  $\Delta s$  if polarized target



# $\Delta g/g$ Measurement- Photon Gluon fusion PGF



$\gamma g \rightarrow q\bar{q}$

•  $q=c$  open charm  $c \rightarrow D^0 \rightarrow K \pi$

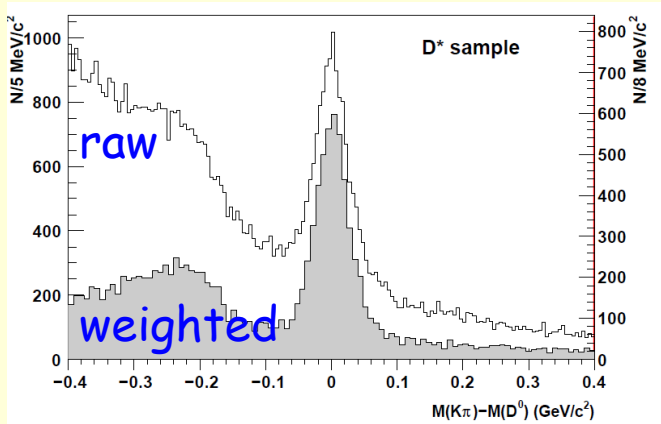
Clean signature of PGF

pQCD scale  $\mu^2 = 4(m_c^2 + p_T^2)$

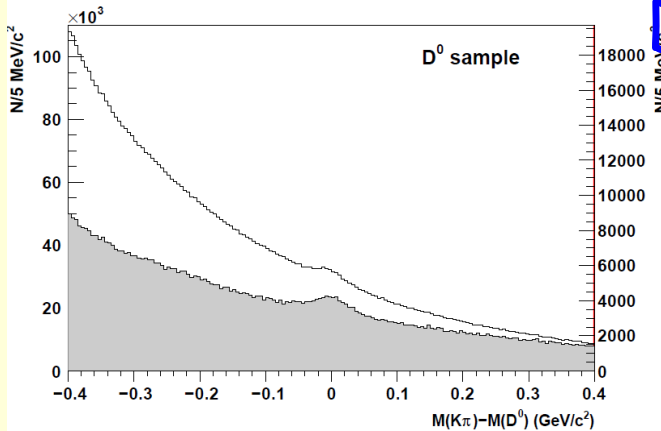
Combinatorial background & limited statistics

COMPASS

# Open charm events from COMPASS for $\Delta g/g$



$D^* \rightarrow D^0 \pi_s \rightarrow K \pi \pi_s$   
8700 events



$D^0 \rightarrow K \pi$   
37400 events

$$\Delta g/g = -0.49 \pm 0.27 \text{ (stat)} \pm 0.11 \text{ (syst)}$$

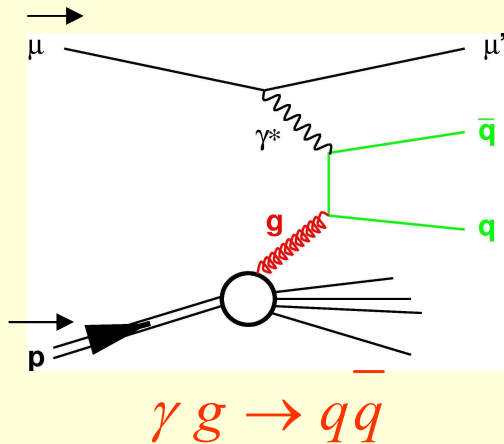
at  $x_g \sim 0.1$  and  $\langle \text{QCD scale} \rangle \sim 13 \text{ GeV}^2$

*Phys. Lett. B, in press*  
*hep-ex 0904.3209*

- $\langle \Delta g/g \rangle$  at LO prefers negative value, but  $\langle 2\sigma$  away from 0
- NLO? Model independent spin asymmetries  $A(\gamma^* N \rightarrow DX)$  in  $(p_T, E_D)$  bins chosen such that  $a_{LL} \sim \text{constant}$ , will be used for comparison to NLO QCD fits and for extraction of  $\Delta g/g$  at NLO. *In progress*



# $\Delta g/g$ Measurement- Photon Gluon fusion PGF



- $q=c$  open charm  $c \rightarrow D^0 \rightarrow K \pi$

Clean signature of PGF

pQCD scale  $\mu^2 = 4(m_c^2 + p_T^2)$

Combinatorial background & limited statistics

COMPASS

- $q=u,d,s$  high  $p_T$  hadron pair  $q q \rightarrow h h$

High statistics

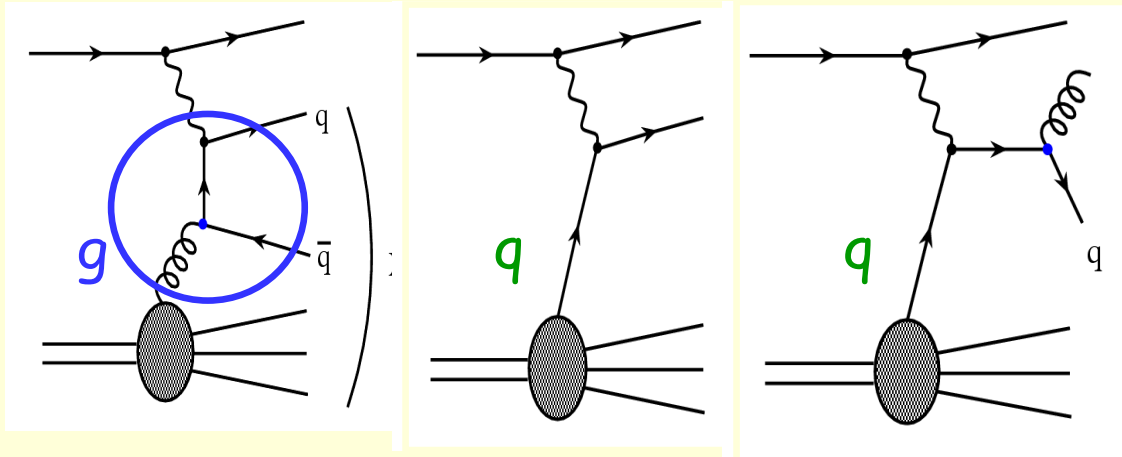
pQCD scale  $Q^2$  or  $\Sigma p_T^2$

Physical background, better described for high  $Q^2$

HERMES & COMPASS

# $\Delta g/g$ from high $p_T$ hadron pairs

$Q^2 > 1 \text{ (GeV/c)}^2$

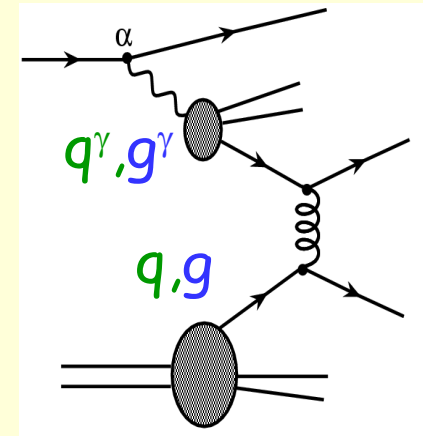


Photon Gluon  
Fusion  $\sim 30\%$

Leading Order

QCD Compton

$Q^2 < 1 \text{ (GeV/c)}^2$



Resolved  $\gamma \sim 50\%$

$R$  and  $a_{LL}$  from effective model in Monte-Carlo for all processes

- **HERMES** : measurement at all  $Q^2$
- **COMPASS** : values for  $Q^2 > 1$  and  $Q^2 < 1$

$\rightarrow \Delta g/g$  values at  $\langle \text{QCD scale} \rangle \sim 3 \text{ GeV}^2$ ,  $x_g \sim 0.1$  ; All compatible with zero

# $\Delta g/g$ direct measurements

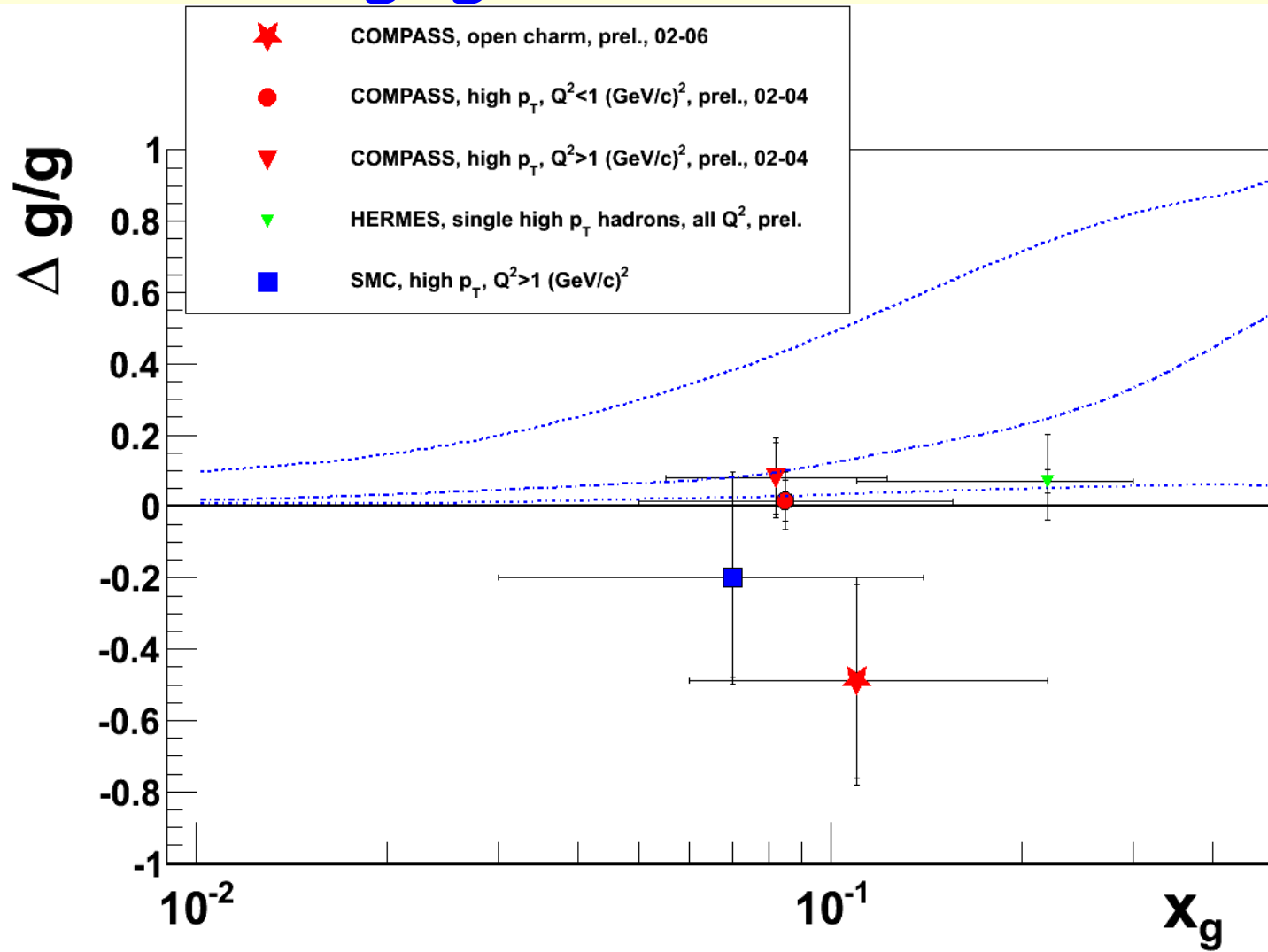
GRSV fits  
to  $g_1(x, Q^2)$

$$\int \Delta g(x) dx = 2.5$$

$$\int \Delta g(x) dx = 0.6$$

$$\int \Delta g(x) dx = 0.2$$

$\Delta g/g$  values  
extracted at LO  
Fits at NLO



$\Delta g/g$  small for  $0.04 < x < 0.2$

Direct measurements exclude  $\Delta G$  as large as GRSV max.

*See RHIC pp Asymmetries in Spin Session*

# Consequence for nucleon spin

$\Delta G = \int \Delta g(x) dx$  not large, both from direct measurements (essentially high  $p_T$  + RHIC) and present  $g_1$  QCD fit:  $|\Delta G| < 0.35$

$$\Delta \Sigma = a_0 + \underbrace{(3\alpha_s/2\pi) \Delta G}$$

within  $\pm 0.06$  for  $\Delta G$  within  $\pm 0.35$  at  $Q^2=3$

$\rightarrow \Delta \Sigma \sim 0.30$  **small** ( $\neq$  predictions)

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

possible scenarios:

$$\left\{ \begin{array}{l} \frac{1}{2} 0.3 + 0.35 + 0.0 \\ \frac{1}{2} 0.3 + 0.0 + 0.35 \\ \frac{1}{2} 0.3 - 0.35 + 0.7 \end{array} \right.$$

# Transversity

- Transversely polarized target
- Measure simultaneously two azimuthal asymmetries

{ Collins: Outgoing hadron direction & quark transverse spin  
Sivers: nucleon spin & quark transverse momentum

## Collins

q transverse spin distr.

$$A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Collins fragm.  
function,  
depends on spin

## Sivers

$$A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^\perp \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

note:  $\Delta_T q$  also measured using  
hadron pair Interference FF, or  
lambda Transverse. Polarization

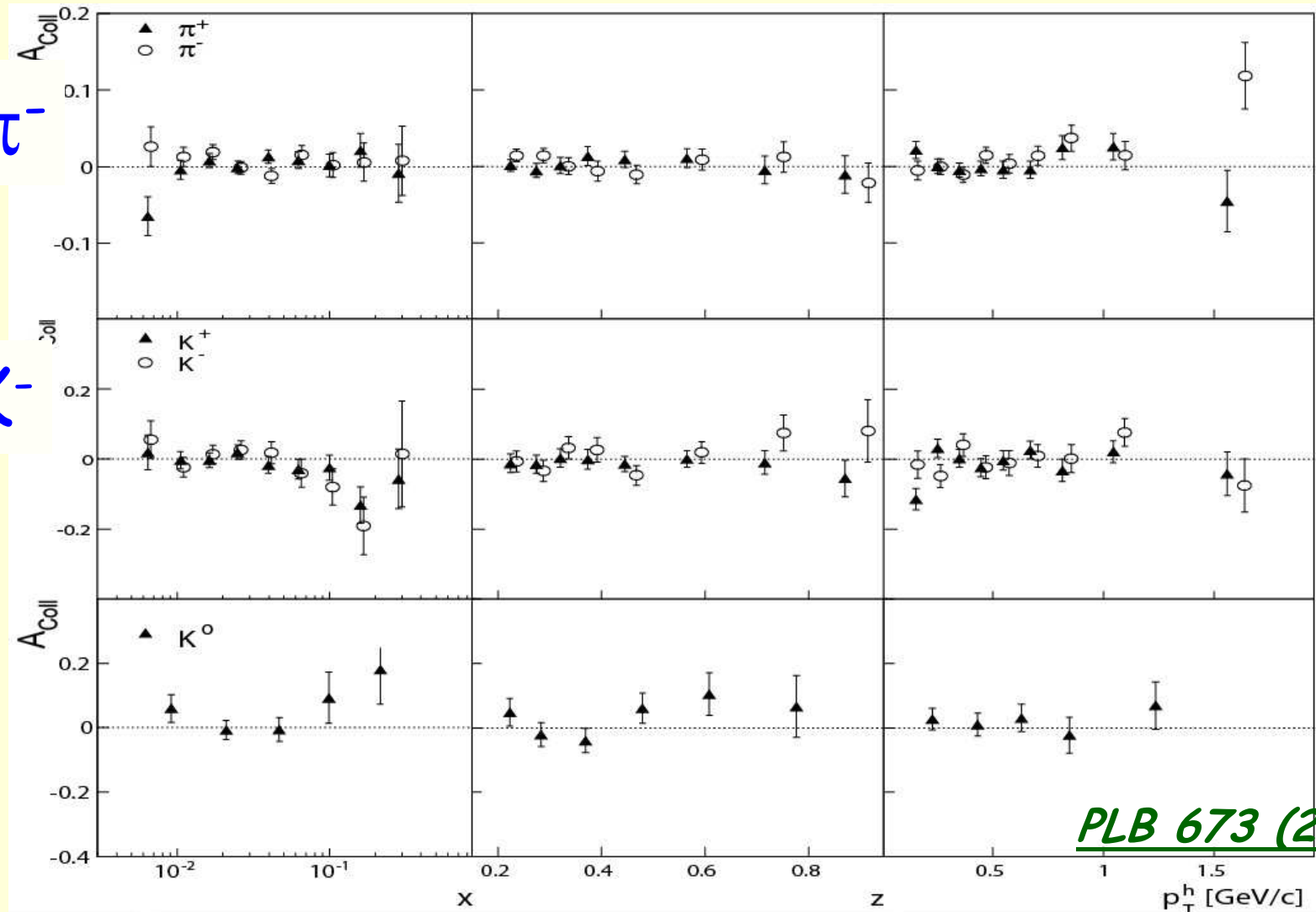
# Transversity : Collins Asymmetry on deuteron

COMPASS

$\pi^+$ ,  $\pi^-$

$K^+$ ,  $K^-$

$K^0$

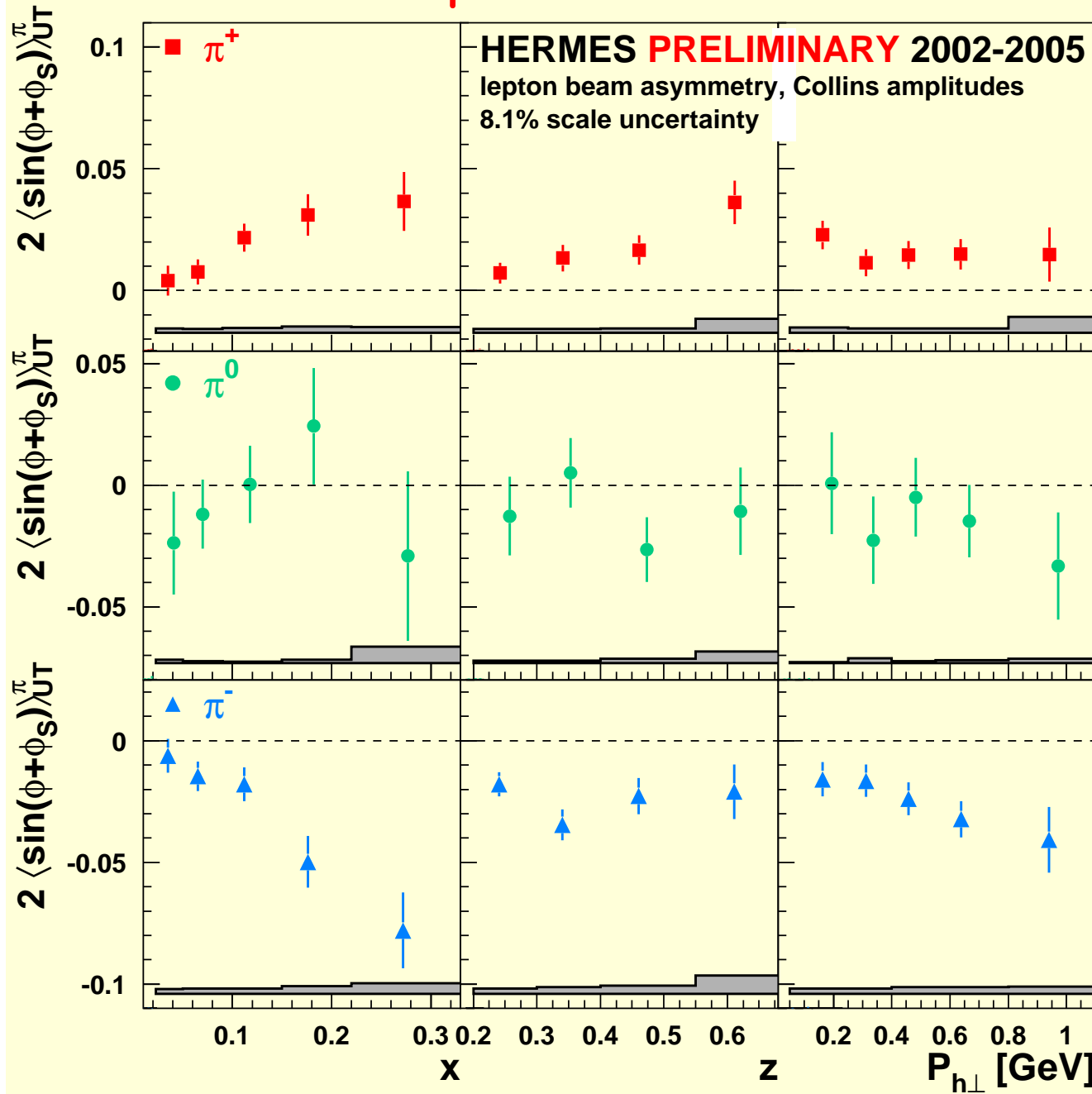


PLB 673 (2009) 127

- All asymmetries **compatible with zero** : hint for  $\Delta u_T + \Delta d_T$  cancellation
- Acces to **d** quark in global fits

# Transversity : Collins Asymmetry on proton

HERMES pions

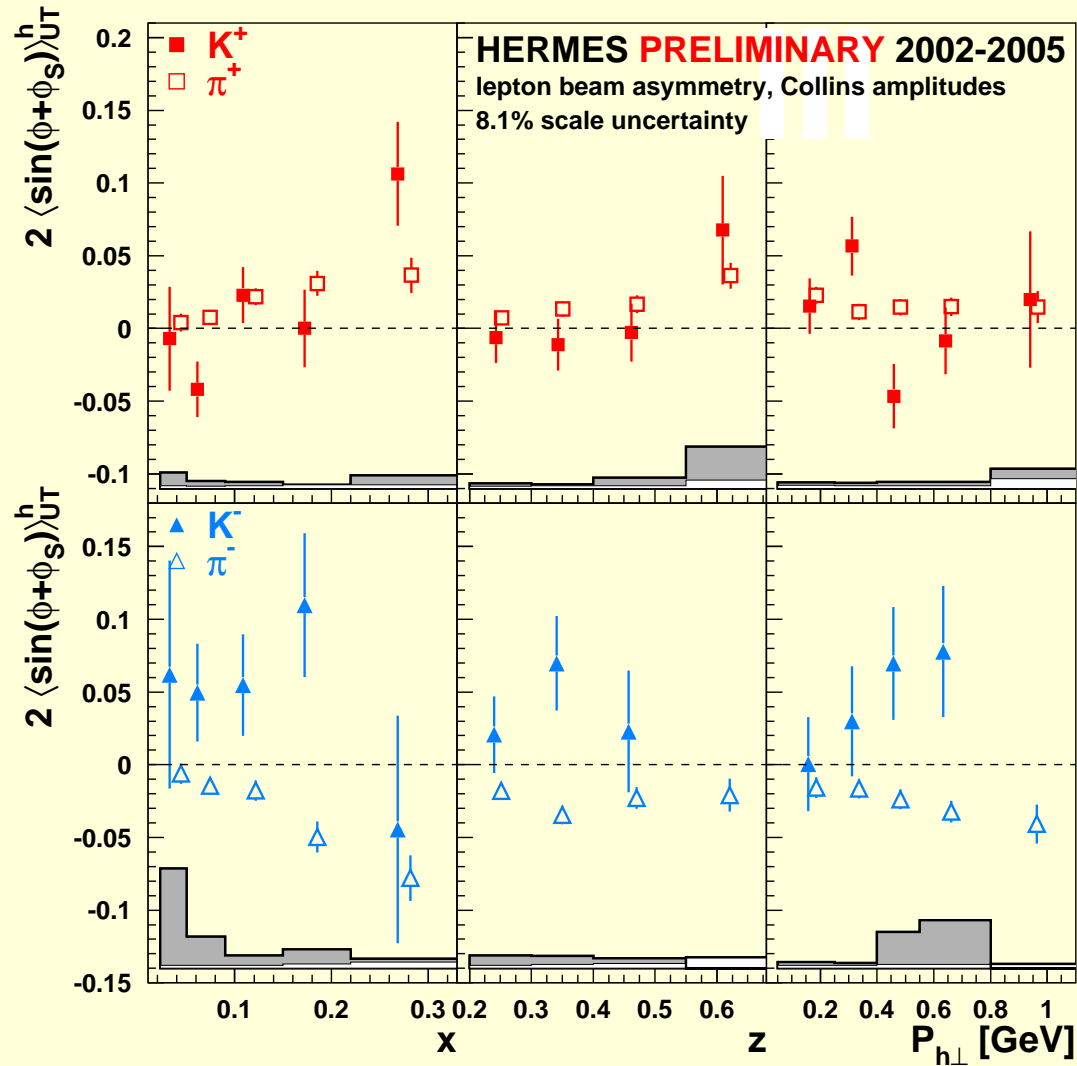


• Both transversity & Collins fragm.function  $\neq 0$

• Opposite results for  $\pi^+$  &  $\pi^-$  suggest opposite  $u$  &  $d$  Collins fragm.function

# Transversity : Collins Asymmetry on proton

## HERMES K/ $\pi$ comparison

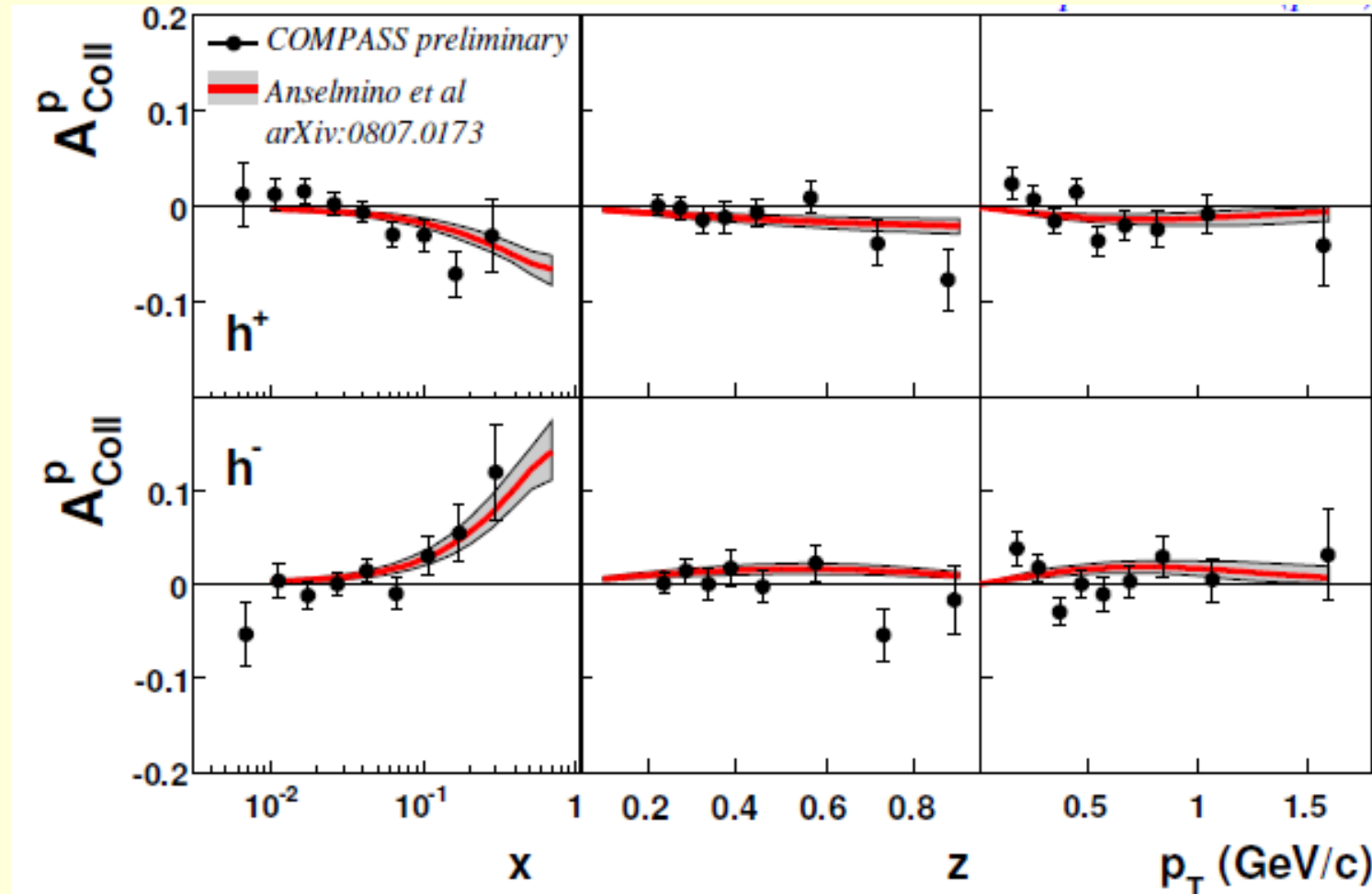


- $K^+$  &  $\pi^+$  : similar (u dominance)
- $K^-$  &  $\pi^-$  opposite ( $K^- = \bar{u}s$  sea quark dominance)



# Transversity : Collins Asymmetry on proton

COMPASS 2007 (part)



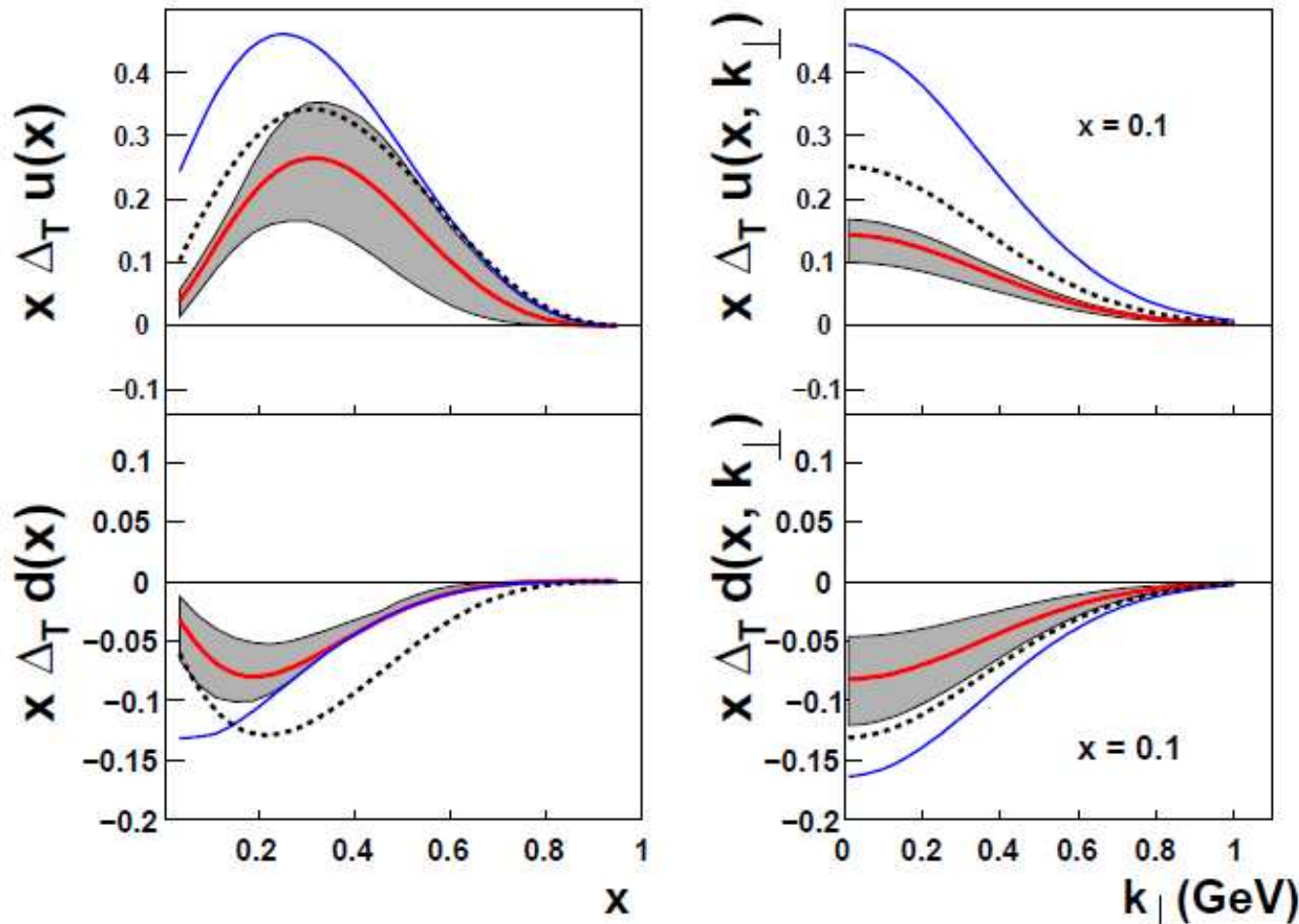
COMPASS data  
not included in  
fit

Combined analysis of deuteron, proton and frag. fct data  
lead to extraction of  $\Delta u_T$  and  $\Delta d_T$

# Extraction of $\Delta u_T$ and $\Delta d_T$

Several combined analyses of **COMPASS** deuteron, **HERMES** proton and **BELLE** fragm.fct. data, by Anselmino et al., Efremov et al., Vogelsang et al. ...

Results from M. Anselmino et al. arXiv:0812.4366:



- $\Delta_T u > 0$  and  $\Delta_T d < 0$
- Do not saturate Soffer bound
- Smaller than helicity

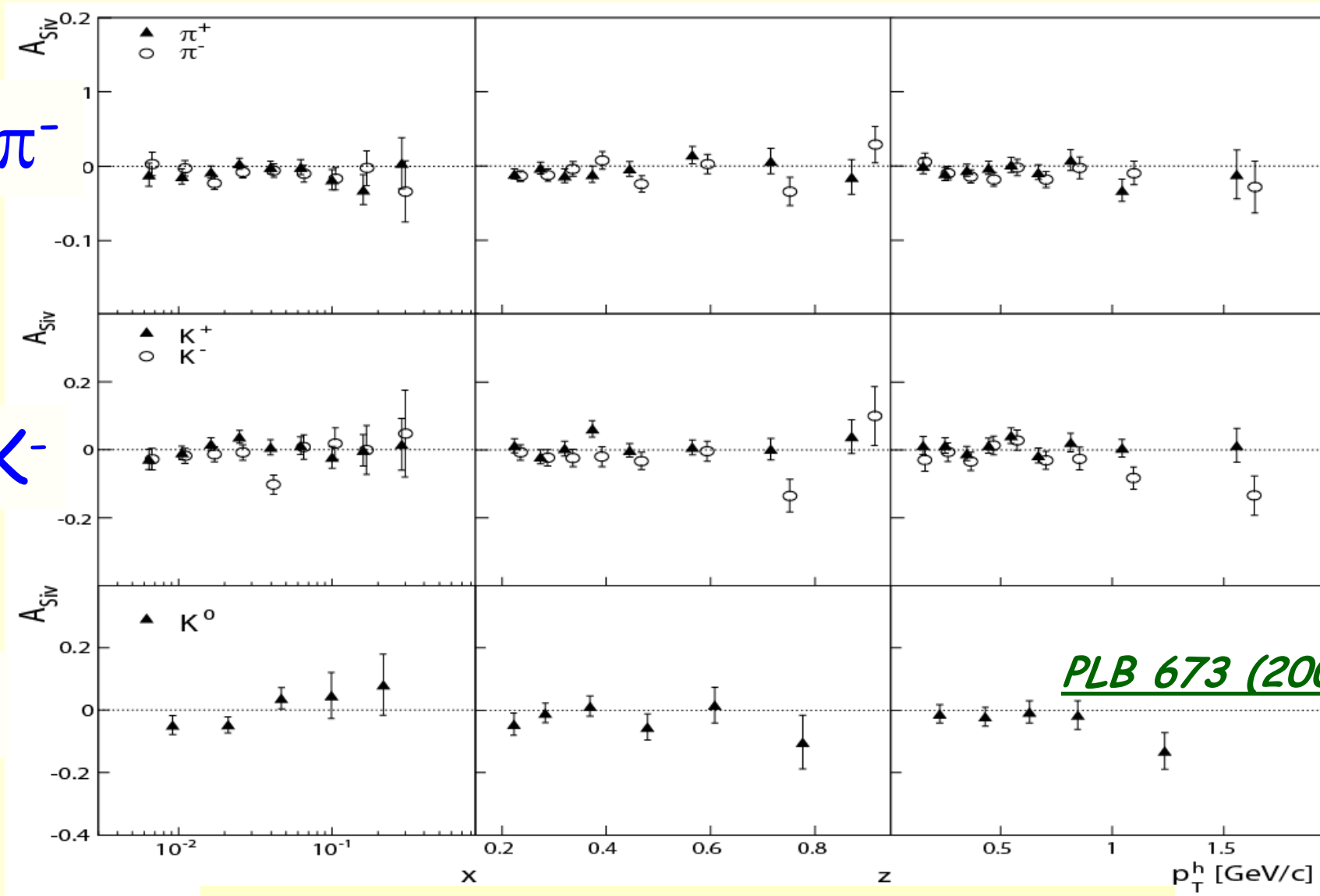
# Sivers Asymmetries on deuteron

COMPASS

$\pi^+$ ,  $\pi^-$

$K^+$ ,  $K^-$

$K^0$



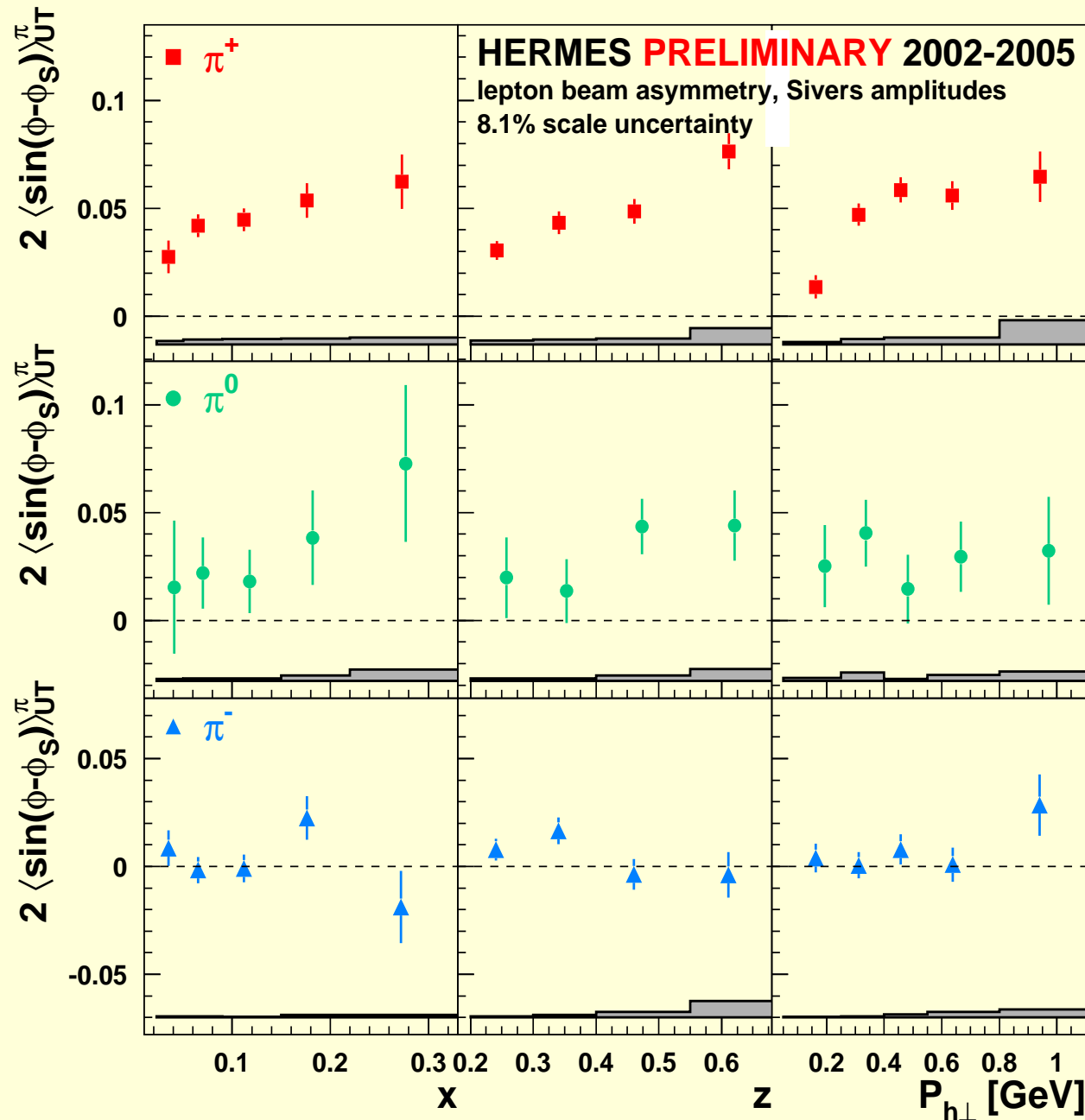
PLB 673 (2009) 127

All asymmetries compatible with 0

Small SIVERS on deuteron: hint for small  $L_g$ ? *Brodsky-Gardner 2006*

# Sivers Asymmetry on proton

HERMES pions



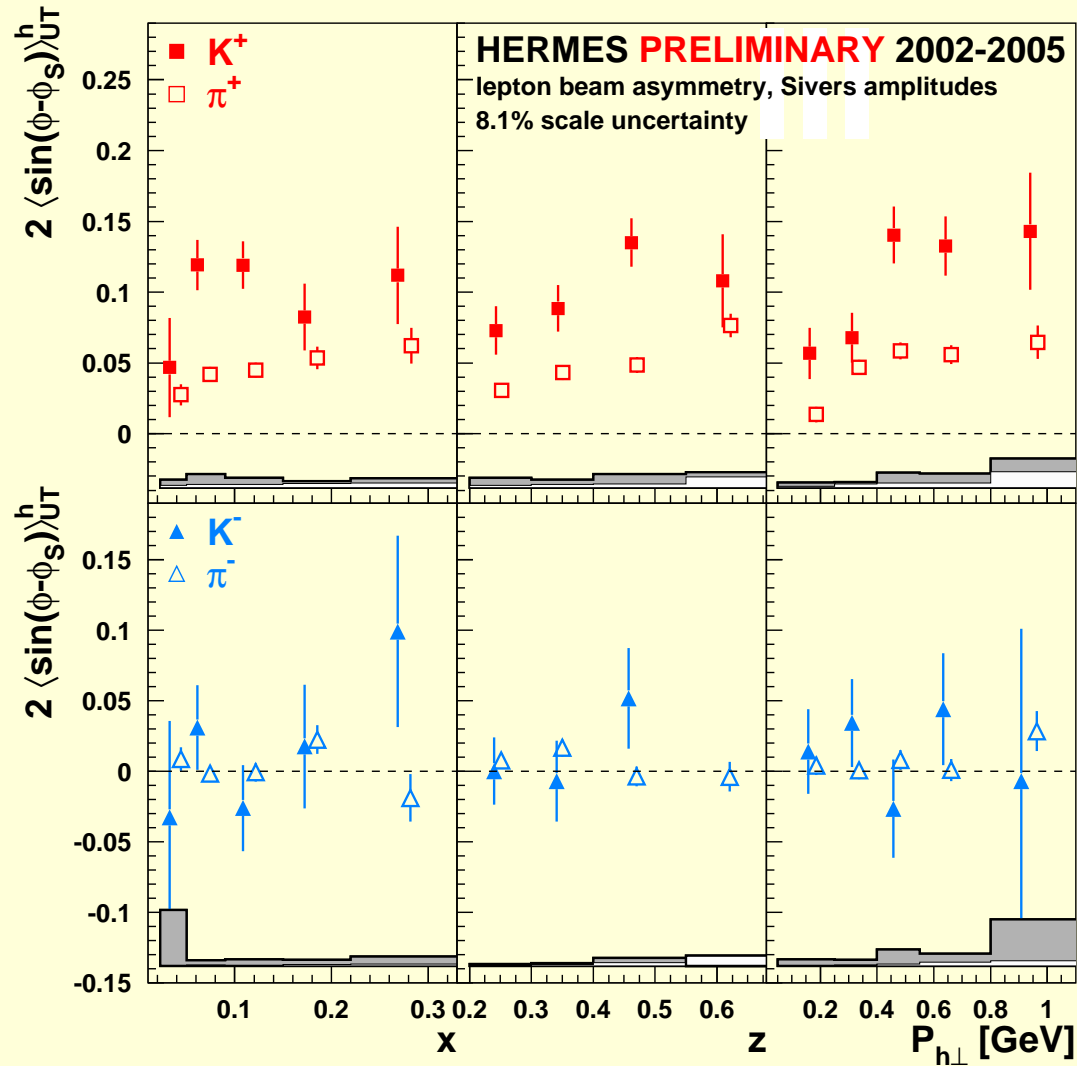
- $> 0$  for  $\pi^+$  and  $\pi^0$

- Non zero Sivers effect first observation

- non zero  $L_q$  ?

# Sivers Asymmetry on proton

HERMES K/  $\pi$  comparison

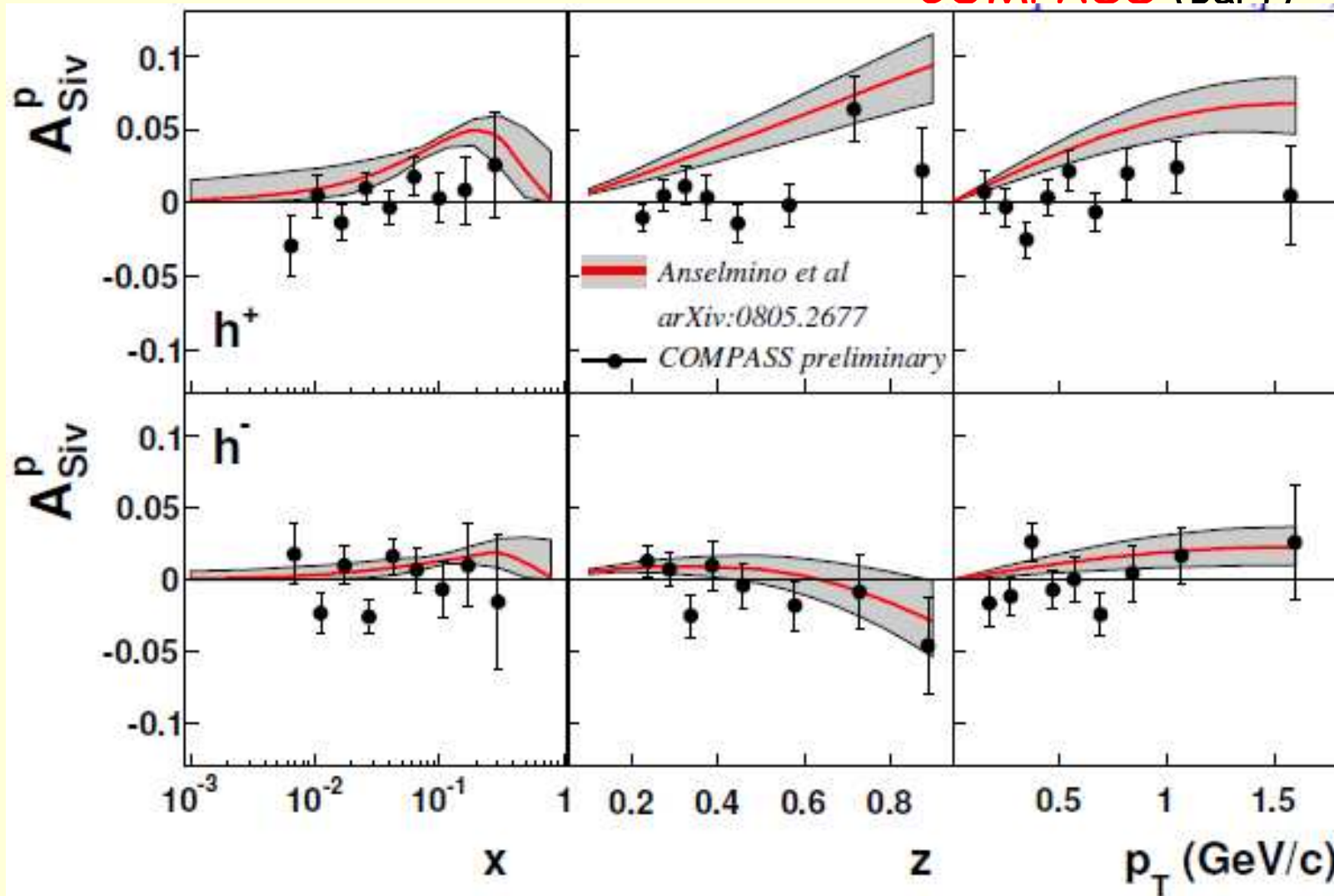


- $K^+$  twice bigger than  $\pi^+$   
Sivers function for the sea quarks  $\bar{s}$  and  $\bar{d}$ ?

- $K^-$  and  $\pi^- \sim 0$   
 $\bar{u}s$        $\bar{u}d$

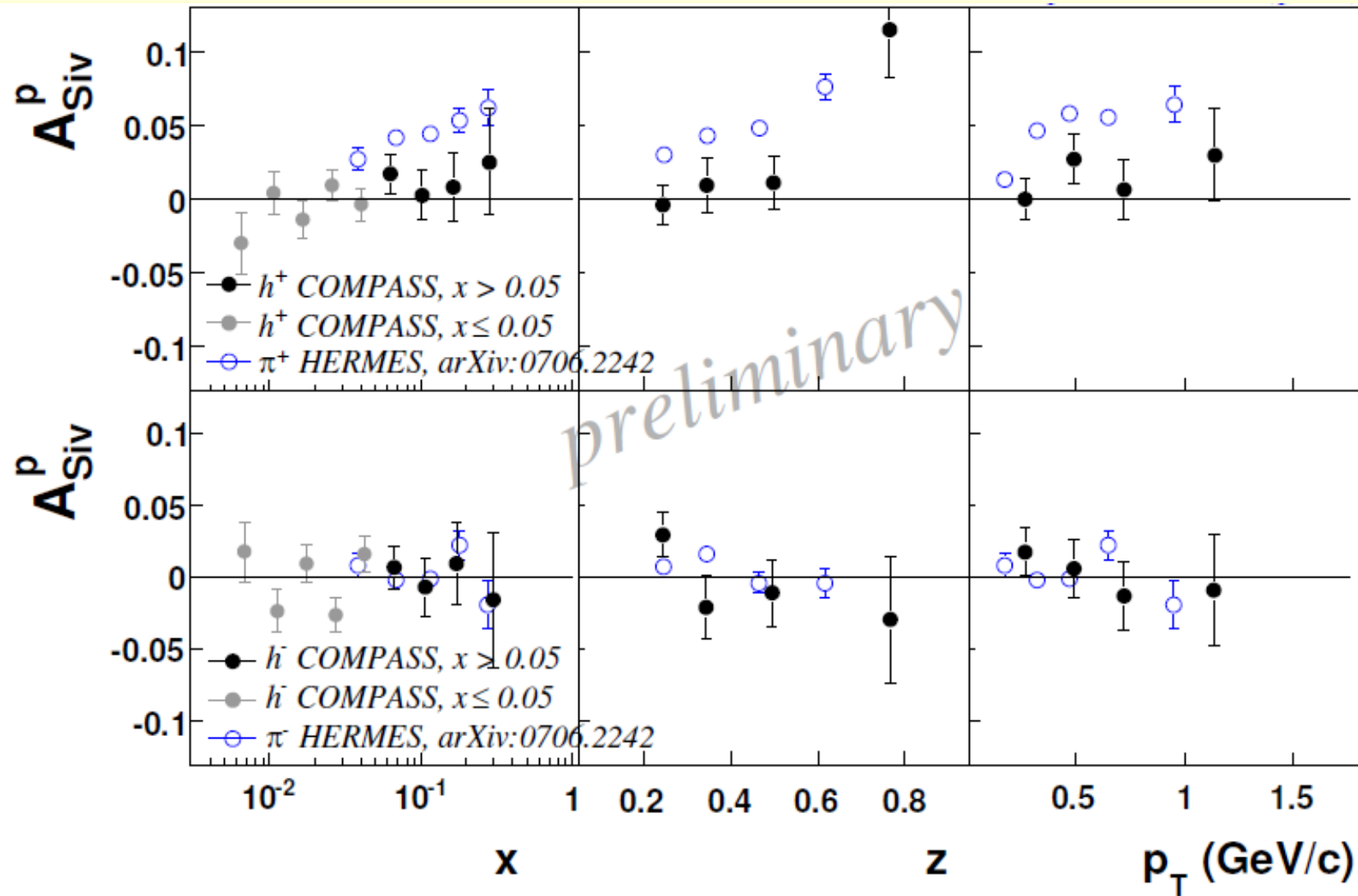
# Sivers Asymmetry on proton

COMPASS (bart)



Proton asymmetry compatible with zero?  
(in contrast to HERMES)

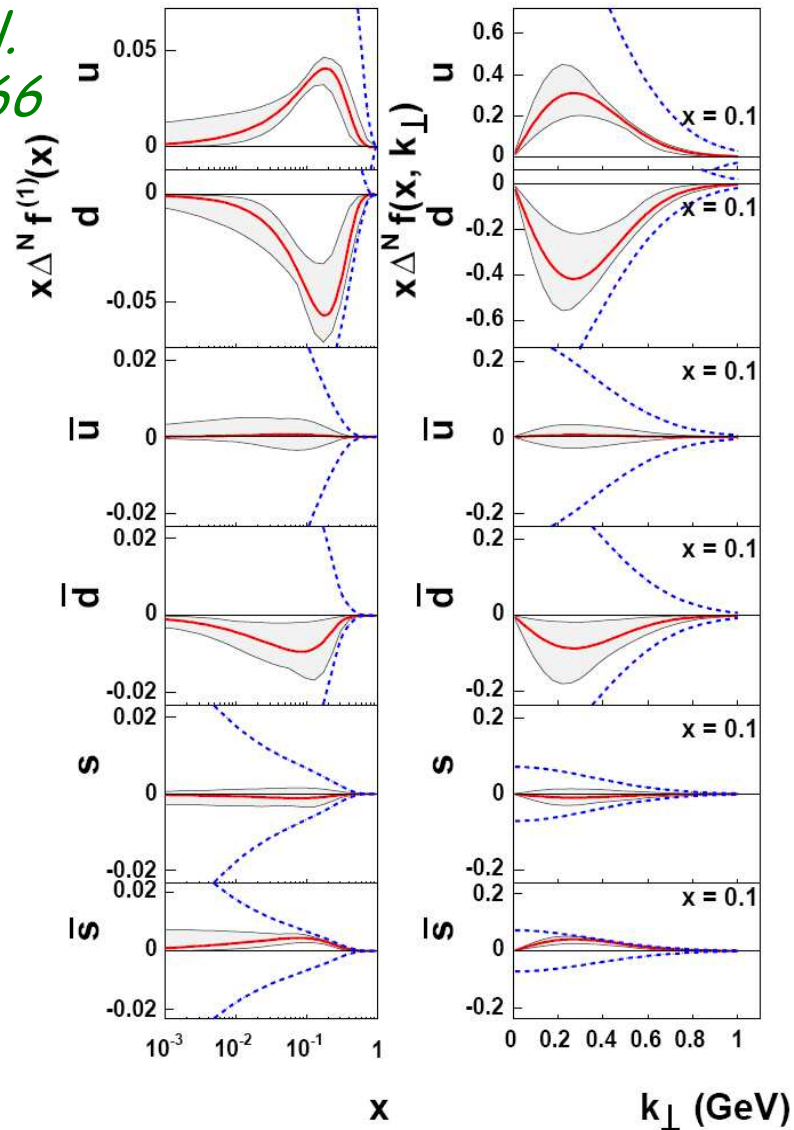
# Sivers Asymmetry HERMES & COMPASS



# Extraction of Sivers functions

Several combined analyses of **COMPASS** deuteron, **HERMES** proton and **BELLE** ff (Anselmino et al., Efremov et al., Vogelsang et al. ...)

*Anselmino et al.*  
*arXiv:0812.4366*

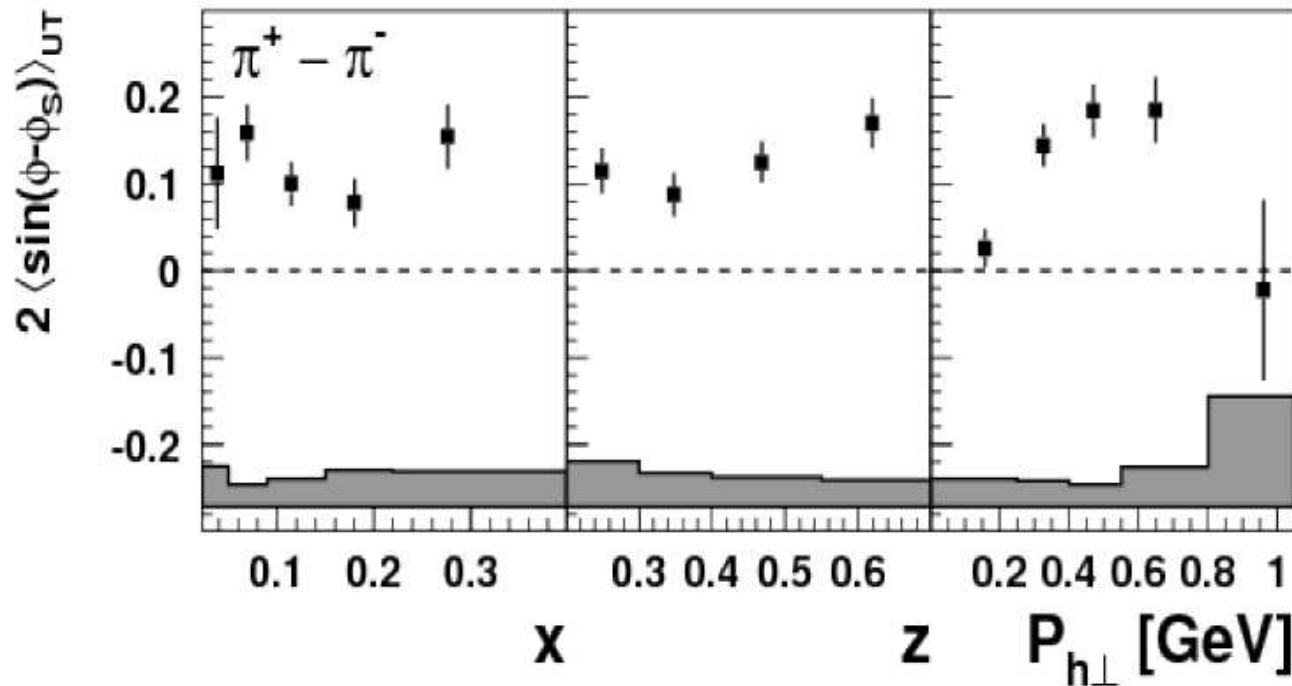




# Sivers Asymmetry ( $\pi^+ - \pi^-$ )

HERMES PRELIMINARY 2002-2005

lepton beam amplitudes, 8.1% scale uncertainty



- Sivers  $d_{\text{valence}} \gg u_{\text{valence}}$   
OR
- Sivers  $u_{\text{valence}}$  large  $< 0$   
(more likely)

*From Ch. Van Hulse, Bochum 2009*

# Summary & Outlook

- **Gluon polarization**

Extracted at LO from charm and high  $p_T$  events  
Need NLO studies

- **Quark helicity** : extraction at LO of  $\Delta u_v, \Delta d_v, \overline{\Delta u}, \overline{\Delta d}$  and  $\Delta s$

- **Transversity distributions**  $\rightarrow \Delta_T u > 0$  and  $\Delta_T d < 0$

- **Sivers Distr. Functions** : Signal in HERMES proton data, not in COMPASS. More statistics needed

Many other results not shown here

And exciting future program in preparation !

**COMPASS future**: proposal to measure GPDs, TMDs from SIDIS and Drell-Yan + More on transversity and Longitudinal spin structure