Measurements of transversity and TMD observables at COMPASS

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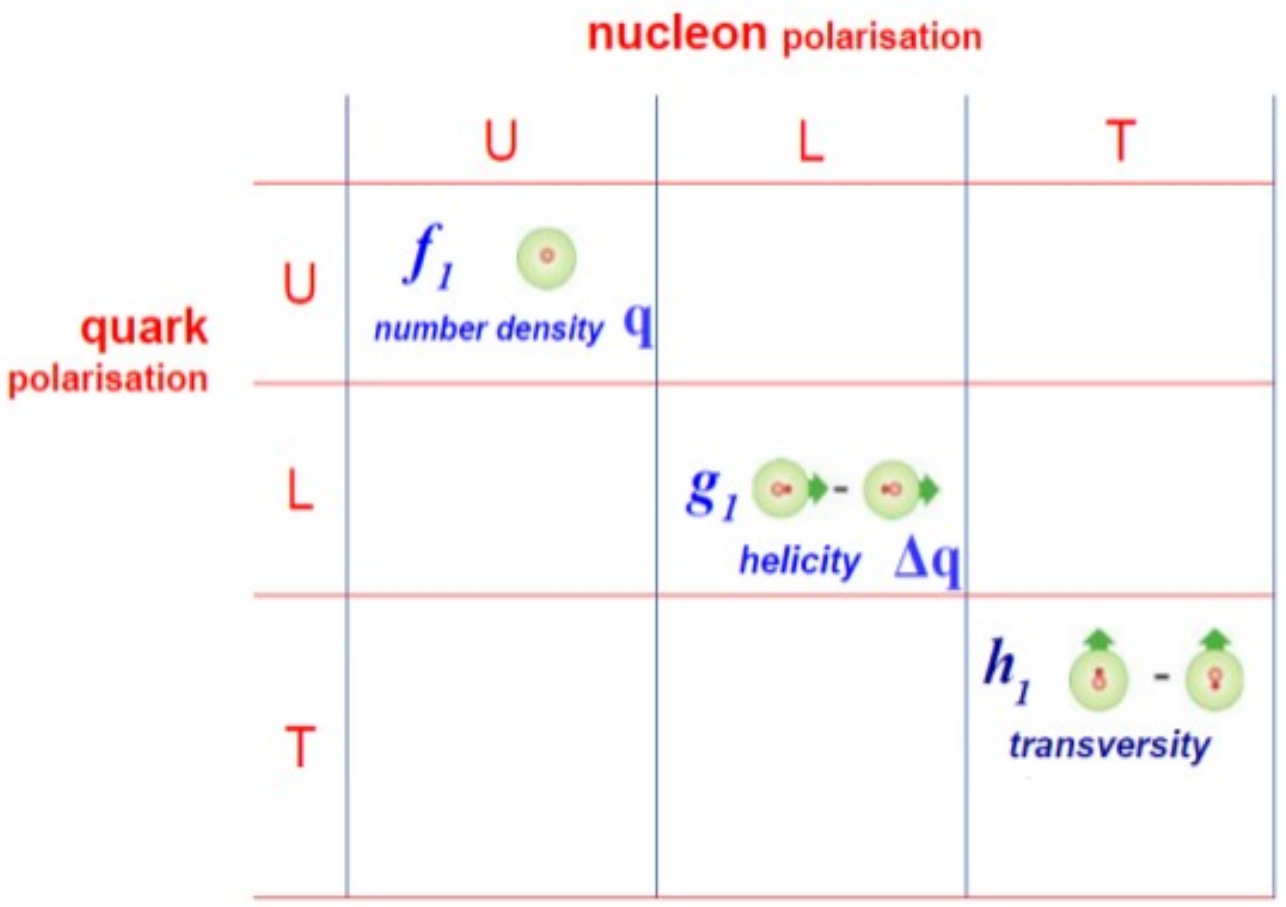
On behalf of the COMPASS collaboration

Outline

- Transverse Momentum Dependent (TMD) functions
- The SIDIS cross-section of the transversely polarized nucleon
- The COMPASS experiment
- COMPASS results on transversity and TMDs from SIDIS:
  - single hadron Collins and Sivers asymmetries
  - two-hadron asymmetry
  - 6 other asymmetries (single hadron)
- Summary and outlook

Spin structure of the nucleon

The inner structure of the nucleon **independent of the transverse momentum k_T** can be described with three **Parton Distribution Functions** (PDF)



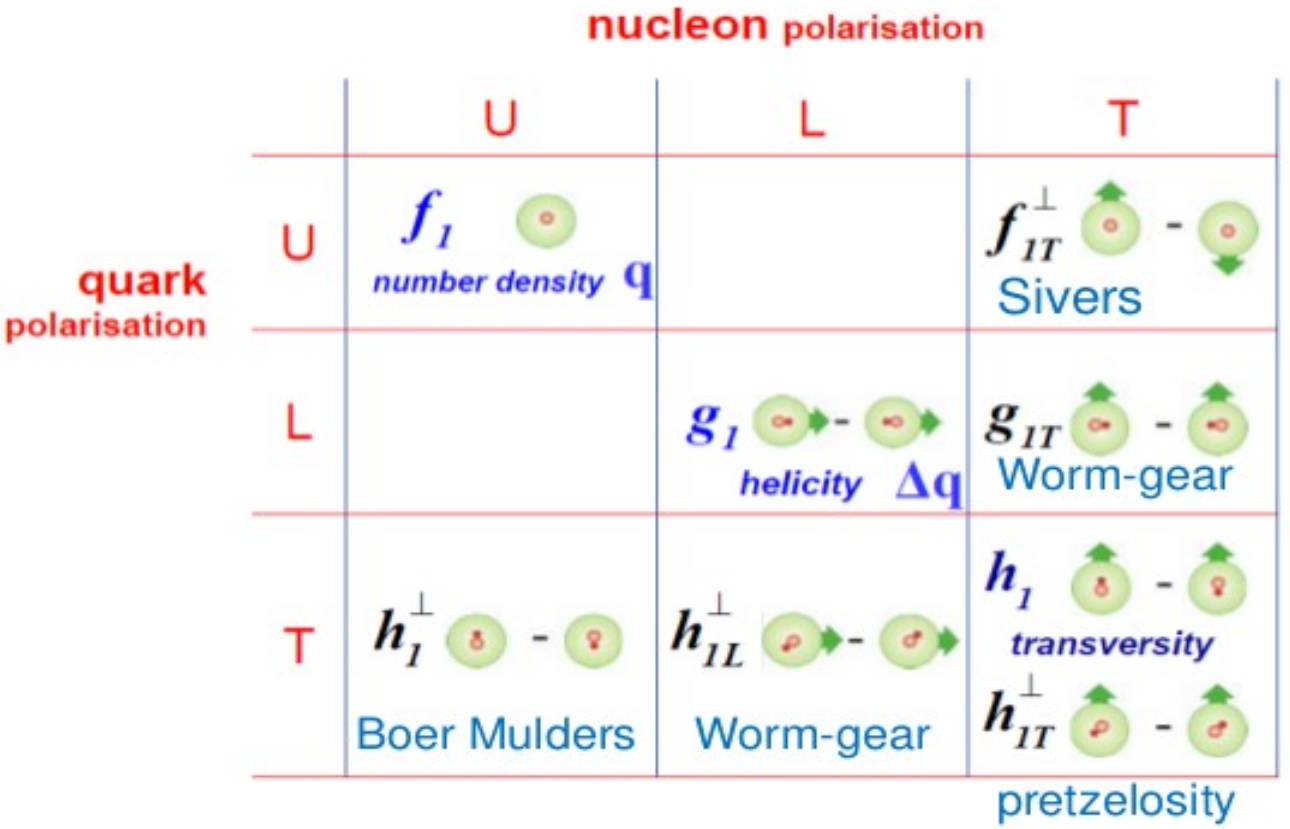
probability distribution of finding a quark with momentum fraction x

difference of probability distributions of finding a quark with momentum fraction x with spin parallel and antiparallel to the parent nucleon in a longitudinally polarized nucleon

... in a transversely polarized nucleon

Transverse Momentum Dependent functions

Taking into account the intrinsic parton transverse momentum the nucleon structure description requires 8 **Transverse Momentum Dependent PDF dependent on x and k_T**. TMDs describe the correlations between the spin and the momentum of quarks and spin of the parent nucleon.



SIDIS cross-section

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\left\{1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\right.$$

$$S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+$$

$$S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+$$

$$S_T\left[\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)\right]+$$

$$S_T\lambda\left[\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)\right]\Bigg\}$$

Sivers & Collins

Pretzelosity

Worm-gear

Higher twists

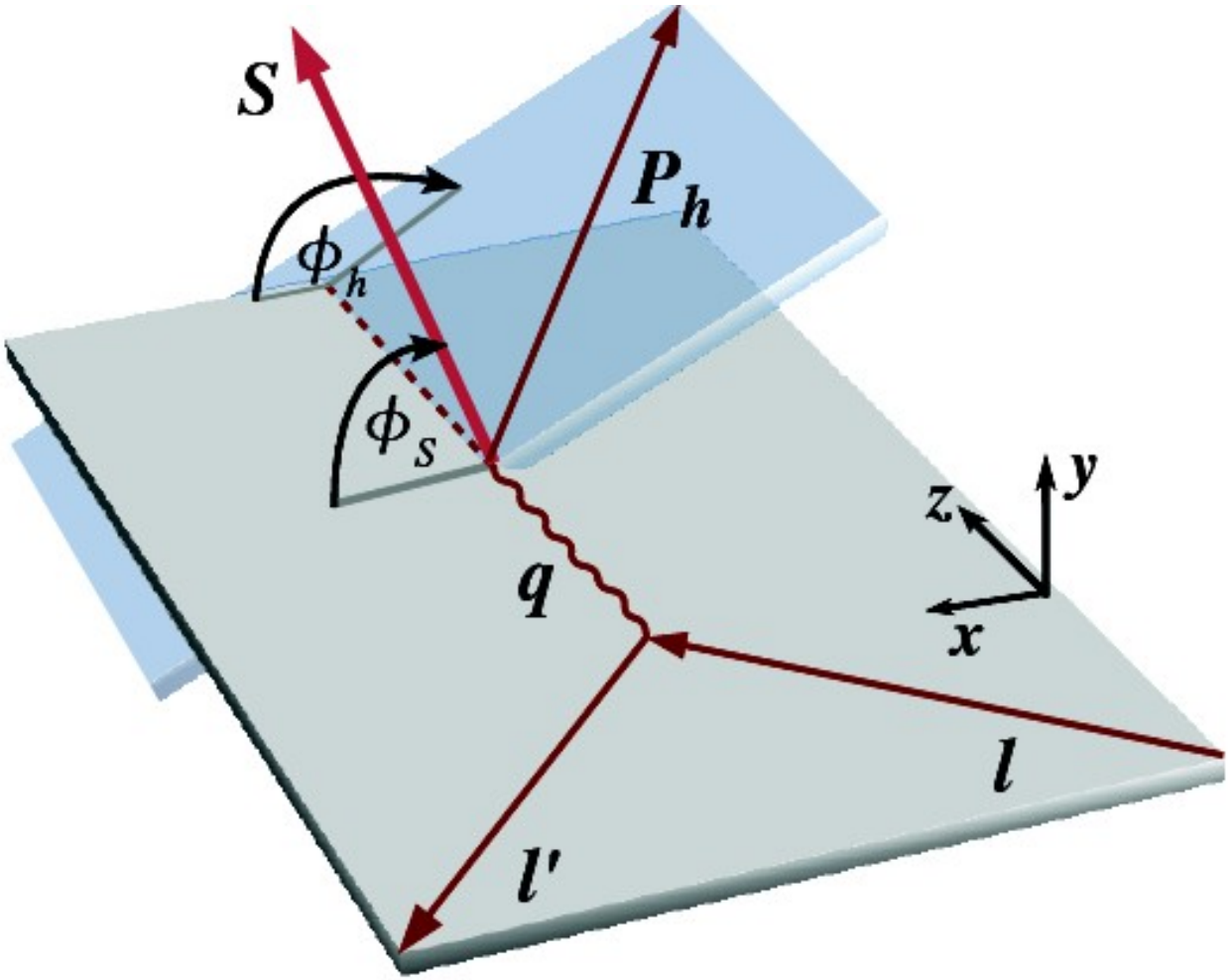
SSA

DSA

Twist-2

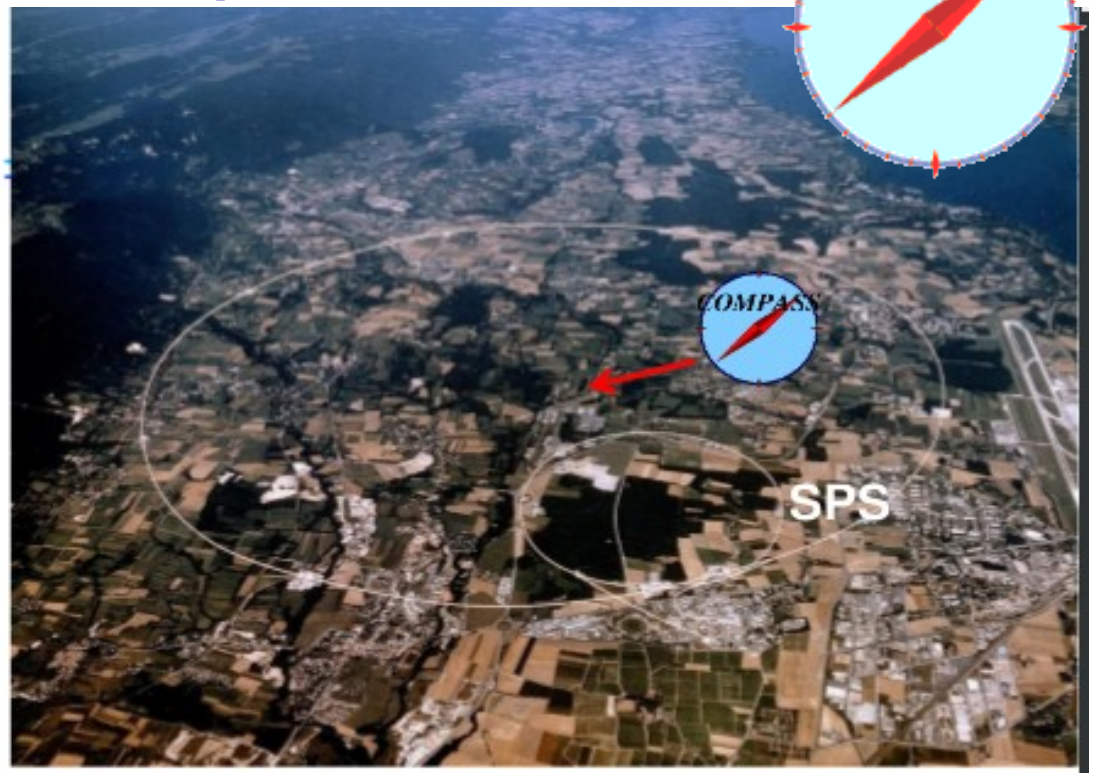
Twist-3

Azimuthal angles



COMPASS Experiment

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy



Fixed target experiment
at CERN SPS
Data taking since 2002

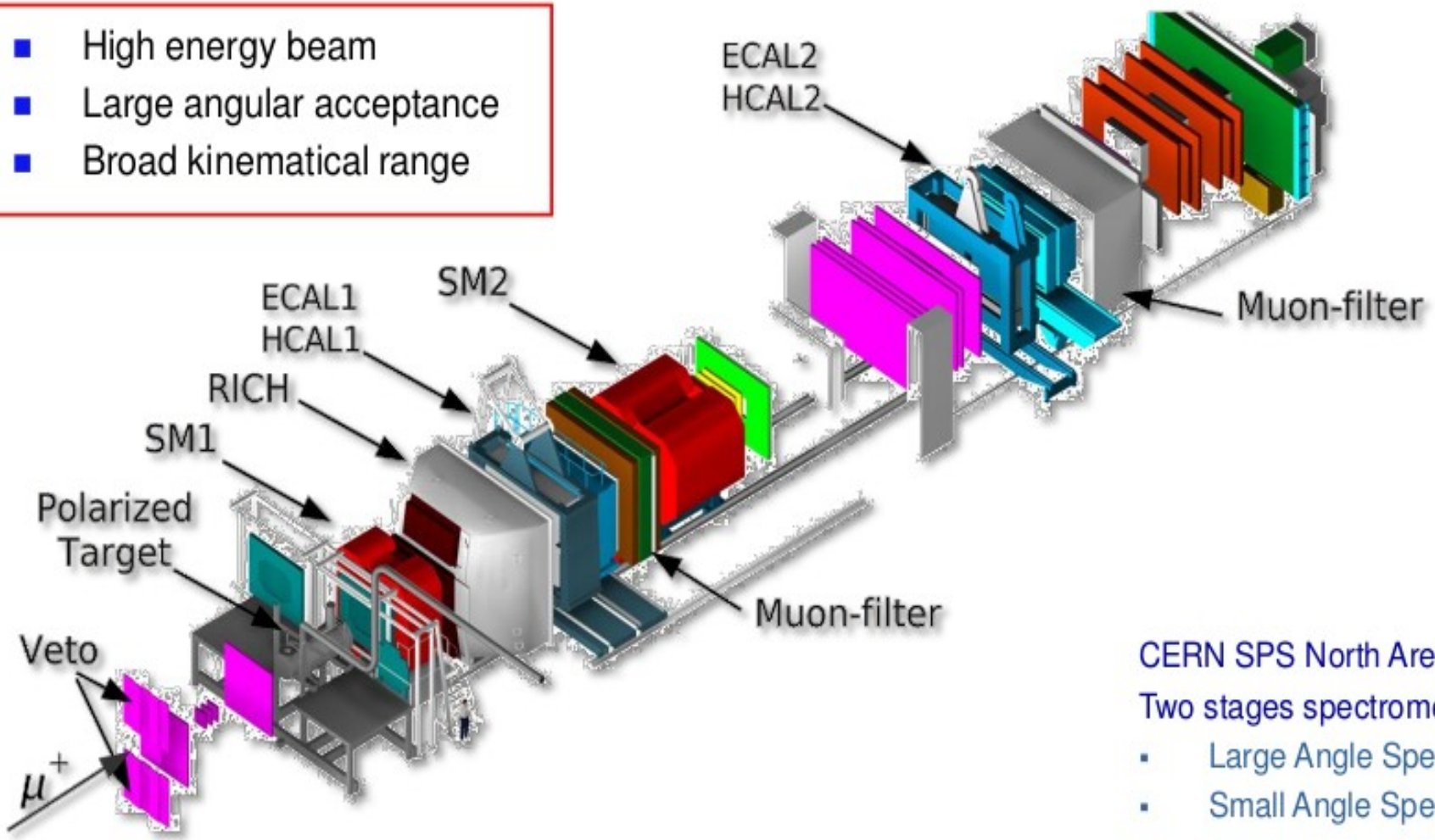
Nucleon spin structure
with high energy muon beams
on longitudinally polarized targets:
- -gluon polarization
- -helicity PDF

Transversely polarized targets:
- transversity PDF
- TMDs

Meson and baryon spectroscopy
with high energy hadron beam

The COMPASS two-stage spectrometer

- High energy beam
- Large angular acceptance
- Broad kinematical range



CERN SPS North Area.

Two stages spectrometer

- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

Hadron & Muon high energy beams.

Beam rates: 10^8 muons/s, $5 \cdot 10^7$ hadrons/s.

Longitudinally polarized μ^+ beam (160 Gev/c).

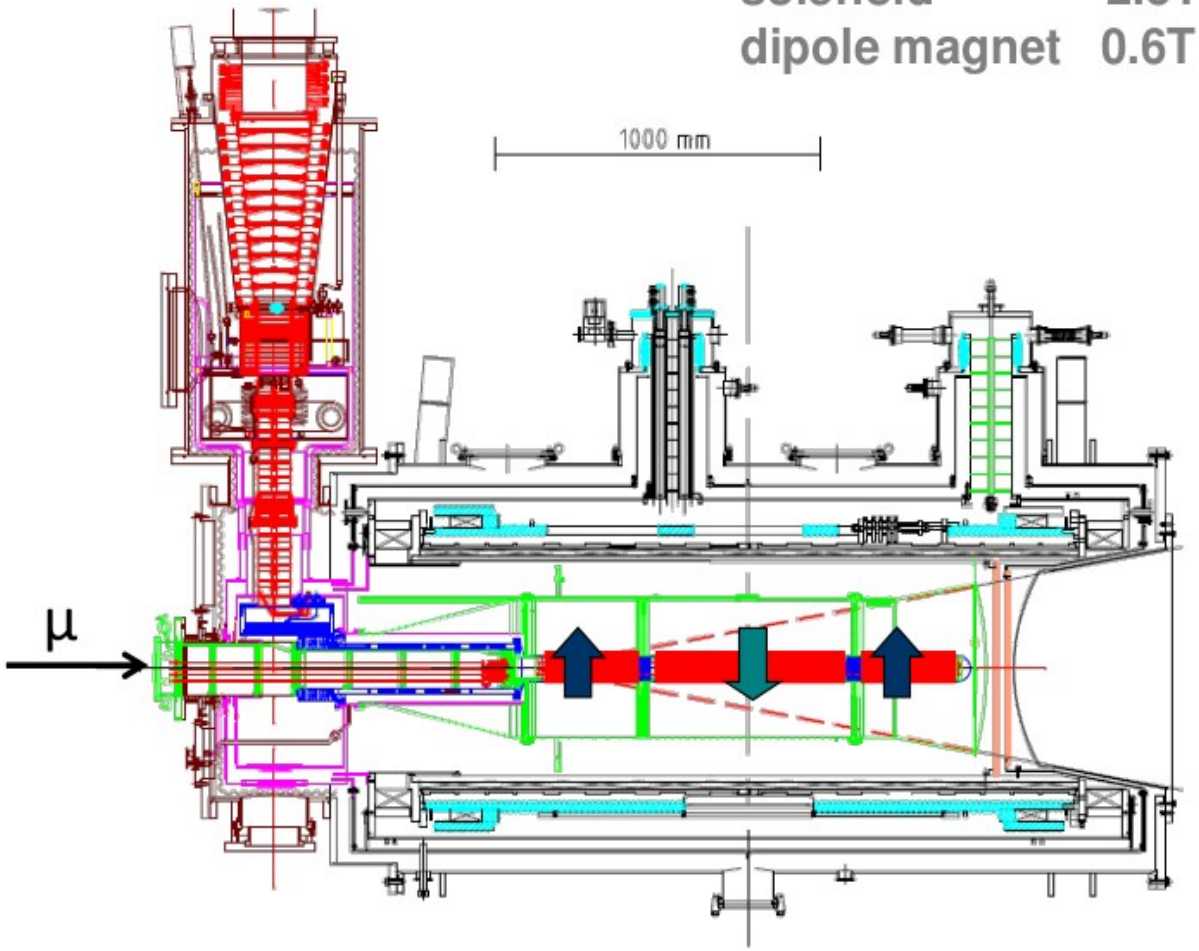
Longitudinally or Transversely polarized ^{6}LiD or NH_3 target

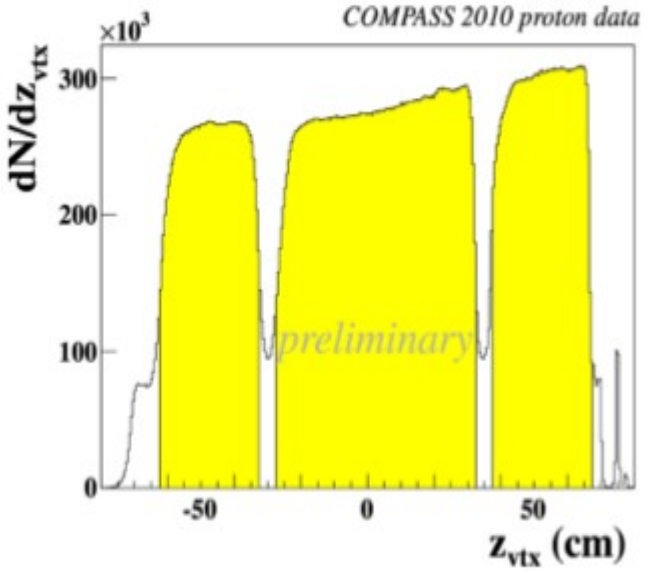
Momentum, tracking and calorimetric measurements, PID

Polarized target

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

solenoid	2.5T
dipole magnet	0.6T





acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite spin orientation

transverse spin reversed every several days
longitudinal every 8 (or 24) hours

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

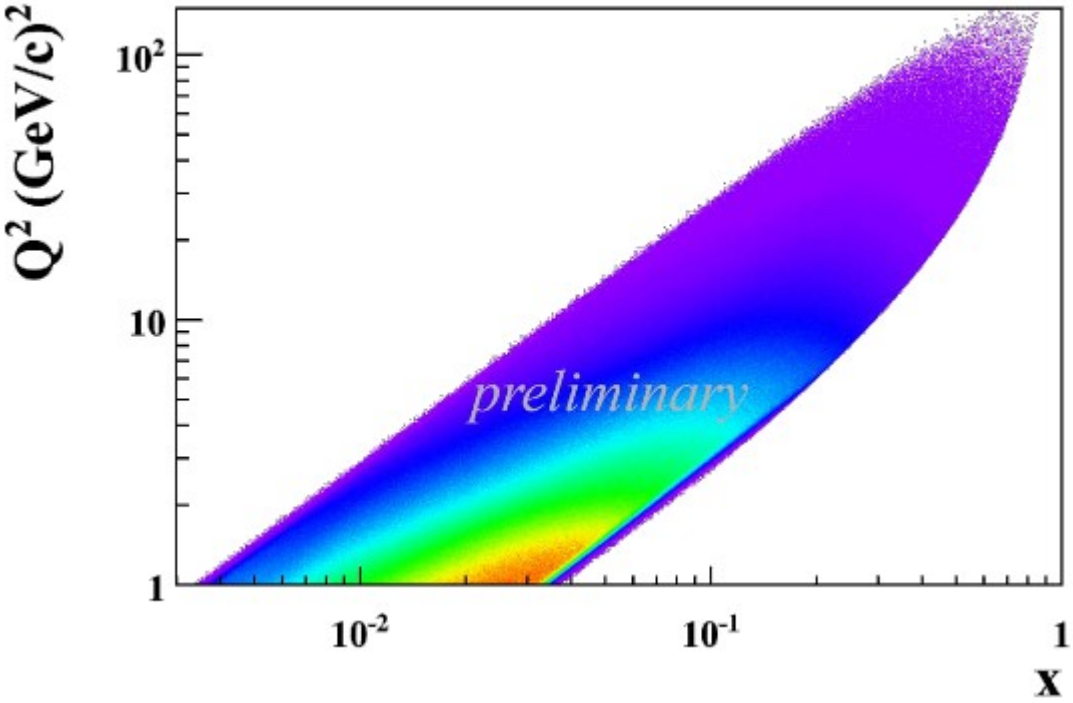
COMPASS data taken with transversely polarized targets

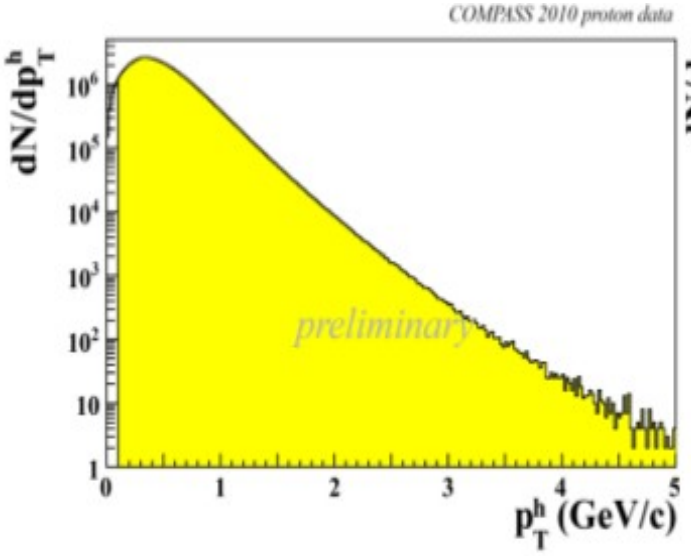
- deuteron (^{6}LiD) target, 160 GeV muon beam: 2002, 2003, 2004

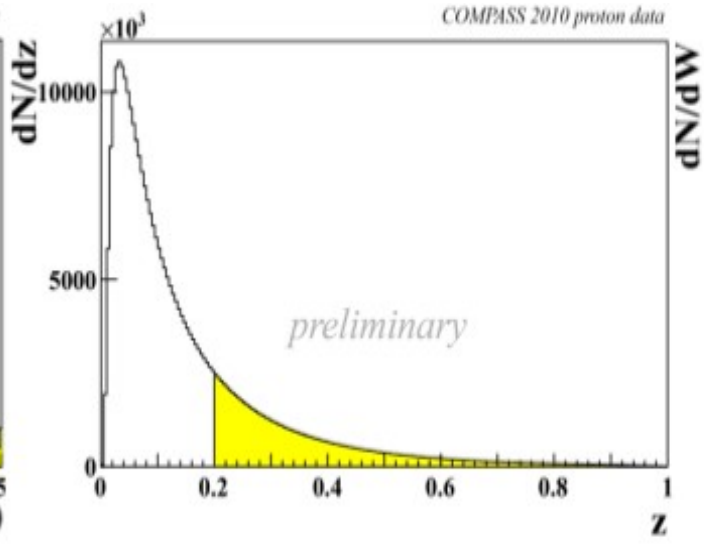
- proton (NH^{3}) target, 160 GeV muon beam: 2007, 2010

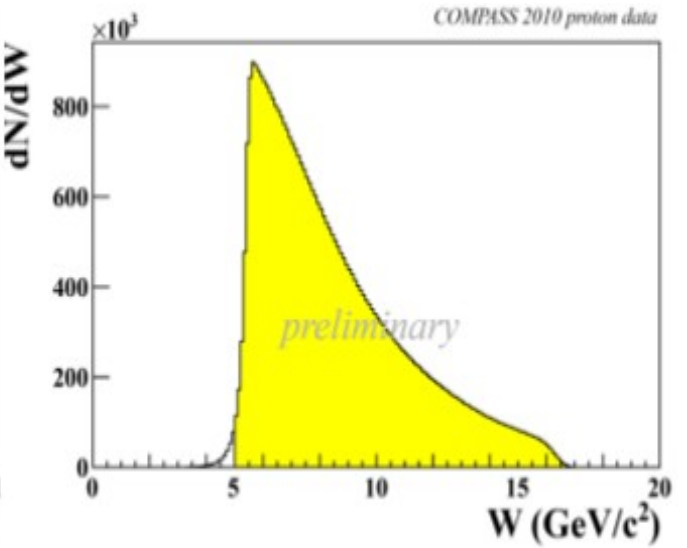
SIDIS event selection

- DIS cuts:
  - $Q^2>1$ (GeV/c)^2
  - $0.1< y <0.9$
  - $W > 5$ GeV/c^2
- hadron cuts:
  - $z > 0.2$
  - $p^h_T > 0.1$ GeV/c









SIDIS off transversely polarized trargets at COMPASS

- Sivers asymmetry

  related to quark orbital angular momentum (OAM)

- Collins asymmetry

  sensitive to transversity

- Two hadron azimuthal asymmetry

  sensitive to transversity

- 6 other azimuthal asymmetries

  sensitive to transversity, Sivers function, worm-gear, pretzelosity

results

Collins asymmetry

proportional to convolution of transversity and Collins FF obtained from BaBar and Belle measuremens

$$A_{Coll}(x, z, p_T^h) = \frac{A_{Coll}^{raw}}{P_T \cdot f \cdot D_{nn}} = \frac{\sum_q e_q^2 h_1^q(x, k_\perp^2) \otimes H_{1,q}^\perp(z, p_\perp^2)}{\sum_q e_q^2 f_1^q(x, k_\perp^2) \otimes D_{1,q}(z, p_\perp^2)}$$

transversity

Collins FF

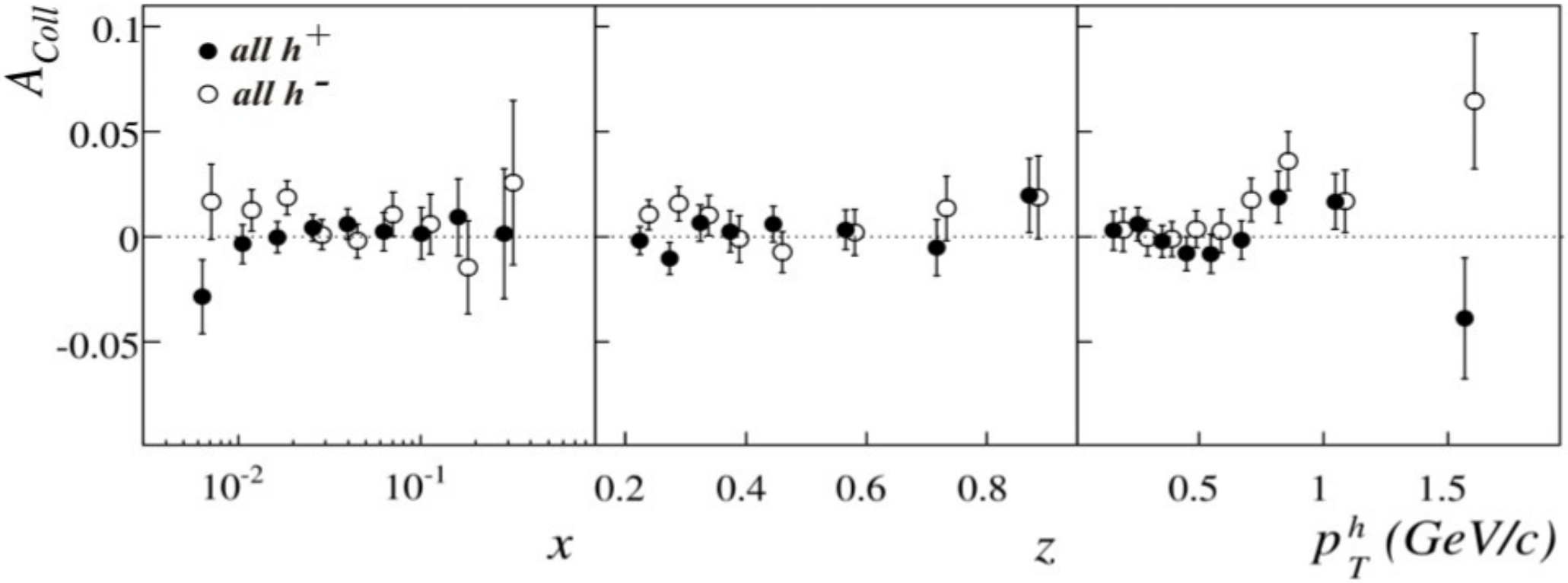
P_T – target polarisation, f – dilution factor

D_{nn} – spin transfer coeff. from initial to struck quark

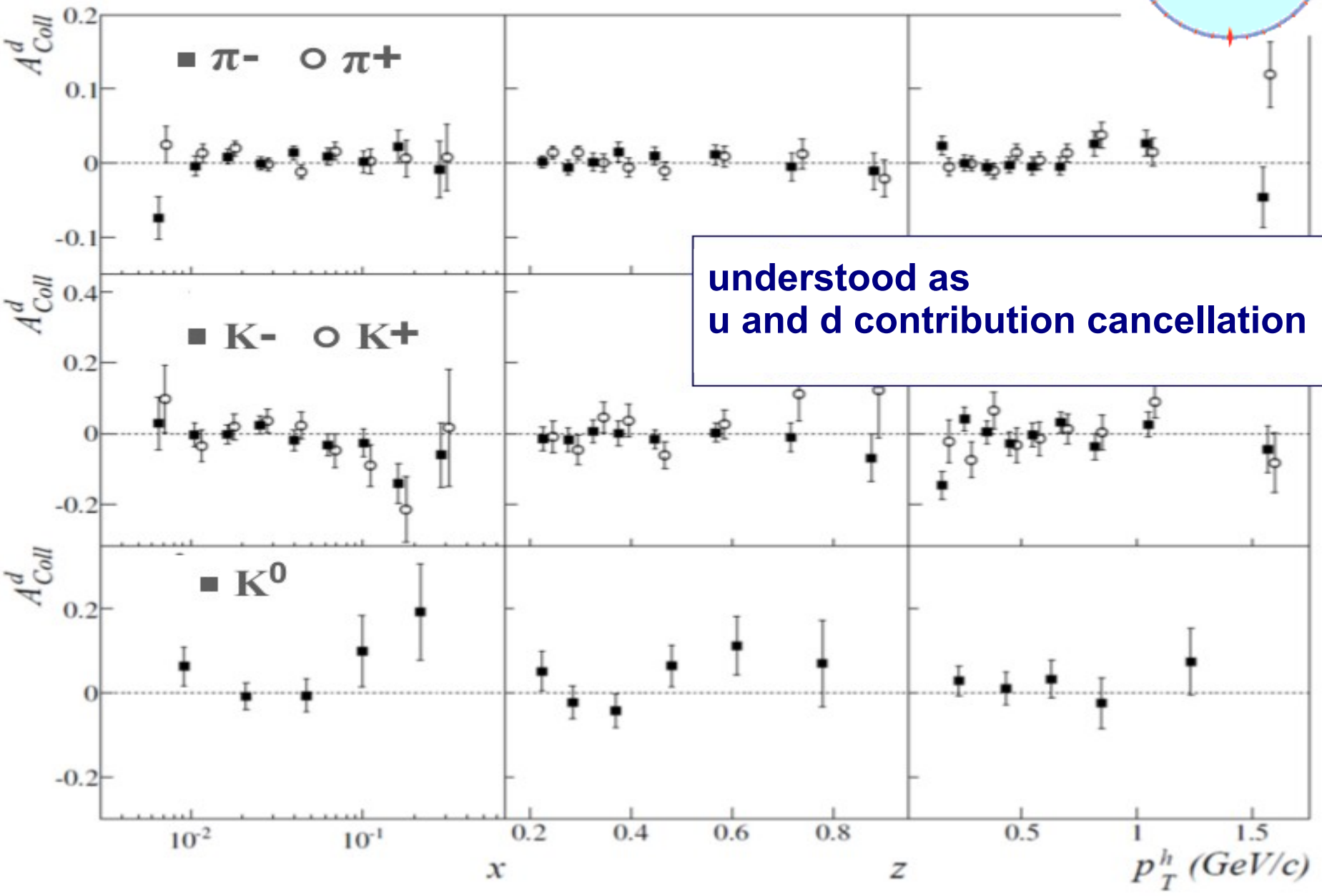
Collins asymmetry. Deuteron

final results 2002-2004 data

PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127



Collins asymmetry on deuteron



understood as
u and d contribution cancellation

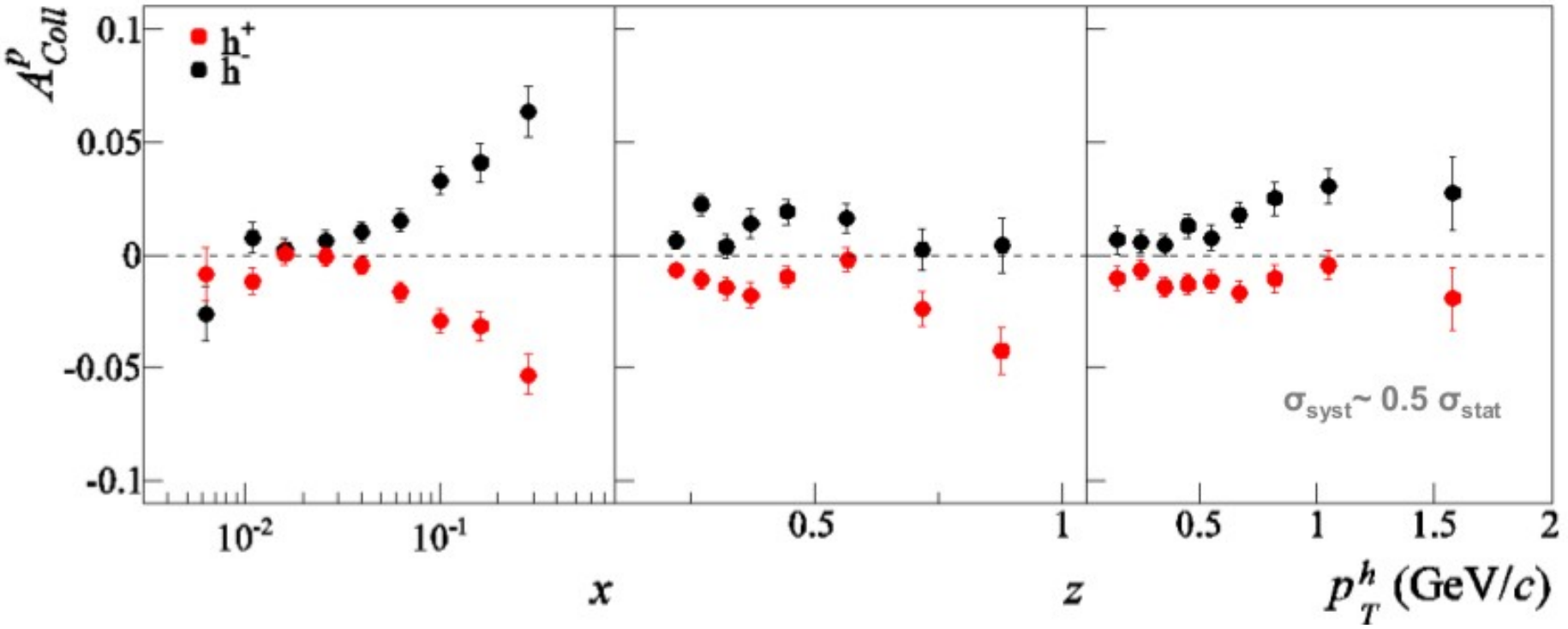
Collins asymmetry on proton

charged hadrons – published 2007 & 2010 data results

PLB 692 (2010) 240 PLB 717 (2012) 376

very good agreement between the two data sets

combined 2007 & 2010 results



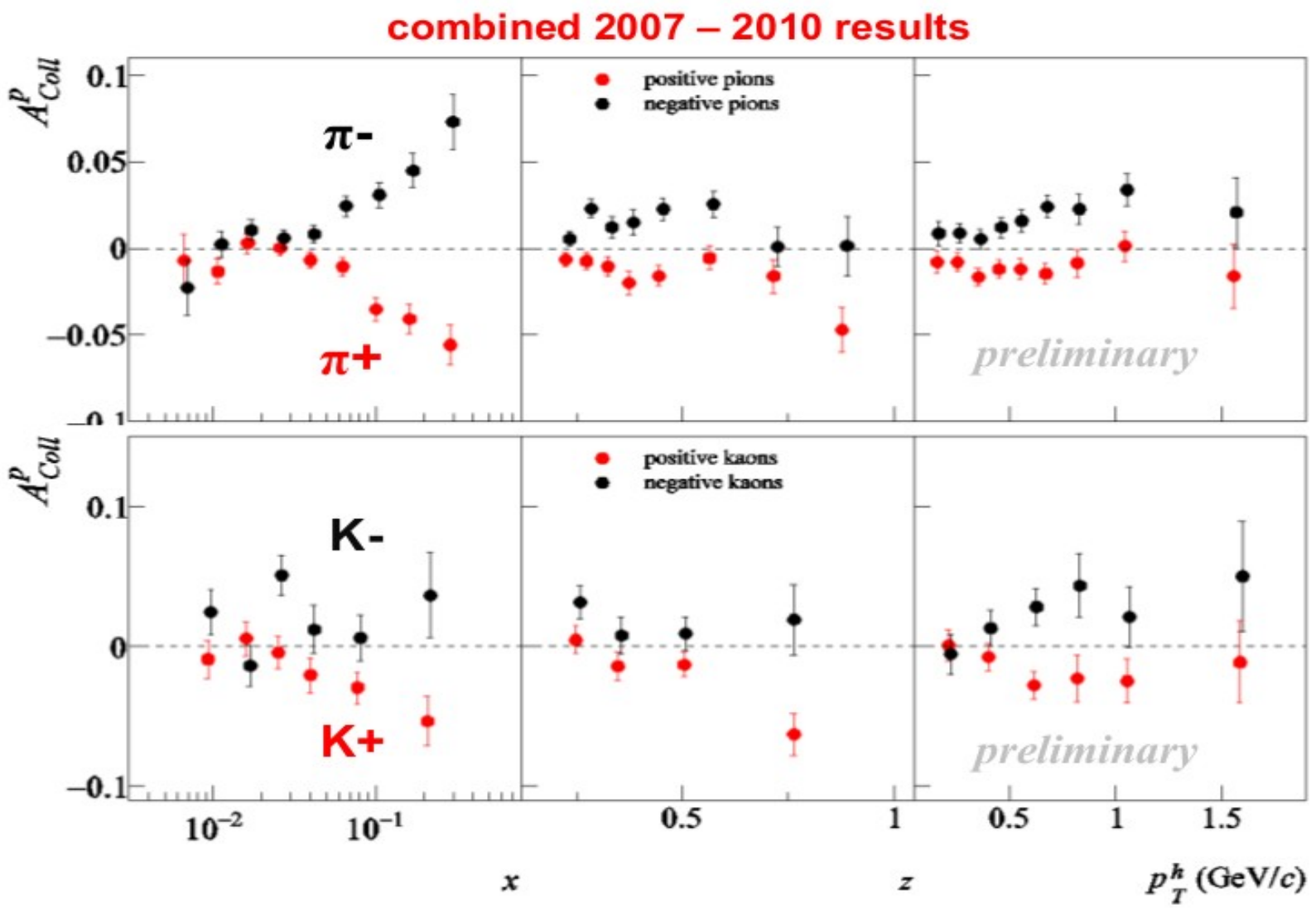
- precise measurements
- clear signal for x>0.03 with opposite signs for h+ and h-

Collins asymmetry on proton.

charged pions and kaons

~ h+ / h-

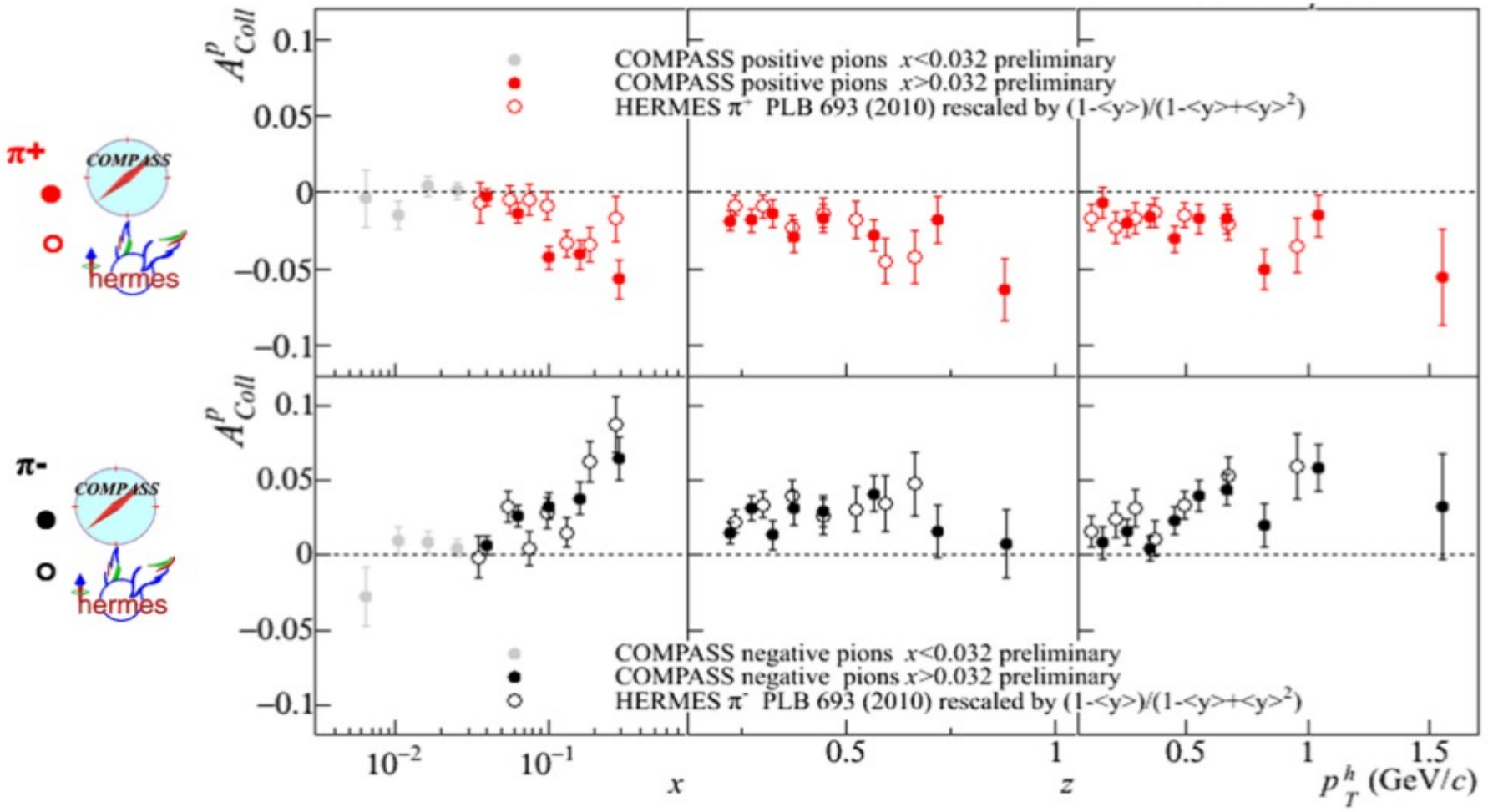
compatible with π+ / π-



Collins asymmetry on proton

charged pions (and kaons), 2010 data, x > 0.032 region

comparison with HERMES



good agreement between experiments despite different Q^2 ranges
(at given x: $\langle Q^2\rangle_{COMPASS} \simeq (2 \div 4)\ \langle Q^2\rangle_{HERMES}$) ⇒ mostly LO effect

results

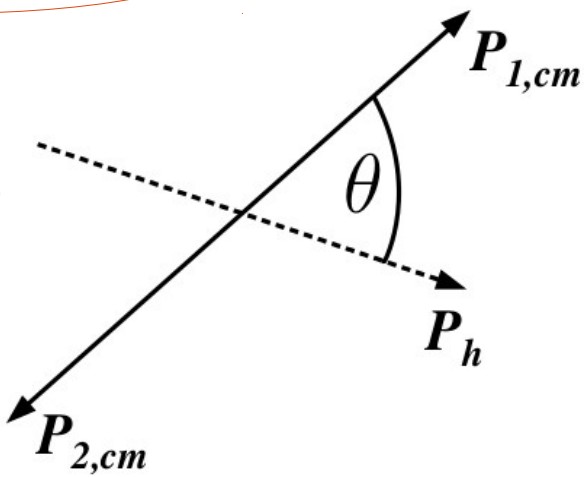
Two-hadron asymmetry

related to the transversity function

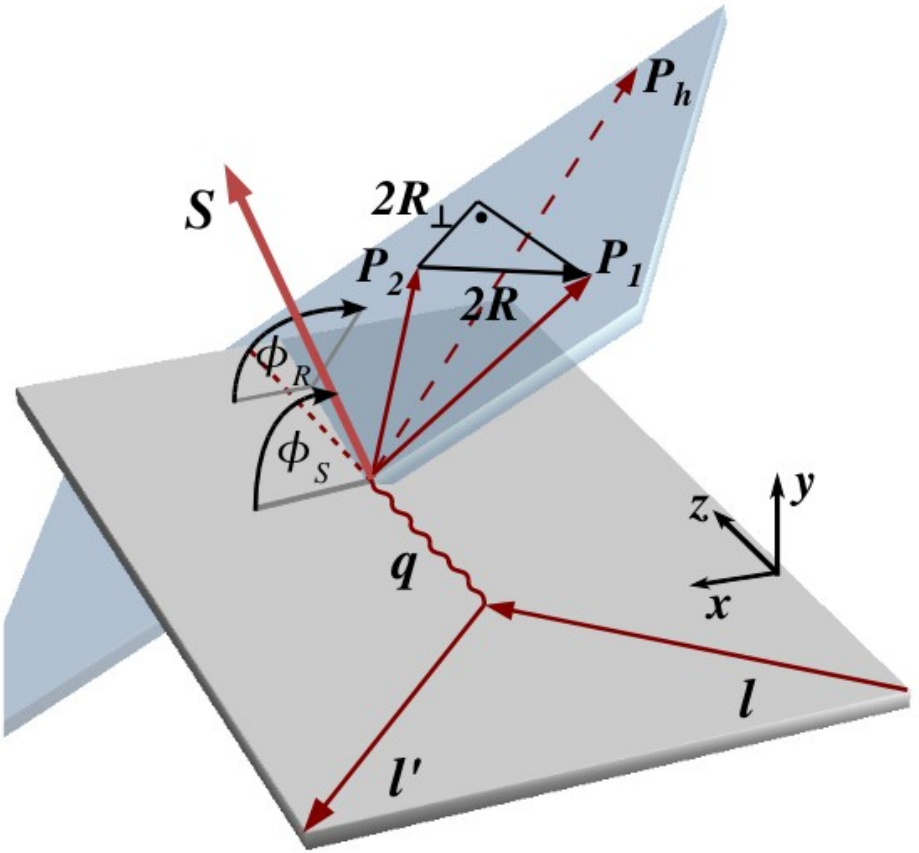
transversity

Interference FF

$$A_{UT}^{\sin\Phi_{RS}}(x,z,M_h) = \frac{|\mathbf{p_1}-\mathbf{p_2}|}{M_h} \frac{\sum_q e_q^2 h_1^q(x)\cdot H_{1,q}^{\sphericalangle}(z,M_h^2,\cos\theta)}{\sum_q e_q^2 f_1^q(x)\cdot D_{1,q}(z,M_h^2,\cos\theta)}$$

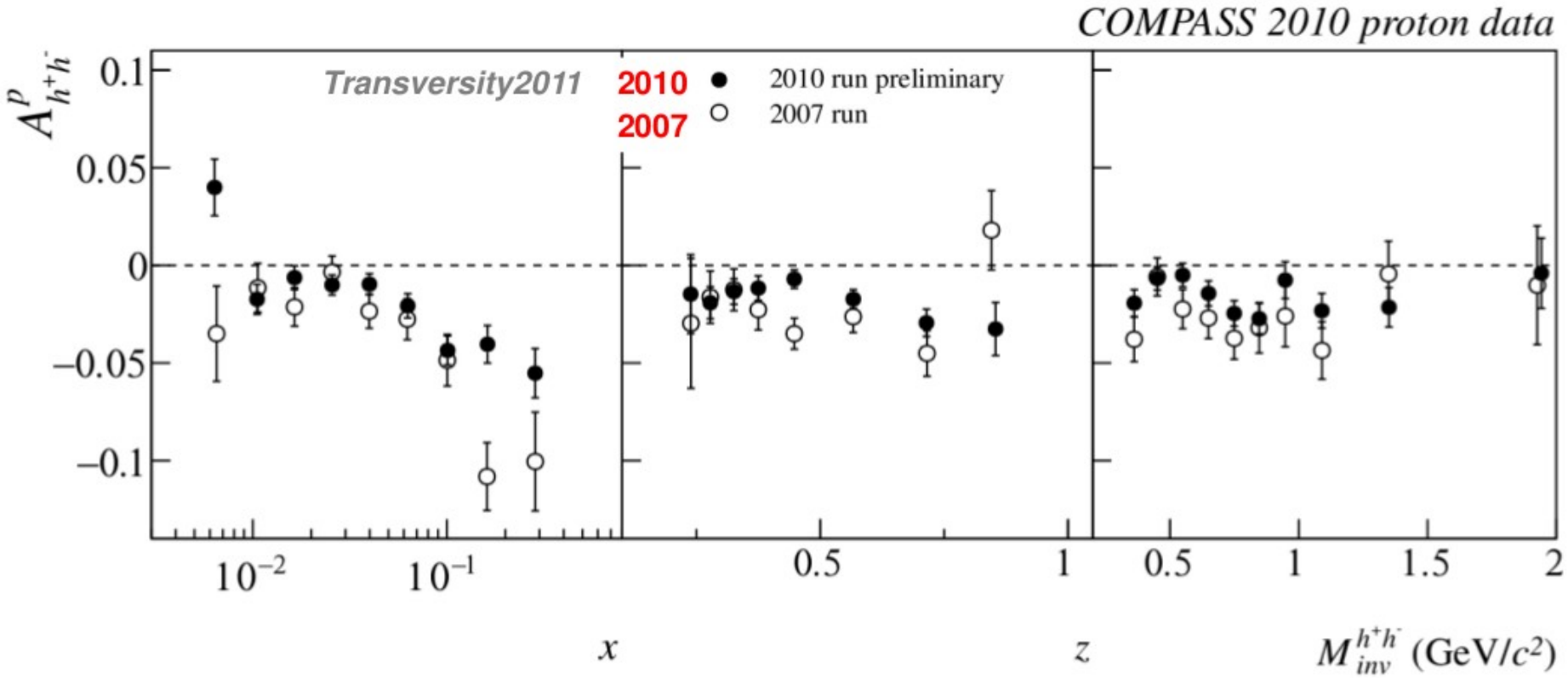


Two-hadron angle



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

Two-hadron asymmetry



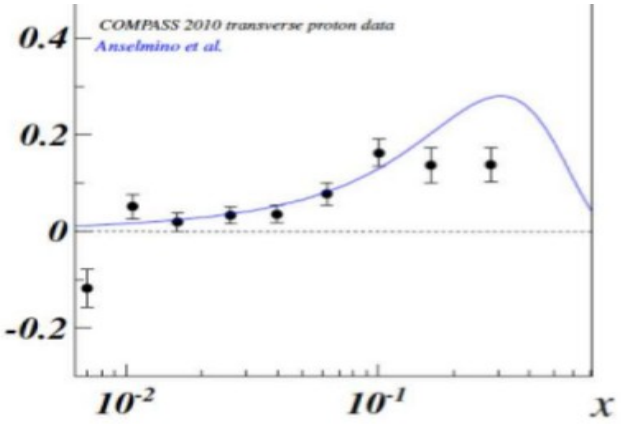
Transversity extracted from two-hadron asymmetry

Using interference FF from Belle following approach of Baccheta, Courtoy and Radici PRL 107:012001, 2001

transversity of u_v and d_v extracted from COMPASS deuteron and 2010 proton data

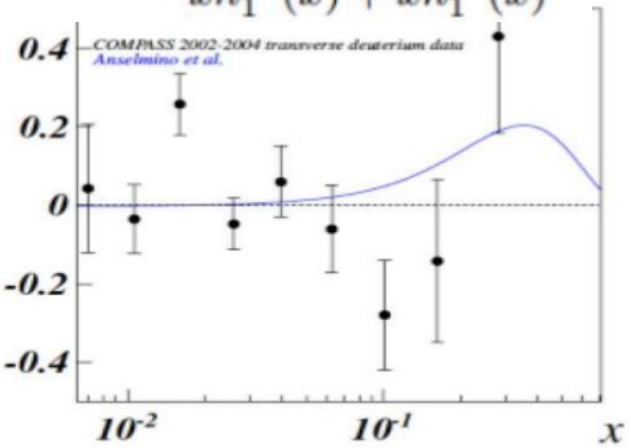
COMPASS 2010 proton data

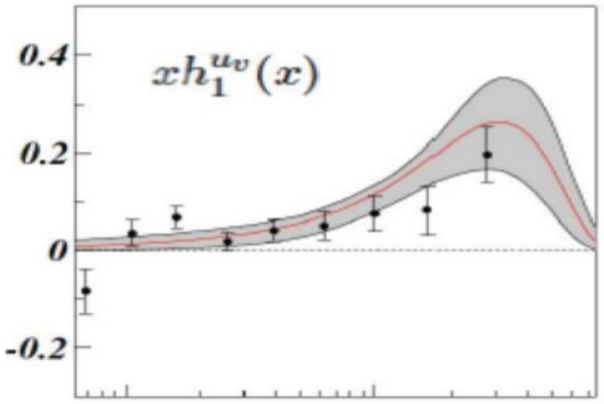
$$xh_1^{u_v}(x) - \frac{1}{4}xh_1^{d_v}(x)$$

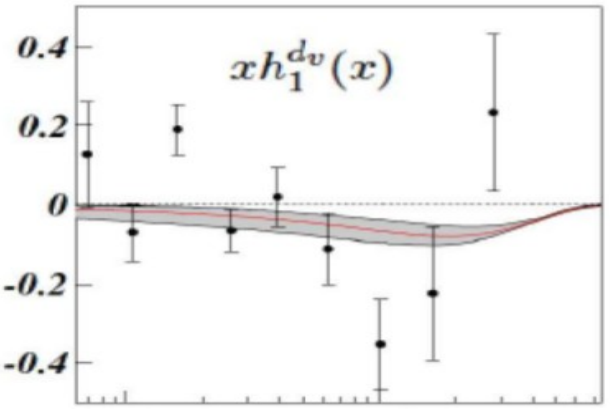


COMPASS deuteron data

$$xh_1^{u_v}(x) + xh_1^{d_v}(x)$$







results

Sivers asymmetry

connected to orbital angular momentum

Sivers function

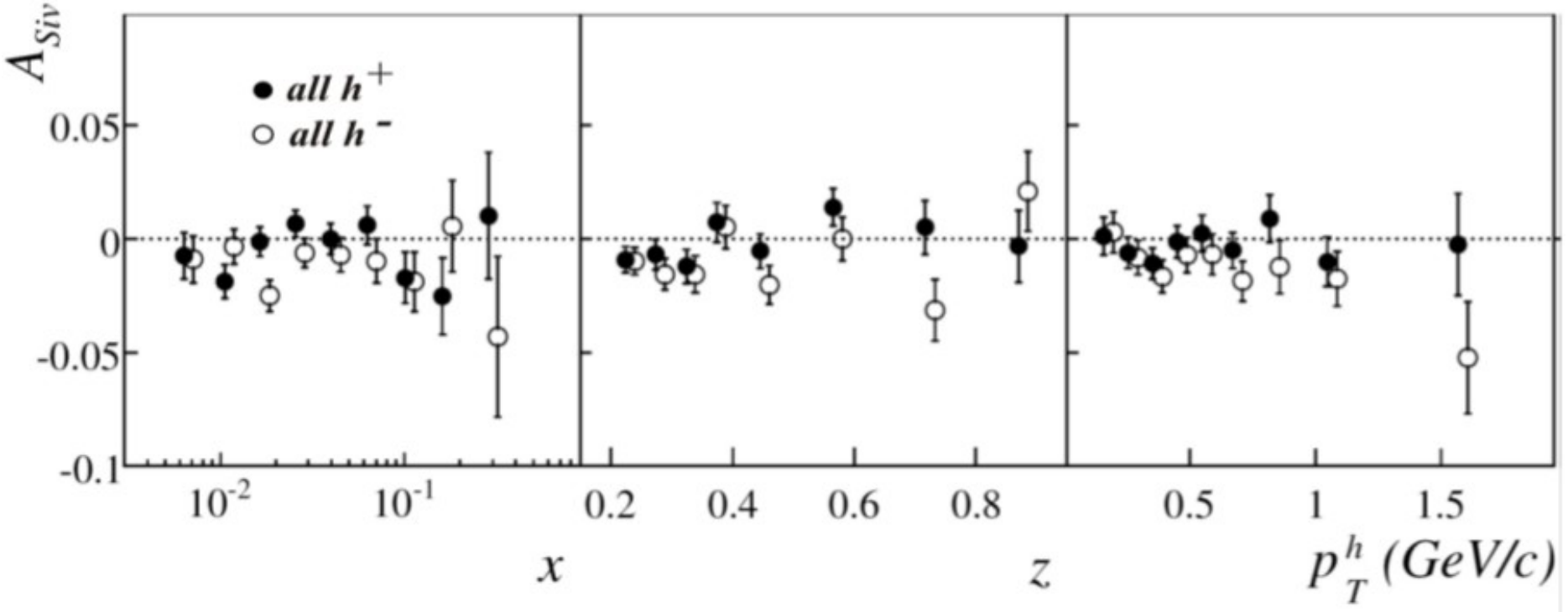
unpolarized FF

$$A_{Siv}(x,z,p_T^h) = \frac{A_{Siv}^{raw}}{P_T \cdot f} = \frac{\sum_q e_q^2 f_{1T}^q(x,k_\perp^2) \otimes D_{1,q}(z,p_\perp^2)}{\sum_q e_q^2 f_1^q(x,k_\perp^2) \otimes D_{1,q}(z,p_\perp^2)}$$

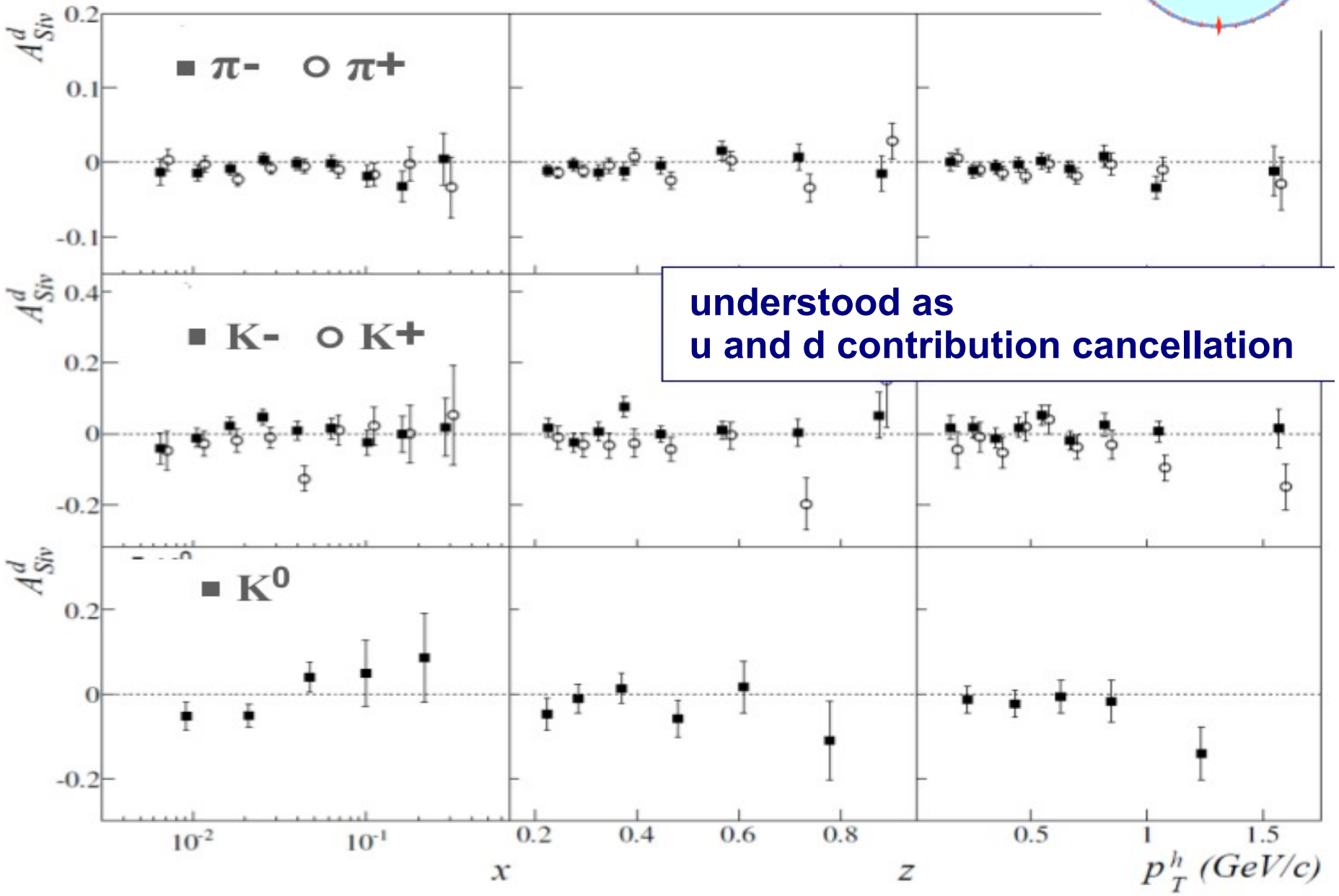
Sivers asymmetry on deuteron

charged hadrons, results from 2002-2004

PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127



Sivers asymmetry on deuteron



understood as
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Sivers asymmetry on proton

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PLB 692 (2010) 240 PLB 717 (2012) 376

good agreement between the two data sets

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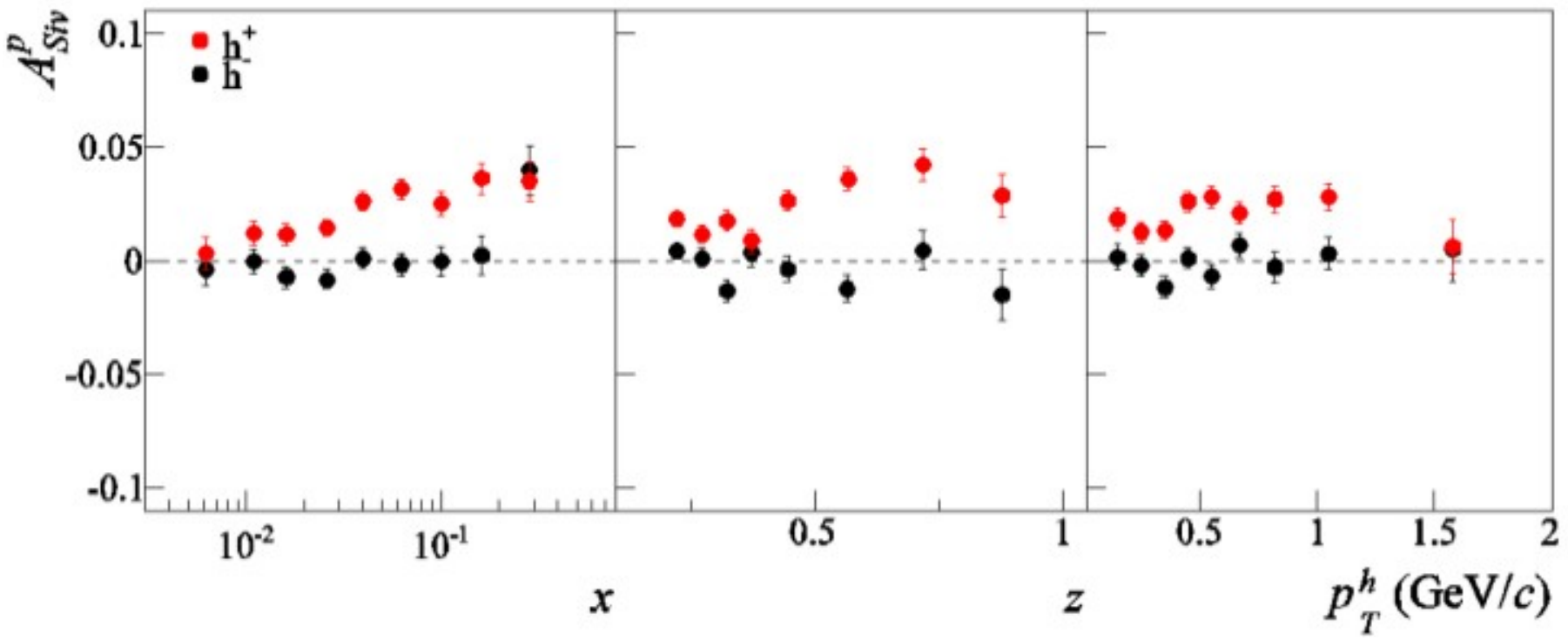


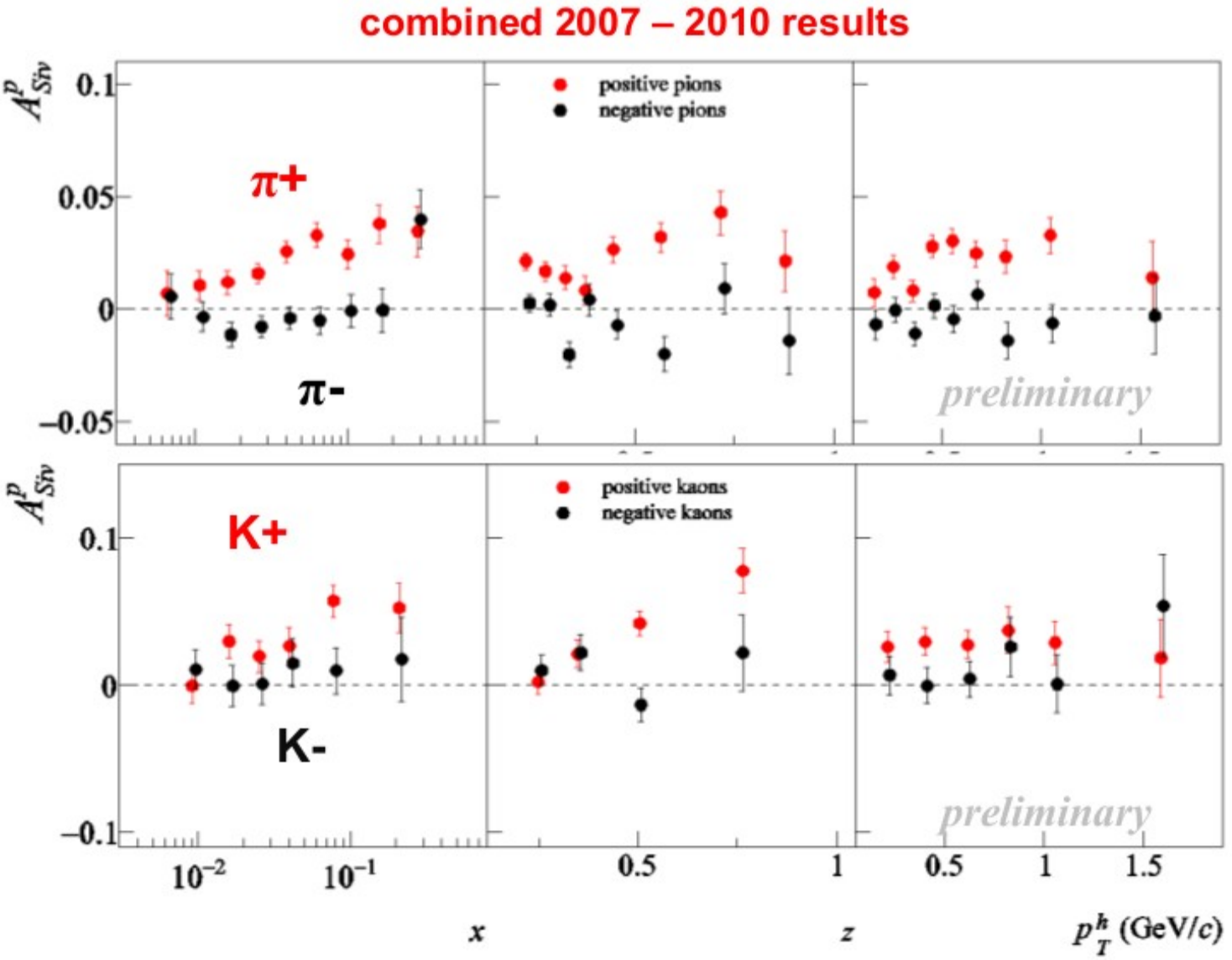
clear signal down to low x, in the previously unmeasured region

Sivers asymmetry on proton

charged pions and kaons

~ h+ / h-

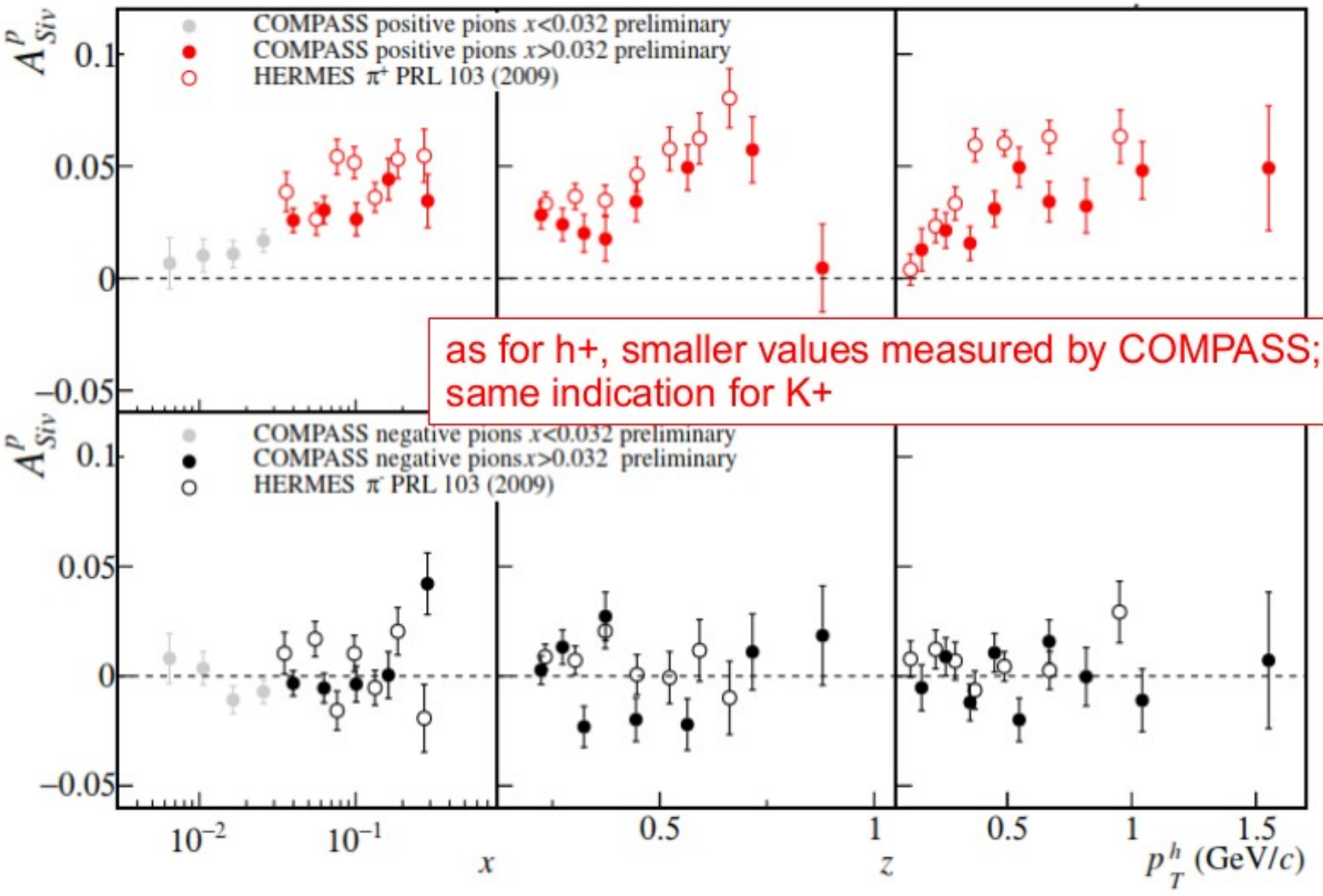
larger than for π+



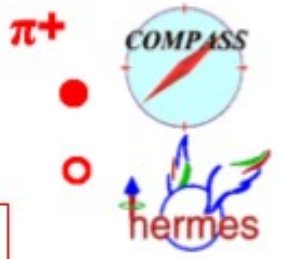
Sivers asymmetry on proton

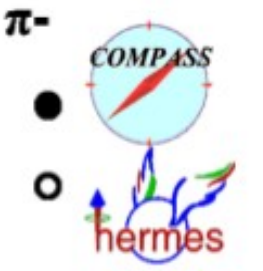
charged pions (and kaons), 2010 data, x > 0.032 region

comparison with HERMES



as for h+, smaller values measured by COMPASS; same indication for K+





Sivers asymmetry on proton

charged pions (and kaons), 2010 data, x > 0.032 region

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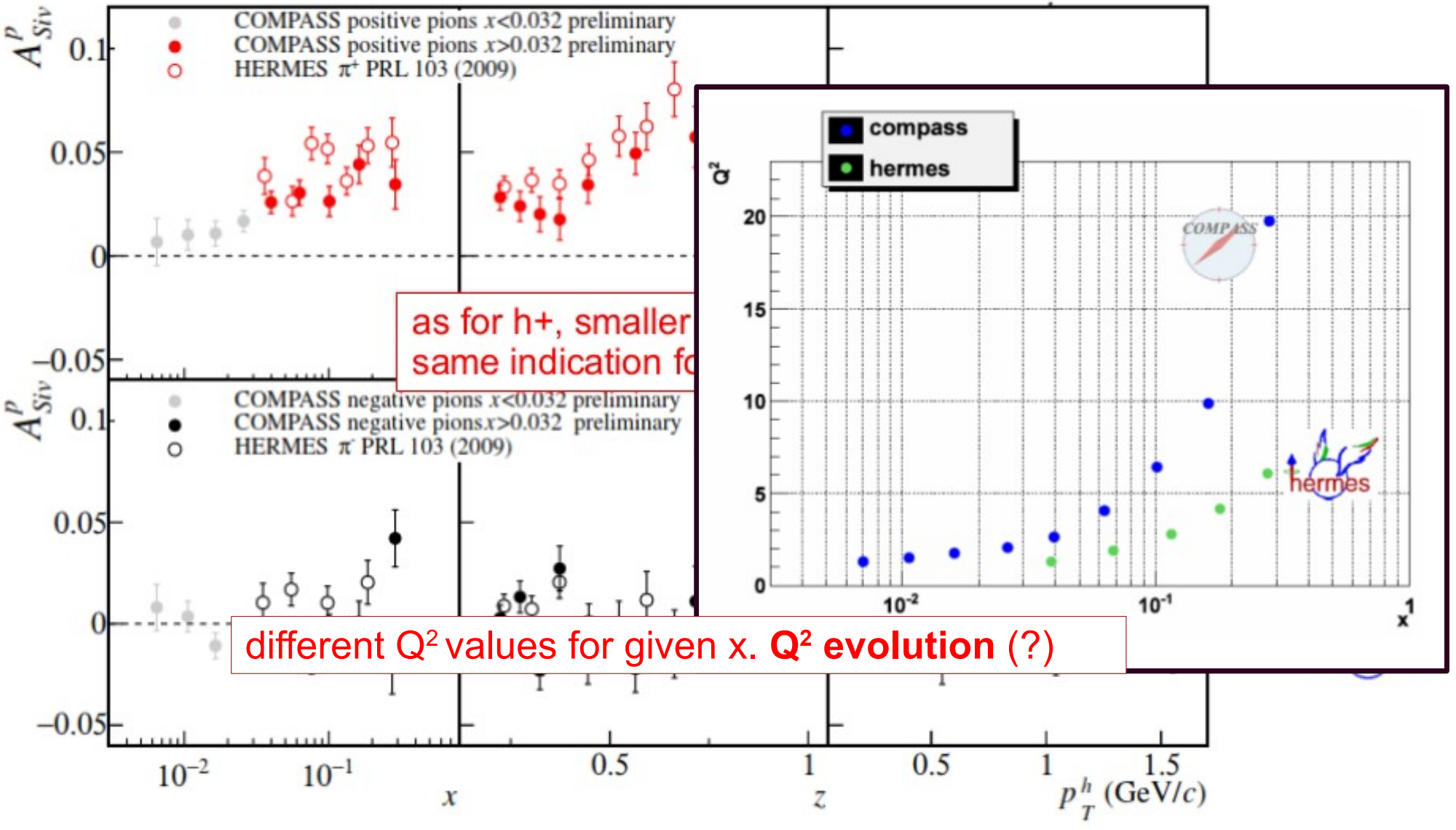
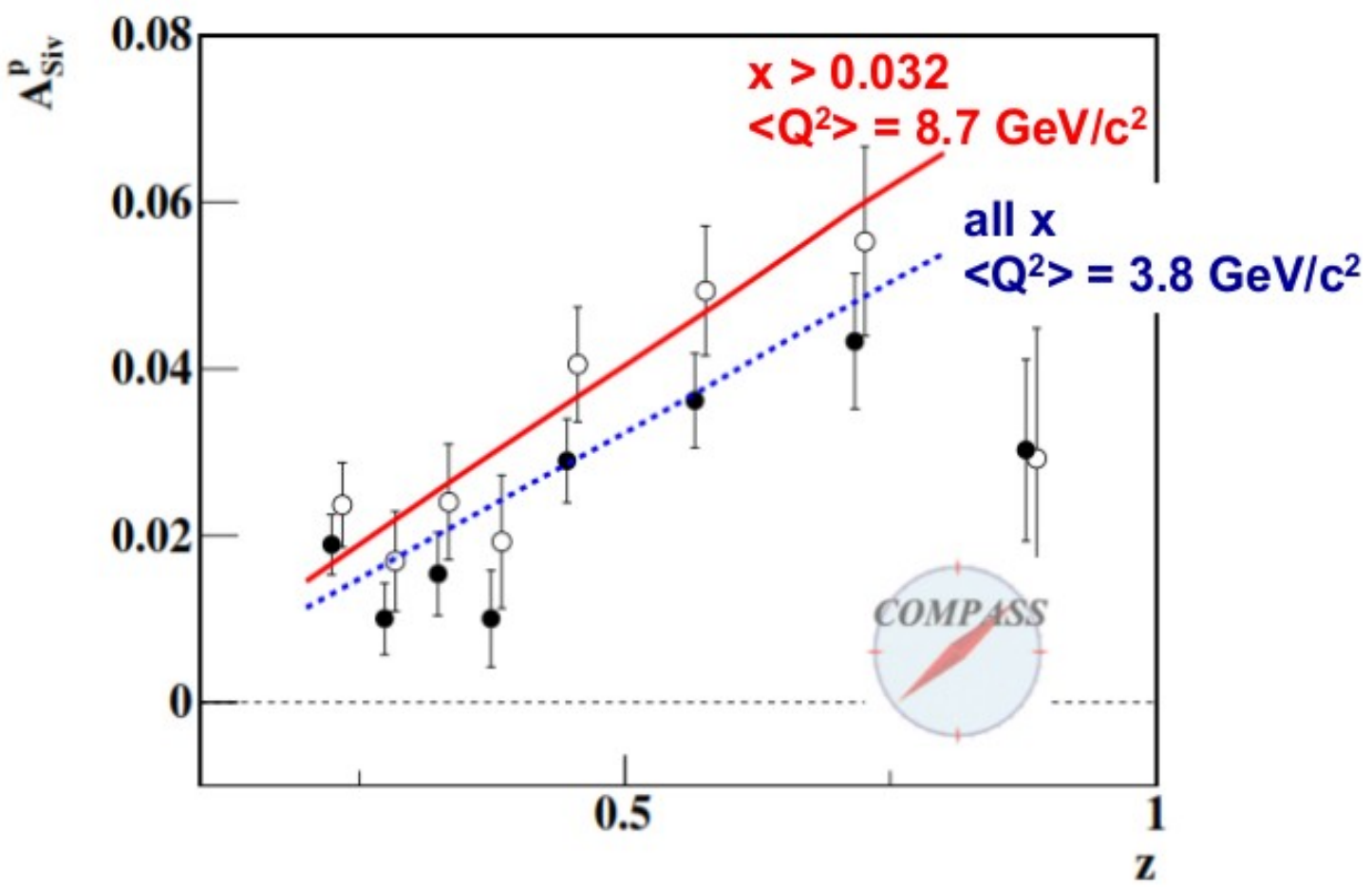


Sivers asymmetry on proton

charged hadrons 2010 data – Q^2 evolution
comparison with
S. M. Aybat, A. Prokudin and T. C. Rogers
calculations PRL 108 (2012) 242003



results

6 other azimuthal asymmetries

6 other azimuthal asymmetries

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}, \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

$$A_{LT}^{\cos\phi_s} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots \right), \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots \right), \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}, \quad \text{"Pretzelosity" PDF } h_{1T}^{\perp q}$$

$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_{1}^{q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \ldots \right), \quad \text{"Transversity" PDF } h_{1}^{q}$$
$$\text{"Sivers" PDF } f_{1T}^{\perp q}$$

$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \ldots \right), \quad \text{"Pretzelosity" PDF } h_{1T}^{\perp q}$$
$$\text{"Sivers" PDF } f_{1T}^{\perp q}$$

6 other azimutal asymmetries

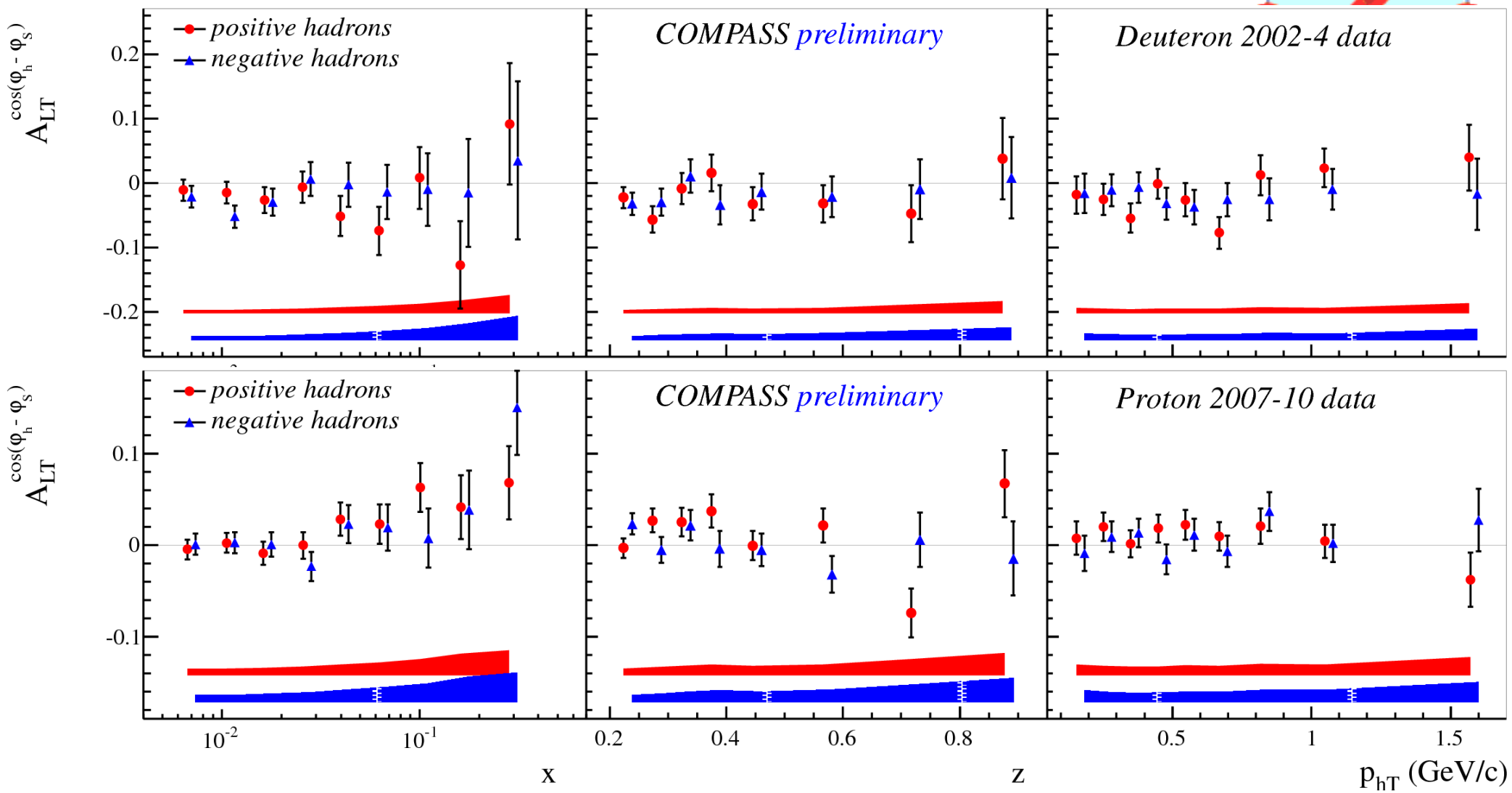
- All 6 (beyond Collins and Sivers) asymmetries measured on deuteron target are compatible with zero within uncertainties
- On proton (2007 & 2010 data) all 6 asymmetries are consistent with zero except:

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}, \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_1^{q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \ldots\right), \text{"Transversity" PDF } h_1^{q}$$

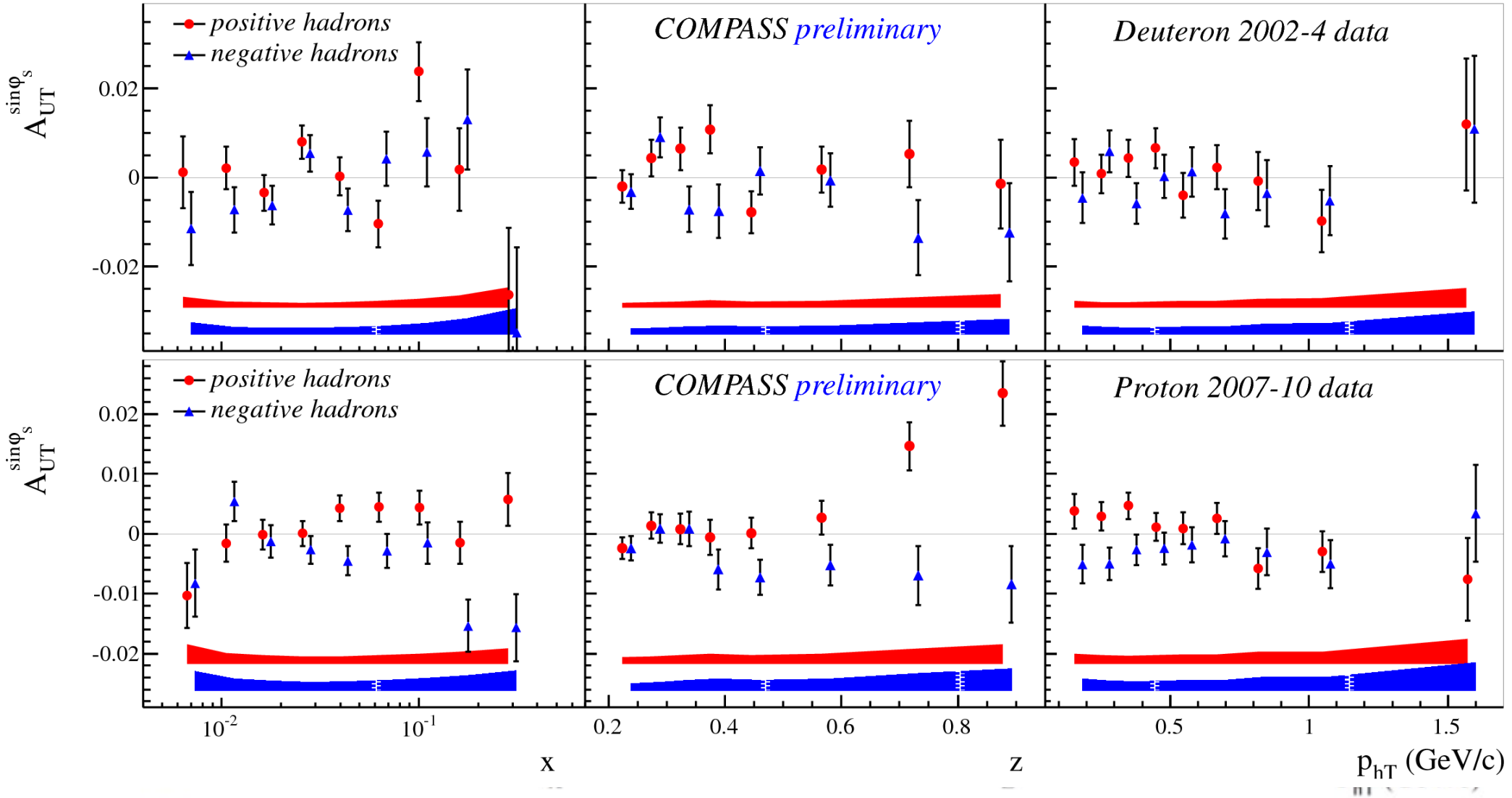
"Sivers" PDF $f_{1T}^{\perp q}$

$A_{LT}^{\cos(\phi_h-\phi_s)}$ asymmetry on proton & deuteron



$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}, \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

$A_{UT}^{\sin\phi_s}$ asymmetry on proton &deuteron



$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

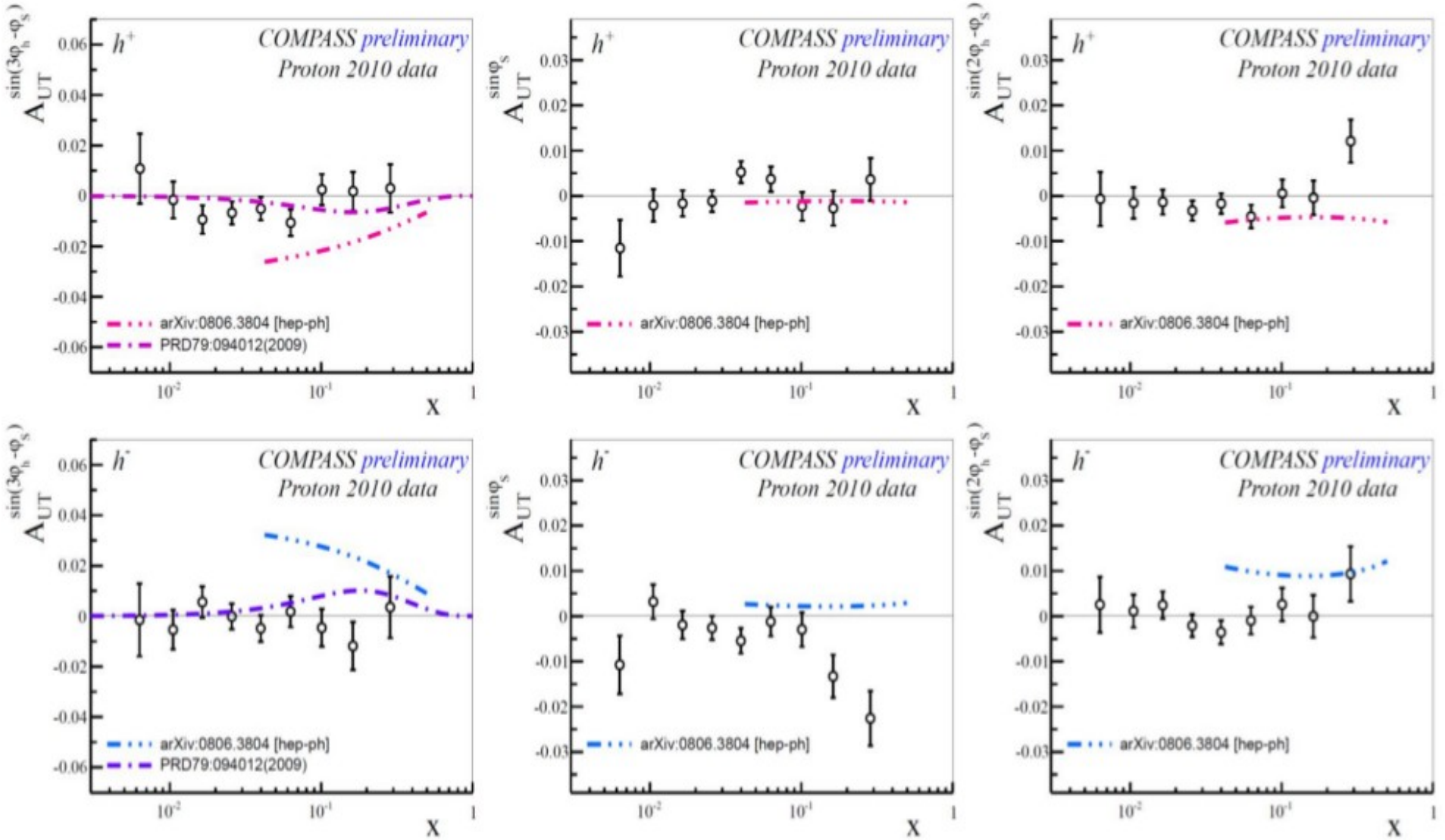
"Transversity" PDF h_1^q

"Sivers" PDF $f_{1T}^{\perp q}$

Theoretical predictions for the 6 asymmetries

“UT” asymmetries and theoretical predictions for the x dependence

S. Boffi, A.V. Efremov, B. Pasquini and P. Schweitzer PRD79:094012(2009)
A. Kotzinian arXiv:0806.3804[hep-ph]



“LT” asymmetries and theoretical predictions for the x dependence

A. Kotzinian, B. Parsamyan, A. Prokudin Phys.Rev.D73:114017 (2006)
S. Boffi, A.V. Efremov, B. Pasquini and P. Schweitzer PRD79:094012(2009)
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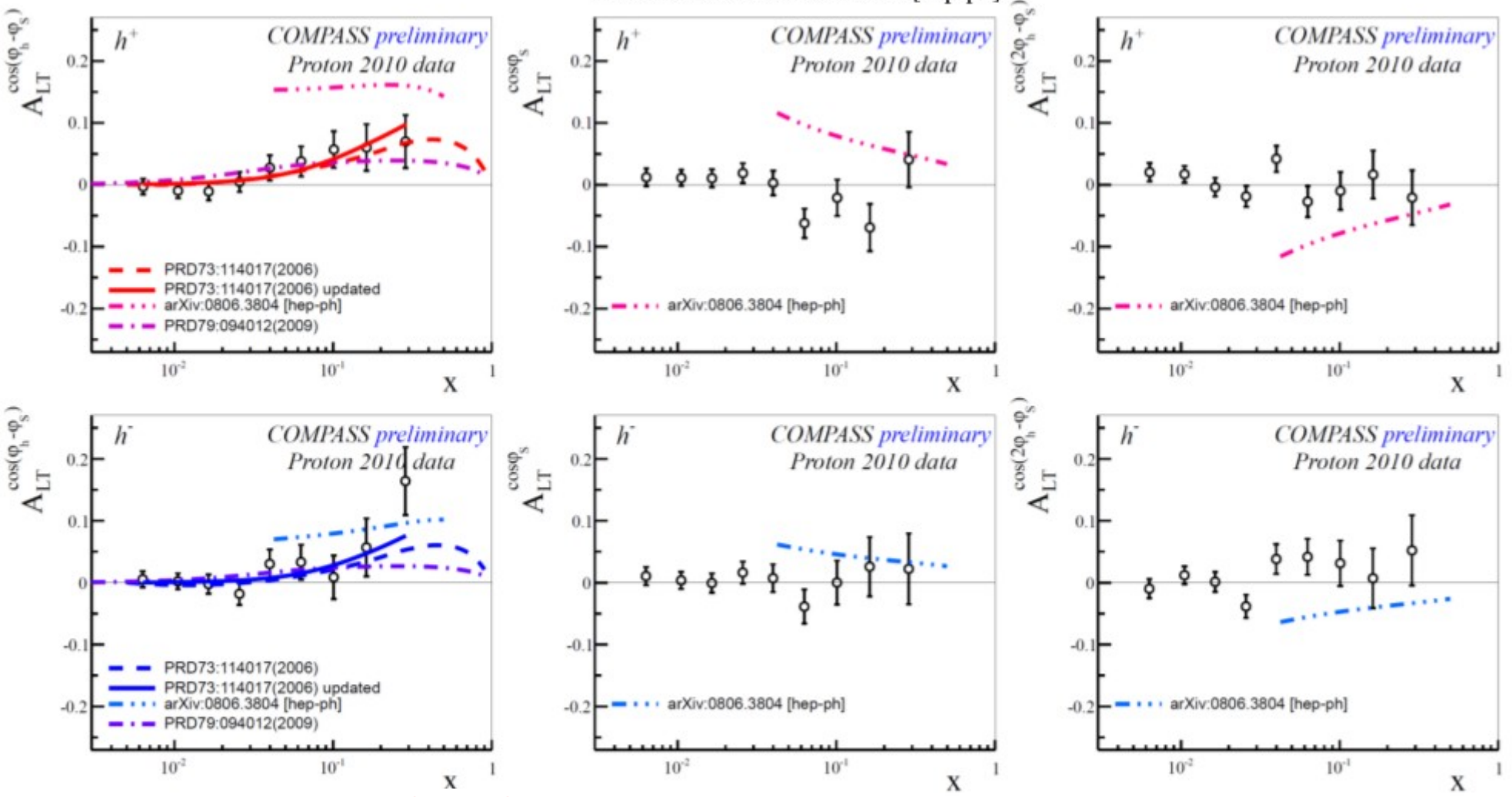


The predictions for $A_{LT}^{\cos(\phi_h-\phi_s)}$ are in agreement with measured asymmetries

Summary.
Collins, Sivers and dihadron asymmetries

- COMPASS has measured Collins, Sivers and dihadron asymmetries on d and p for charged and identified hadrons

On deuteron:

- All azimuthal asymmetries measured on transversely polarized target are compatible with zero
  - approximate cancelation of u and d quark contributions
  - important for global fits to disentagle flavour contributions

On proton:

- Collins asymmetry significantly different from zero down to x=0.03, no significant dependence on Q^2/y
- h+ and h- Collins asymmetry show mirror symmetry
- Two hadron asymmetry: large in valence region, no clear dependence on $\mathbf{M^{h+h-}_{inv}}$
- h+ Sivers asymmetry: clear signal different from zero. Signature of nonzero OAM, dependence on Q^2/y over all x range
- h- Sivers asymmetry : compatible with zero

Summary
6 other azimuthal asymmetries

Six beyond Collins and Sivers transverse spin asymmetries

$A_{UT}^{\sin(3\phi_h-\phi_s)}$, $A_{UT}^{\sin\phi_s}$, $A_{UT}^{\sin(2\phi_h-\phi_s)}$, $A_{LT}^{\cos(\phi_h-\phi_s)}$, $A_{LT}^{\cos\phi_s}$, $A_{LT}^{\cos(2\phi_h-\phi_s)}$

have been extracted from COMPASS deuteron 2002-2004 and proton 2007-2010 data

On deuteron:

- all asymmetries found to be consistent with zero within the statistical uncertainty

On proton:

- nonzero values for $A_{LT}^{\cos(\phi_h-\phi_s)}$ and $A_{UT}^{\sin\phi_s}$ amplitudes
- COMPASS results for $A_{LT}^{\cos(\phi_h-\phi_s)}$ show good agreement with theoretical predictions
- precise measurements enables to discriminate between theoretical models

Outlook

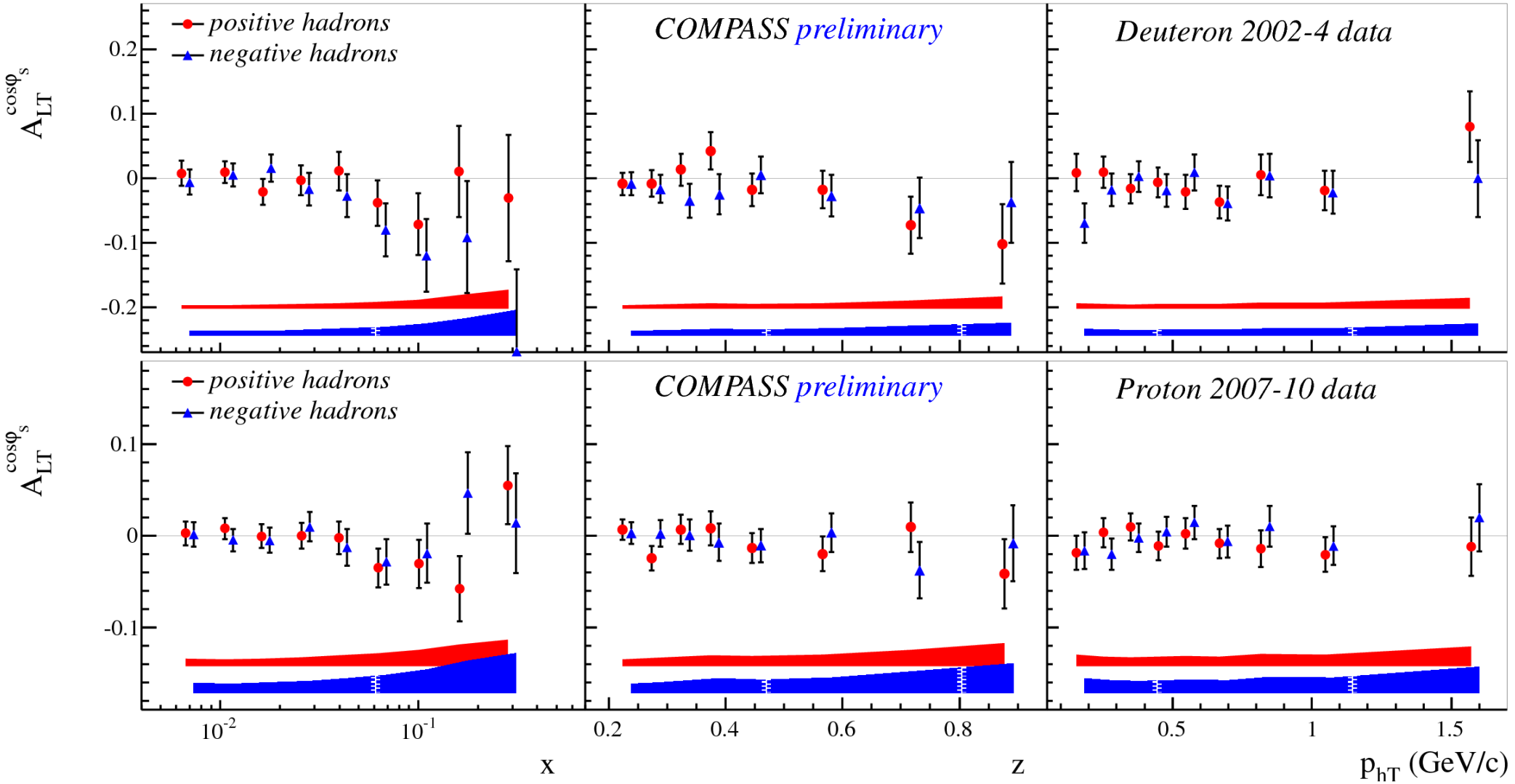
to be done soon:

- 6 asymmetries (beyond Collins and Sivers) for kaons and pions
- multidimentional analysis for all azimuthal asymmetries
- Sivers asymmetry of gluons

Thank you!

Backup slides

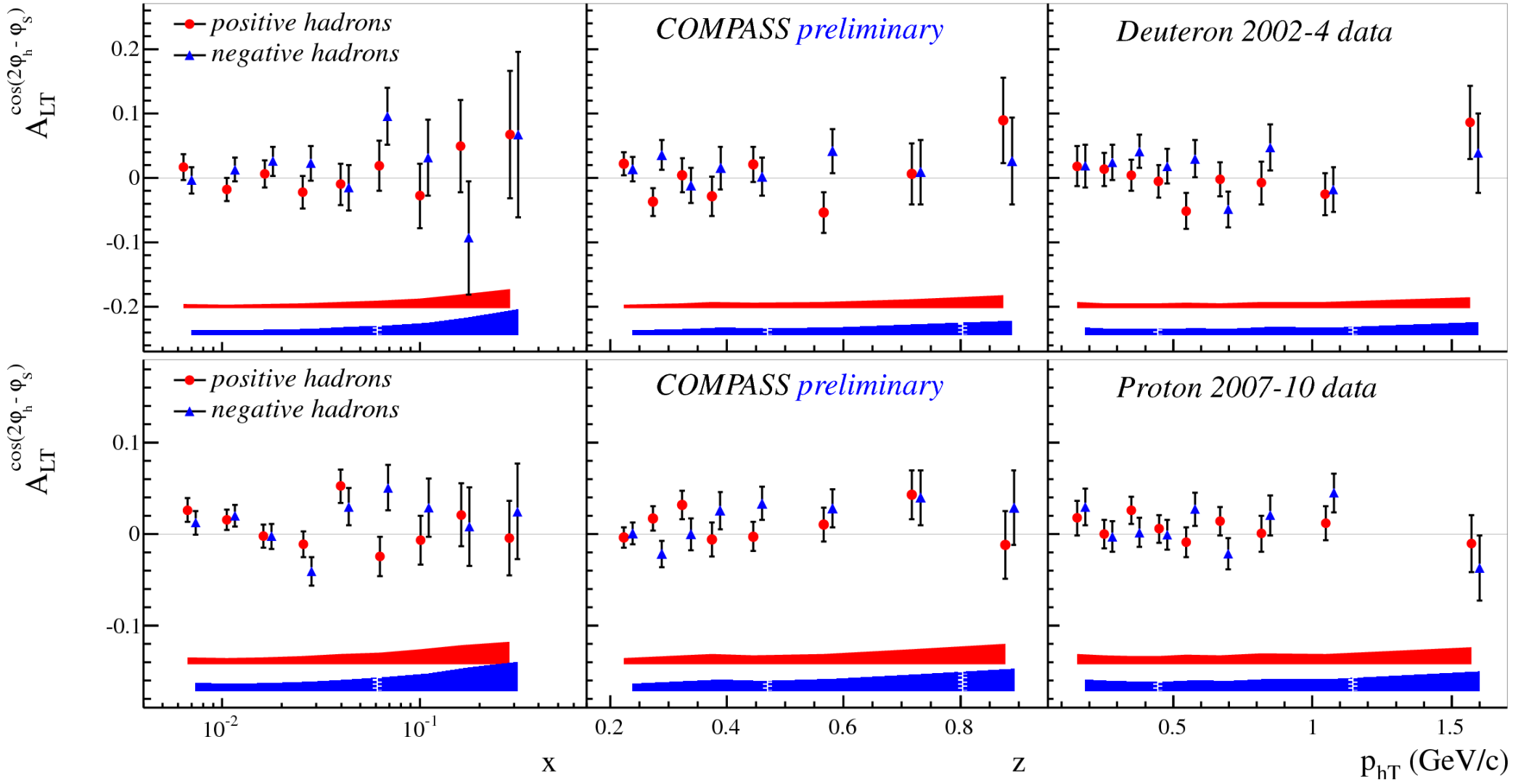
$A_{LT}^{\cos\phi_s}$ asymmetry on proton & deuteron



$$A_{LT}^{\cos\phi_s} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots\right), \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

Asymmetries both for proton and deuteron are compatible with zero within uncertainties

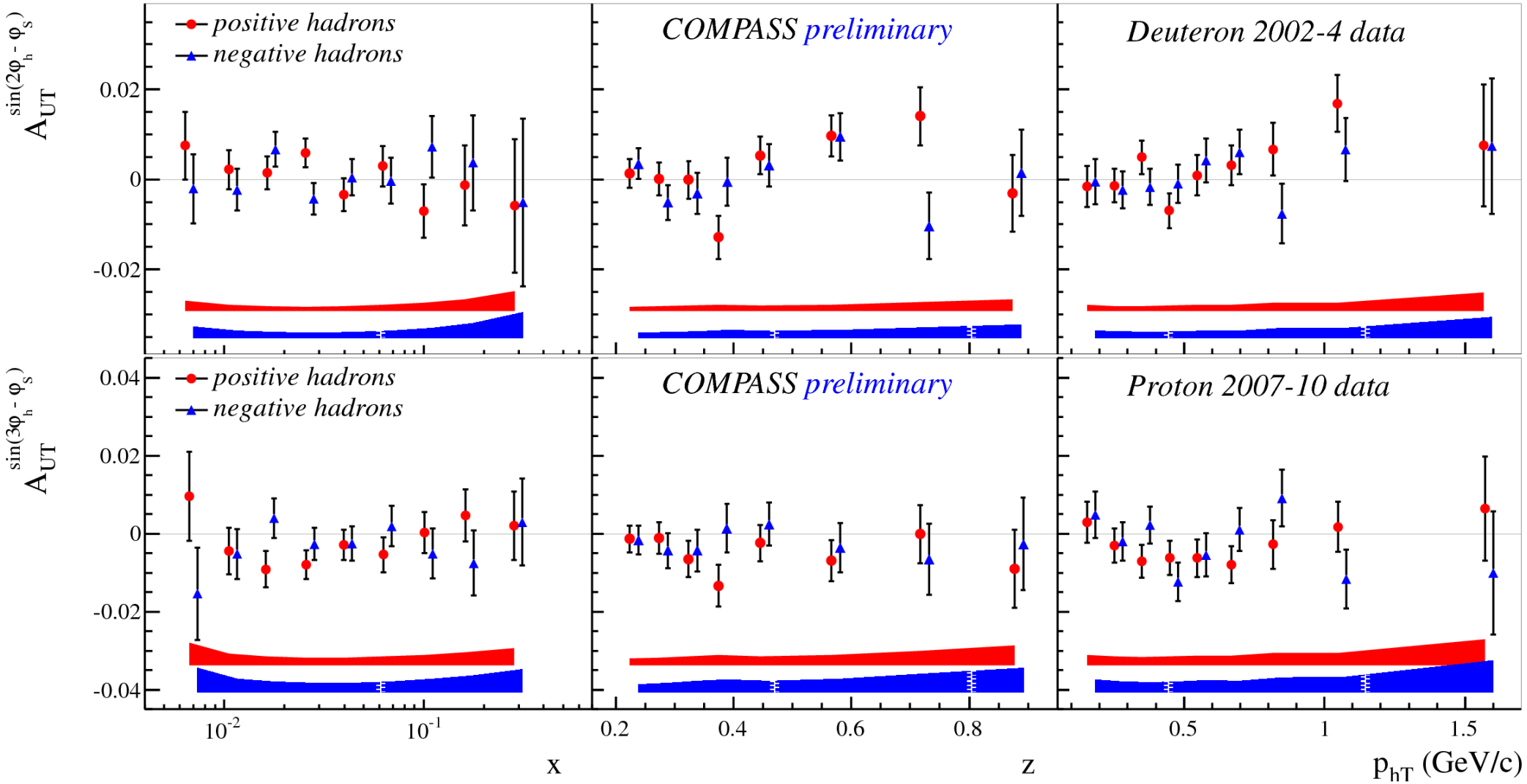
$A_{LT}^{\cos(2\phi_h-\phi_s)}$ asymmetry on proton & deuteron



$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots \right), \quad \text{"Worm Gear" PDF } g_{1T}^{q}$$

At low $|\mathbf{P_{hT}}|$ expected to be suppressed by a factor of ~$|\mathbf{P_{hT}}|$ with respect to the Collins and Sivers Asymmetries for both proton and deuteron are compatible with zero within uncertainties

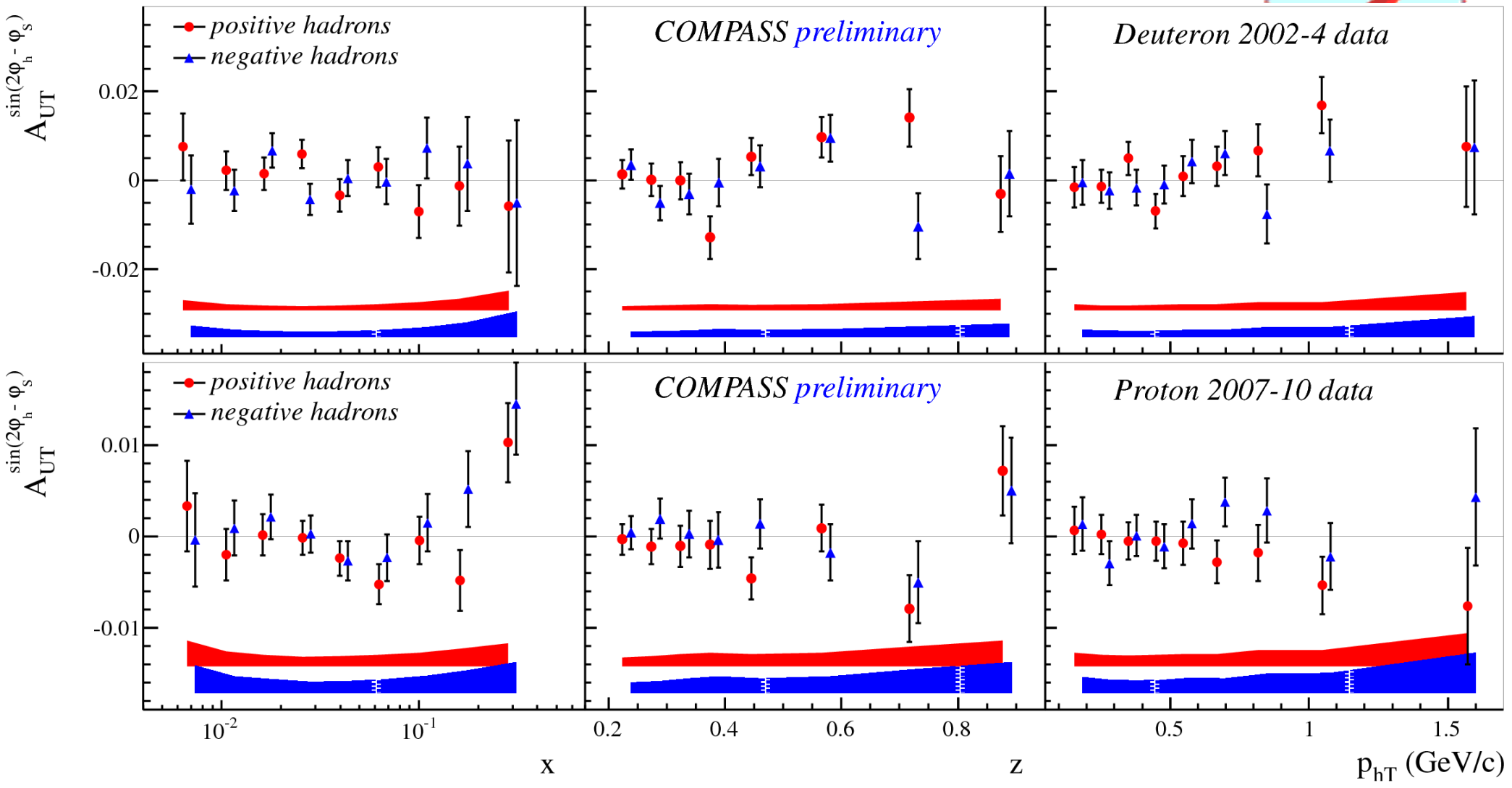
$A_{UT}^{\sin(3\phi_h-\phi_s)}$ asymmetry on proton & deuteron



$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$, "Pretzelosity" PDF $h_{1T}^{\perp q}$

Expected to be suppressed by a factor of ~$|\mathbf{P}_{hT}|^2$ with respect to the Collins and Sivers amplitudes
Asymmetries for both proton and deuteron are compatible with zero within uncertainties

$A_{UT}^{\sin(2\phi_h-\phi_s)}$ asymmetry on proton & deuteron



$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h} + f_{1T}^{\perp q}\otimes D_{1q}^{h} + \ldots\right)$$

"Pretzelosity" PDF $h_{1T}^{\perp q}$

"Sivers" PDF $f_{1T}^{\perp q}$

At low $|\mathbf{P_{hT}}|$ expected to be suppressed by a factor of ~$|\mathbf{P_{hT}}|$ with respect to the Collins and Sivers

Asymmetries for both proton and deuteron are compatible with zero within uncertainties