TMD measurements at COMPASS

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on behalf of the **COMPASS** collaboration

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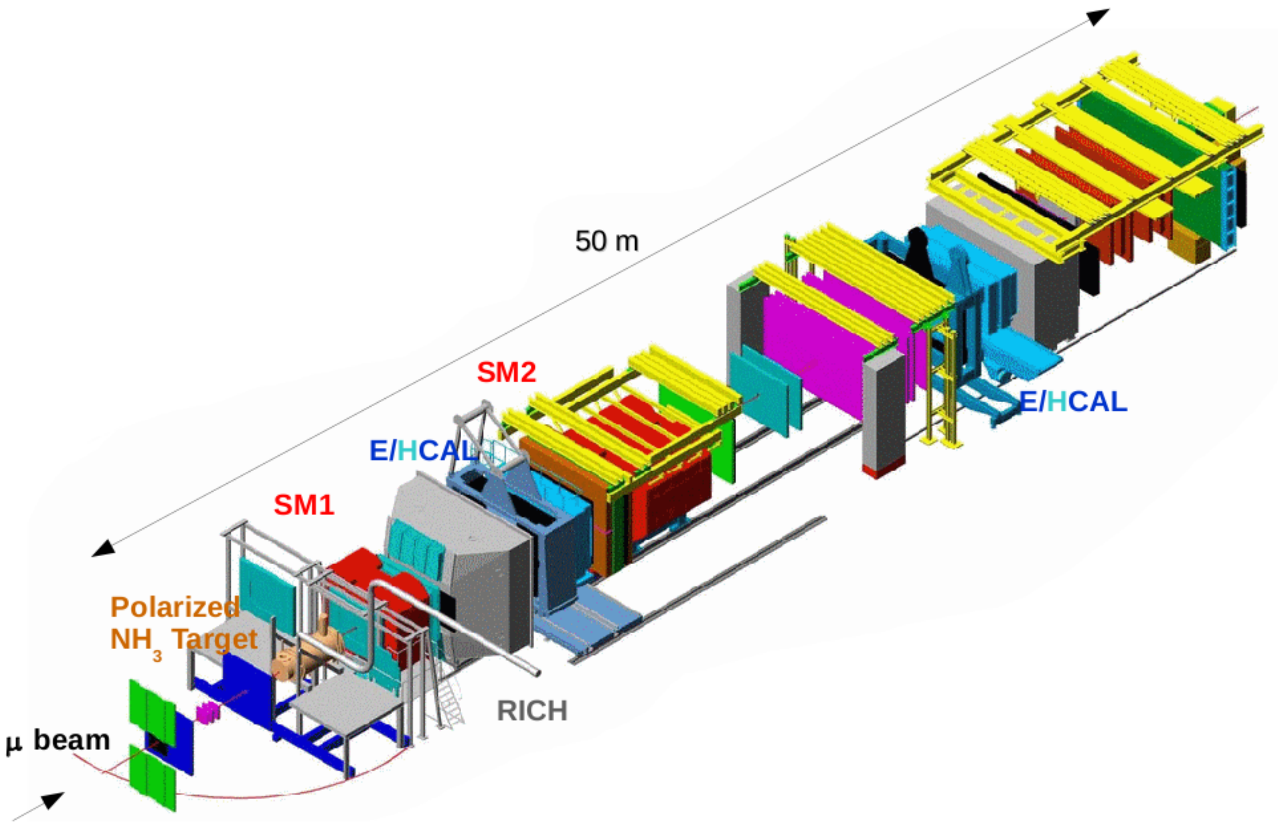
NATURWISSENSCHAFTLICHE FAKULTÄT

Outline

The COMPASS experiment

The COMPASS experiment ▶ at CERN

The COMPASS experiment ▶ spectrometer & lepton beam



e.g.

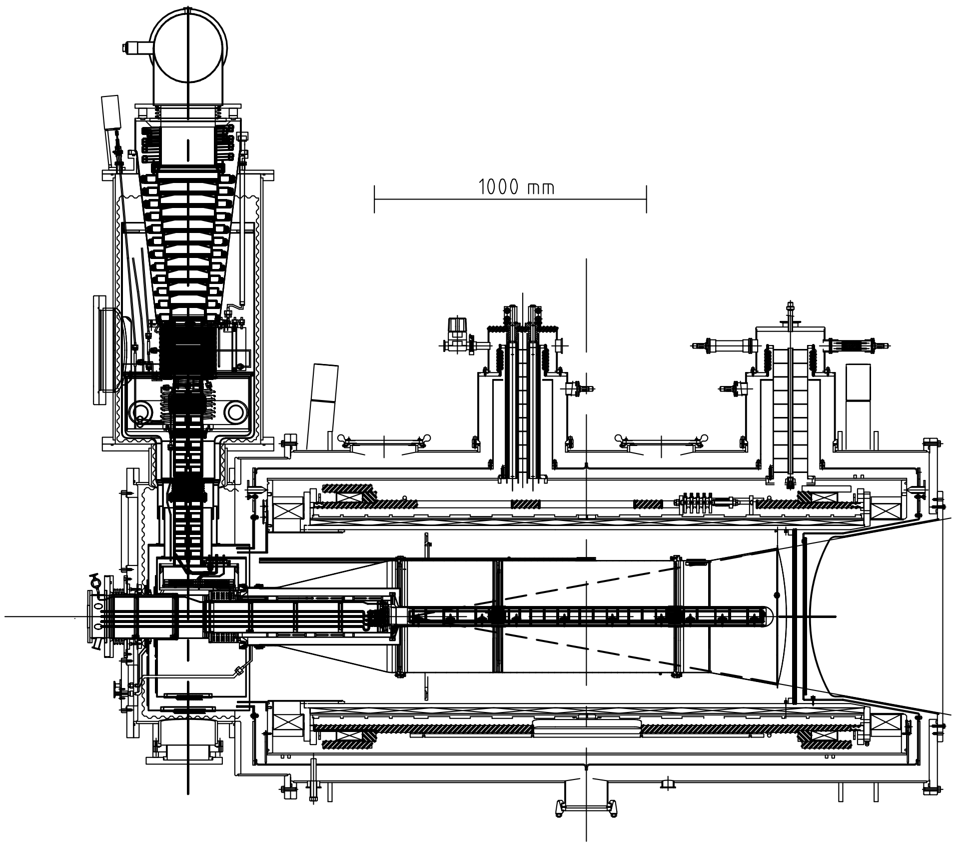
COMPASS setup 2007

- p_{beam} 2007/10 160 GeV/c
- Intensity per spill $3.5 \cdot 10^8 \mu^+$
- Luminosity $5 \cdot 10^{32} \text{cm}^{-2}\,\text{s}^{-1}$
- polarization $\lambda \approx 80$ %

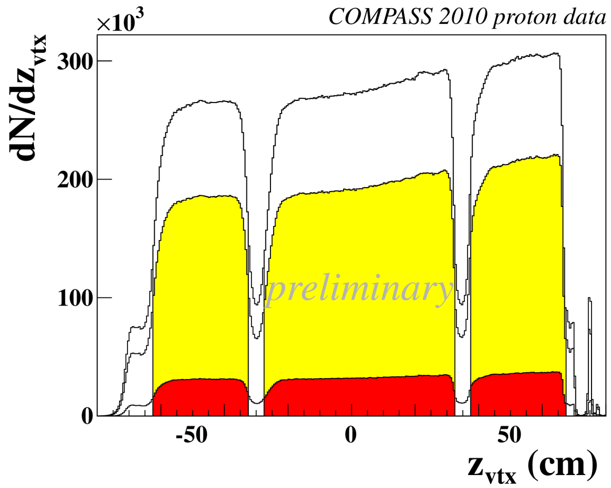
- Two stage spectrometer
- Longitudinally polarized μ^+-beam
- 2002-04 transversely polarized deuteron (^{6}LiD) target
- 2007/10 transversely polarized proton (NH_3) target
- 2011 longitudinally polarized proton (NH_3) target

- Tracking
- Calorimetry
- PID (RICH)

The COMPASS experiment ▶ polarized target system



- Upgrade of target system in 2005
- Three cells with opposite polarization
- ±180 mrad geometrical acceptance
- Transverse polarization reversed every week via microwave



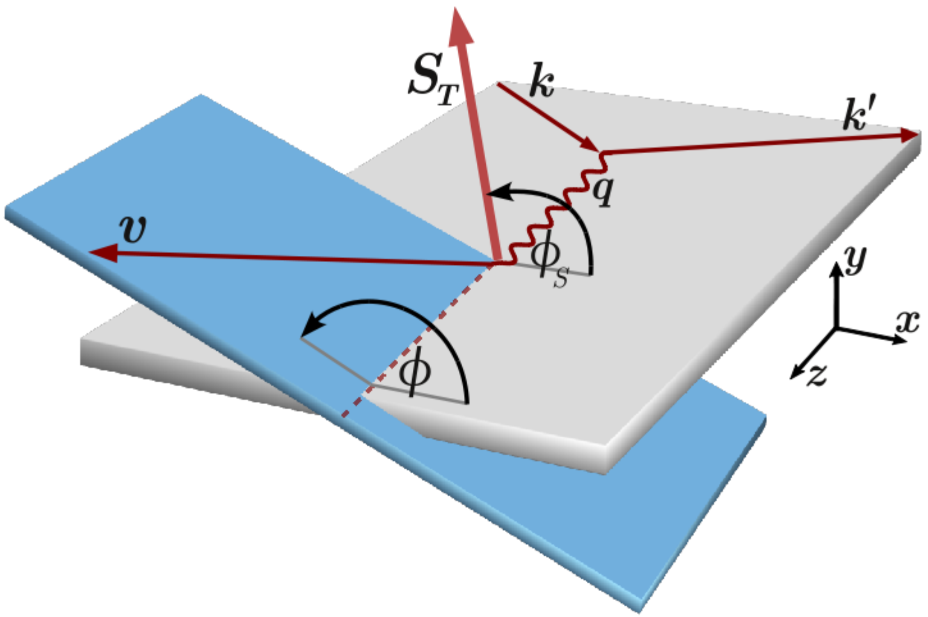
- proton (NH_3):
  - polarization $P_T \approx 90\ \%$
  - dilution factor $f \approx 16\ \%$
- deuteron (^{6}LiD):
  - $P_T \approx 50\ \%$
  - $f \approx 40\ \%$

Theoretical framework

Theoretical framework ▶ single hadron reaction scheme

$l\ p^{\uparrow} \quad \rightarrow \quad l'\ h$

Fragmentation of a transversely polarized quark into one unpolarized hadron



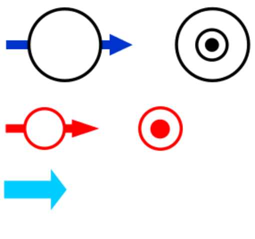
in courtesy of H. Wollny

- k, k' and q are 4-momenta of incomming l, scattered lepton l' and virtual photon γ^*
- P is the 4-momenta of the scattered nucleon
- Φ_S azimuthal angle of the spin of the fragmenting quark S_T
- Φ_h azimuthal angle of the lepton scattering plane *w.r.t.* the lepton plane
- $Q^2 = -q^2$
- $W = \sqrt{(P+q)^2}$
- $x = \frac{Q^2}{2P \cdot q}$
- $y = \frac{P \cdot q}{p \cdot k} \underset{\text{lab}}{=} \frac{E - E'}{E}$
- $z = \frac{P \cdot p}{P \cdot q} \underset{\text{lab}}{=} \frac{E_h}{E - E'}$

Theoretical framework ▶ from spin structure to Transversity

3 independent parton distribution functions (PDFs) are necessary to describe the spin structure of the nucleon in leading order in the collinear case:

nucleon \ quark	U	L	T
U	$f_1^q(x)$		
L		$g_1^q(x)$ -	
T			$h_1^q(x)$ -



nucleon with transverse or longitudinal spin

nucleon with transverse or longitudinal spin

parton transverse momentum

Proton goes out of the screen.
Photon goes into the screen.

in courtesy of B. Parsamyan

Quark distribution:
$f_1^q(x) = q^+(x) + q^-(x)$

Helicity distribution:
$g_1^q(x) = q^+(x) - q^-(x)$

Transversity distribution:
$h_1^q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

Collins FF: $lN^\uparrow \rightarrow l'h$
Interference FF: $lN^\uparrow \rightarrow l'hh$
Λ FF: $lN^\uparrow \rightarrow l'\Lambda$

Taking into account the quark intrinsic transverse momentum k_T, at leading order in total 8 TMD PDFs are needed for a full description of the nucleon structure:

nucleon \ quark	U	L	T
U	quark dstrbtn $f_1^q(x)$		$h_1^{\perp q}$ Boer-Mulders
L		Helicity $g_1^q(x)$	$h_{1L}^{\perp q}$ Worm-gear L
T	$f_{1T}^{\perp q}$ Sivers	g_{1T}^q Worm-gear T	$h_1^q(x)$ Transversity $h_{1T}^{\perp q}$ Pretzelosity

Theoretical framework ▶ SIDIS cross-section

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \Bigg($$

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

$$S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right] + \quad \textit{see talk by M. Stolarski}$$

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

$$S_T\Big[$$

$$\sin\phi_S \times (\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S})$$

$$\sin(\phi_h-\phi_S)\times(A_{UT}^{\sin(\phi_h-\phi_S)})$$

$$\sin(\phi_h+\phi_S)\times(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)})$$

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

$$\sin(3\phi_h-\phi_S)\times(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)})$$

$$\Big] + S_T\lambda\Big[$$

$$\cos\phi_S \times (\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S)})$$

$$\cos(\phi_h-\phi_S)\times(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)})$$

$$\cos(2\phi_h-\phi_S)\times(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)})$$

$$\Big]\Bigg)$$

Twits-2 ;
Twist-2 + k_T/Q kinematical corrections

$$A_{U(L),T}^{\omega(\phi_h,\phi_S)} = \frac{F_{U(L),T}^{\omega(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2} \quad , \quad \gamma = \frac{2Mx}{Q}$$

Kotzinian, Nucl. Phys. B441, 234 (1995)
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel, JHEP (2007) 0702:093

Within QCD parton model $A_i \propto \mathbf{DF} \otimes \mathbf{FF}$ with $i = 1, ..., 11$

Twist-2

unpolarized

$A_{UU}^{\cos\phi_h} \propto$
$f_1^q \otimes D_{1q}^h + h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$

$A_{UU}^{\cos 2\phi_h} \propto$
$f_1^q \otimes D_{1q}^h + h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$

single spin

$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$

$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

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

double spin

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

Twist-2 + k_T/Q kinematical corrections

unpolarized

$A_{LU}^{\sin\phi_h}$

single spin

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

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

double spin

$A_{LT}^{\cos\phi_S} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$

$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$

Theoretical framework ▶ From raw to physics asymmetries

$$A_{UU}^{\omega(\phi_h,\phi_S)} = \frac{A_{UU,raw}^{\omega(\phi_h,\phi_S)}}{D^{\omega(\phi_h,\phi_S)}(y)} \quad ; \quad A_{LU}^{\omega(\phi_h,\phi_S)} = \frac{A_{LU,raw}^{\omega(\phi_h,\phi_S)}}{D^{\omega(\phi_h,\phi_S)}(y)\lambda}$$

$$A_{UT}^{\omega(\phi_h,\phi_S)} = \frac{A_{UT,raw}^{\omega(\phi_h,\phi_S)}}{D^{\omega(\phi_h,\phi_S)}(y)f|P_T|} \quad ; \quad A_{LT}^{\omega(\phi_h,\phi_S)} = \frac{A_{LT,raw}^{\omega(\phi_h,\phi_S)}}{D^{\omega(\phi_h,\phi_S)}(y)f\lambda|P_T|}$$

$D^{\sin(\phi_h-\phi_S)}(y) = 1$

$D^{\cos(2\phi_h)}(y) = D^{\sin(\phi_h+\phi_S)}(y) = D^{\sin(3\phi_h-\phi_S)}(y) = \varepsilon \approx \frac{2(1-y)}{1+(1-y)^2}$

$D^{\cos(\phi_h-\phi_S)}(y) = \sqrt{1-\varepsilon^2} \approx \frac{y(2-y)}{1+(1-y)^2}$

$D^{\cos(\phi_h)}(y) = D^{\sin(2\phi_h-\phi_S)}(y) = D^{\sin(\phi_S)}(y) = \sqrt{2\varepsilon(1+\varepsilon)} \approx \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$

$D^{\sin(\phi_h)}(y) = D^{\cos(2\phi_h-\phi_S)}(y) = D^{\cos(\phi_S)}(y) = \sqrt{2\varepsilon(1-\varepsilon)} \approx \frac{2y\sqrt{1-y}}{1+(1-y)^2}$

$D^{\omega_i(\phi_h,\phi_S)}$ = depolarization factor
f = target dilution factor
P_T = target polarization
λ = beam polarization

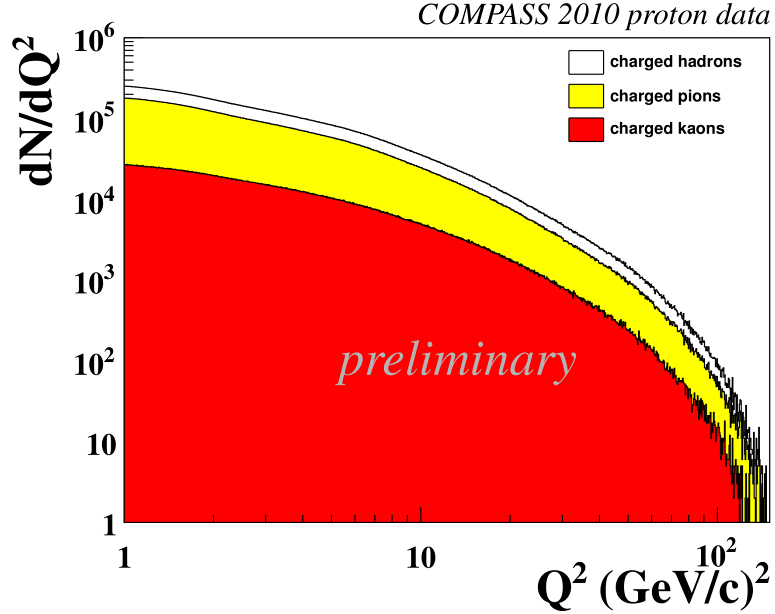
Data selection

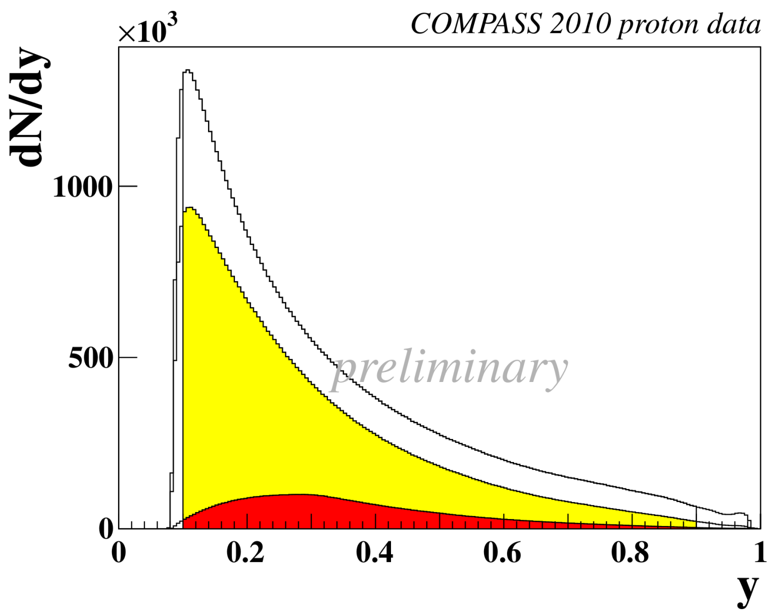
Data selection ▶ DIS cuts

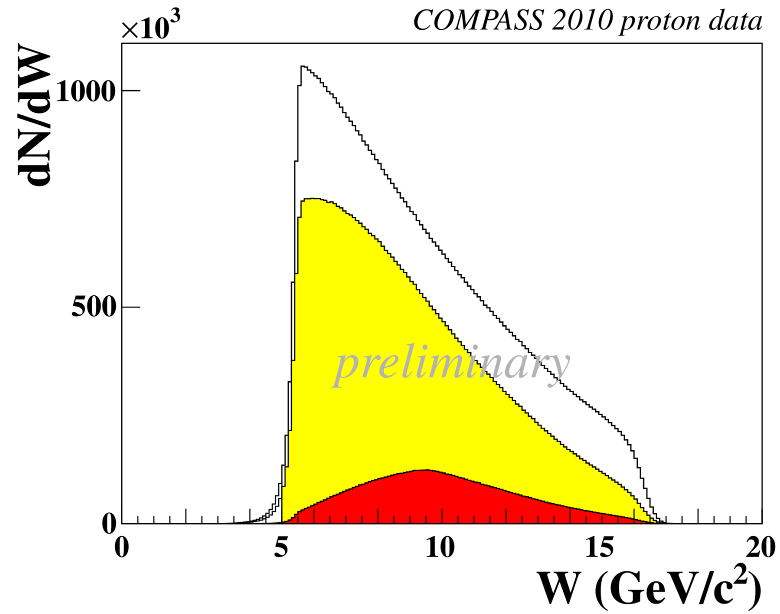
DIS cuts on events:

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

- spectrometer acceptance: $0.003 < x < 0.7$



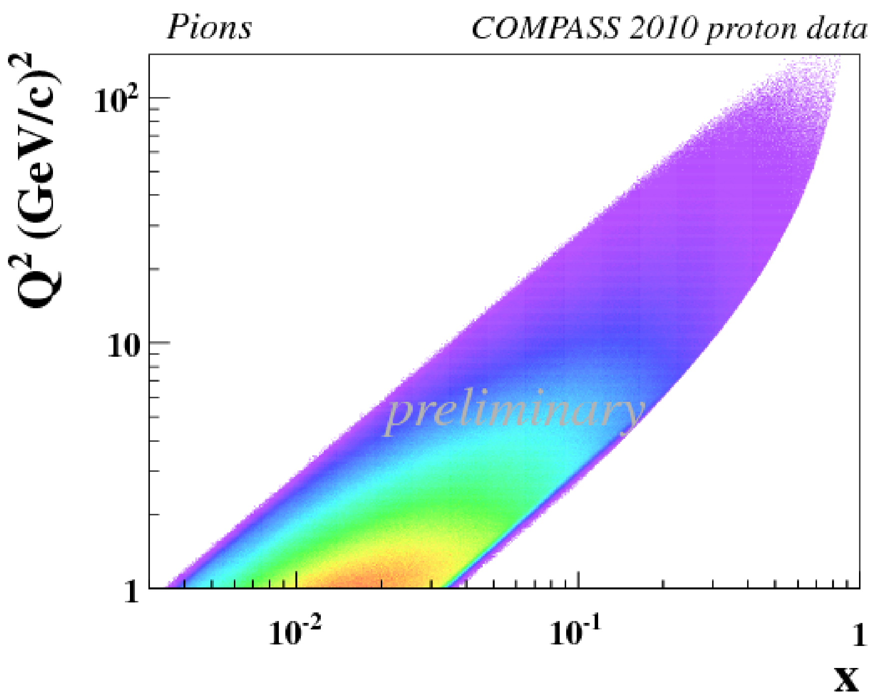


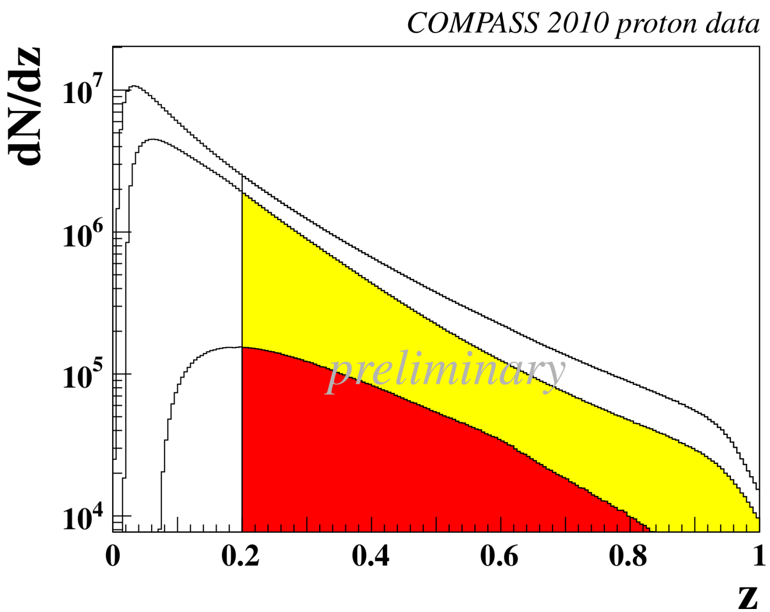


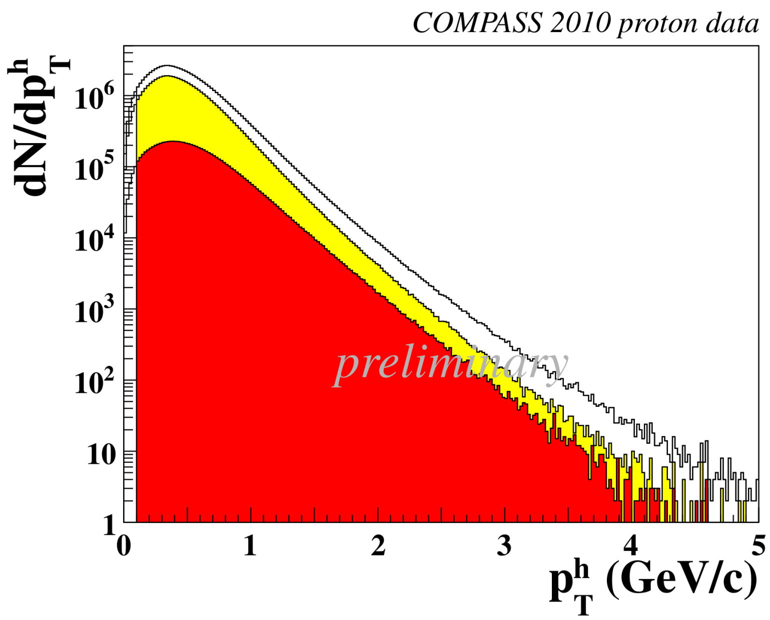
Data selection ▶ single hadron cuts

single hadron cuts:

- $z > 0.2$ for A_{UT} analysis
- $0.2 > z > 0.85$ for $A_{UU/LU}$ analysis
- $p_T > 0.1$ GeV/c







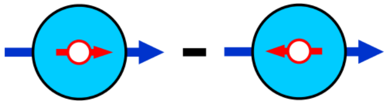
⇒ For the first time the recent COMPASS results on TMDs were shown at **SPIN2010** in Dubna September 2012.

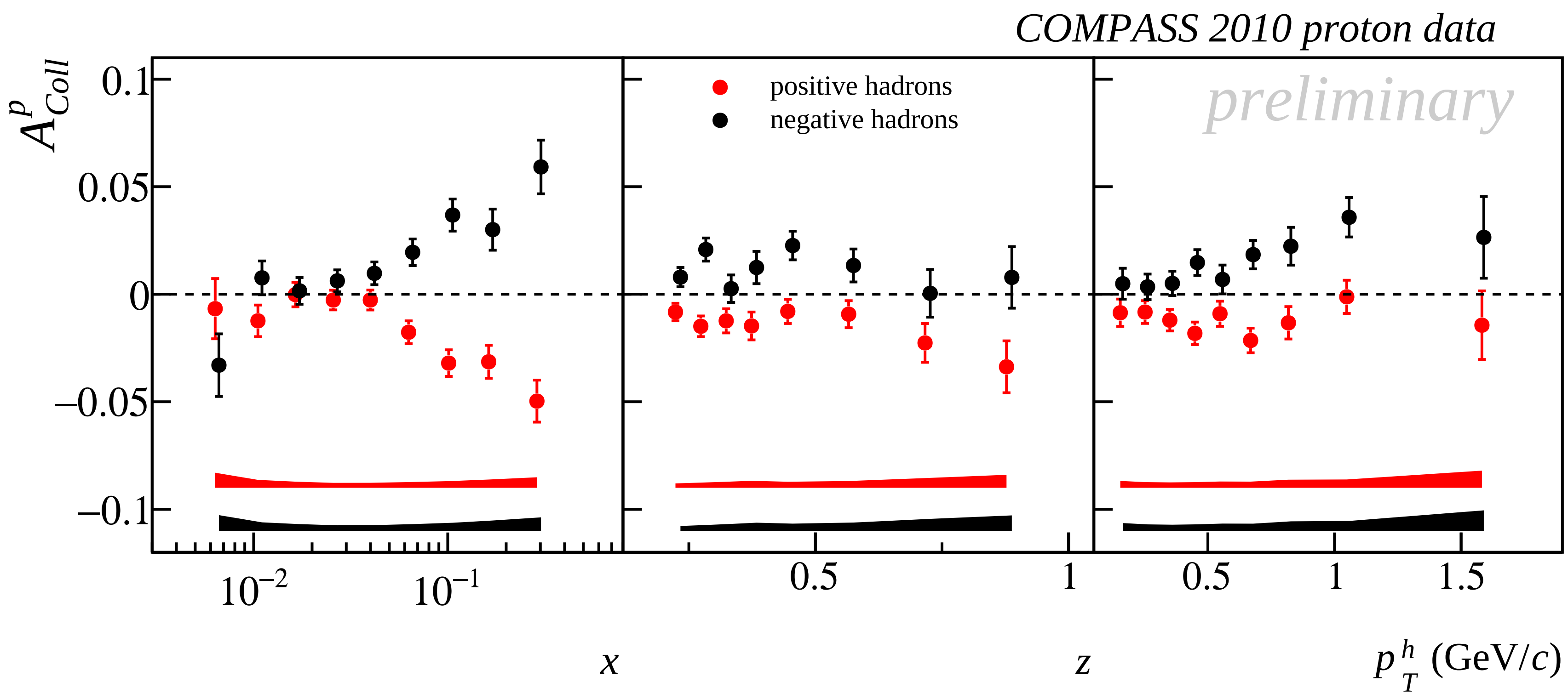
Asymmetries	hadrons/-pairs	target	year of data	by
Collins and Sivers	$\pi^{+/-}$,$K^{+/-}$	p	07/10	A. Martin
Other 6	$h^{+/-}$	d, p	02-04,07/10	B. Parsamyan
Unpolarized	$h^{+/-}$	d	04	G. Sbrizzai
Dihadron	$\pi^+\pi^-$, K^+K^- π^+K^-, $K^+\pi^-$	p	10	C. Braun

Collins asymmetry

proton data 2010

Collins asymmetry ▶ charged hadrons ▶ 2010 data

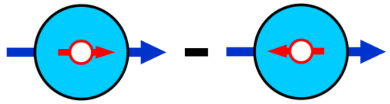
Twist-2 $A_{UT}^{\sin(\phi_h+\phi_S)}$ $h_1^q(x)$ 

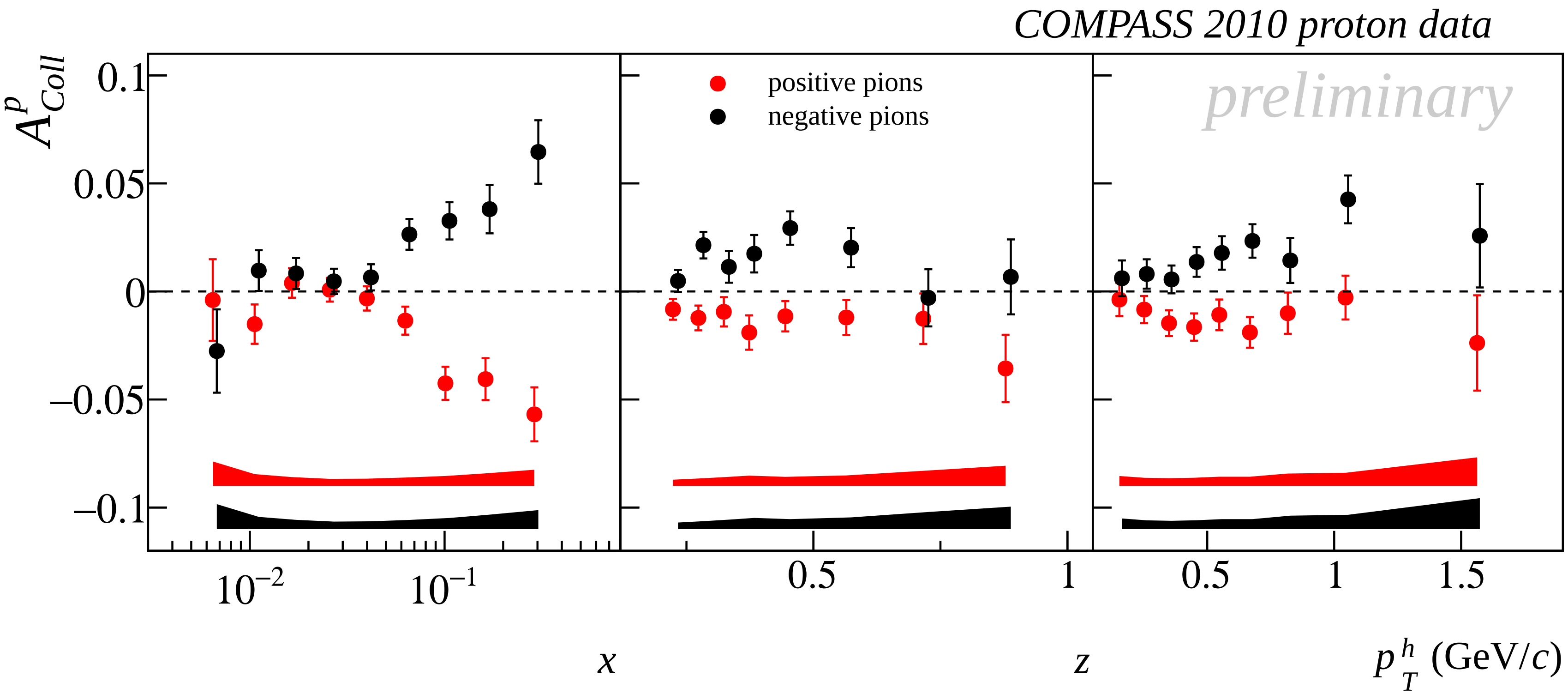


the COMPASS collaboration, C. Adolph *et al.*, Phys. Lett. B 717 (2012), 376-382

↪ very **precise** measurement of the Collins asymmetry of $h^{+/-}$
↪ clear signal

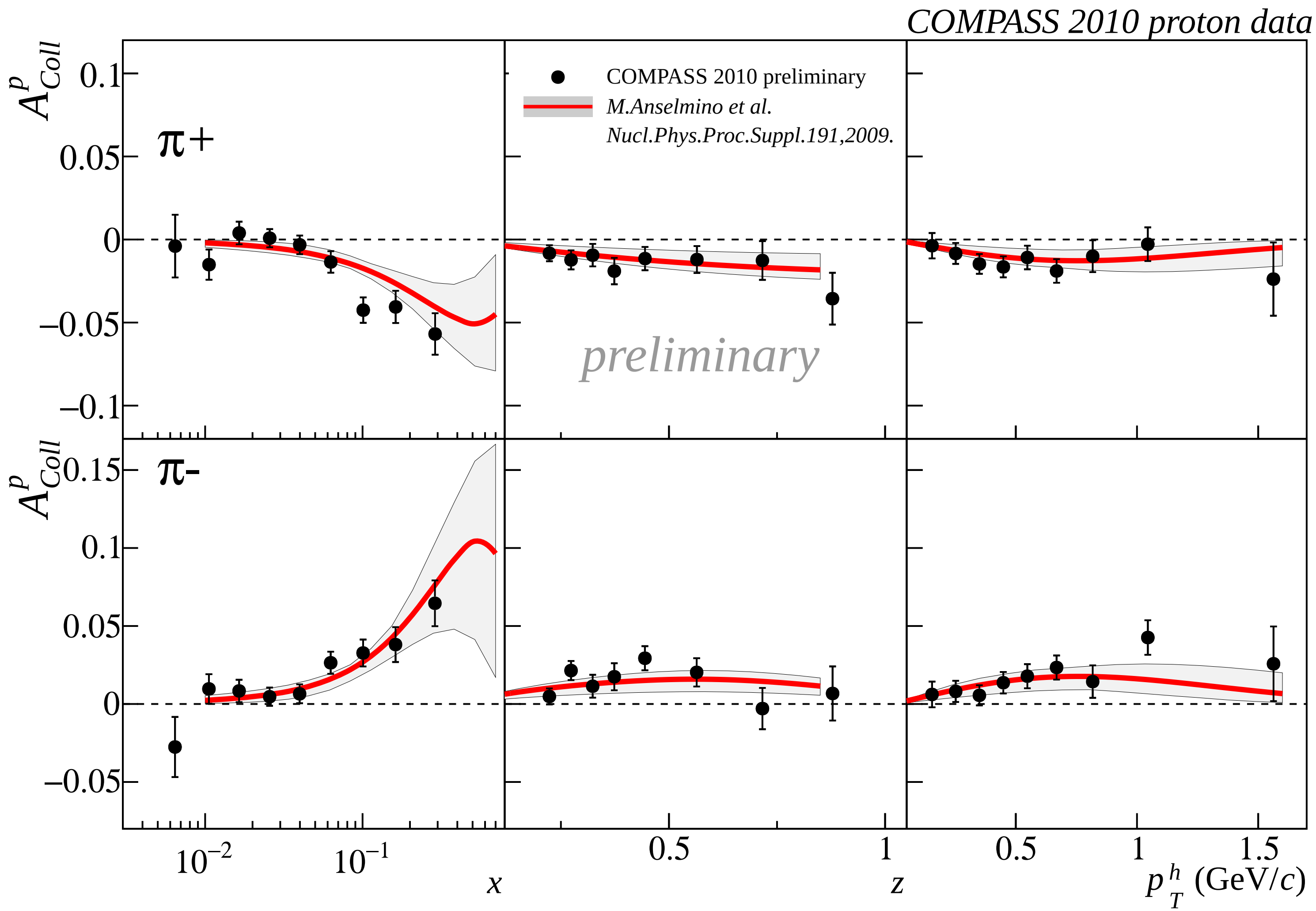
Collins asymmetry ▶ pions ▶ 2010 data

Twist-2 $A_{UT}^{\sin(\phi_h+\phi_S)}$ $h_1^q(x)$ 



↪ Very **precise** measurement of Collins asymmetry of pions
↪ clear signal up to 7 %
↪ opposite signs for $\pi^{+/-}$ in x, z and p_T^h
↪ high statistics at small x are important for the extraction of the tensor charge

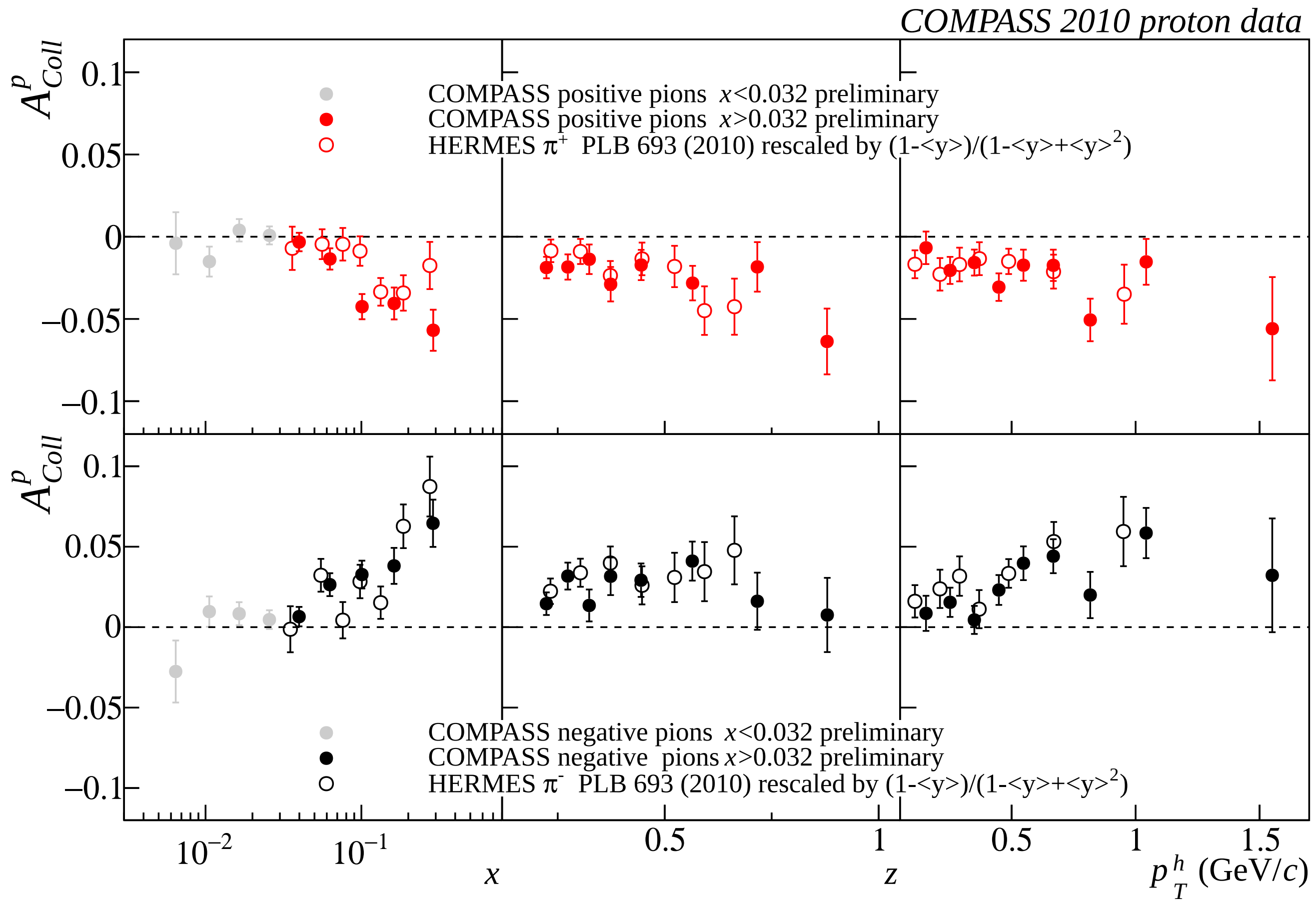
Collins asymmetry ▶ pions ▶ 2010 data *vs.* model predictions



↪ good agreement for x, z and p_T^h within the uncertainties

... but some more work to be done.

Collins asymmetry ► pions ► $x > 0.032$ and HERMES comp.



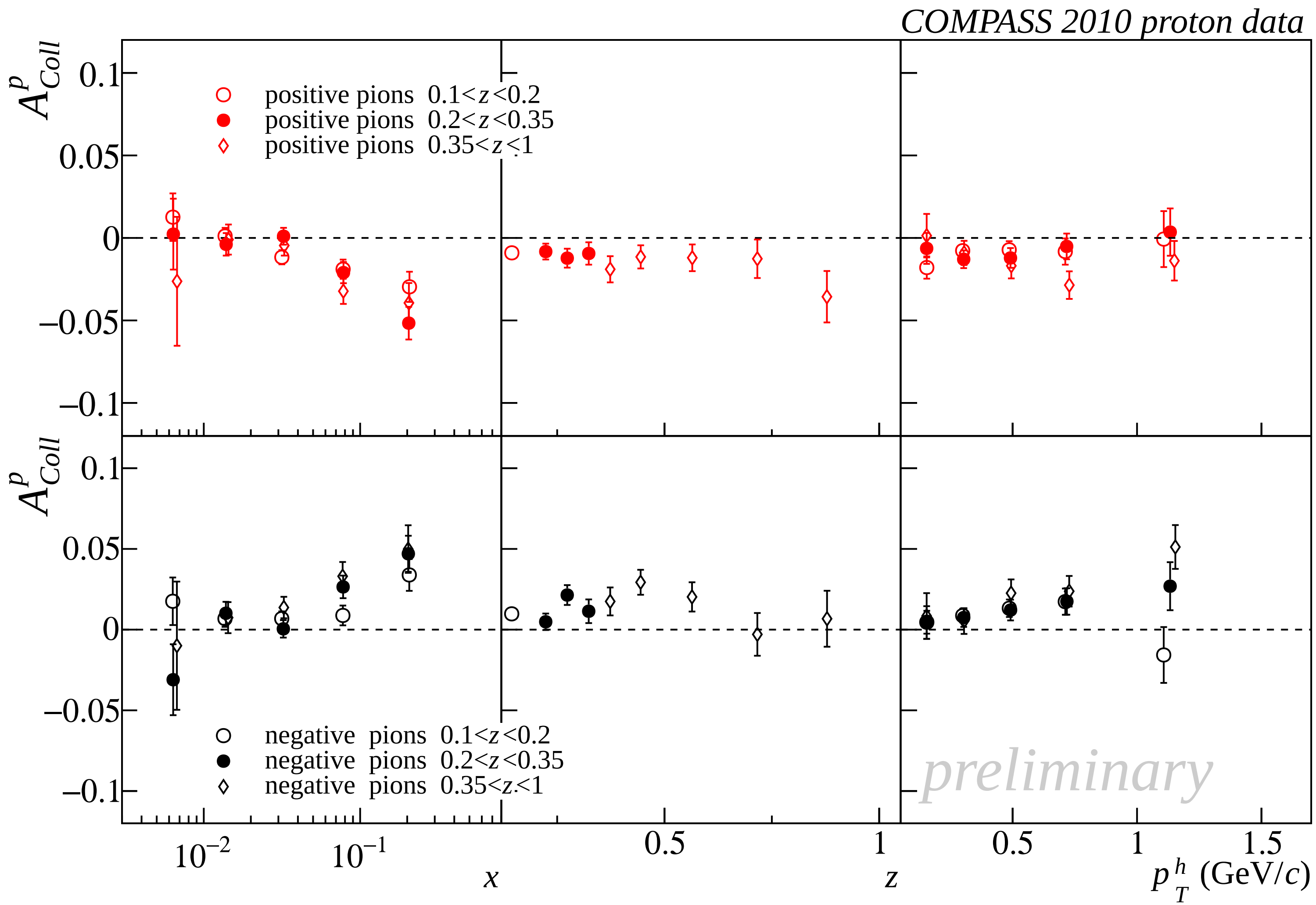
$\hookrightarrow$ Clearer dependence in z and p_T^h for $x > 0.032$

$\hookrightarrow$ Same strength of the signal within the uncertainties

but different $< Q^2 >$ values of HERMES (≈ 4) and COMPASS (≈ 12)

$\Rightarrow$ Indication for non higher twist effect & no strong Q^2 dependence

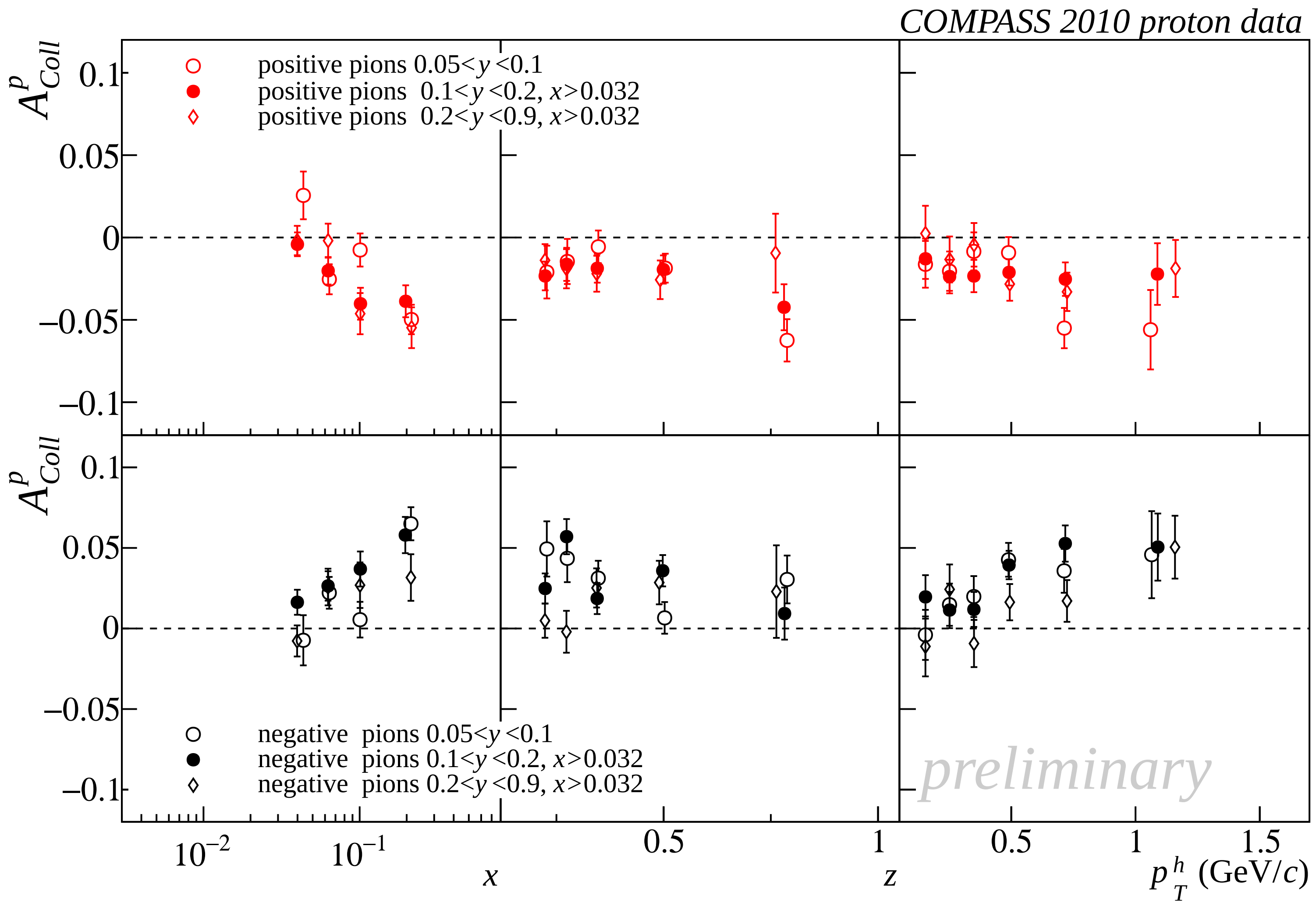
Collins asymmetry ▶ pions ▶ multi-dimensional analysis in z



$3\ z$ ranges: $0.1 < z_{\text{low}} < 0.2 < z_{\text{mid}} < 0.35 < z_{\text{high}} < 1.0$

$\hookrightarrow$ no clear dependence in x and p_T^h

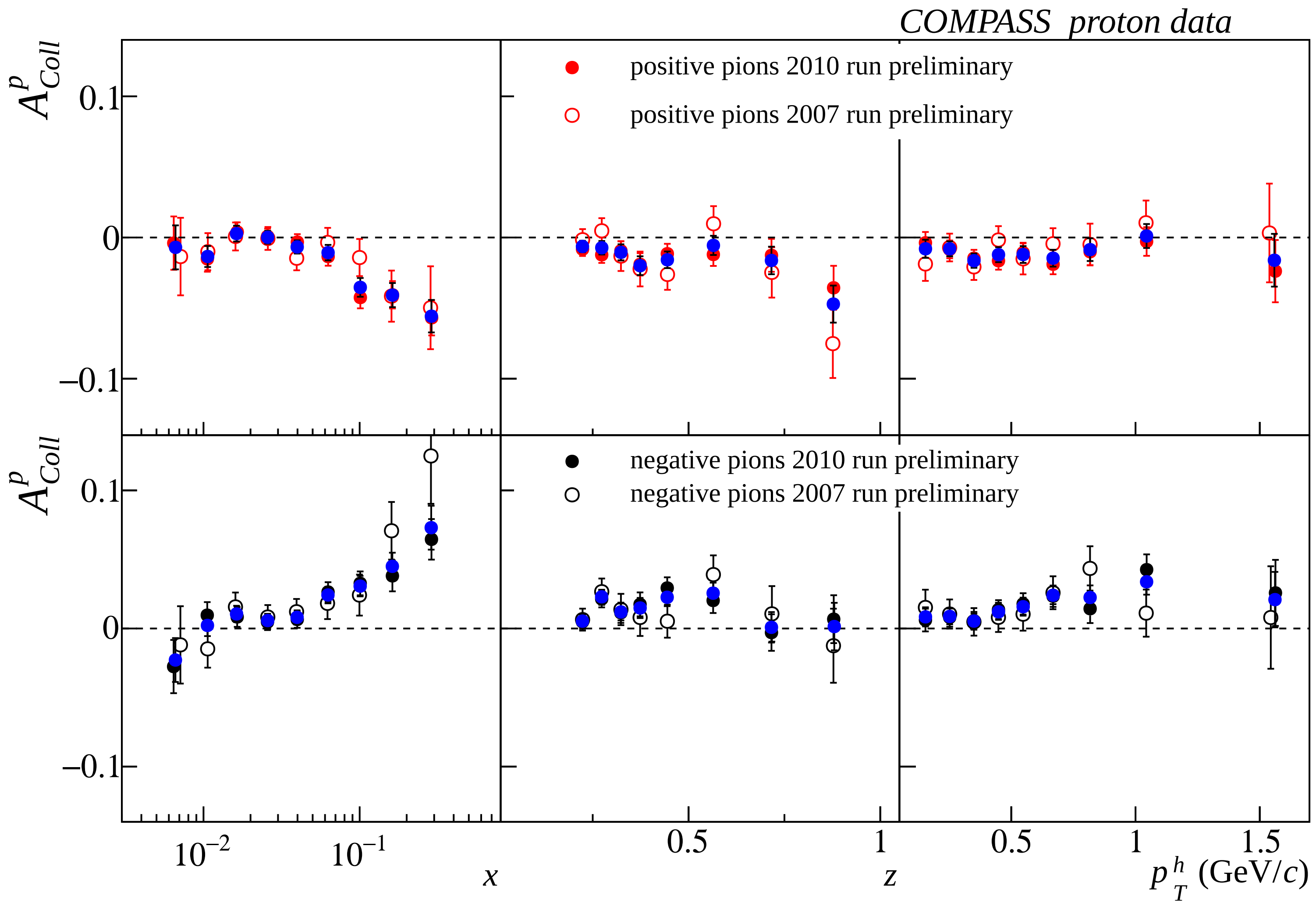
Collins asymmetry ▶ pions ▶ multi-dimensional analysis in y



3 y ranges: $0.05 < y_{\text{low}} < 0.1 < y_{\text{mid}} < 0.2 < y_{\text{high}} < 0.9$

↪ no clear dependence *w.r.t.* the uncertainties

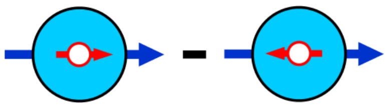
Collins asymmetry ▶ pions ▶ combined '07 and '10 data

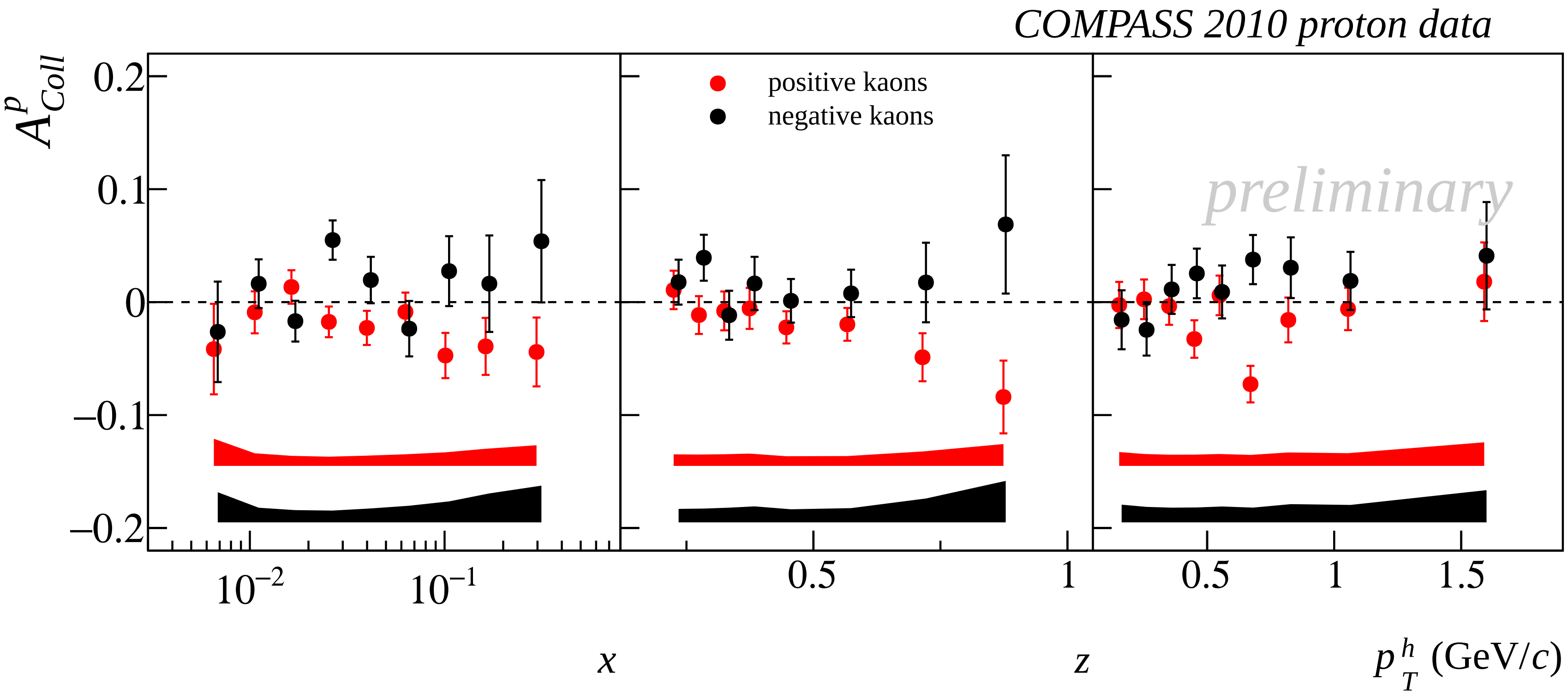


↪ '10 confirm '07 results with improved statistics

data combined by taking into account statistical and systematical uncertainties

Collins asymmetry ▶ kaons ▶ 2010 data

Twist-2 $A_{UT}^{\sin(\phi_h+\phi_S)}$ $h_1^q(x)$ 

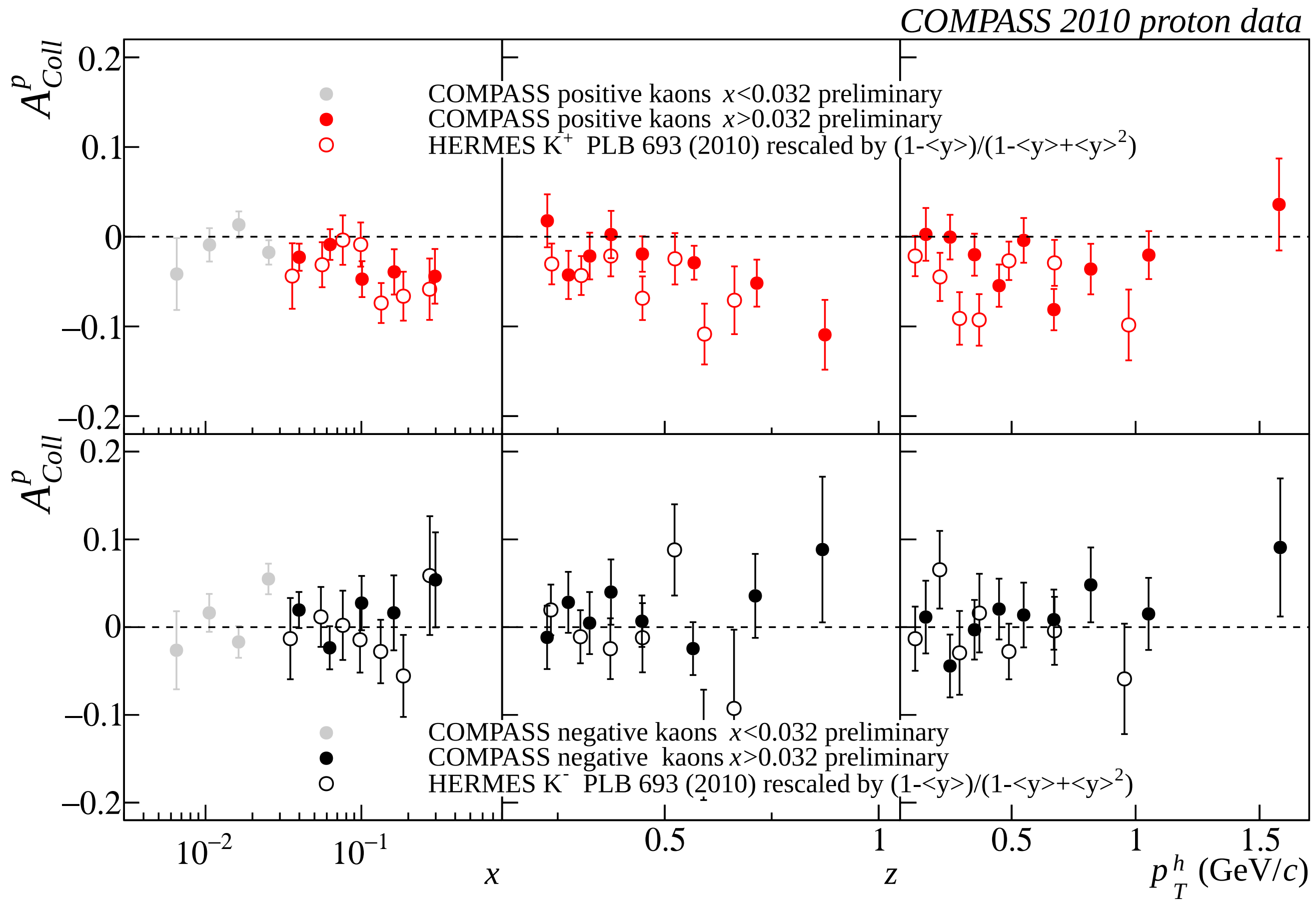


↪ different from zero

↪ indication of opposite signs for $K^{+/-}$ mean values

↪ indication for signal also at very small x

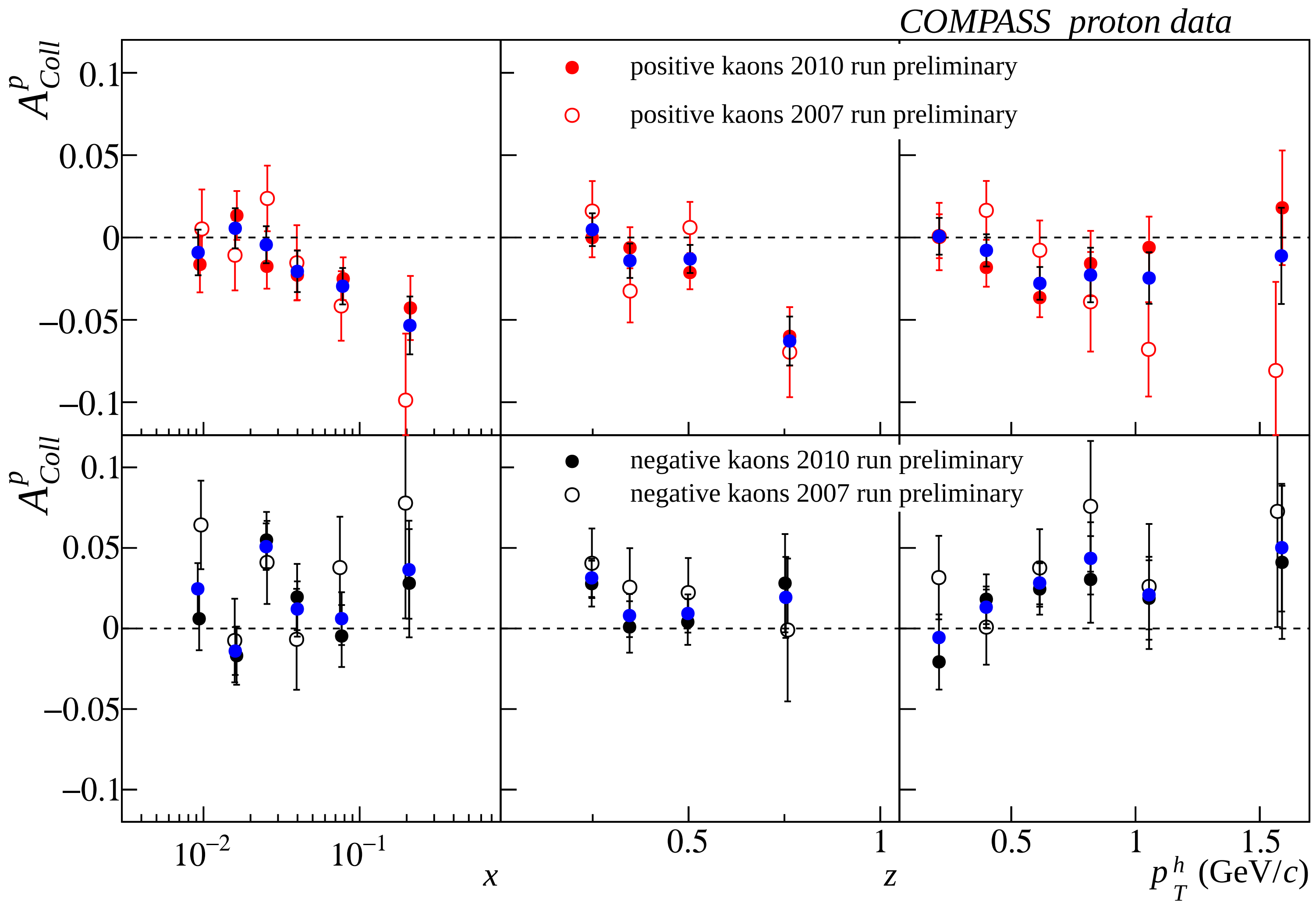
Collins asymmetry ▶ kaons ▶ $x > 0.032$ and HERMES comp.



$\hookrightarrow$ HERMES and COMPASS compatible within the uncertainties

HERMES asymmetries systematical larger for K^+ in x, z and p_T^h

Collins asymmetry ▶ kaons ▶ combined ’07 and ’10 data



↪ ’10 confirm ’07 results with improved statistics

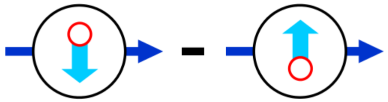
data combined by taking into account statistical and systematical uncertainties

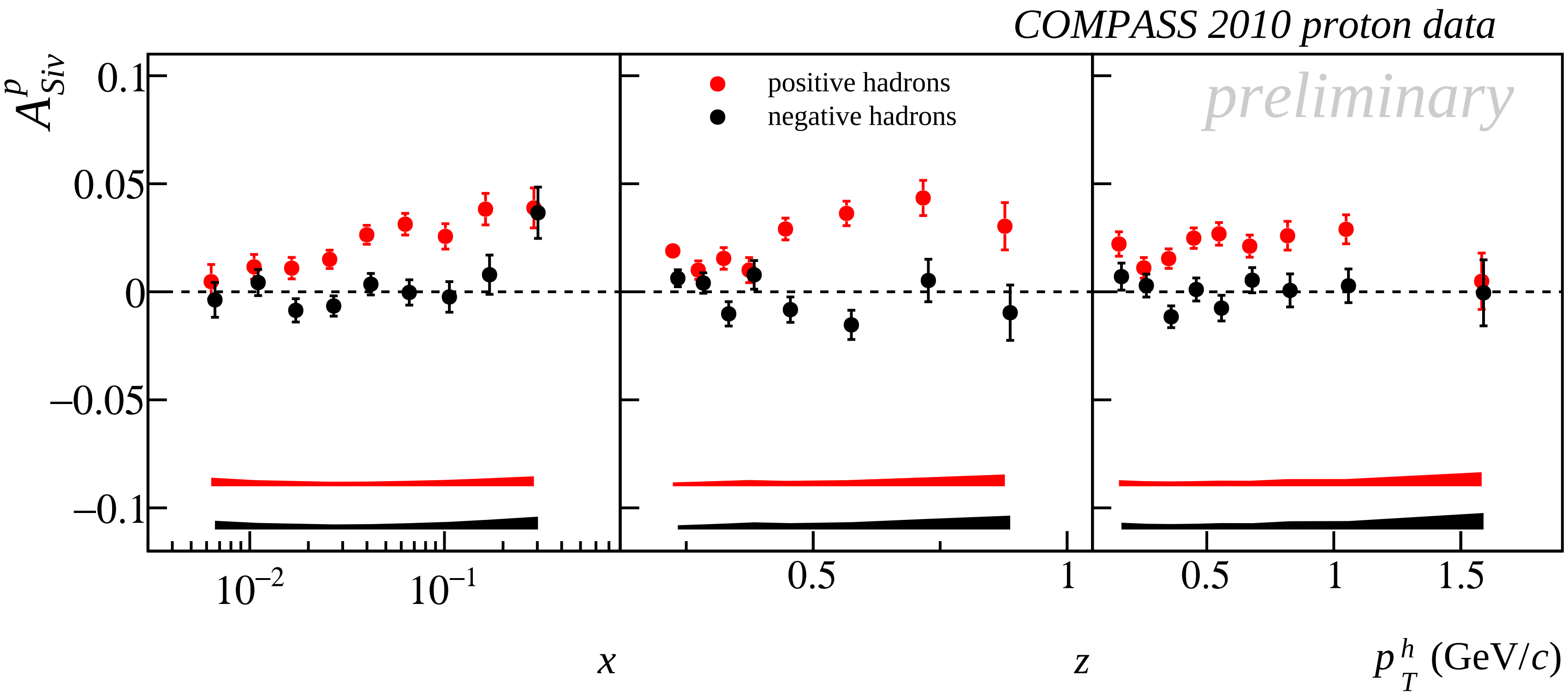
Sivers asymmetry

proton data 2010

Sivers asymmetry ▶ charged hadrons ▶ 2010 data

Twist-2 $A_{UT}^{\sin(\phi_h-\phi_S)}$ $f_{1T}^{\perp q}(x)$



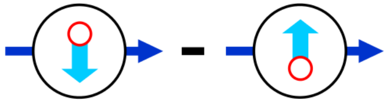


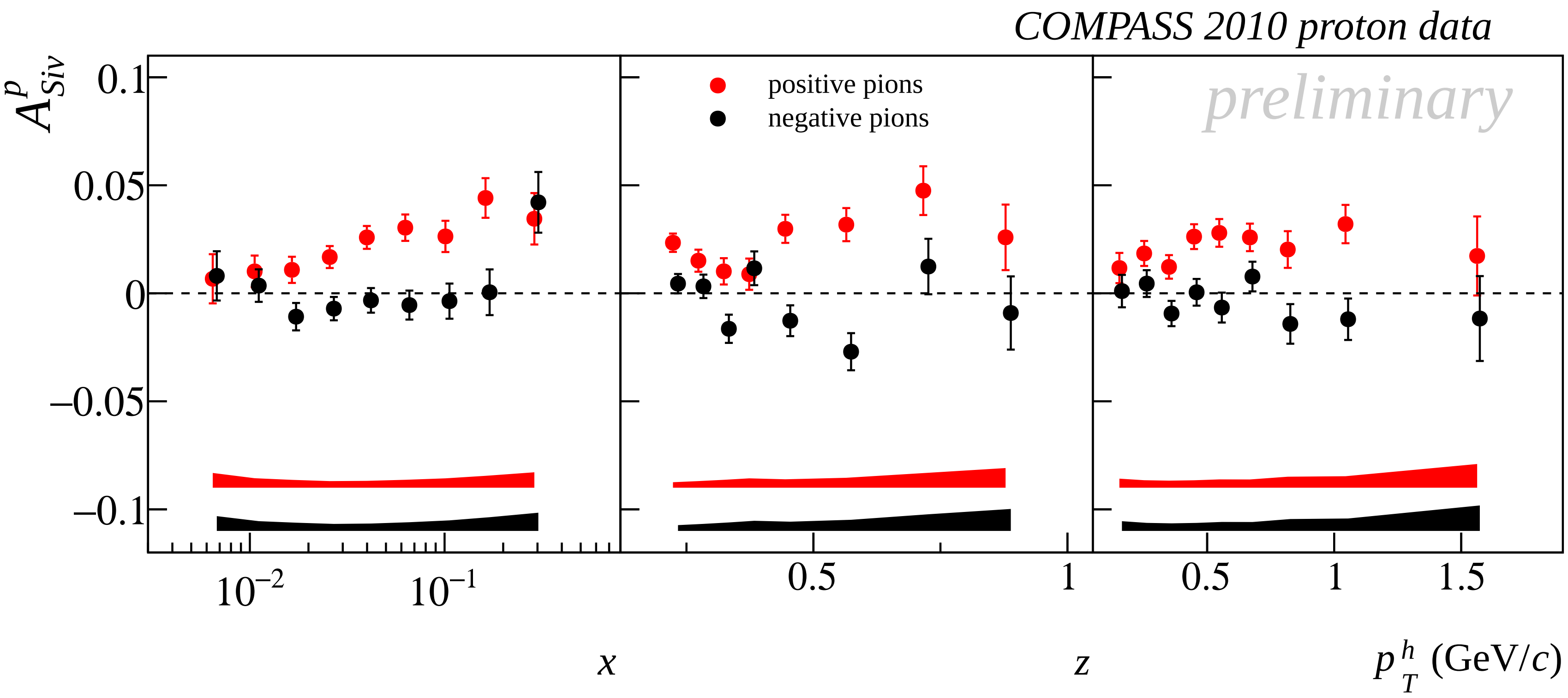
the COMPASS collaboration, C. Adolph *et al.*, Phys. Lett. B 717 (2012), 383-389

↪ very **precise** measurement of the Sivers asymmetry of $h^{+/-}$
↪ clear signal for positive hadrons

Sivers asymmetry ▶ pions ▶ 2010 data

Twist-2 $A_{UT}^{\sin(\phi_h-\phi_S)}$ $f_{1T}^{\perp q}(x)$



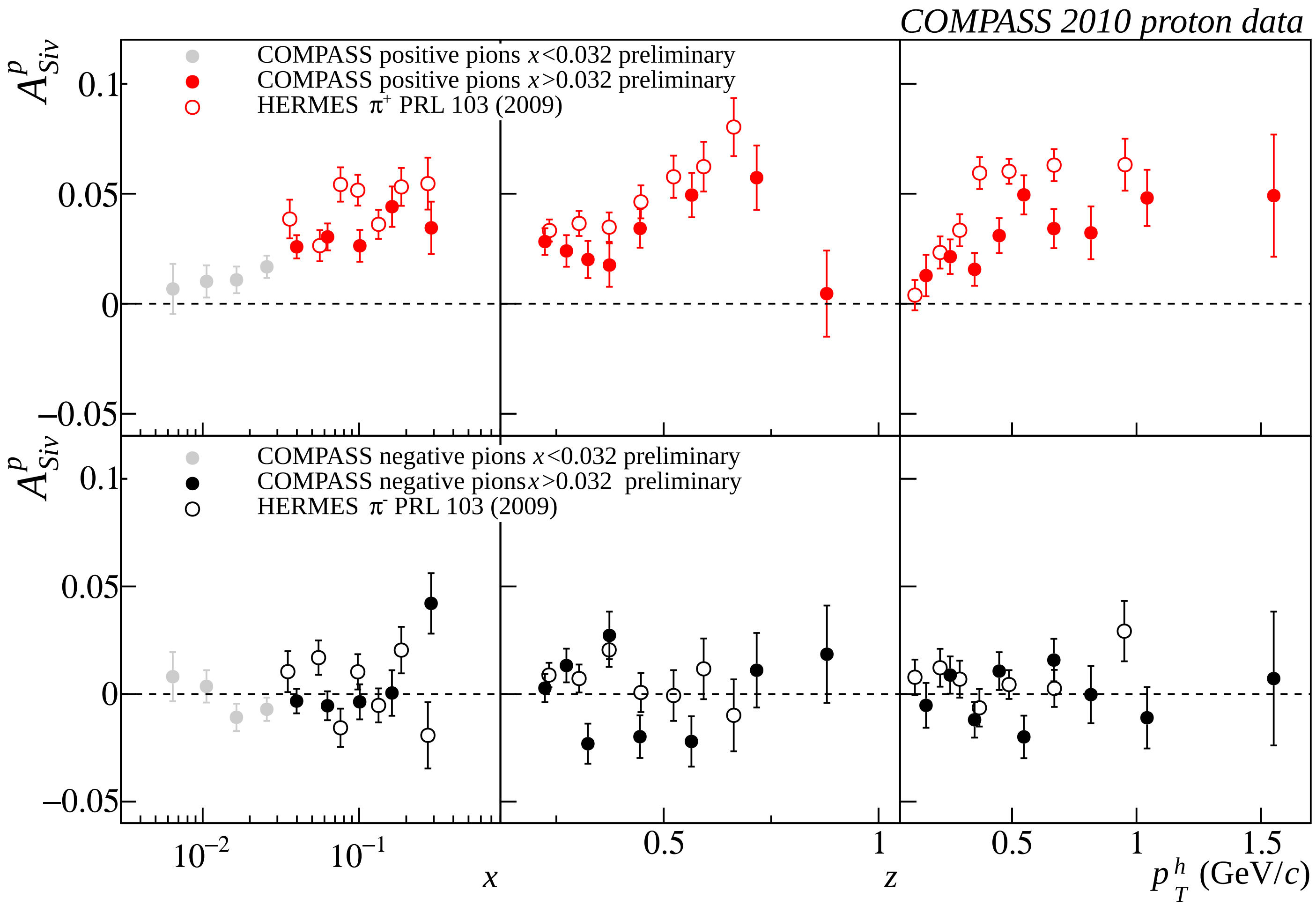


↪ π^+: clear signal up to 5 % in x, z and p_T^h

↪ π^+: signal also at very small x, as for h^+

↪ π^-: mostly compatible with zero within the uncertainties

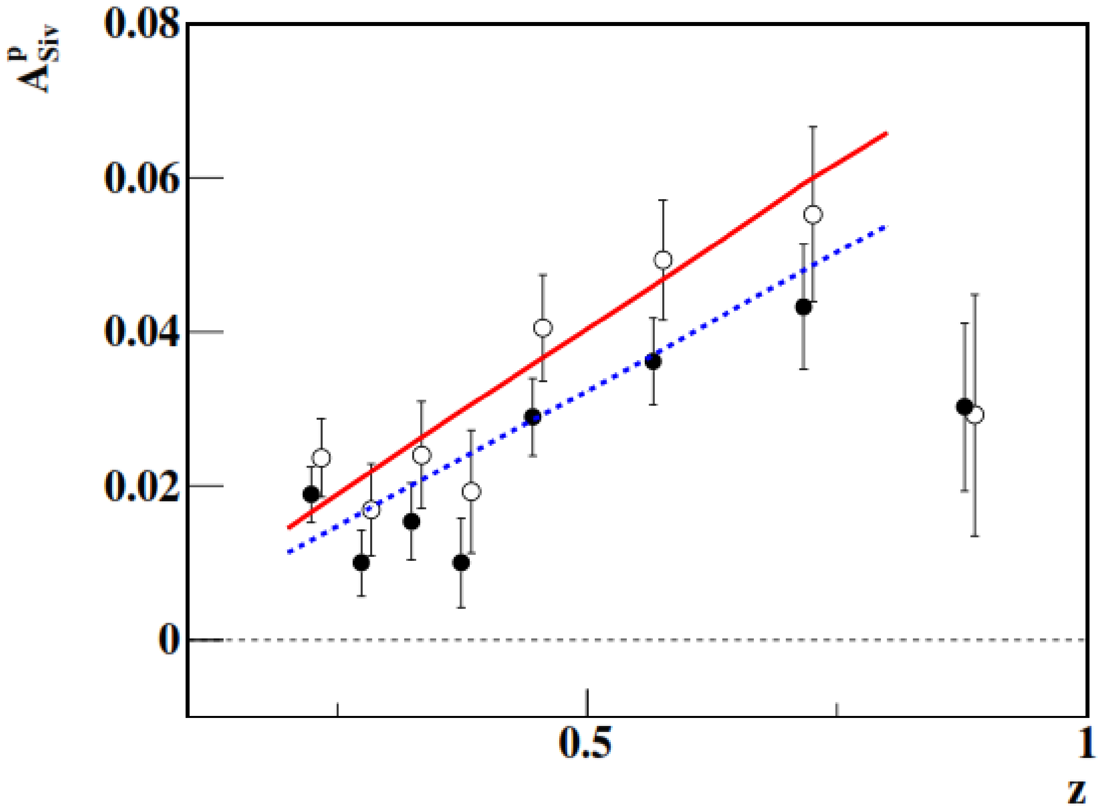
Sivers asymmetry ▶ pions ▶ $x > 0.032$ and HERMES comp.



↪ same trend for HERMES and COMPASS

HERMES asymmetries systematical larger for π^+ in x, z and p_T^h

Q^2 evolution ▶ charged hadrons ▶ model calculations *vs.* COMPASS 2010 data



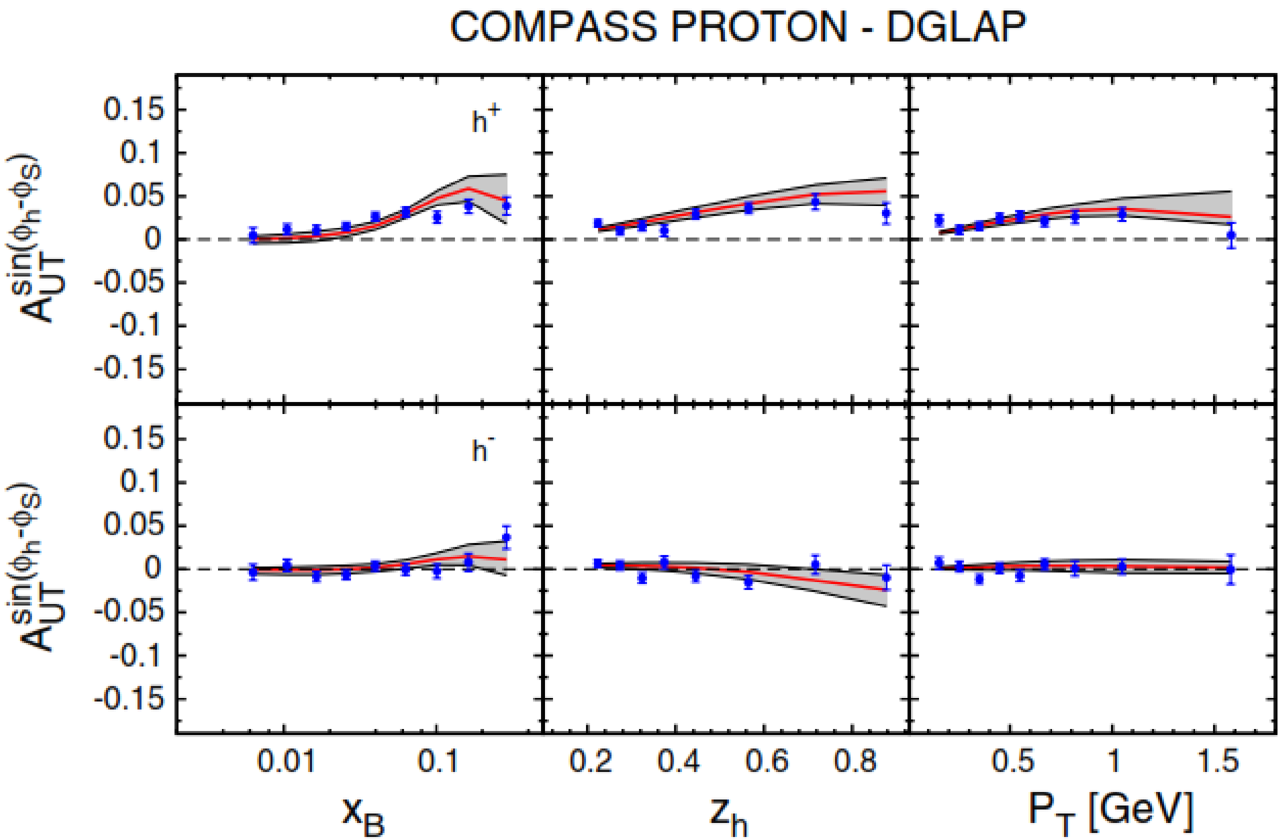
$x > 0.032 \Rightarrow$
$< Q^2 > = 8.7$ GeV/c^2

full x range $\Rightarrow$
$< Q^2 > = 3.8$ GeV/c^2

S. M. Aybat, A. Prokudin and T. C. Rogers, PRL 108 (2012) 242003

↪ good agreement between data and model calculations

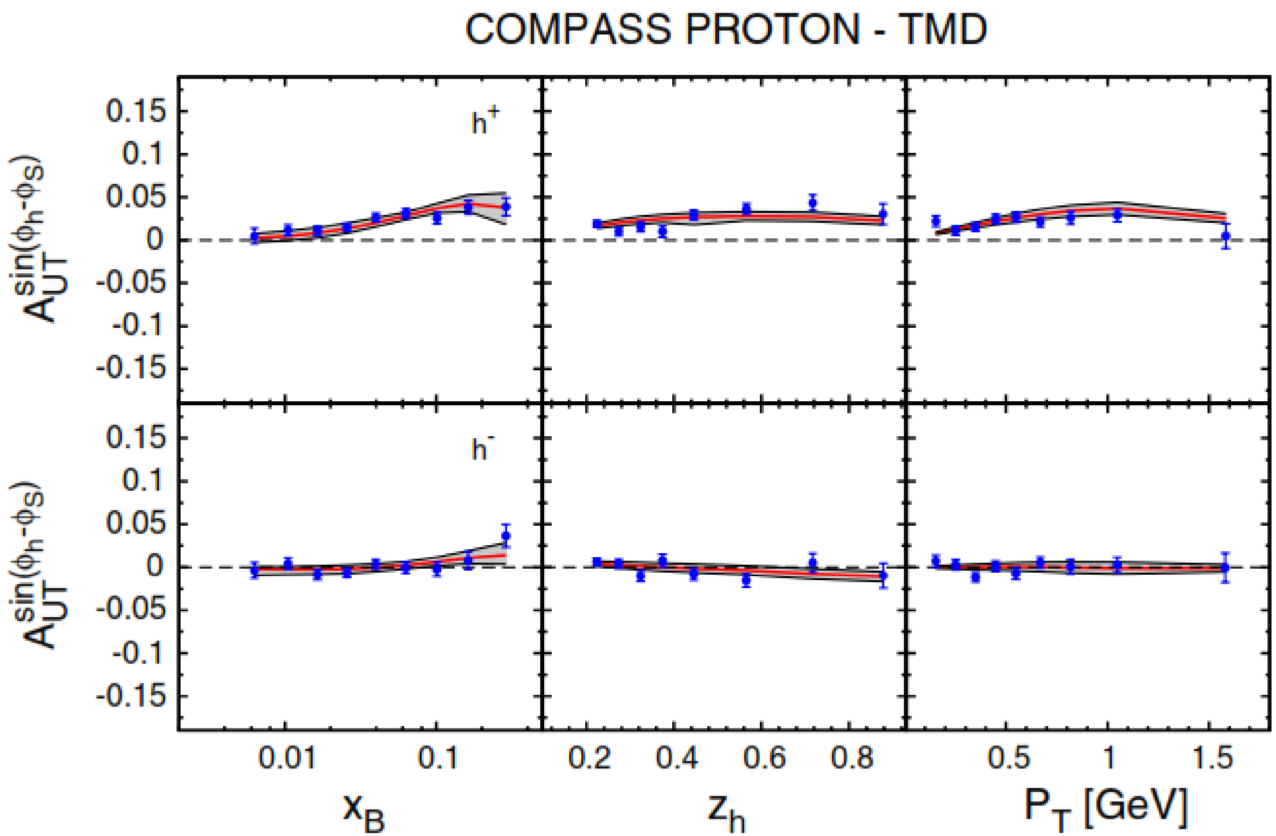
Q^2 evolution ▶ charged hadrons ▶ model calculations *vs.* COMPASS 2010 data



M. Anselmino, M. Boglione and S. Melis, PRD86 (2012) 014028

- Calculated with a fit to HERMES p and COMPASS d and p 2010 data
- Evolution was calculated using the **DGLAP** equation

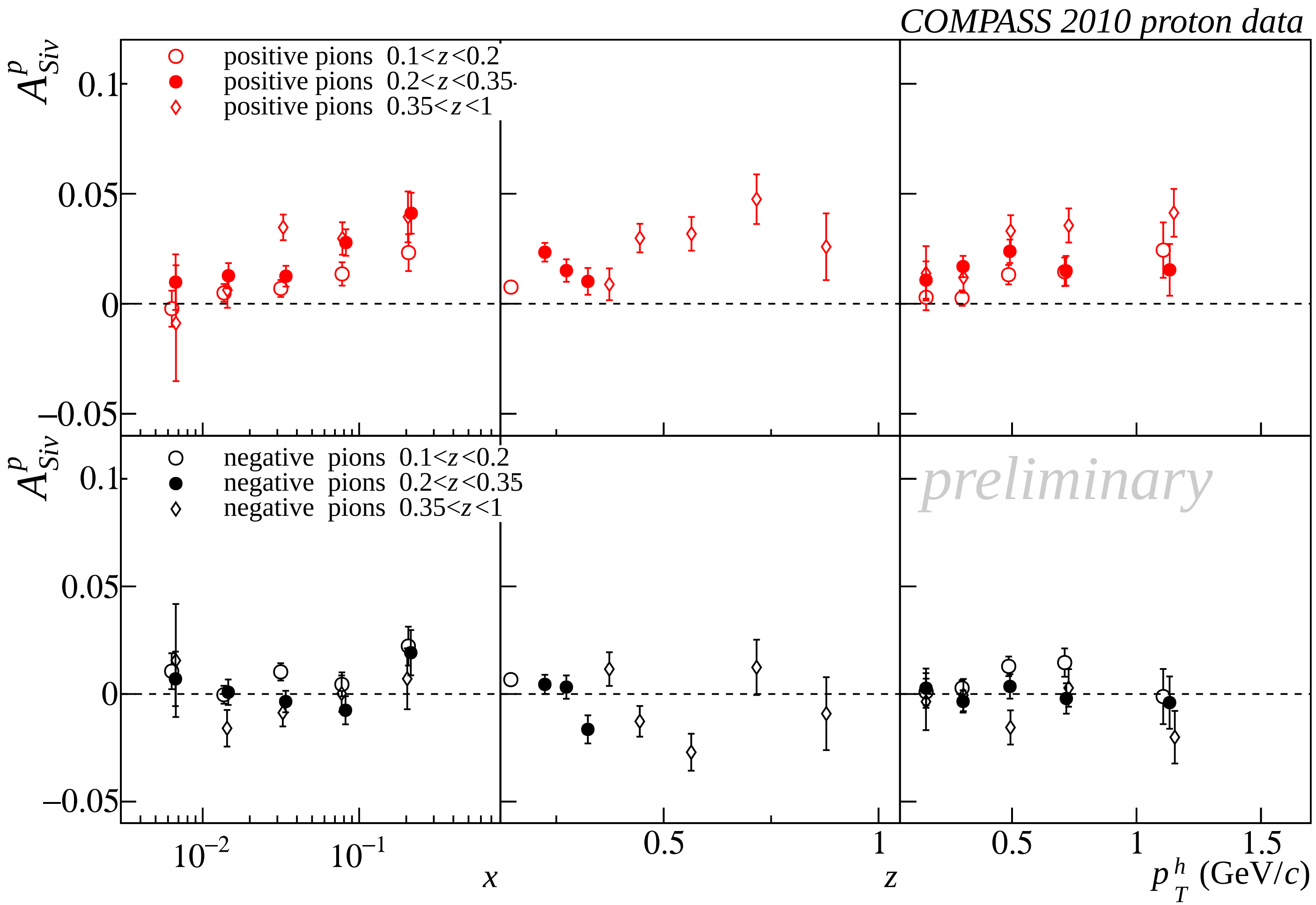
Q^2 evolution ▶ charged hadrons ▶ model calculations *vs.* COMPASS 2010 data



M. Anselmino, M. Boglione and S. Melis, PRD86 (2012) 014028

↪ better agreement between data and model calculations with Q^2 evolution

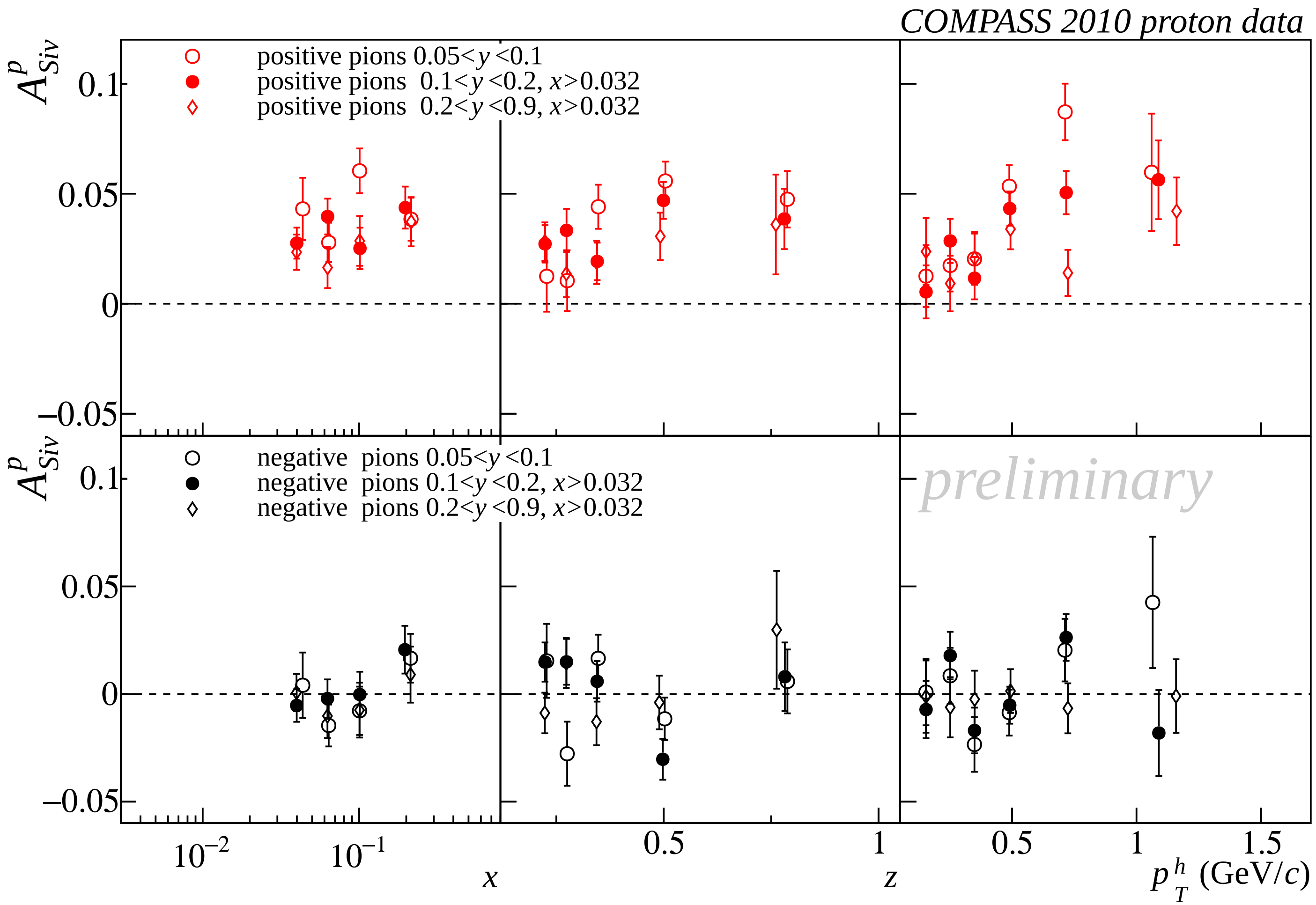
Sivers asymmetry ▸ pions ▸ multi-dimensional analysis in z



3 z ranges: $0.1 < z_{\text{low}} < 0.2 < z_{\text{mid}} < 0.35 < z_{\text{high}} < 1.0$

$\hookrightarrow$ smaller asymmetries for π^+ in z_{low} region

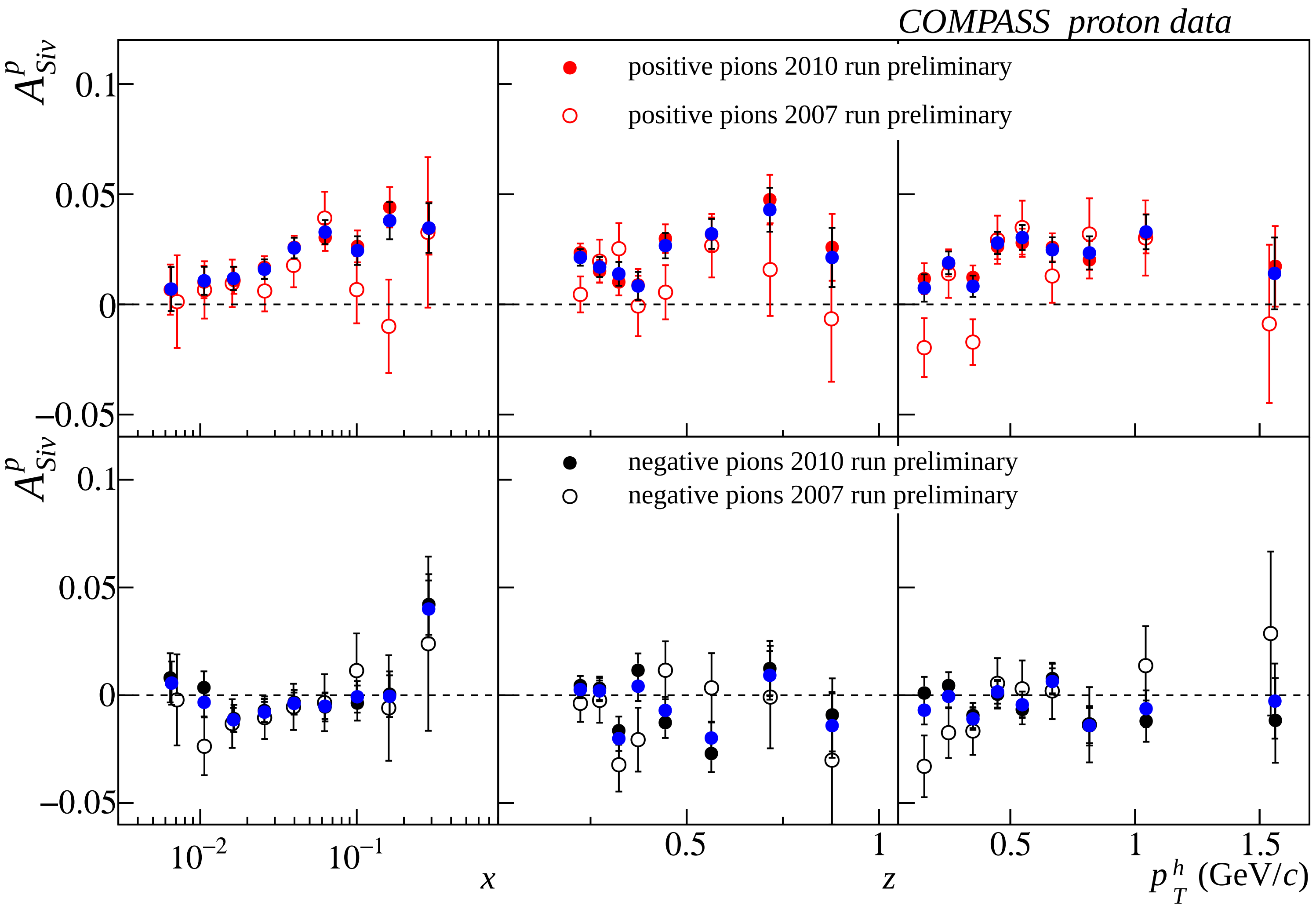
Sivers asymmetry ▶ pions ▶ multi-dimensional analysis in y



3 y ranges: $0.05 < y_{\text{low}} < 0.1 < y_{\text{mid}} < 0.2 < y_{\text{high}} < 0.9$

↪ no significant systematic effect *w.r.t.* the uncertainties

Sivers asymmetry ▶ pions ▶ combined '07 and '10 data

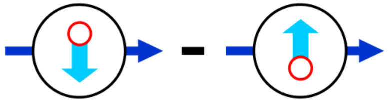


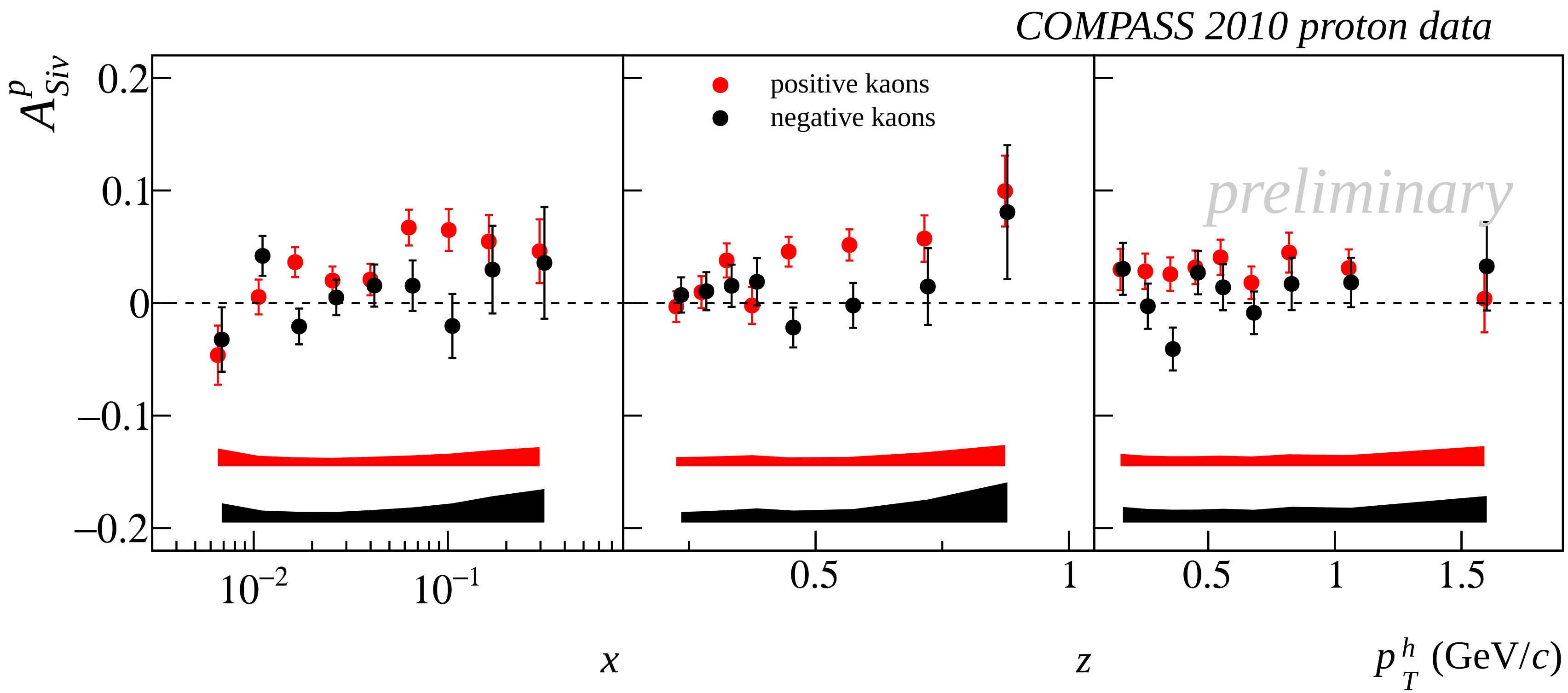
↪ good agreement of '10 and '07 data

data combined by taking into account statistical and systematical uncertainties

Sivers asymmetry ▶ kaons ▶ 2010 data

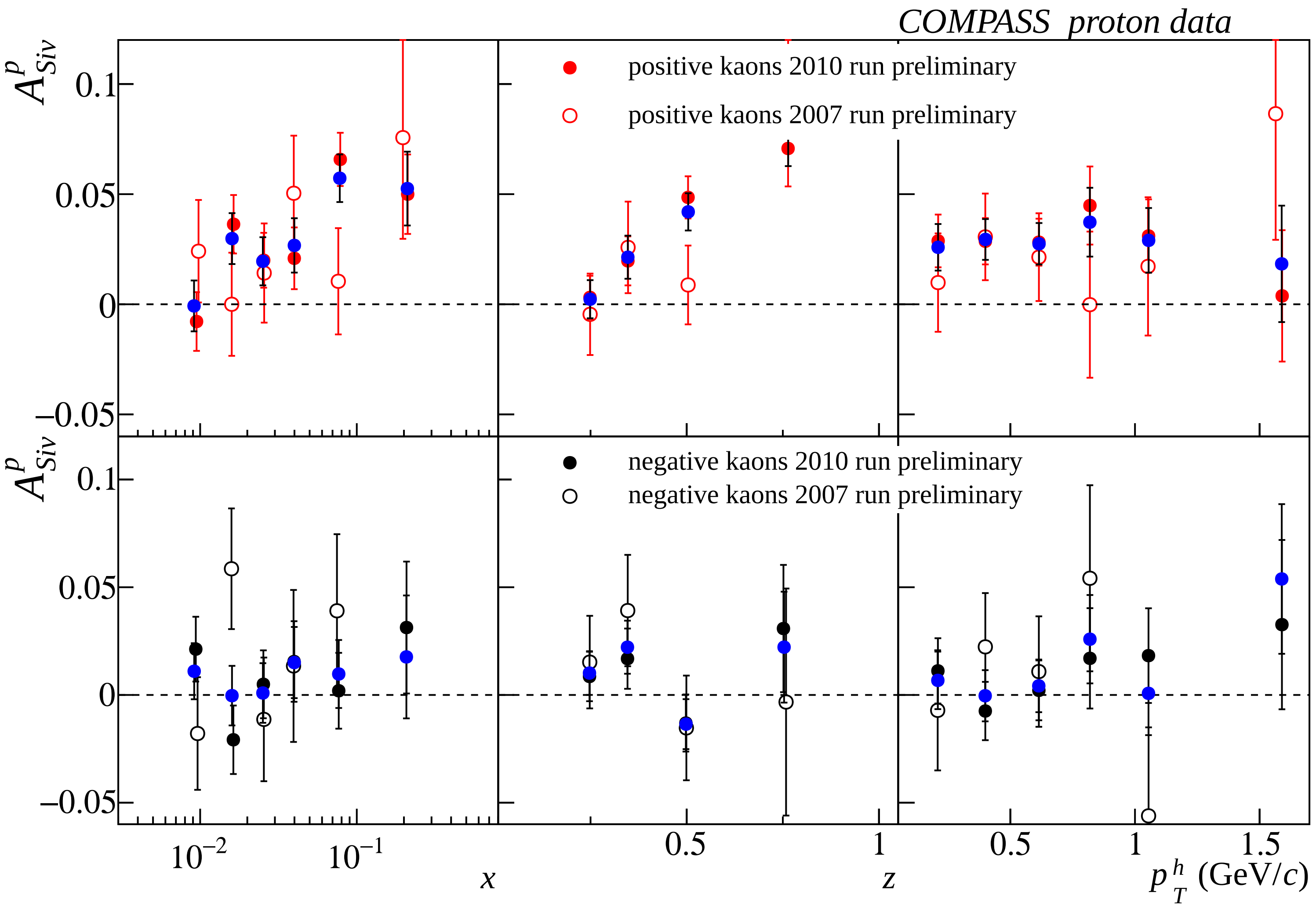
Twist-2 $A_{UT}^{\sin(\phi_h - \phi_S)}$ $f_{1T}^{\perp q}(x)$





$\hookrightarrow$ K^+: clear signal up to 7 % in x, 10 % in z and non-zero in p_T^h
$\hookrightarrow$ K^-: mostly compatible with zero within the uncertainties

Sivers asymmetry ▶ kaons ▶ combined ’07 and ’10 data



↪ ’10 with its higher statistics dominates combined results

↪ clear non-zero asymmetry for K^+

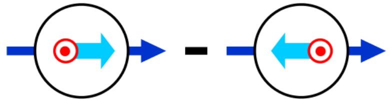
data combined by taking into account statistical and systematical uncertainties

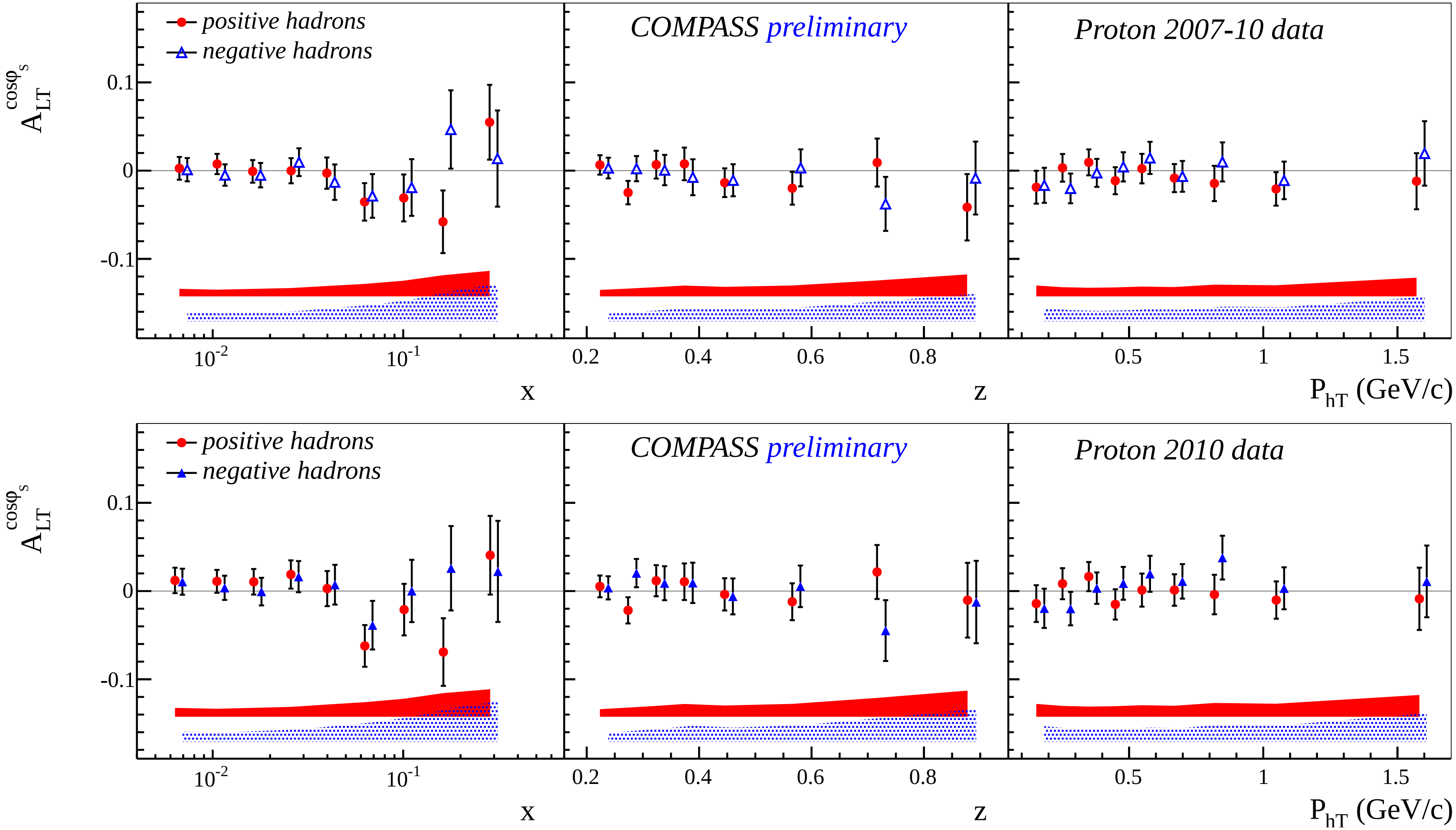
The +6 transverse spin asymmetries

deuteron date 2002-04 & proton data 2007 and 2010

A_{LT1} ▶ charged hadrons ▶ p 2010 and combined data

Twist-3 $A_{LT}^{\cos(\phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$

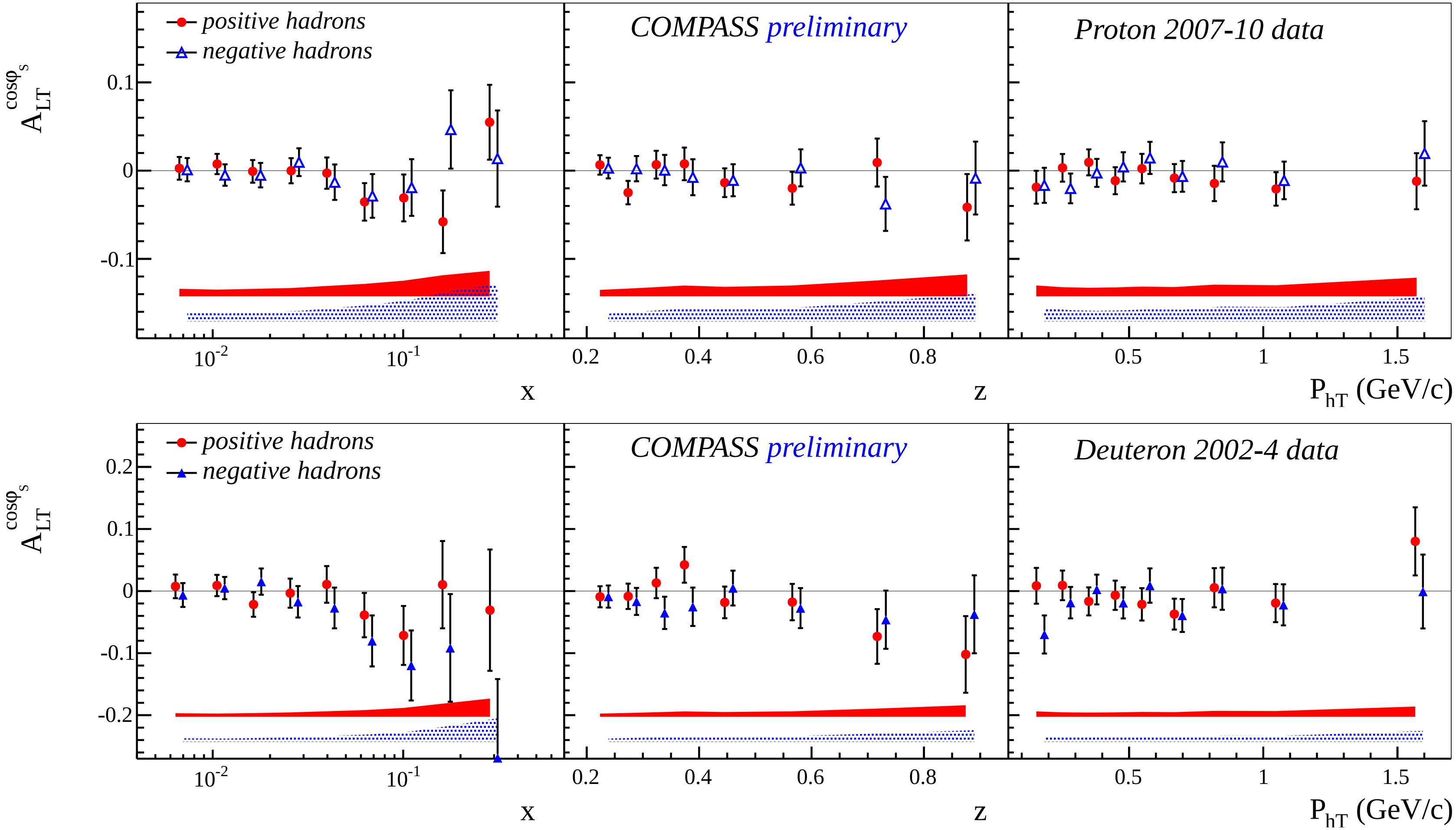




↪ proton data compatible with zero within the uncertainties

A_{LT1} ▶ charged hadrons ▶ proton *vs.* deuteron data

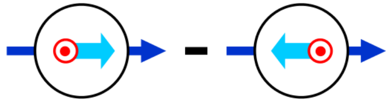
Twist-3 $A_{LT}^{\cos(\phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$

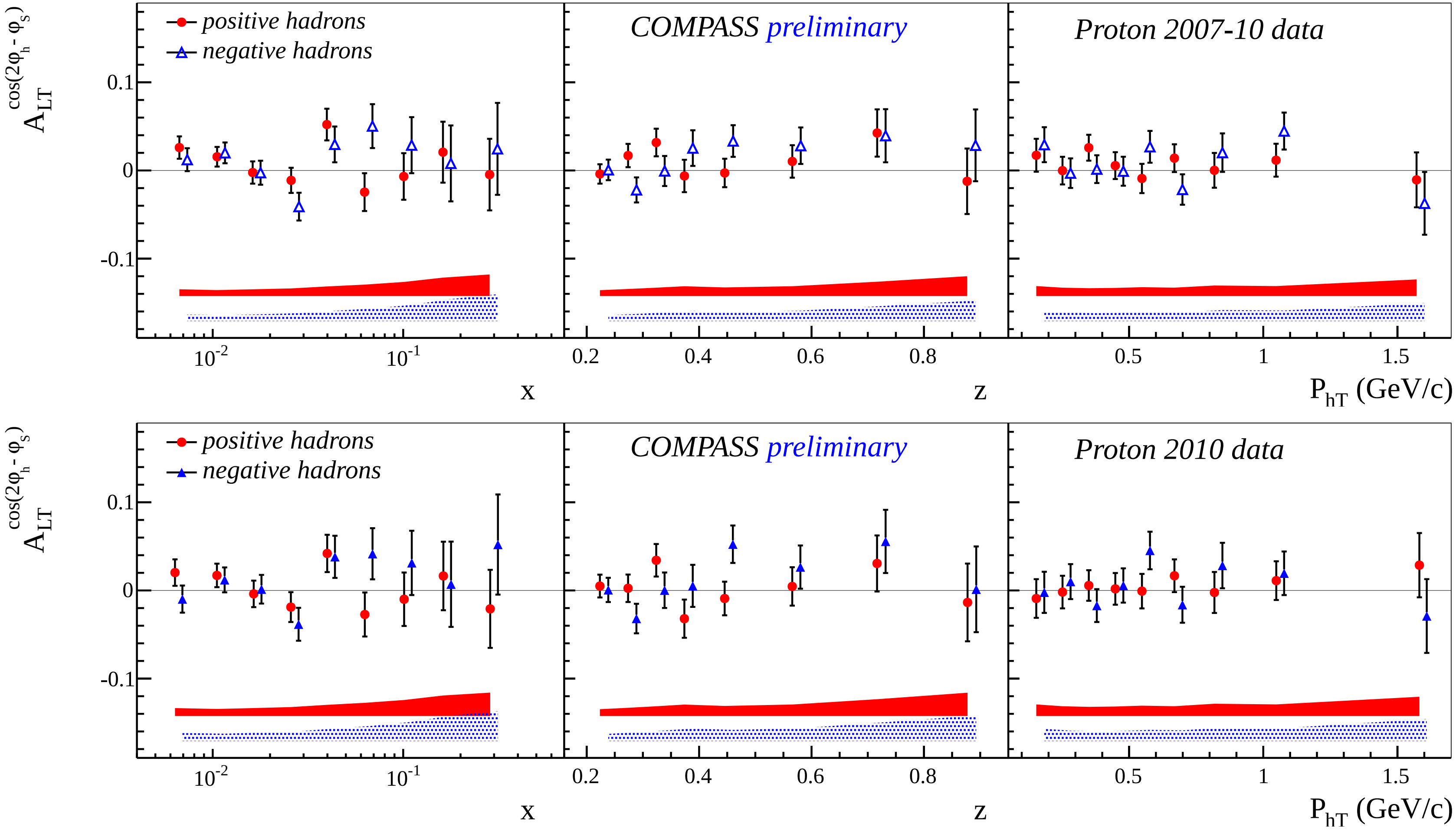


↪ deuteron data compatible with zero within the uncertainties

A_{LT2} ▶ charged hadrons ▶ p 2010 and combined data

Twist-3 $A_{LT}^{\cos(2\phi_h-\phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$

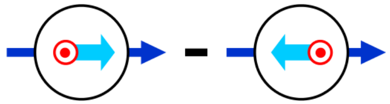


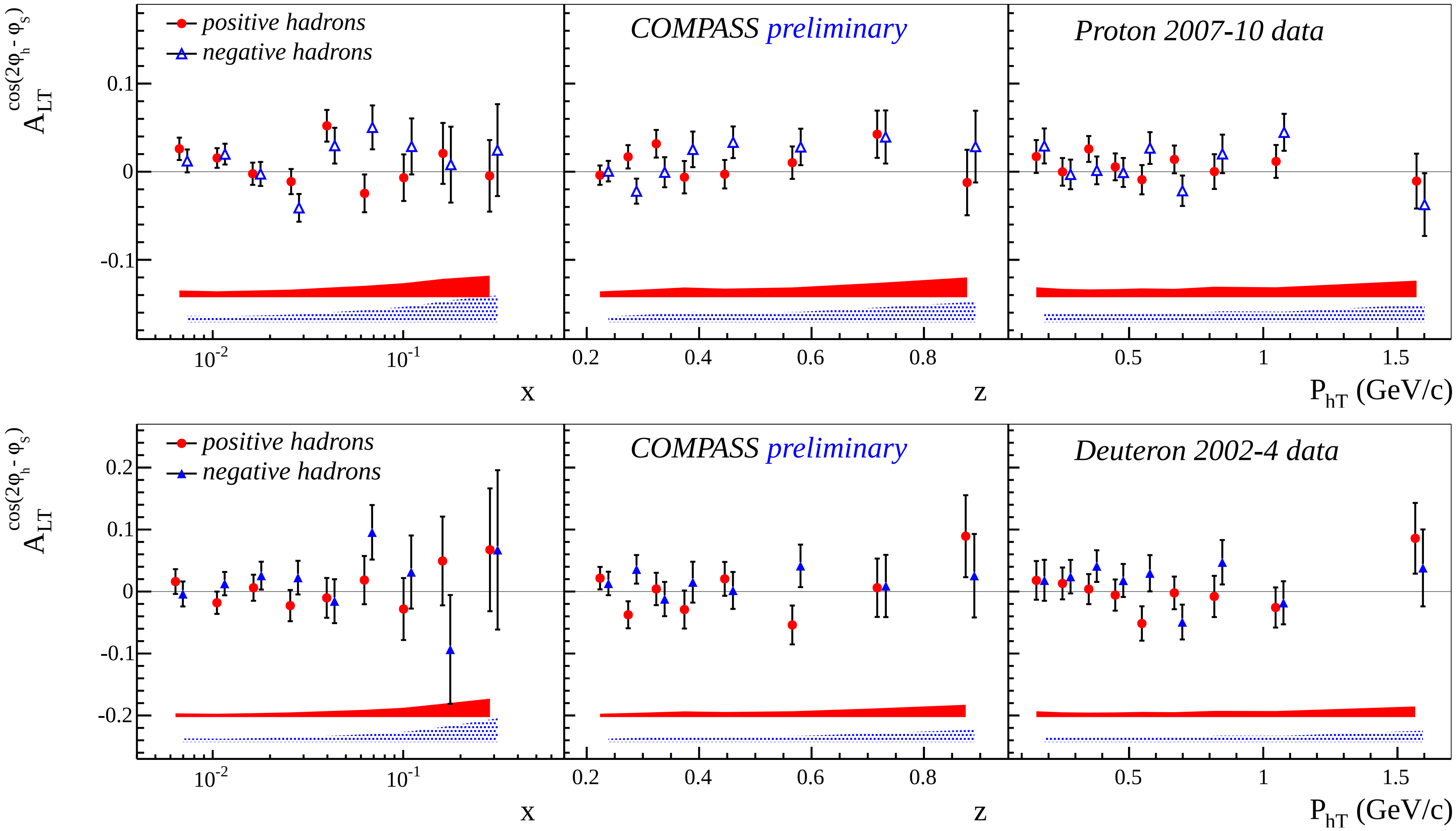


↪ proton data compatible with zero within the uncertainties

A_{LT2} ▶ charged hadrons ▶ proton *vs.* deuteron data

Twist-3 $A_{LT}^{\cos(2\phi_h - \phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$

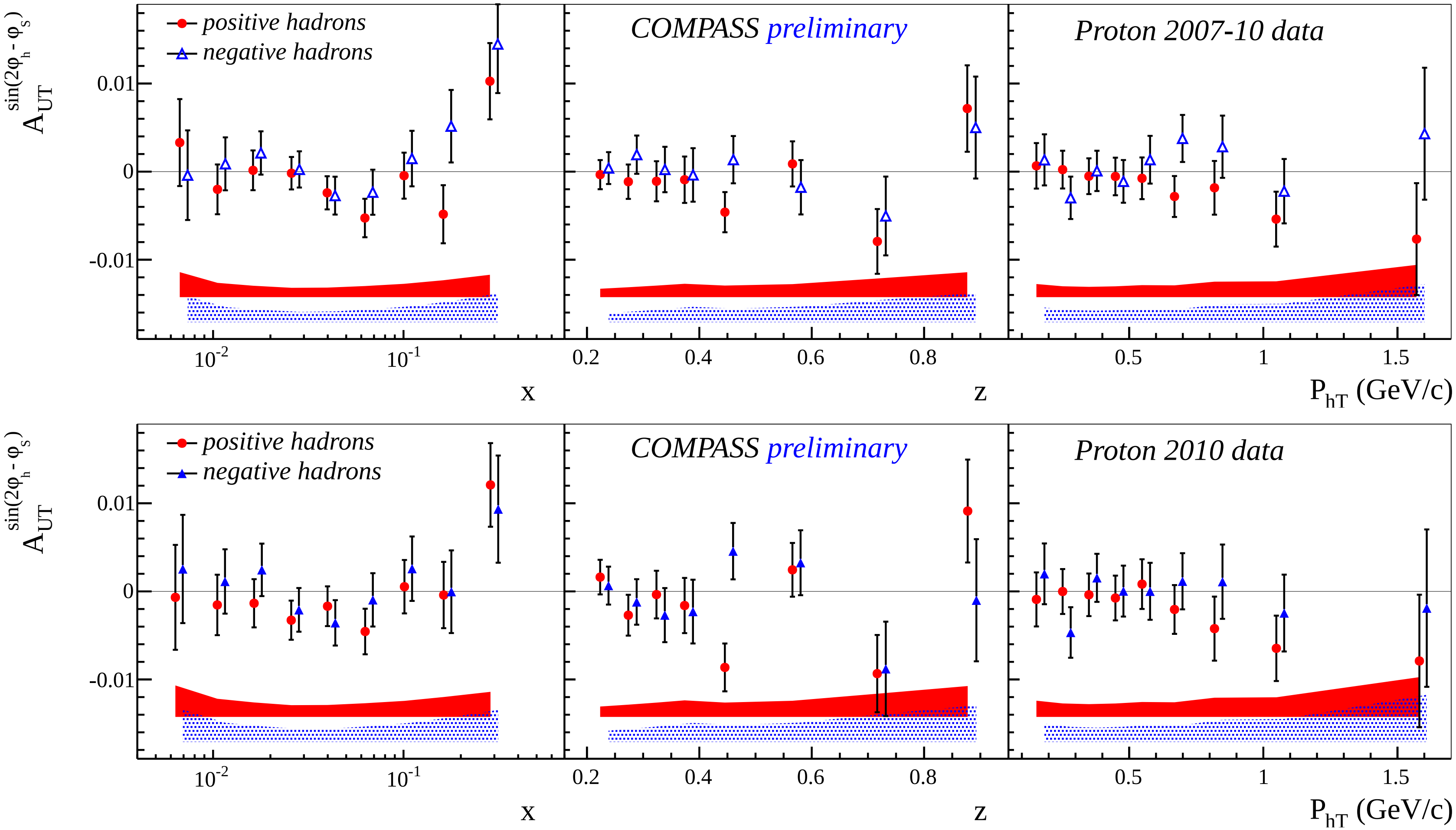




↪ deuteron data compatible with zero within the uncertainties

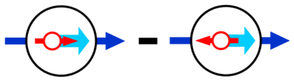
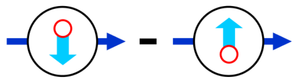
A_{UT2} ▶ charged hadrons ▶ p 2010 and combined data

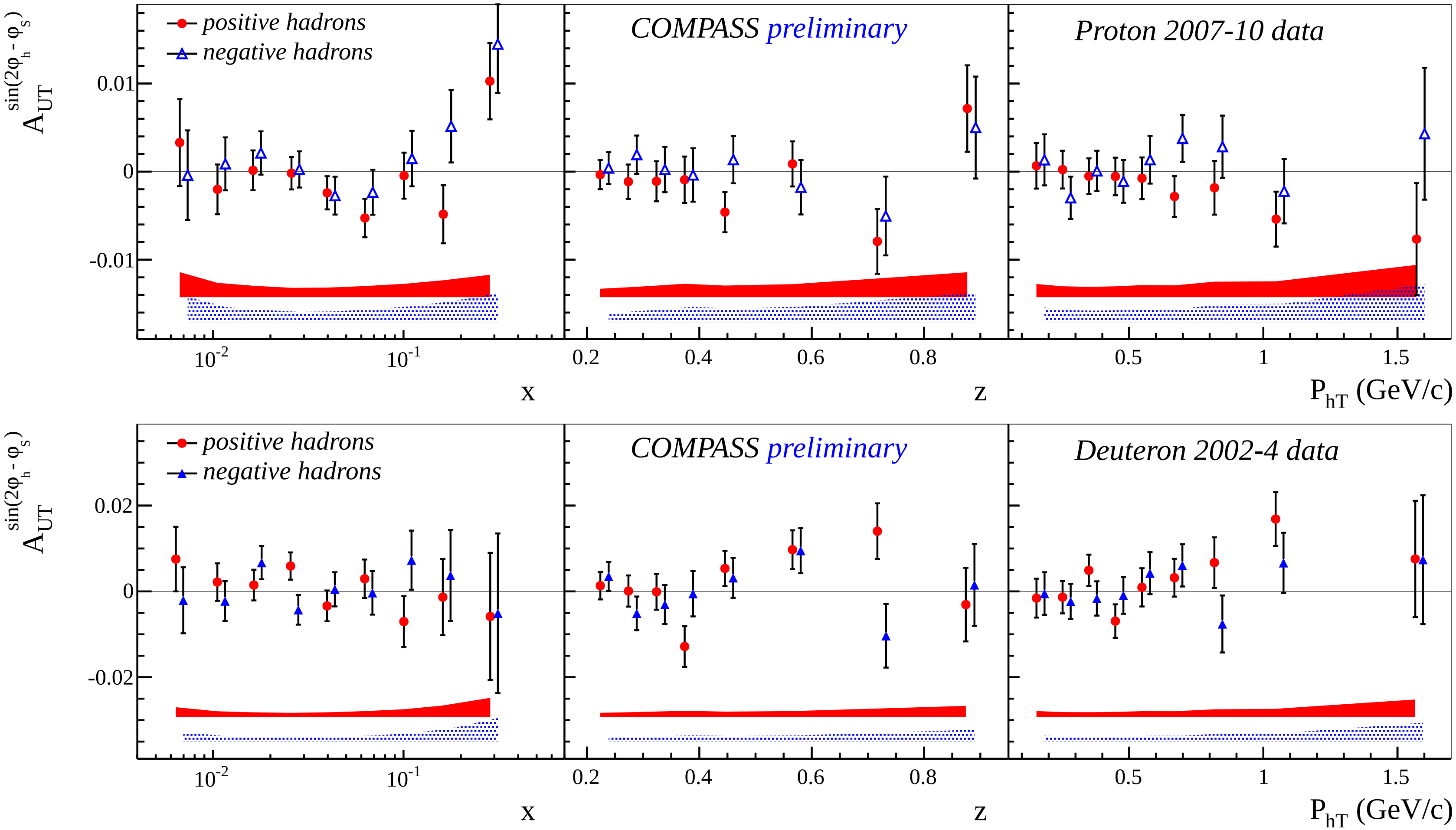
Twist-3 $A_{UT}^{\sin(2\phi_h-\phi_S)}$ Pretzelosity $h_{1T}^{q\perp}(x)$; Sivers $f_{1T}^{\perp q}(x)$



↪ proton data compatible with zero within the uncertainties

A_{UT2} ▶ charged hadrons ▶ proton *vs.* deuteron data

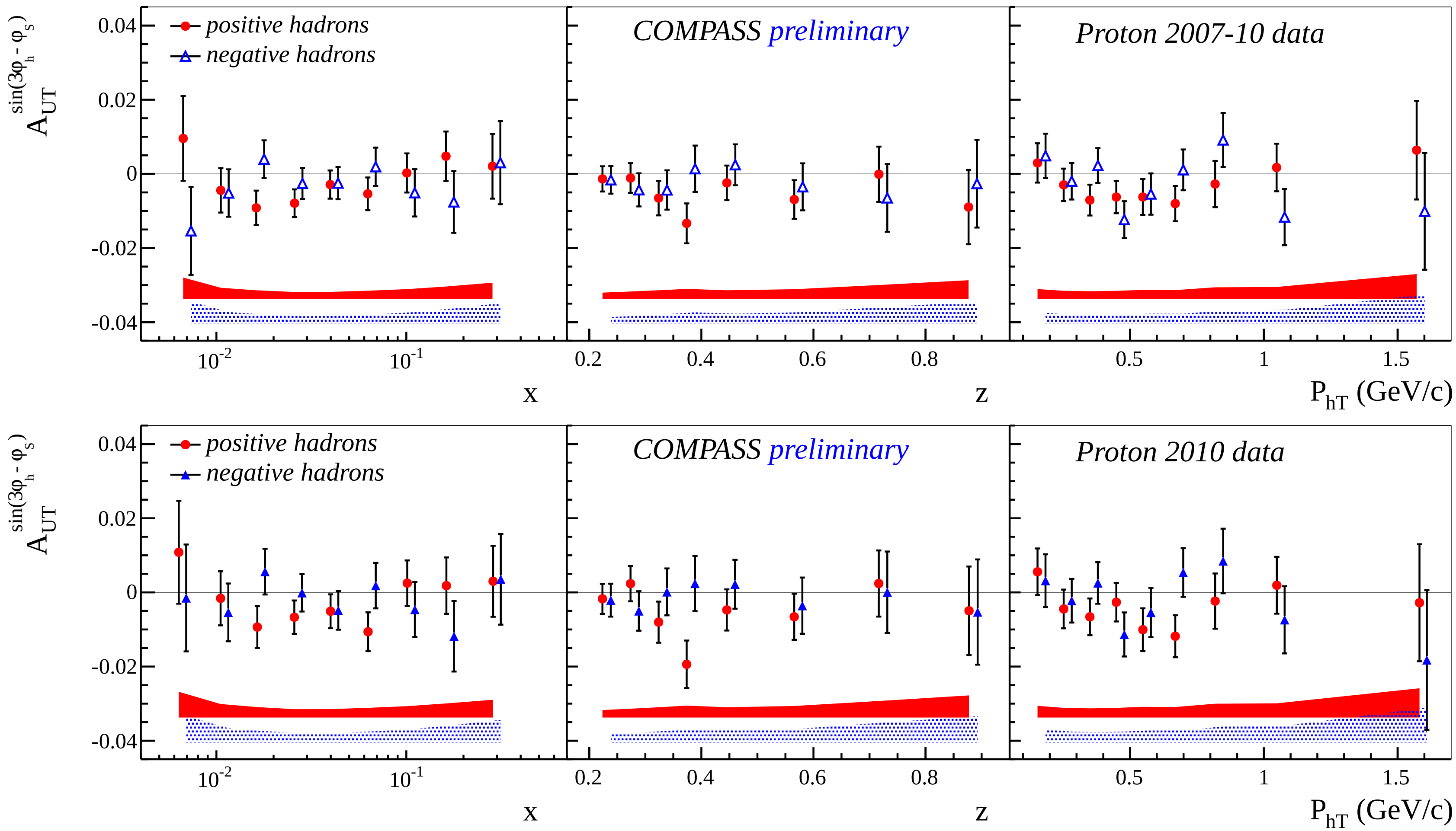
Twist-3 $A_{UT}^{\sin(2\phi_h - \phi_S)}$ Pretzelosity $h_{1T}^{q\perp}(x)$  ; Sivers $f_{1T}^{\perp q}(x)$ 



↪ deuteron data non-zero in mid z range

Pretzelosity ▶ charged hadrons ▶ p 2010 and combined data

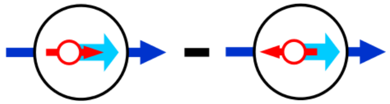
Twist-2 $A_{UT}^{\sin(3\phi_h-\phi_S)}$ Pretzelosity $h_{1T}^{q\perp}(x)$

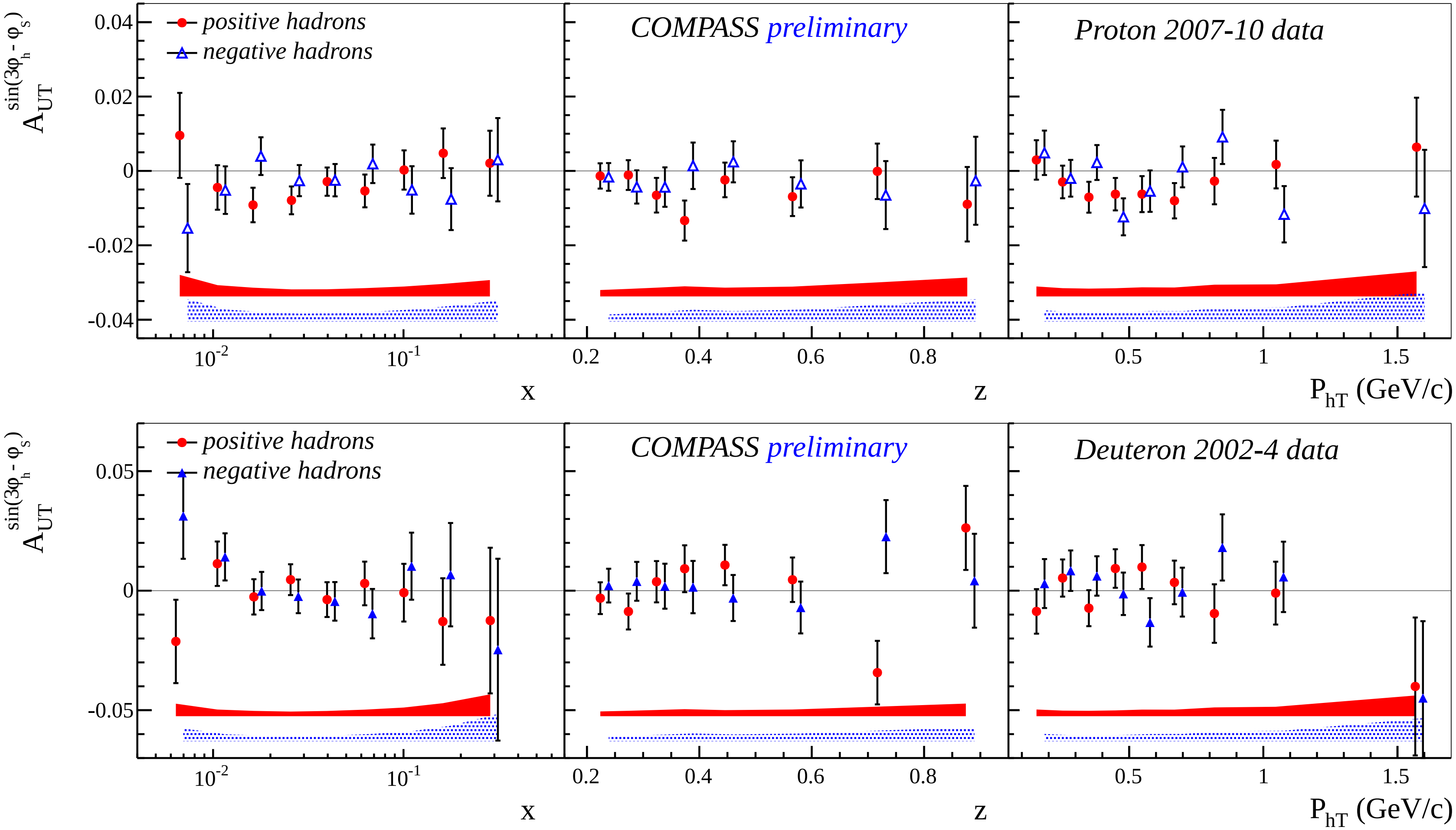


↪ proton data compatible with zero within the uncertainties

Pretzelosity ▶ charged hadrons ▶ proton *vs.* deuteron data

Twist-2 $A_{UT}^{\sin(3\phi_h-\phi_S)}$ Pretzelosity $h_{1T}^{q\perp}(x)$

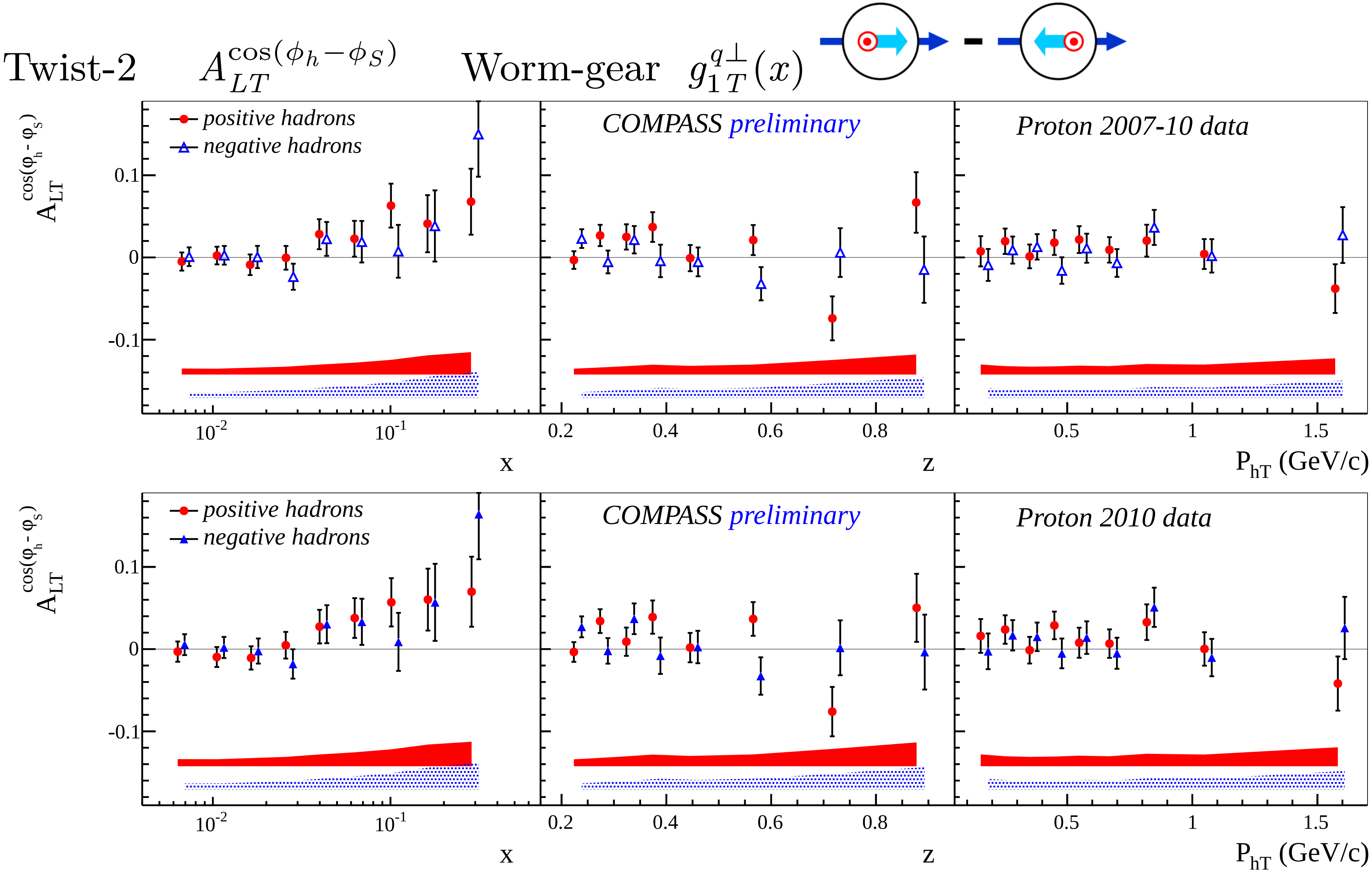




↪ deuteron data compatible with zero within the uncertainties

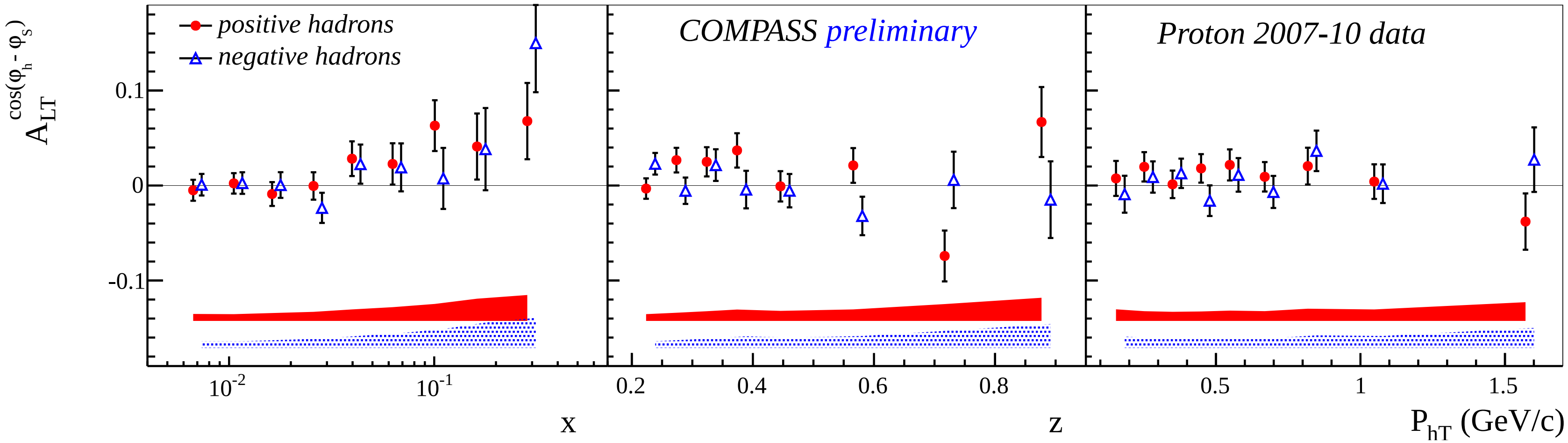
Worm-gear ▶ charged hadrons ▶ p 2010 and combined data

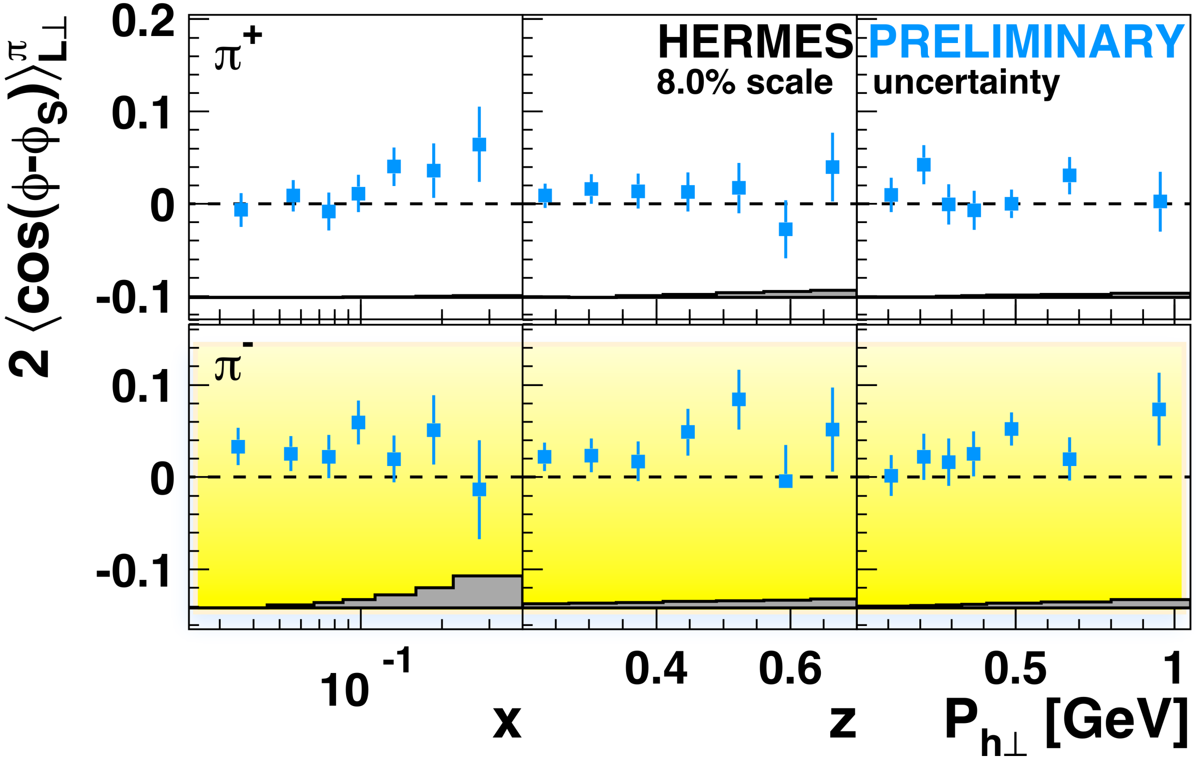
Twist-2 $A_{LT}^{\cos(\phi_h - \phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$



↪ proton data shows non-zero trend in x for positive charged hadrons at relatively large x

Worm-gear ▶ charged hadrons ▶ HERMES *vs.* COMPASS

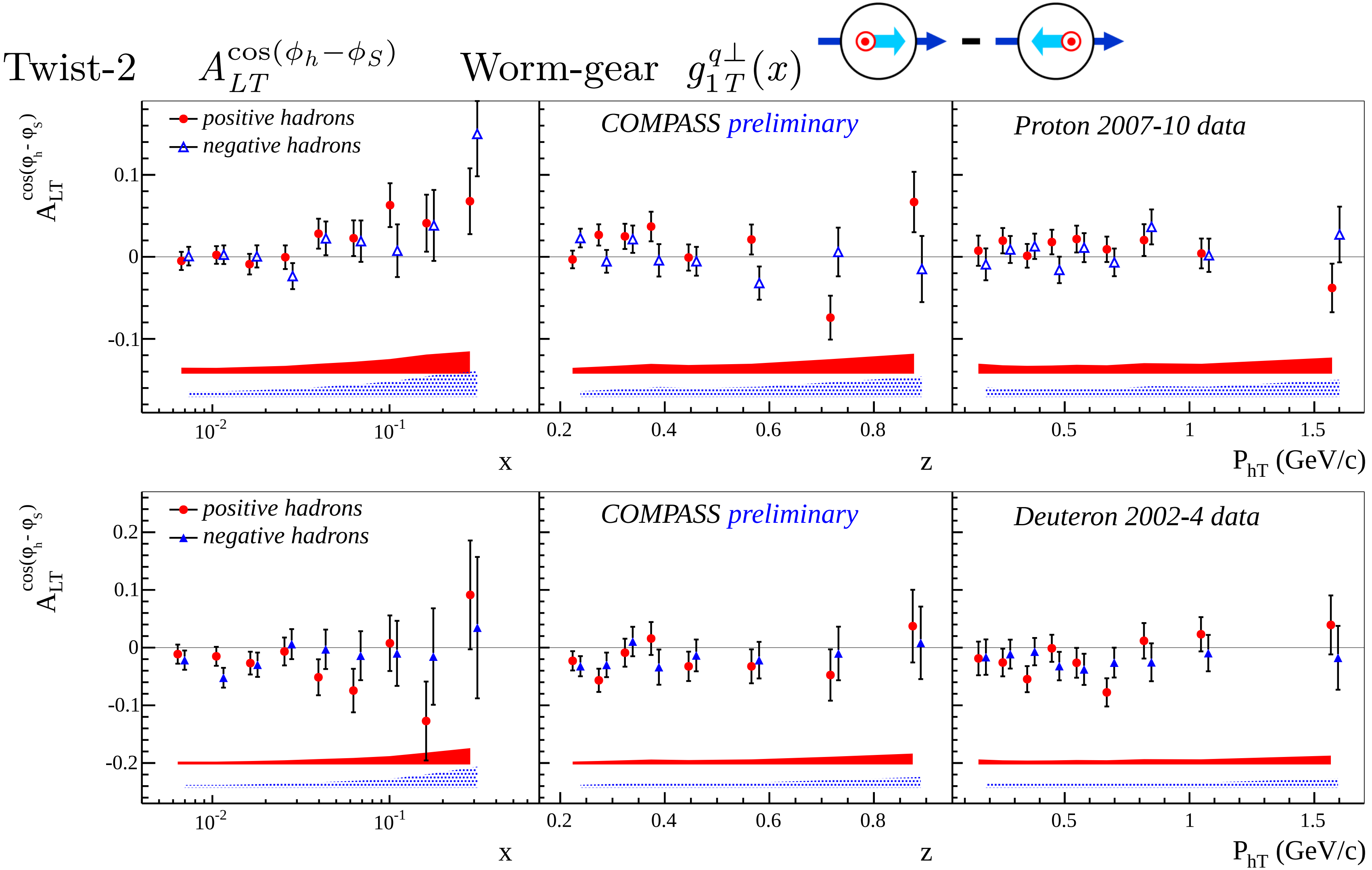




↪ Similar trend in x for HERMES and COMPASS

Worm-gear ► charged hadrons ► proton *vs.* deuteron data

Twist-2 $A_{LT}^{\cos(\phi_h-\phi_S)}$ Worm-gear $g_{1T}^{q\perp}(x)$

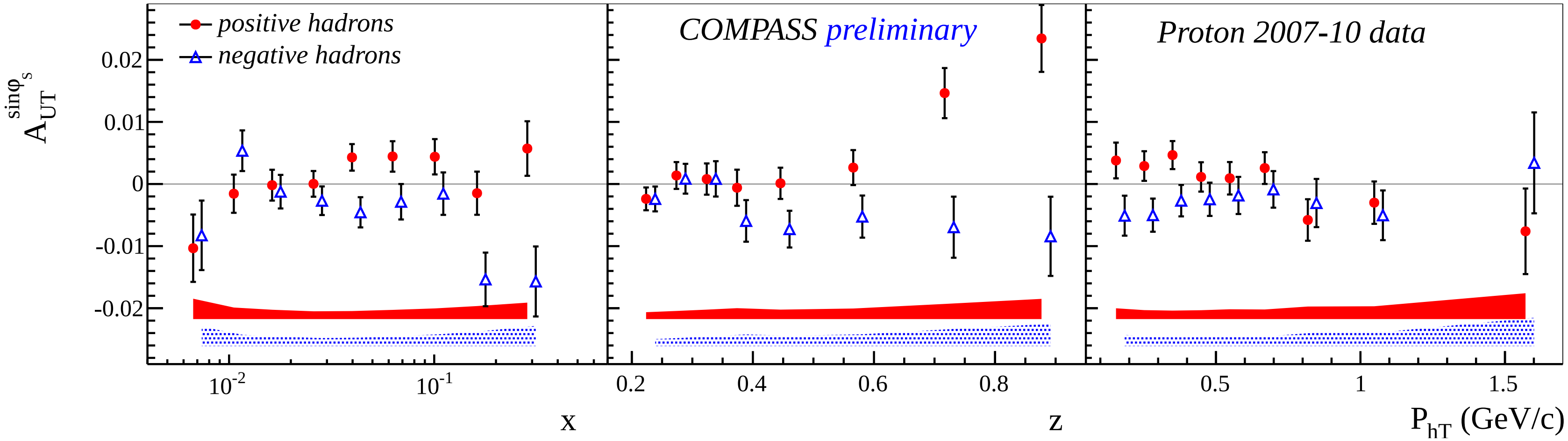


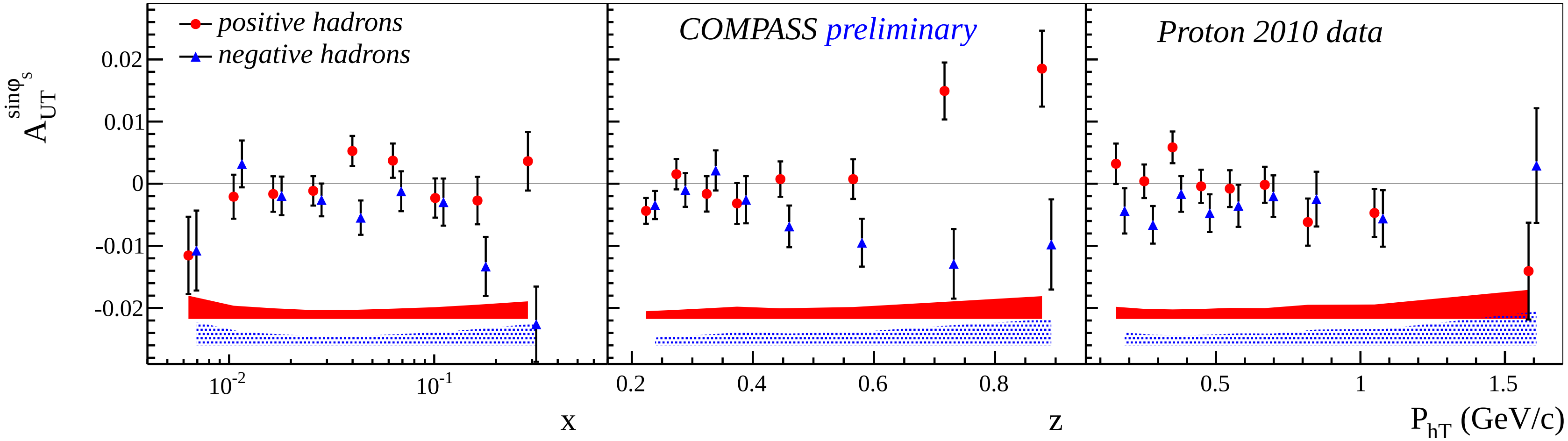
↪ deuteron data compatible with zero within the uncertainties

↪ indication of negative mean value

A_{UT1} ▶ charged hadrons ▶ p 2010 and combined data

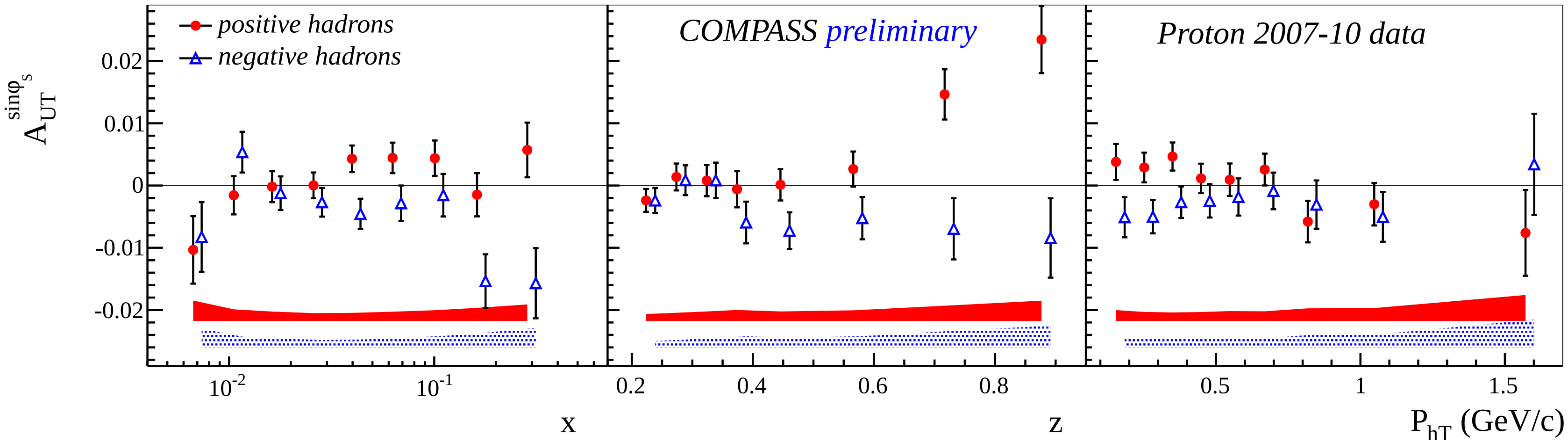
Twist-3 $A_{UT}^{\sin(\phi_S)}$ Transversity $h_1^q(x)$; Sivers $f_{1T}^{\perp q}(x)$

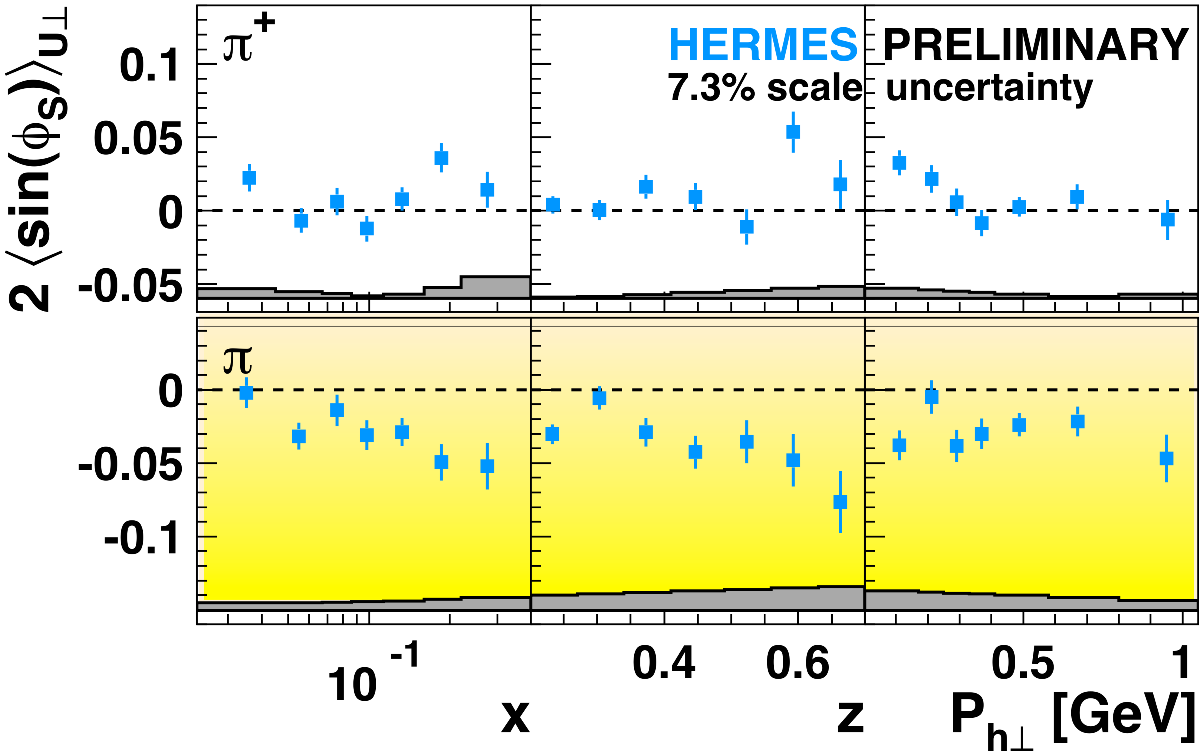




$\hookrightarrow$ proton data shows non-zero negative trend for h^- in x

A_{UT1} ► charged hadrons ► HERMES *vs.* COMPASS

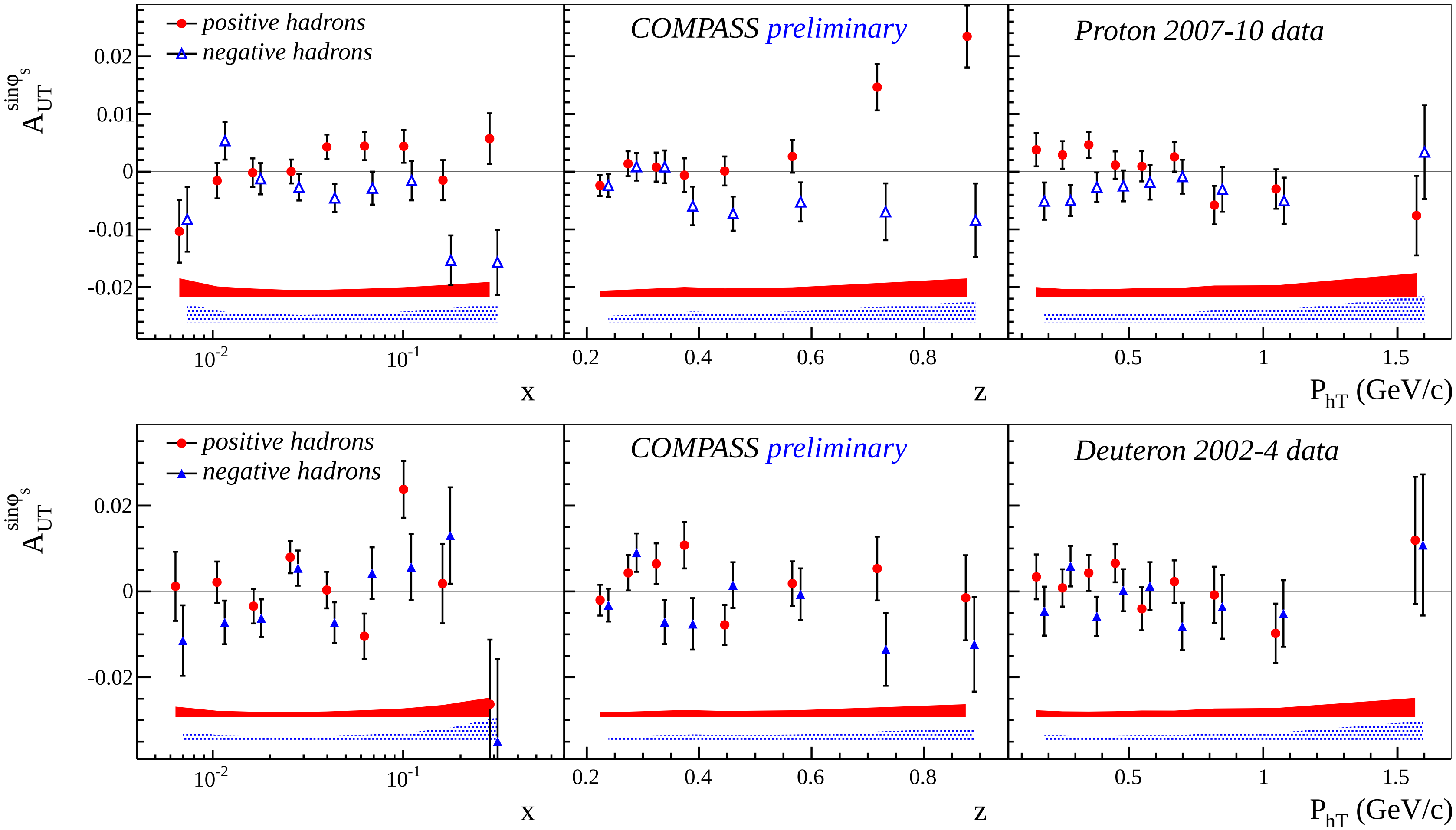




↪ similar trends in x, z and p_T^h for HERMES π^- and COMPASS h^-

A_{UT1} ► charged hadrons ► proton *vs.* deuteron data

Twist-3 $A_{UT}^{\sin(\phi_S)}$ Transversity $h_1^q(x)$; Sivers $f_{1T}^{\perp q}(x)$

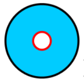


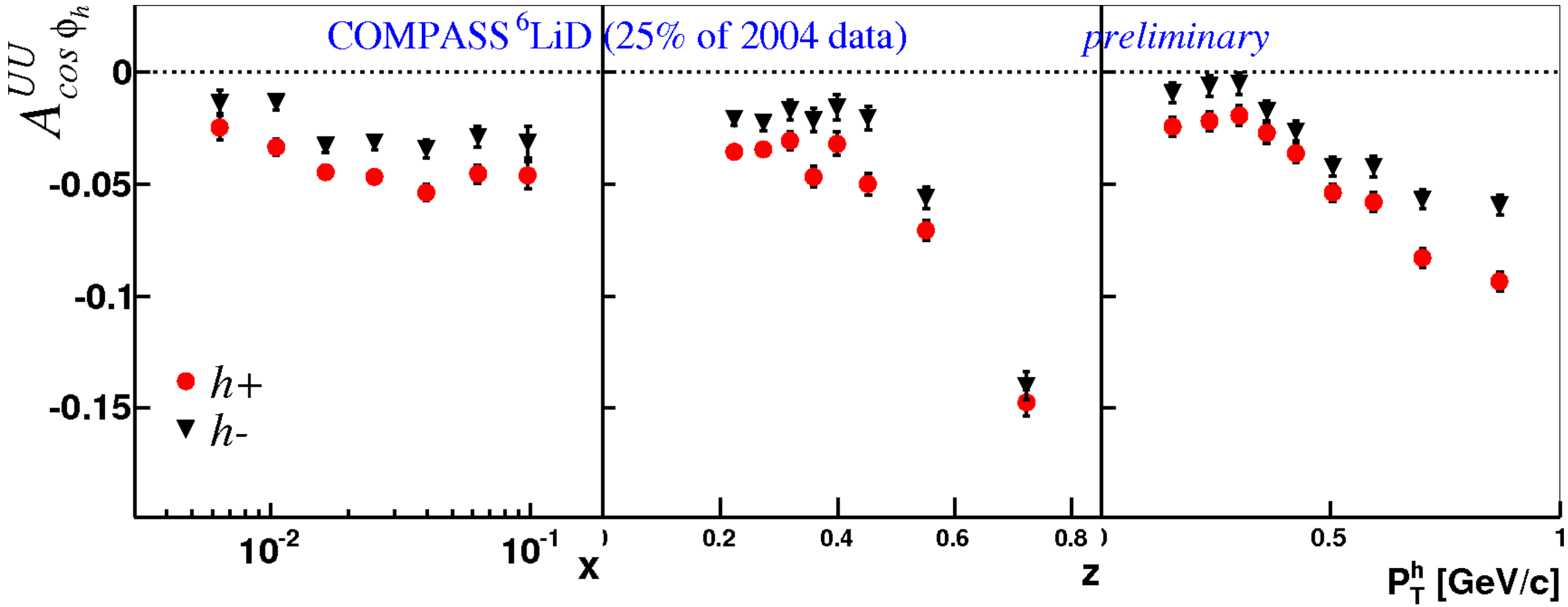
↪ deuteron data is compatible with zero within the uncertainties

Unpolarized (target) azimuthal asymmetries

deuteron data 2004

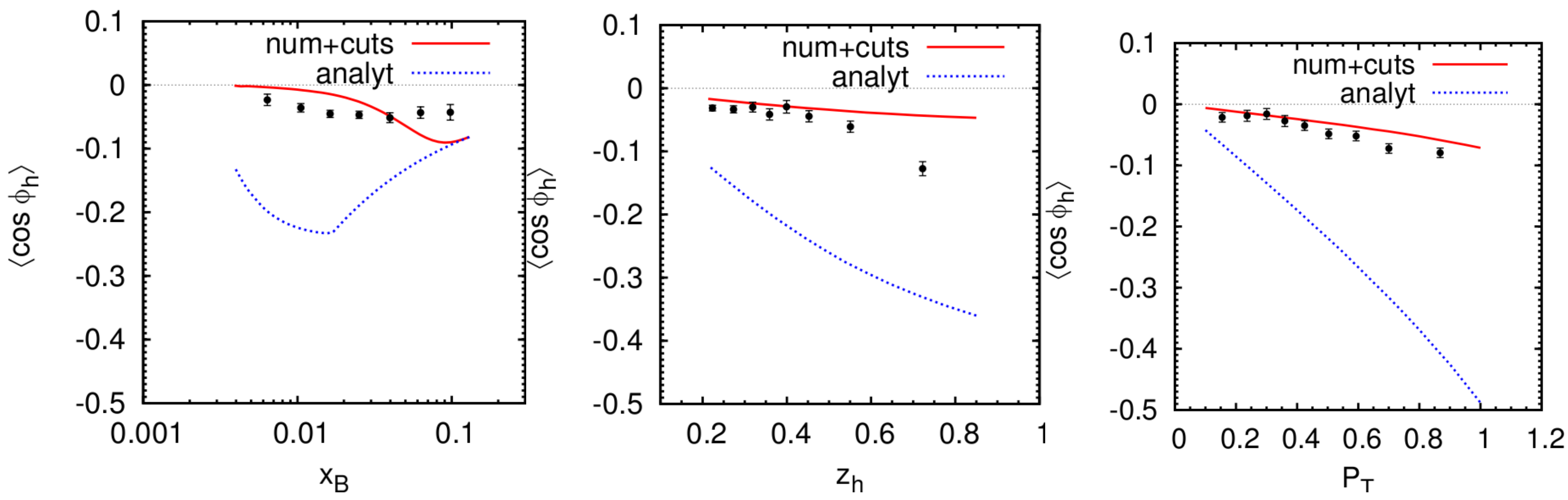
A_{UU1} ▶ charged hadrons ▶ 2004 data

Twist-2 $A_{UU}^{\cos\Phi_h}$ Cahn $f_1^q(x)$ ; Boer-Mulders $h_1^{\perp q}(x)$ 



- ↪ clear asymmetry in x and p_T^h
- ↪ strong z dependence for $z > 0.5$
- ↪ h^+ asymmetries systematical larger then h^-

A_{UU1} ▶ h^+ ▶ 2004 data *vs.* model calculations



M.Boglione, S. Melis and A. Prokudin, Phys.Rev.D84, arXiv:1107.4436v1

↪ same trend and strength in p_T^h and low z region

Unpolarized ▶ charged hadrons ▶ 2004 data

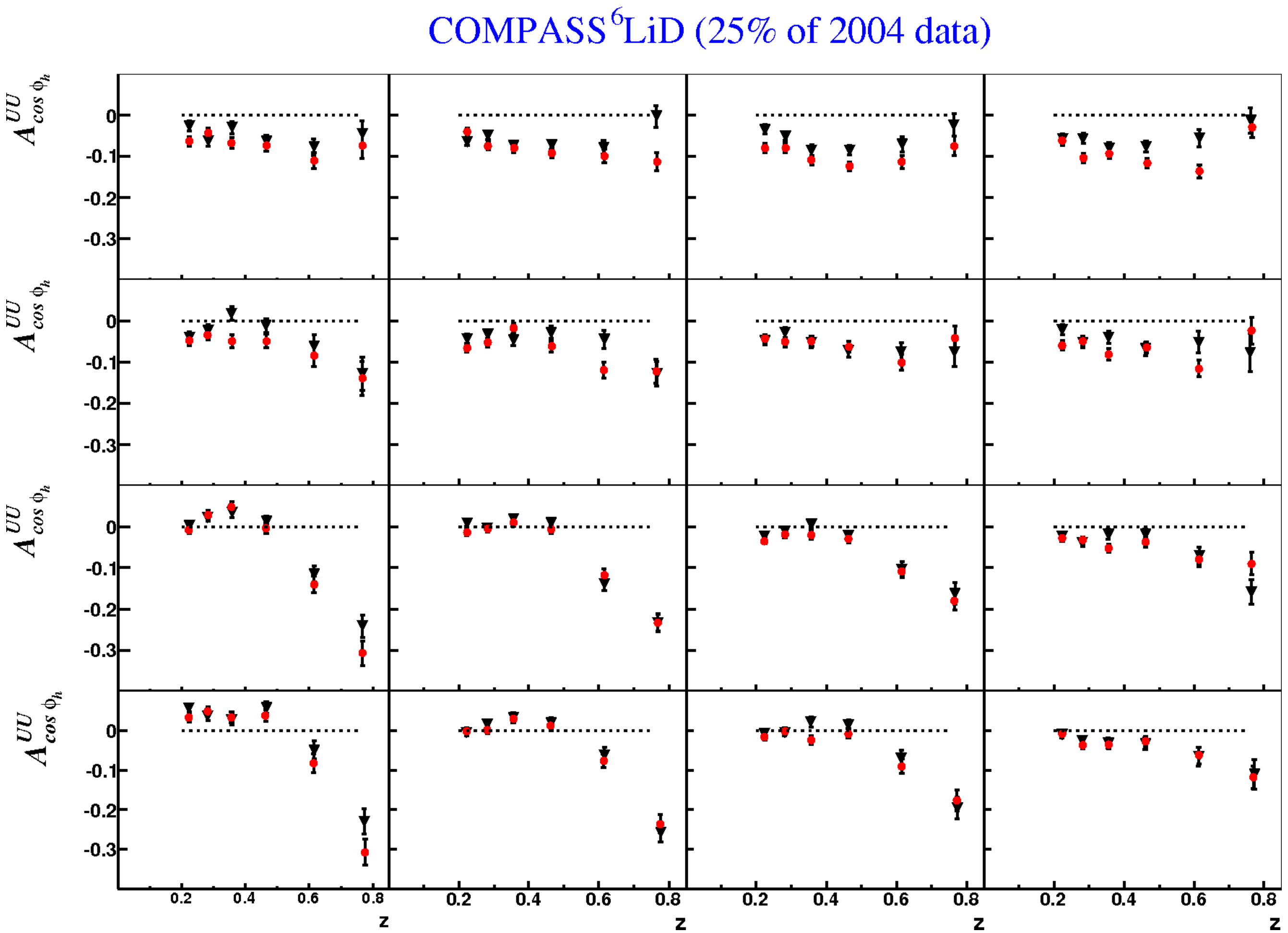
Towards a multi dimensional analysis:

to get a better understanding of the kinematical dependencies in x, z and p_T^h.

Using a simultaneous binning:

x	p_T^h	z
0.003 – 0.012	0.10 – 0.30	0.20 – 0.25
0.012 – 0.020	0.30 – 0.50	0.25 – 0.32
0.020 – 0.038	0.50 – 0.64	0.32 – 0.40
0.038 – 0.130	0.64 – 1.00	0.40 – 0.55
		0.55 – 0.70
		0.70 – 0.85

A_{UU1} ▶ charged hadrons ▶ 2004 data preliminary

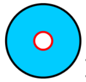
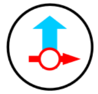


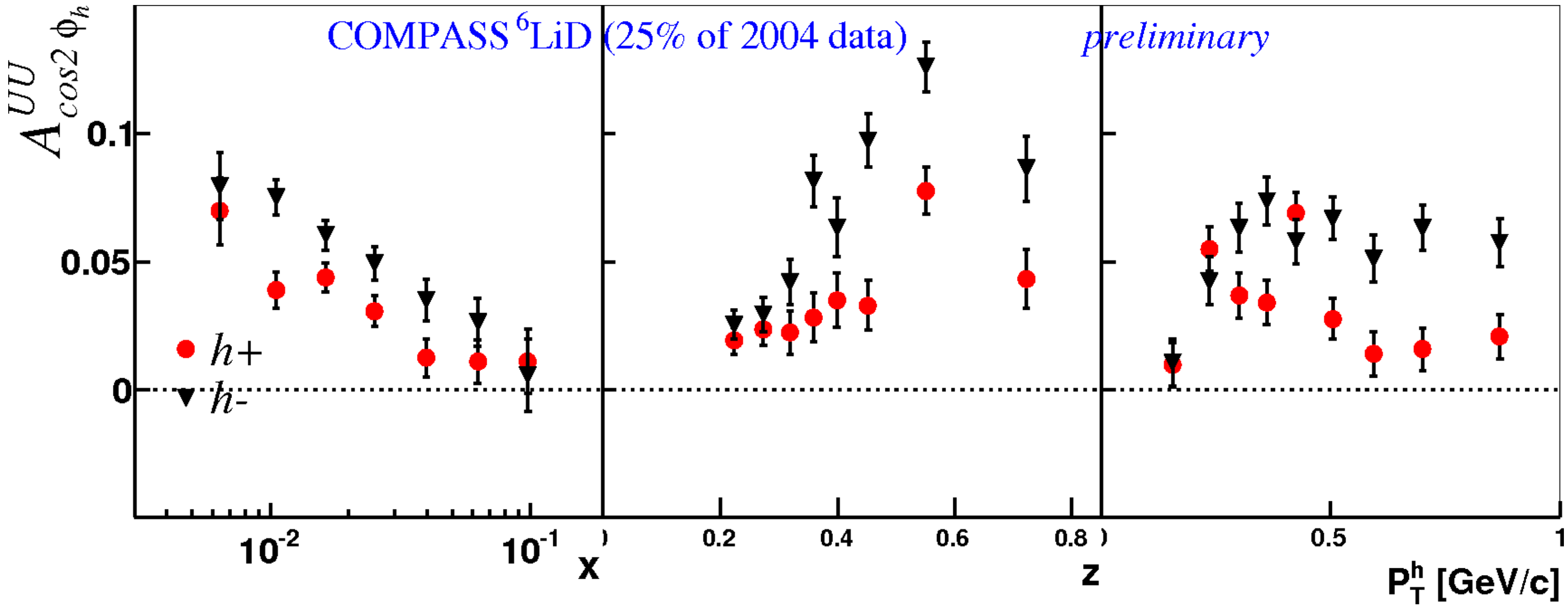
$\uparrow p_T^h; \rightarrow x$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ strong dependence in z more evident at small x and small p_T^h

A_{UU2} ▶ charged hadrons ▶ 2004 data

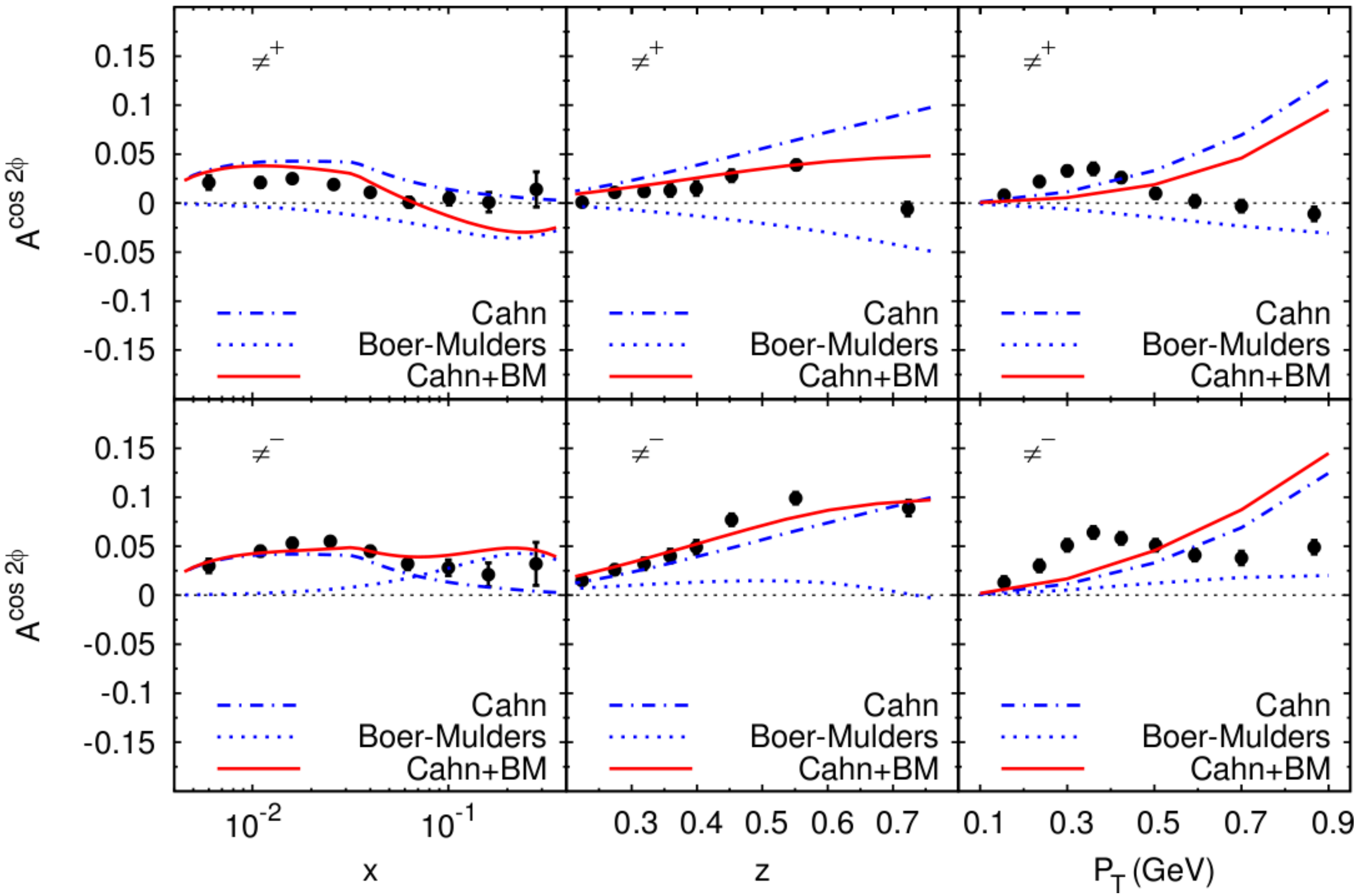
Twist-2 $A_{UU}^{\cos 2\Phi_h}$ Cahn $f_1^q(x)$ ; Boer-Mulders $h_1^{\perp q}(x)$  - 



first shown at SPIN2010 by G. Sbrizzai

↪ clear asymmetry in low x and high z
↪ p_T^h dependence shows saturation for h^-
↪ h^- asymmetries systematical larger then h^+

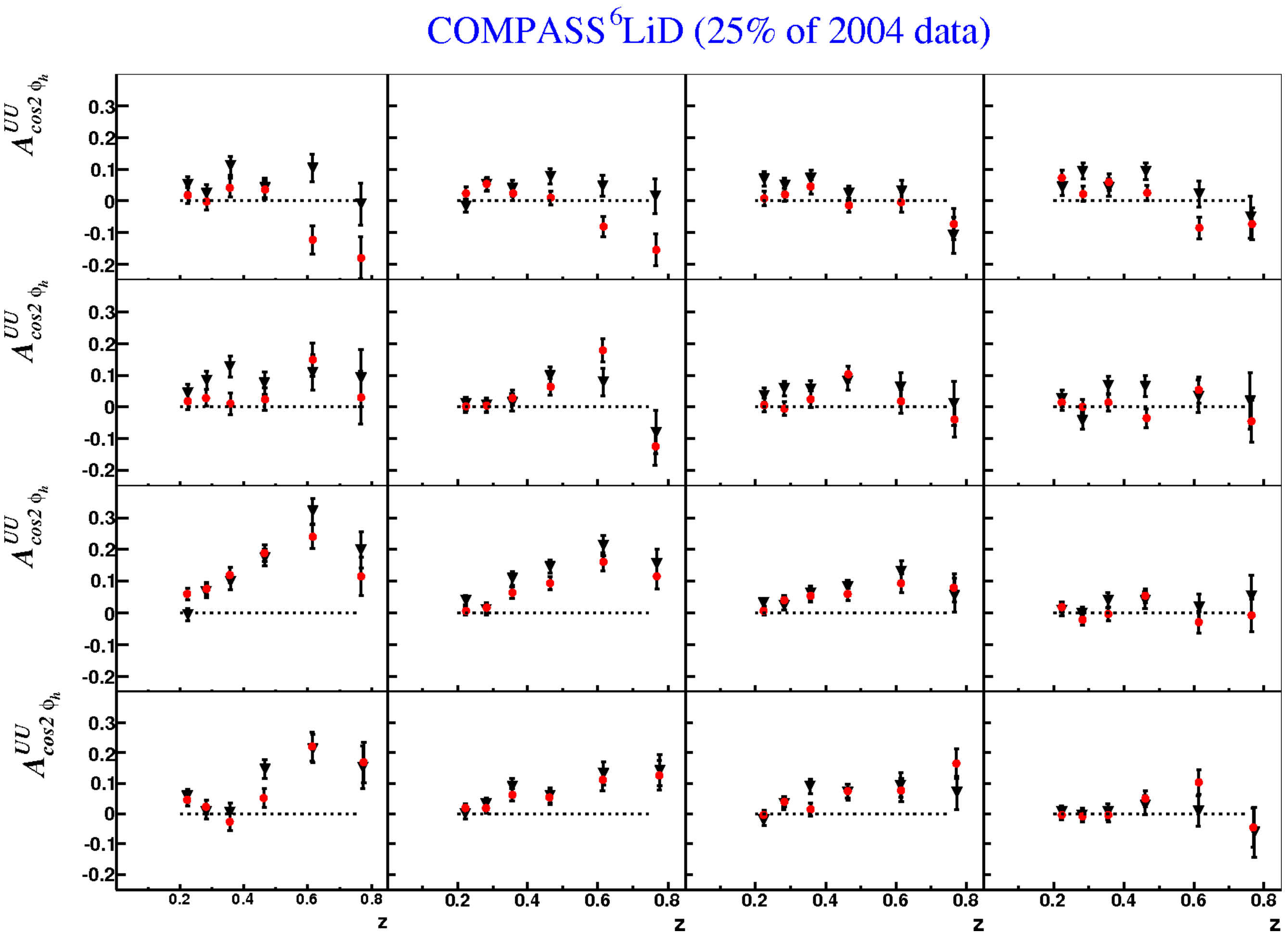
A_{UU2} ▶ charged hadrons ▶ 2004 data *vs.* model calculations



V. Barone, S. Melis and A. Prokudin, Phys.Rev.D81, arXiv:0912.5194v2

↪ same trend and strength in x and low z region
↪ p_T^h dependence difficult to reproduce

A_{UU2} ▶ charged hadrons ▶ 2004 data preliminary



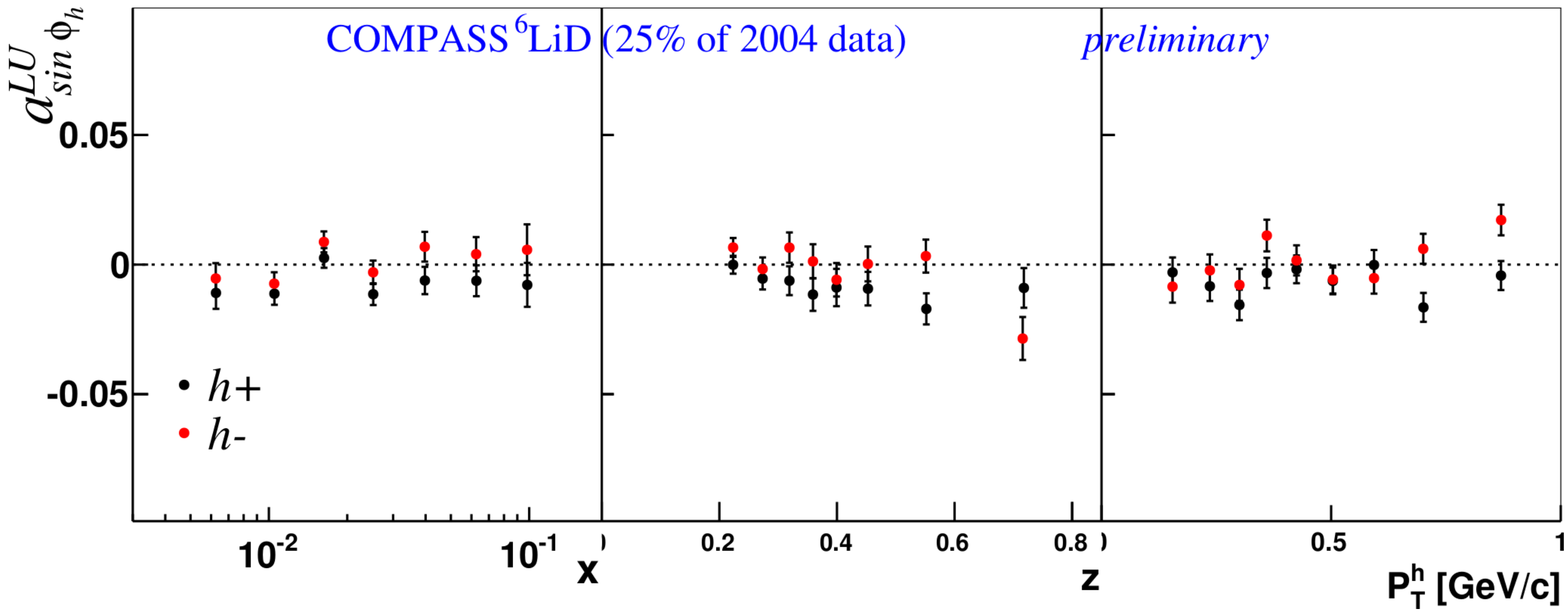
$\uparrow p_T^h; \rightarrow x$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ strongest signal at low x and low p_T^h

A_{LU} ▶ charged hadrons ▶ 2004 data

Twist-3 $A_{LU}^{\sin\phi_h}$



first shown at SPIN2010 by G. Sbrizzai

↪ mostly compatible with zero for all charged hadrons

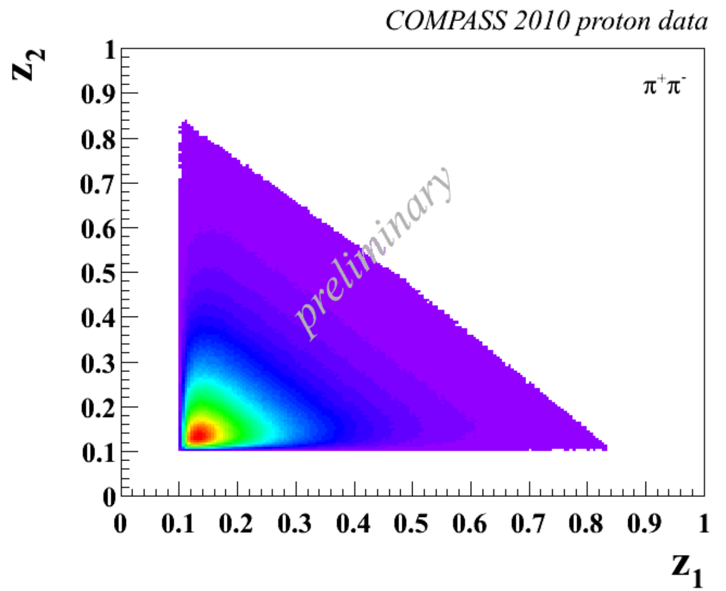
Dihadron asymmetry

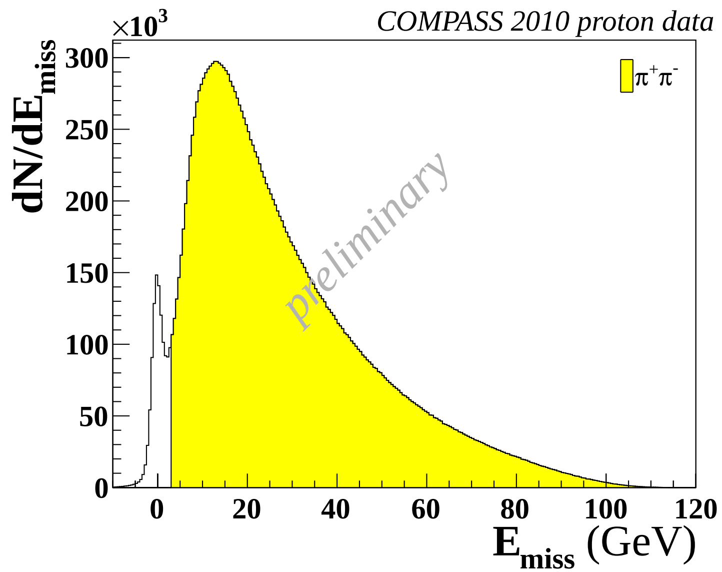
proton data 2010

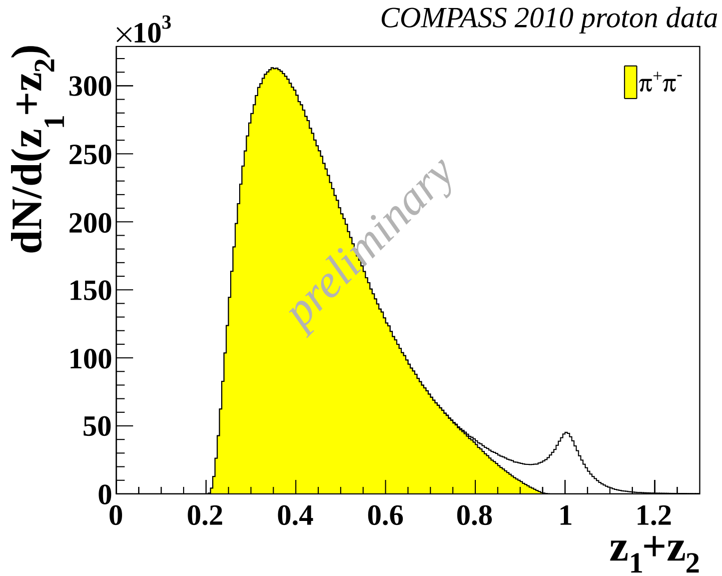
Data selection ▶ dihadron asymmetry

hadron & hadron pair cuts:

- at least 2 outgoing hadrons with opposite charge
- $z > 0.1$ for each hadron
- $x_F > 0.1$ for each hadron
- $E_{miss} > 3$ GeV/c^2 for each pair
- $R_T > 0.07$ GeV/c for each pair

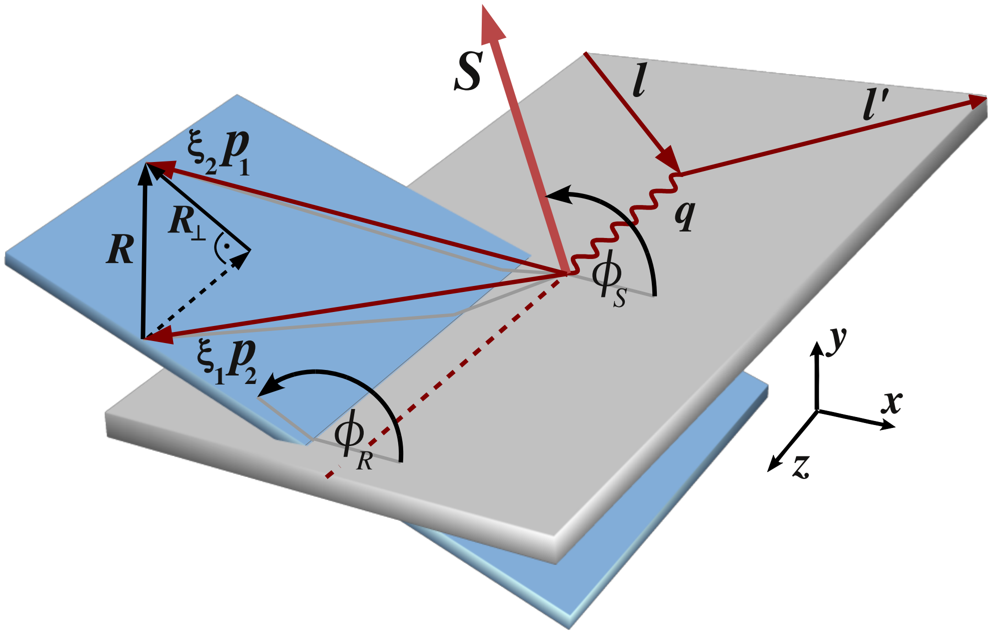






$l\ p^{\uparrow} \ \rightarrow \ l'\ h_1\ h_2$

Fragmentation of transversely polarized quark into two unpolarized hadrons



in courtesy of H. Wollny

- l, l' and q are 3-momenta of incomming l, scattered lepton l' and virtual photon γ^*
- Φ_S azimuthal angle of the spin of the fragmenting quark S
- $z_i = \frac{\mathbf{p_i}}{\mathbf{p}}$
- $\mathbf{R} = \frac{z_2\mathbf{p_1} - z_1\mathbf{p_2}}{z_1+z_2} = \xi_2\mathbf{p_1} - \xi_1\mathbf{p_2}$
- $\mathbf{R_T}$ is the component of $\mathbf{R}$ perpendicular to $\mathbf{q}$
- Azimuthal angle of $\mathbf{R}$:

  $\Phi_R = \frac{(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}}{|(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}|}\arccos\left(\frac{(\mathbf{q}\times\mathbf{l})\cdot(\mathbf{q}\times\mathbf{R})}{|\mathbf{q}\times\mathbf{l}||\mathbf{q}\times\mathbf{R}|}\right)$

The differential two-hadron cross section reads:

$$\frac{\mathrm{d}^7\sigma}{\mathrm{d}\cos\theta\ \mathrm{d}M_h^2\ \mathrm{d}\Phi_R\ \mathrm{d}z\ \mathrm{d}x\ \mathrm{d}y\ \mathrm{d}\Phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y}\Big((1-y+\tfrac{y^2}{2})\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_h^2, \cos\theta)$$

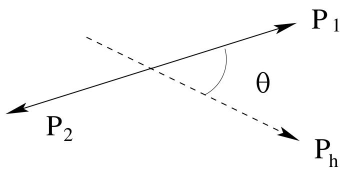
$$+(1-y) S_\perp \sum_q e_q^2 \frac{|\mathbf{p_1}-\mathbf{p_2}|}{2M_h} \sin(\theta) h_1^q(x) H_{1,q}^{\sphericalangle}(z, M_h^2, \cos\theta) \sin(\Phi_{RS})\Big)$$

with $\Phi_{RS} = \Phi_R + \Phi_S - \pi$

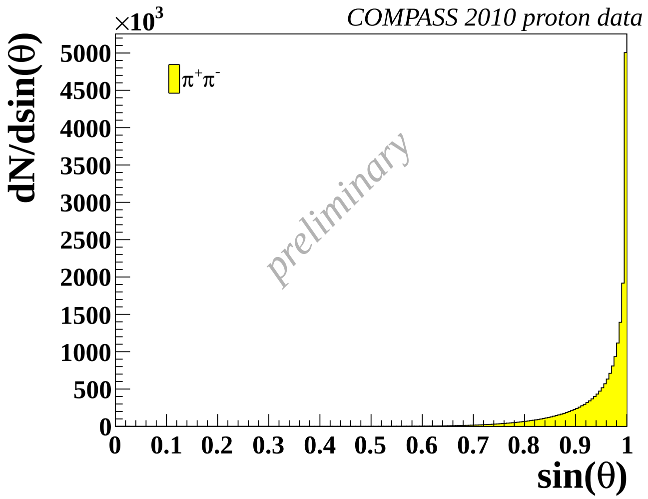
Where $h_1(x)$ is the Transversity PDF and $H_{1,q}^{\sphericalangle}$ is the two-hadron Interference FF, which describes the Fragmentation of a transversely polarized quark into two unpolarized hadrons. $D_{1,q}$ is the unpolarized two-hadron fragmentation function[2].

[2] see Nour Makke's talk on hadron multiplicities

$$N_{2h}(x, y, z, M_h^2, \cos(\theta), \Phi_{RS}) \propto$$
$$\sigma_{UU}(1 \pm f P_T D_{NN} A_{UT}^{\sin\Phi_{RS}} \sin\theta \sin\Phi_{RS})$$



h^+h^- center of mass frame



$\langle \sin\theta \rangle = 0.943$
$\Rightarrow$ can be neglected

σ_{UU} = unpolarized cross section

$\pm$ indicates nucleon spin orientation

f = target dilution factor

P_T = target polarization

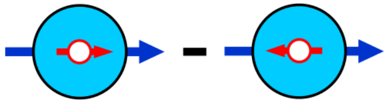
D_{NN} = transv. spin transfer coef.

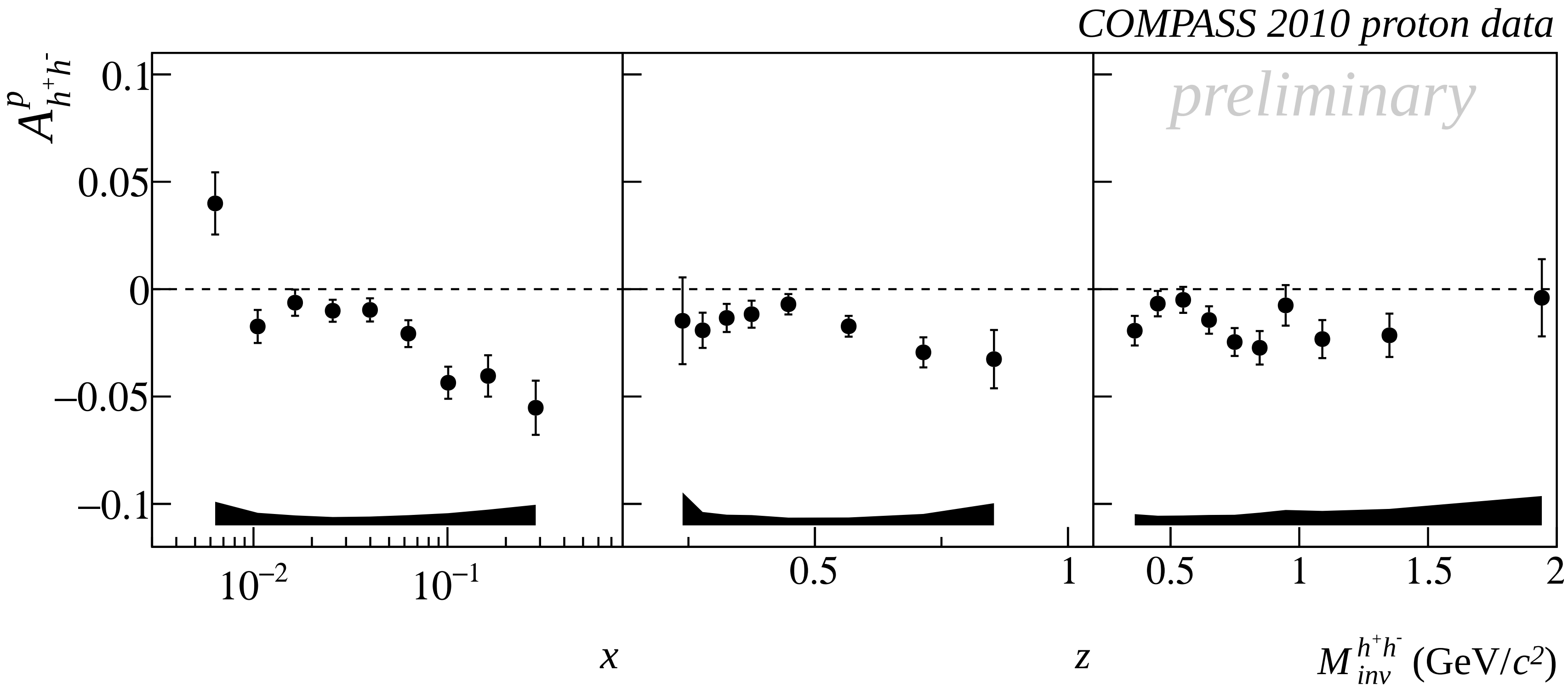
$D_{NN} = \frac{1-y}{1-y+\frac{y^2}{2}}$

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

$A_{UT}^{\sin\Phi_{RS}}$ ▶ charged hadrons ▶ 2010 data

Twist-2 $A_{UT}^{\sin\Phi_{RS}}$ h_1^q



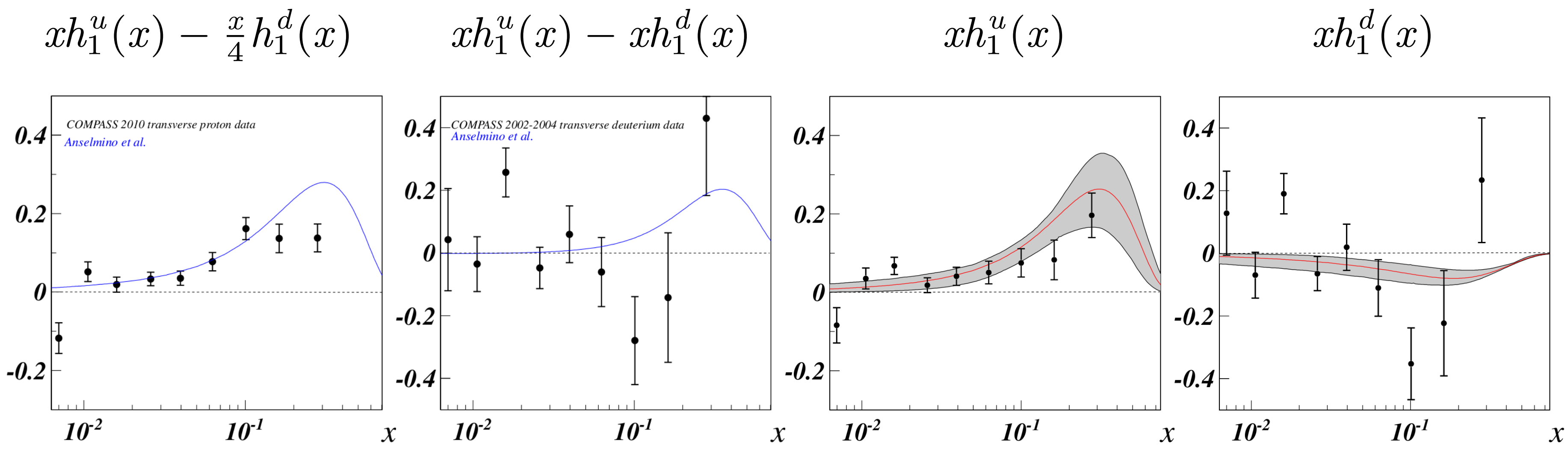


↪ Clear asymmetries of h^+h^- with improved errors *w.r.t.* 2007 data

TRANSVERSITY 2011 proceedings:
Braun C. *o.b.o.* the COMPASS Collab. Nuovo Cimento C **035** (2012) 02

$A_{UT}^{\sin\Phi_{RS}}$ ▶ 1^{st} extraction of u and d transversity from 2010 proton data

Extract information on DiFF from BELLE data as in "Bacchetta, Courtoy, Radici, PRL 107:012001,2011"
→ u and d transversity PDFs can be extracted using COMPASS deuterium and 2010 proton data



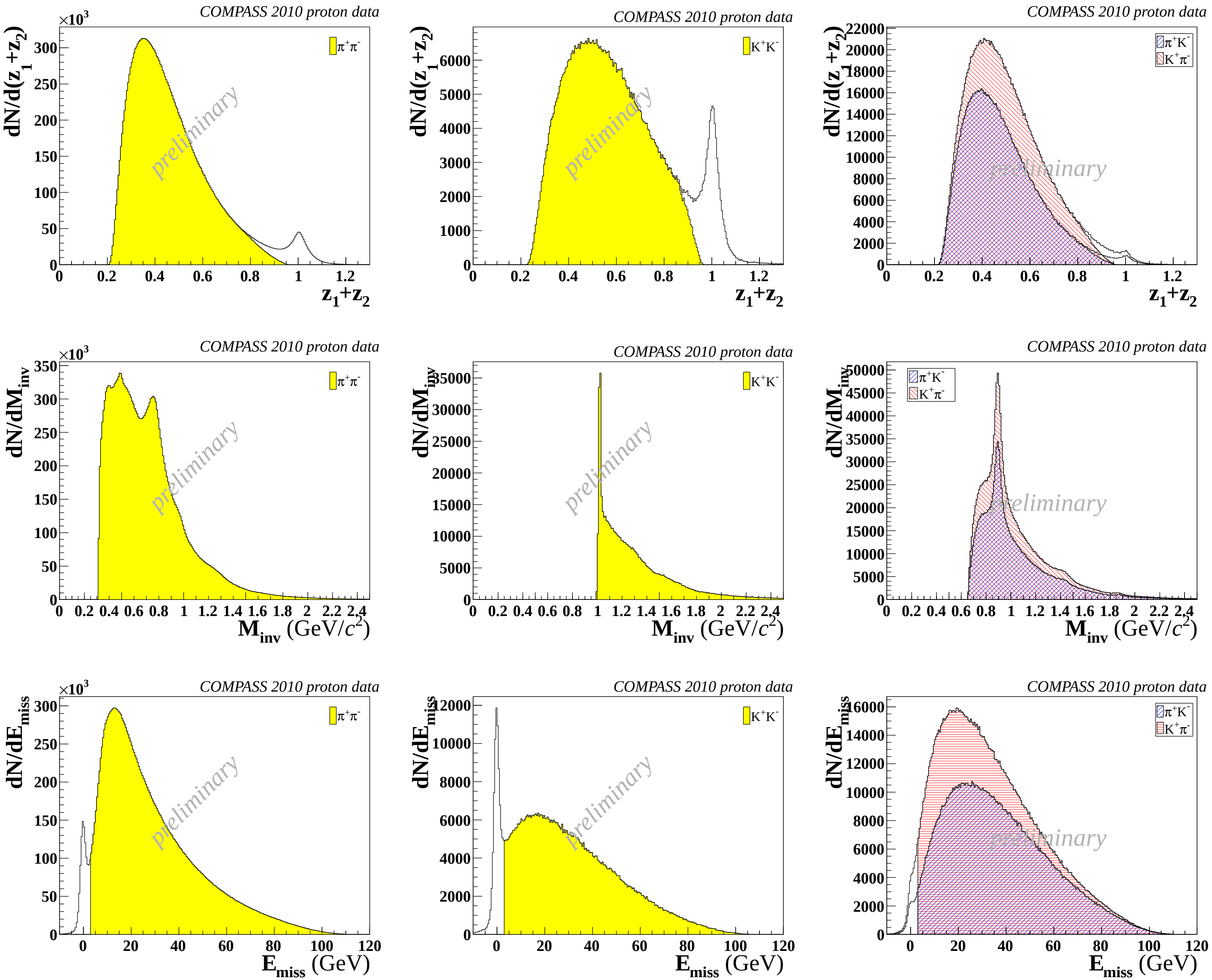
PhD thesis C. Elia, Trieste 2011 & F.Sozzi at IWHSS 2012

See also DIS2012 proceeding by

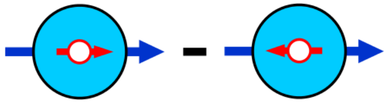
A. Courtoy, A. Bachetta & M. Radici, arXiv:1206.1836

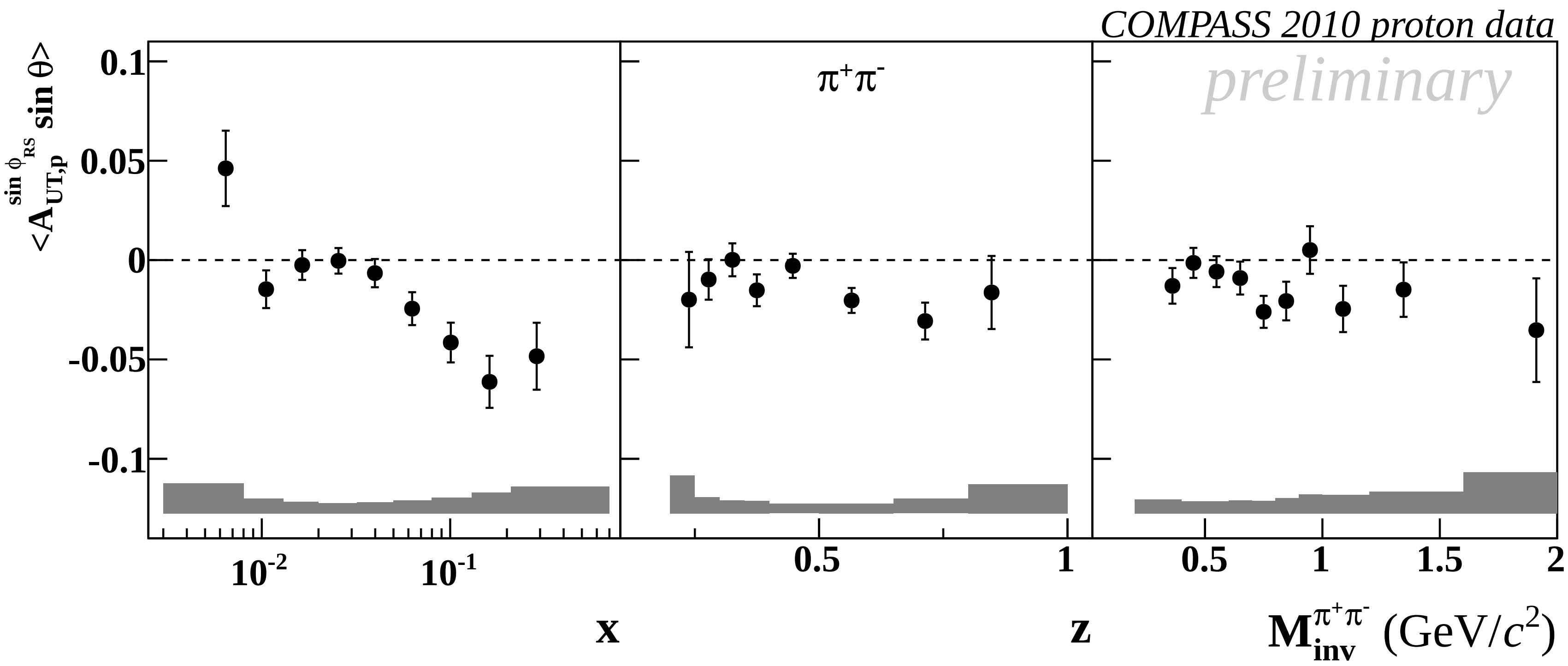
$A_{UT}^{\sin\Phi_{RS}}$ ▶ kin. distributions $z_1 + z_2$, M_{inv} and E_{miss}

$\pi^+\pi^-$ | K^+K^- | $\pi^+K^-\&K^+\pi^-$



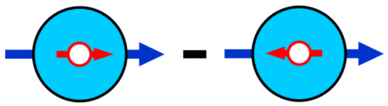
$A_{UT}^{\sin\Phi_{RS}}$ ▶ $\pi^+\pi^-$ pairs ▶ p 2010 data

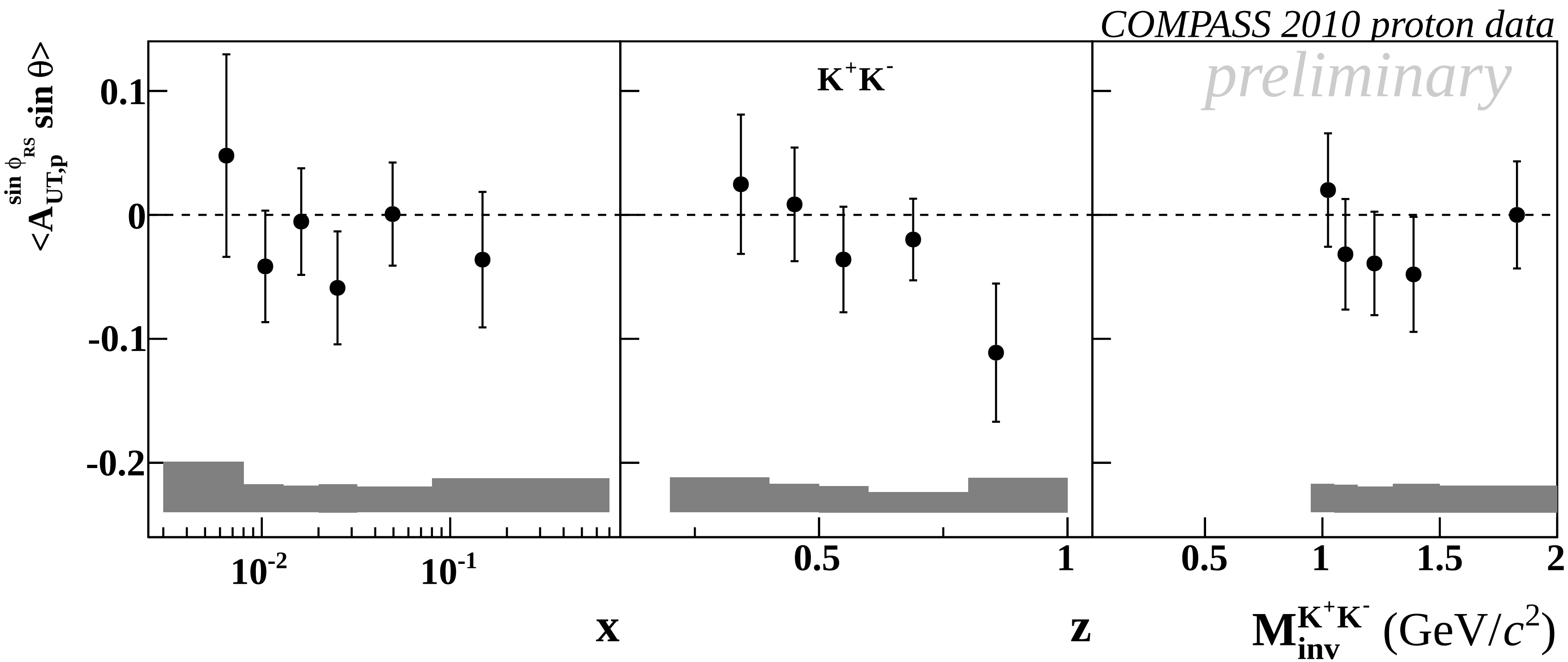
Twist-2 $A_{UT}^{\sin\Phi_{RS}}$ h_1^q 



↪ Clear asymmetries of $\pi^+\pi^-$ pairs ↪ x: up to 6 %
↪ z: compatible with a constant function
↪ M_{inv}: peak around ρ^0 mass

$A_{UT}^{\sin\Phi_{RS}}$ ▶ K^+K^- **pairs** ▶ p **2010 data**

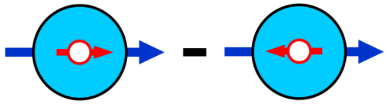
Twist-2 $A_{UT}^{\sin\Phi_{RS}}$ h_1^q 

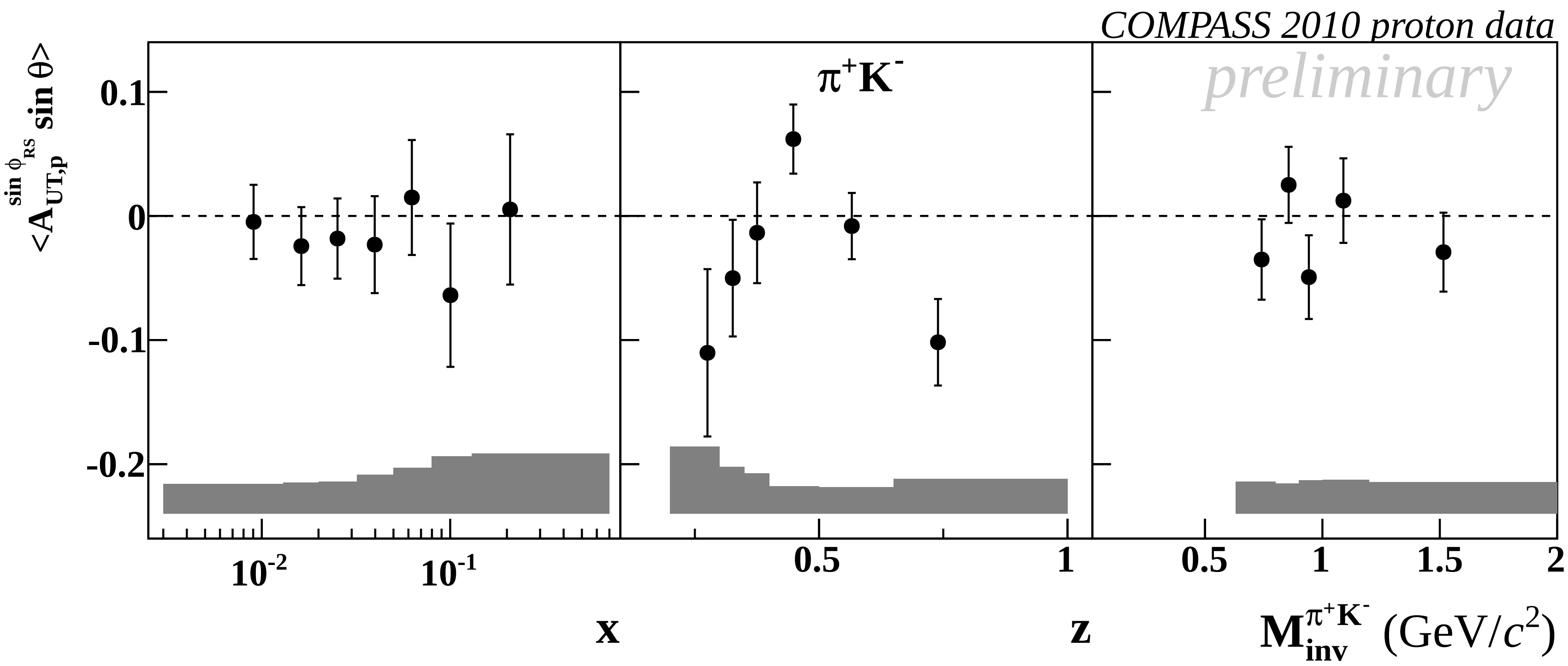


↪ no clear trend & compatible with 0 within the statistical errors
↪ no signal in x and z
↪ M_{inv}: negative mean value

$A_{UT}^{\sin\Phi_{RS}}$ ▶ π^+K^- pairs ▶ 2010 data

Twist-2 $A_{UT}^{\sin\Phi_{RS}}$ h_1^q

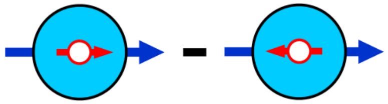


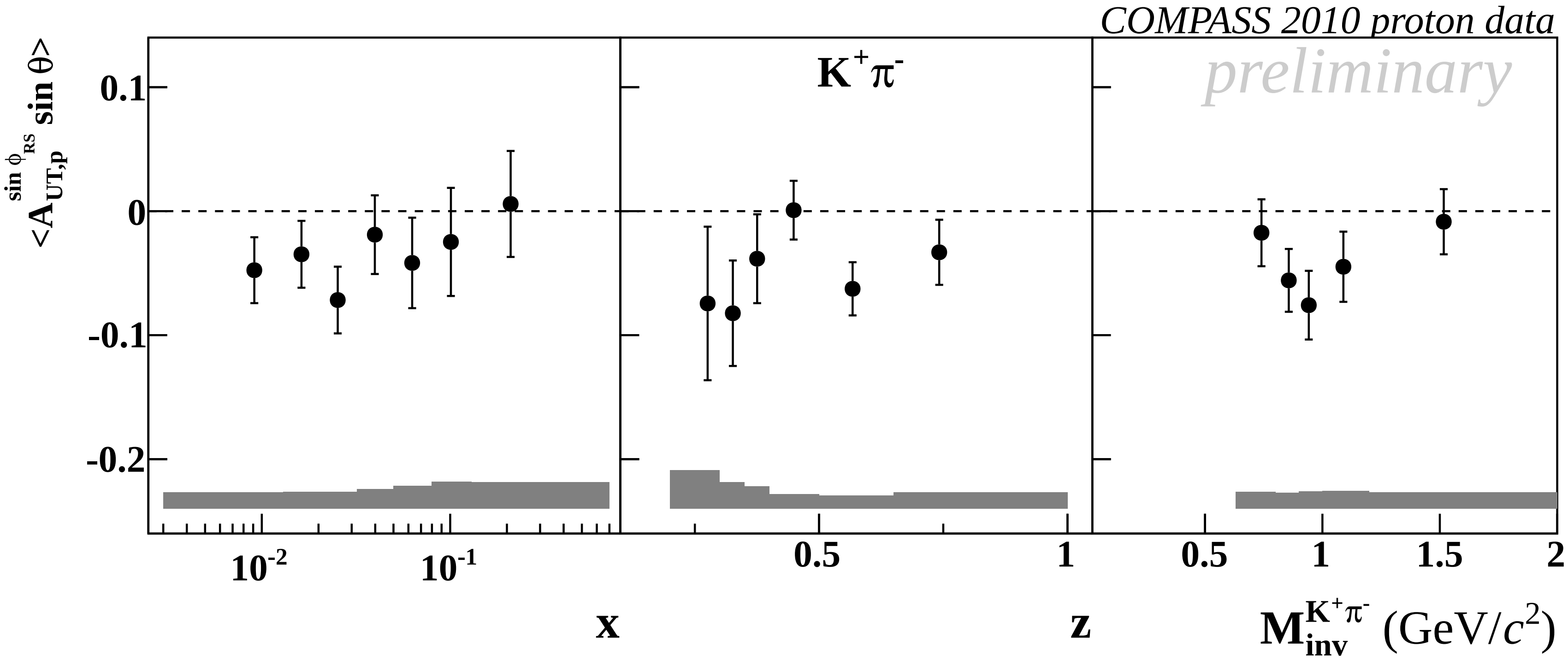


↪ no clear trend & compatible with 0 within the statistical errors
↪ x: no signal
↪ z: negative mean value with positive peak around 0.45
↪ M_{inv}: no signal

$A_{UT}^{\sin\Phi_{RS}}$ ▶ $K^+\pi^-$ pairs ▶ 2010 data

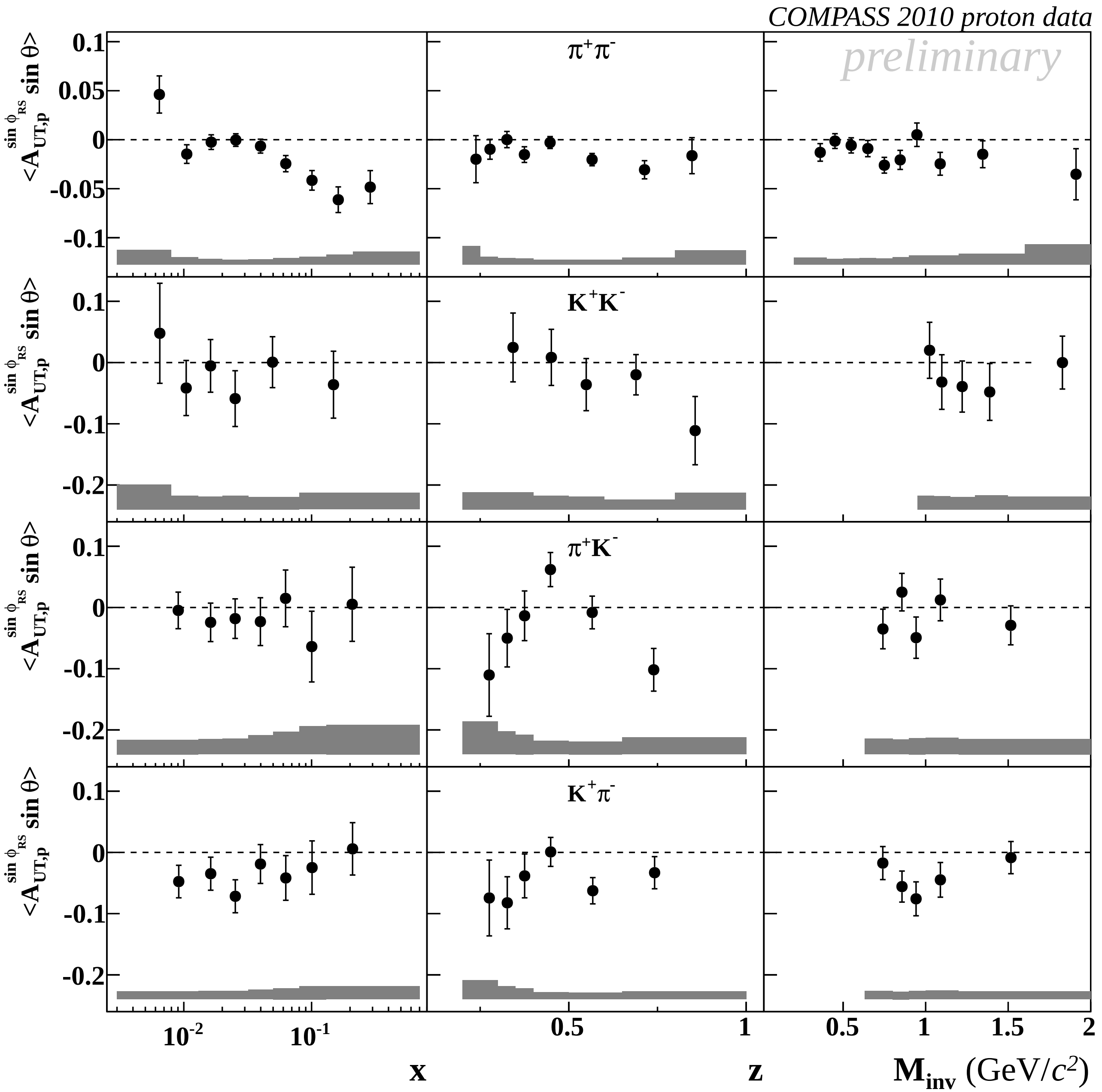
Twist-2 $A_{UT}^{\sin\Phi_{RS}}$ h_1^q



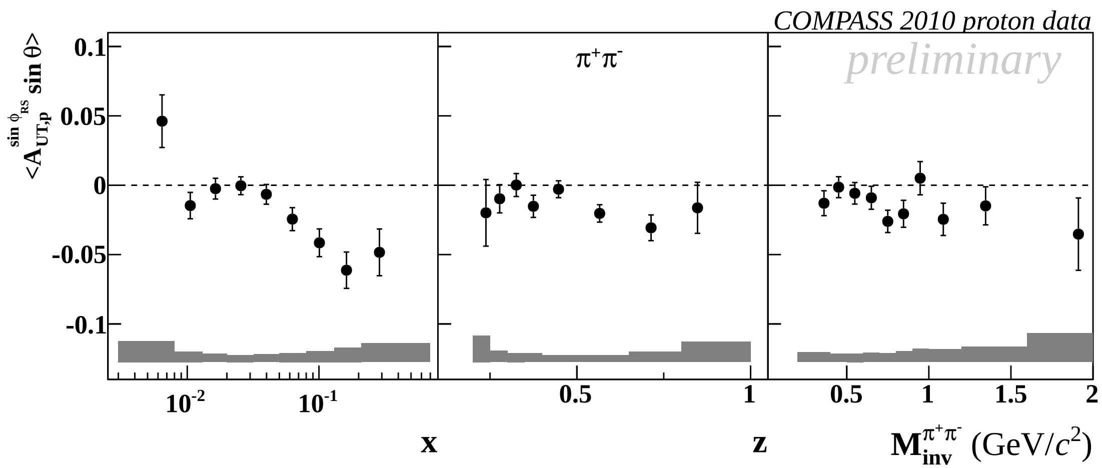


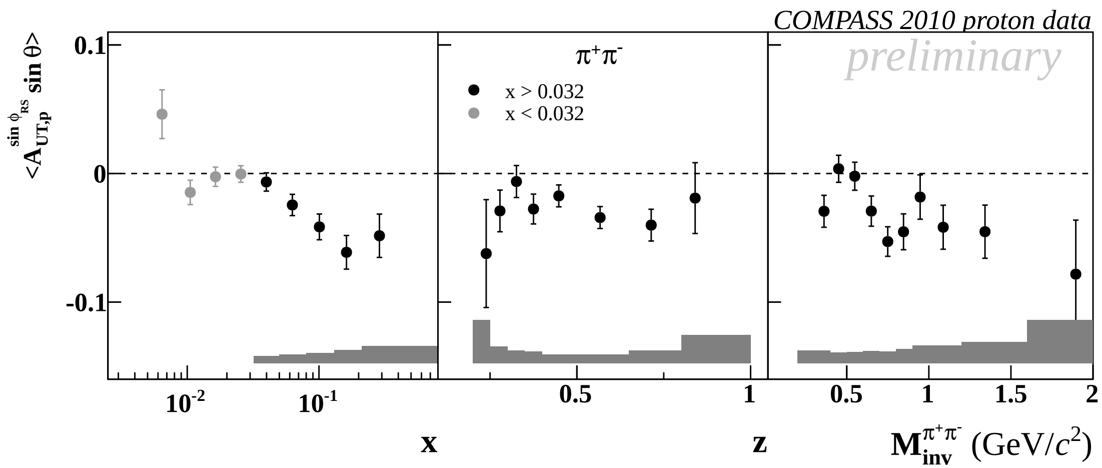
↪ compatible with 0 within the statistical errors ↪ x: negative mean value
↪ z: negative mean value
↪ M_{inv}: negative peak peak around 0.9 GeV/c^2

$A_{UT}^{\sin\Phi_{RS}}$ ▶ identified pairs ▶ 2010 data



$A_{UT}^{\sin\Phi_{RS}}$ ▶ $\pi^+\pi^-$ valence region ▶ 2010 data

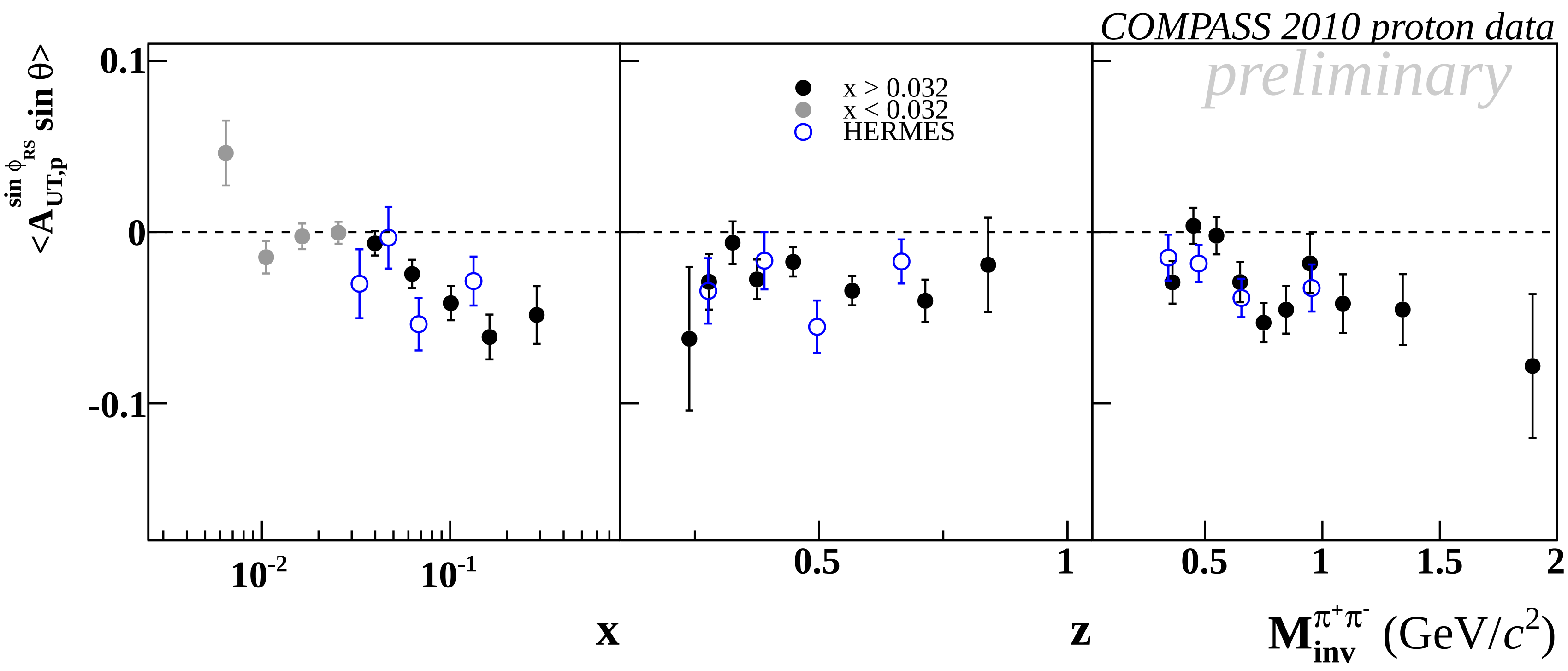




$\hookrightarrow \pi^+\pi^-$ valence region $x_{bj} > 0.032$

clear signal around ρ^0 mass is pronounced in valence region sample

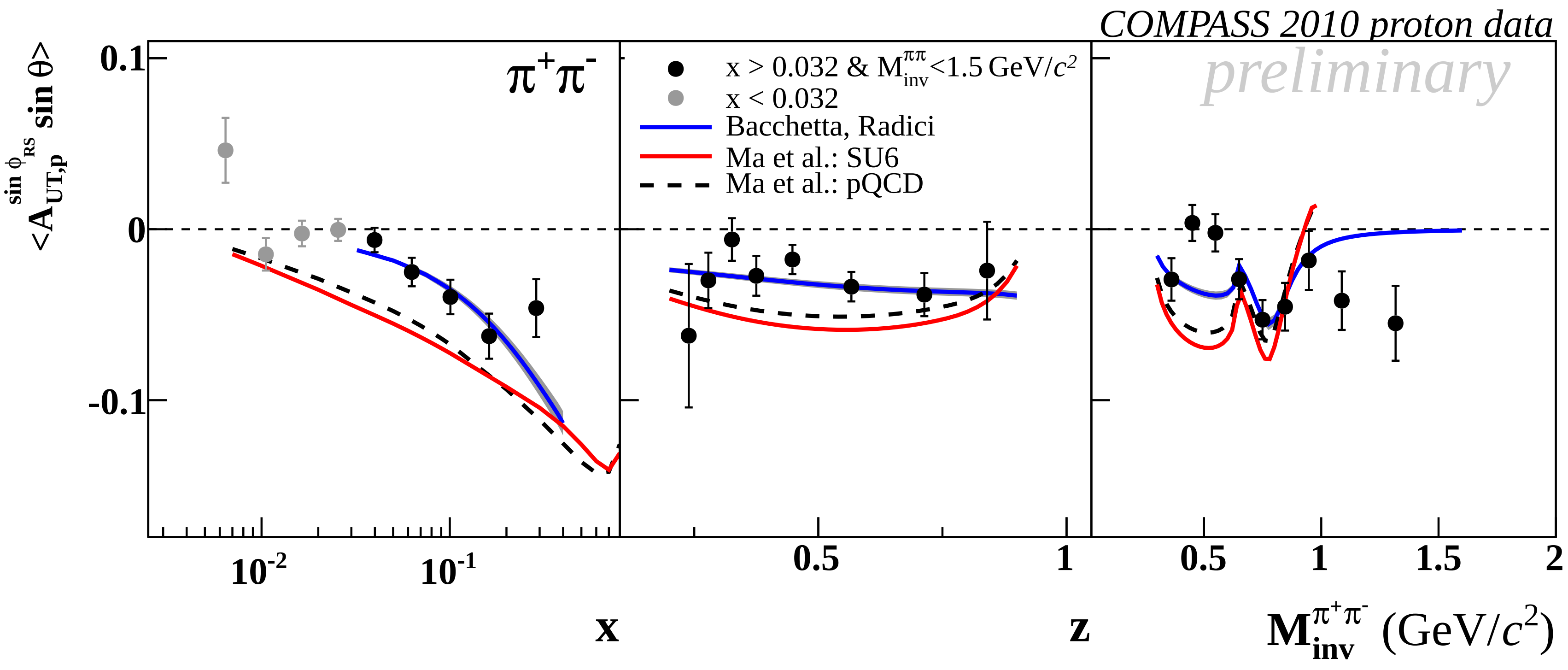
$A_{UT}^{\sin\Phi_{RS}}$ ▶ $\pi^+\pi^-$ ▶ HERMES *vs.* COMPASS data



Airapetian *et. al.*, JHEP, **06** (2008) 017 scaled with $\frac{1}{D_{nn}}$ and sign changed

↪ Good agreement of COMPASS $\pi^+\pi^-$ data, with its higher precision, with HERMES $\pi^+\pi^-$ data within the error bars

$A_{UT}^{\sin\Phi_{RS}}$ ▸ $\pi^+\pi^-$ valence region ▸ COMPASS *vs.* model predictions



Bachetta *et al.*, hep-ph/0608037
Ma *et al.*, arXiv:0711.0817

↪ x_{bj}: *Ma* trend confirmed | *Bachetta* good agreement
↪ z: compatible within the errors
↪ M_{inv}: good agreement around ρ^0 mass

Conclusions

- Clear signals of Collins and Sivers asymmtries on proton target for charged and identified hadrons
- Interesting kinematical dependences for different z and y ranges
- New inputs to study Q^2 evolution and for the extraction of Transversity and Sivers PDFs
- Six beyond-Collins-and-Sivers transverse spin asymmetries on proton and deuteron
- Non-zero trend for the $A_{LT}^{\cos(\phi_h-\phi_S)}$ and $A_{UT}^{\sin\phi_S}$ amplitudes
- Interesting kinematical dependencies of unpolarized asymmetries investigated in the x, z and p_T^h grid
- For the first time COMPASS proton data on transverse spin asymmetries in identified dihadron production
  - $\pi^+\pi^-$ also measured by HERMES
  - K^+K^-, π^+K^- and $K^+\pi^-$ never measured before
- Important new input for the extraction of the Transversity PDF

Outlook

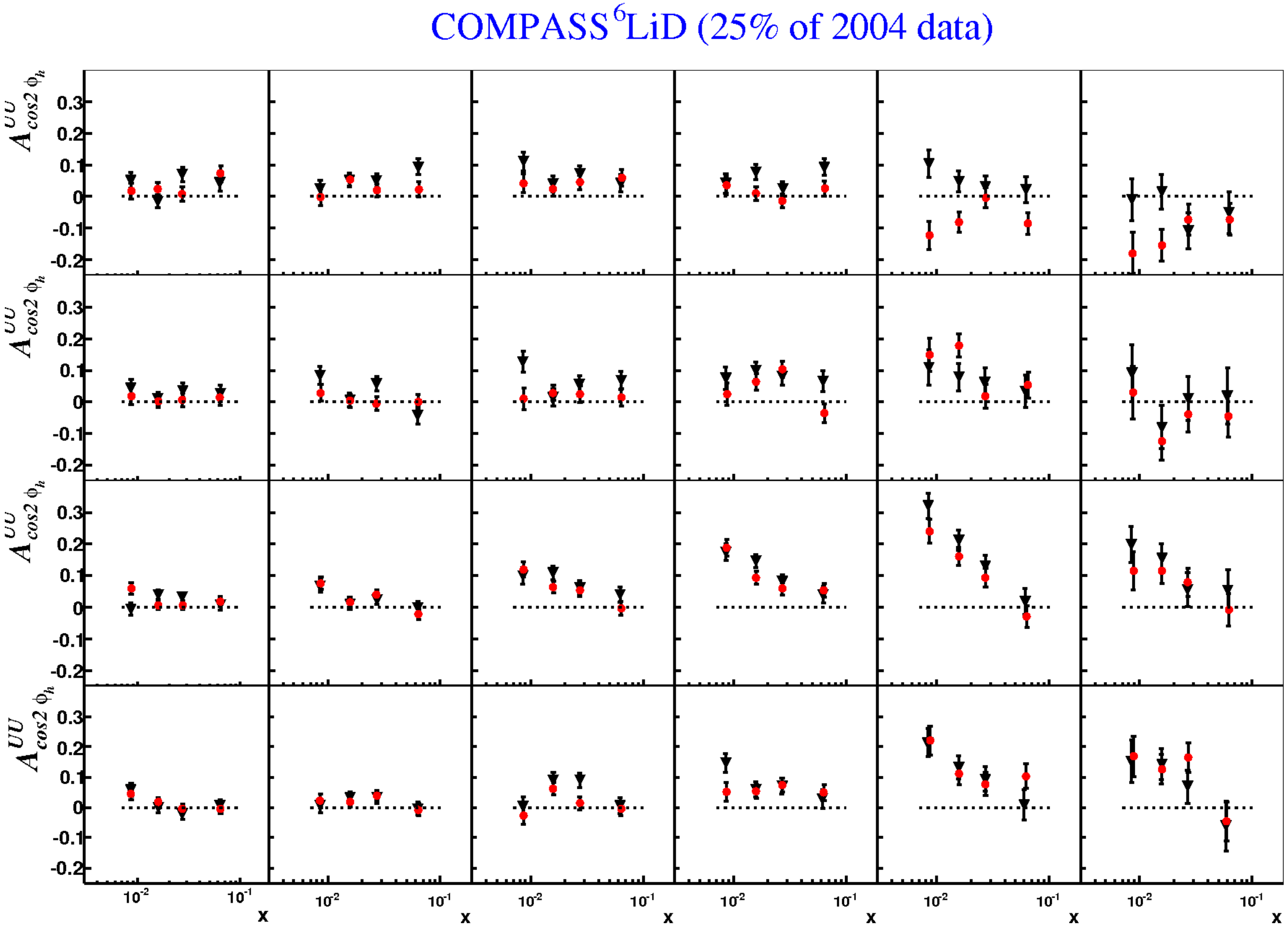
- Multi-dimensional analysis in x, z, p_T^h and Q^2 using proton data
- Possible measurements with:
  - transversely polarized proton target at 100 GeV/c to further investigate on Q^2 evolution
  - transversely polarized deuteron target to improve the extraction of u and d quarks PDFs
- Other six asymmetries for pions and kaons
- New measurement starting from 2015 of the unpolarized azimuthal asymmetries at COMPASS II with a LH-target in parallel to DVCS
- Combined 2007/2010 results on identifed dihadron asymmetries

Thank you for your attention!

electronic address: christopher.braun@cern.ch

Back up

A_{UU2} ▶ charged hadrons ▶ 2004 data preliminary



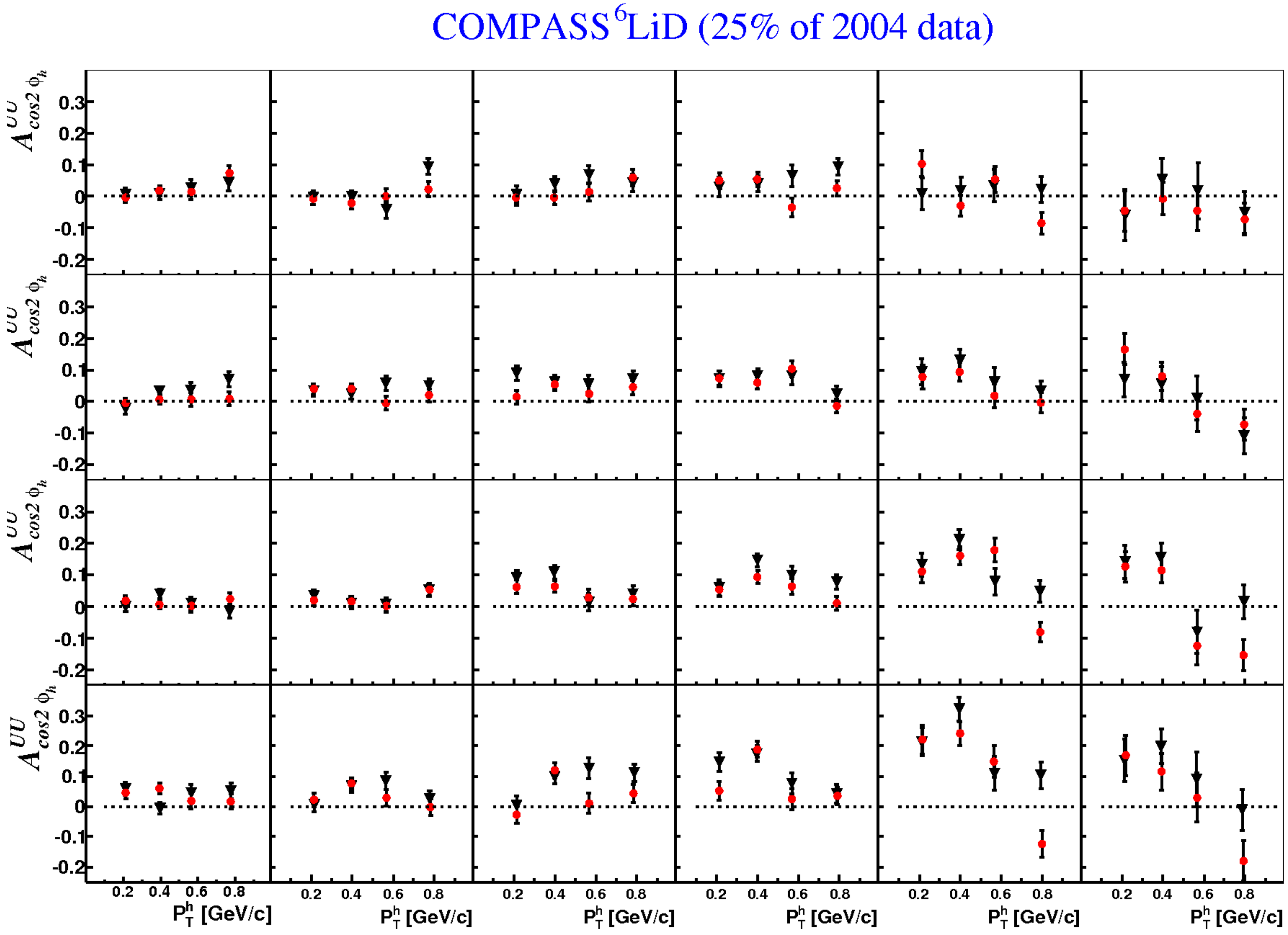
$\uparrow p_T^h; \rightarrow z$ $\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ largest difference between h^+ and h^- at large p_T^h

$\hookrightarrow$ x trend changes going from small to large z values

same as for $A_{UU}^{\cos\Phi_h}$

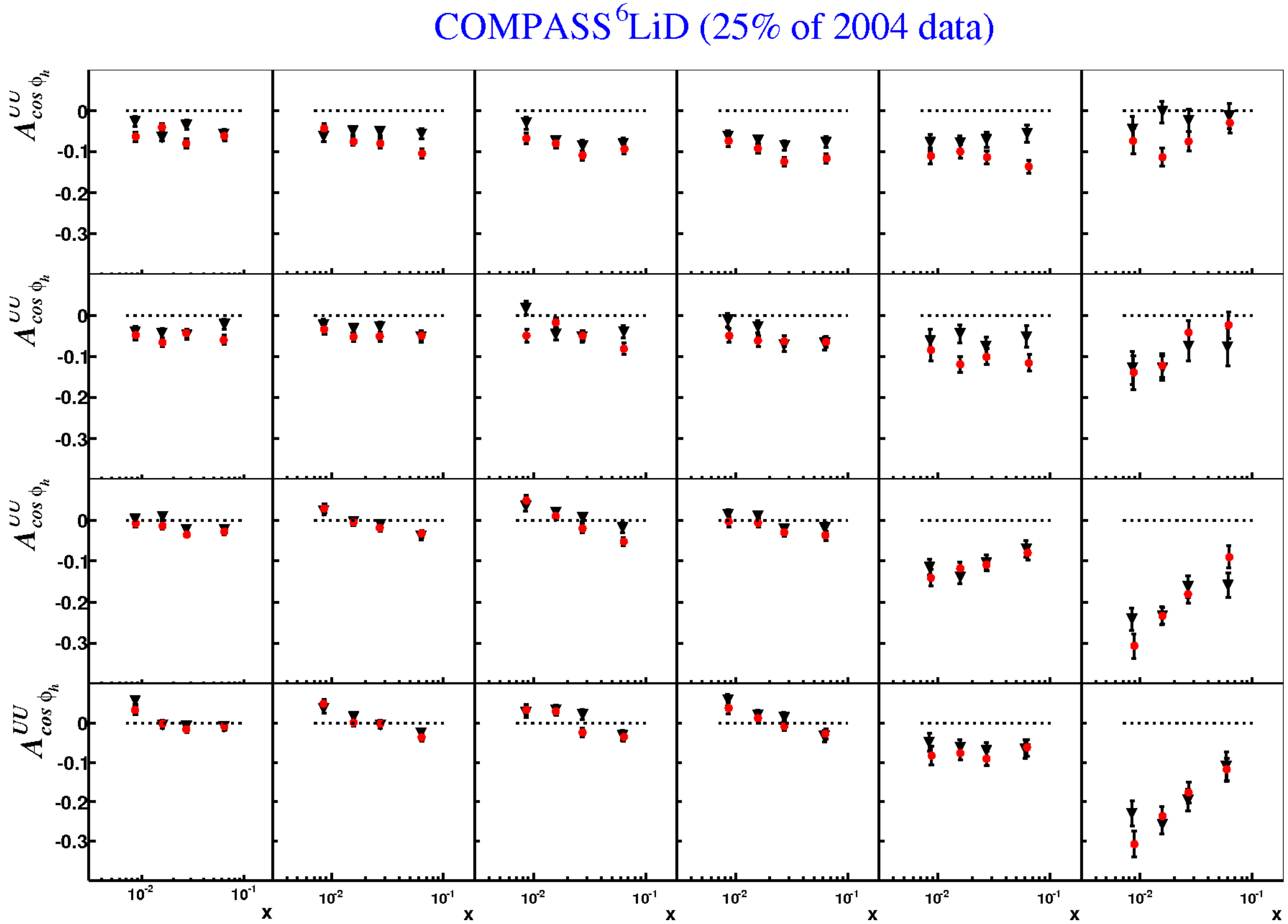
A_{UU2} ▶ charged hadrons ▶ 2004 data preliminary



$\uparrow x; \rightarrow z$ $\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ p_T^h trend changes going from small to large z values
$\hookrightarrow$ The p_T^h trend, which is difficult to reproduce by models originates form large z and low x

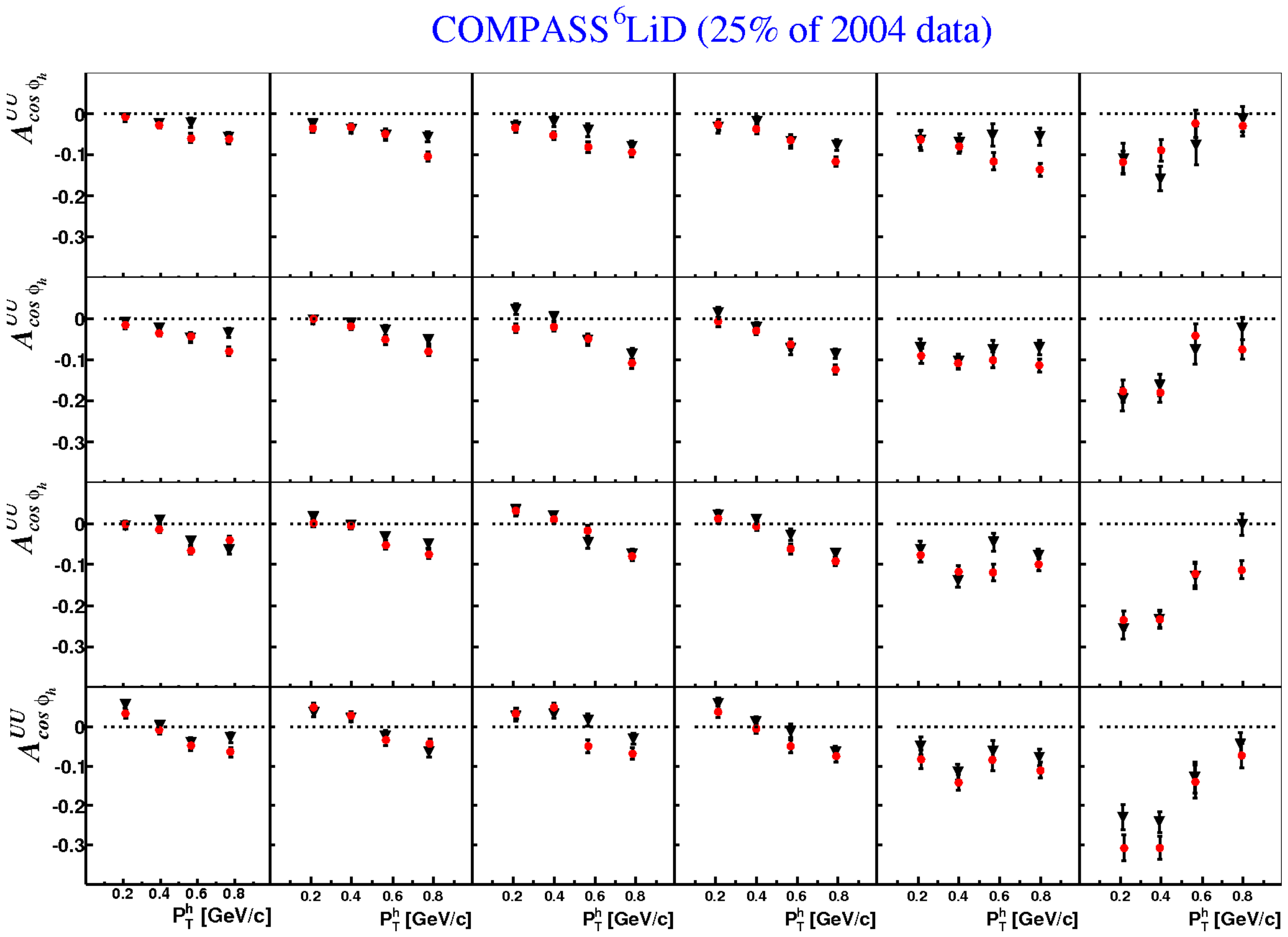
A_{UU1} ▶ charged hadrons ▶ 2004 data preliminary



$\uparrow p_T^h; \rightarrow z$ $\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ largest difference between h^+ and h^- at large p_T^h
$\hookrightarrow$ x trend changes going from small to large z values

A_{UU1} ▶ charged hadrons ▶ 2004 data preliminary

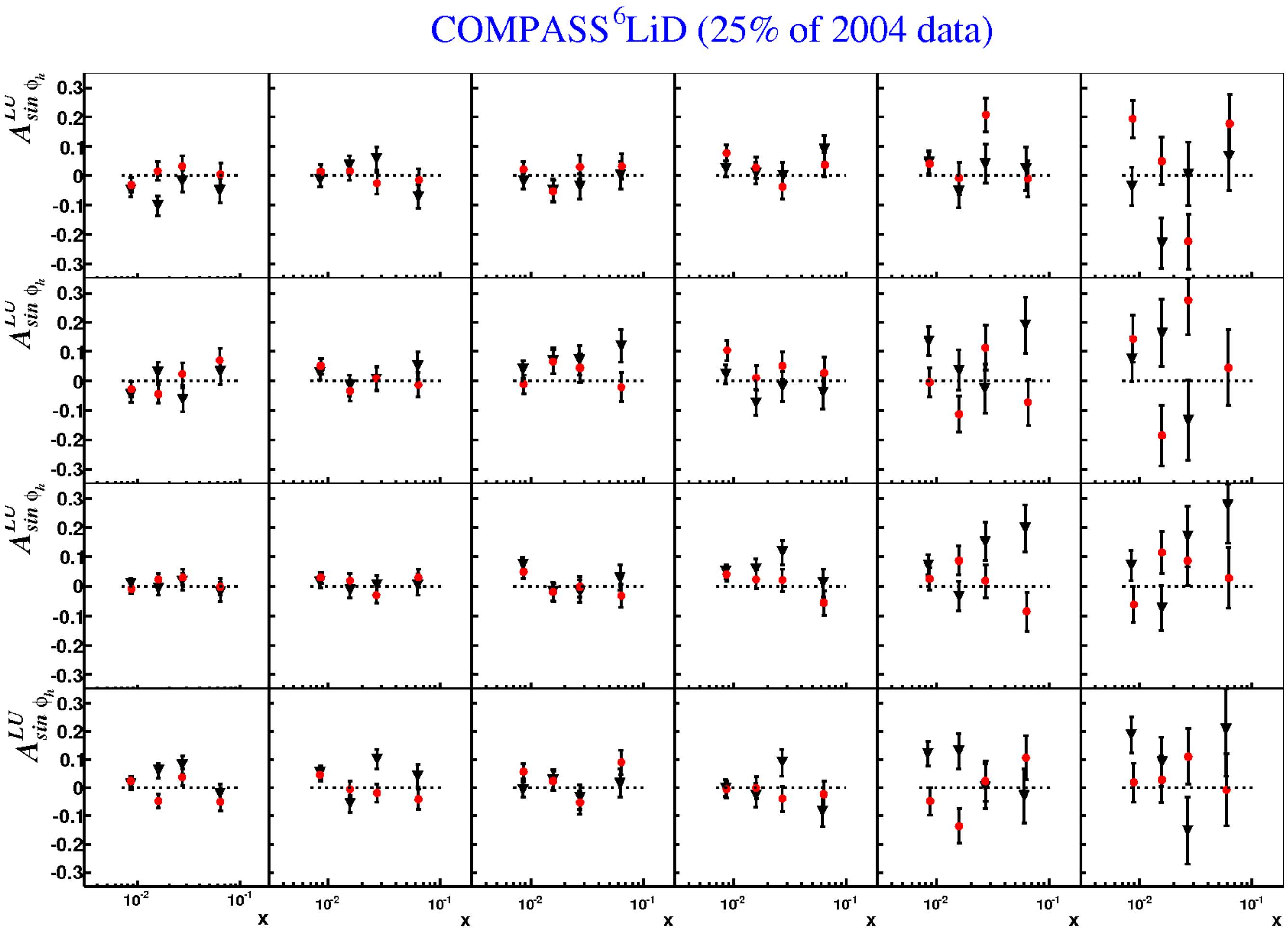


↑ x; → z

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

↪ p_T^h trend changes going from small to large z values
↪ roughly same trend for all x intervals

A_{LU} ▶ charged hadrons ▶ 2004 data preliminary

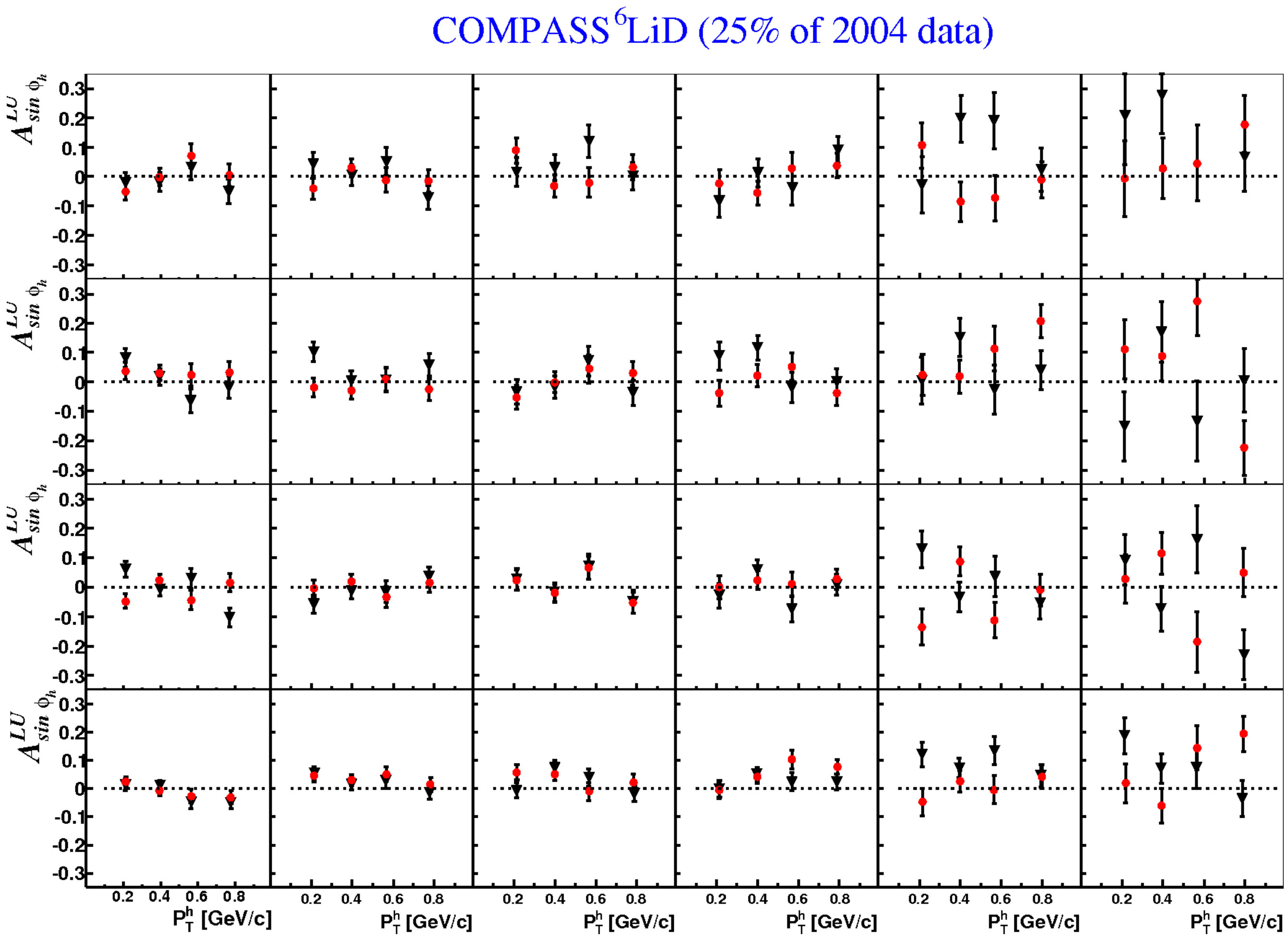


$\uparrow p_T^h; \rightarrow z$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ no significant signal within the uncertainties

A_{LU} ▶ charged hadrons ▶ 2004 data preliminary

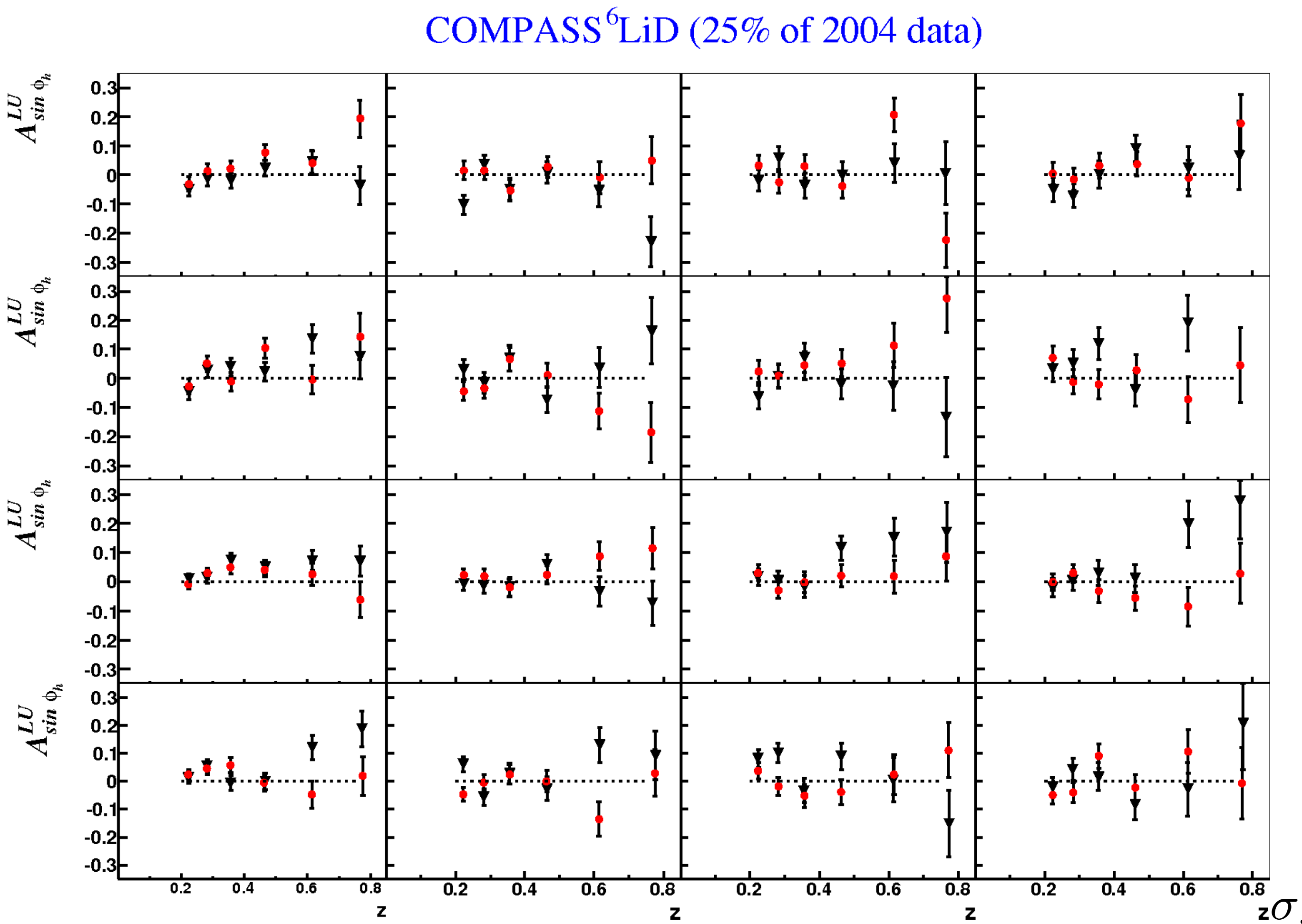


$\uparrow x; \rightarrow z$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

$\hookrightarrow$ some opposite trend for negative and positive charged hadrons visible

A_{LU} ▶ charged hadrons ▶ 2004 data preliminary

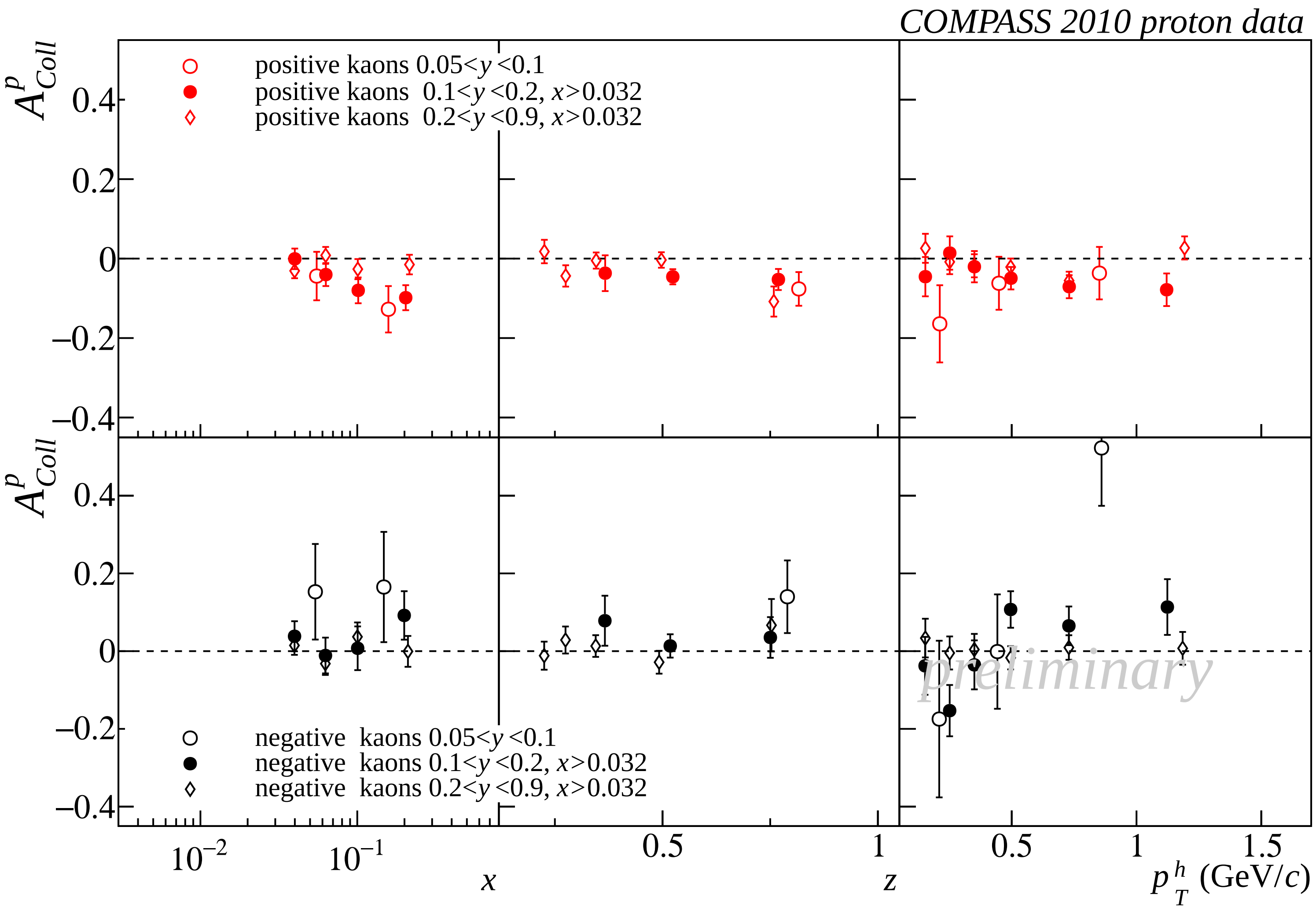


$\uparrow p_T^h; \rightarrow x$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

↪ some opposite trend for negative and positive charged hadrons visible

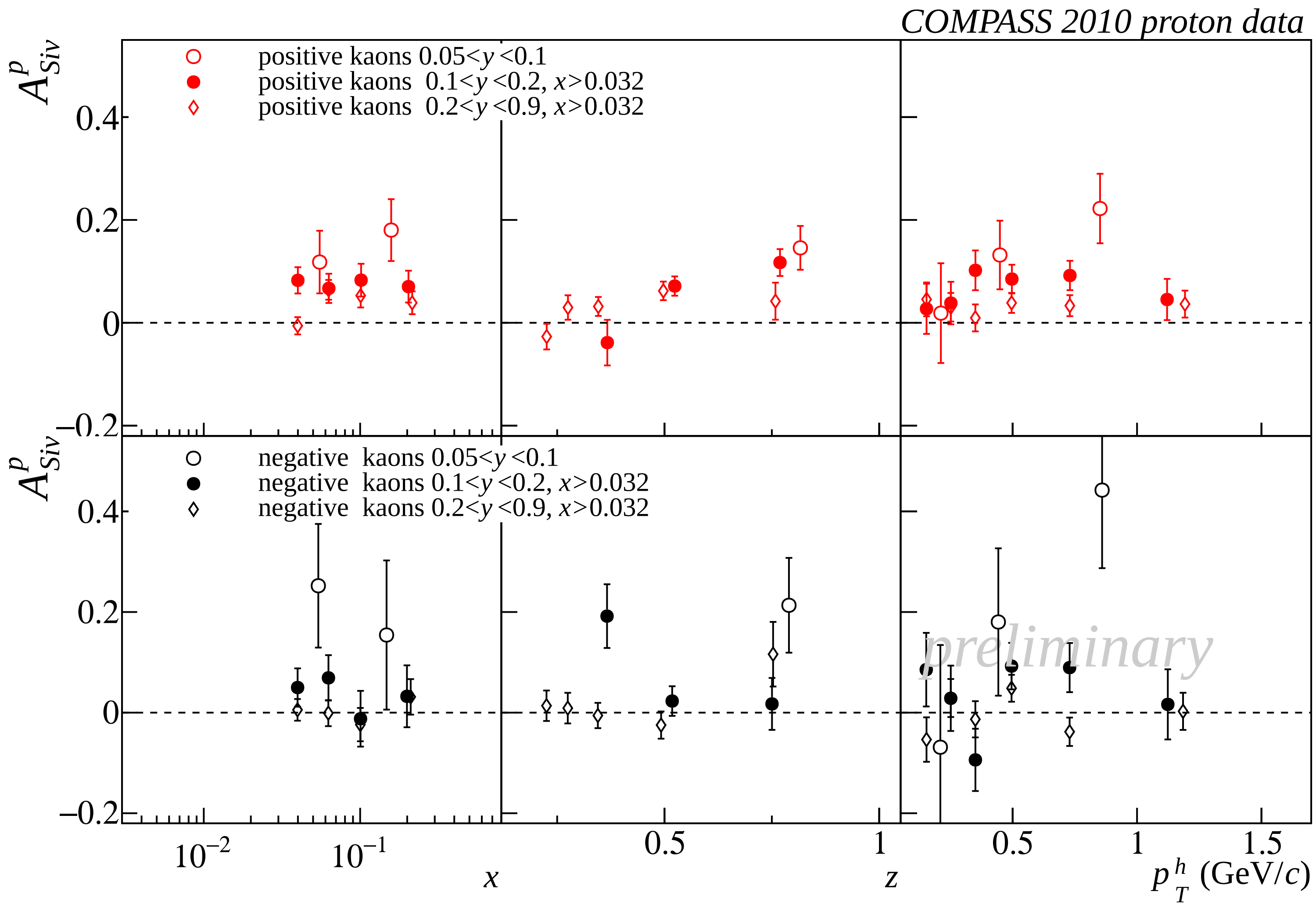
Collins asymmetry ▶ kaons ▶ multi-dimensional analysis in y



3 y ranges: $0.05 < y_{\text{low}} < 0.1 < y_{\text{mid}} < 0.2 < y_{\text{high}} < 0.9$

↪ no significant systematic effect *w.r.t.* the uncertainties

Sivers asymmetry ▶ kaons ▶ multi-dimensional analysis in y

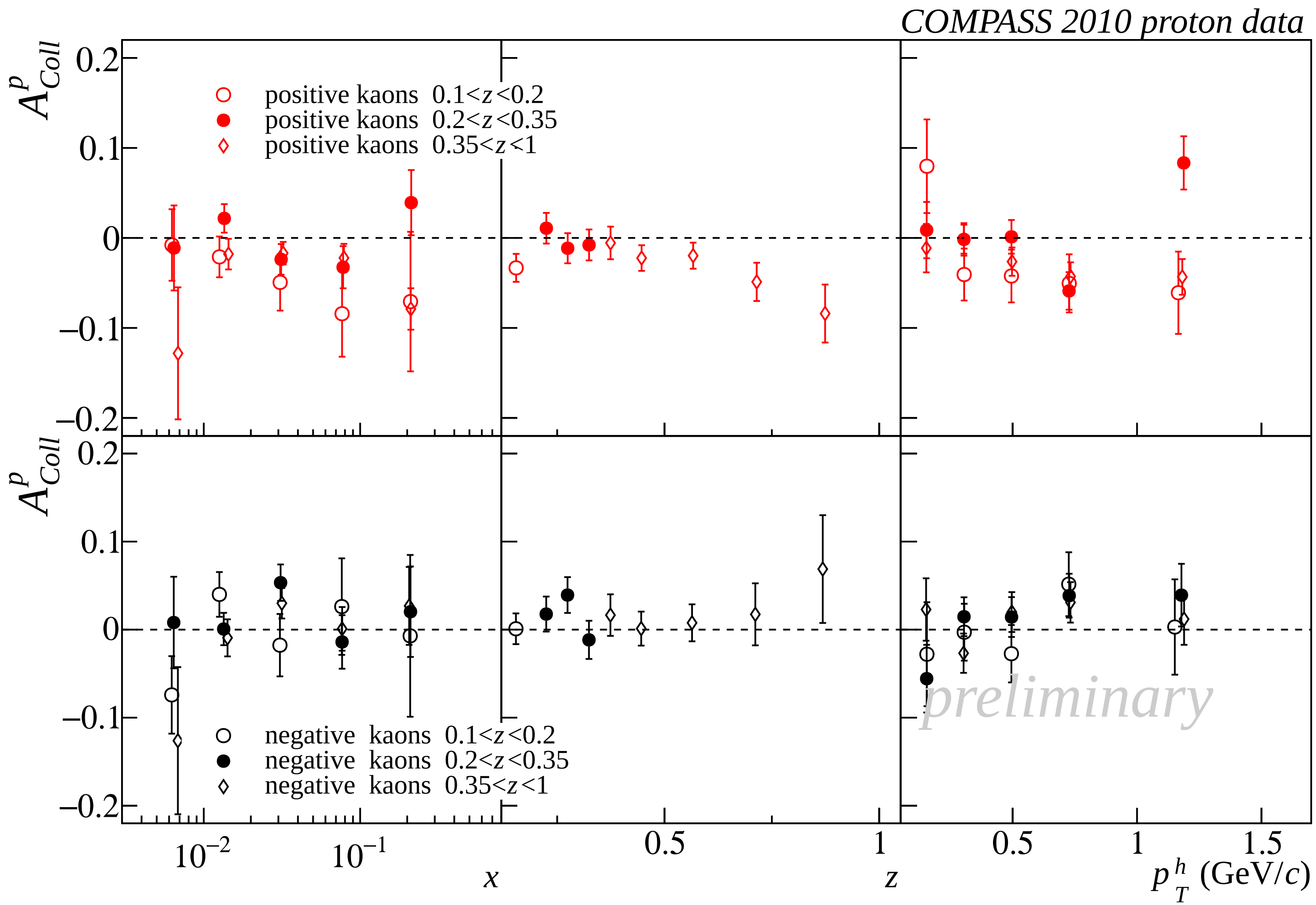


3 y ranges: $0.05 < y_{\text{low}} < 0.1 < y_{\text{mid}} < 0.2 < y_{\text{high}} < 0.9$

$\hookrightarrow$ very low statistics in y_{low} sample

$\hookrightarrow$ y_{mid} sample shows larger asymmetries then y_{high} sample

Collins asymmetry ▶ kaons ▶ multi-dimensional analysis in z

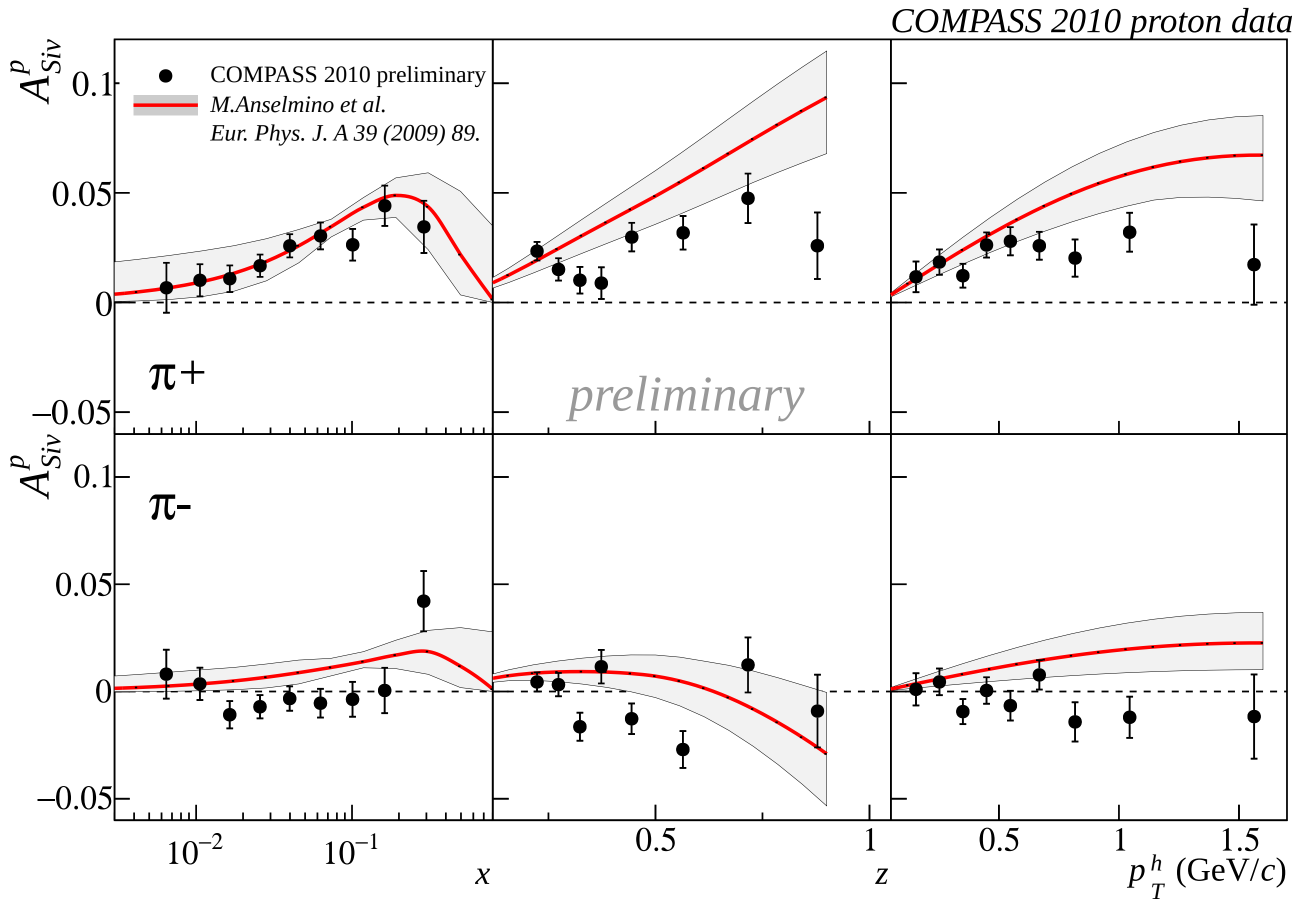


3 z ranges: $0.1 < z_{\text{low}} < 0.2 < z_{\text{mid}} < 0.35 < z_{\text{high}} < 1.0$

↪ larger asymmetries for K^+ in z_{low} region

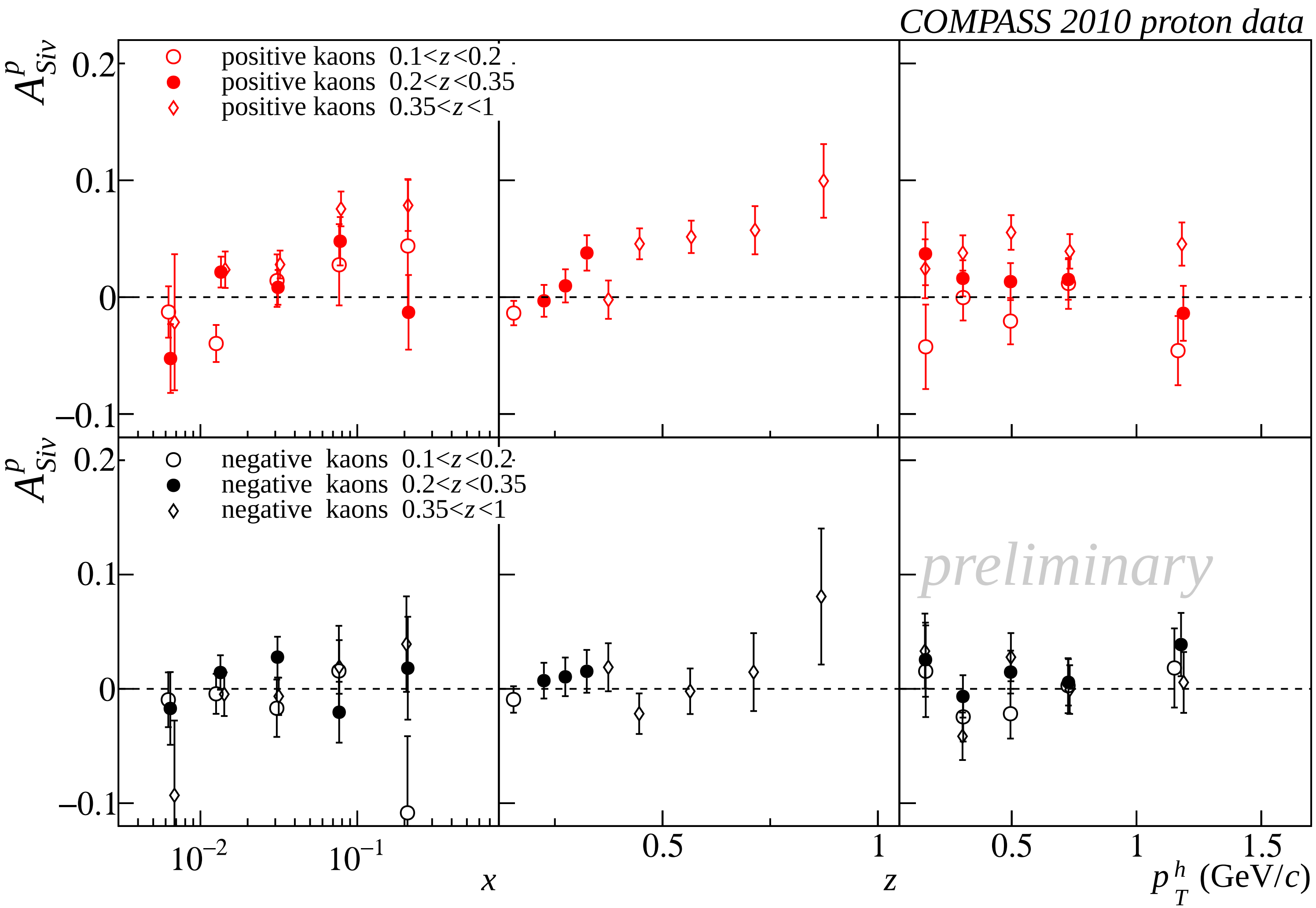
↪ but large statistical uncertainties

Sivers asymmetry ▶ pions ▶ 2010 data *vs.* model predictions



↪ π^+: good agreement in x
↪ π^+: predictions are larger then data for z & p_T^h
↪ π^-: less compatible, indication for opposite sign in x and p_T^h

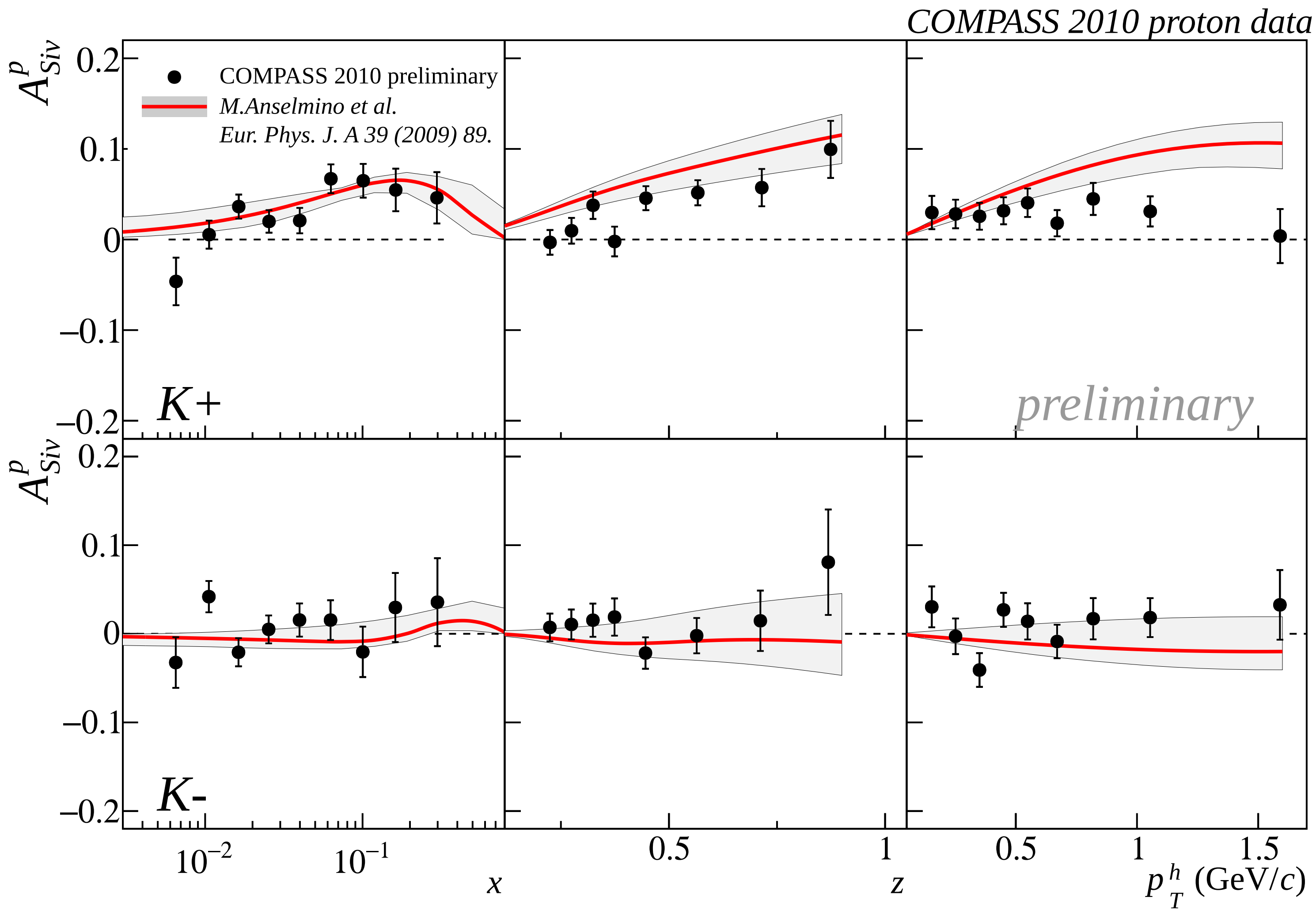
Sivers asymmetry ▶ kaons ▶ multi-dimensional analysis in z



3 z ranges: $0.1 < z_{\text{low}} < 0.2 < z_{\text{mid}} < 0.35 < z_{\text{high}} < 1.0$

$\hookrightarrow$ indication of different sign in p^h_T dependence for low and high z_{low} sample

Sivers asymmetry ► kaons ► 2010 data *vs.* model predictions

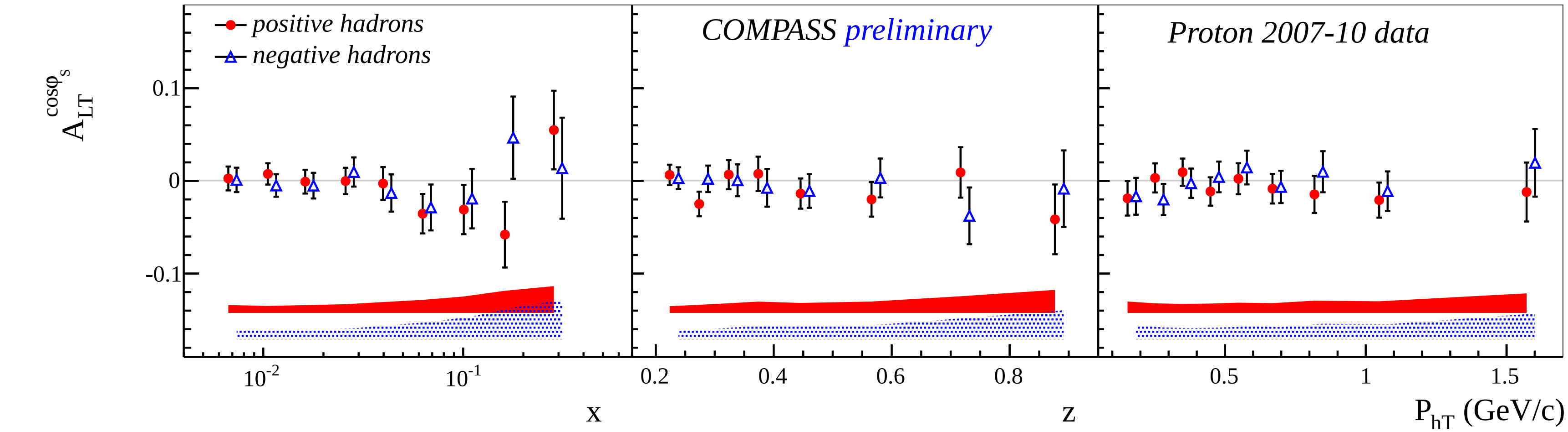


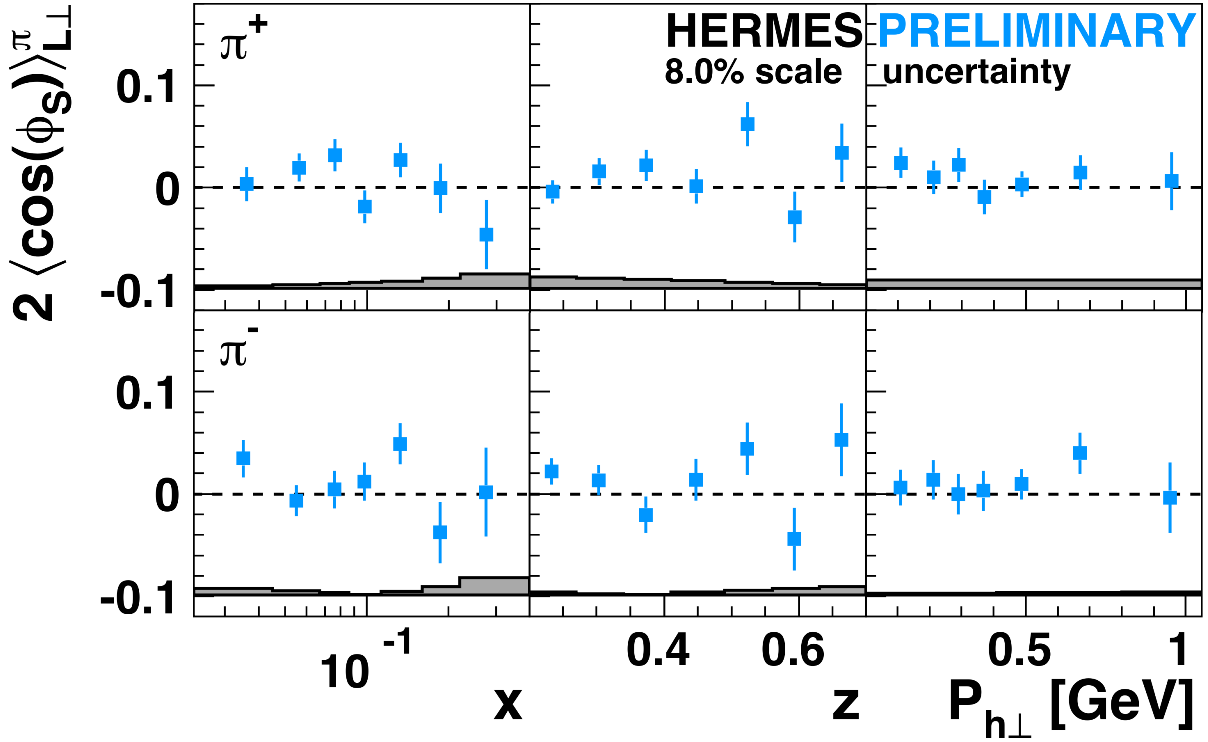
↪ good agreement in x and z within the uncertainties for $K^{+/-}$

↪ K^+: overestimated for p_T^h dependence

↪ K^-: model and data compatible with zero in p_T^h

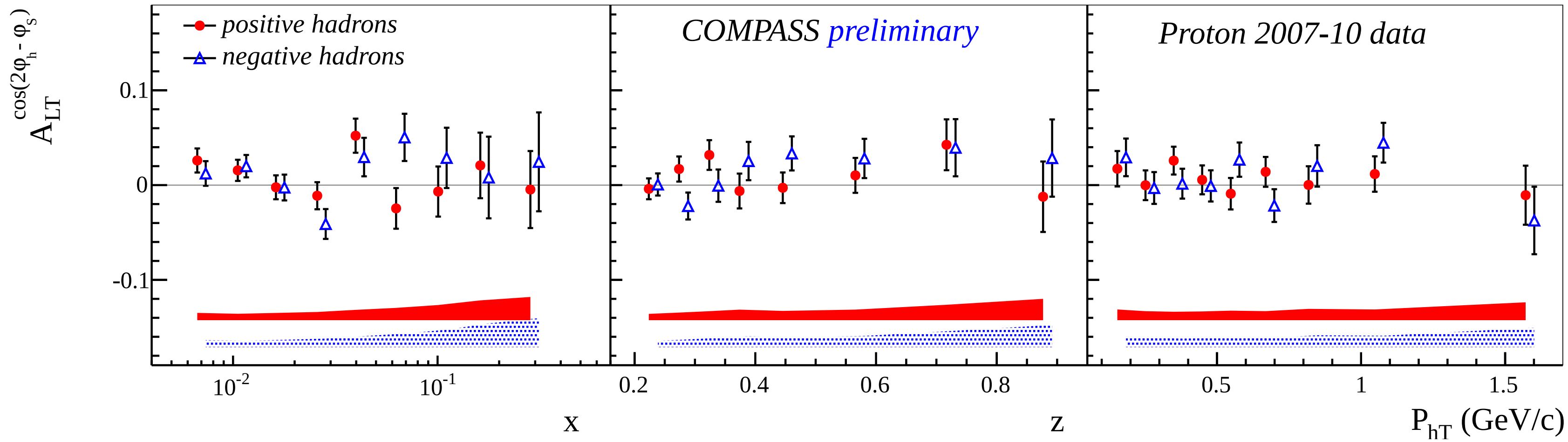
A_{LT1} ▶ charged hadrons ▶ HERMES *vs.* COMPASS

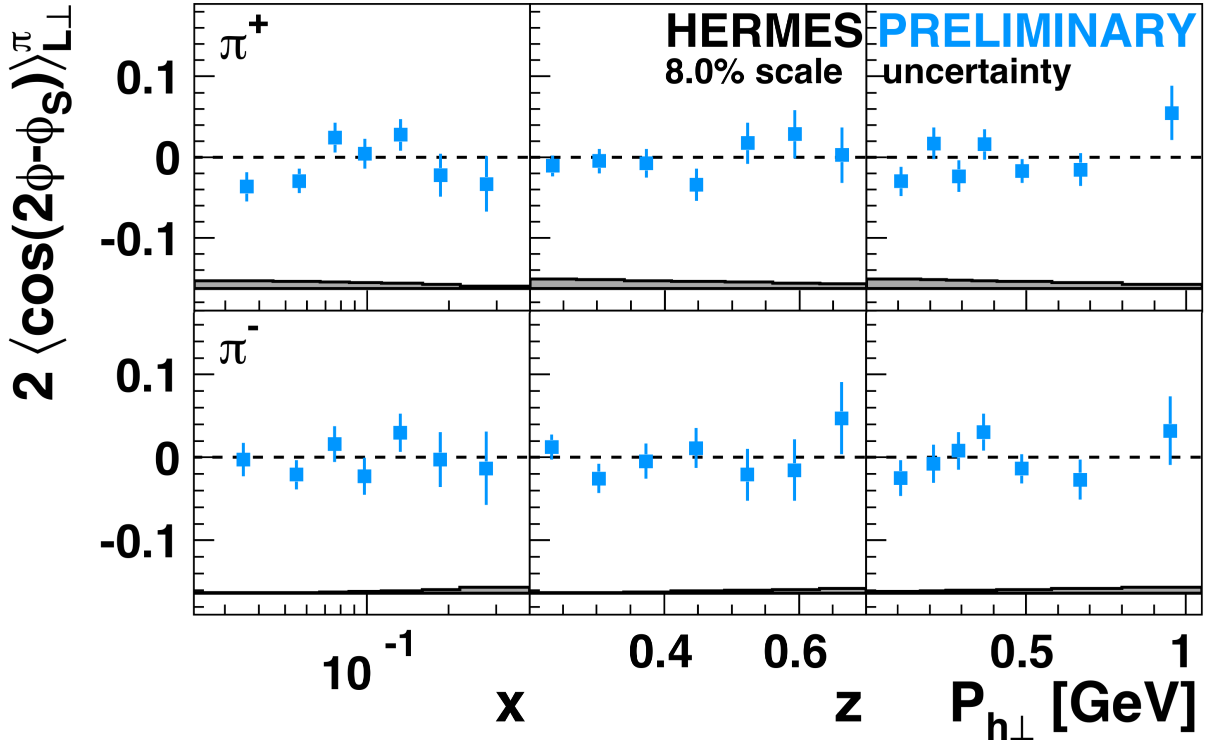




↪ compatible with zero within the uncertainties for both HERMES and COMPASS

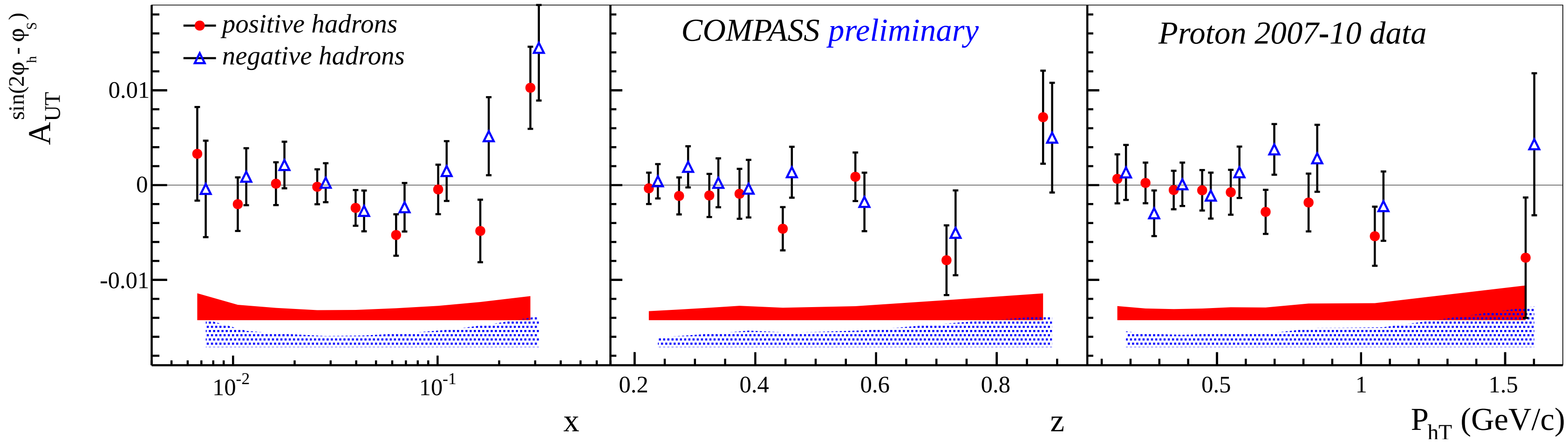
A_{LT2} ▶ charged hadrons ▶ HERMES *vs.* COMPASS

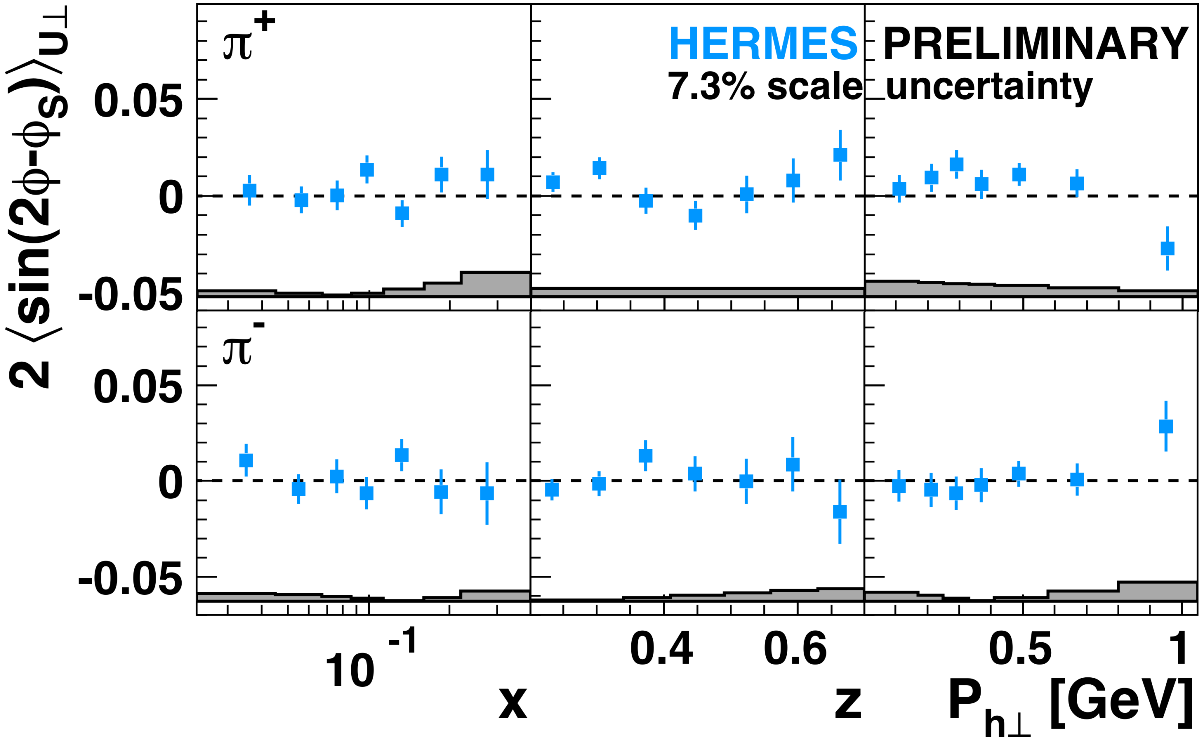




↪ compatible with zero within the uncertainties for both HERMES and COMPASS

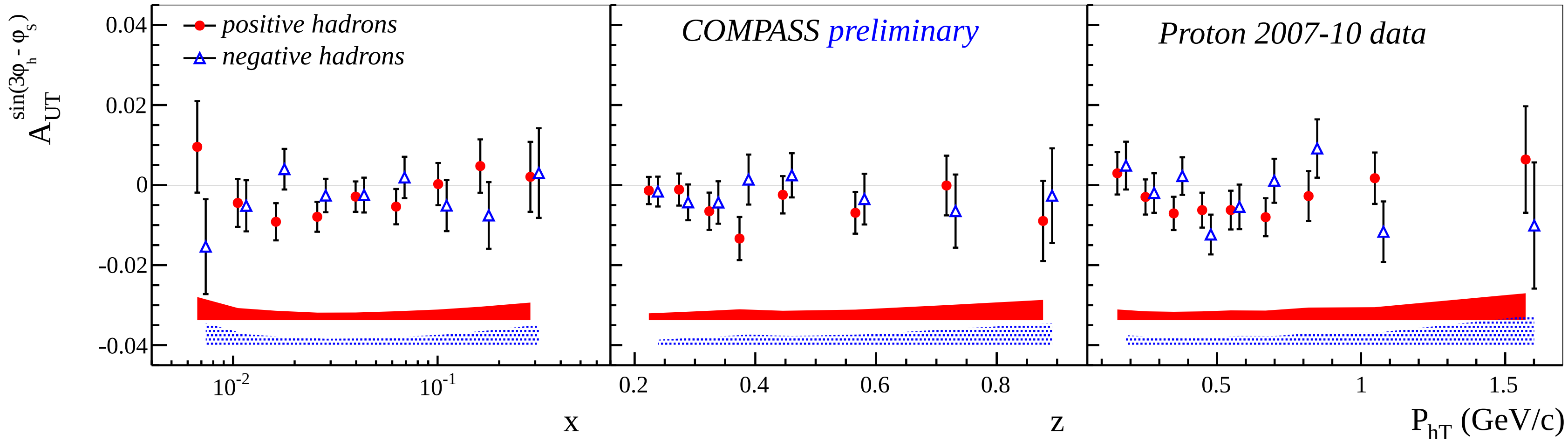
A_{UT2} ▶ charged hadrons ▶ HERMES *vs.* COMPASS

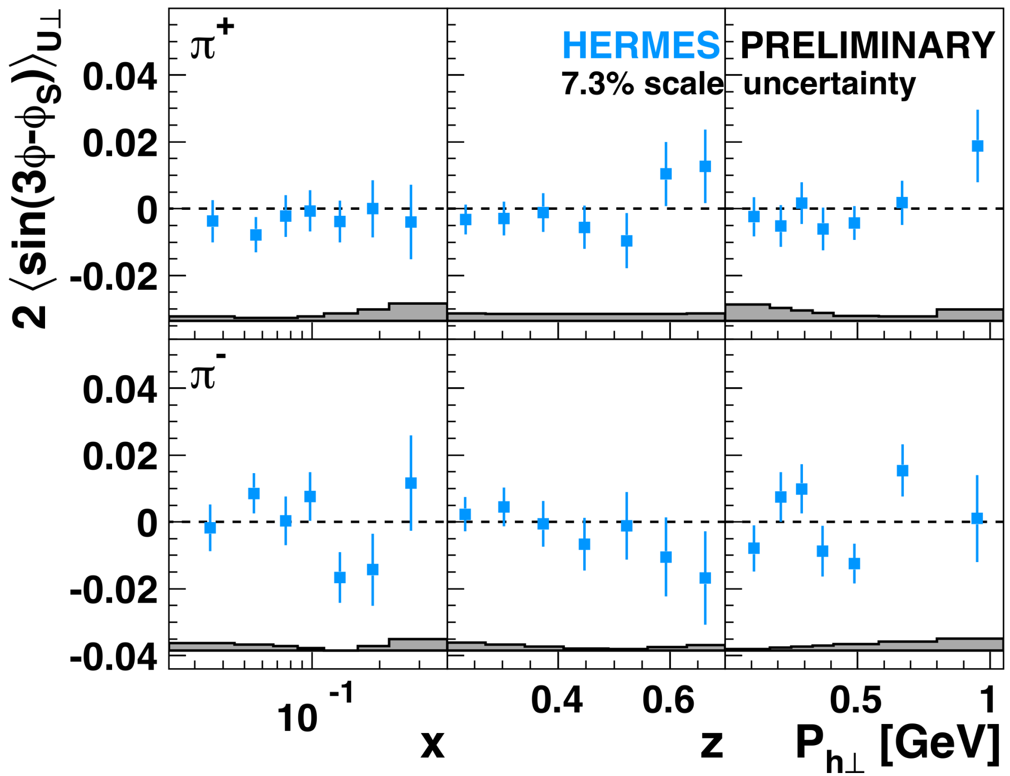




↪ compatible with zero within the uncertainties for both HERMES and COMPASS

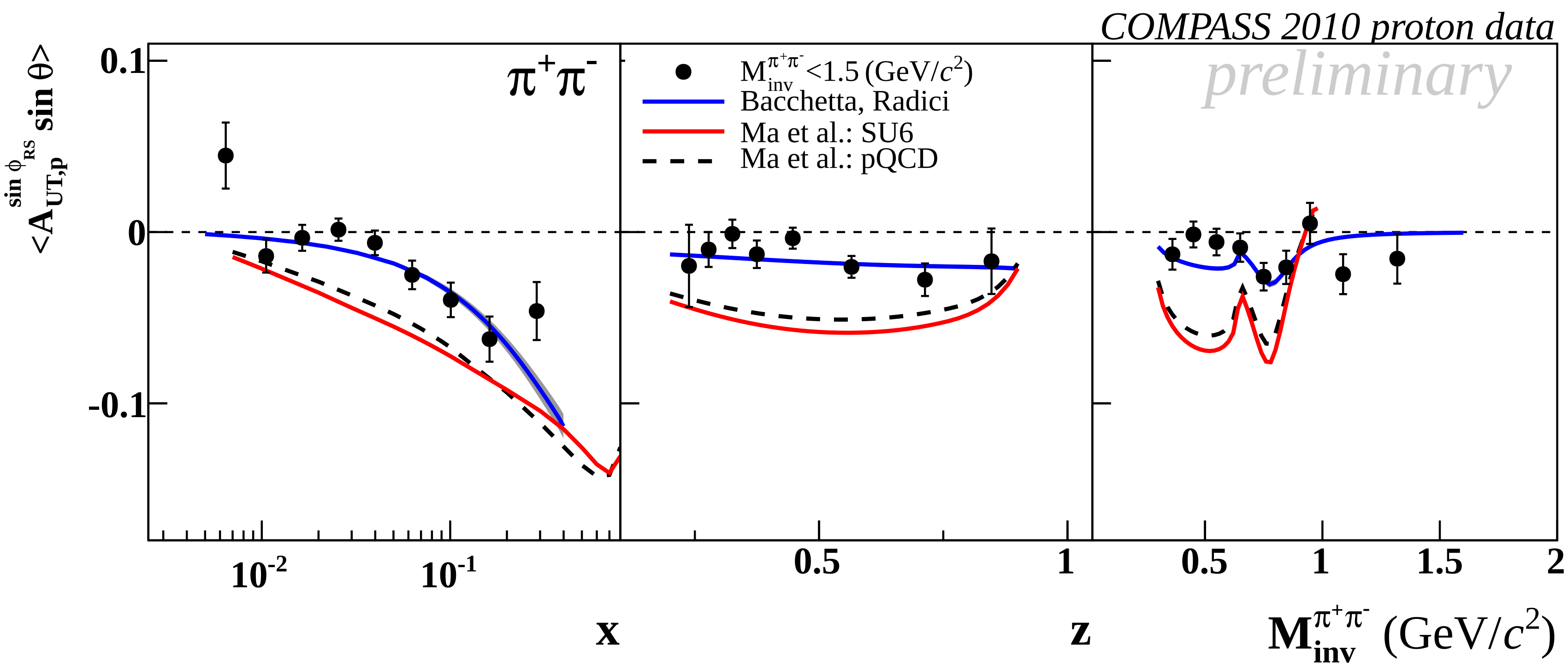
Pretzelosity ▶ charged hadrons ▶ HERMES *vs.* COMPASS





↪ compatible with zero within the uncertainties for both HERMES and COMPASS

$A_{UT}^{\sin\Phi_{RS}}$ ► $\pi^+\pi^-$ ► COMPASS *vs.* model predictions



Bachetta *et al.*, hep-ph/0608037
Ma *et al.*, arXiv:0711.0817

$\hookrightarrow$ x_{bj}: *Ma* trend confirmed | *Bachetta* good agreement
$\hookrightarrow$ z: *Ma* too large | *Bachetta* compatible
$\hookrightarrow$ M_{inv}: *Ma* too large | *Bachetta* good agreement around ρ^0 mass