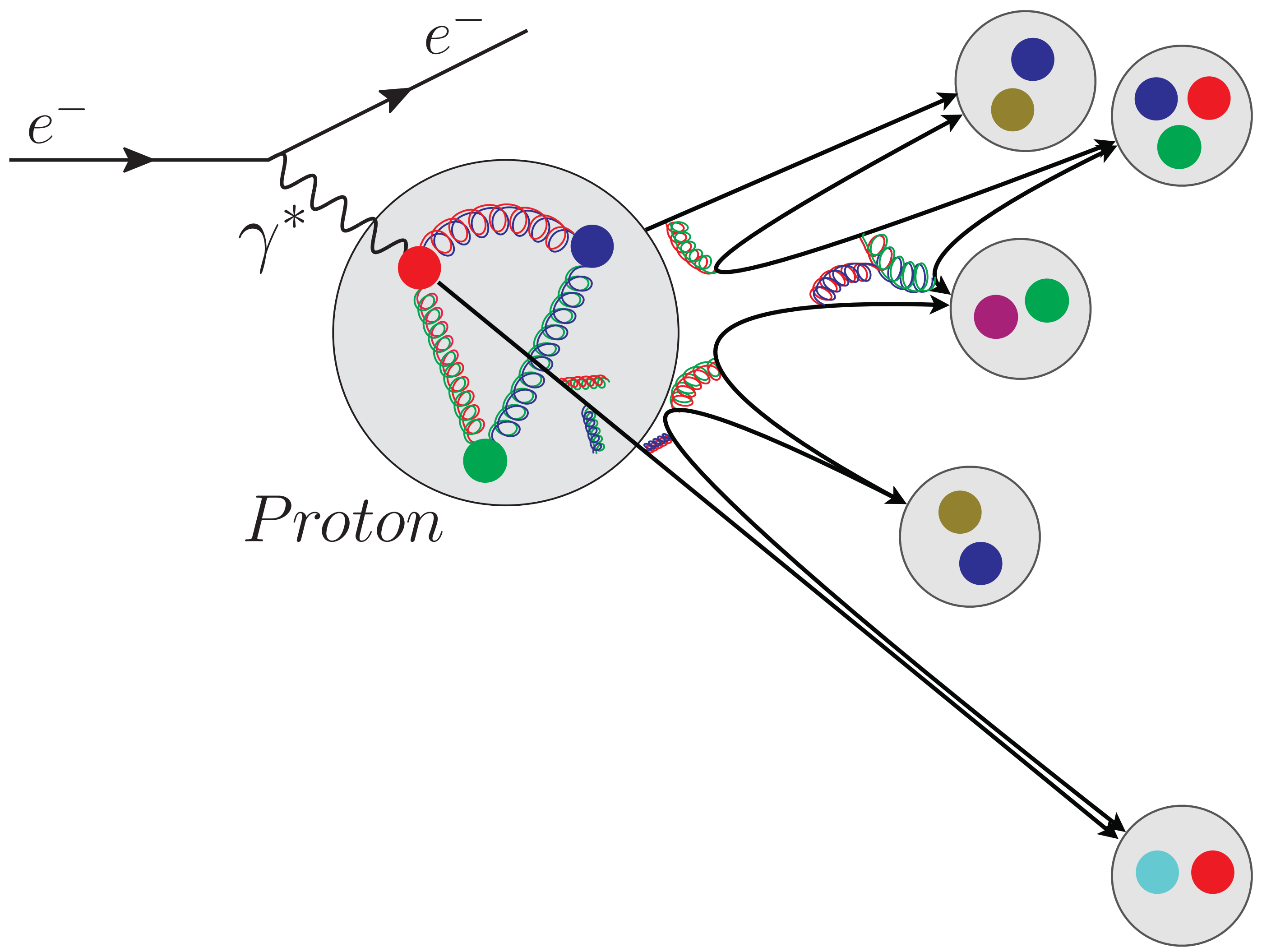
IWHSS 2020



Transverse-momentum distributions from semi-inclusive DIS

Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

disclaimer

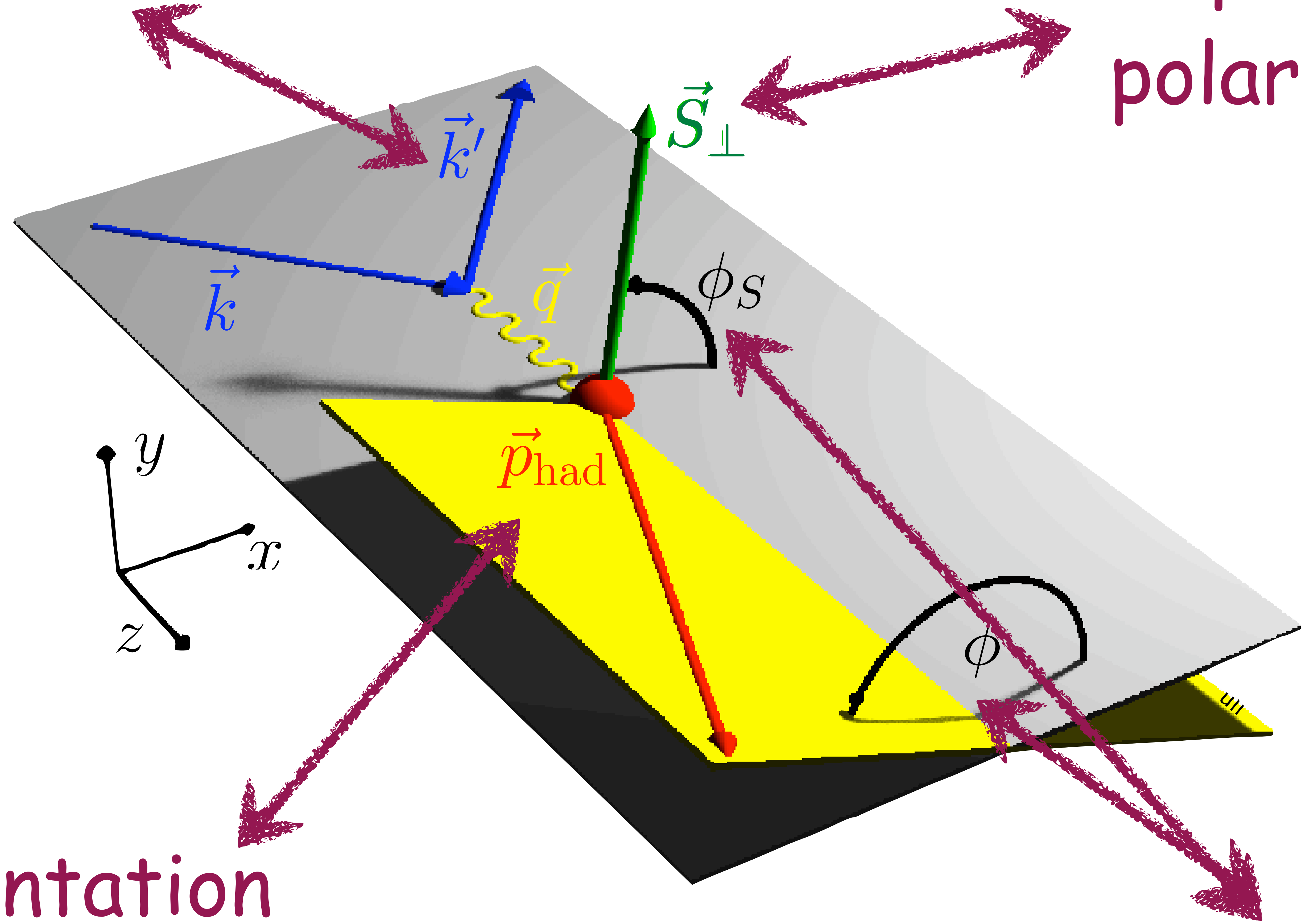
- too many results to cover — personal selection
- concentrate mainly on polarization
  - for COMPASS unpolarized targets:
- clear bias towards latest HERMES papers
  - dedicated talks for COMPASS and JLab …
  - … as well as of future programs
- instead of a comprehensive theory intro, rely on Alessandro's expertise

☛ Jan Matousek (We)

☛ Patrizia Rossi (Tue)
☛ Harut Avagyan (Tue)
☛ Haiyan Gao (Tue)
☛ Marco Contalbrigo (next)

☛ previous talk

one-hadron production (ep→ehX)



parton kinematics

parton
polarization

fragmentation
kinematics

FF selector

Spin-momentum structure of the nucleon

$$\frac{1}{2}\mathrm{Tr}\Big[\left(\gamma^{+}+\lambda\gamma^{+}\gamma_5\right)\Phi\Big] \;=\; \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + \lambda\Lambda\,g_1 + \lambda\,S^i k^i\,\frac{1}{m}\,g_{1T}\Big]$$

$$\frac{1}{2}\mathrm{Tr}\Big[\left(\gamma^{+}-s^j i\sigma^{+j}\gamma_5\right)\Phi\Big] \;=\; \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^i S^i h_1$$

$$+\, s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^i k^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]$$

quark pol.

nucleon pol.

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1,\ h_{1T}^{\perp}$

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

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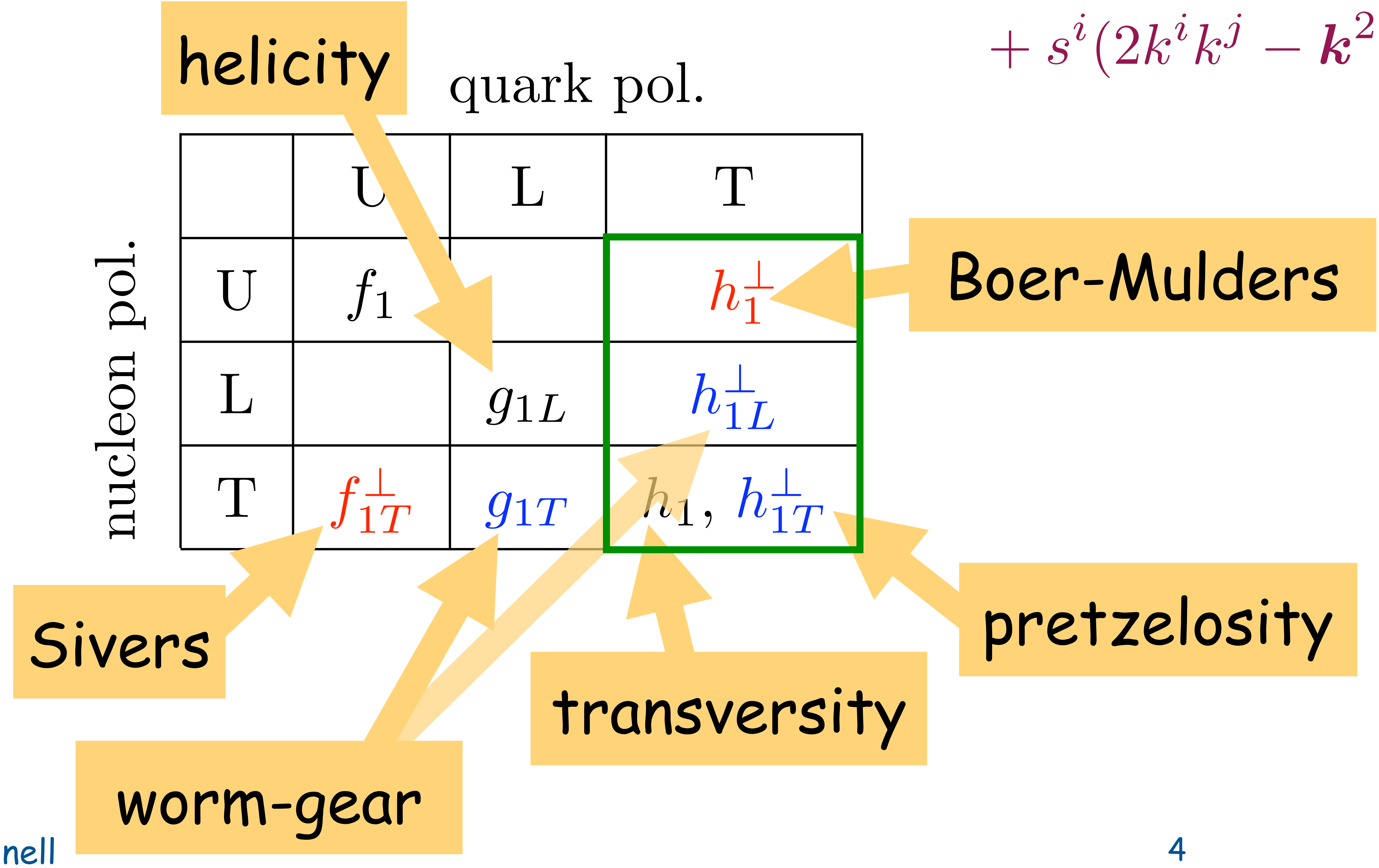

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T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- each TMD describes a particular spin-momentum correlation
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TMDs in hadronization

quark pol.

		U	L	T
hadron pol.	U	D_1		$H_1^\perp$
	L		G_1	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

TMDs in hadronization

		quark pol.		
		U	L	T
hadron pol.	U	D_1		$H_1^\perp$
	L		G_1	$H_{1L}^\perp$
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☛ relevant for unpolarized final state

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L		G_1	$H_{1L}^\perp$
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☛ relevant for unpolarized final state

Collins FF: $H_1^{\perp,q\to h}$

ordinary FF: $D_1^{q\to h}$

TMDs in hadronization

quark pol.

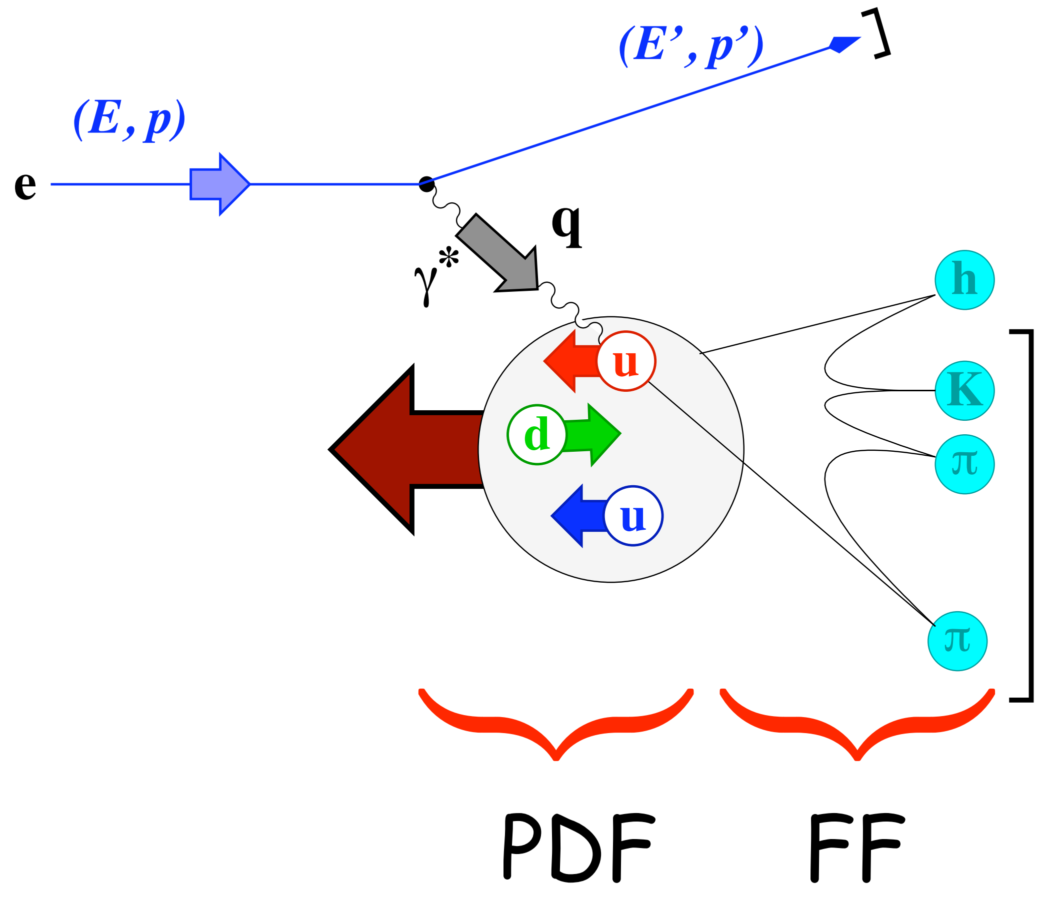
hadron pol.

	U	L	T
U	$\boxed{D_1}$		$\boxed{H_1^\perp}$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☛ relevant for unpolarized final state

} polarized final-state hadrons

Probing TMDs in semi-inclusive DIS



		quark pol.		
		U	L	T
nucleon pol.	U	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$

ordinary FF: $D_1^{q\to h}$

➟ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

… results …

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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$P_{h\perp}$-multiplicity landscape

	EMC [11]	HERMES [15]	JLAB [31]	COMPASS [16]	COMPASS (This paper)
Target	p/d	p/d	d	d	d
Beam energy (GeV)	100–280	27.6	5.479	160	160
Hadron type	$h^\pm$	$\pi^\pm$, K$^\pm$	$\pi^\pm$	$h^\pm$	$h^\pm$
Observable	$M^{h^+ + h^-}$	M^h	σ^h	M^h	M^h
Q^2_{min} (GeV/c)^2	2/3/4/5	1	2	1	1
W^2_{min} (GeV/c^2)^2	-	10	4	25	25
y range	[0.2,0.8]	[0.1,0.85]	[0.1,0.9]	[0.1,0.9]	[0.1,0.9]
x range	[0.01,1]	[0.023,0.6]	[0.2,0.6]	[0.004,0.12]	[0.003,0.4]
P^2_{hT} range (GeV/c)^2	[0.081, 15.8]	[0.0047,0.9]	[0.004,0.196]	[0.02,0.72]	[0.02,3]

[11] J. Ashman et al. (EMC), Z. Phys.C 52, 361 (1991).

[15] A. Airapetian et al. (HERMES), Phys. Rev. D87, 074029 (2013).

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["This paper"] M. Aghasyan et al. (COMPASS), Phys. Rev. D 97, 032006 (2018).

… as well as more limited measurements by H1 and Zeus

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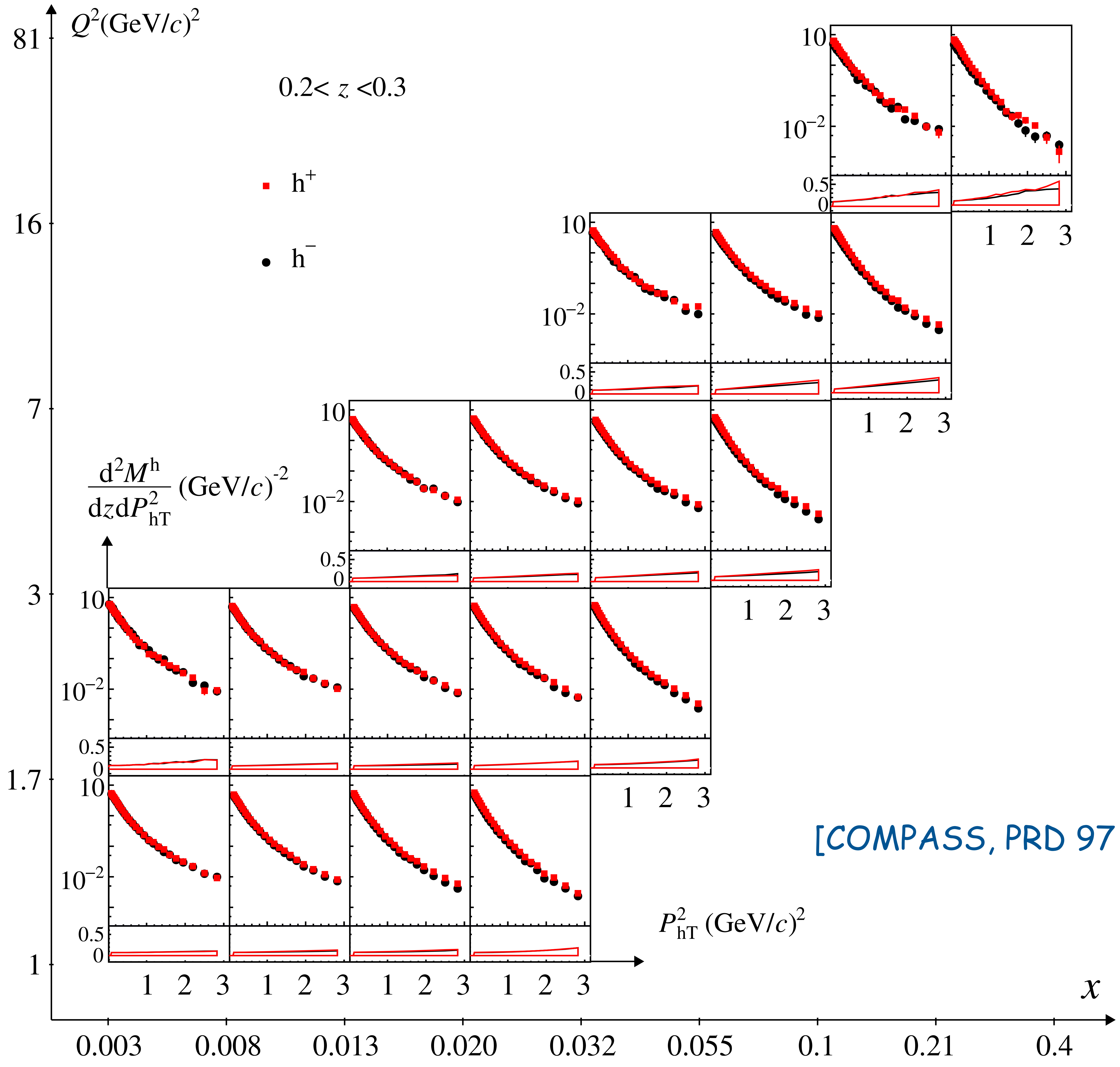
$P_{h\perp}$ dependence

- data on LiD target
- differential in x, z, Q^2, $P_{h\perp}{}^2$
- just one example (lowest z bin)
- high statistical precision allows detailed studies
- also have **high-statistics** data set on **pure proton target** to be analyzed



[COMPASS, PRD 97 (2018) 032006]

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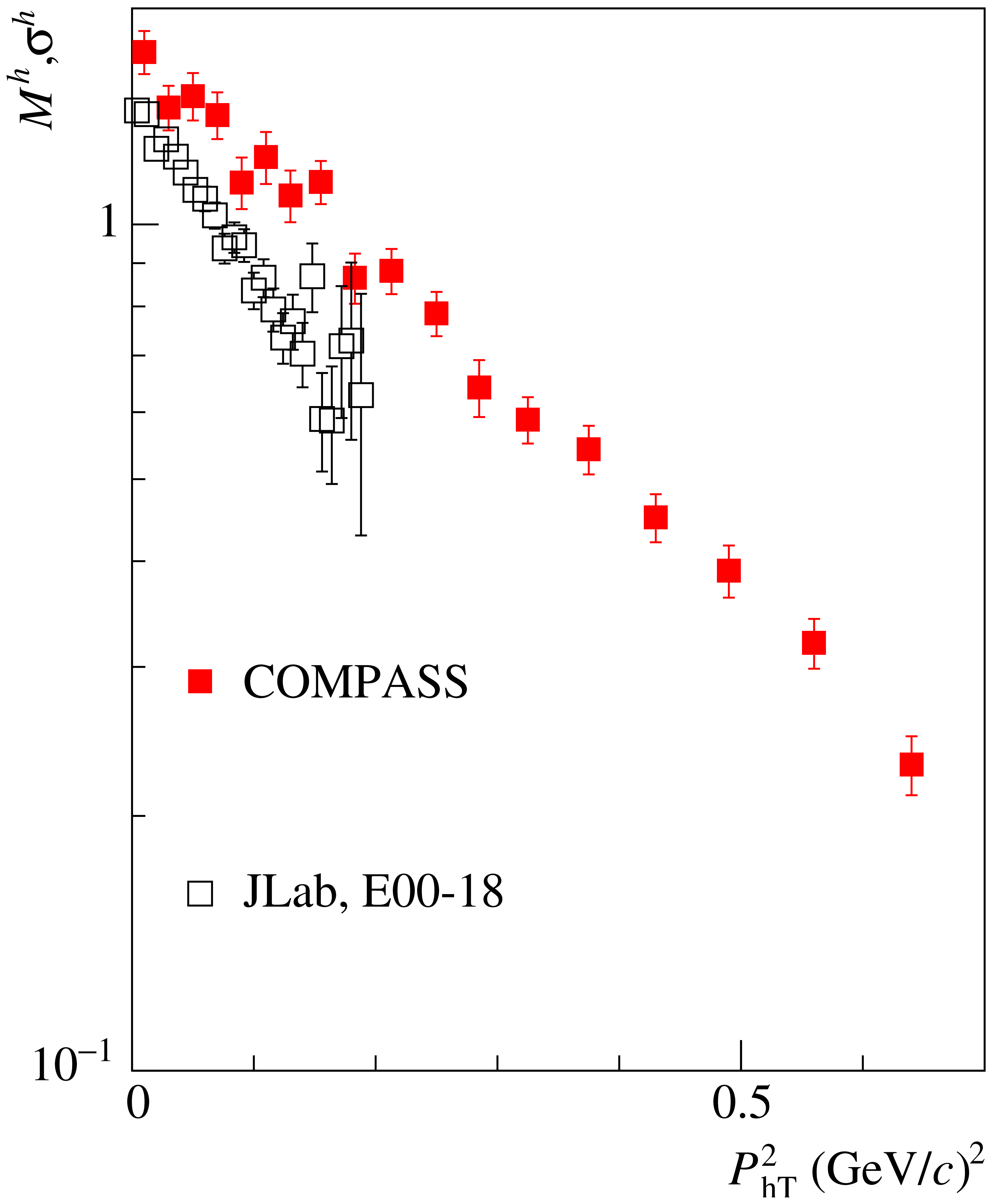
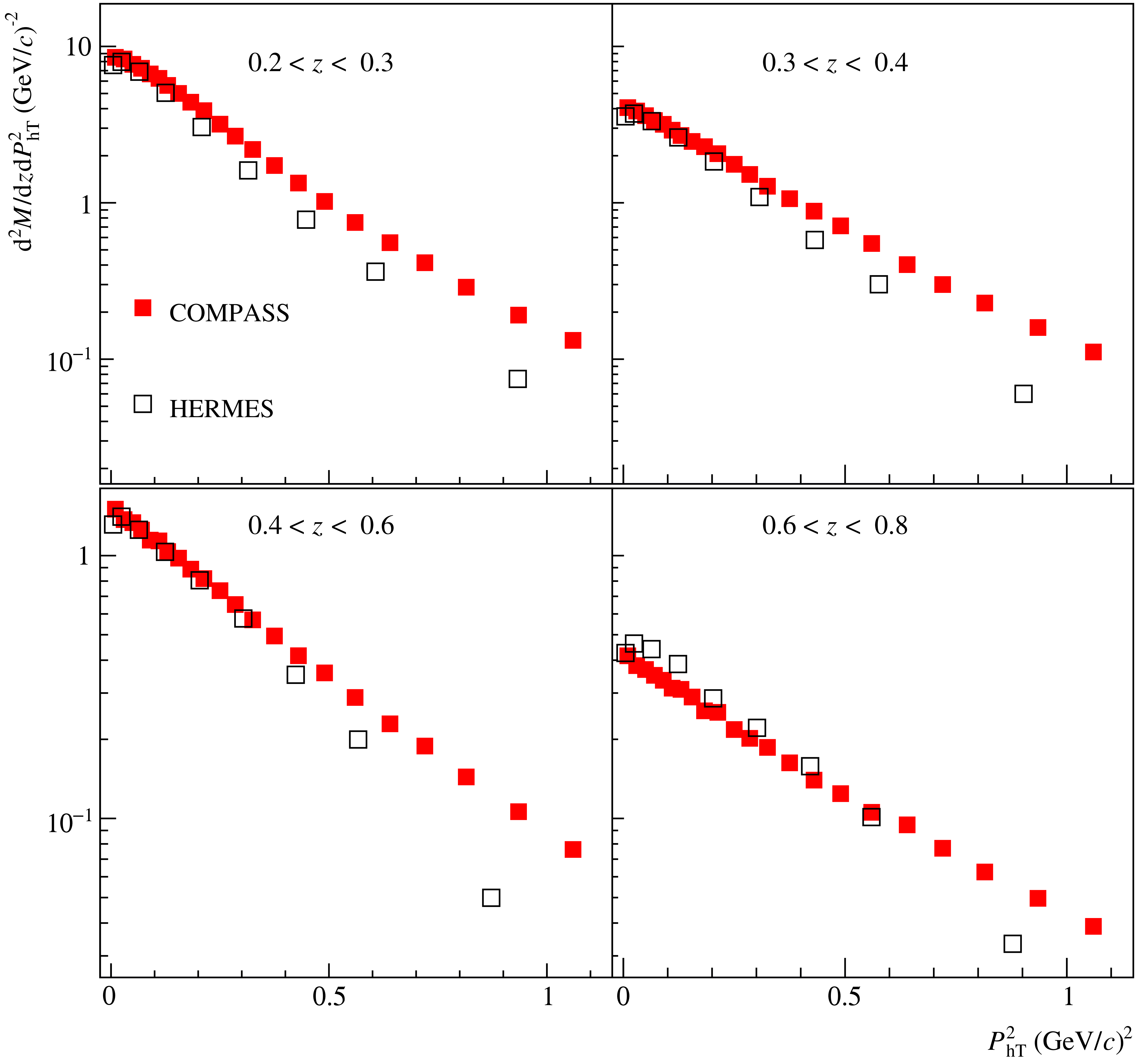
COMPASS vs. JLab & HERMES



[COMPASS, PRD 97 (2018) 032006]



[COMPASS, PRD 97 (2018) 032006]

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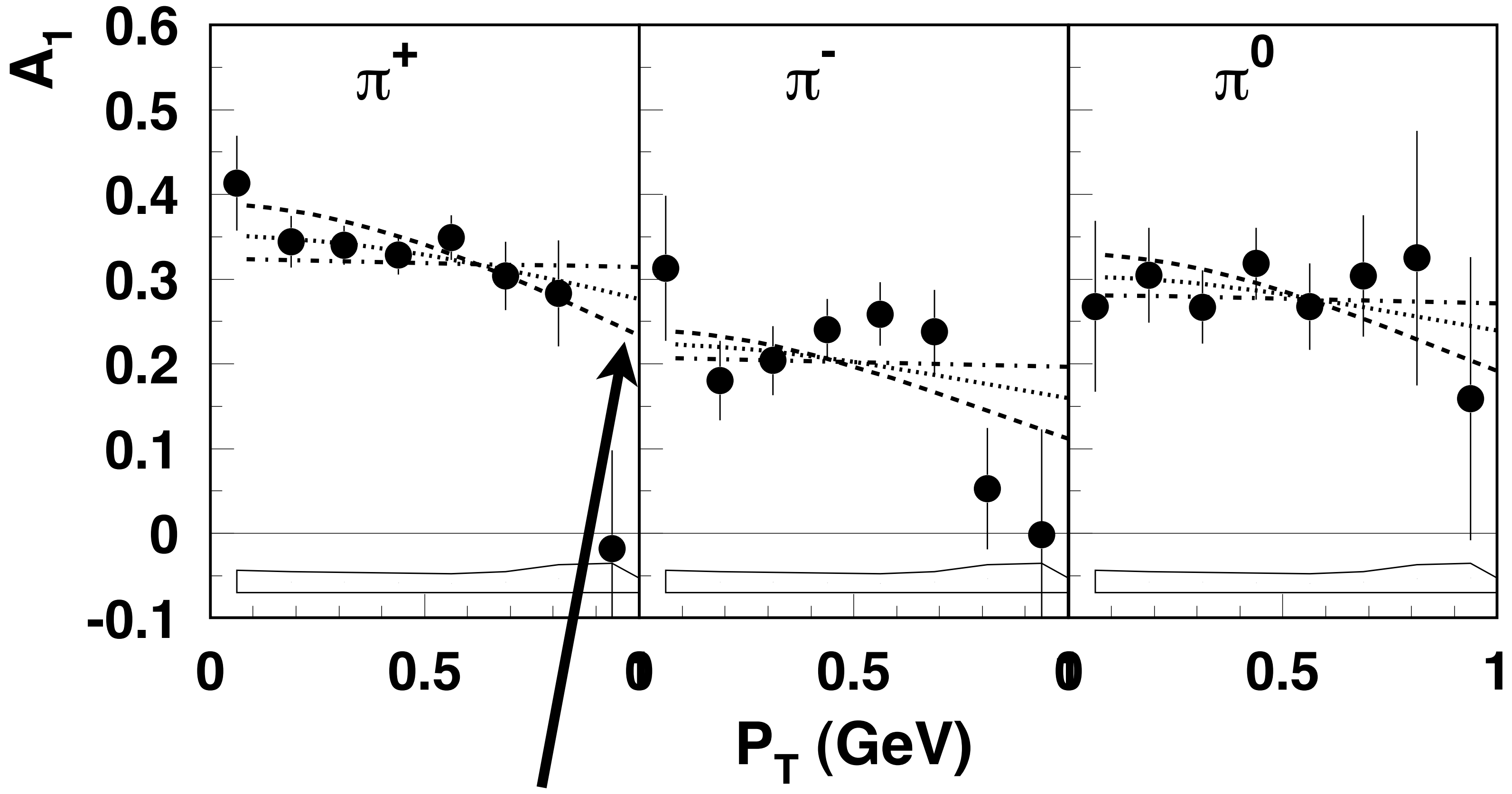
Helicity density



[CLAS, PRL 105, 262002 (2010)]

CLAS data hints at width μ_2 of g_1 that is less than the width μ_0 of f_1

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

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... also suggested by lattice QCD

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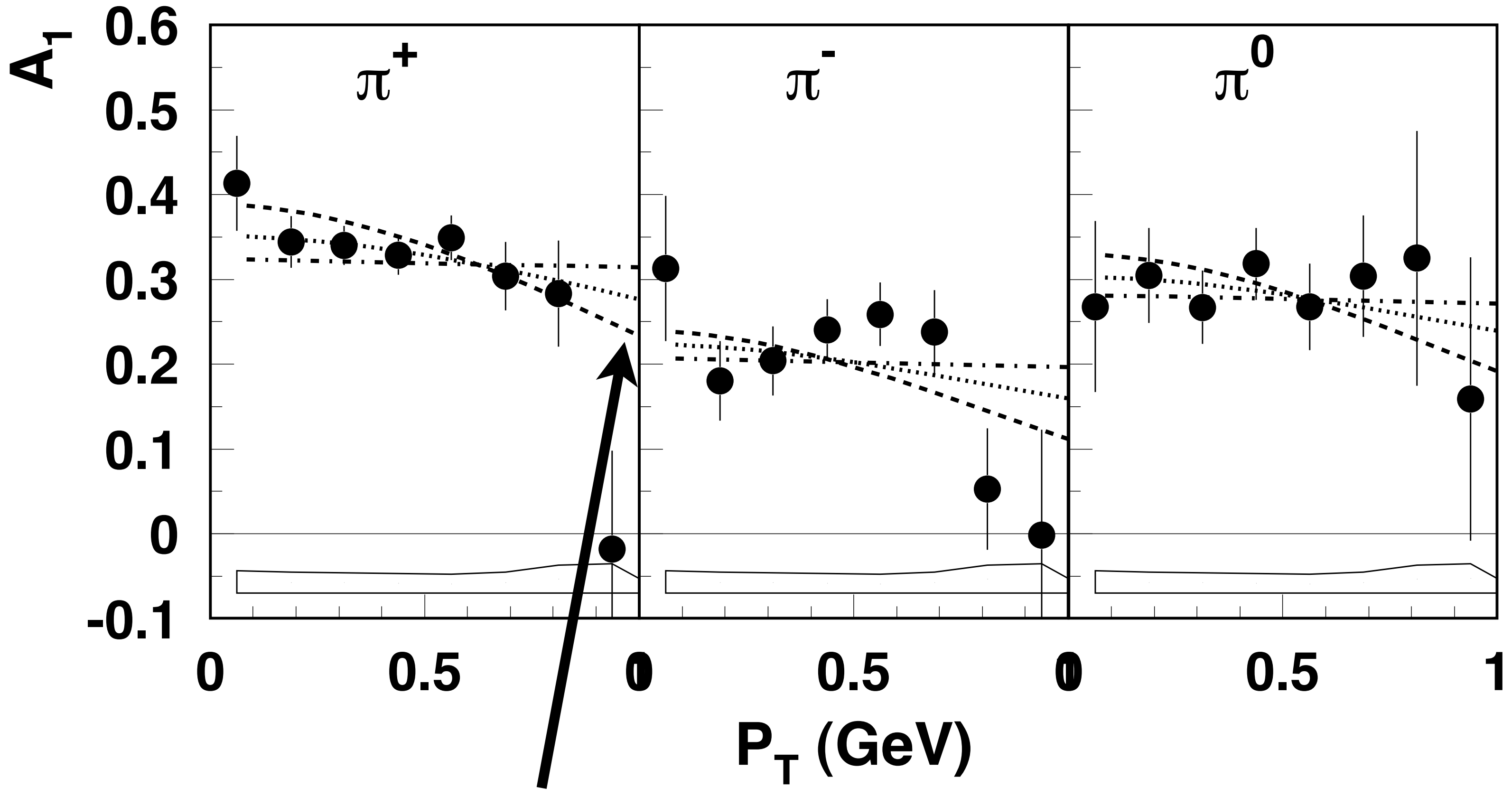

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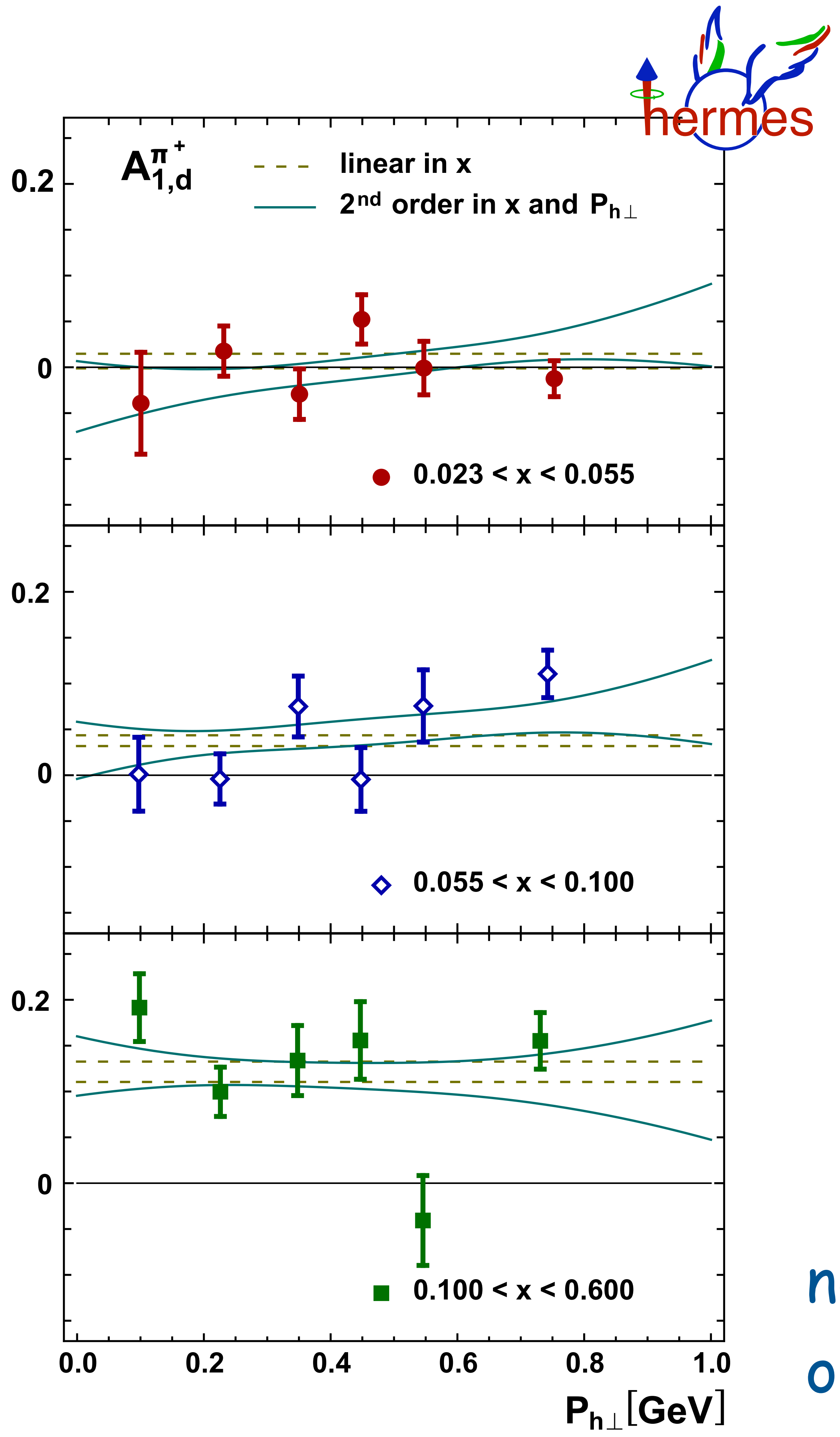
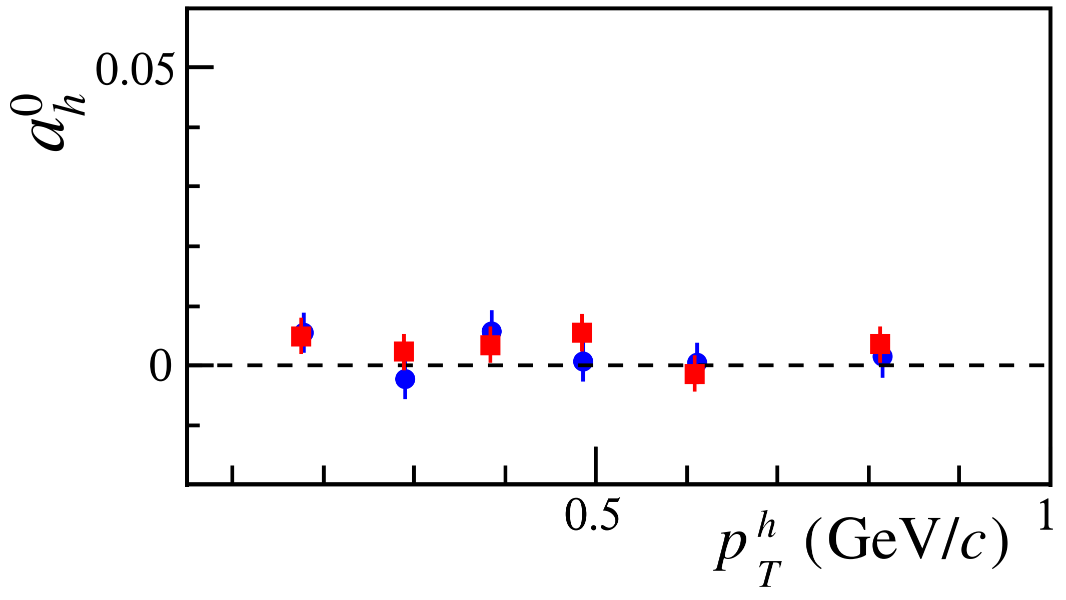


[COMPASS, EPJ C78 (2018) 952]



no significant $P_{h\perp}$ dependences seen on D at HERMES and COMPASS

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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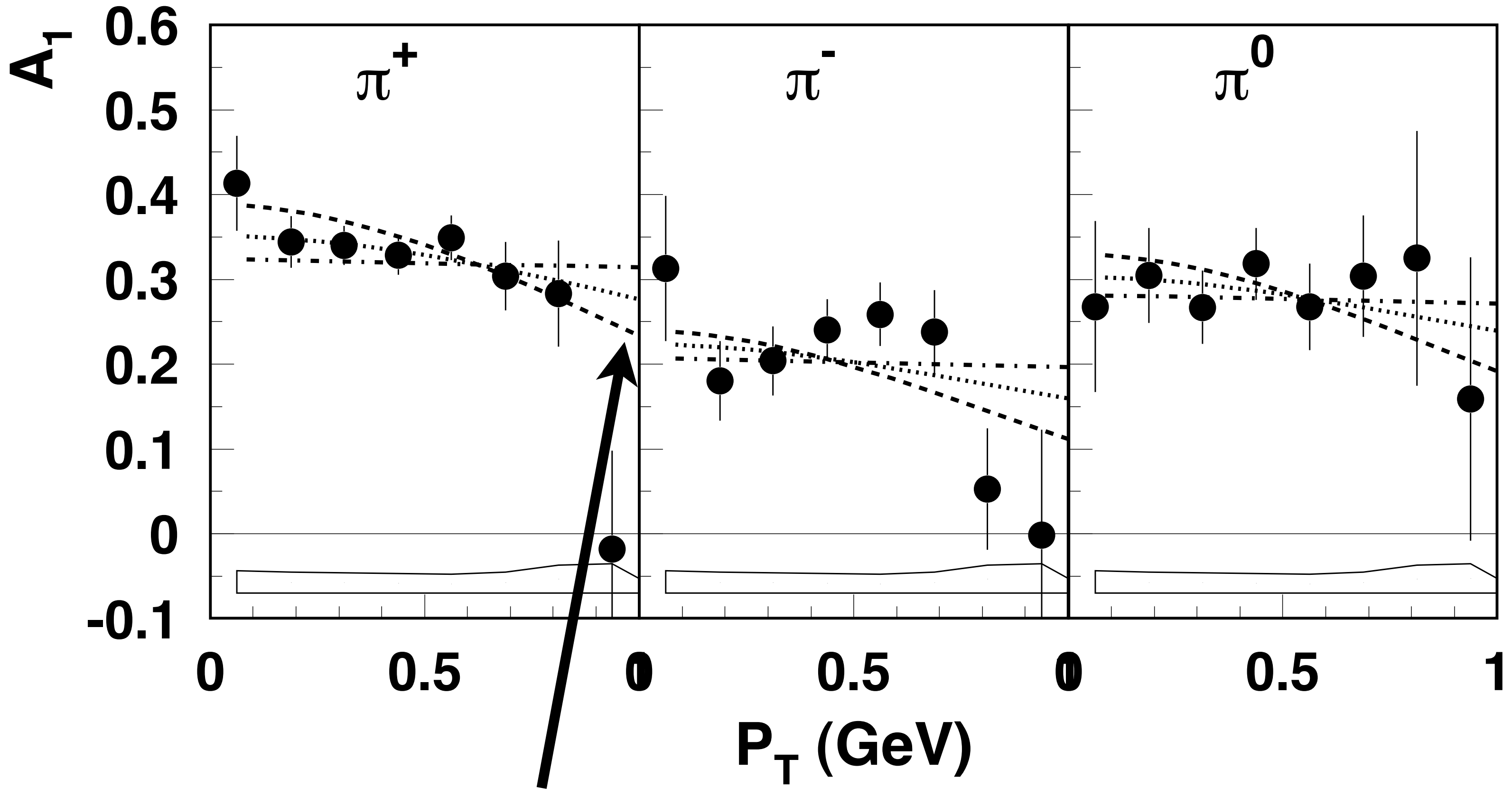

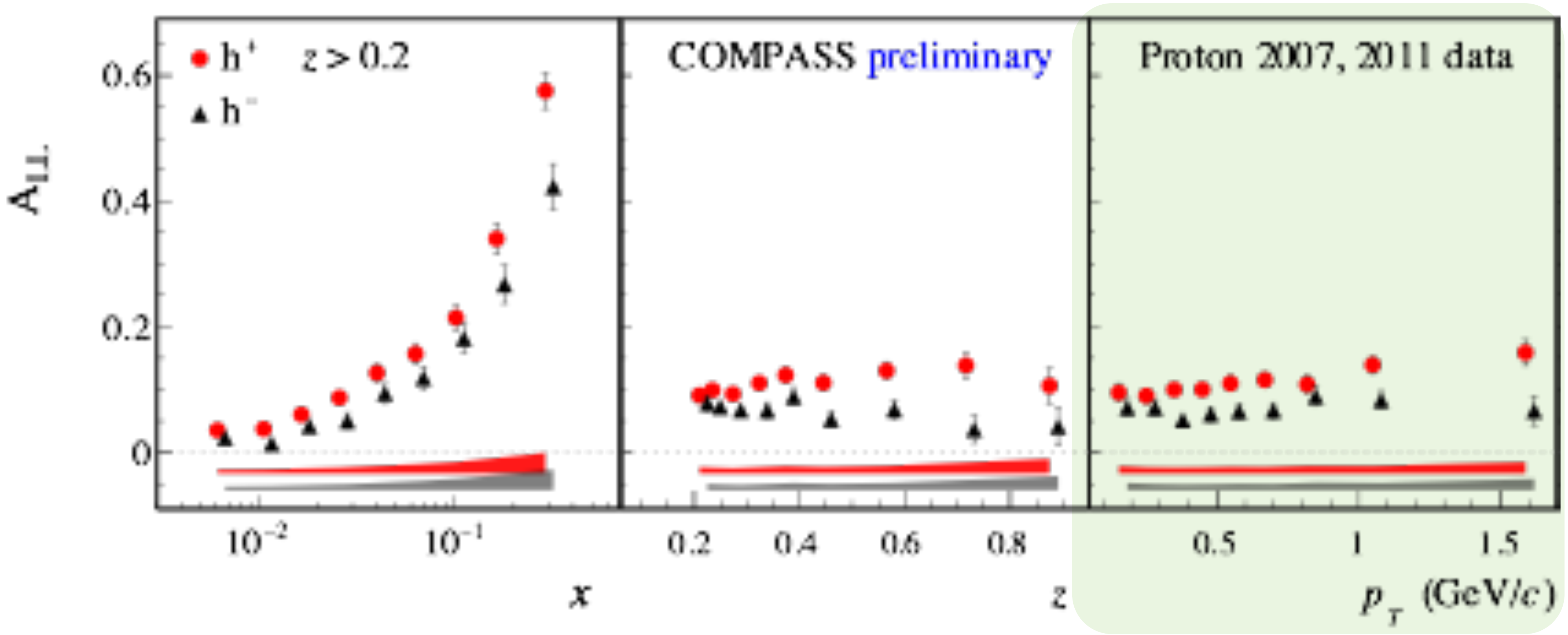

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… also suggested by lattice QCD

perhaps a hint on protons at COMPASS?
(but opposite trend than at CLAS)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

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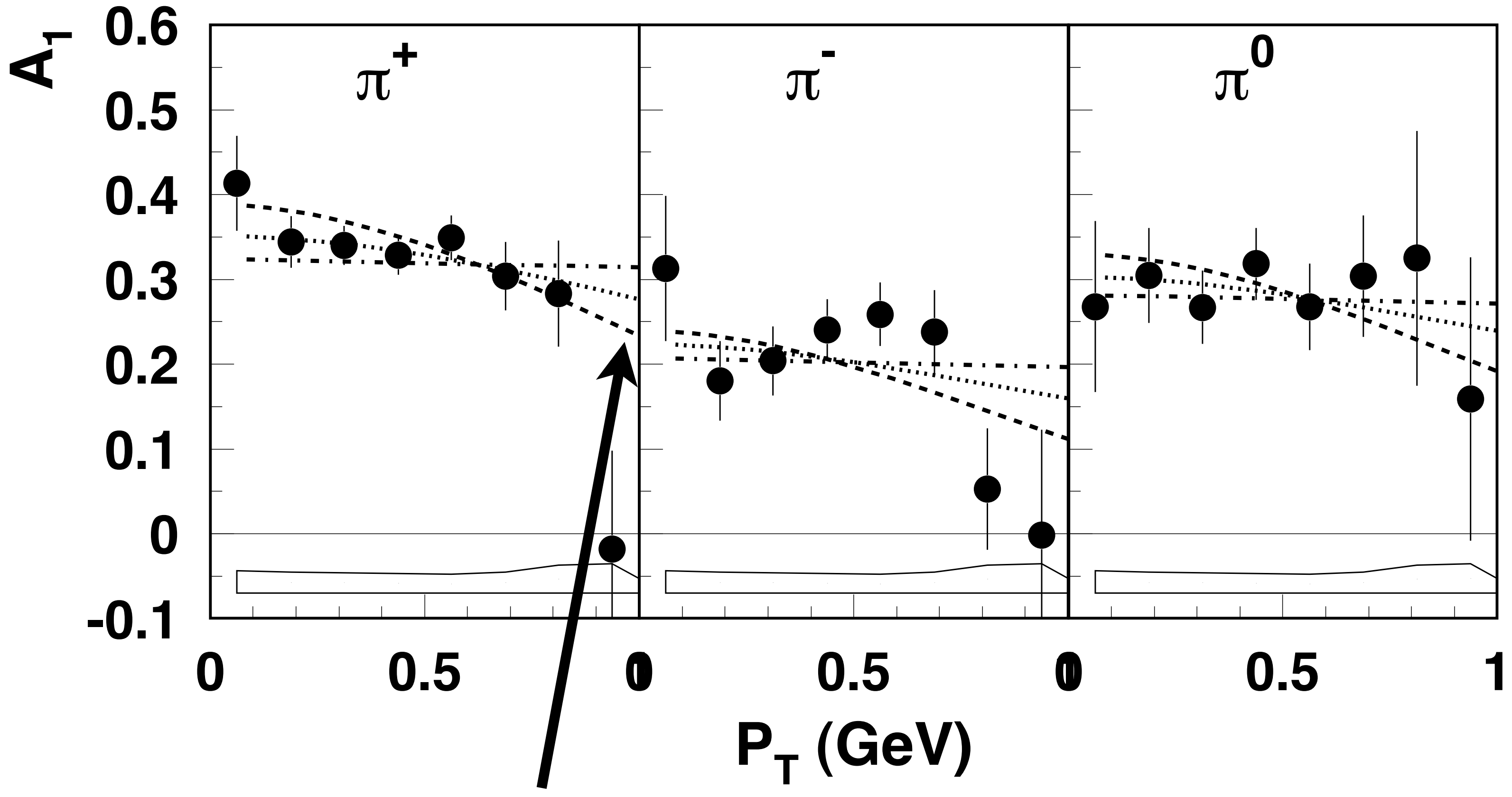

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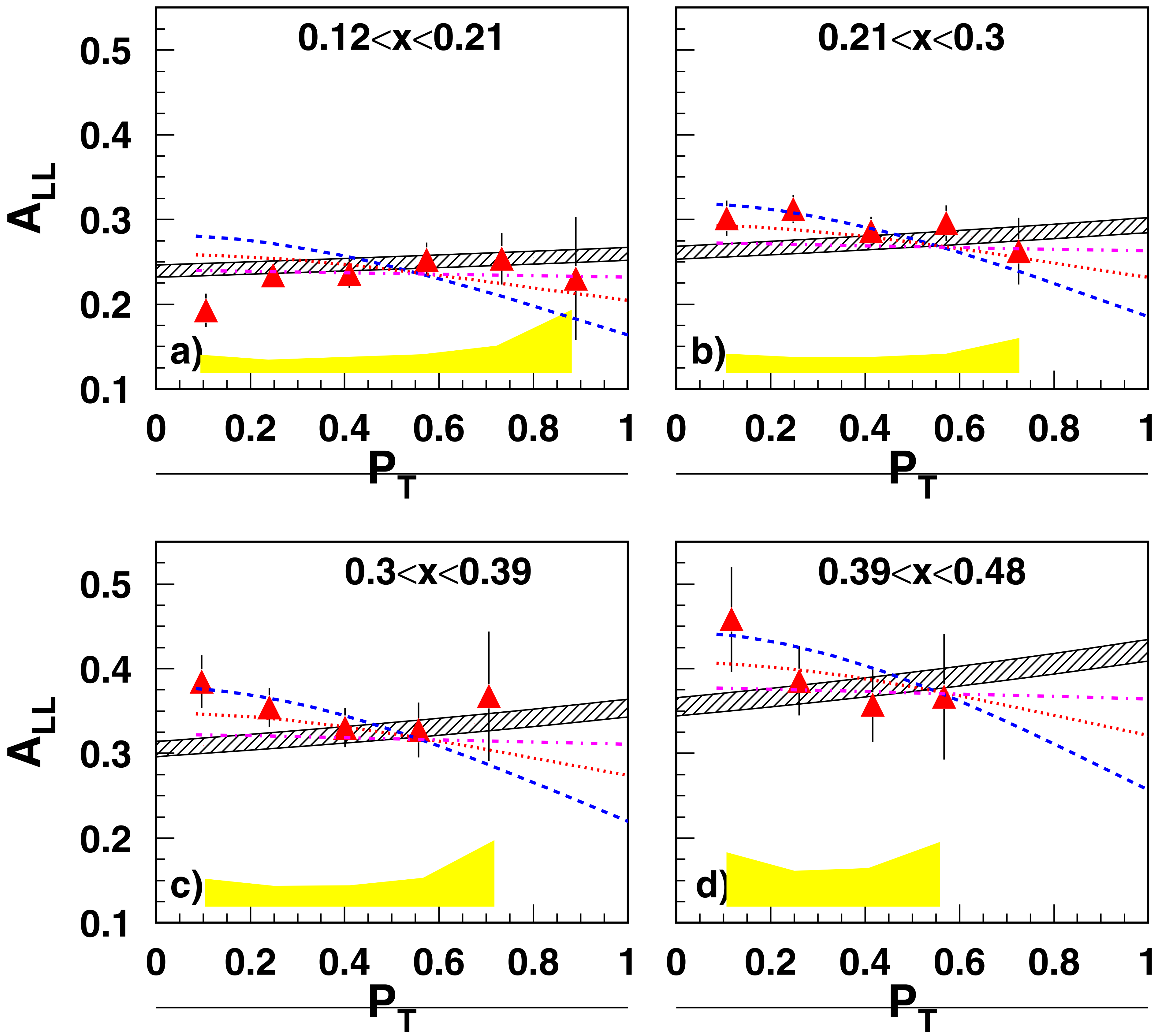
[CLAS, PLB 782 (2018) 662-667]

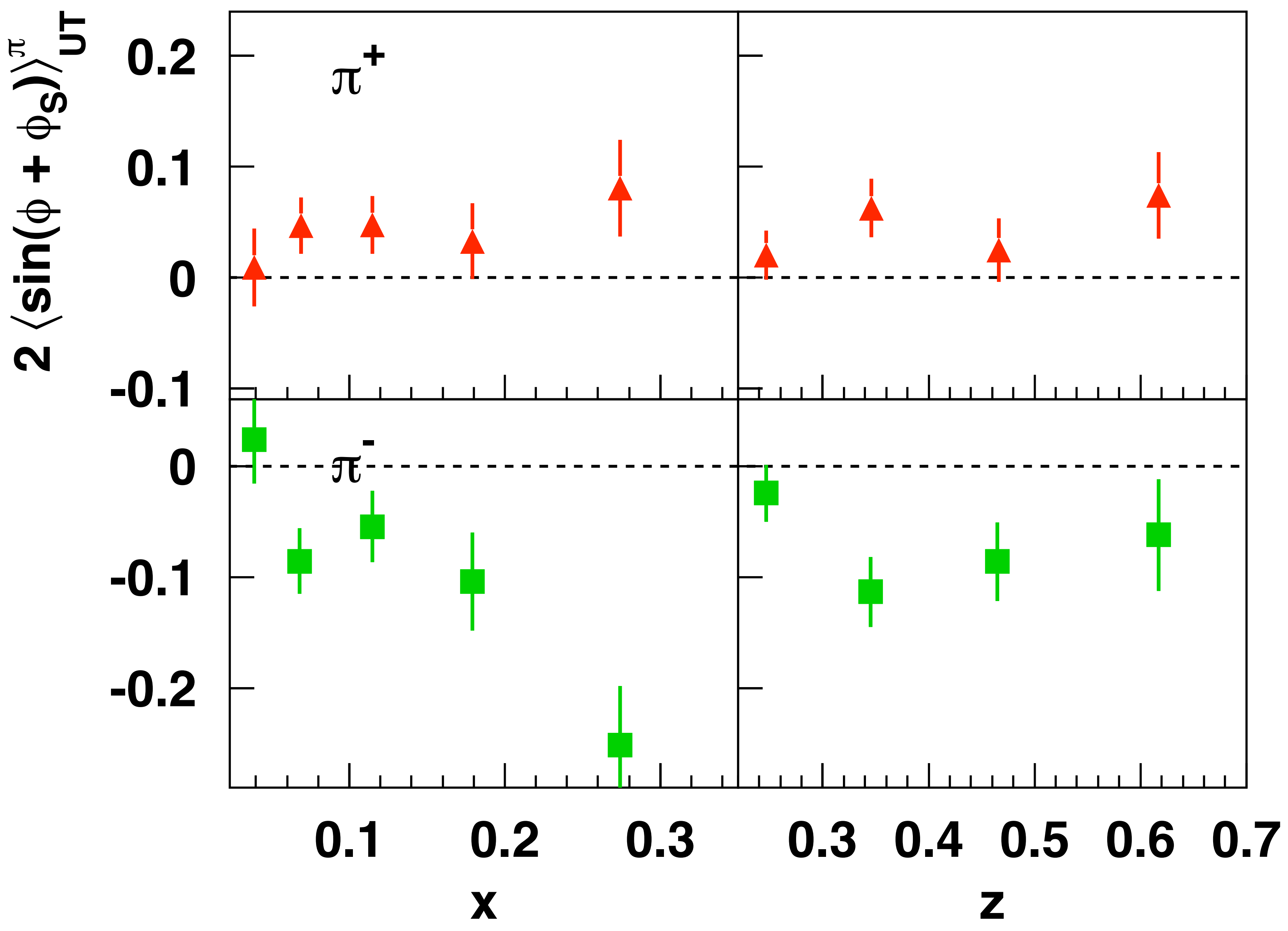


new CLAS data in 2d binning still not conclusive

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity
(Collins fragmentation)

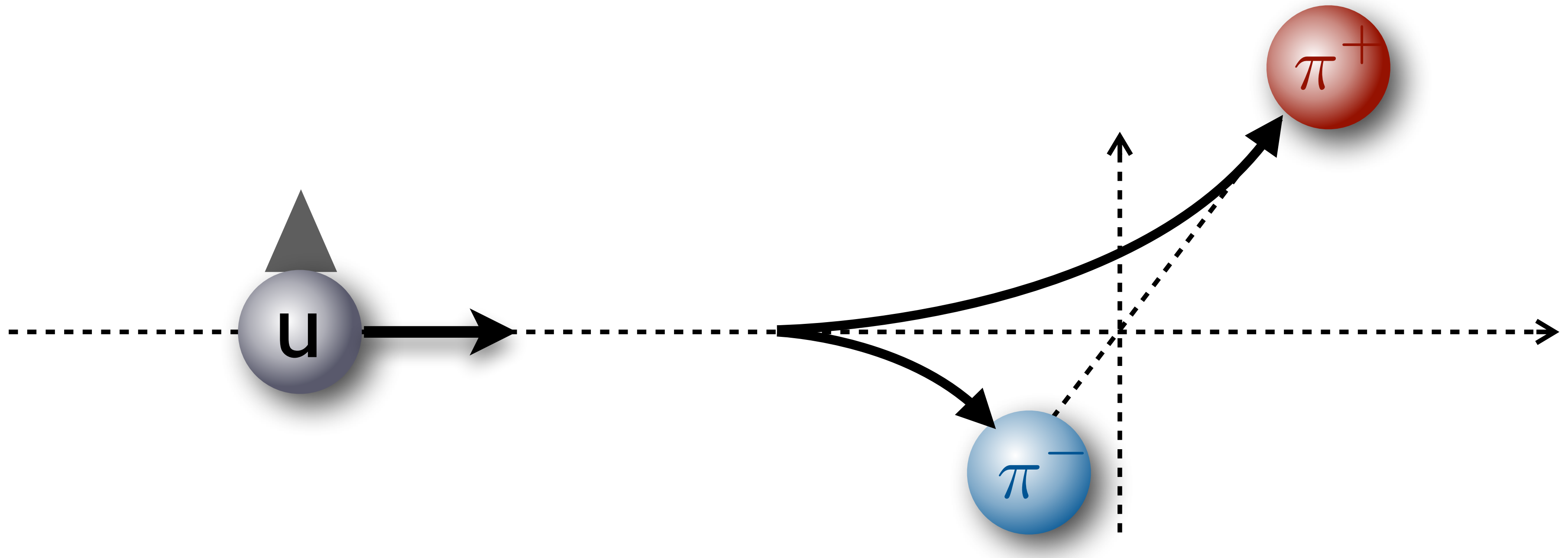
[A. Airapetian et al, PRL 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

- significant in size and opposite in sign for charged pions
- **disfavored** Collins FF **large** and **opposite in sign** to favored one



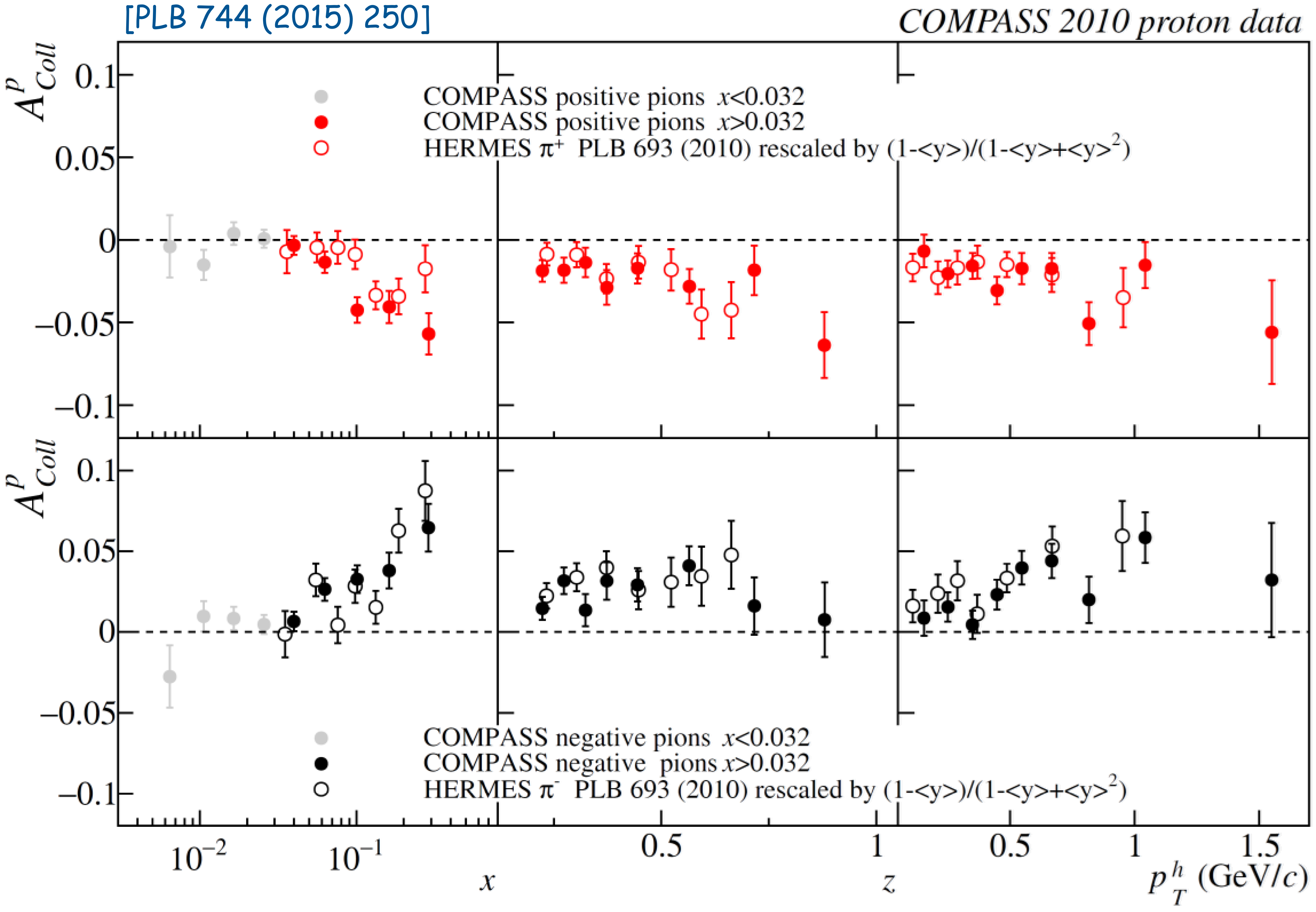
- leads to various cancellations in SSA observables

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

- since those early days, a wealth of new results:
  - **COMPASS**
    [PLB 692 (2010) 240, PLB 717 (2012) 376, PLB 744 (2015) 250, PLB 770 (2017) 138]
  - **HERMES**
    [PLB 693 (2010) 11, arXiv:2007.07755]
  - **Jefferson Lab**
    [PRL 107 (2011) 072003, PRC 90 (2014) 055201]

[PLB 744 (2015) 250]



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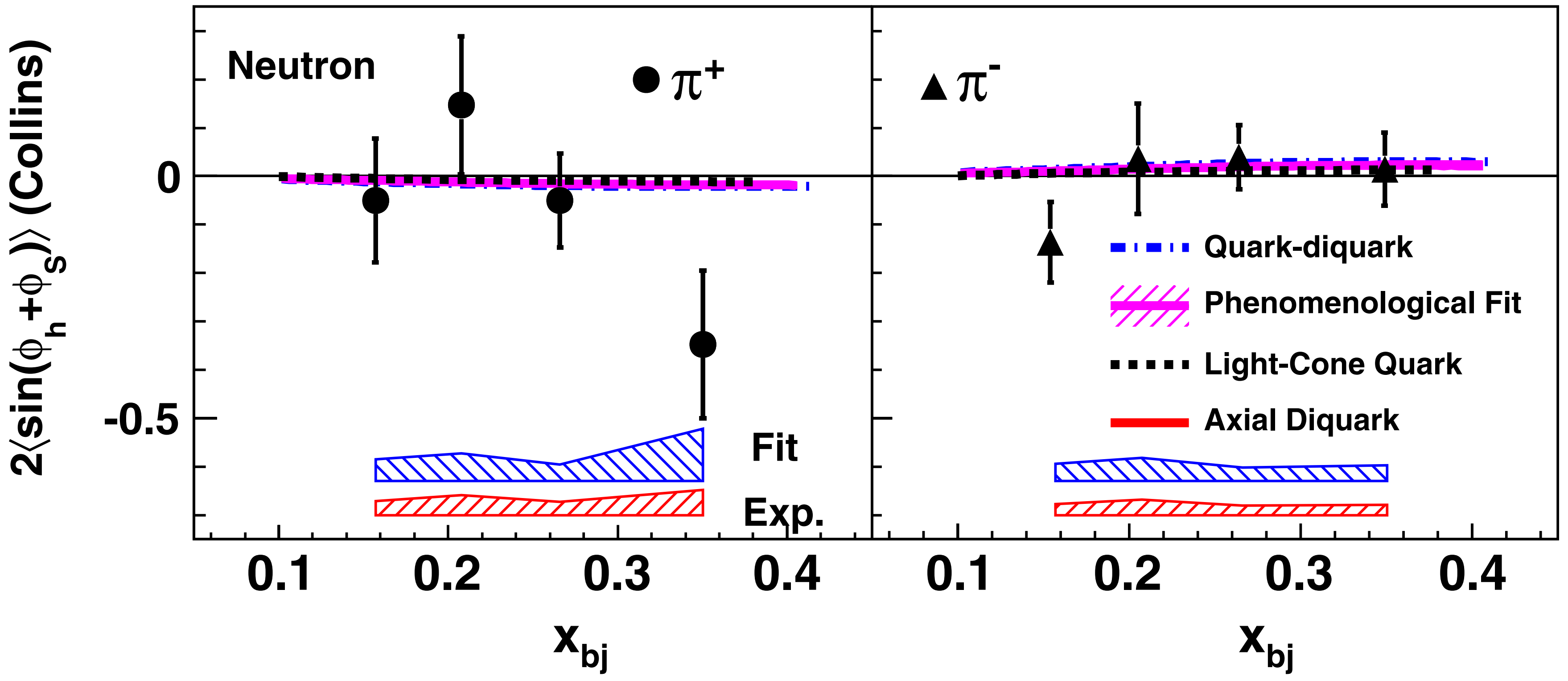

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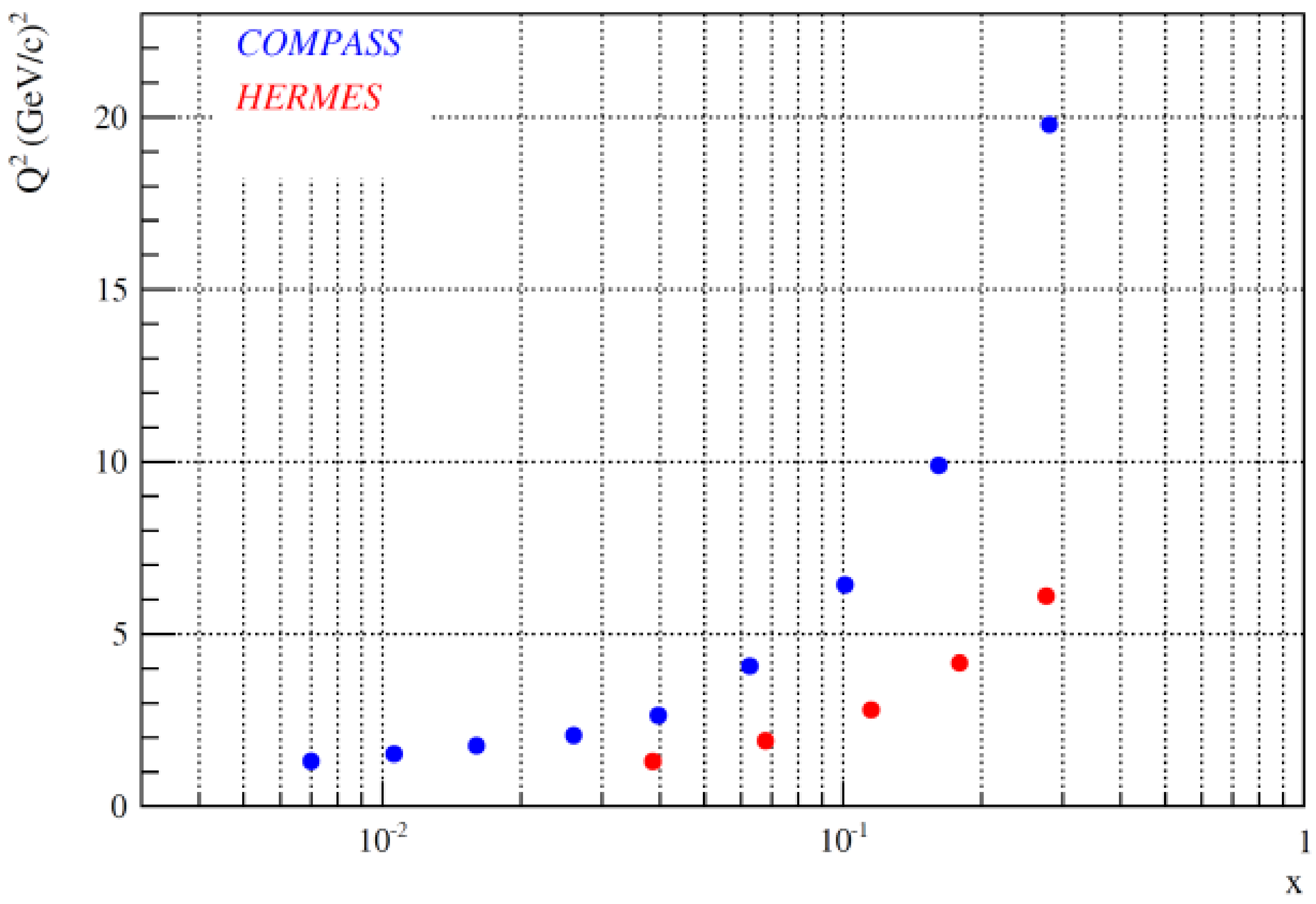

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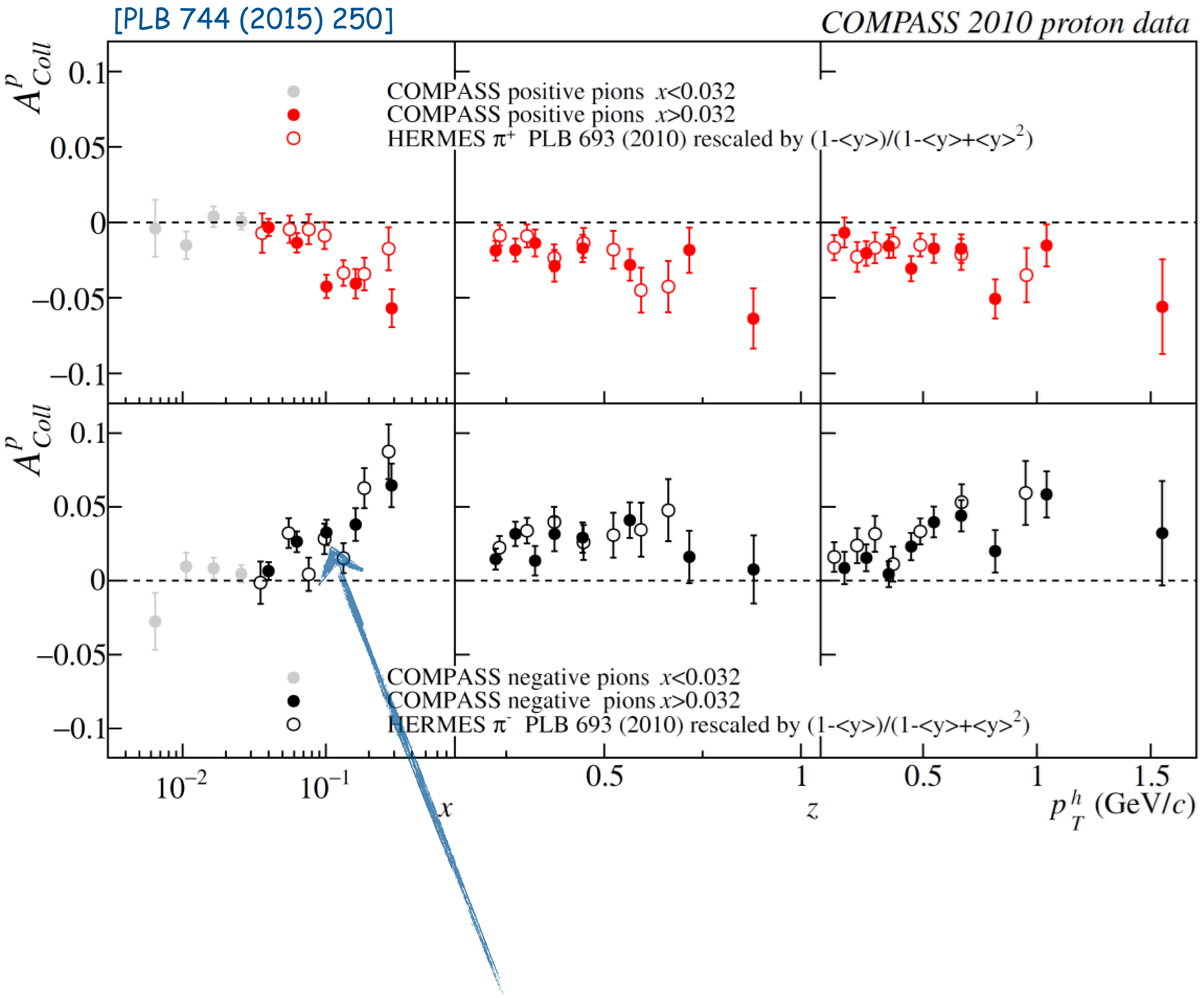

- excellent agreement of various proton data [also with neutron results]
- no indication of strong evolution effects

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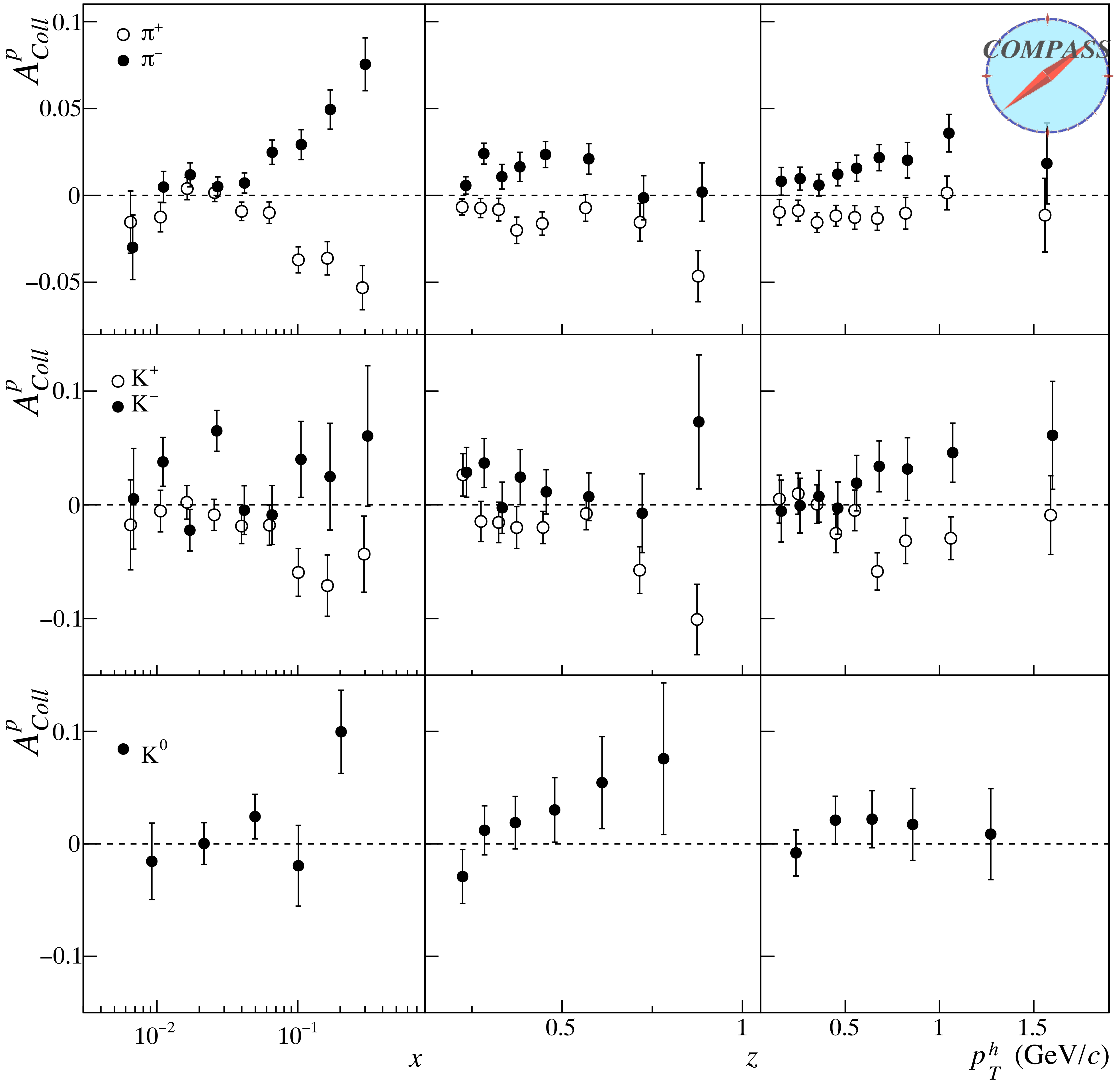
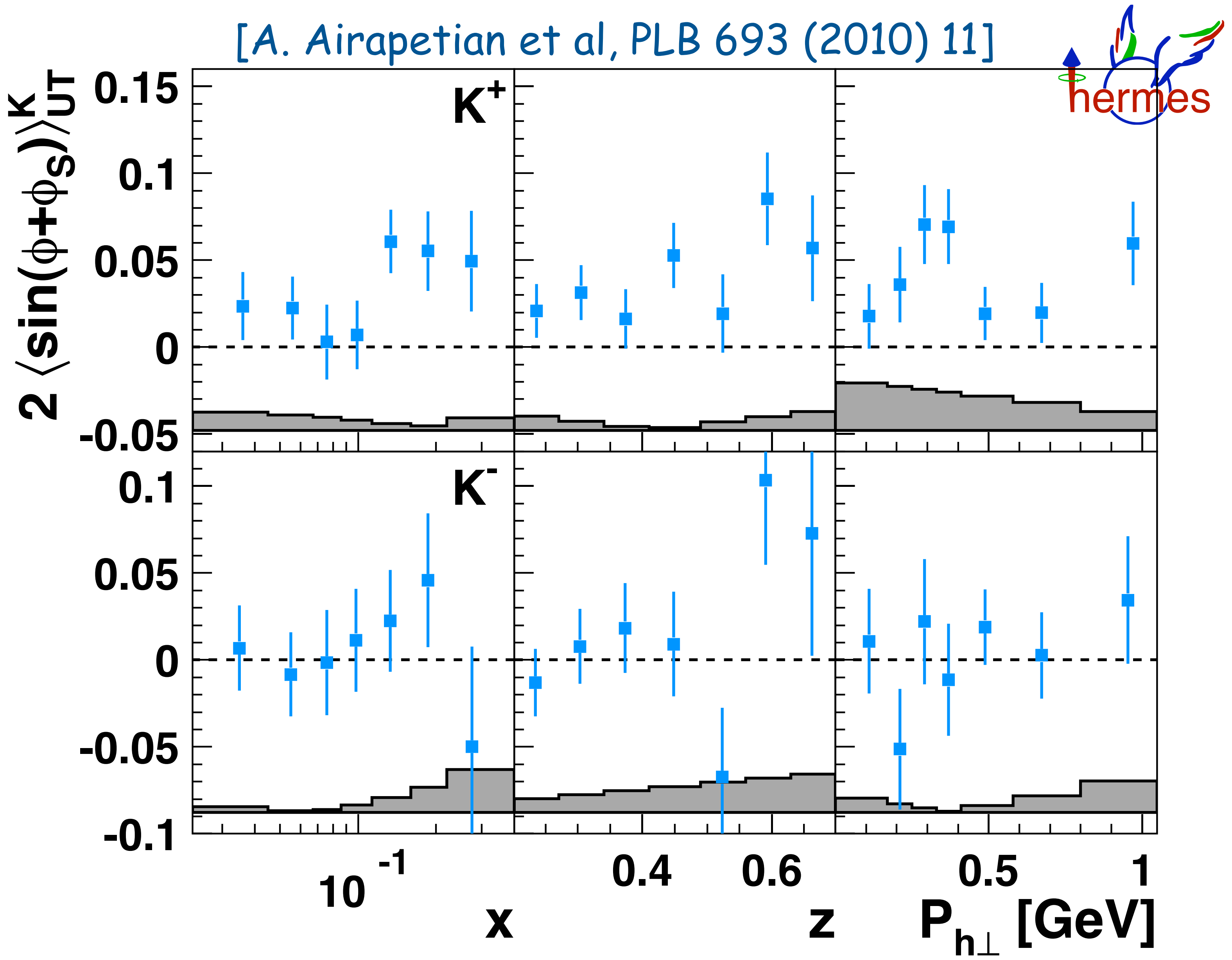


[A. Airapetian et al, PLB 693 (2010) 11]



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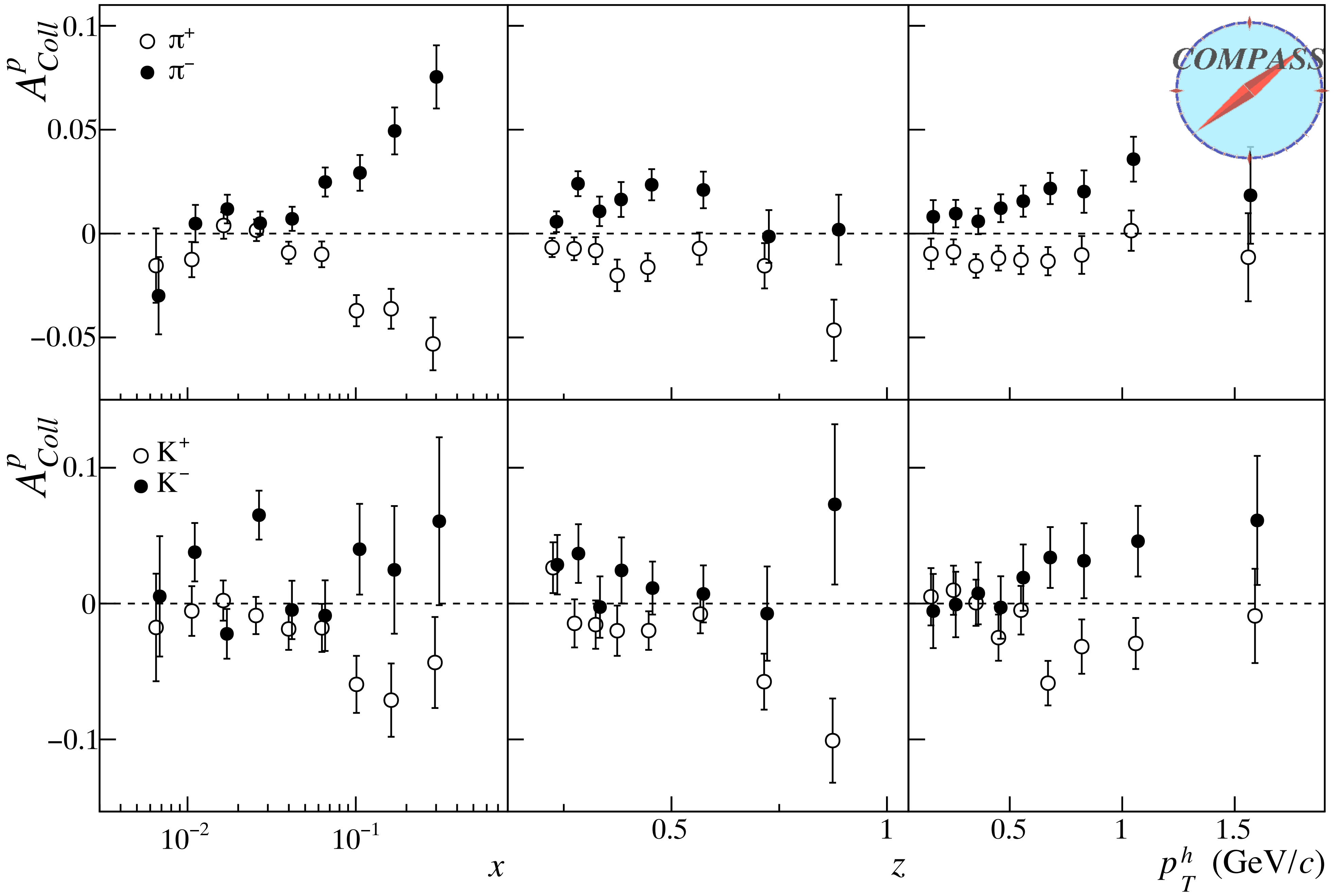

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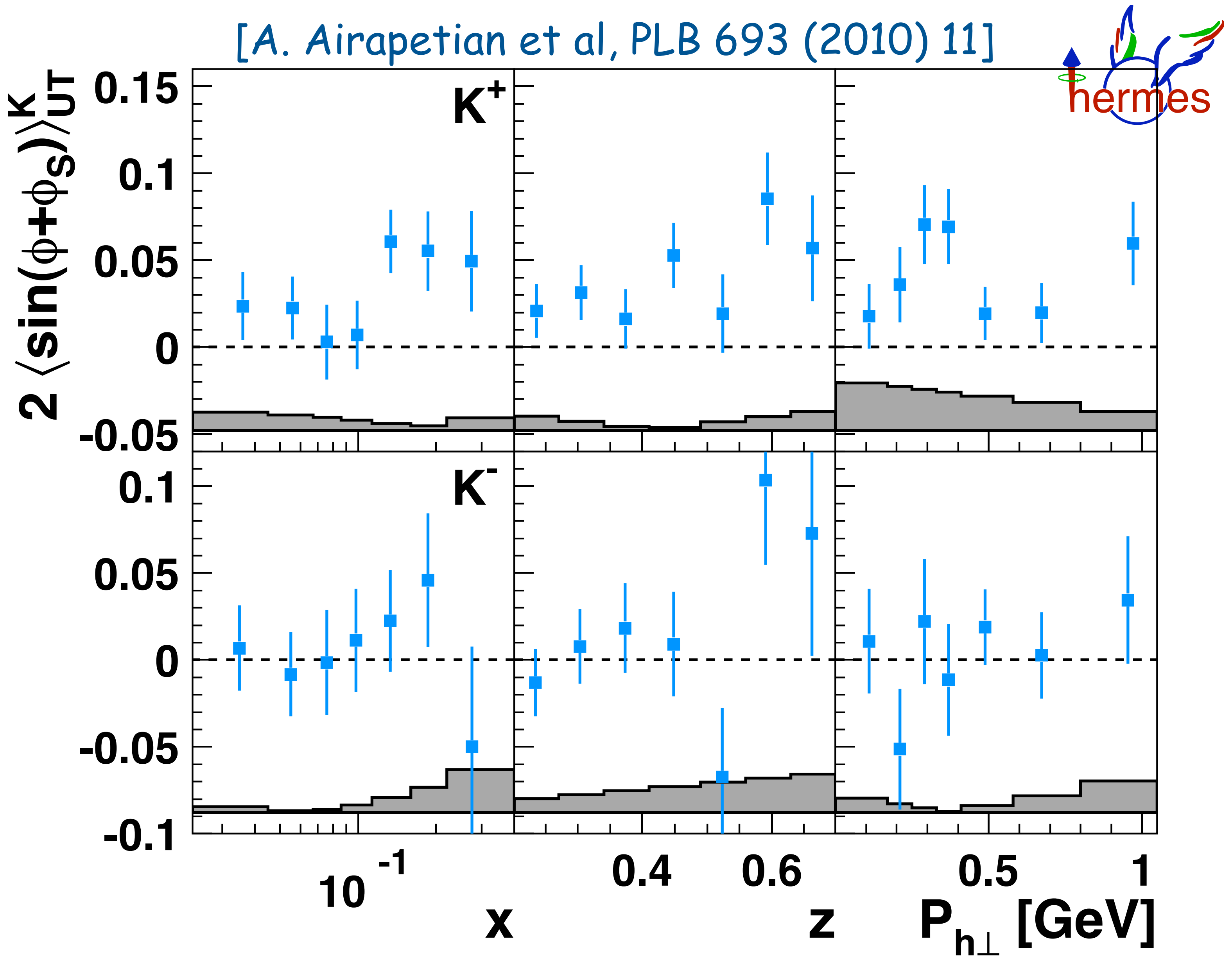
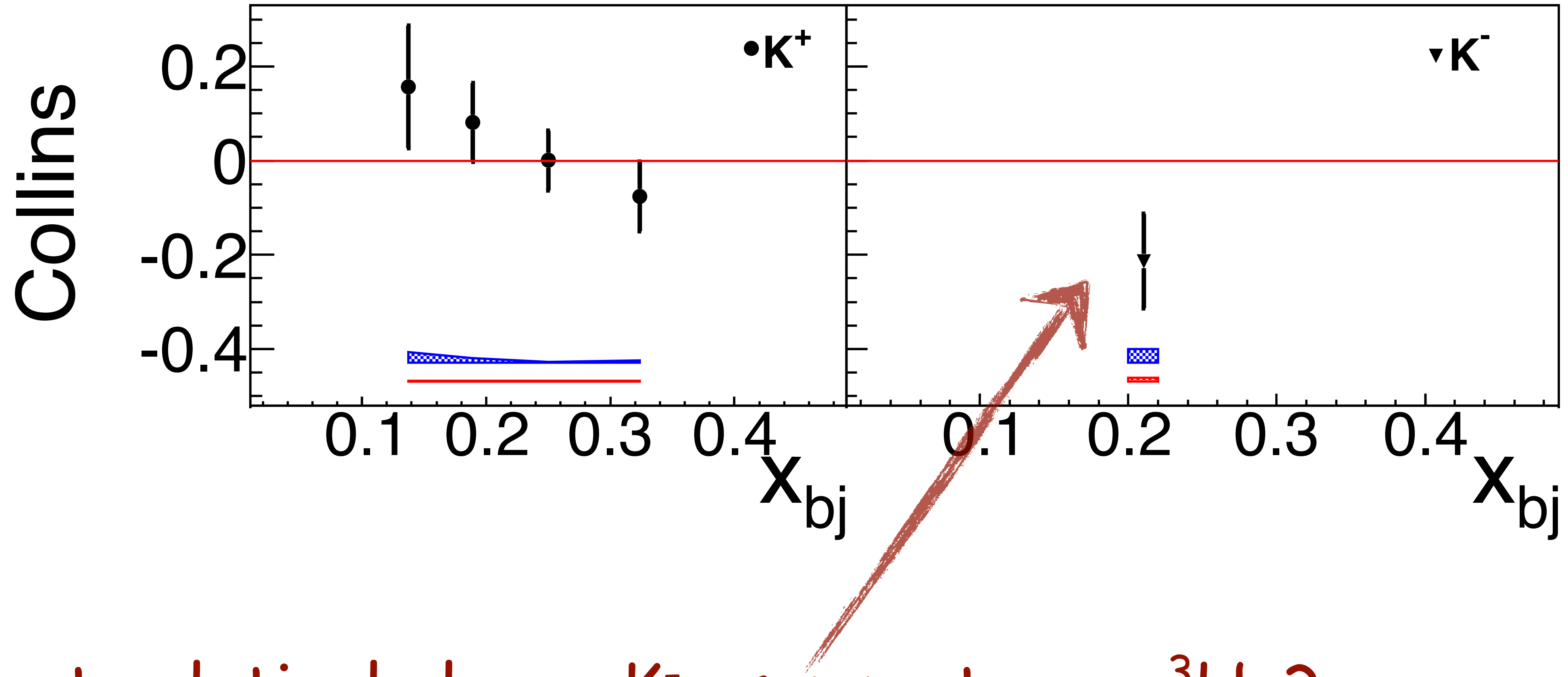


[Y.X. Zhao et al., PRC90 (2014).055201]

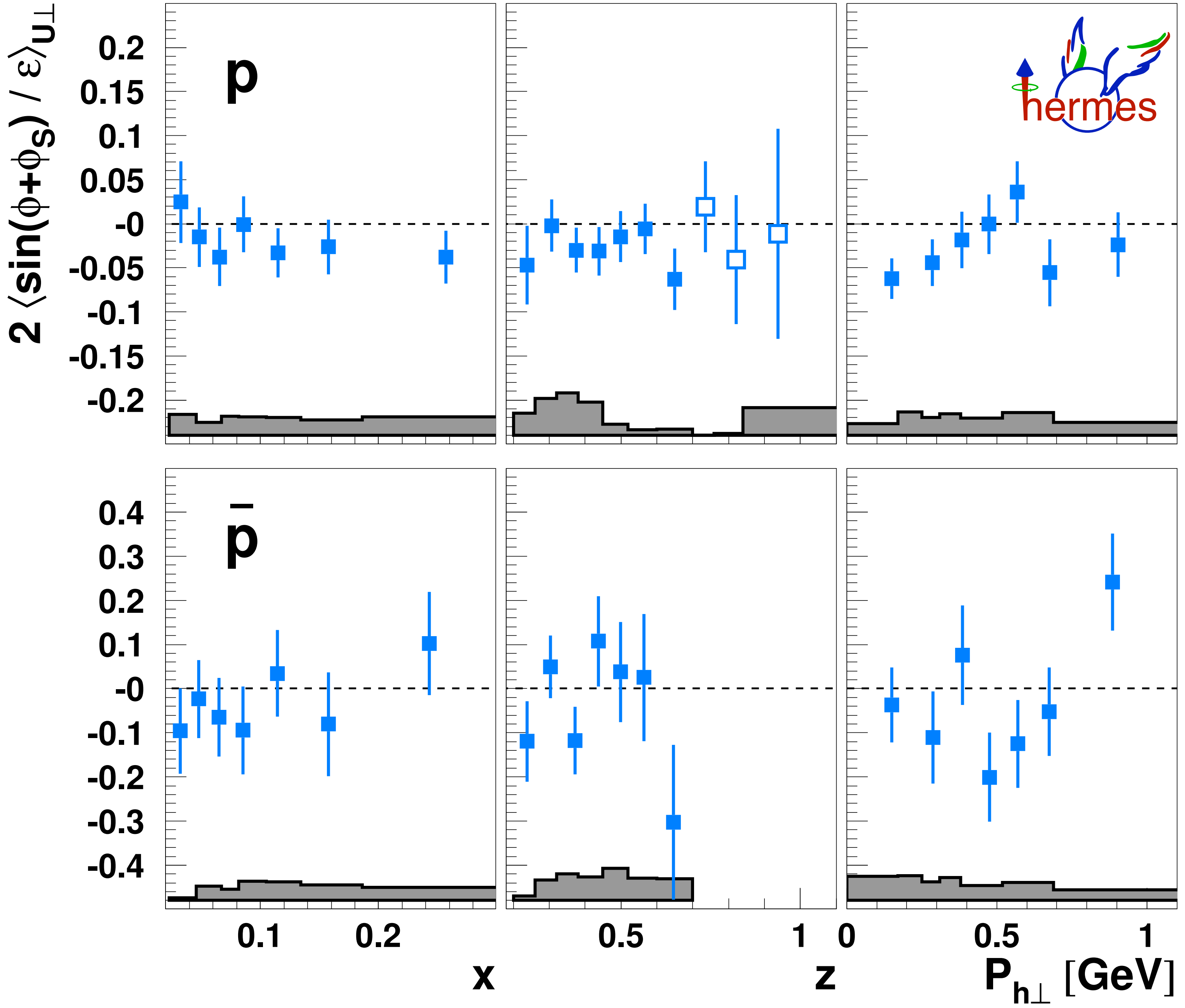


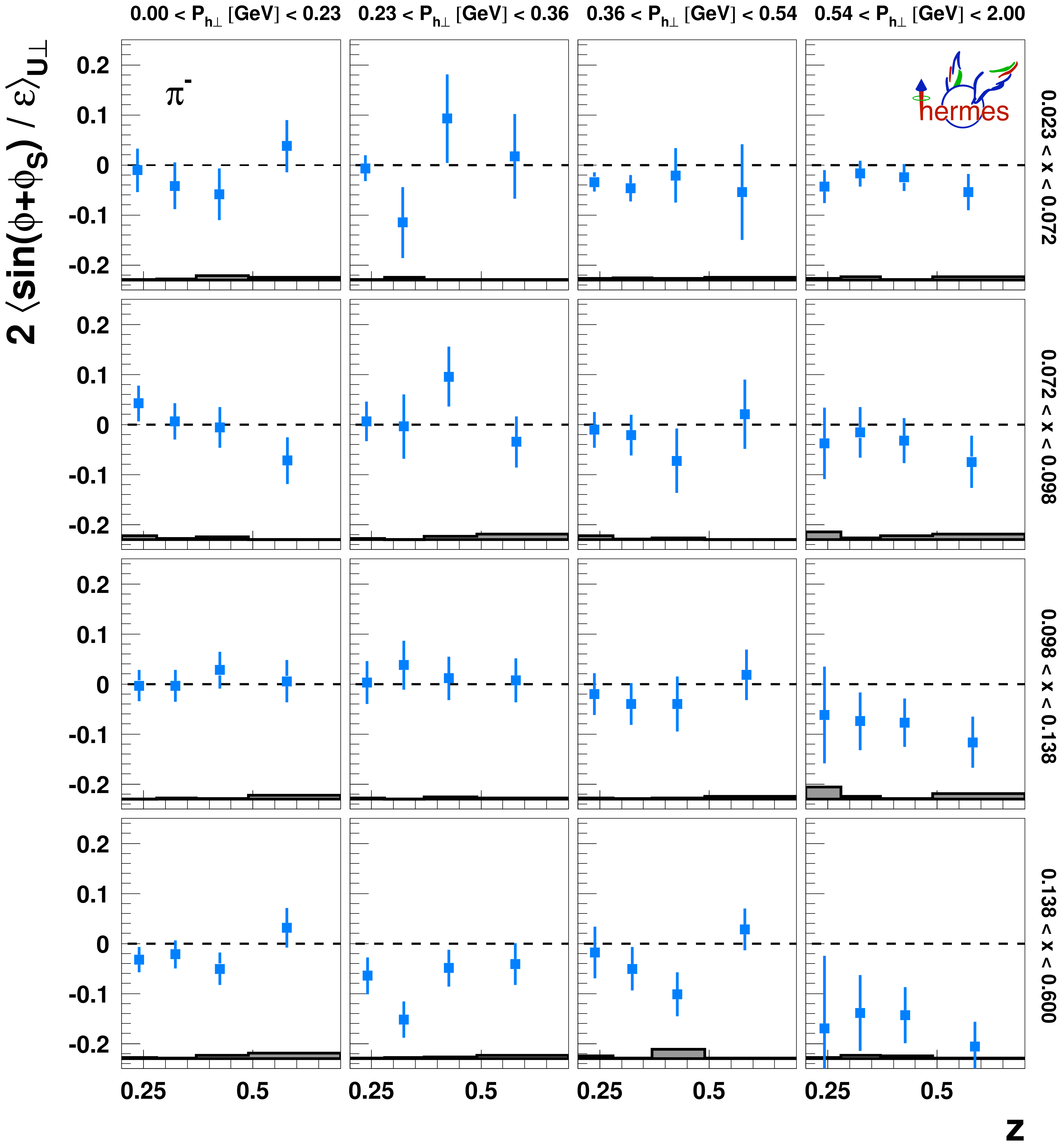
but relatively large K^- asymmetry on ^{3}He?

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

new HERMES results on Collins amplitudes

[A. Airapetian et al., arXiv:2007.07755]





- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic “depolarization” prefactor

	U	L	T
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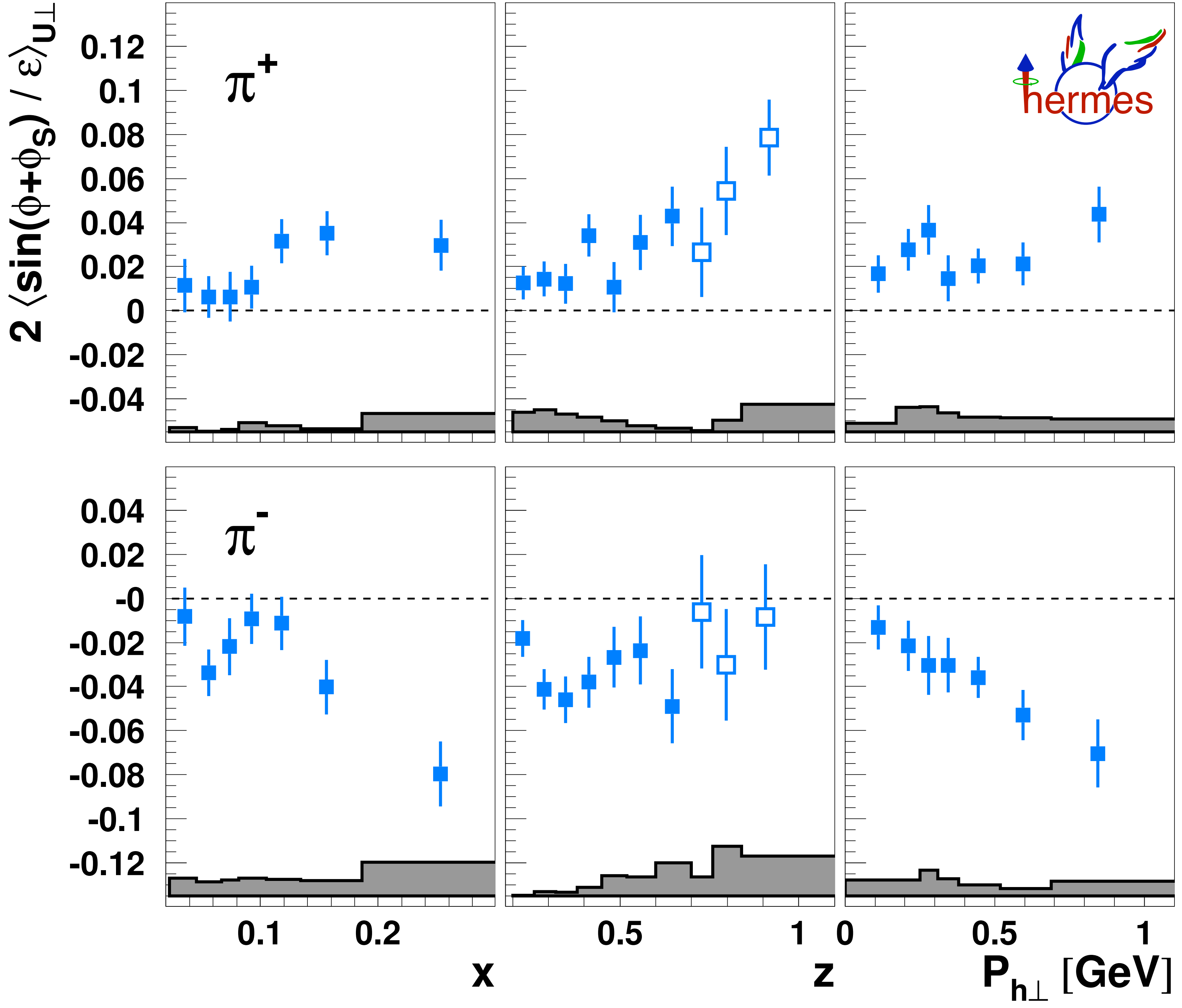
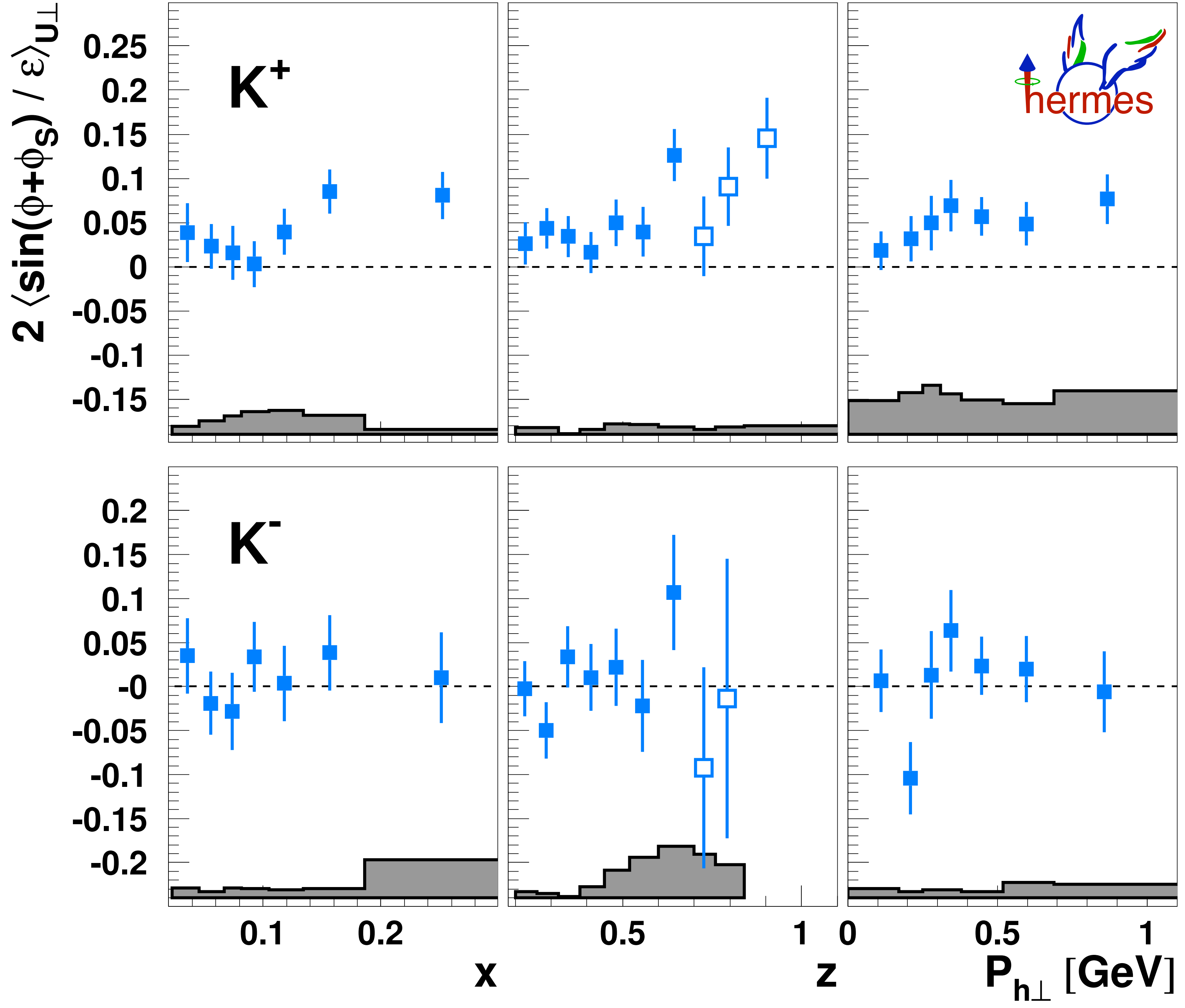


[A. Airapetian et al., arXiv:2007.07755]



[A. Airapetian et al., arXiv:2007.07755]

- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic "depolarization" prefactor
- **high-z region** probes transition region to exclusive domain (with increasing amplitudes for positive pions and kaons)

the “Collins trap”

$$H_{1,\text{fav}}^{\perp} \simeq -H_{1,\text{dis}}^{\perp}$$

thus

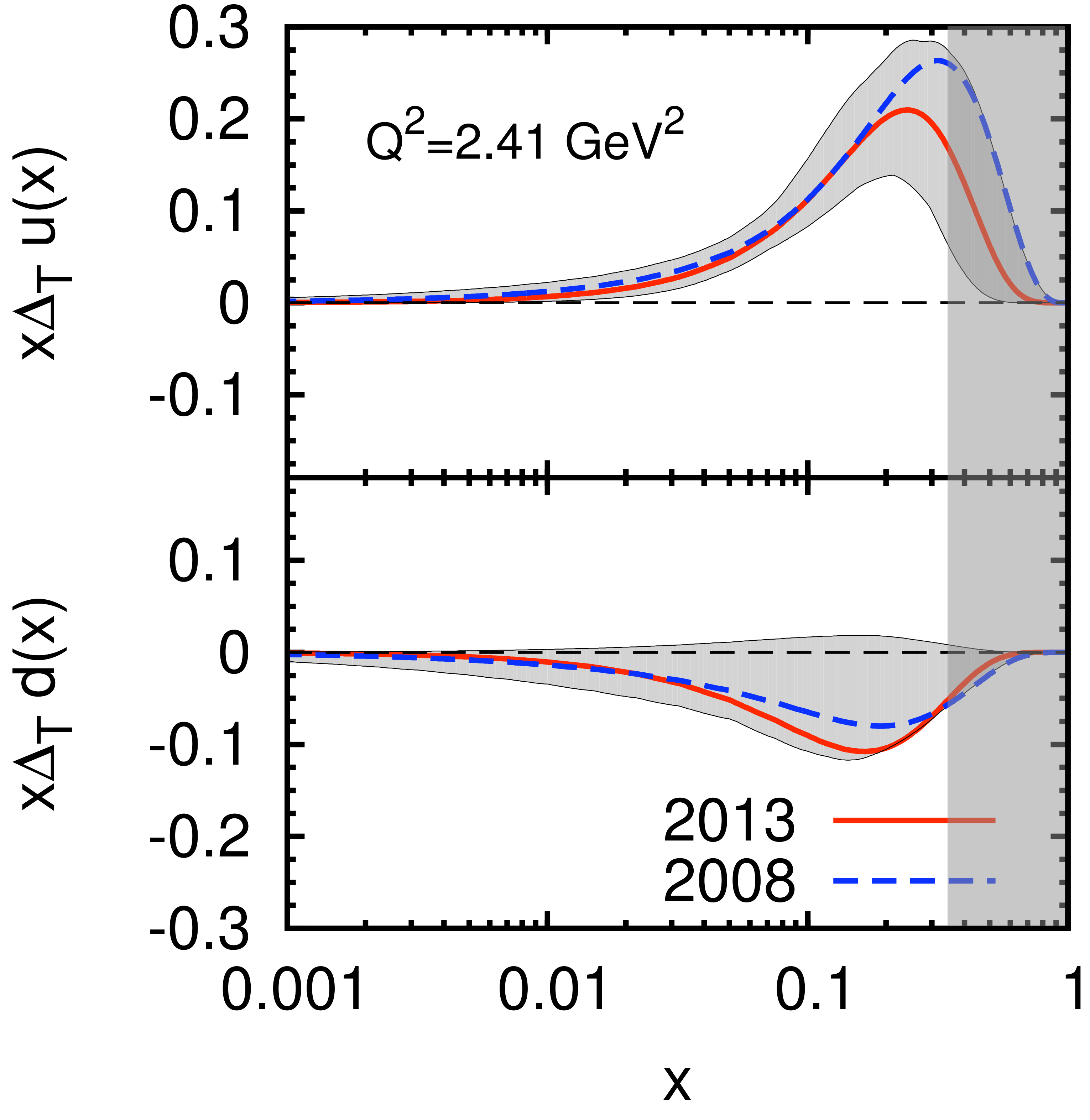
$$\langle\sin(\phi+\phi_S)\rangle_{UT}^{\pi^+} \sim \left(4h_1^u - h_1^d\right) H_{1,\text{fav}}^{\perp}$$

$$\langle\sin(\phi+\phi_S)\rangle_{UT}^{\pi^-} \sim -\left(4h_1^u - h_1^d\right) H_{1,\text{fav}}^{\perp}$$

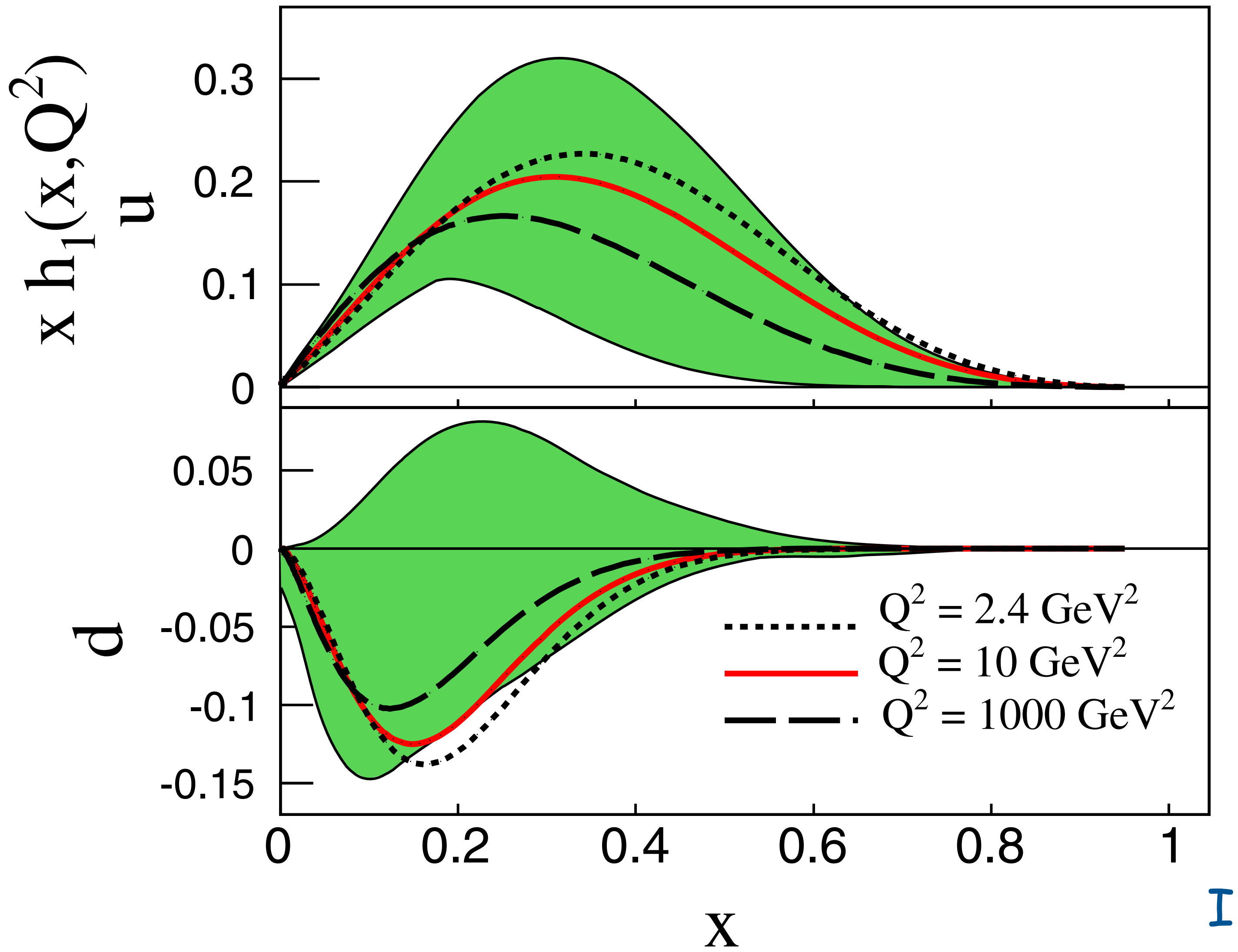
“impossible” to disentangle u/d transversity

current limits driven mainly by Soffer bound?

[M. Anselmino et al., PRD 87 (2013) 094019]



[Z.B. Kang et al. PRD93 (2016) 014009]



the "Collins trap"

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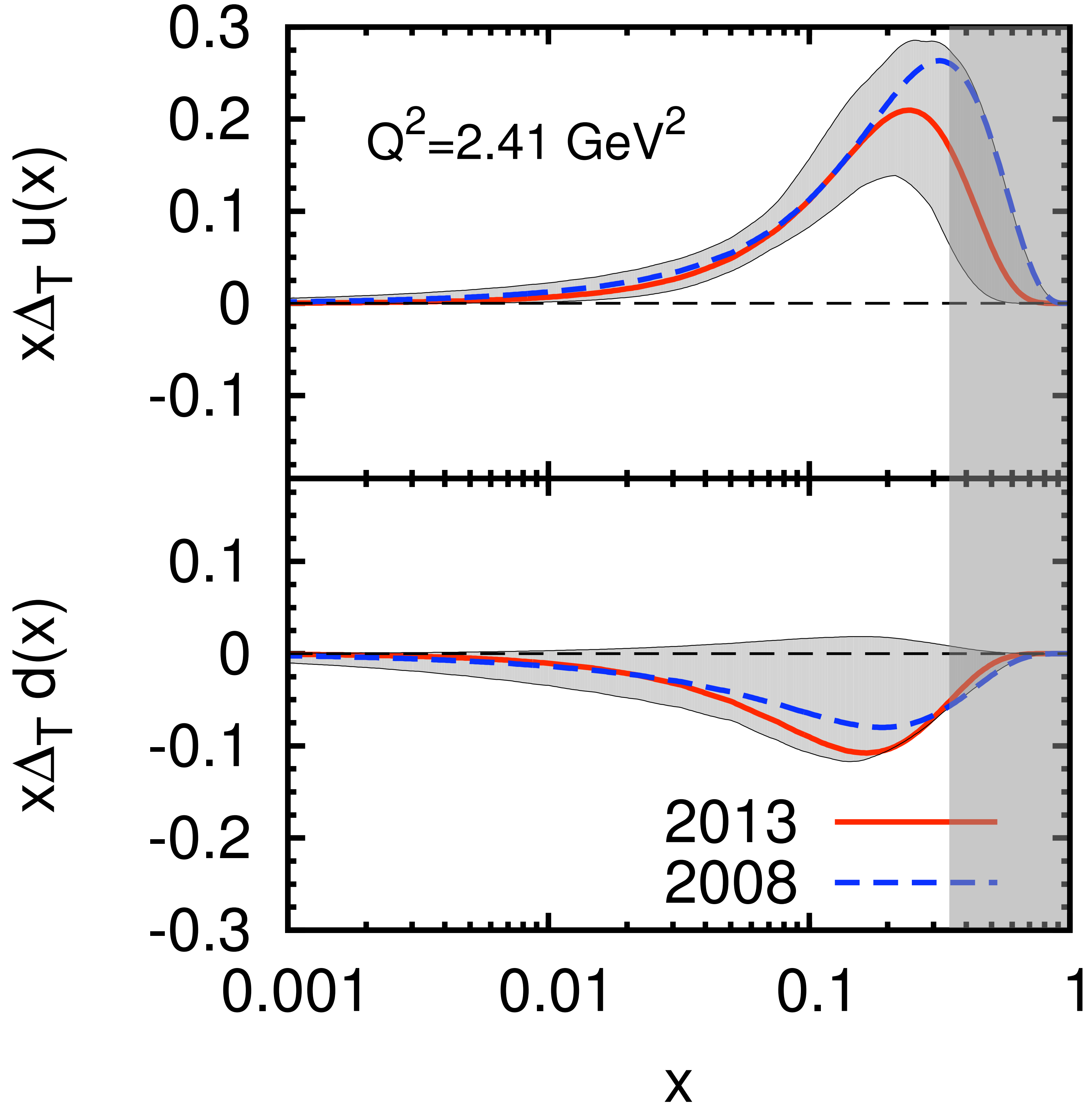
"impossible" to disentangle u/d transversity
current limits driven mainly by Soffer bound?

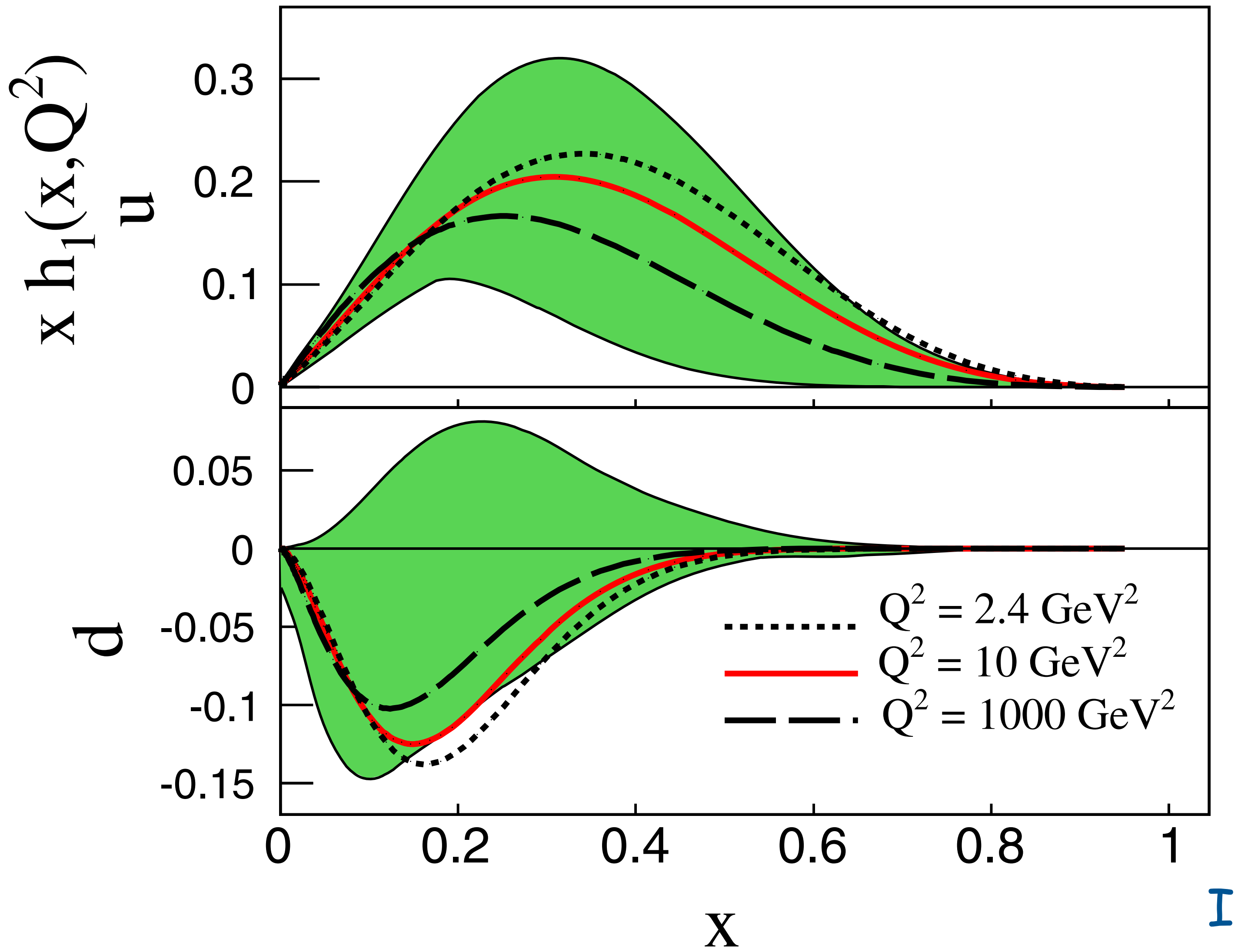
clearly need precise data from "neutron" target(s), e.g., COMPASS d, and later JLab12 & EIC

(valid for all chiral-odd TMDs)

[M. Anselmino et al., PRD 87 (2013) 094019]

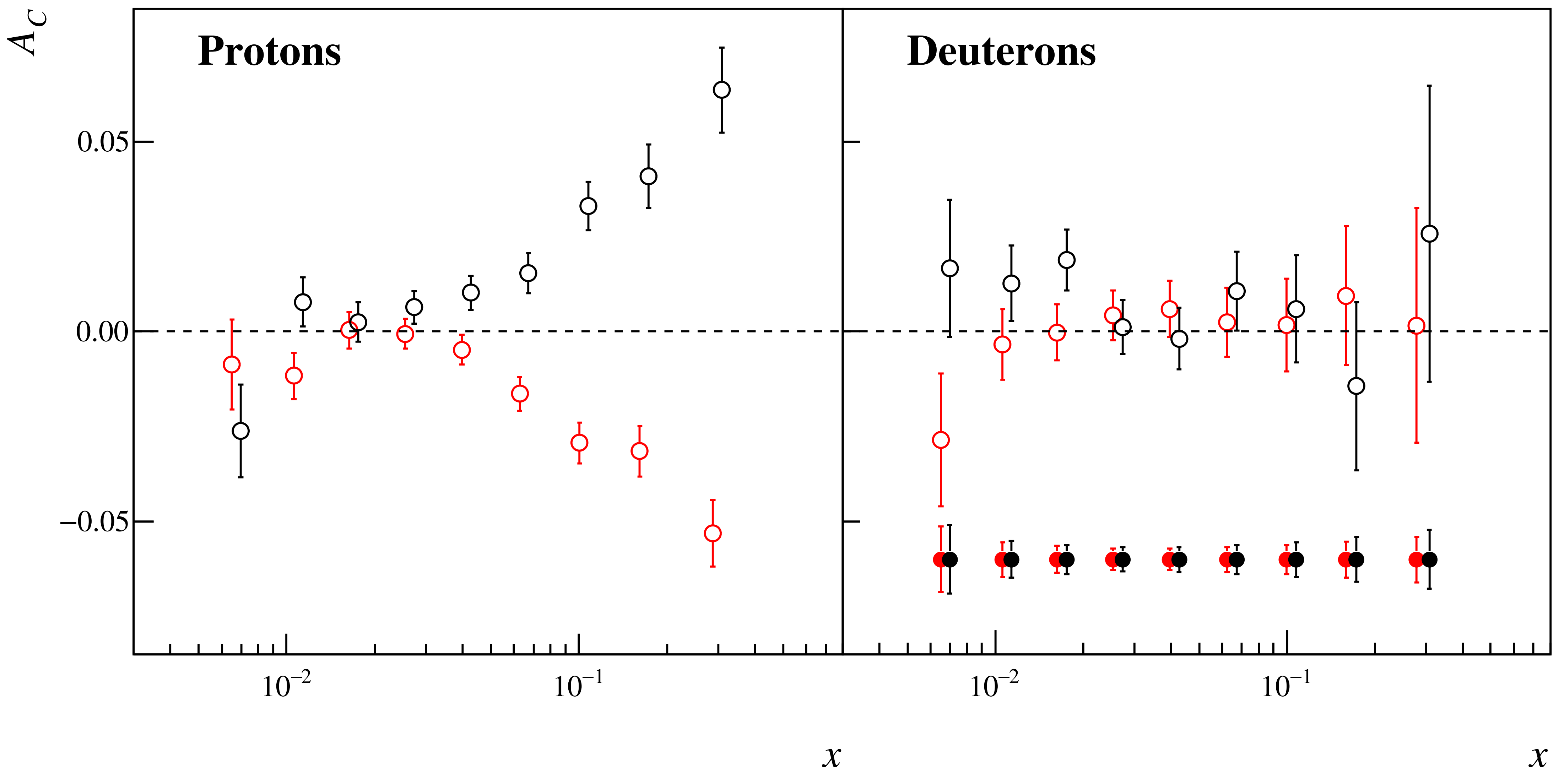


[Z.B. Kang et al. PRD93 (2016) 014009]

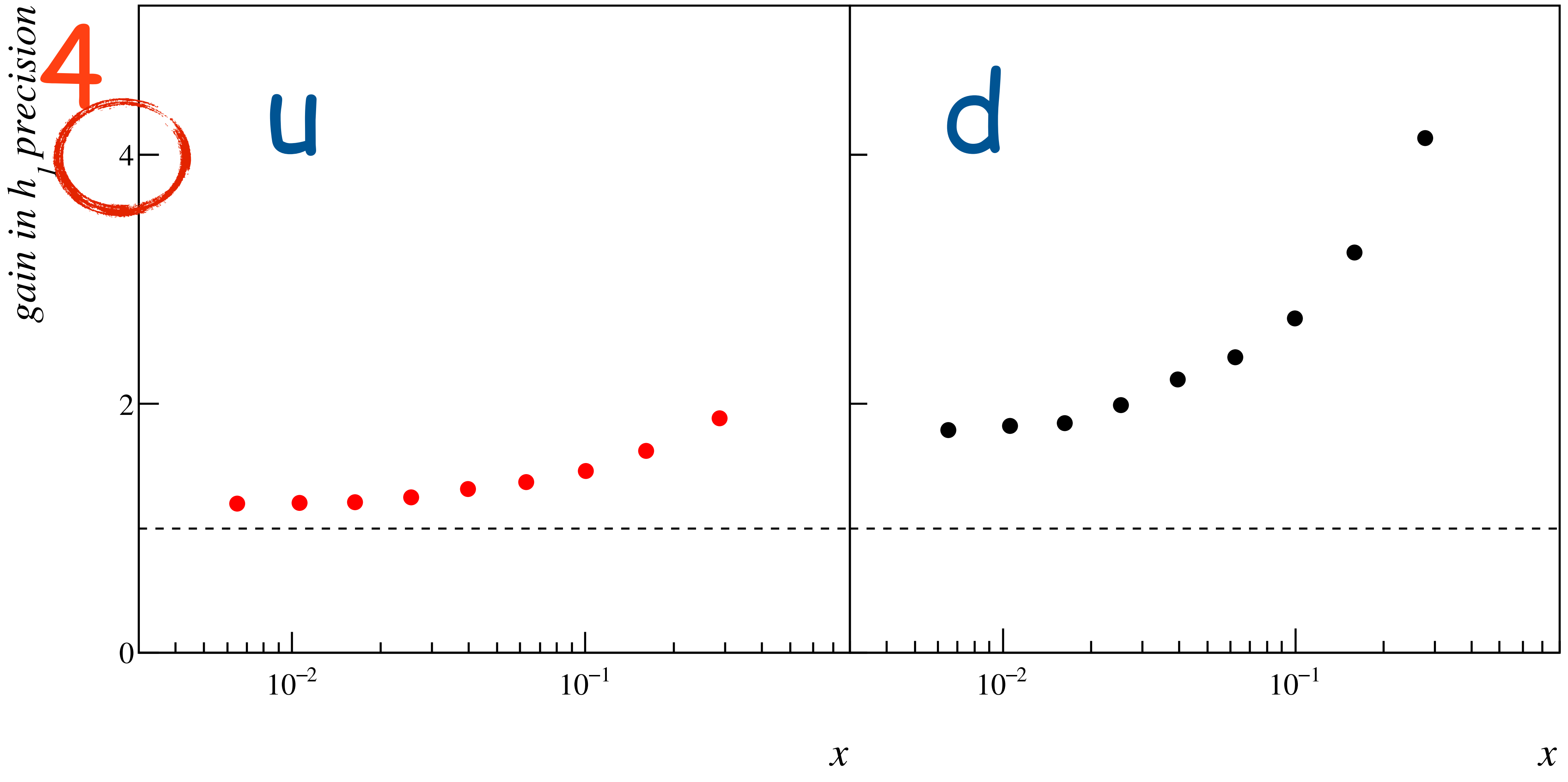


d-transversity running at COMPASS

- currently much more p than d data available
- add another year of d running after CERN Long Shutdown 2 (2021/22)
  - large impact on d-transversity
  - reduced correlations between u and d transversity
    (note, correlations important in tensor-charge calculation)



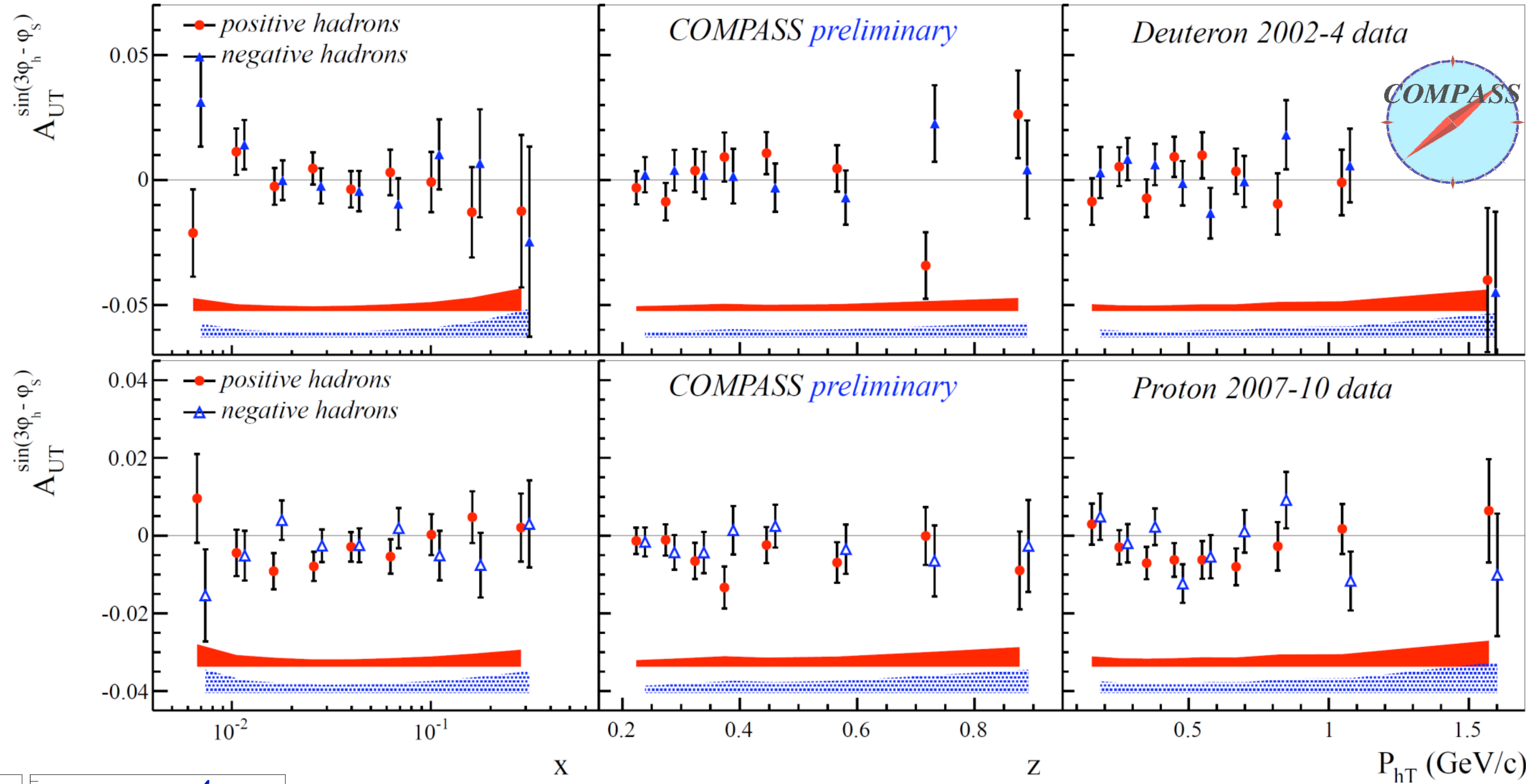
gain in h_1 precision



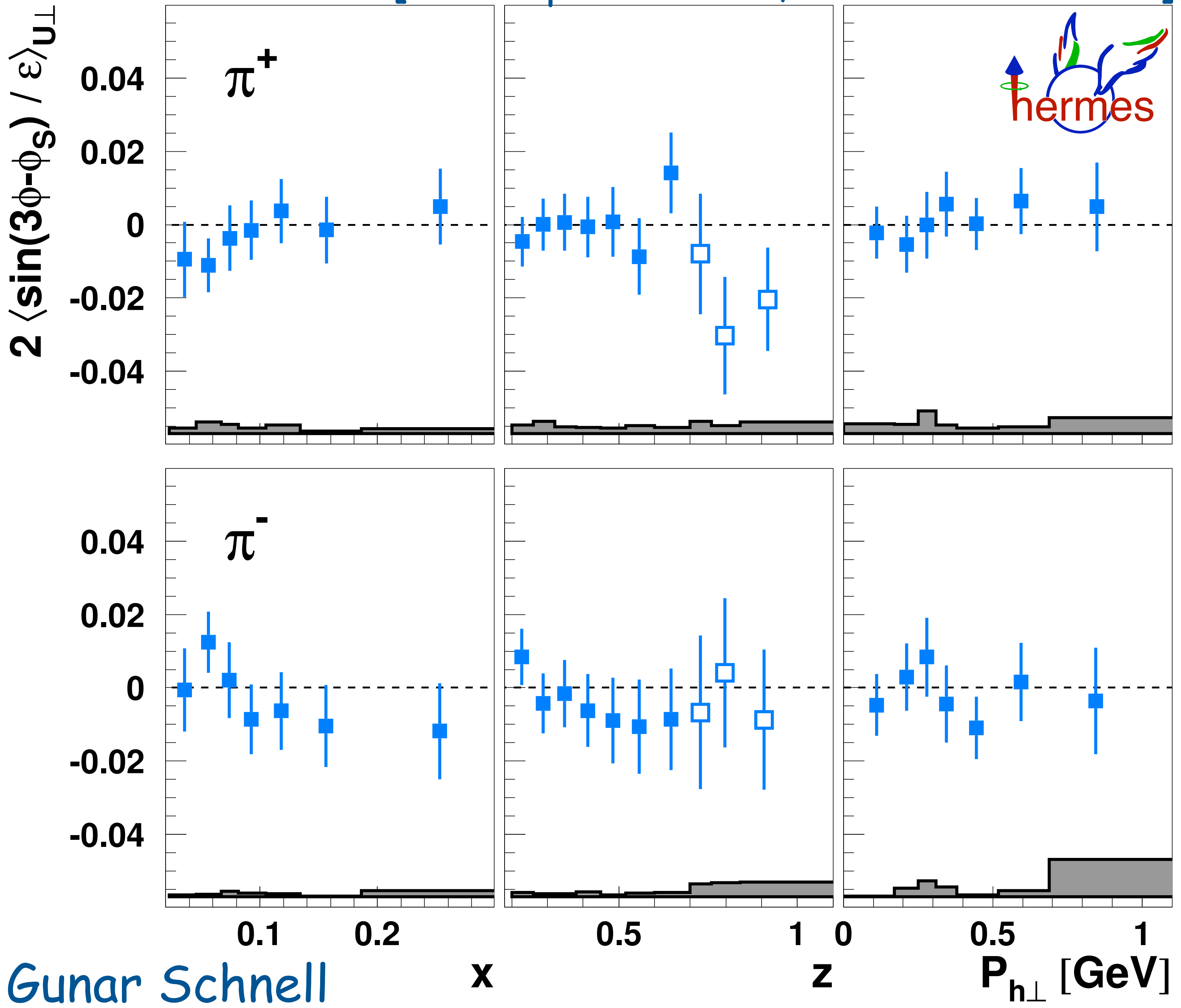
Pretzelosity

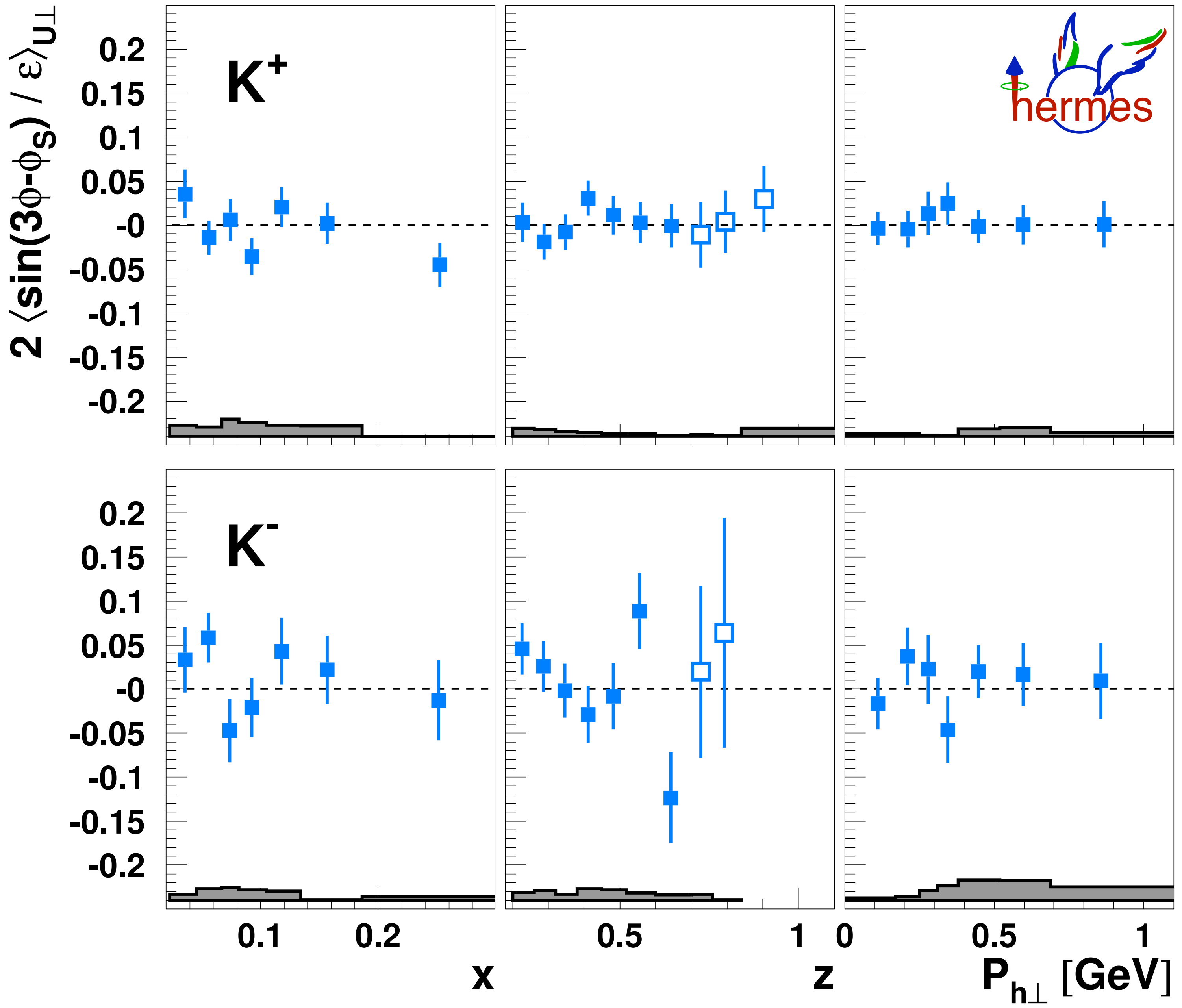
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

- chiral-odd ➥ needs Collins FF (or similar)
- ^{1}H, ^{2}H & ^{3}He data consistently small
- cancelations? pretzelosity=zero? or just the additional suppression by two powers of $P_{h\perp}$

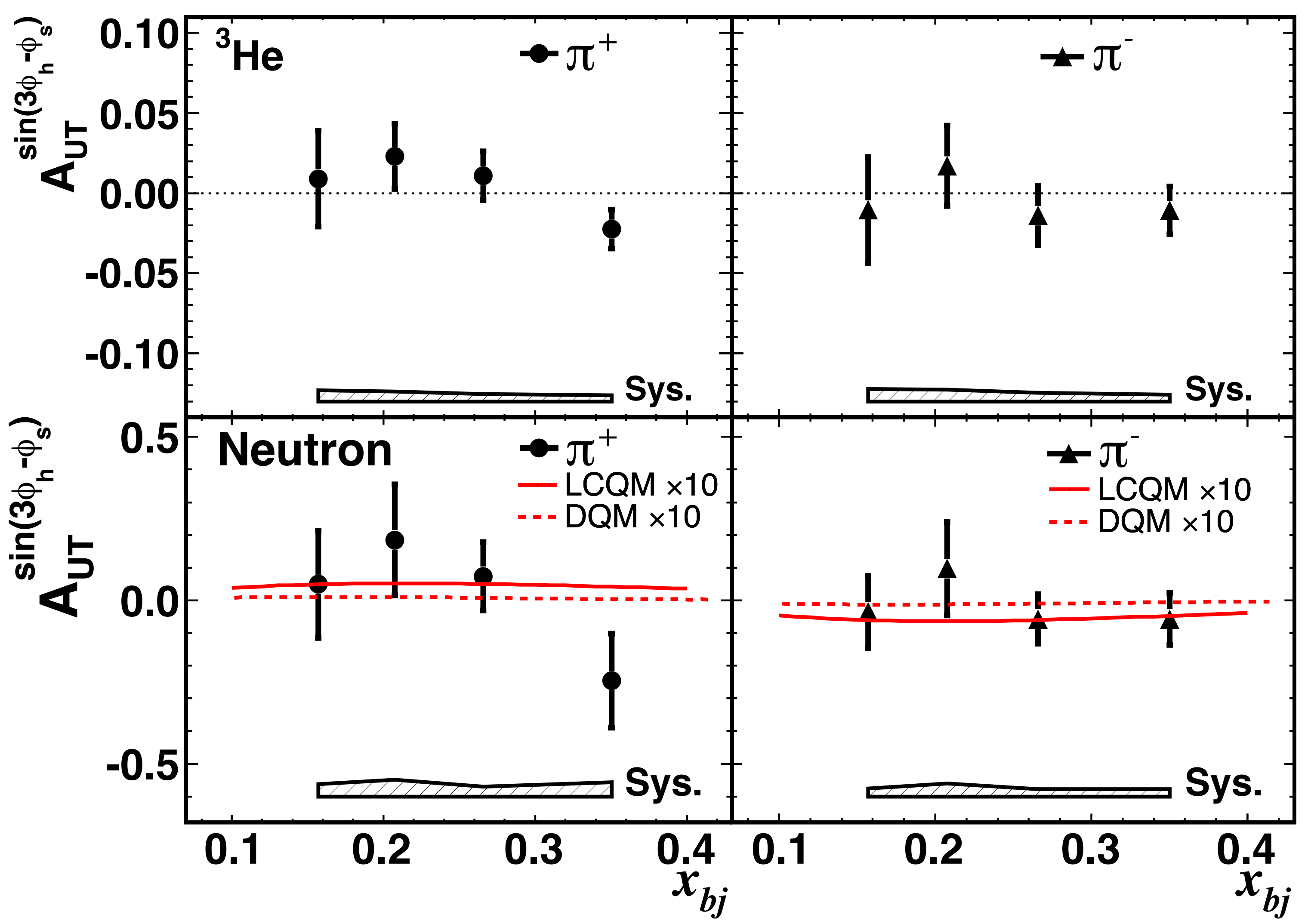


[A. Airapetian et al., arXiv:2007.07755]

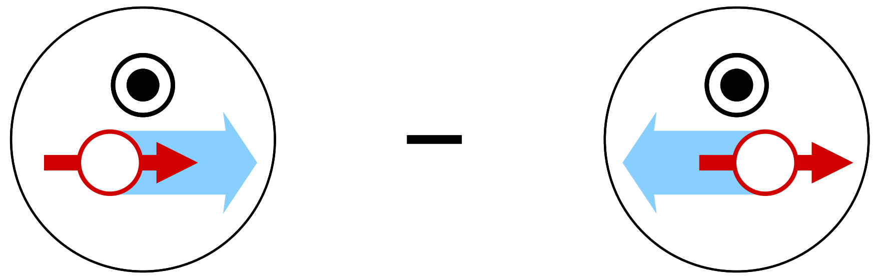




[JLab Hall A, PRC 90 (2014) 055209]



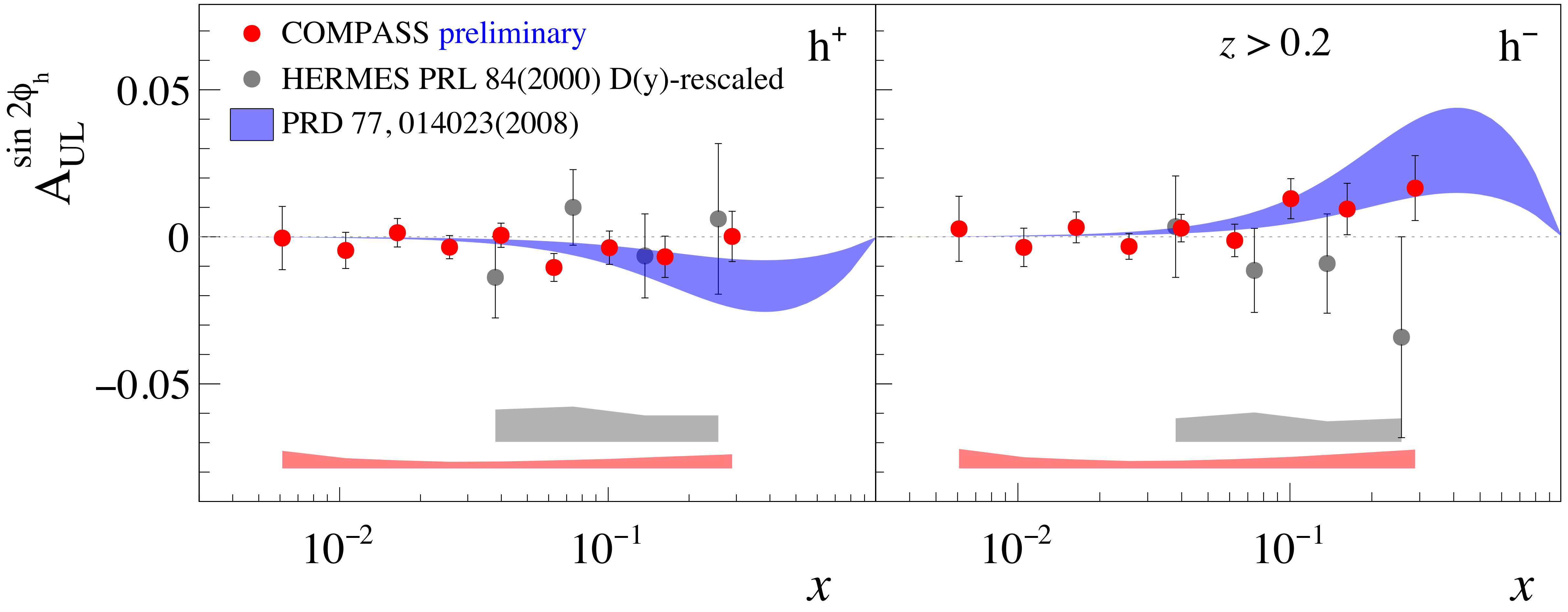
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



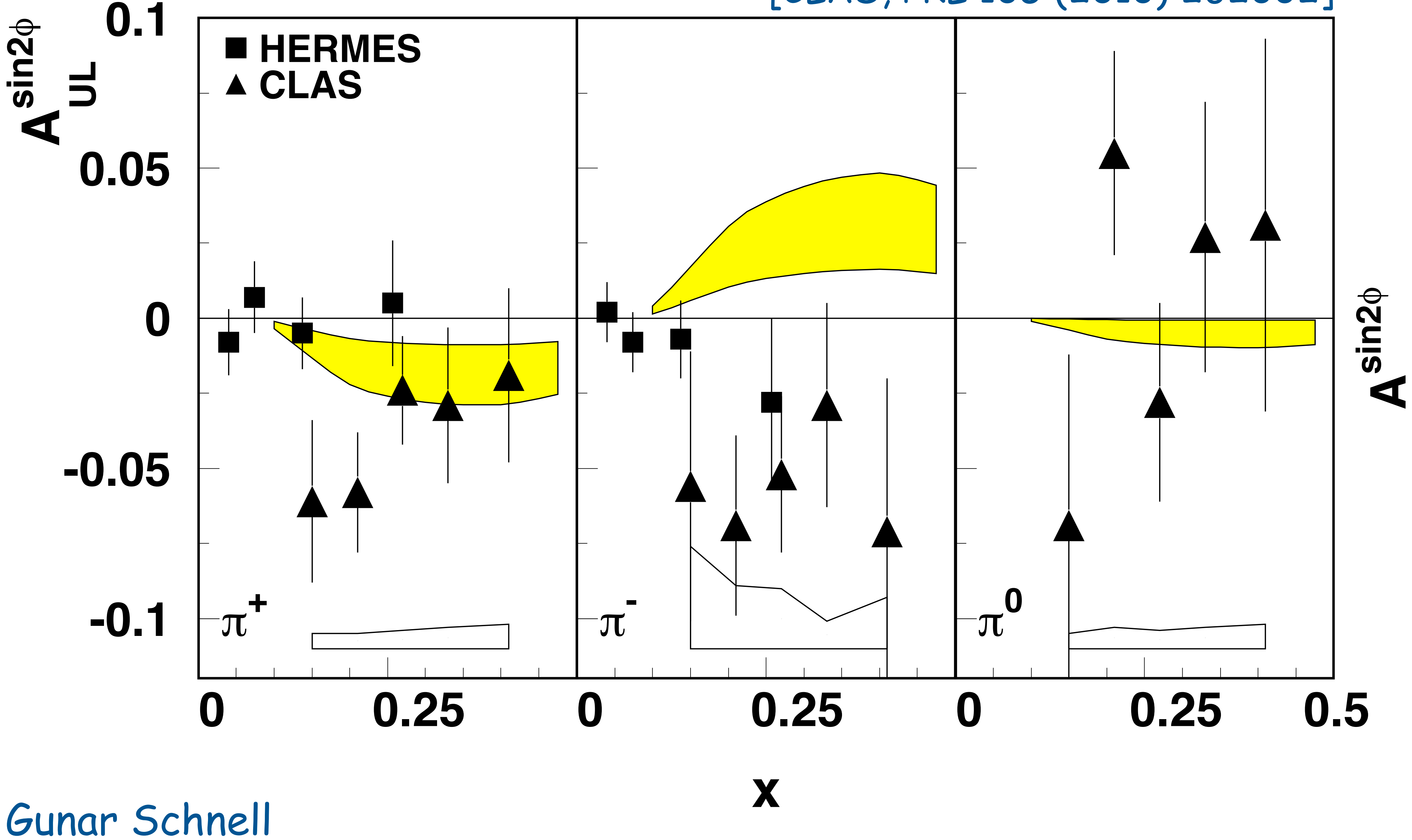
Worm-Gear I

- evidence from CLAS?
- consistent with zero at COMPASS and HERMES for both proton and deuteron targets (slight hint for non-zero valence-x h⁻ asymmetry)
- new results from CLAS not supportive, but only π^0

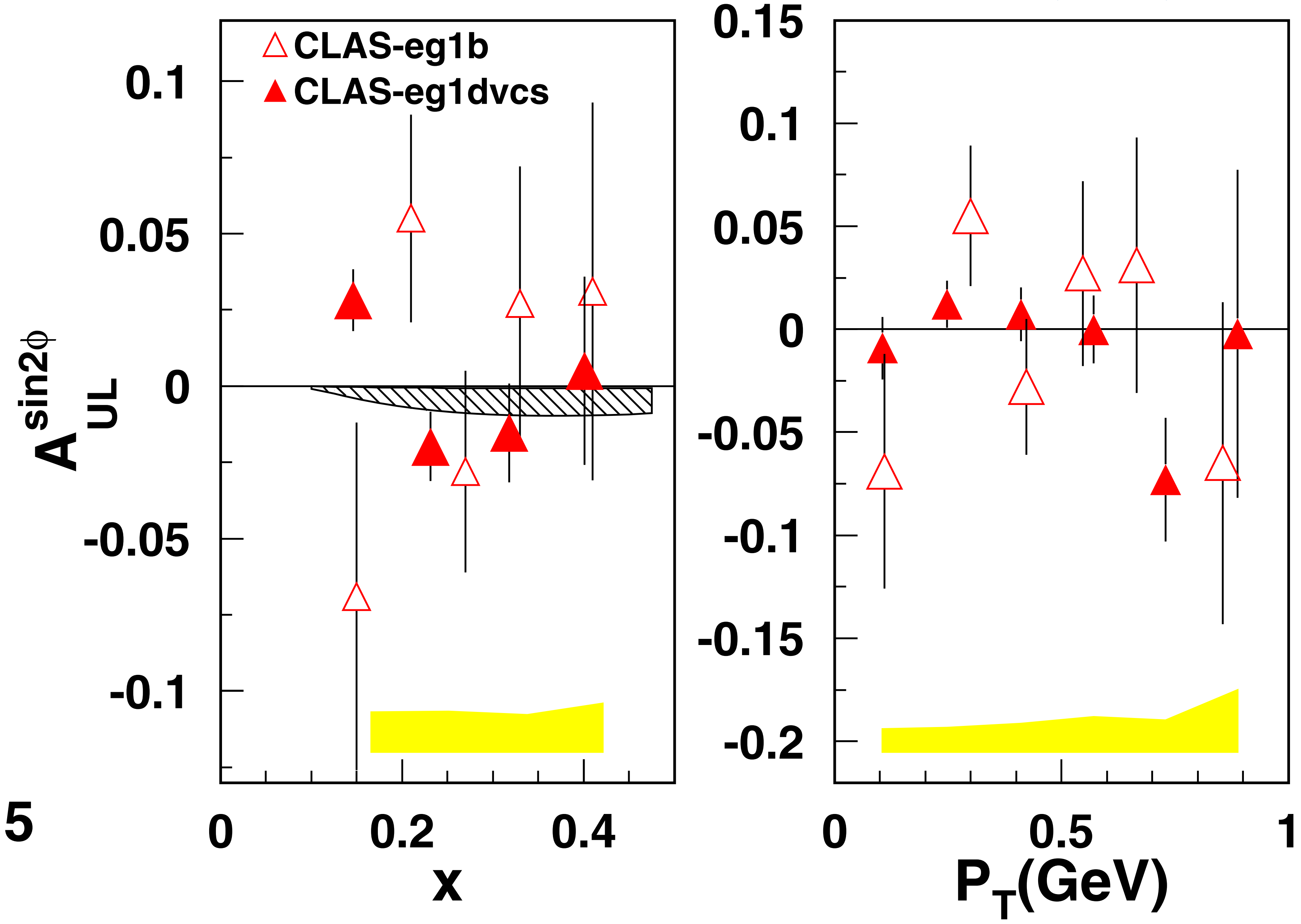
[JHEP 06 (2019) 007]



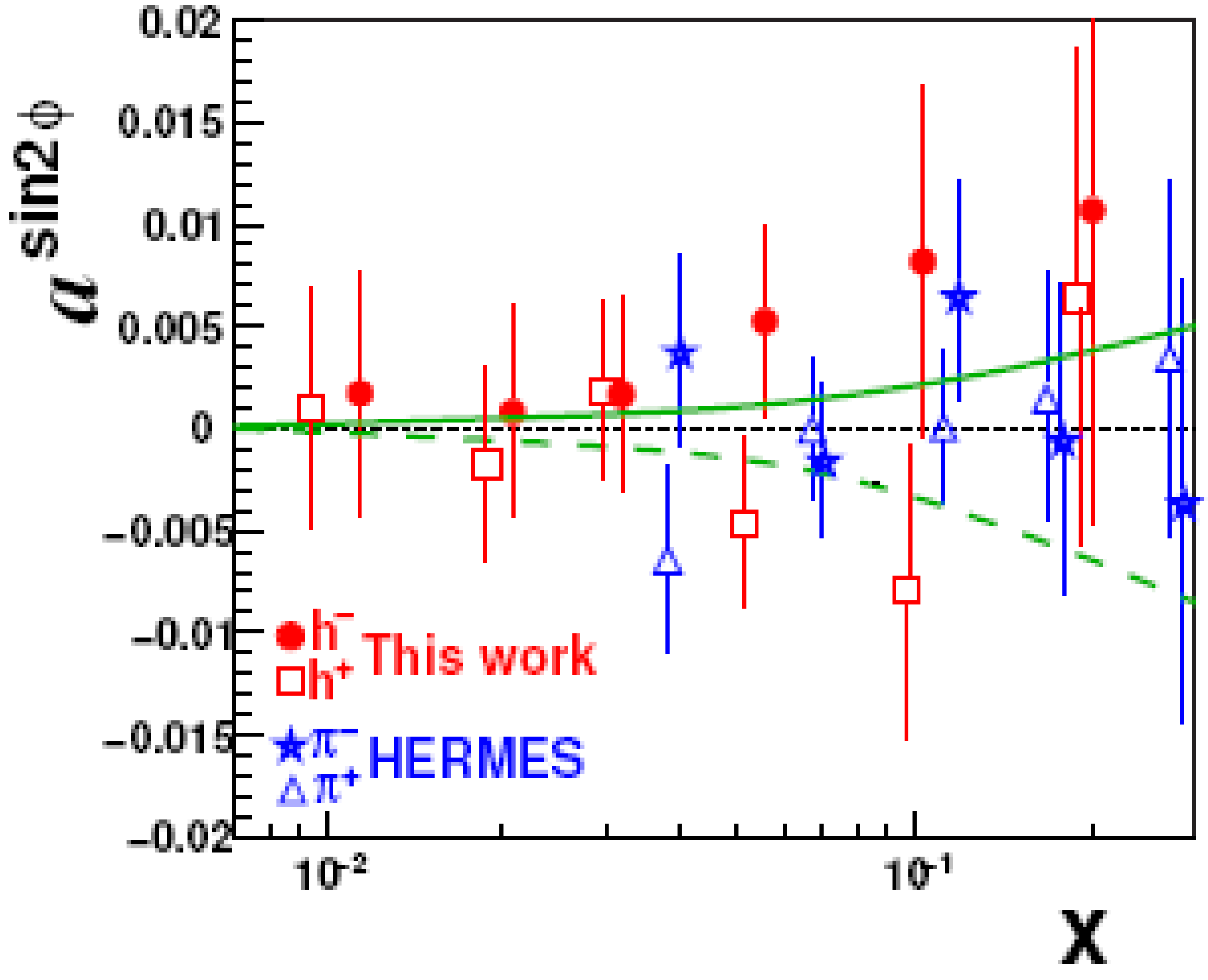
[CLAS, PRL 105 (2010) 262002]



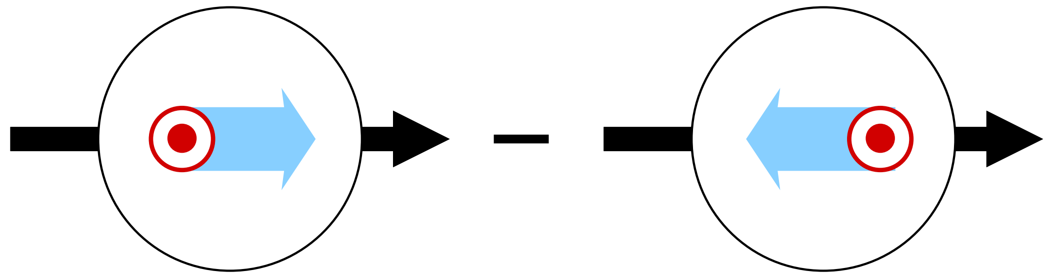
[CLAS, PLB 782 (2018) 662]



[COMPASS, EPJ C 70 (2010) 39]

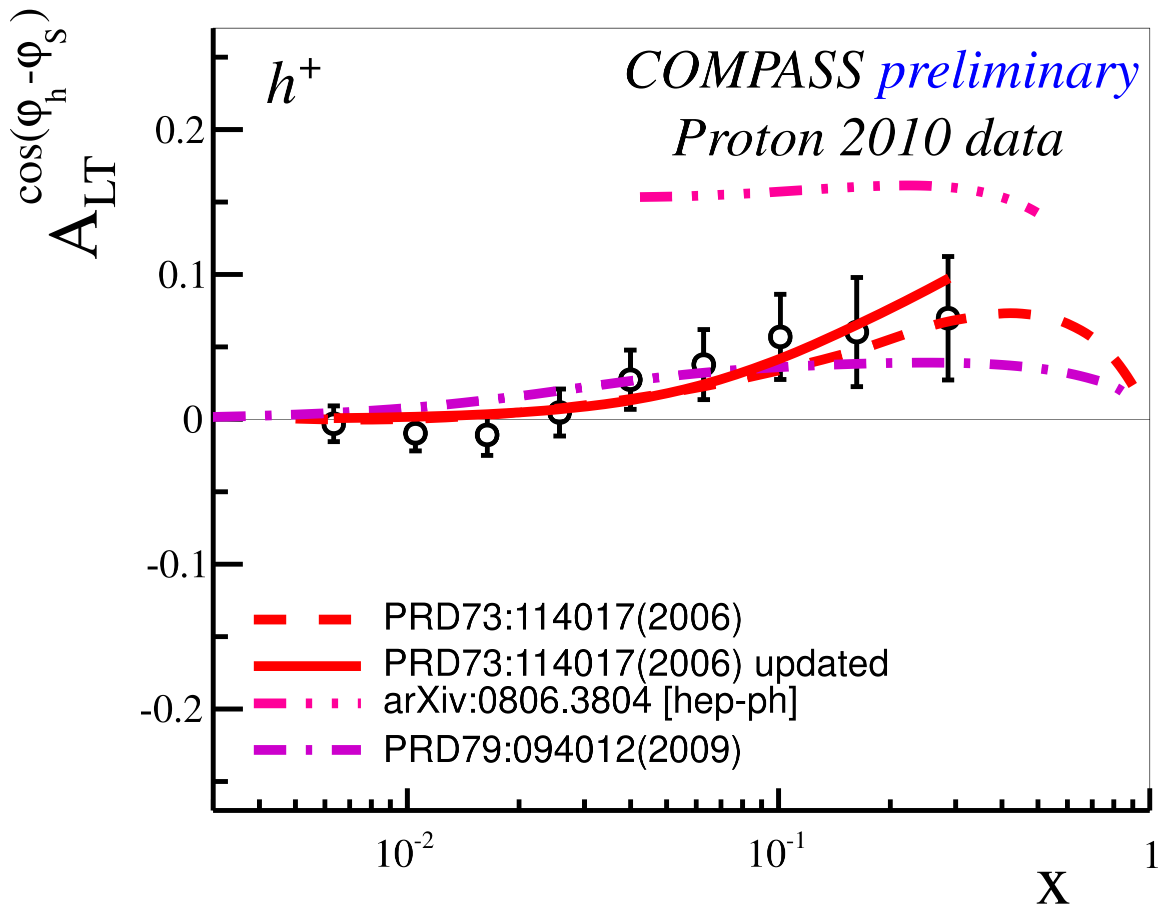


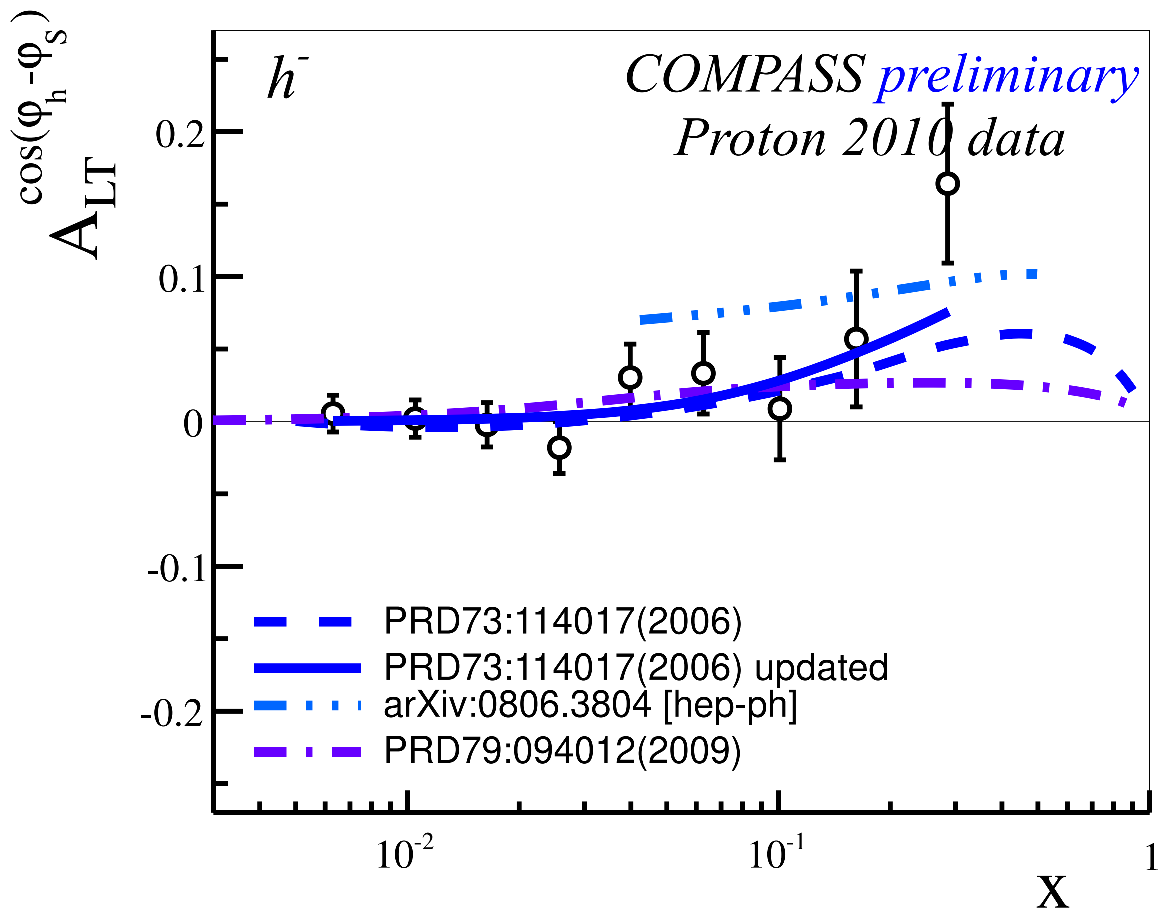
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



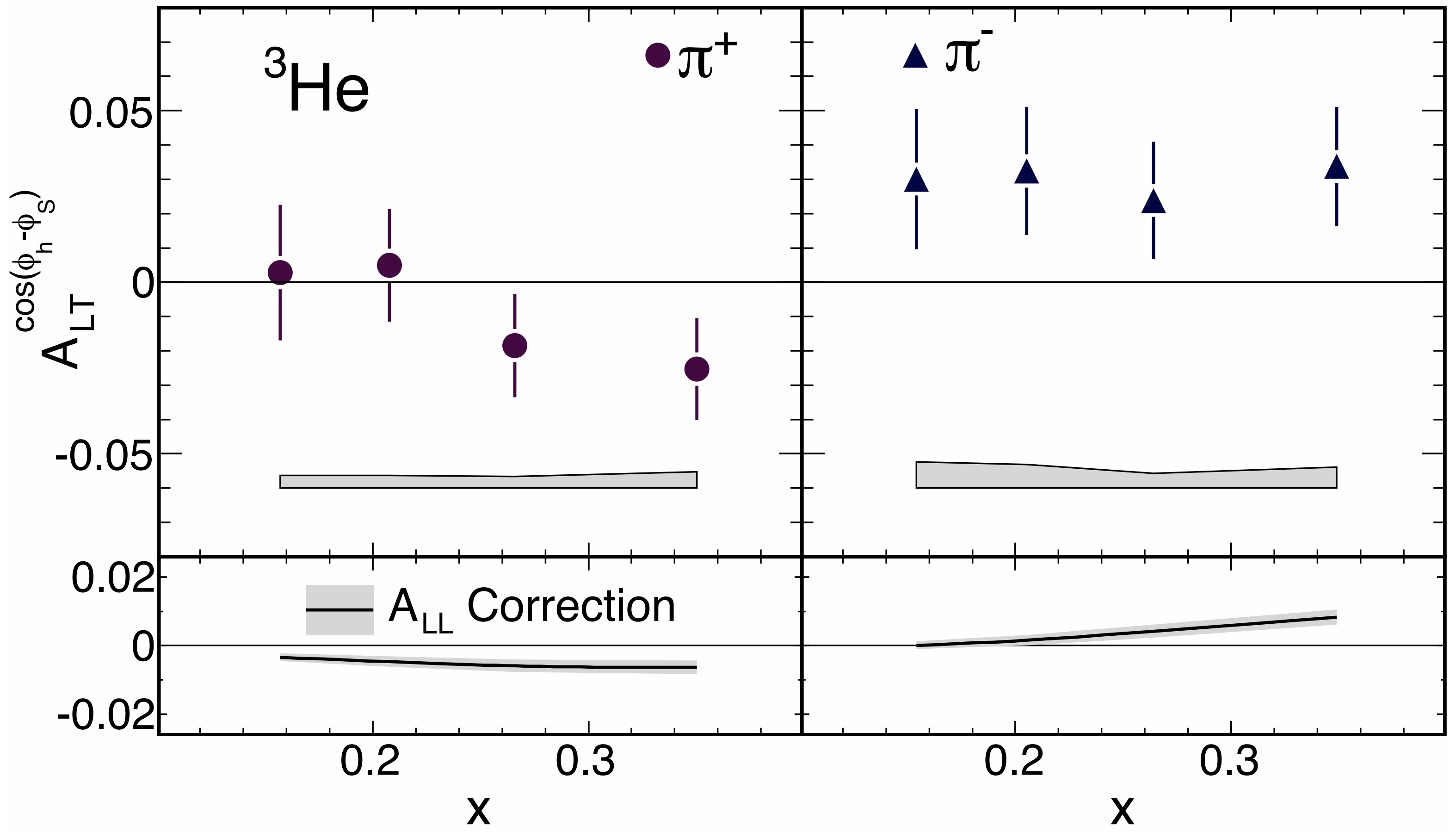
Worm-Gear II

- chiral even, couples to D_1
- evidences from
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES





[PRL 108 (2012) 052001]



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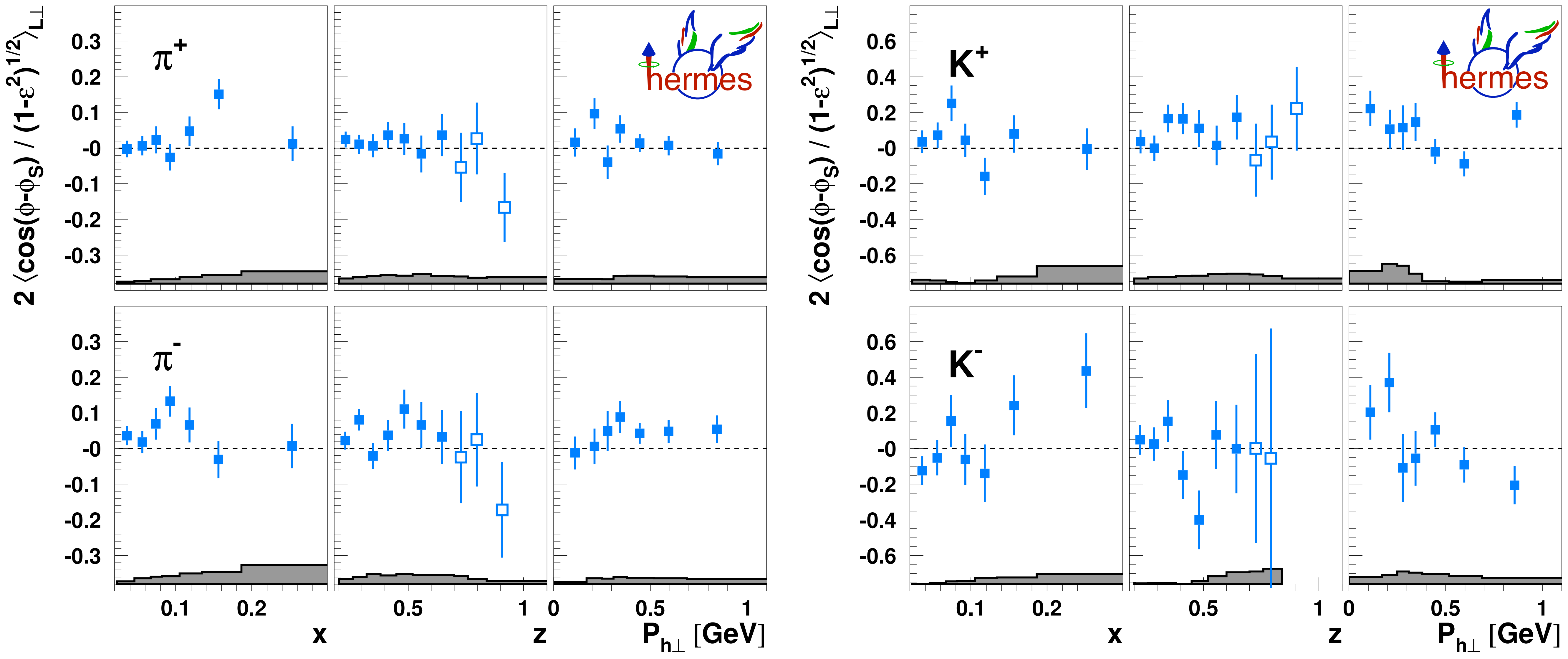
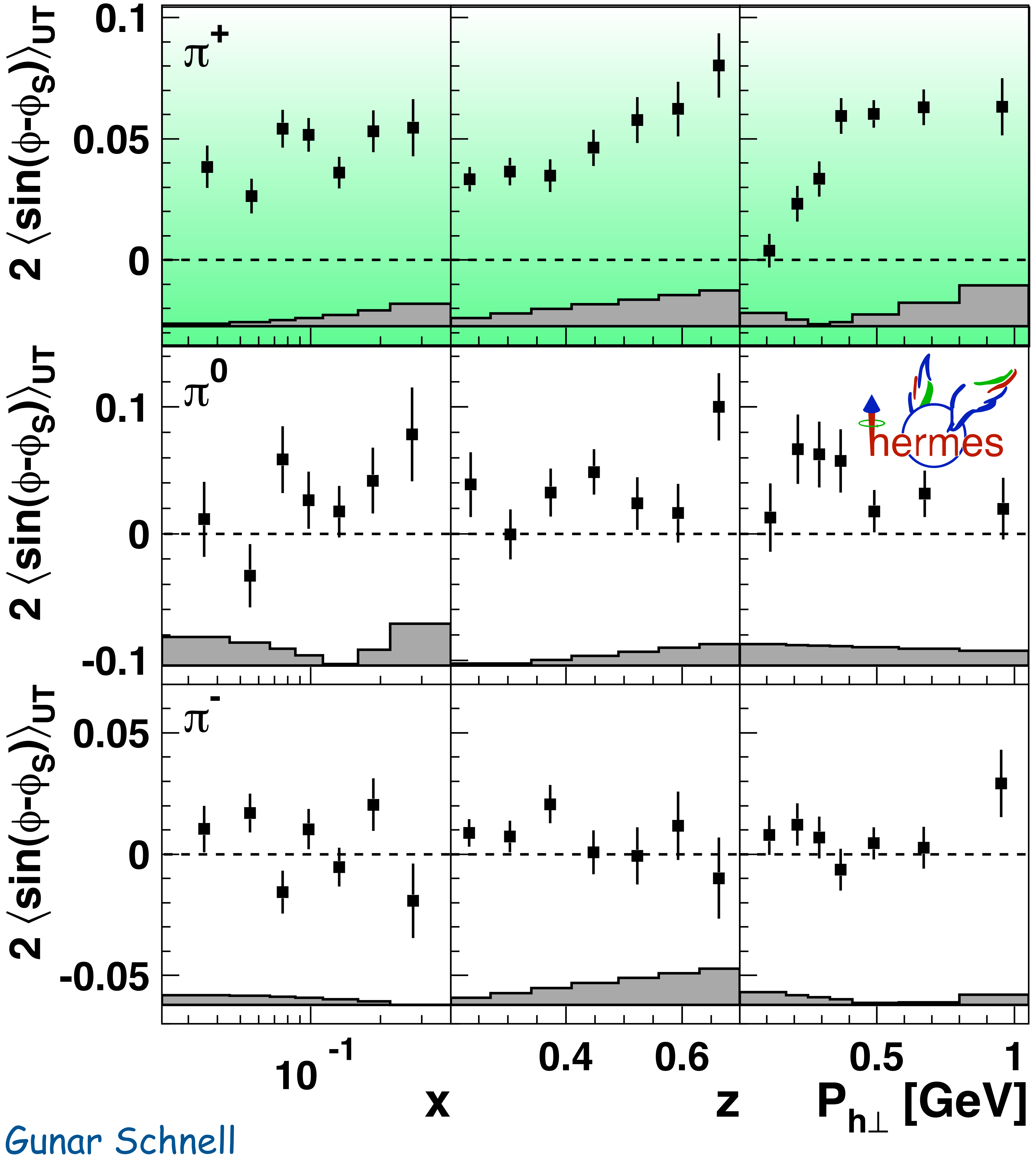


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2)\otimes\mathcal{W}\, D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

7.3% scale uncertainty [PRL 103 (2009) 152002]



	U	L	T
U	f_1		$h_1^\perp$
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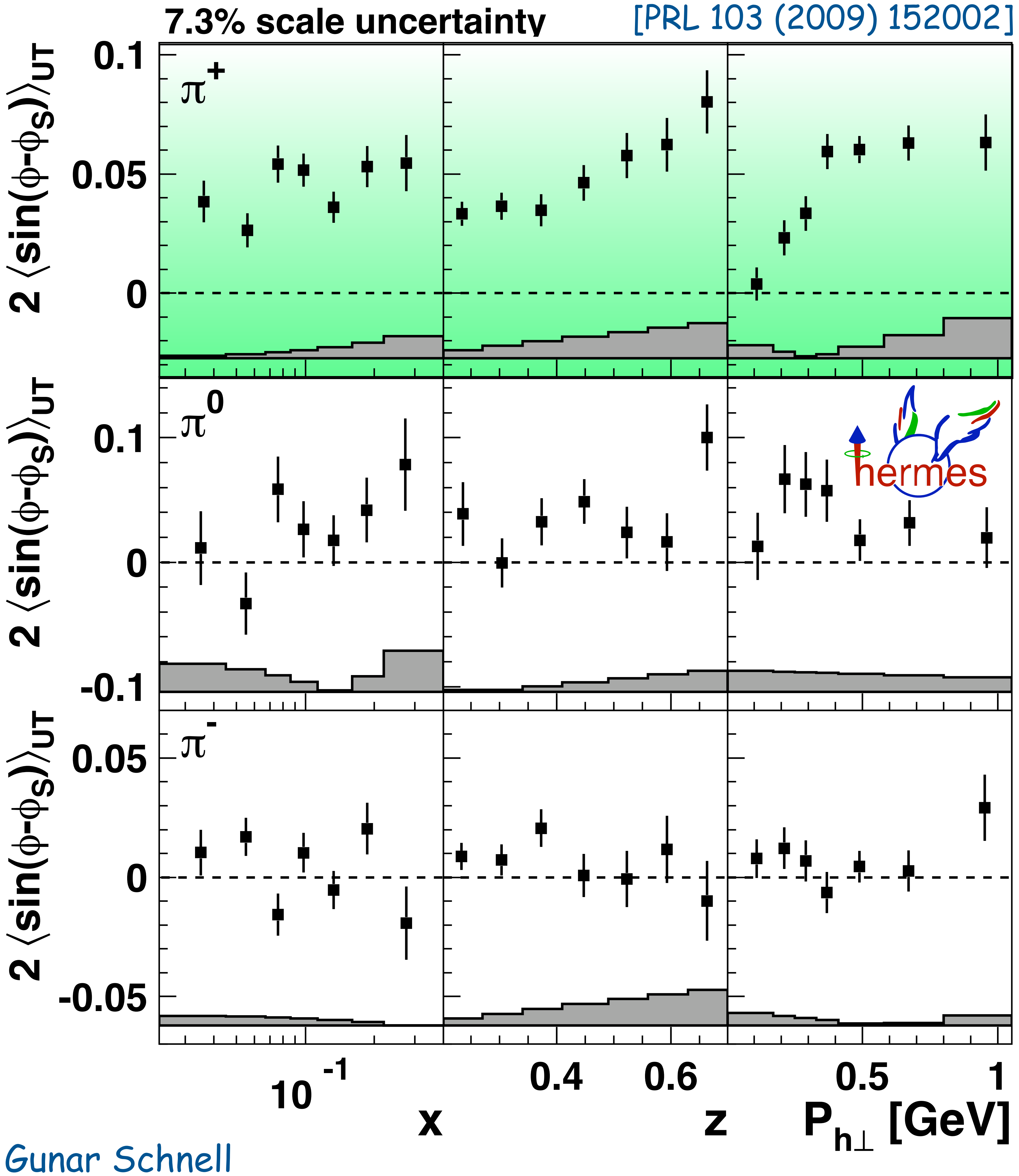

[PRL 103 (2009) 152002]

π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

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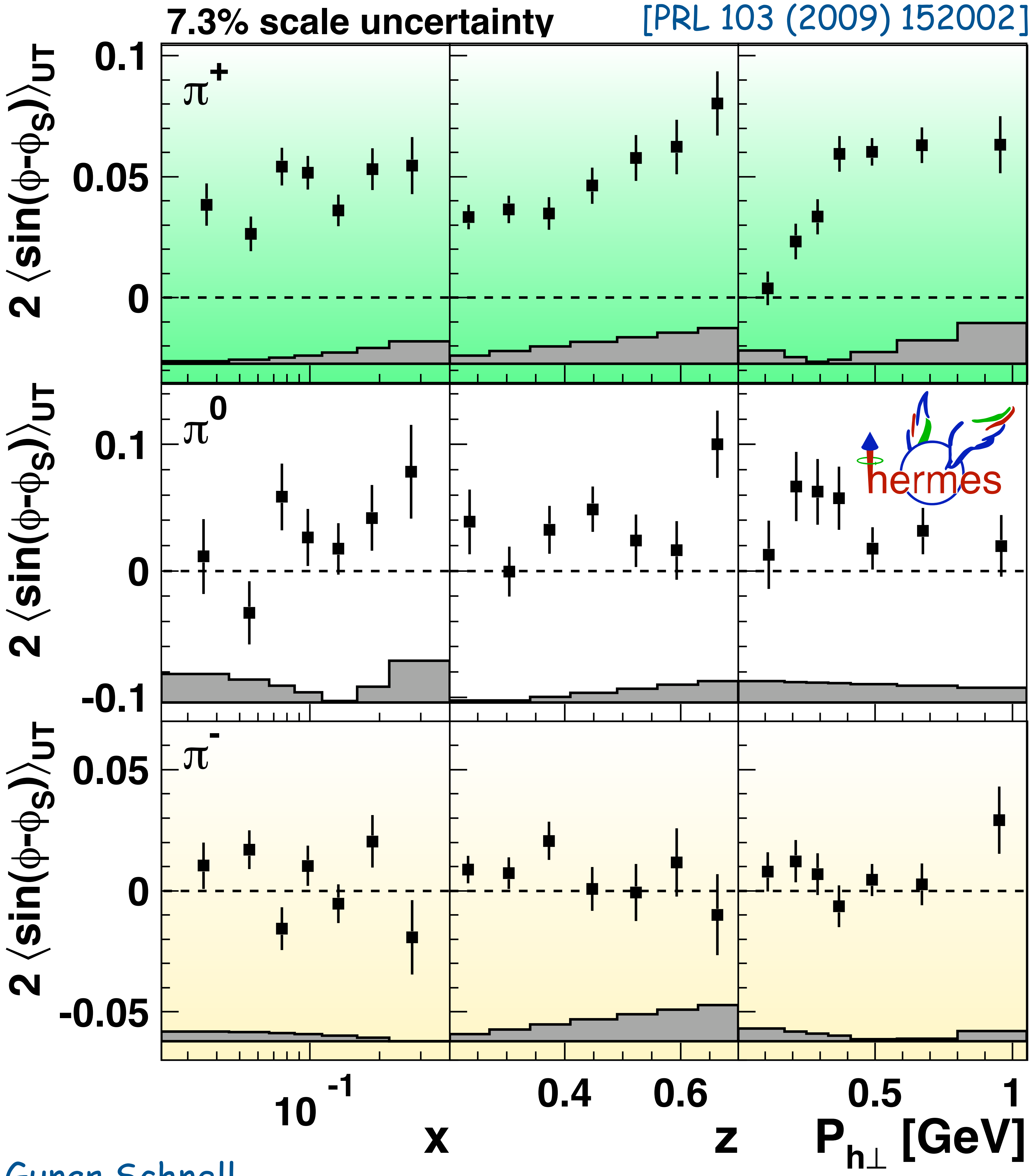
Sivers amplitudes for pions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[PRL 103 (2009) 152002]

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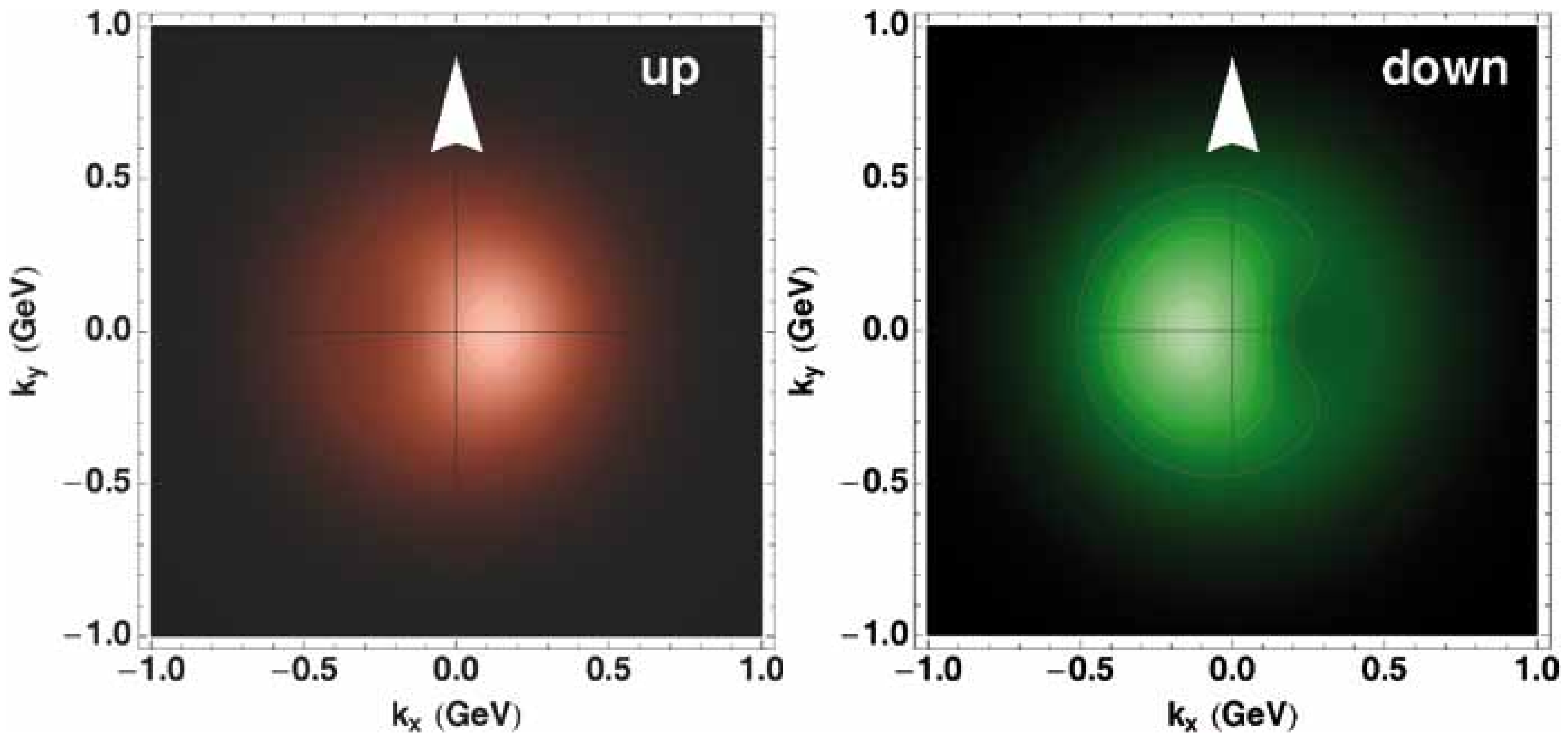
☛ u-quark Sivers DF < 0

☛ d-quark Sivers DF > 0

(cancelation for π^-)

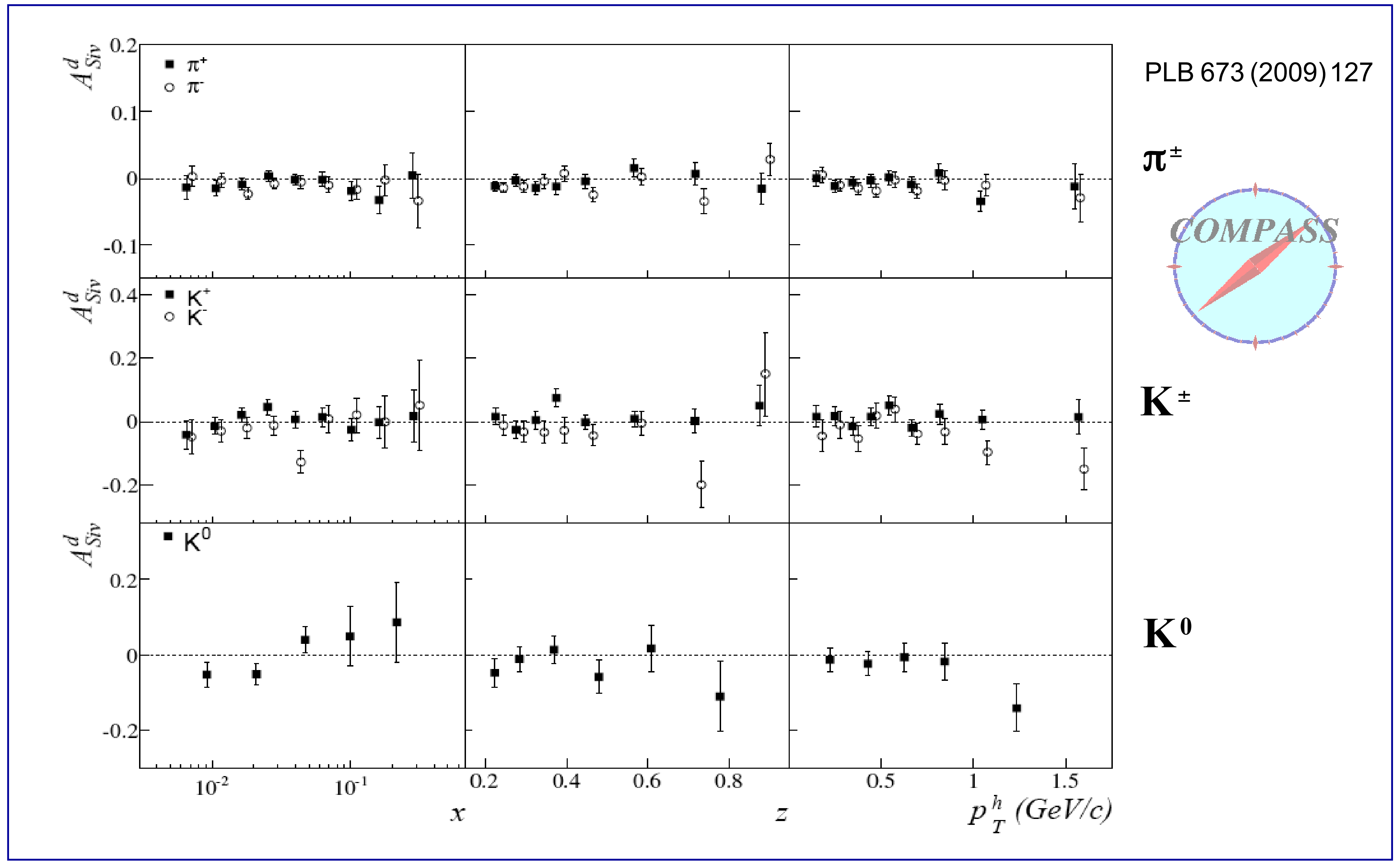
Sivers amplitudes

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$



[A. Bacchetta et al.]

- cancelation for D target supports opposite signs of up and down Sivers



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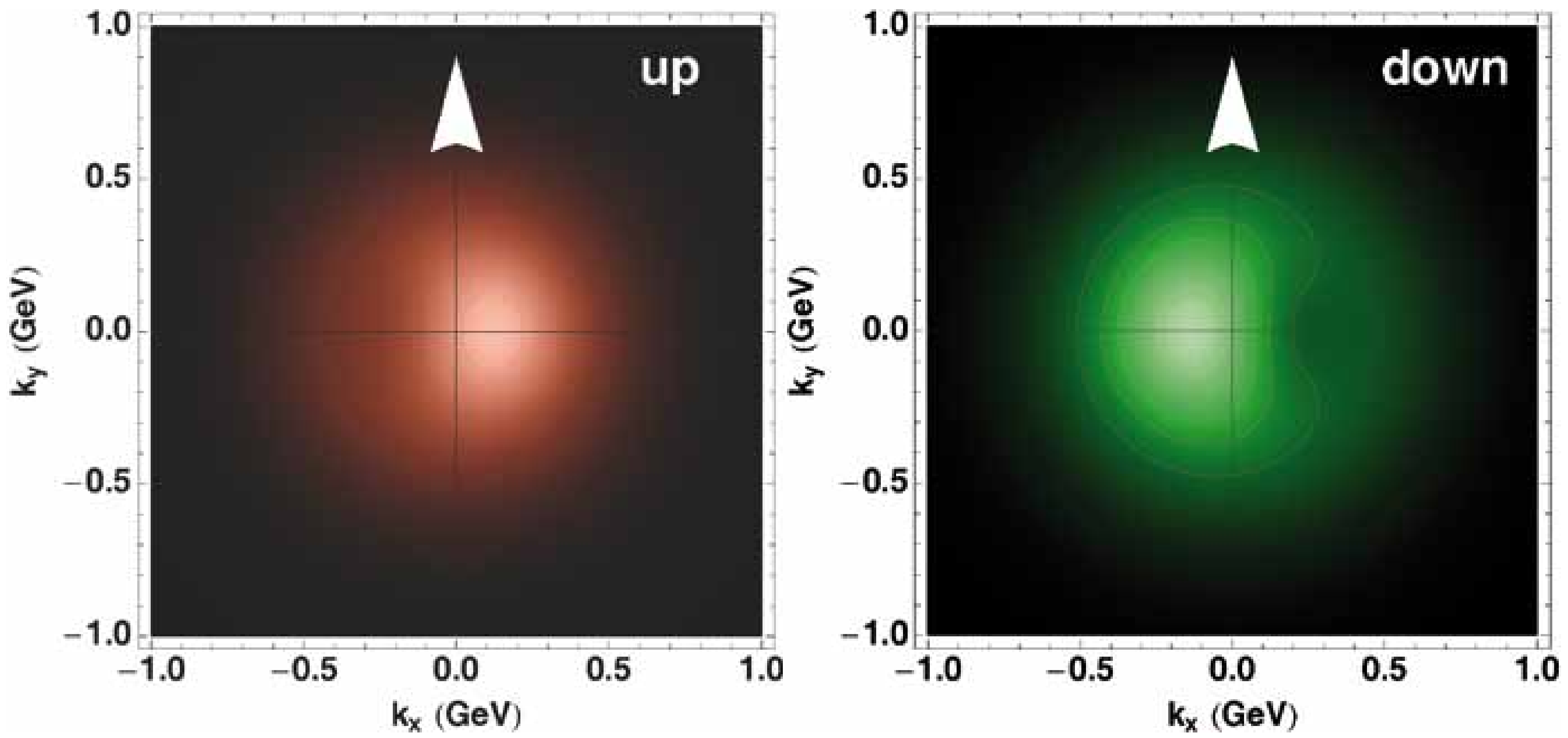

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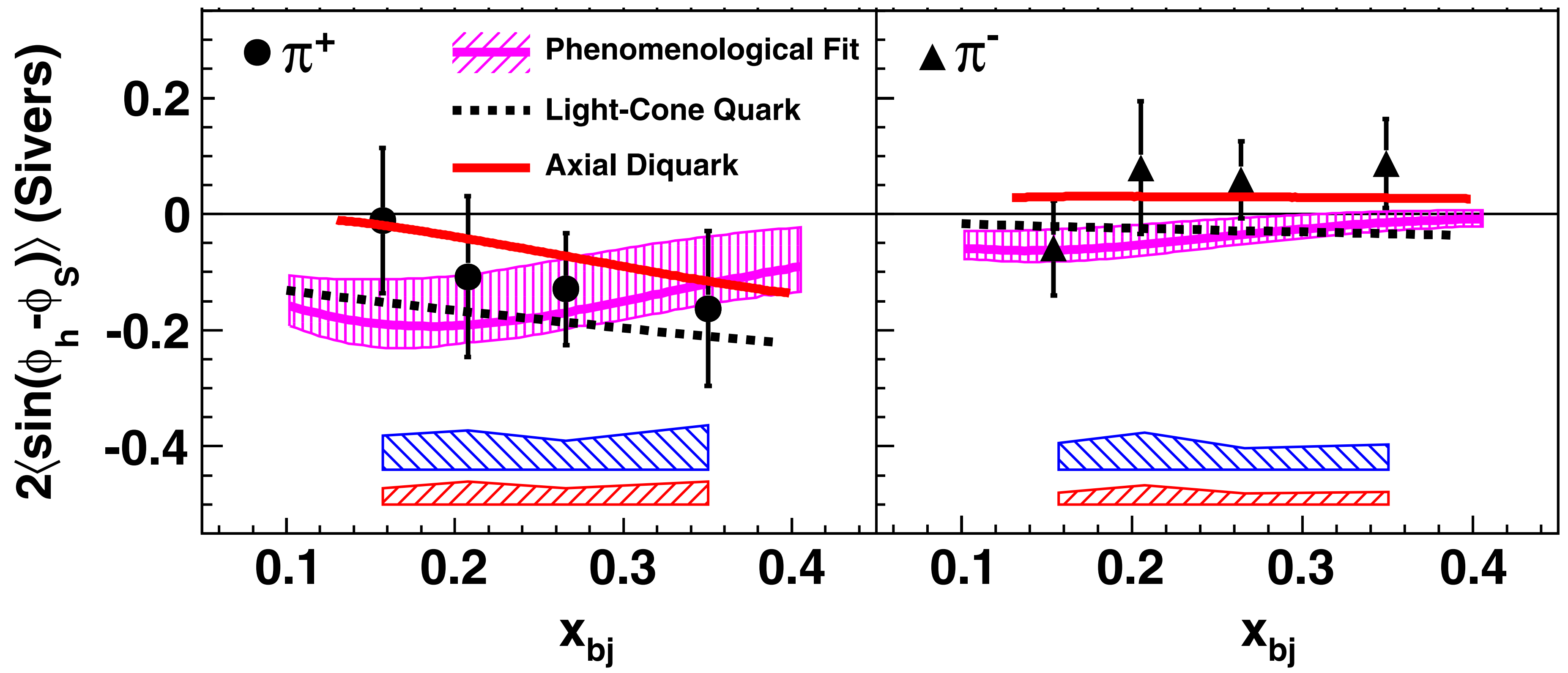
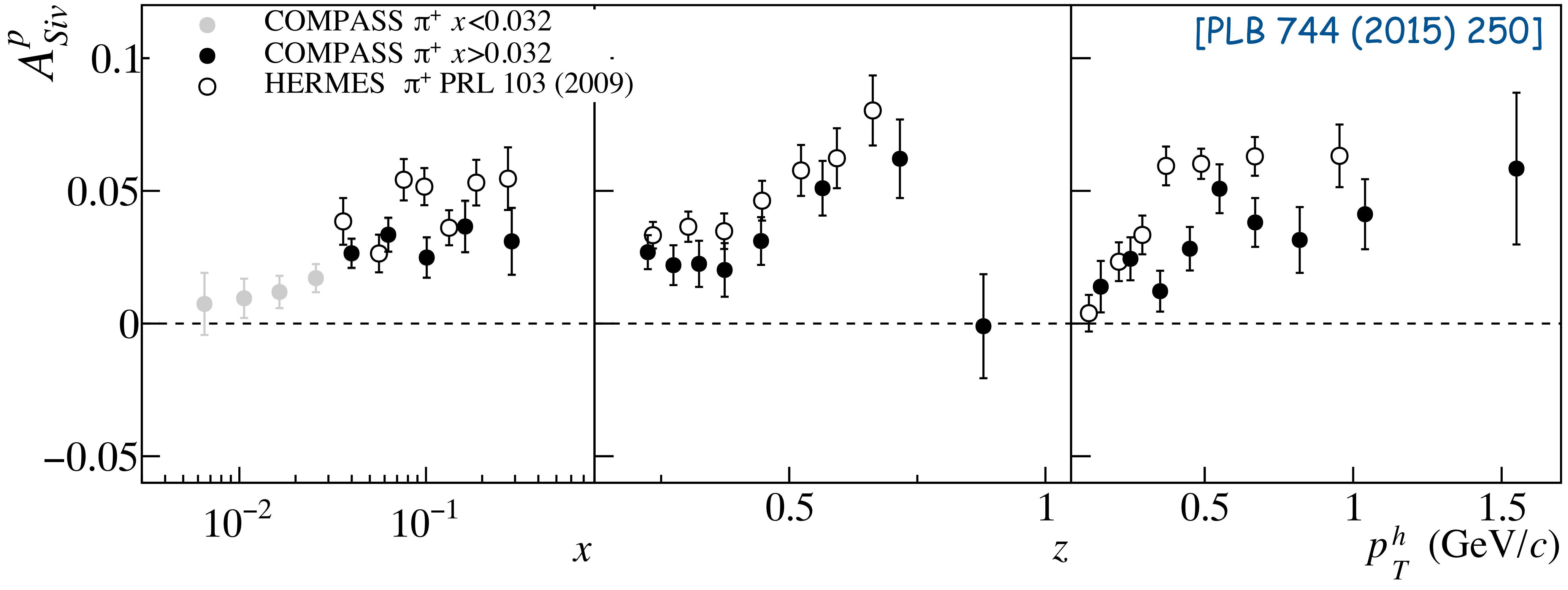
[PRL 107 (2011) 072003]





[PLB 744 (2015) 250]

	U	L	T
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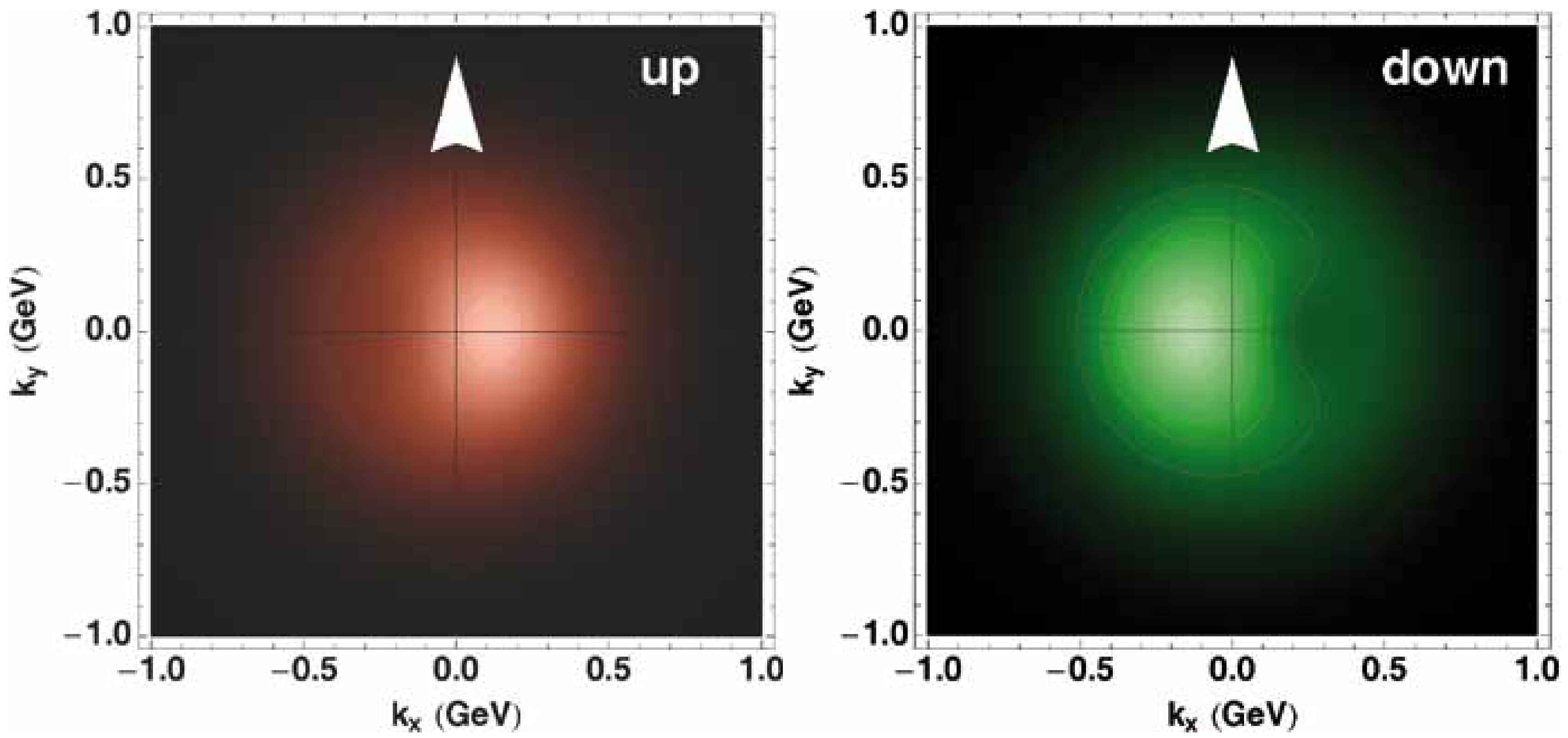

[A. Bacchetta et al.]

Sivers amplitudes

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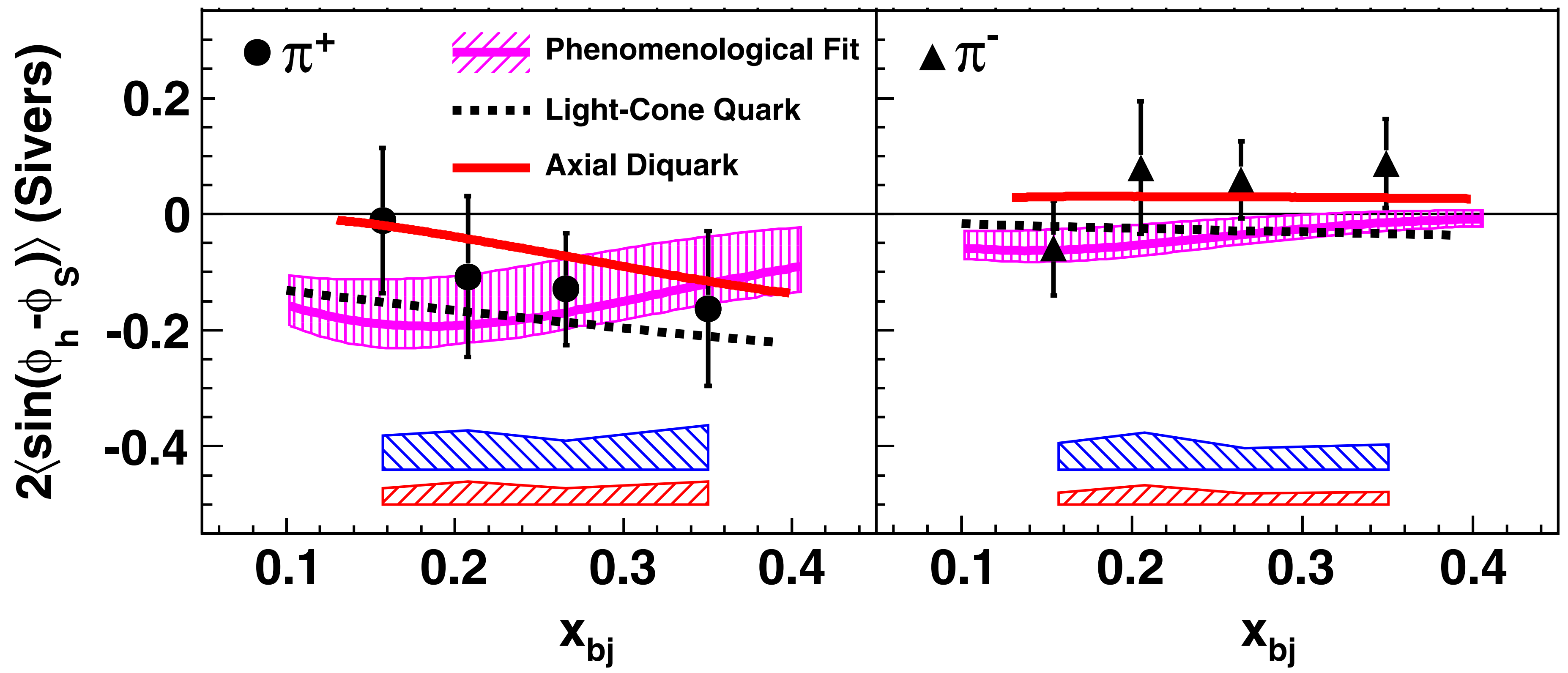
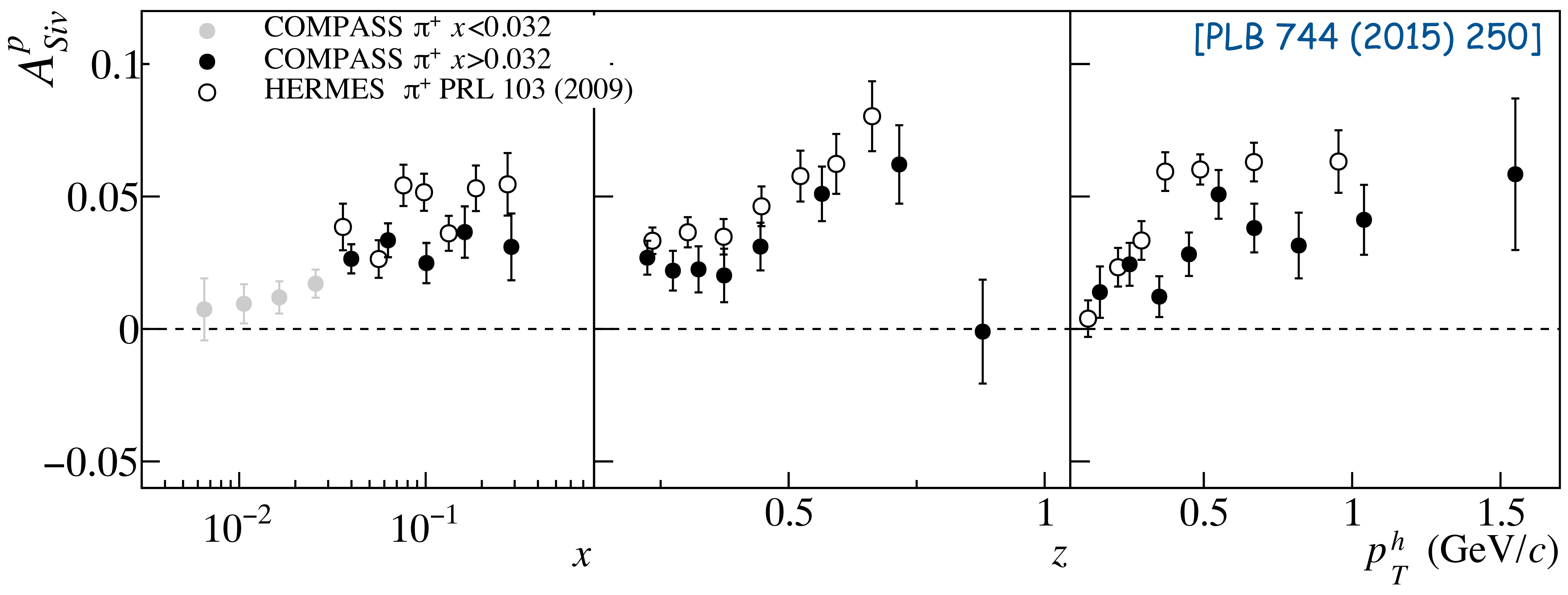


- cancelation for D target supports opposite signs of up and down Sivers
- newer results from JLab using ^{3}He target and from COMPASS for proton target (also multi-d)
- hint of discrepancy between COMPASS and HERMES
  - ➠ Q^2 dependence or just different kinematics (other than Q^2)



[PLB 744 (2015) 250]

	U	L	T
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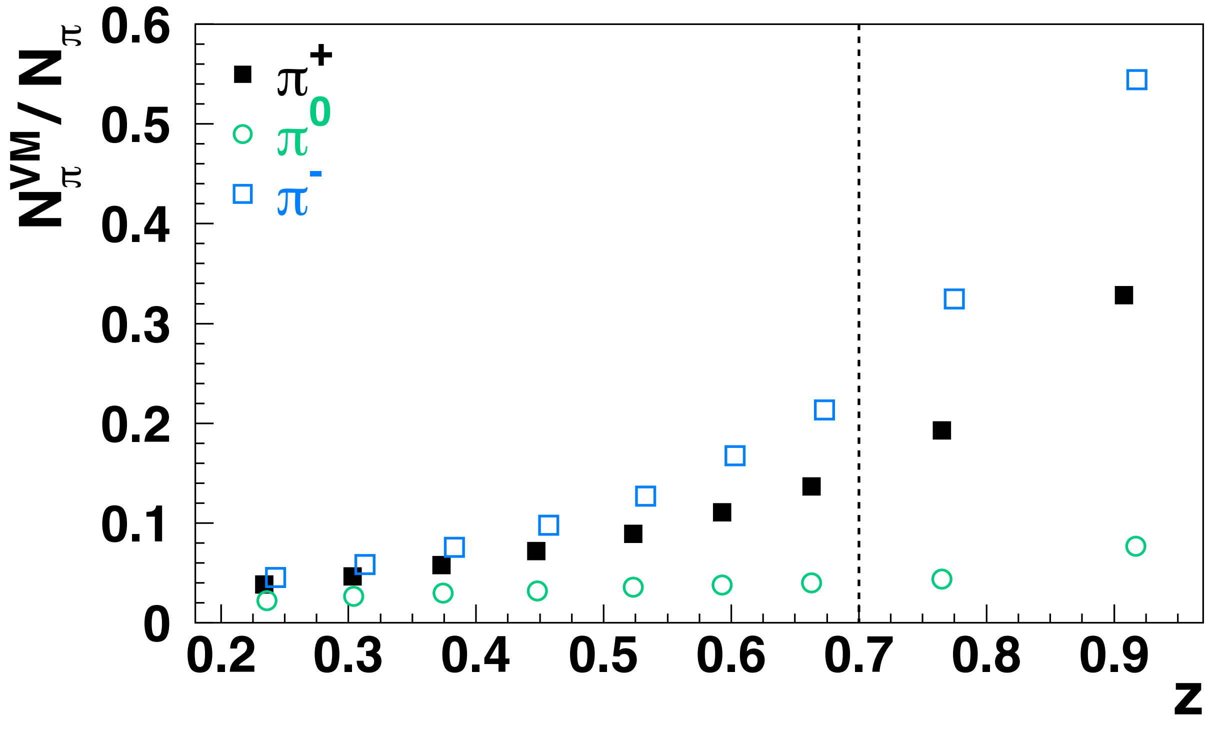
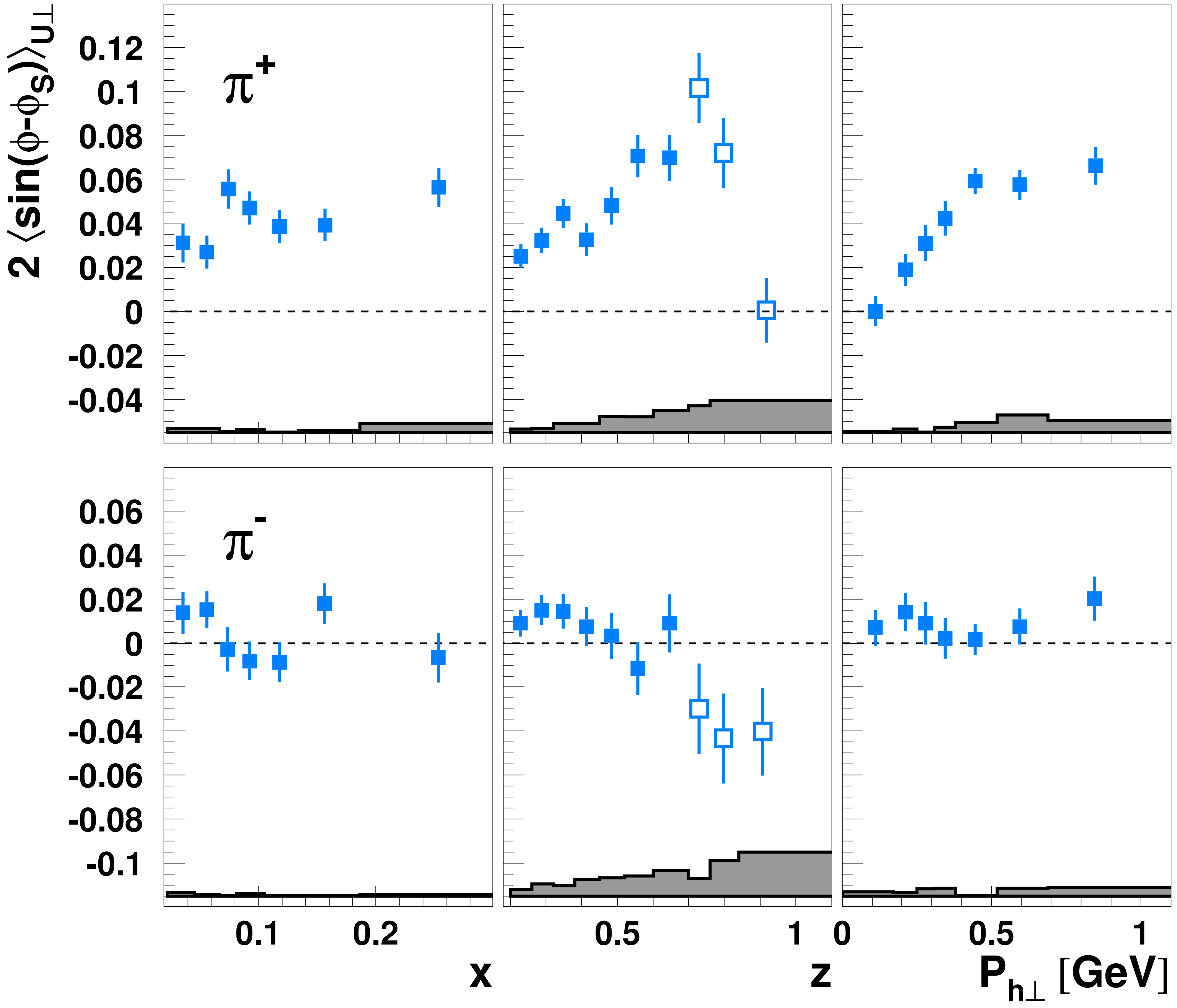
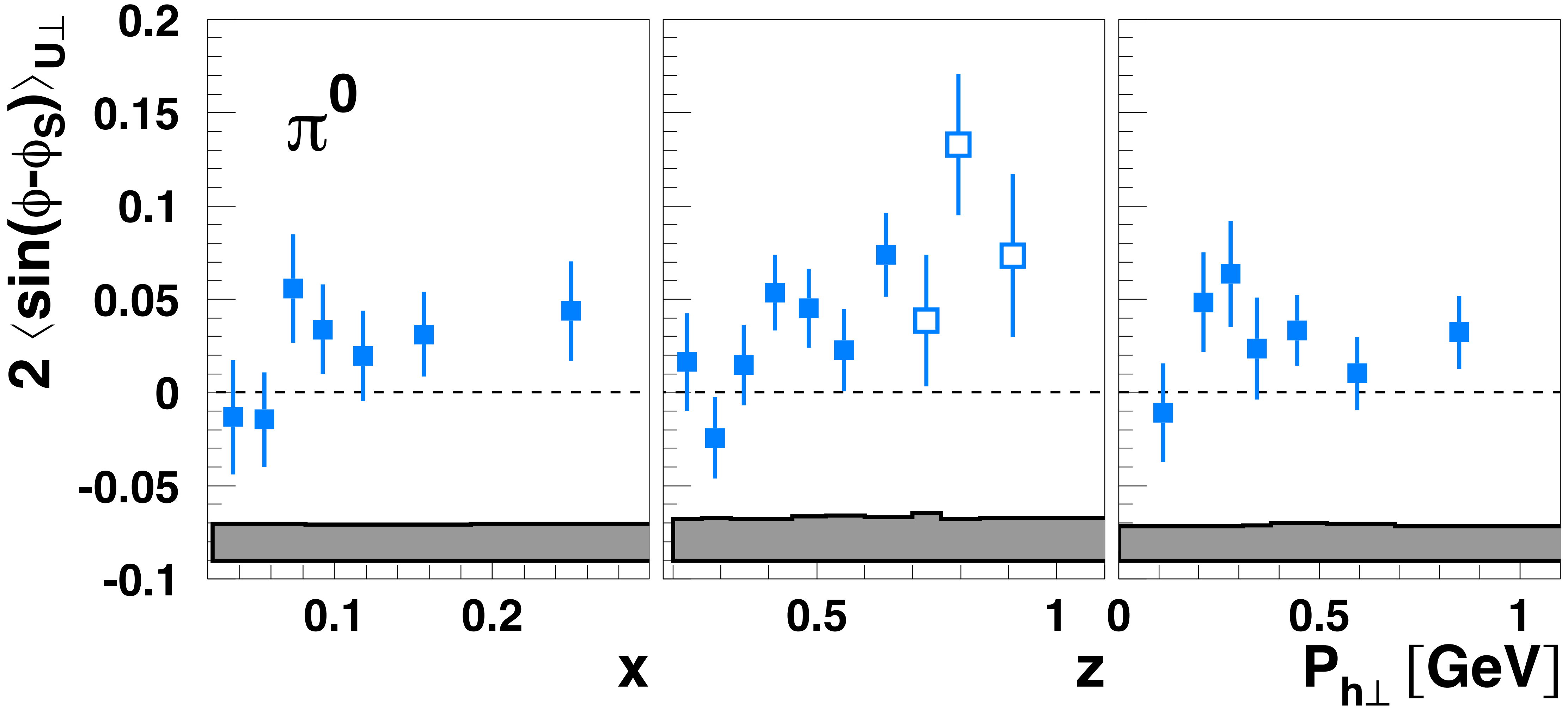


Sivers amplitudes for pions

- high-z data probes region where contributions from exclusive vector-meson production becomes significant
- only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)

[A. Airapetian et al., arXiv:2007.07755]





Sivers amplitudes for pions

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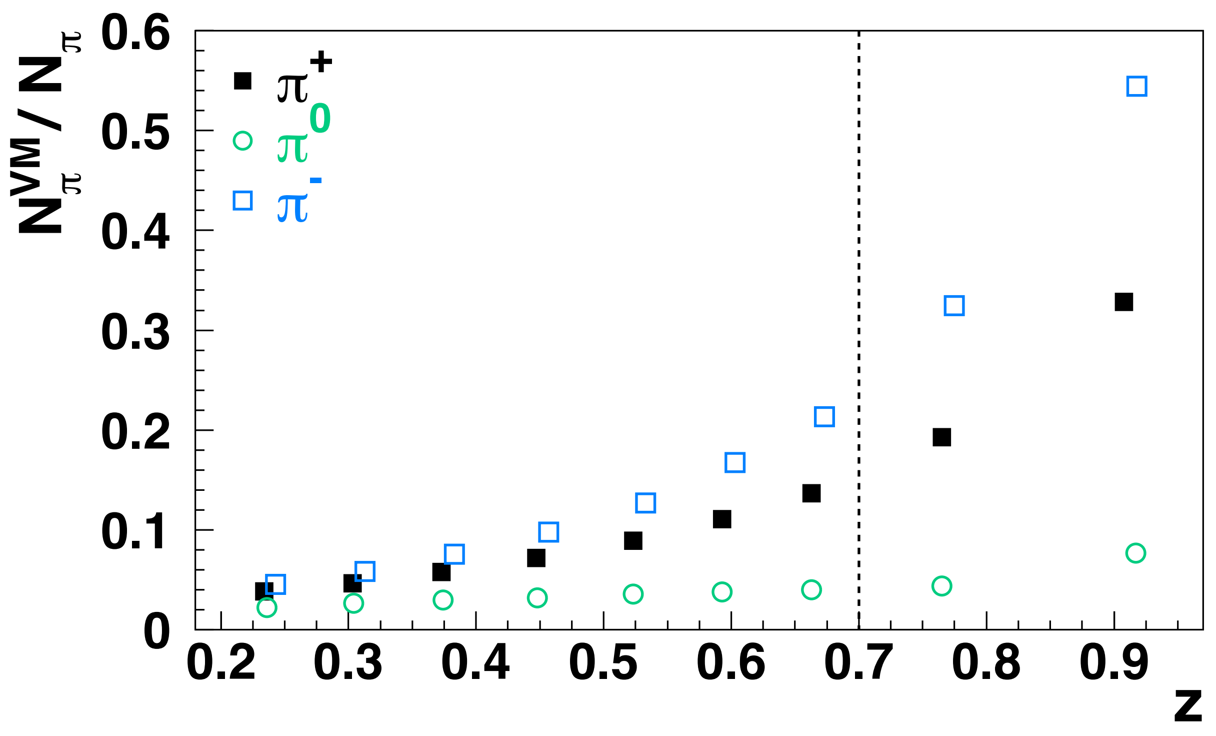
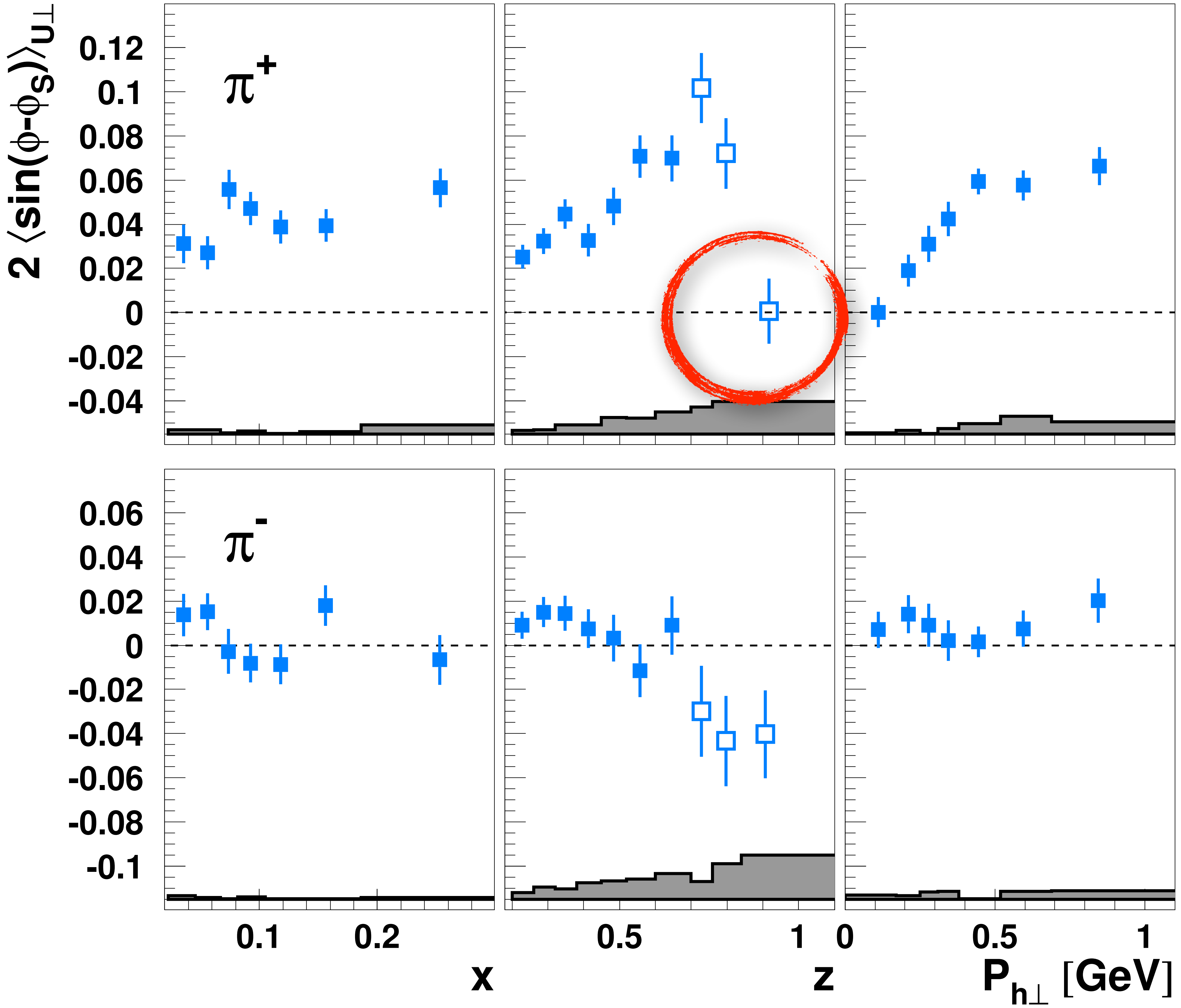
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

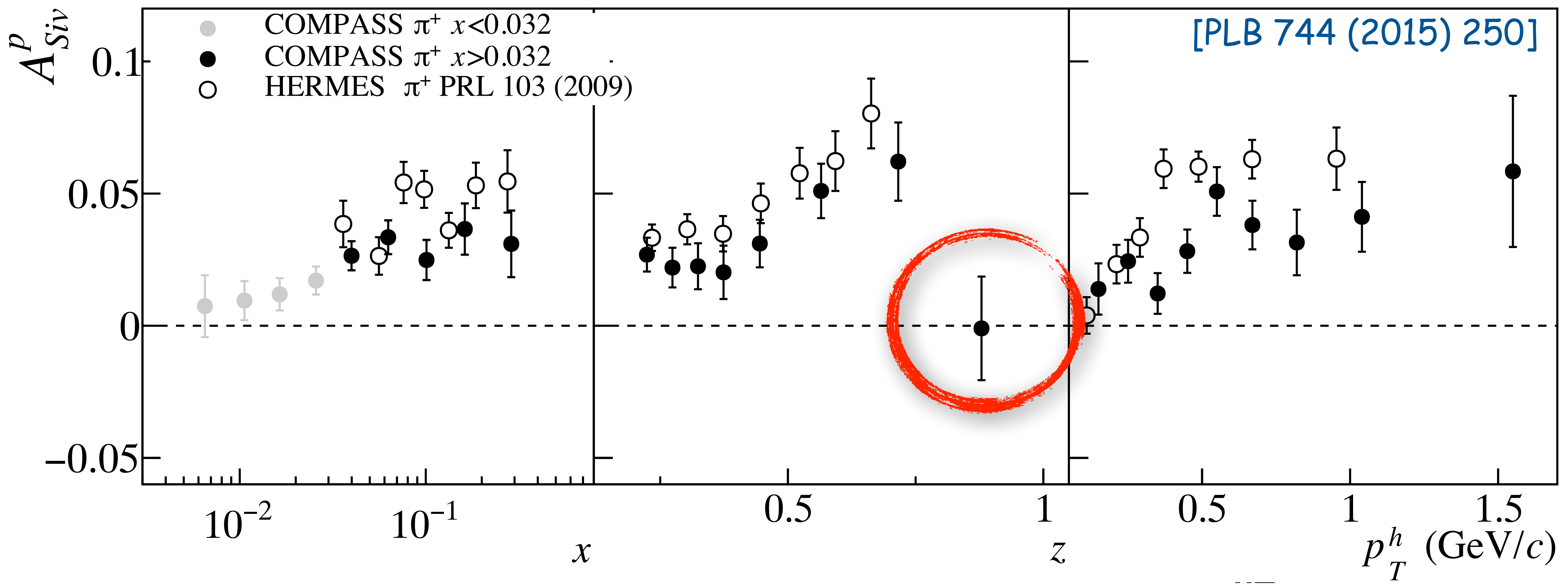


- high-z data probes region where contributions from exclusive vector-meson production becomes significant
- only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)
- incidentally, same drop of asymmetry at large z seen at COMPASS

[A. Airapetian et al., arXiv:2007.07755]



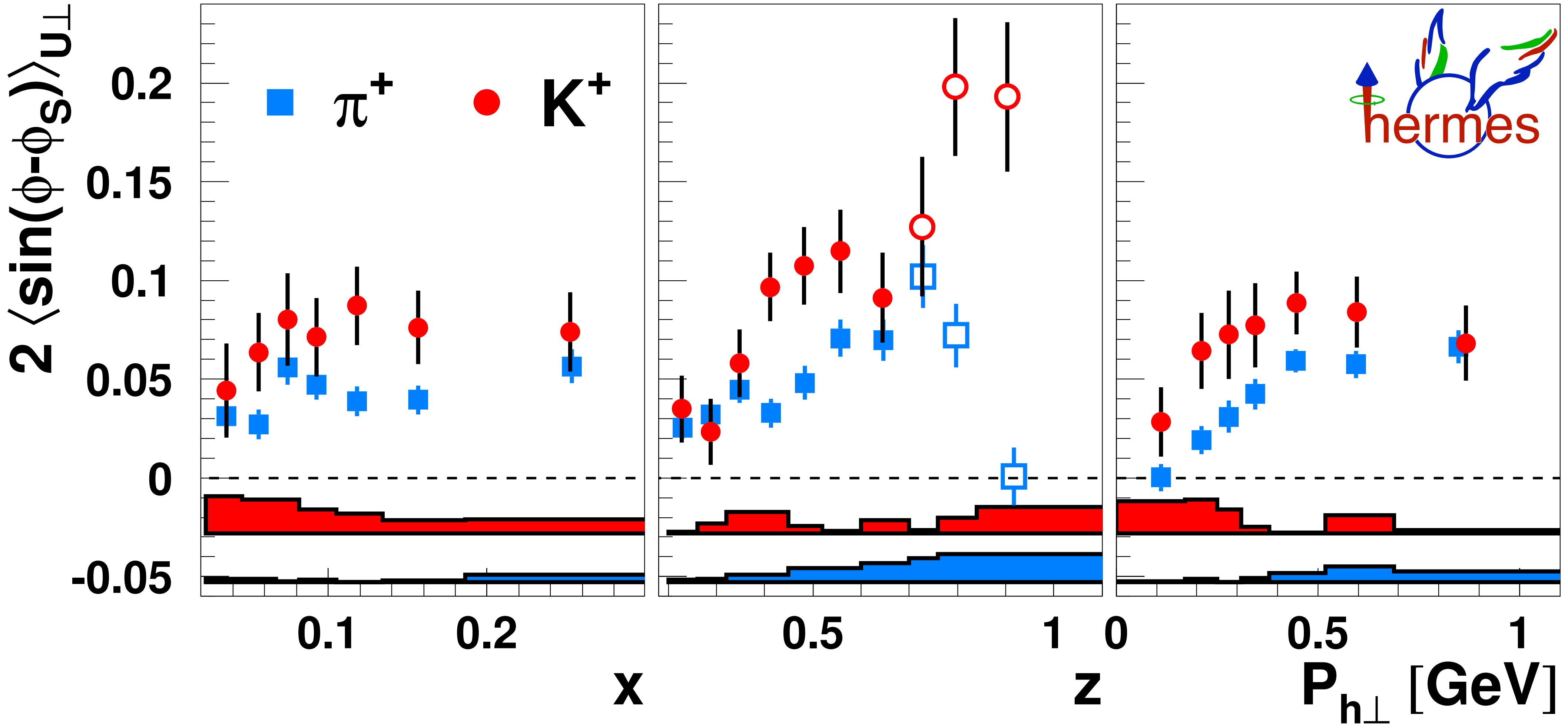
[PLB 744 (2015) 250]



	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes
pions vs. kaons

[A. Airapetian et al., arXiv:2007.07755]

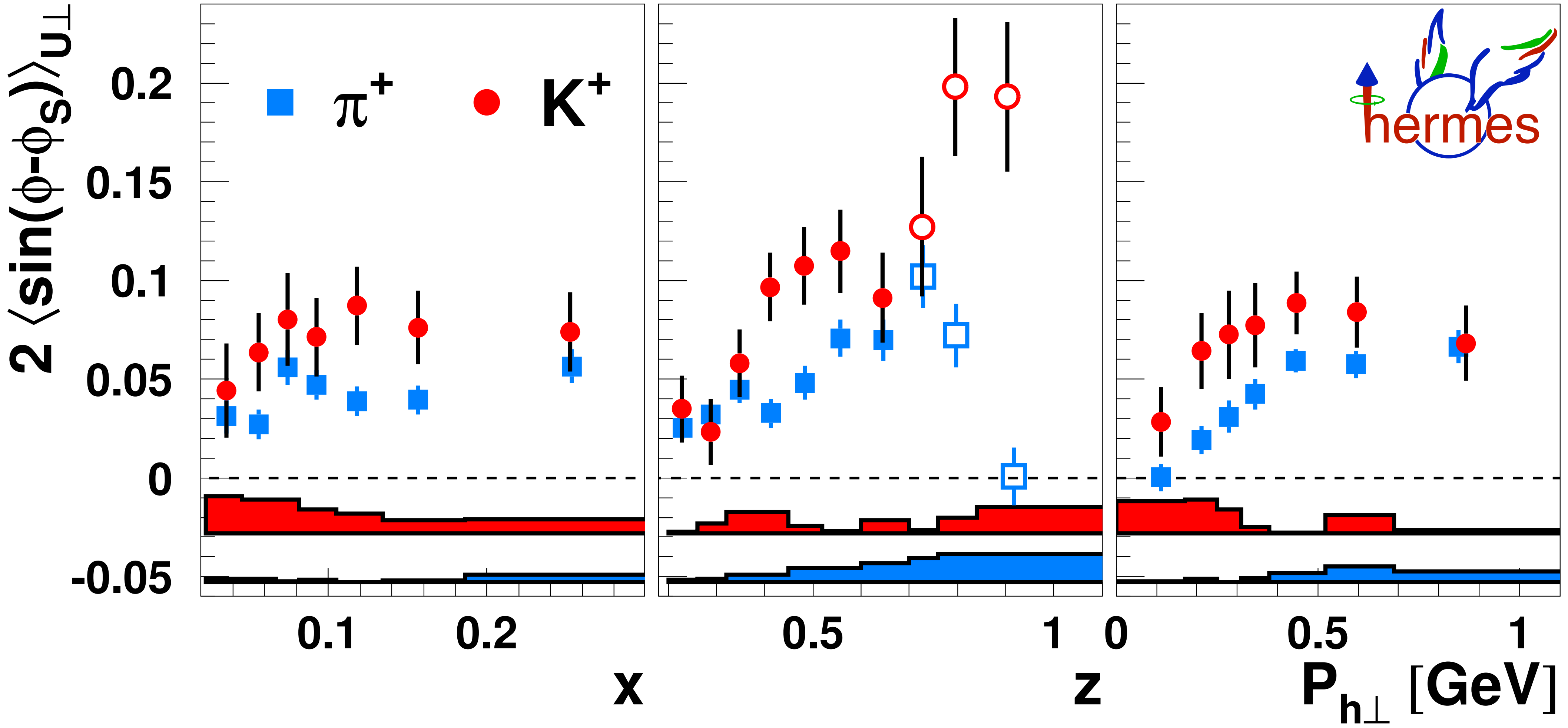


somewhat unexpected if dominated by scattering from u-quarks:

$$\simeq - \frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$$

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

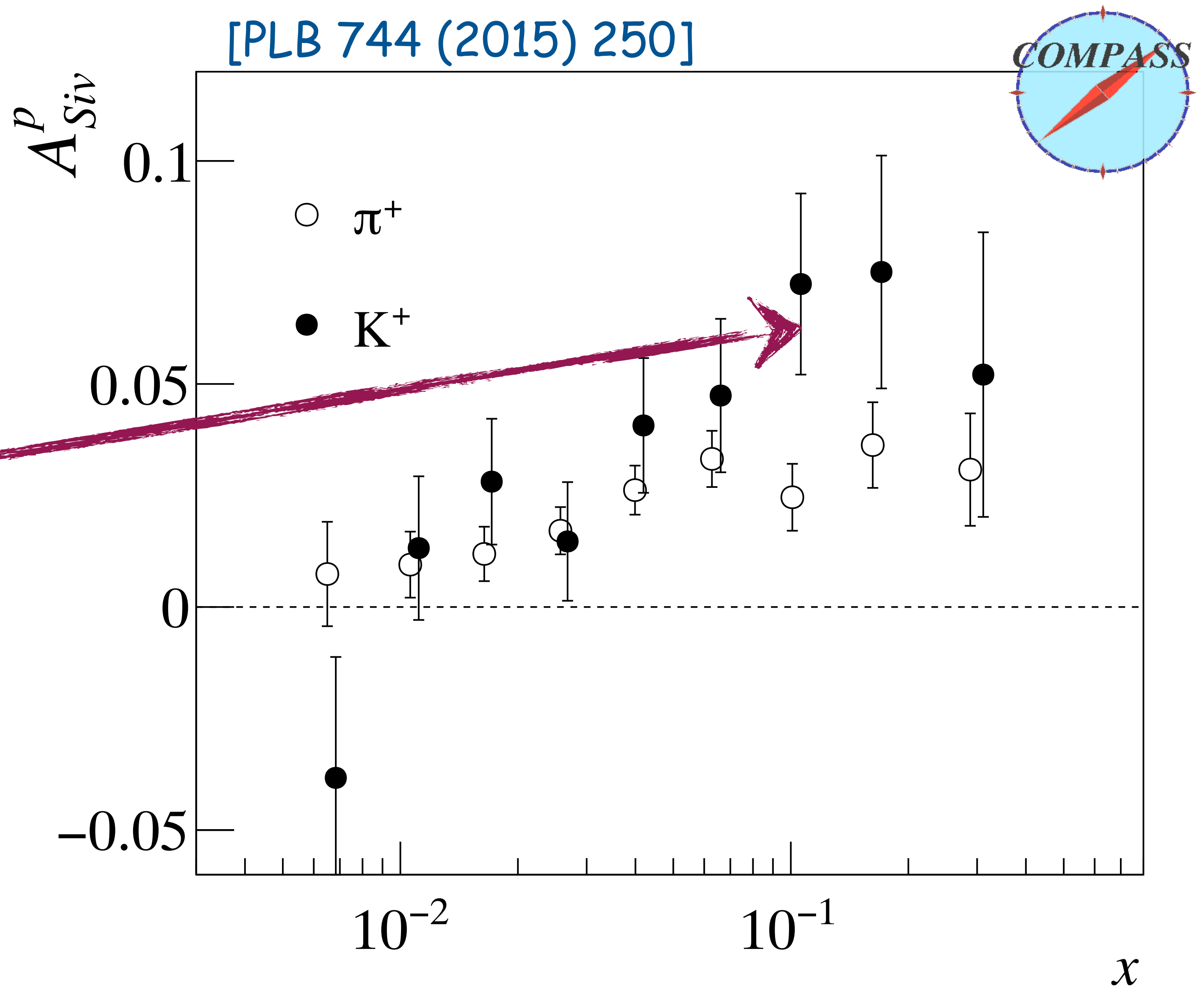
Sivers amplitudes
pions vs. kaons



[A. Airapetian et al., arXiv:2007.07755]

somewhat unexpected if dominated by scattering from u-quarks:

$$\simeq - \frac{\mathbf{f_{1T}^{\perp,u}(x, p_T^2)} \otimes_{\mathcal{W}} \mathbf{D_1^{u\to\pi^+/K^+}(z, k_T^2)}}{\mathbf{f_1^u(x, p_T^2)} \;\otimes \mathbf{D_1^{u\to\pi^+/K^+}(z, k_T^2))}}$$



[PLB 744 (2015) 250]

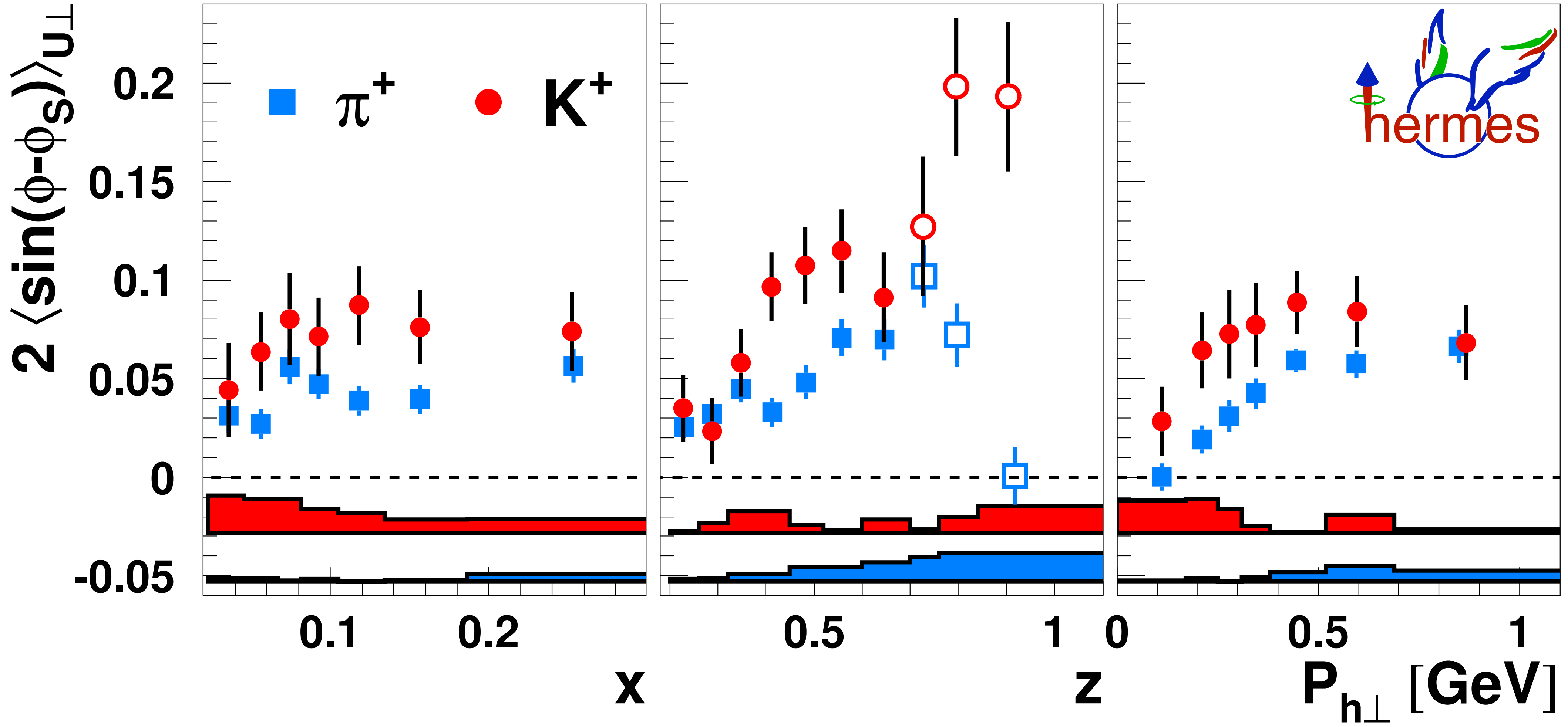
larger amplitudes seen also by COMPASS

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes

pions vs. kaons

[A. Airapetian et al., arXiv:2007.07755]



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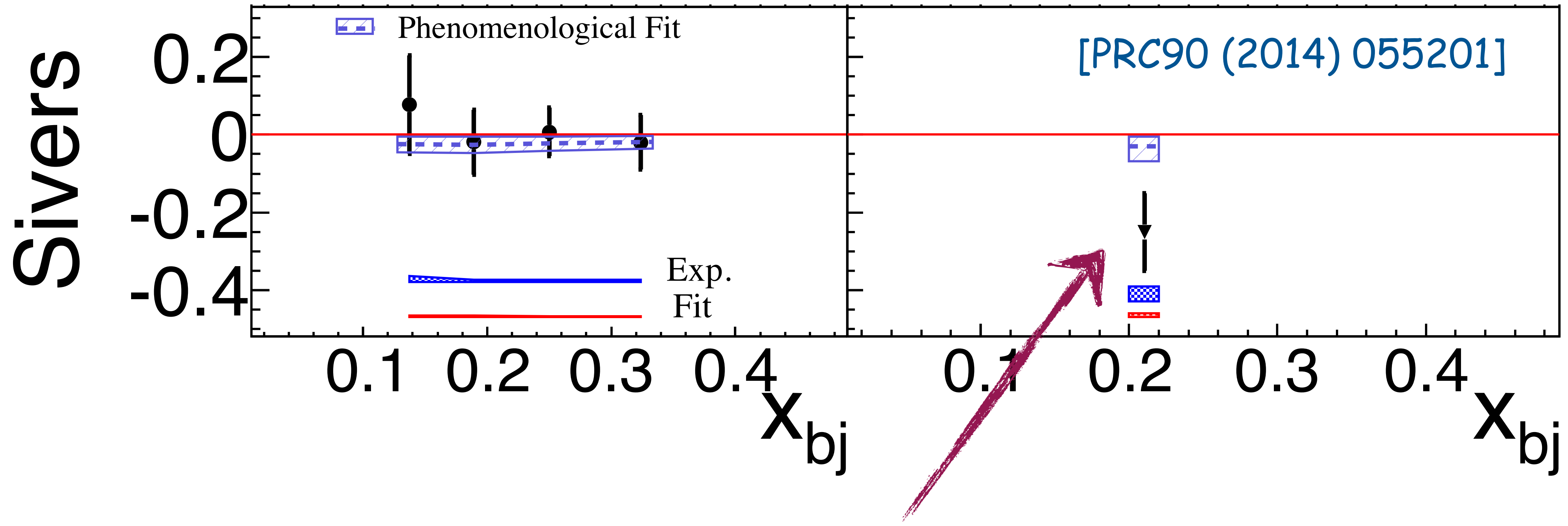
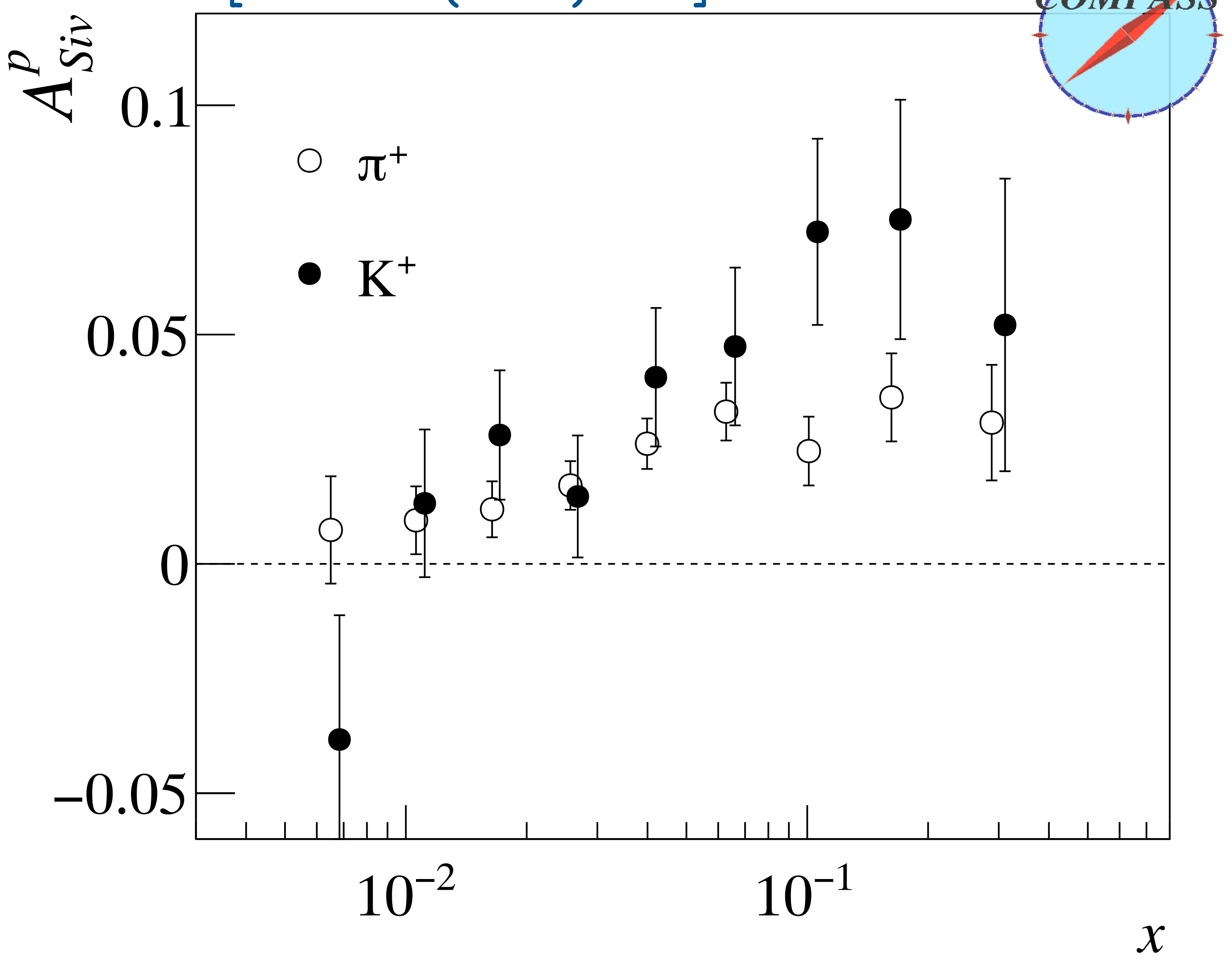
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$$



[PRC90 (2014) 055201]

surprisingly large K$^-$ asymmetry for ^{3}He target (but zero for K$^+$?!)

[PLB 744 (2015) 250]



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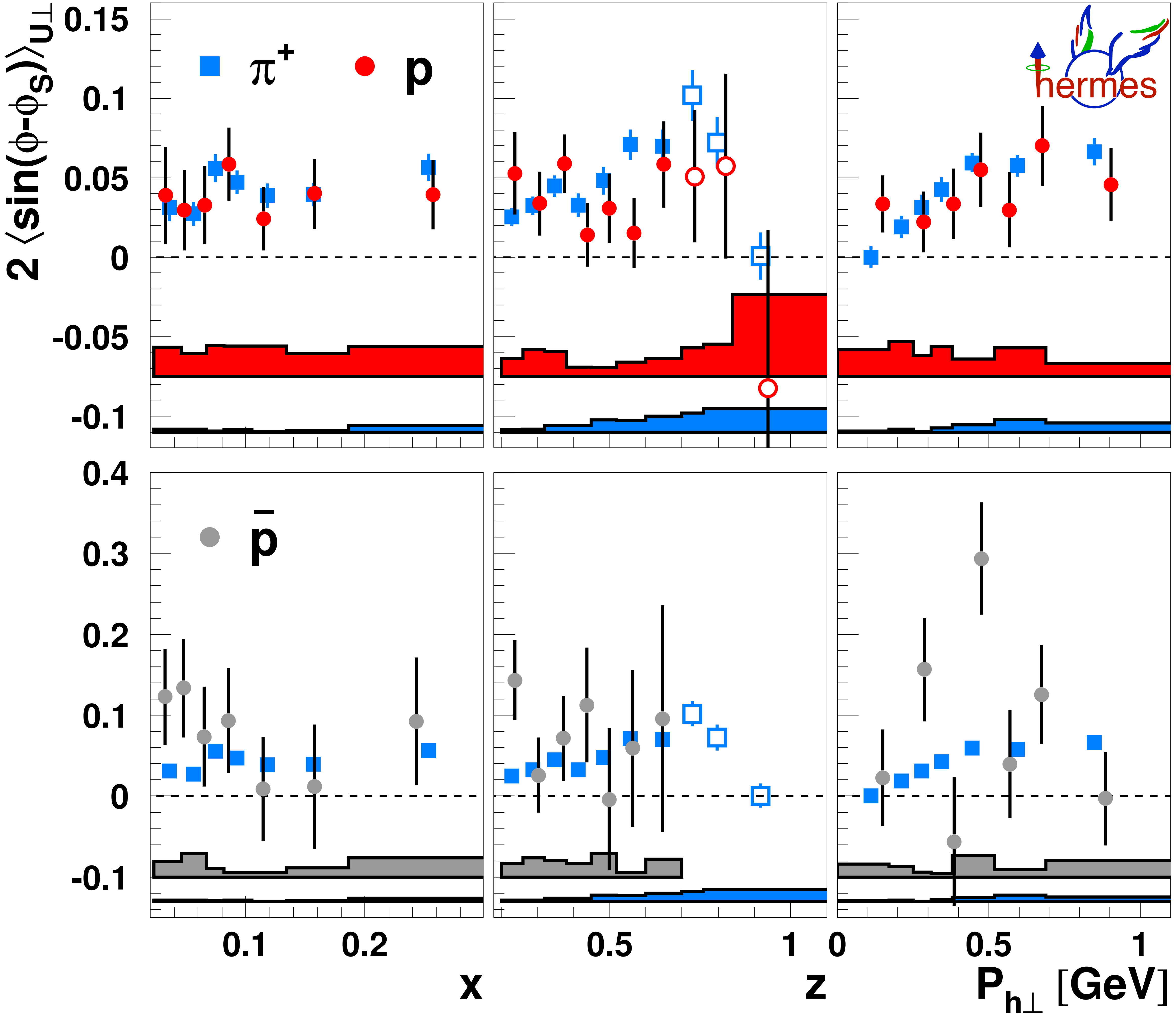
Sivers amplitudes

pions vs. (anti)protons


[A. Airapetian et al., arXiv:2007.07755]

similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

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Sivers amplitudes
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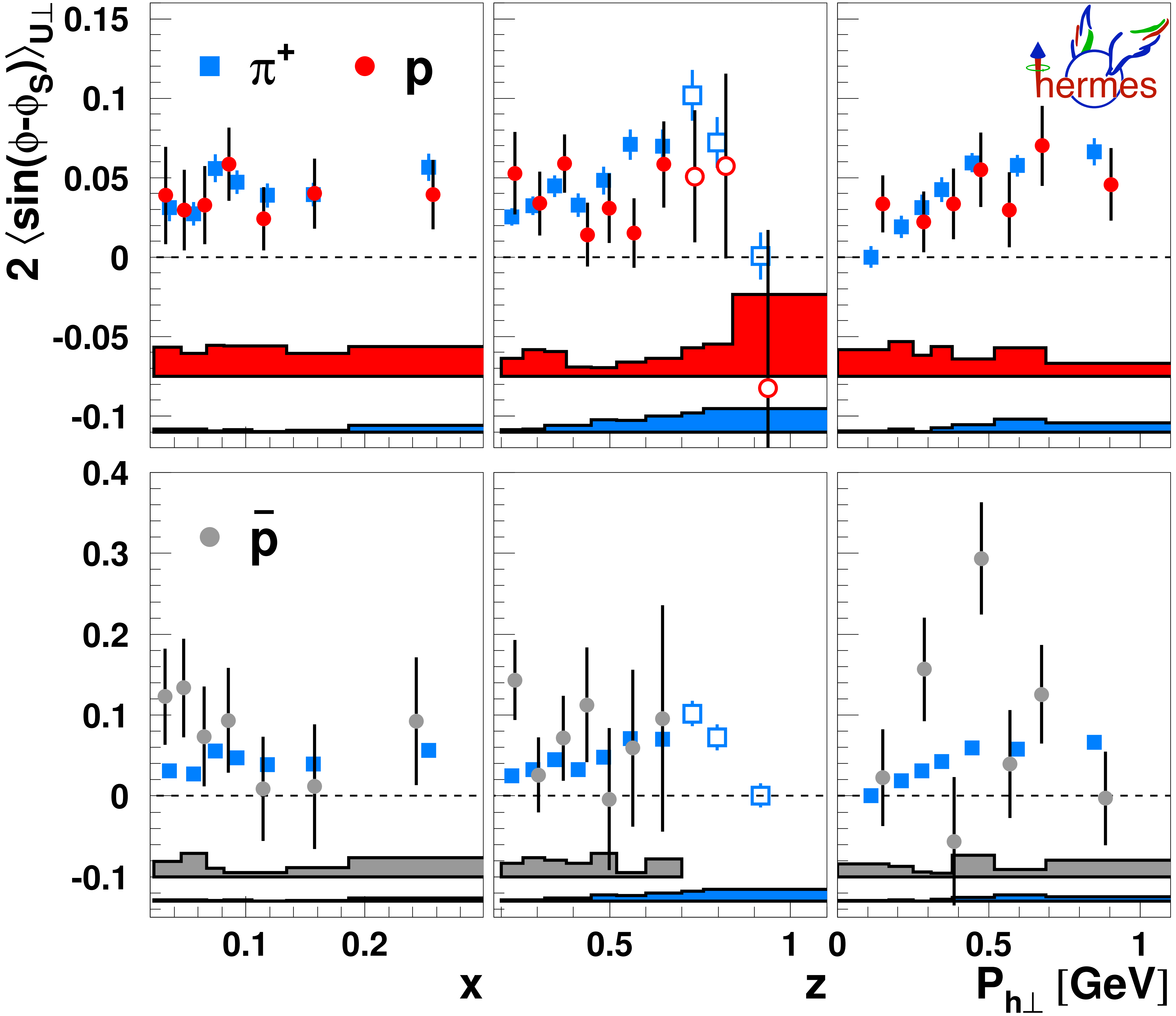

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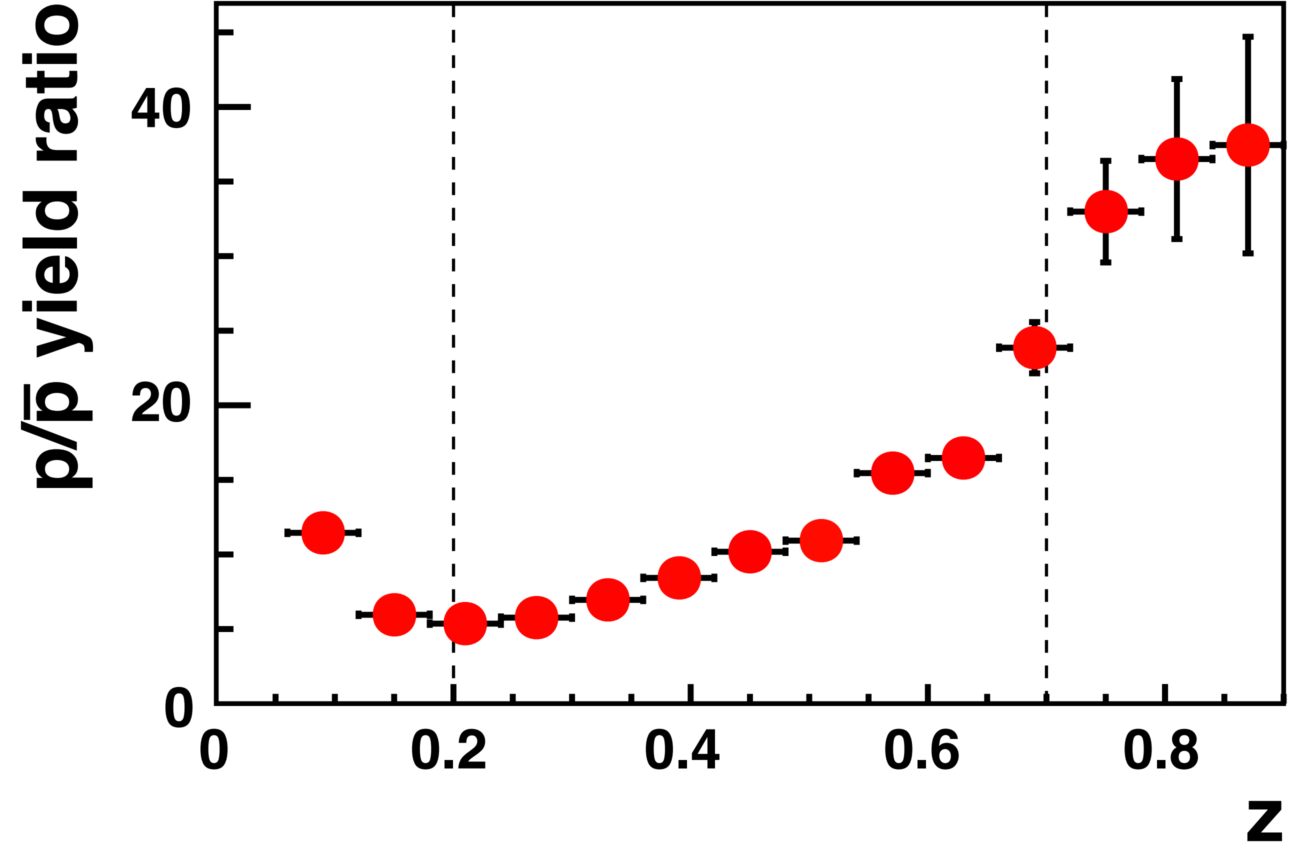

possibly, onset of target fragmentation only at lower z

	U	L	T
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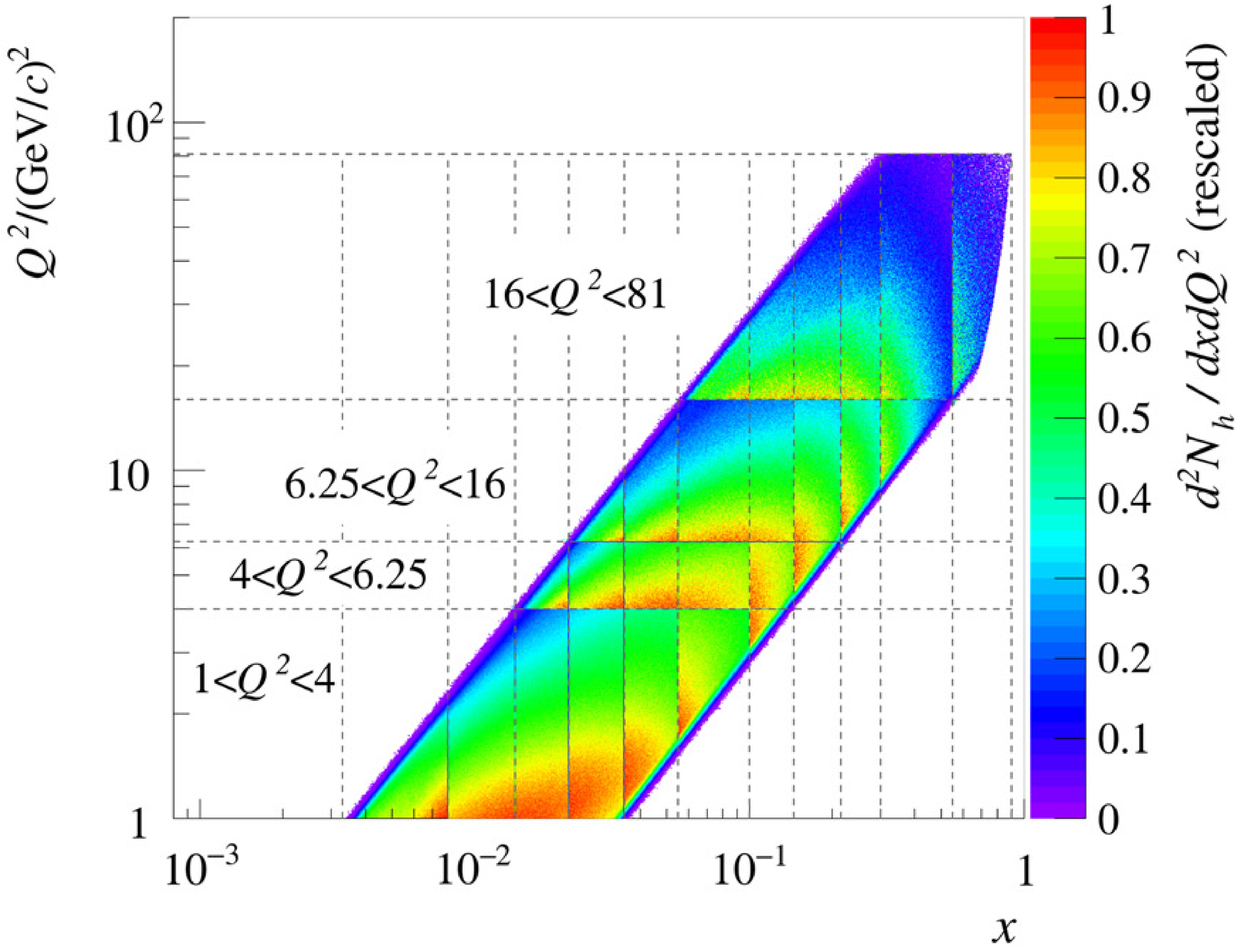
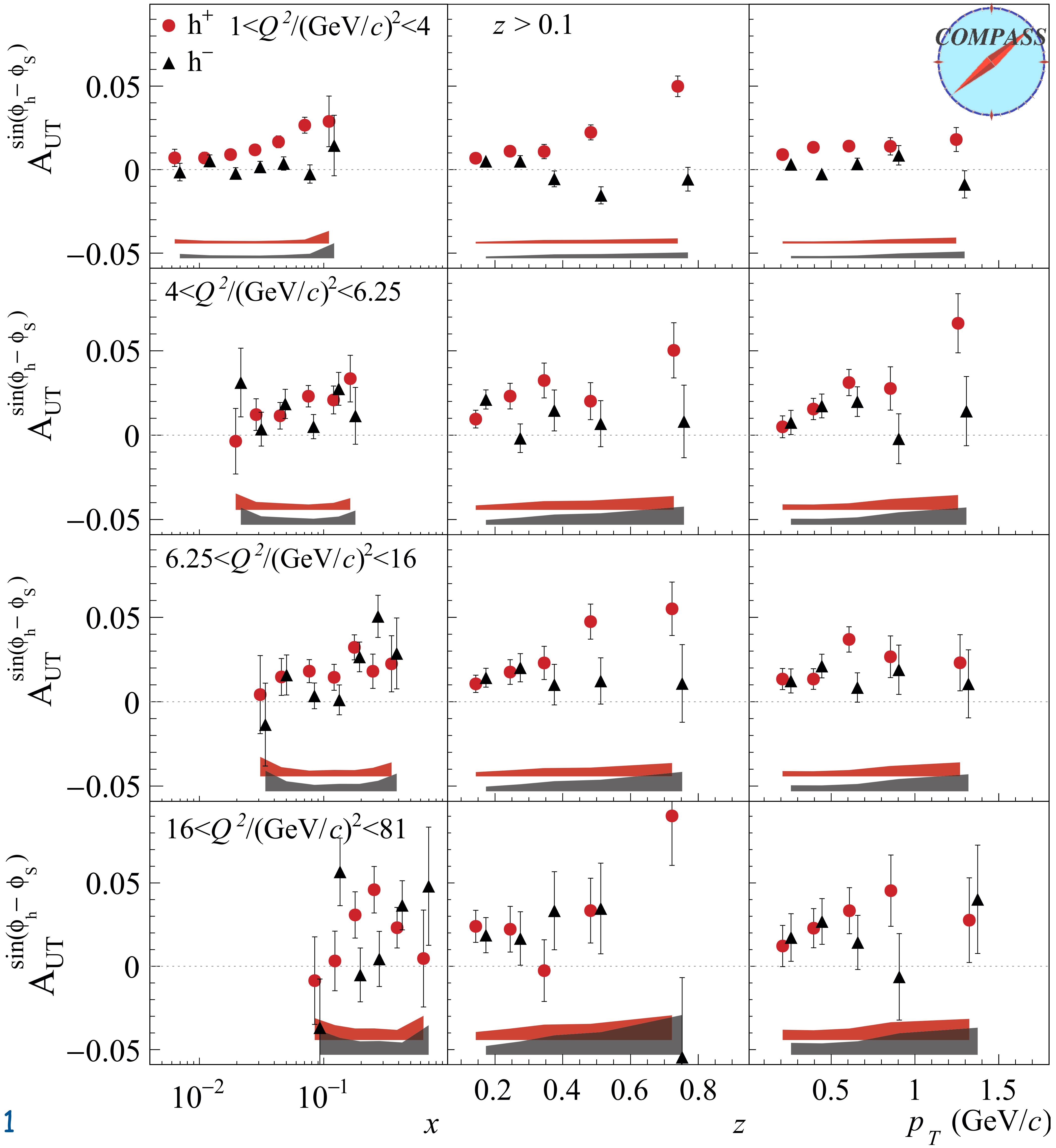
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes multi-dimensional analysis

- 2d analysis to match Q^2 range probed in Drell-Yan



- allows also more detailed evolution studies



[Adolph et al., Phys. Lett. B 770, 138-145 (2017)]

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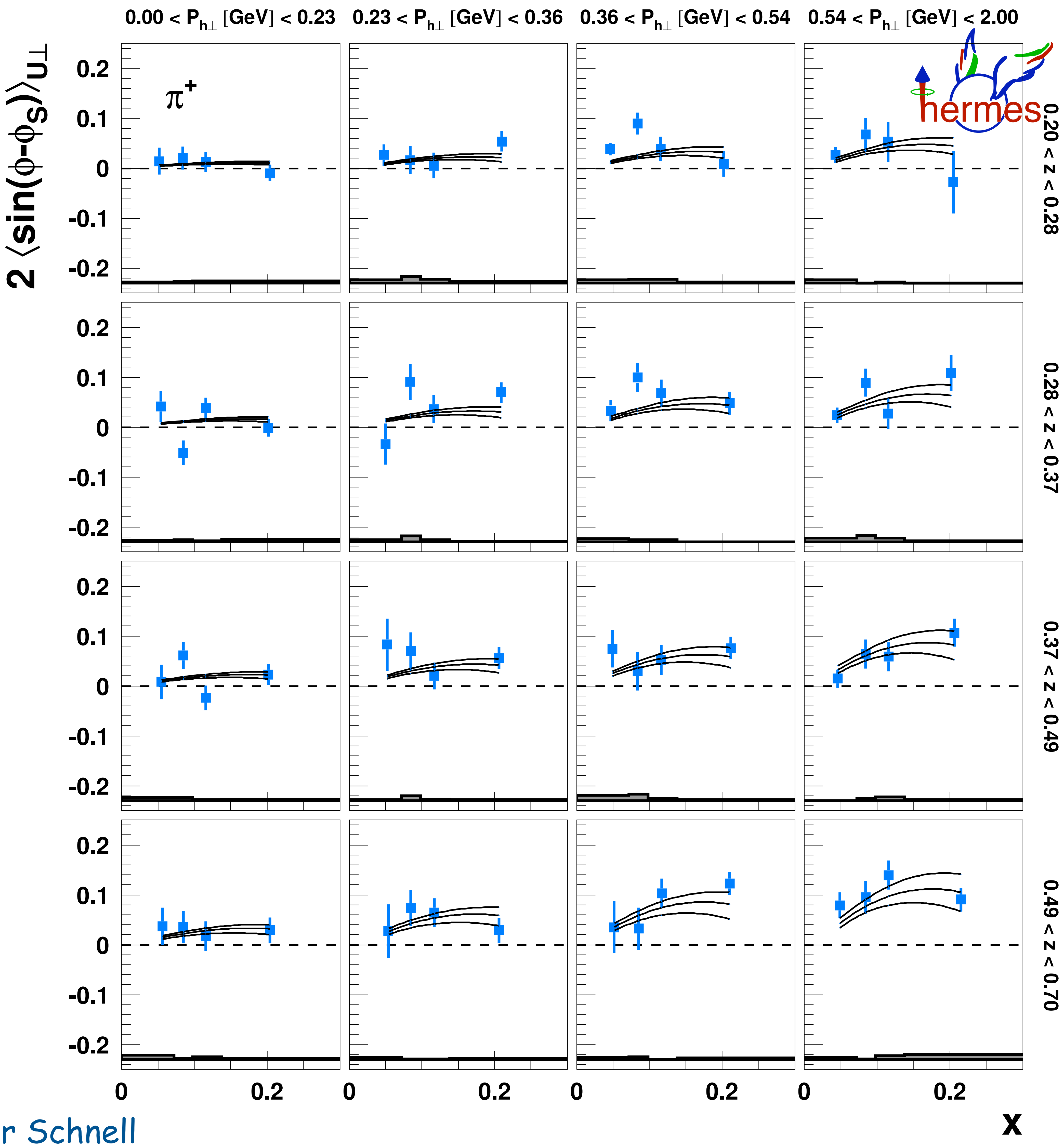
Sivers amplitudes
multi-dimensional analysis

[A. Airapetian et al., arXiv:2007.07755]



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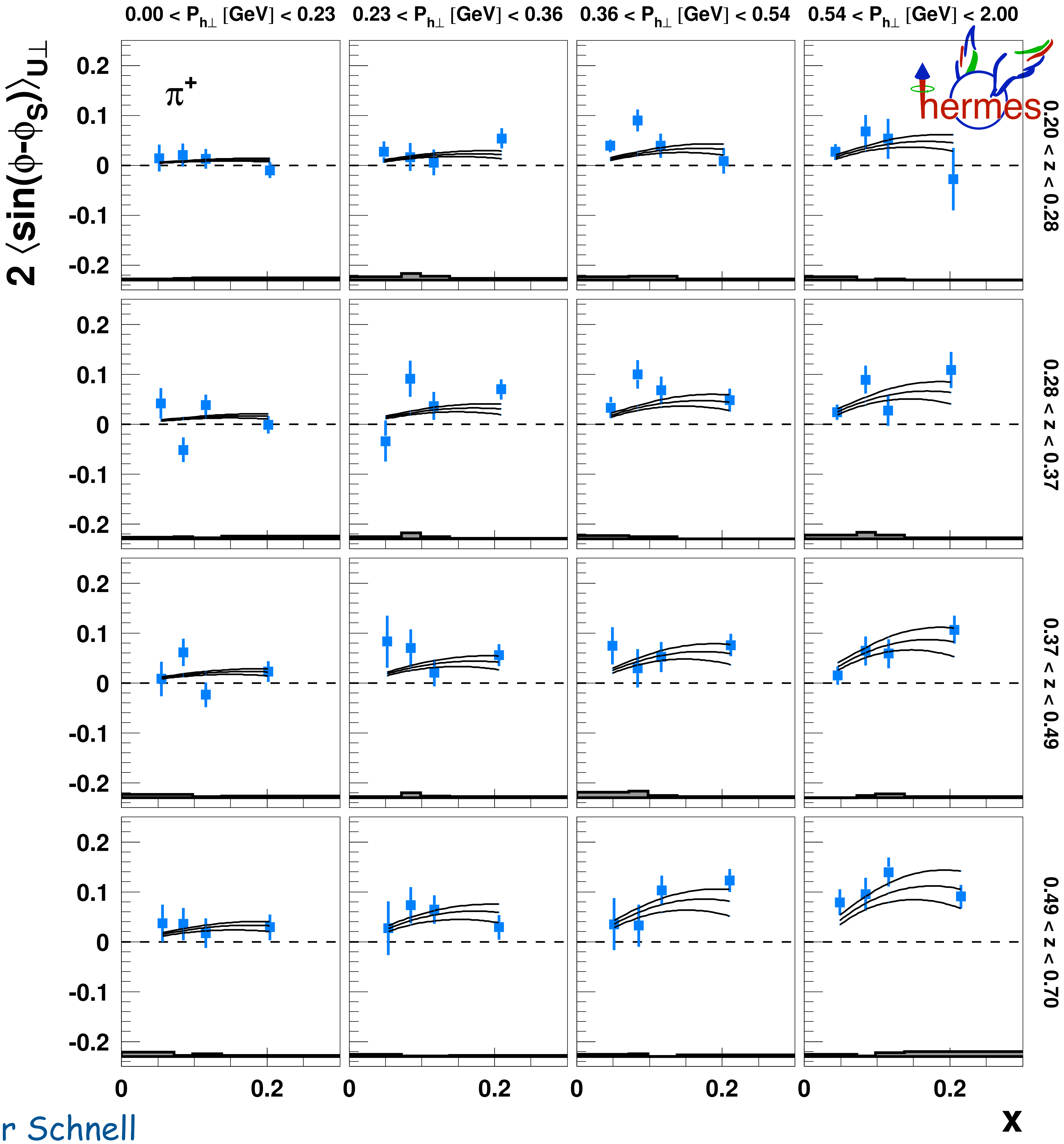

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$

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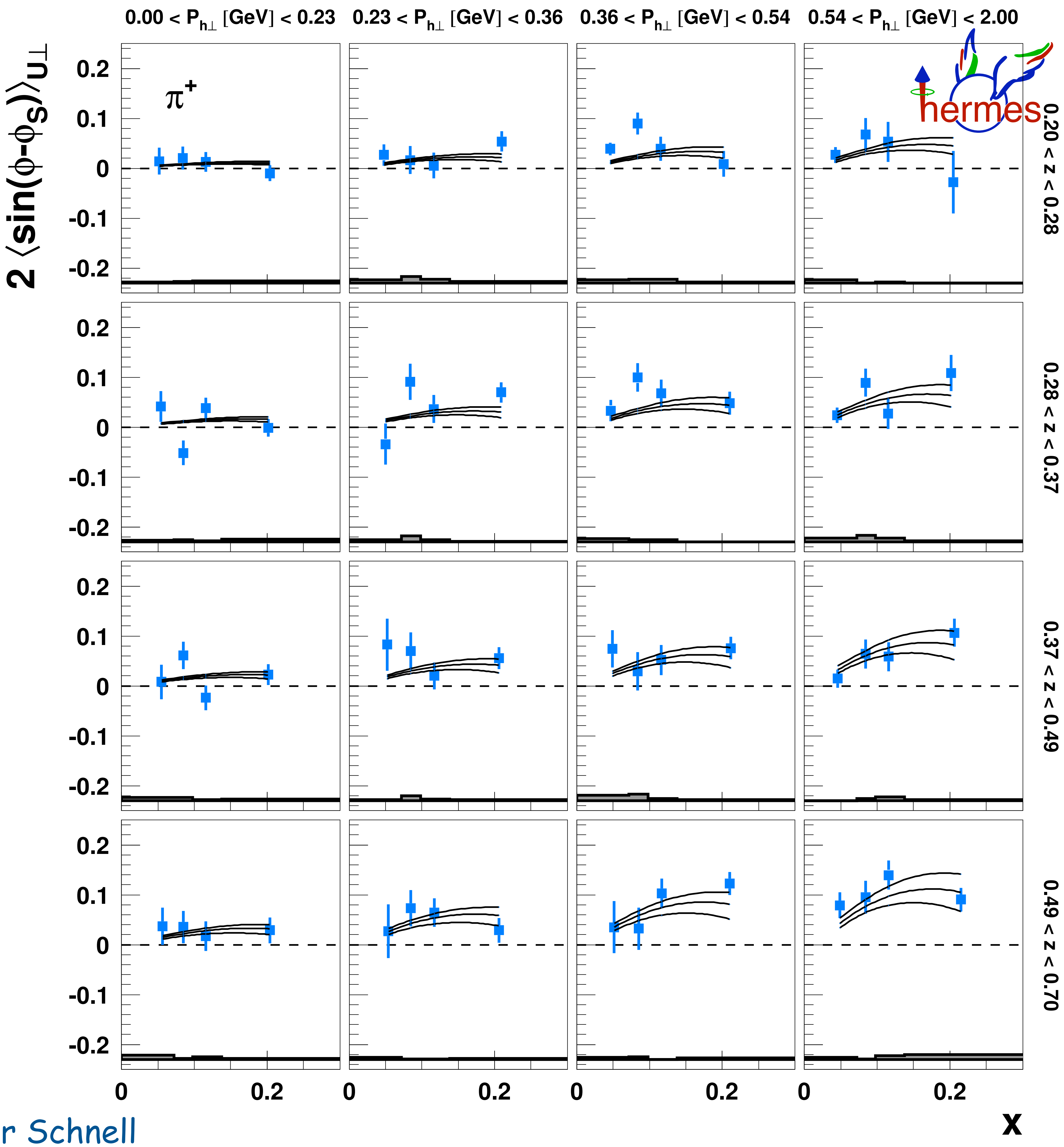

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- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations

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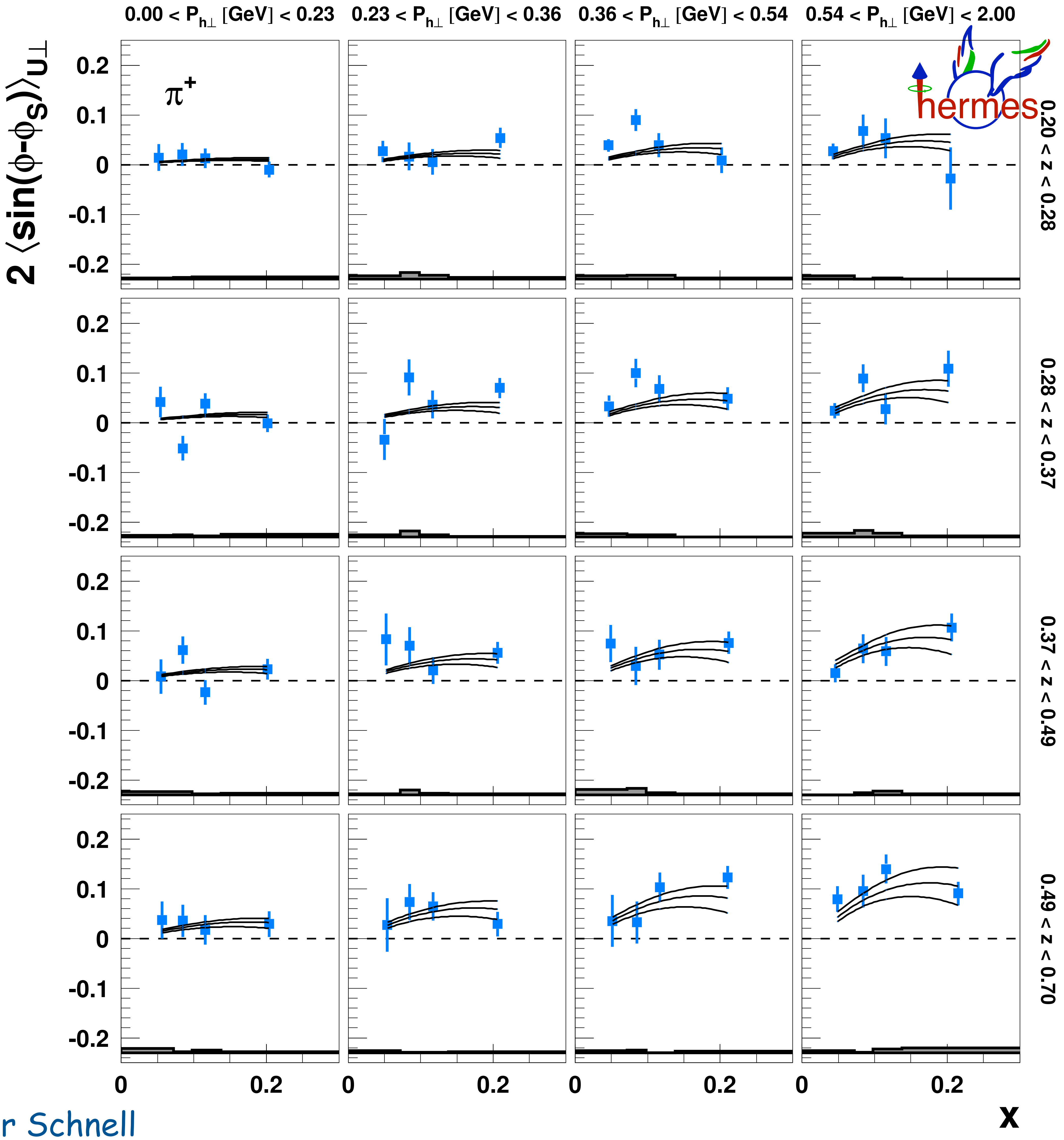
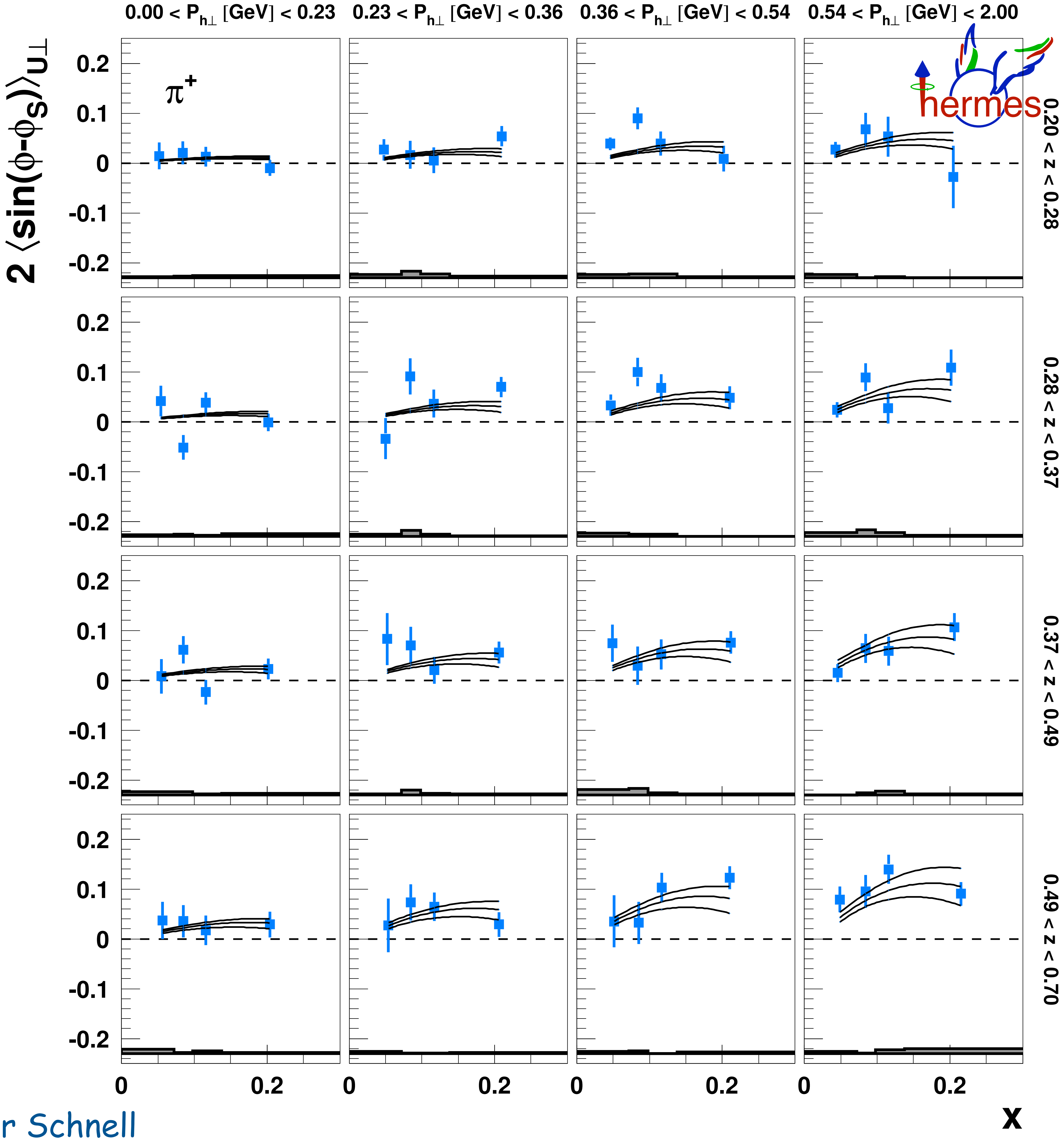


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

Sivers amplitudes
multi-dimensional analysis

[A. Airapetian et al., arXiv:2007.07755]



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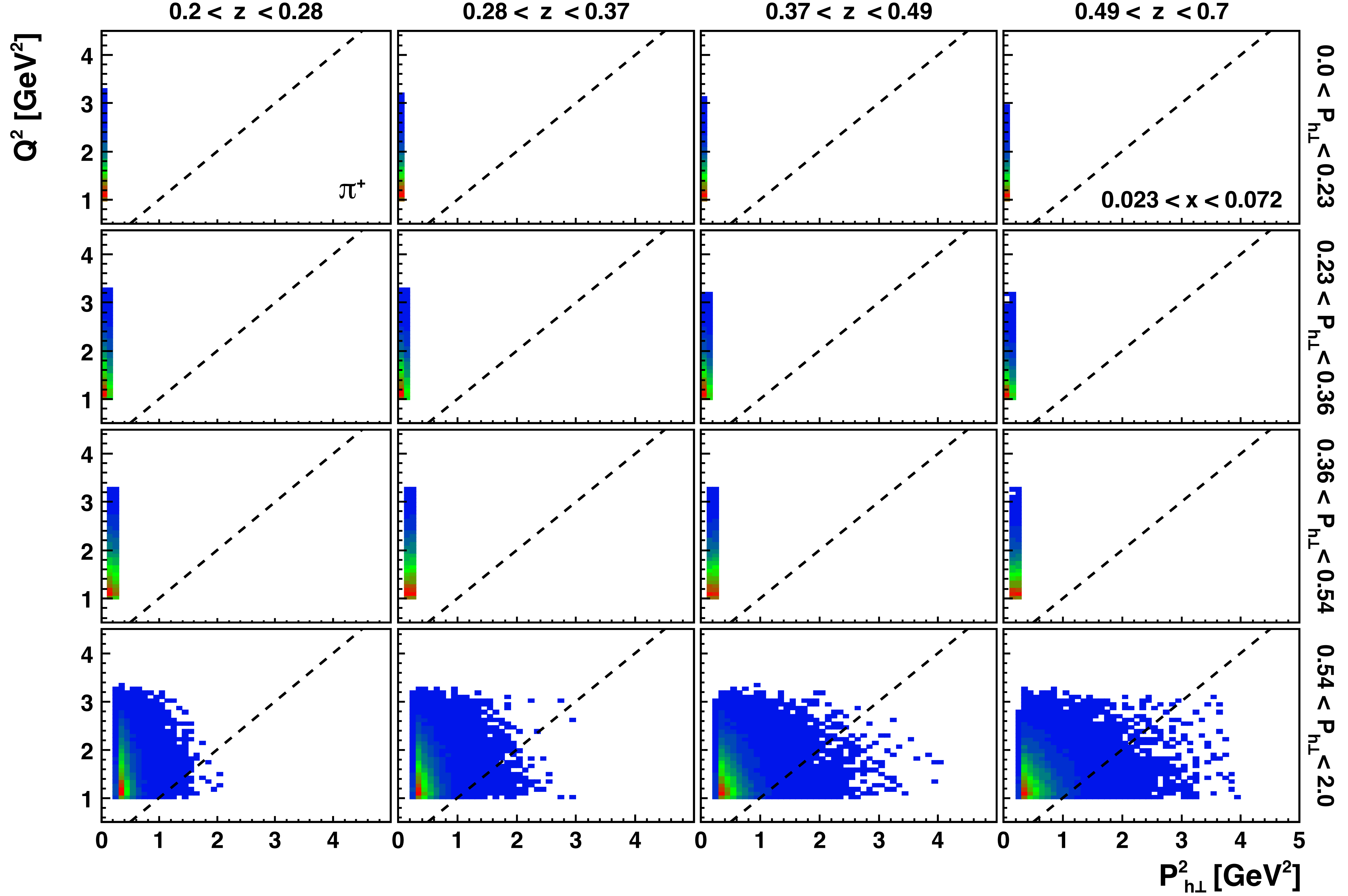
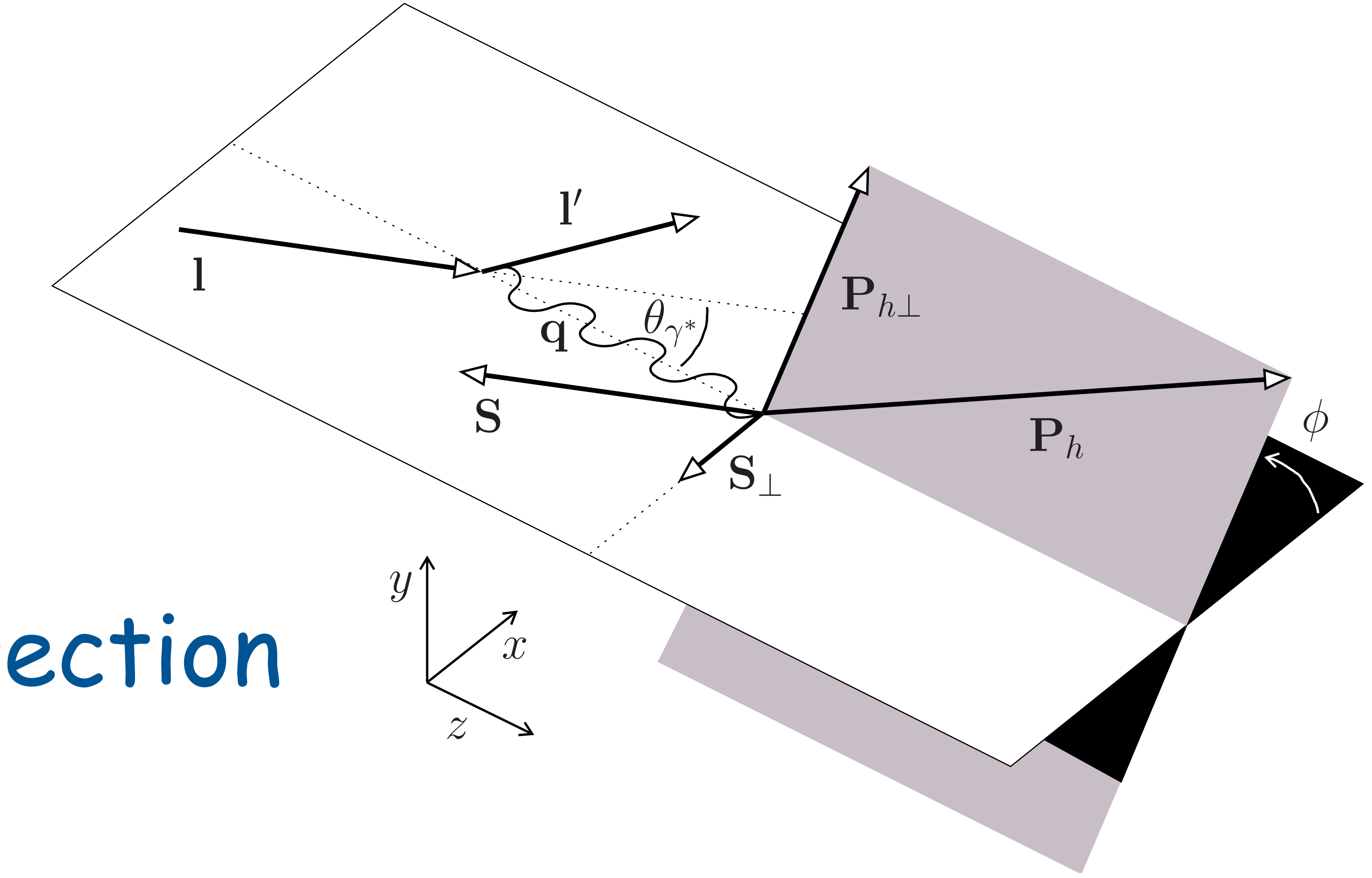


multi-d dependence and kinematical distribution should facilitate analyses within TMD formalism

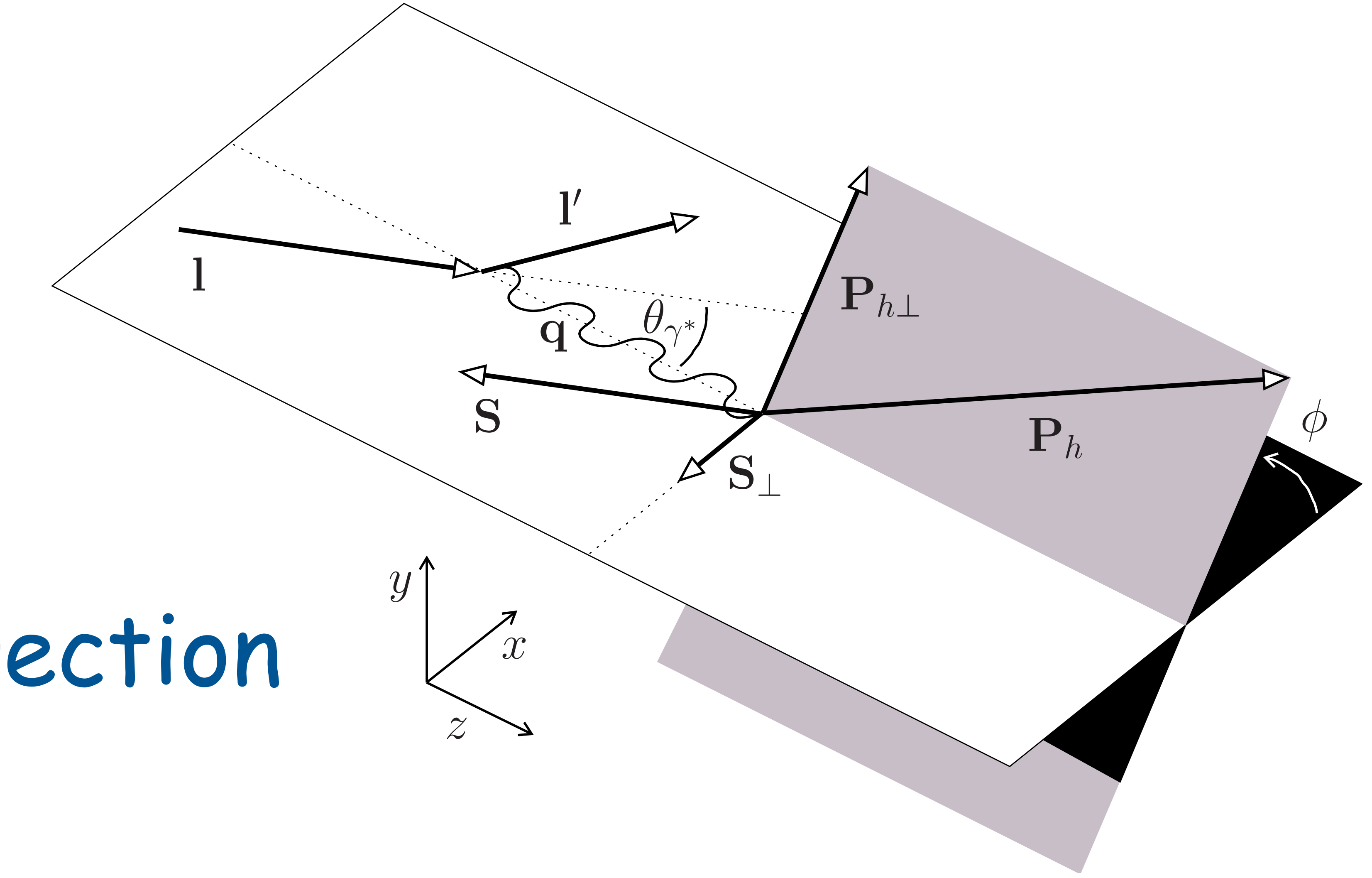
non-vanishing twist-3

subleading twist I - $\langle\sin(\phi)\rangle_{UL}$



- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

subleading twist I - <sin(ϕ)>$_{UL}$



- theory done w.r.t. virtual-photon direction
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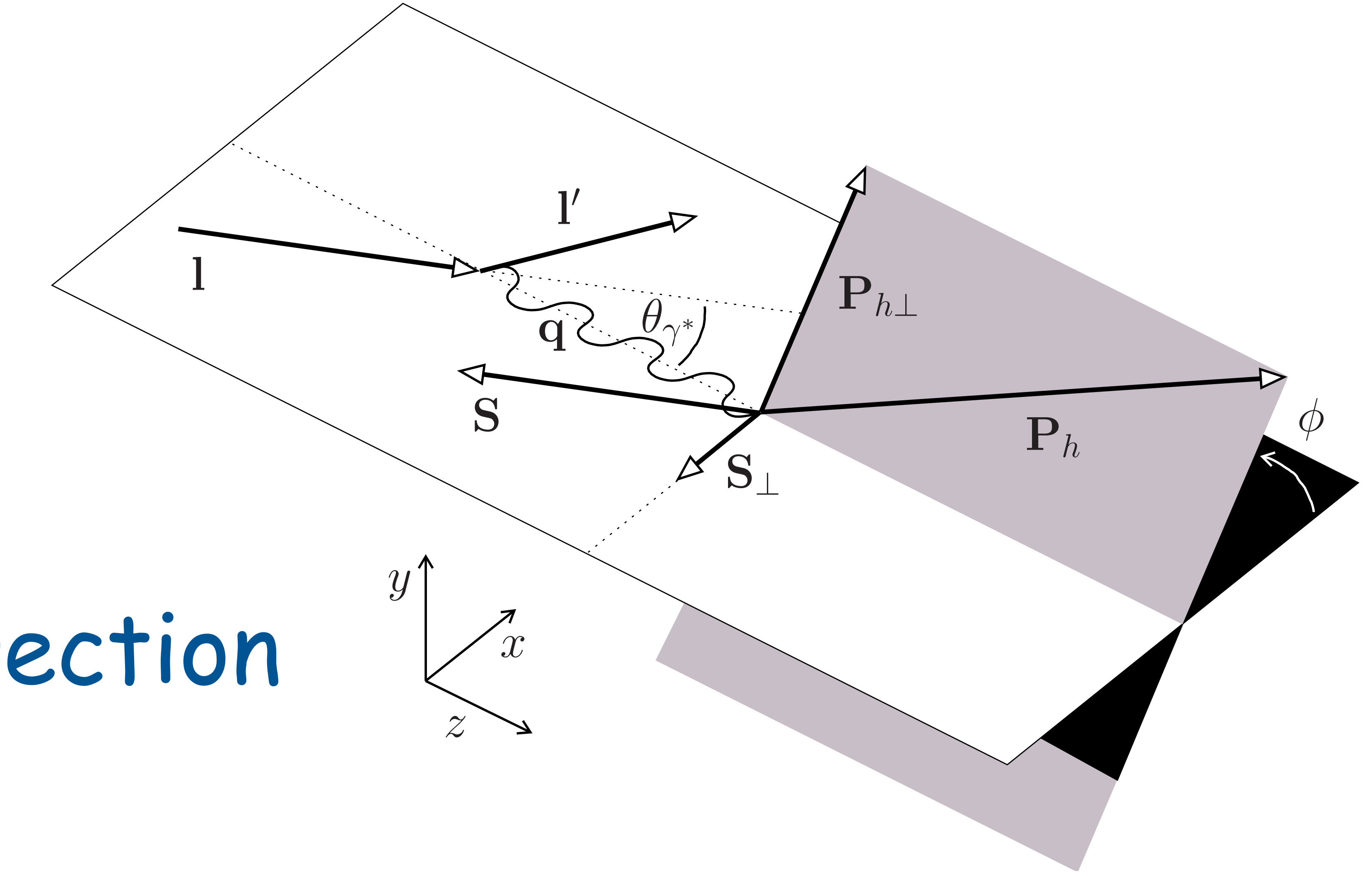
➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\mathrm{l}} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\mathrm{l}} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\mathrm{l}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\mathrm{q}} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT} \end{pmatrix}$$

subleading twist I - <sin(φ)>UL



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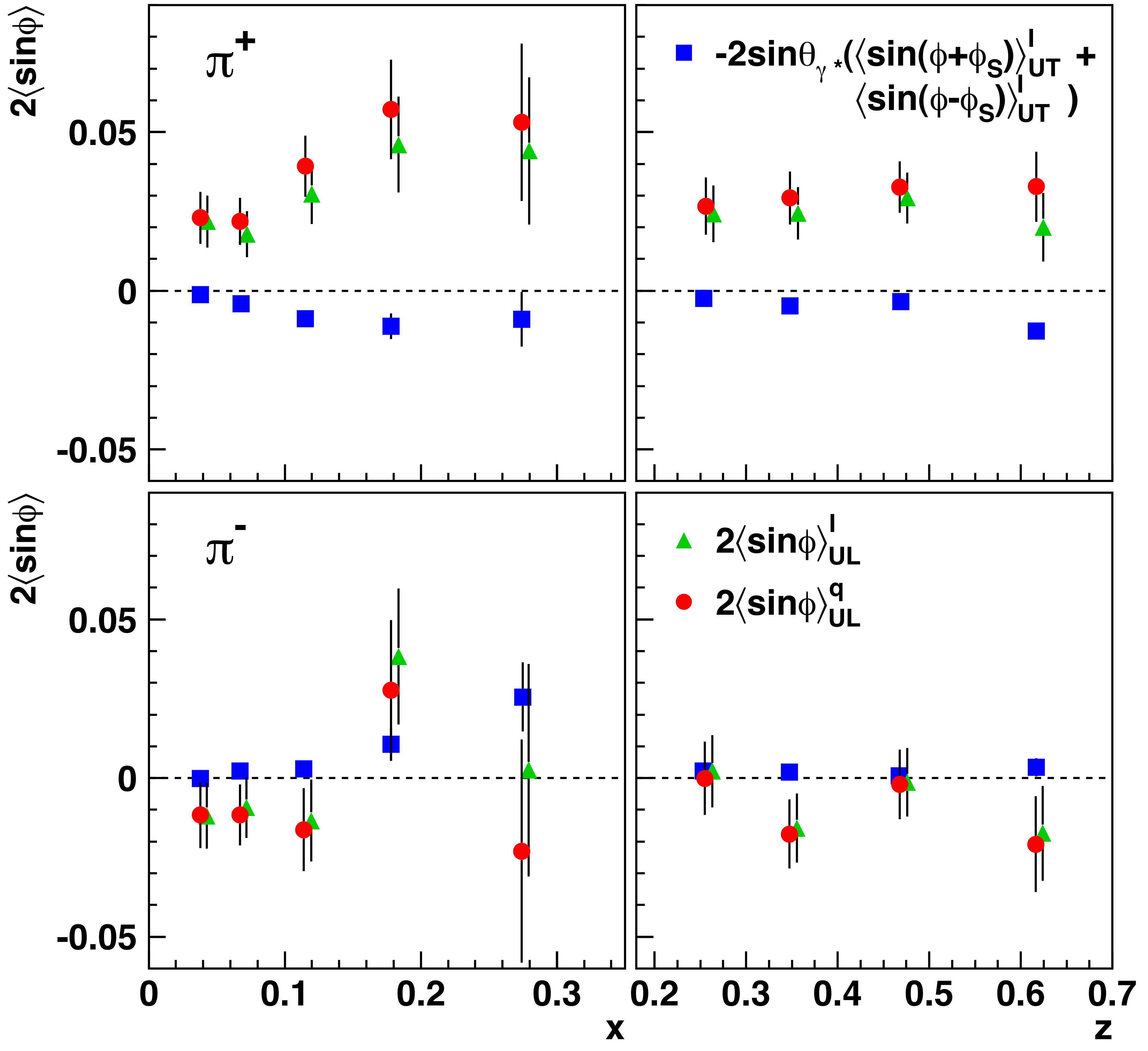
➡ need data on same target for both polarization orientations!

subleading twist I - <sin(ϕ)>$_{UL}$

$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*}\left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l}\right)$$

[Airapetian et al., PLB 622 (2005) 14]

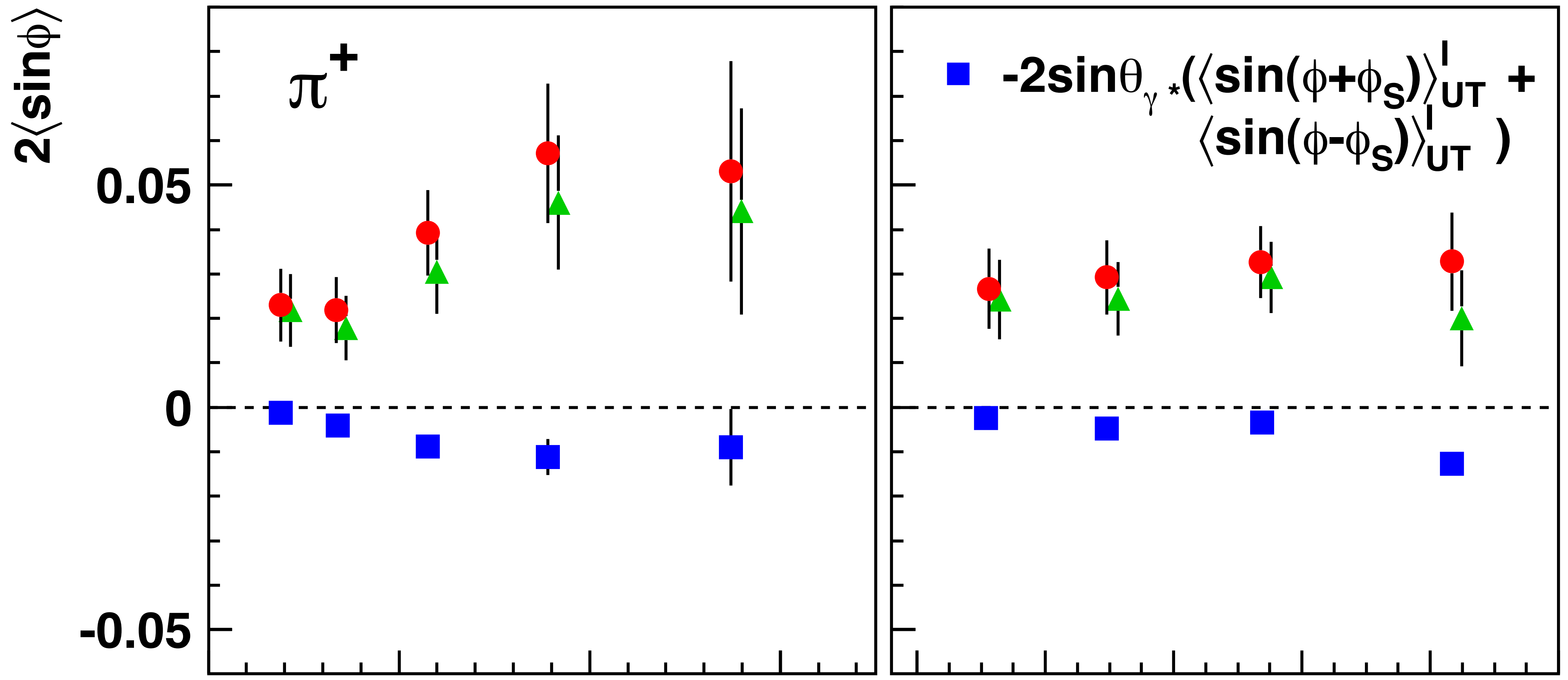


- experimental A_{UL} dominated by twist-3 contribution
- correction for A_{UT} contribution **increases** the longitudinal asymmetry for positive pions
- consistent with zero for π^-

subleading twist I - <sin(ϕ)>$_{UL}$

$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$

[Airapetian et al., PLB 622 (2005) 14]



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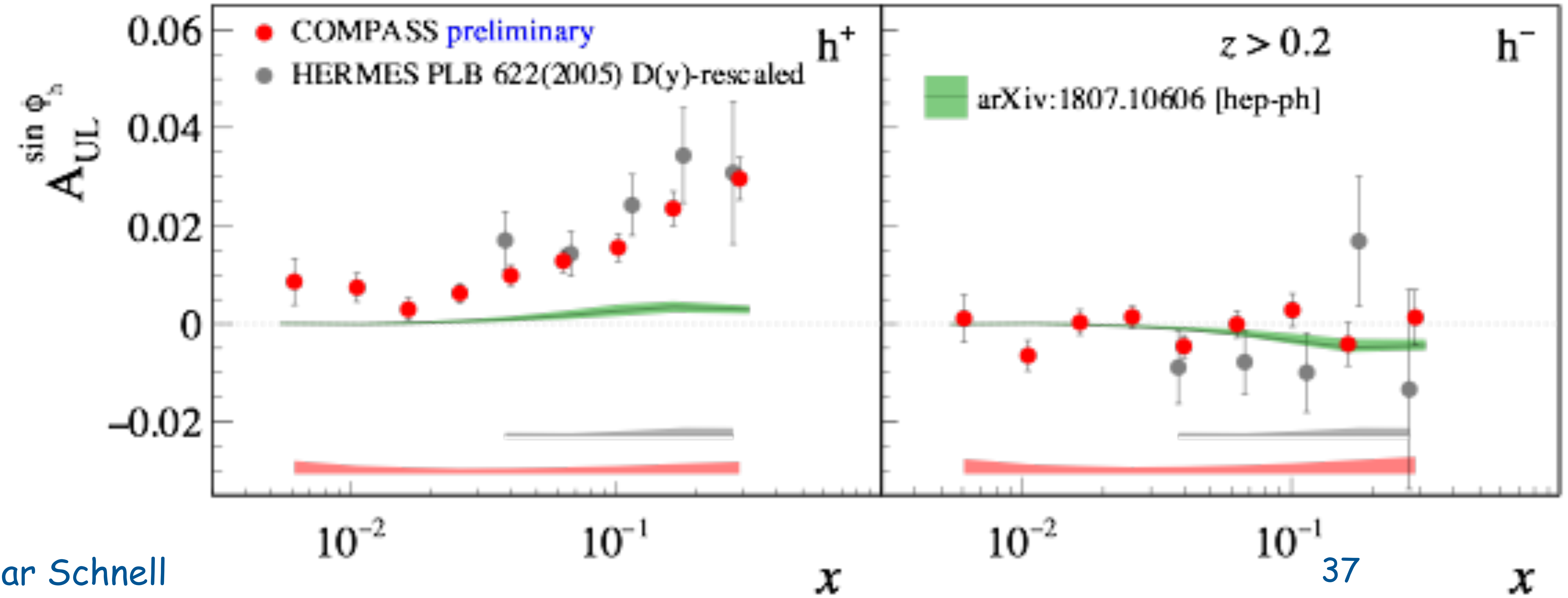
- in contrast to WW-type approximation [1807.10606] (both COMPASS and HERMES data)



subleading twist I - <sin(ϕ)>$_{UL}$

$$\left\langle \sin\phi \right\rangle^{q}_{UL} = \left\langle \sin\phi \right\rangle^{l}_{UL} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle^{l}_{UT} + \left\langle \sin(\phi-\phi_S) \right\rangle^{l}_{UT} \right)$$

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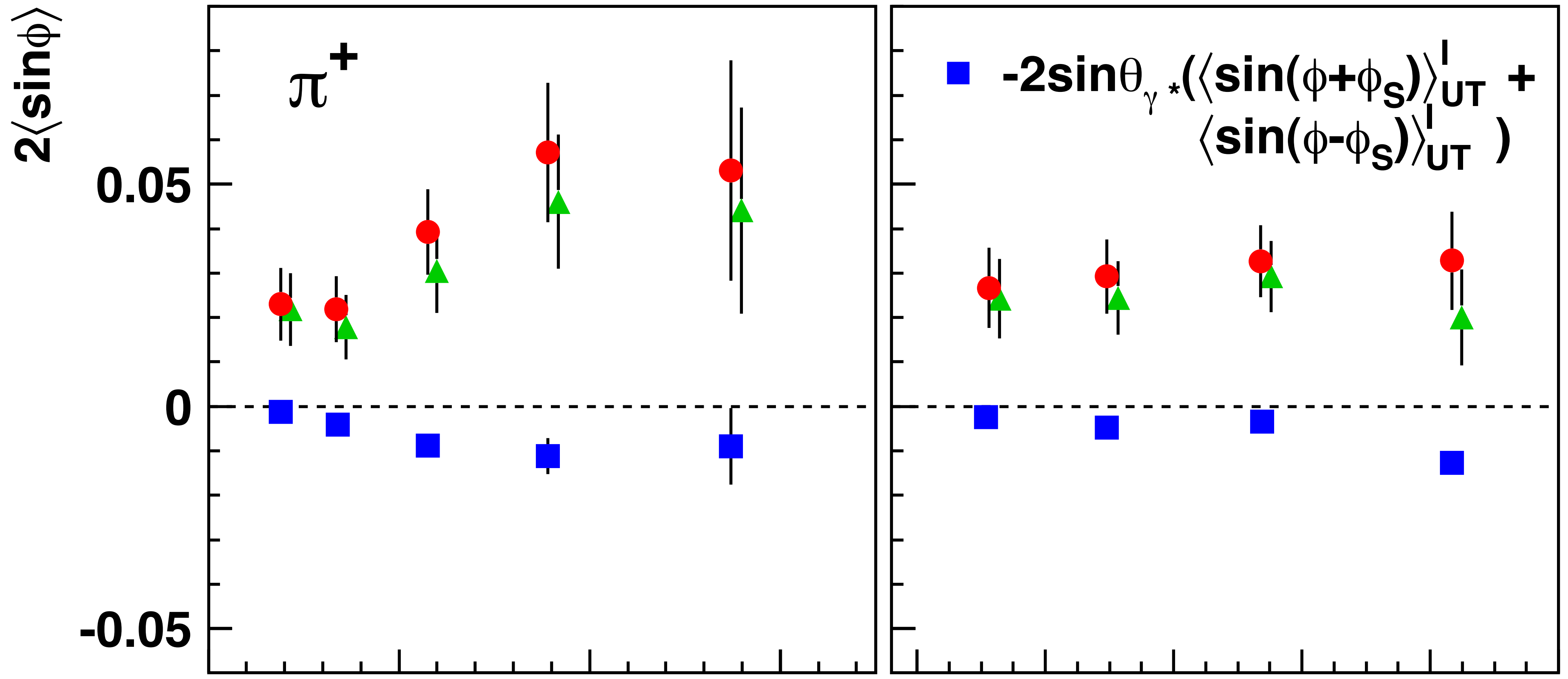

- experimental A_{UL} dominated by twist-3 contribution
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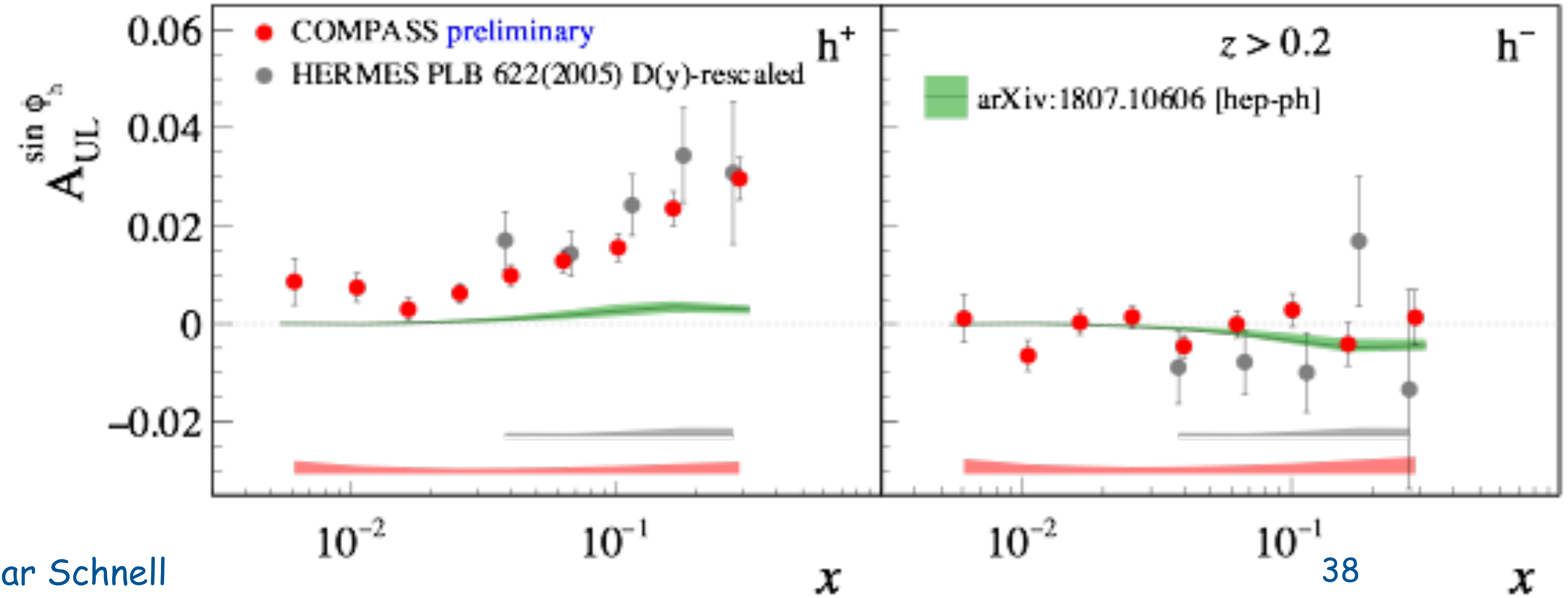
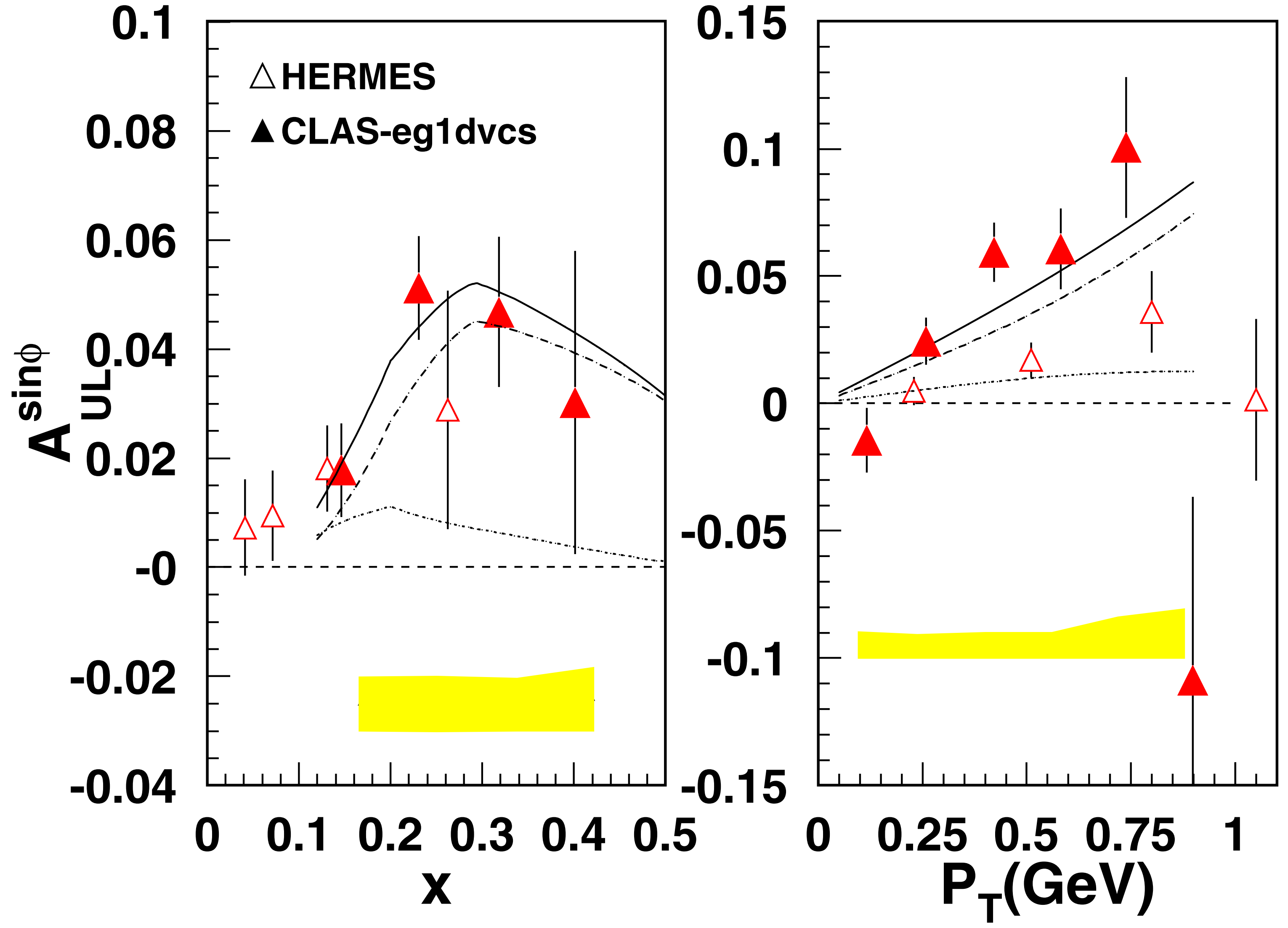
- sizable also for new CLAS neutral-pion data



[CLAS, PLB 782 (2018) 662-667]



subleading twist II - <sin(ϕ)>$_{LU}$

$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$

- naive-T-odd Boer-Mulders (BM) function coupled to a twist-3 FF
  - signs of BM from unpolarized SIDIS
  - little known about interaction-dependent FF
- little known about naive-T-odd $g^\perp$; singled out in A_{LU} in jet production
- large unpolarized f_1, coupled to interaction-dependent FF
- twist-3 e survives integration over $P_{h\perp}$; here coupled to Collins FF
  - e linked to the pion–nucleon σ-term
  - interpreted as color force (from remnant) on transversely polarized quarks at the moment of being struck by virtual photon

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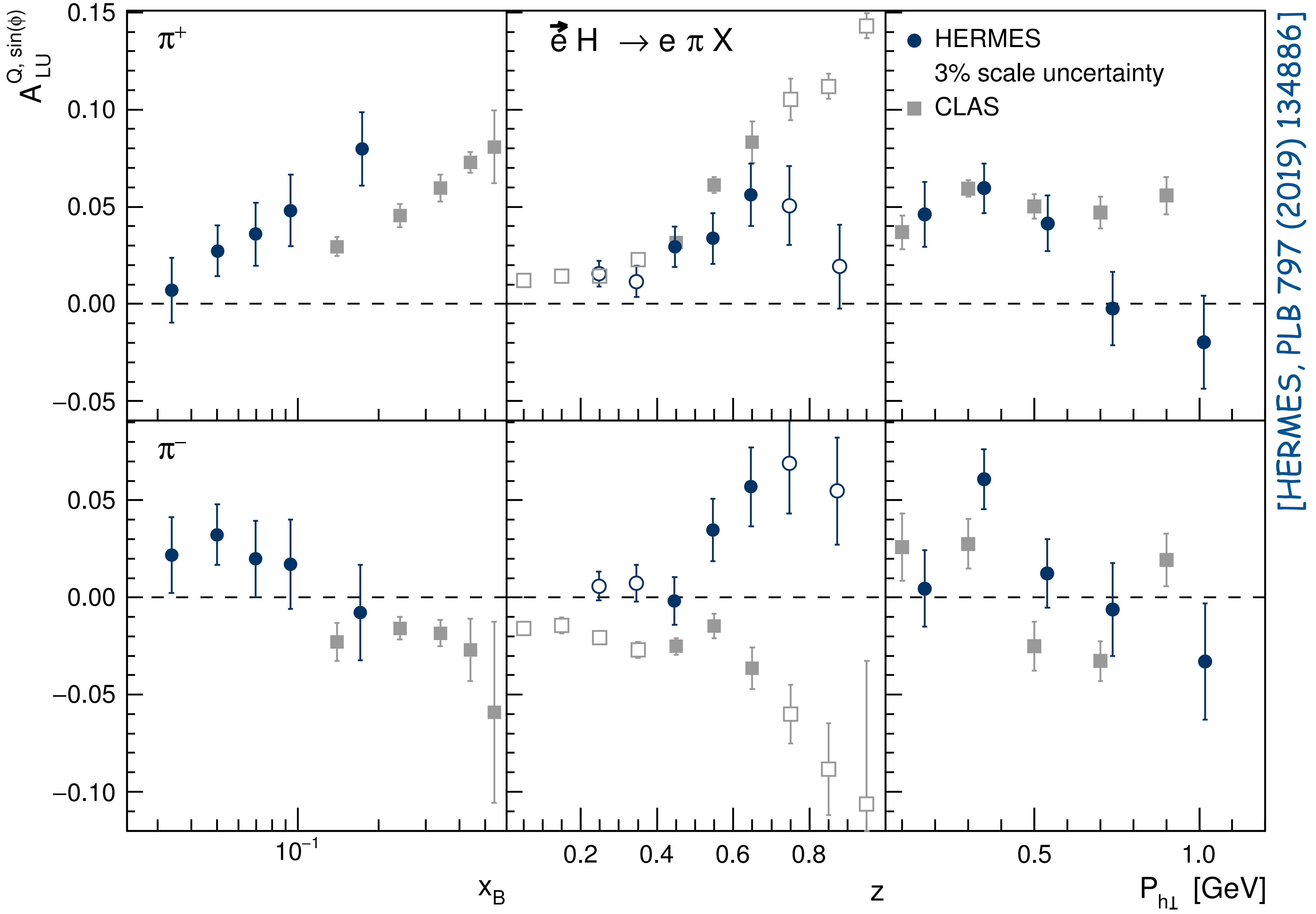
  - e linked to the pion-nucleon σ-term
  - interpreted as color force (from remnant) on transversely polarized quarks at the moment of being struck by virtual photon
- **all terms vanish in WW-type approximation**

subleading twist II - <sin(ϕ)>$_{LU}$ HERMES & CLAS

$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$

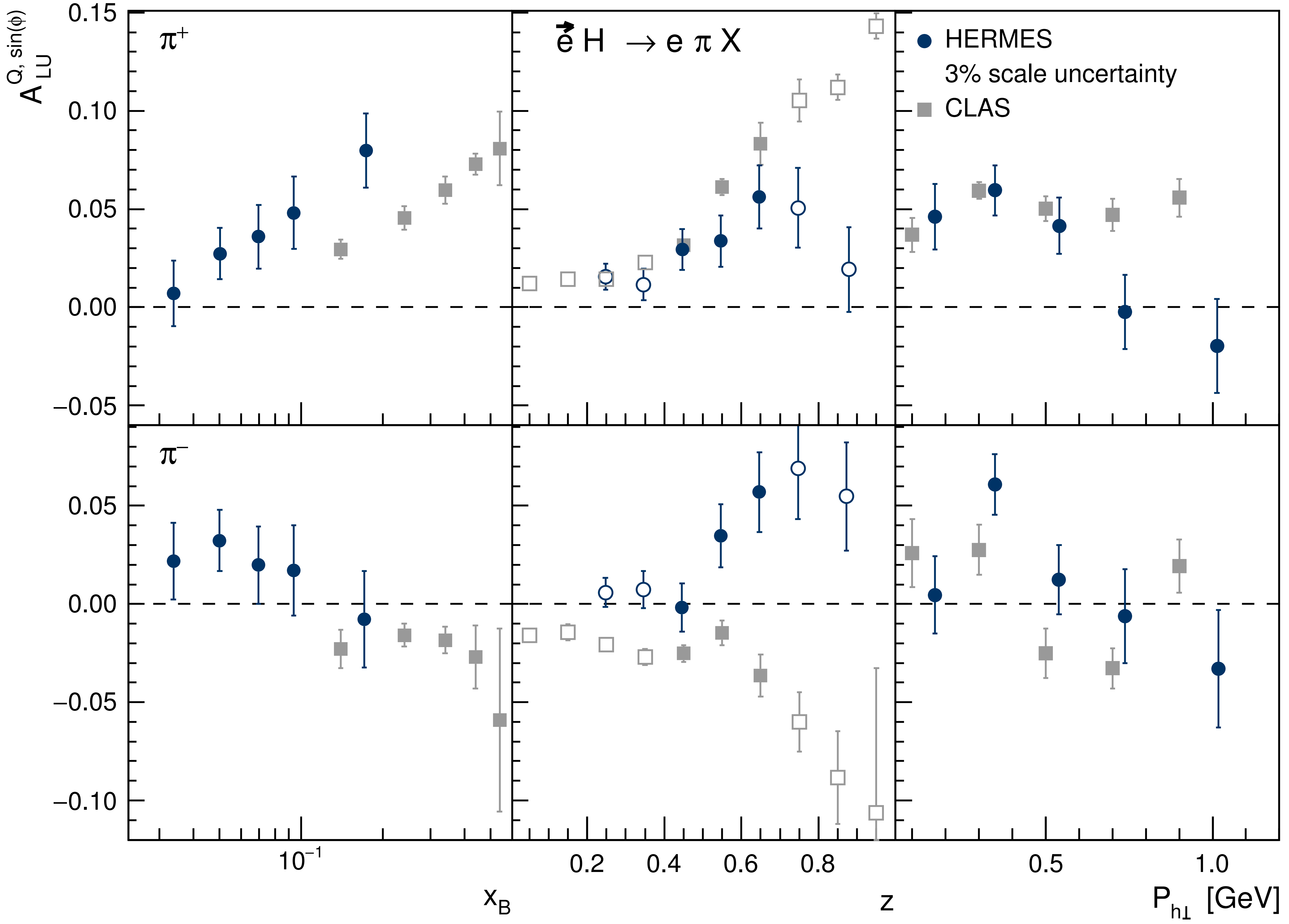


[HERMES, PLB 797 (2019) 134886]

- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed

subleading twist II - <sin(ϕ)>$_{LU}$ HERMES & CLAS

$$\frac{M_h}{Mz} h_1^{\perp} \tilde{E} \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^{\perp} \oplus xeH_1^{\perp}$$



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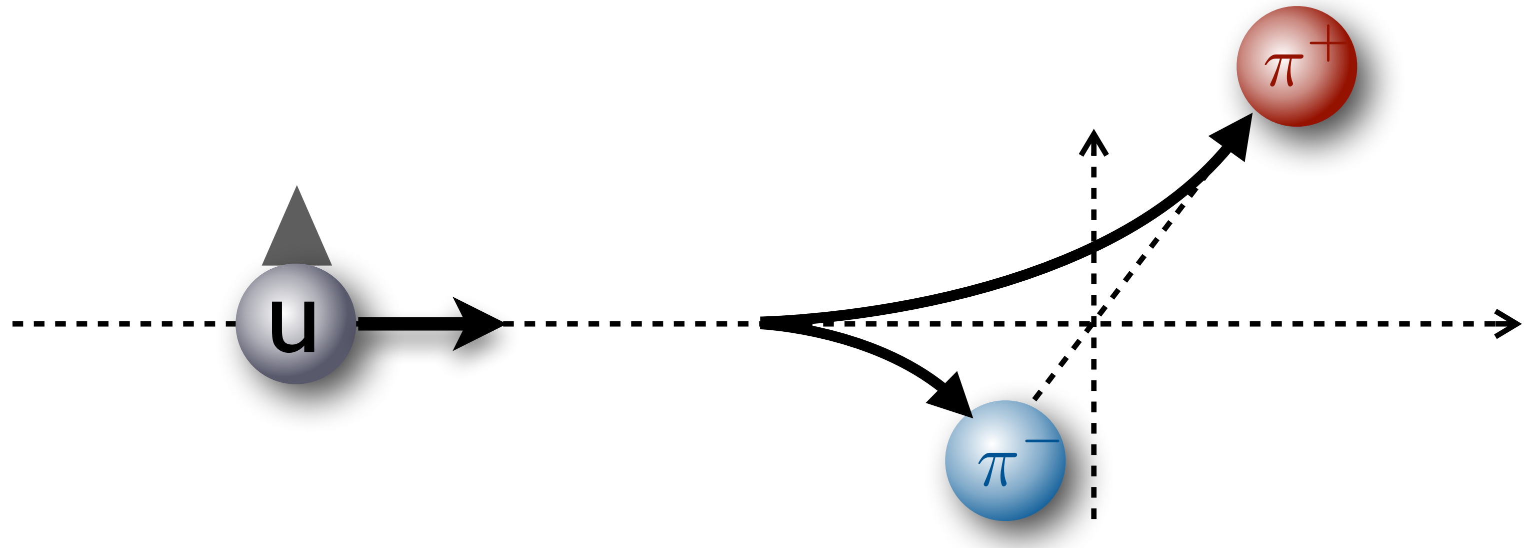
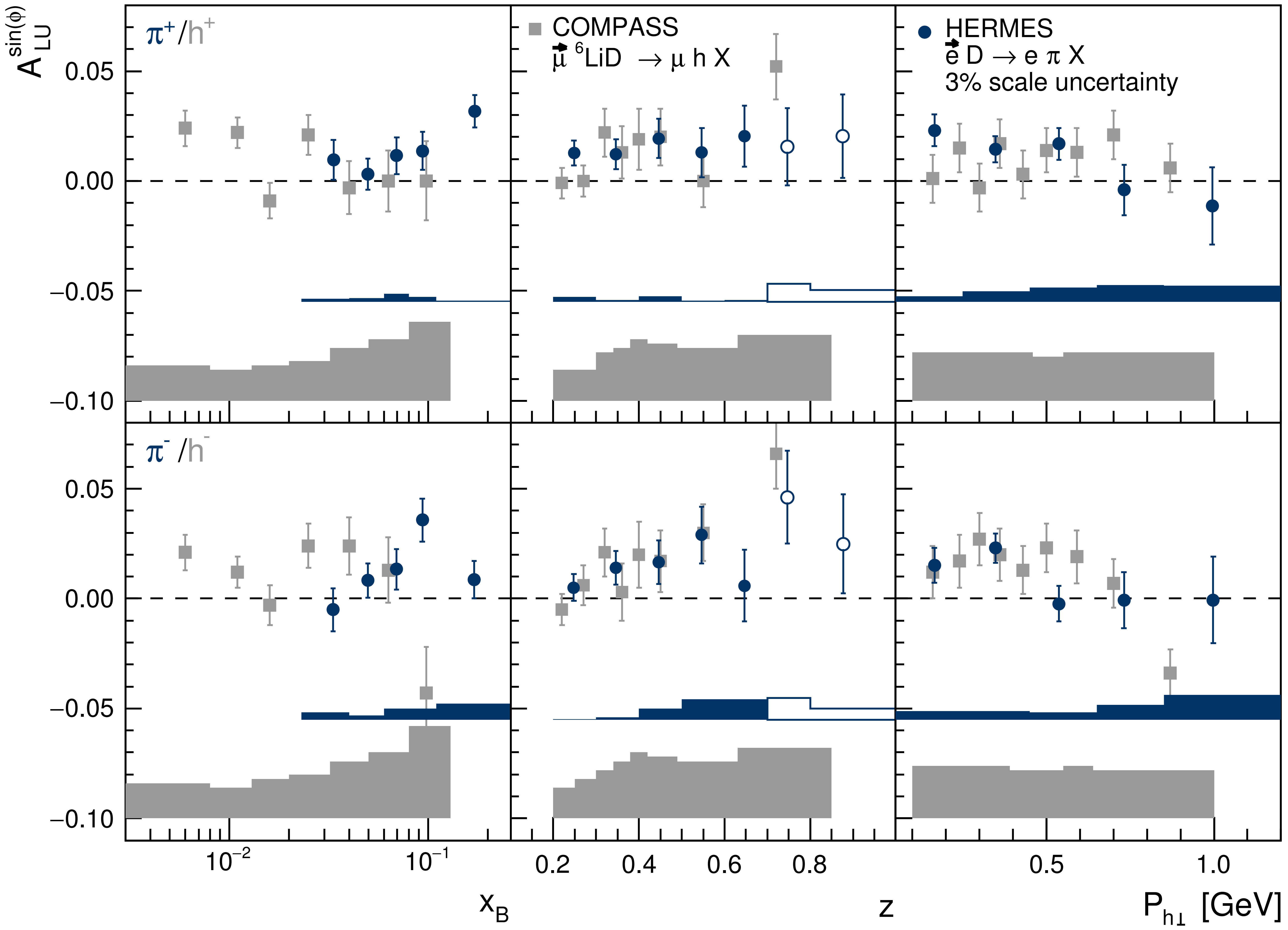


- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x)Collins term due to higher x probed?

subleading twist II - <sin(ϕ)>$_{LU}$ HERMES & COMPASS

$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$



[HERMES, PLB 797 (2019) 134886]

consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets

subleading twist III - $\langle\sin(\phi_s)\rangle_{UT}$

- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

$$\begin{aligned}\propto\ & \left(\mathbf{x f_T^{\perp} D_1} - \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{h_1}\frac{\mathbf{\tilde{H}}}{\mathbf{z}}\right)\\ & - \mathcal{W}(\mathbf{p_T},\mathbf{k_T},\mathbf{P_{h\perp}})\left[\left(\mathbf{x h_T H_1^{\perp}} + \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{g_{1T}}\frac{\mathbf{\tilde{G}^{\perp}}}{\mathbf{z}}\right)\right.\\ & \qquad\qquad\qquad\qquad \left. - \left(\mathbf{x h_T^{\perp} H_1^{\perp}} - \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{f_{1T}^{\perp}}\frac{\mathbf{\tilde{D}^{\perp}}}{\mathbf{z}}\right)\right]\end{aligned}$$

- non-vanishing collinear limit:

$$F_{\mathrm{UT}}^{\sin(\phi_S)}\left(x, Q^2, z\right) = \int d^2\mathbf{P}_{h\perp}\, F_{\mathrm{UT}}^{\sin(\phi_S)}\left(x, Q^2, z, P_{h\perp}\right) = -x\frac{2M_h}{Q}\sum_q e_q^2\, h_1^q \frac{\tilde{H}^q(z)}{z}$$

subleading twist III - <sin(ϕ_s)>$_{UT}$

- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

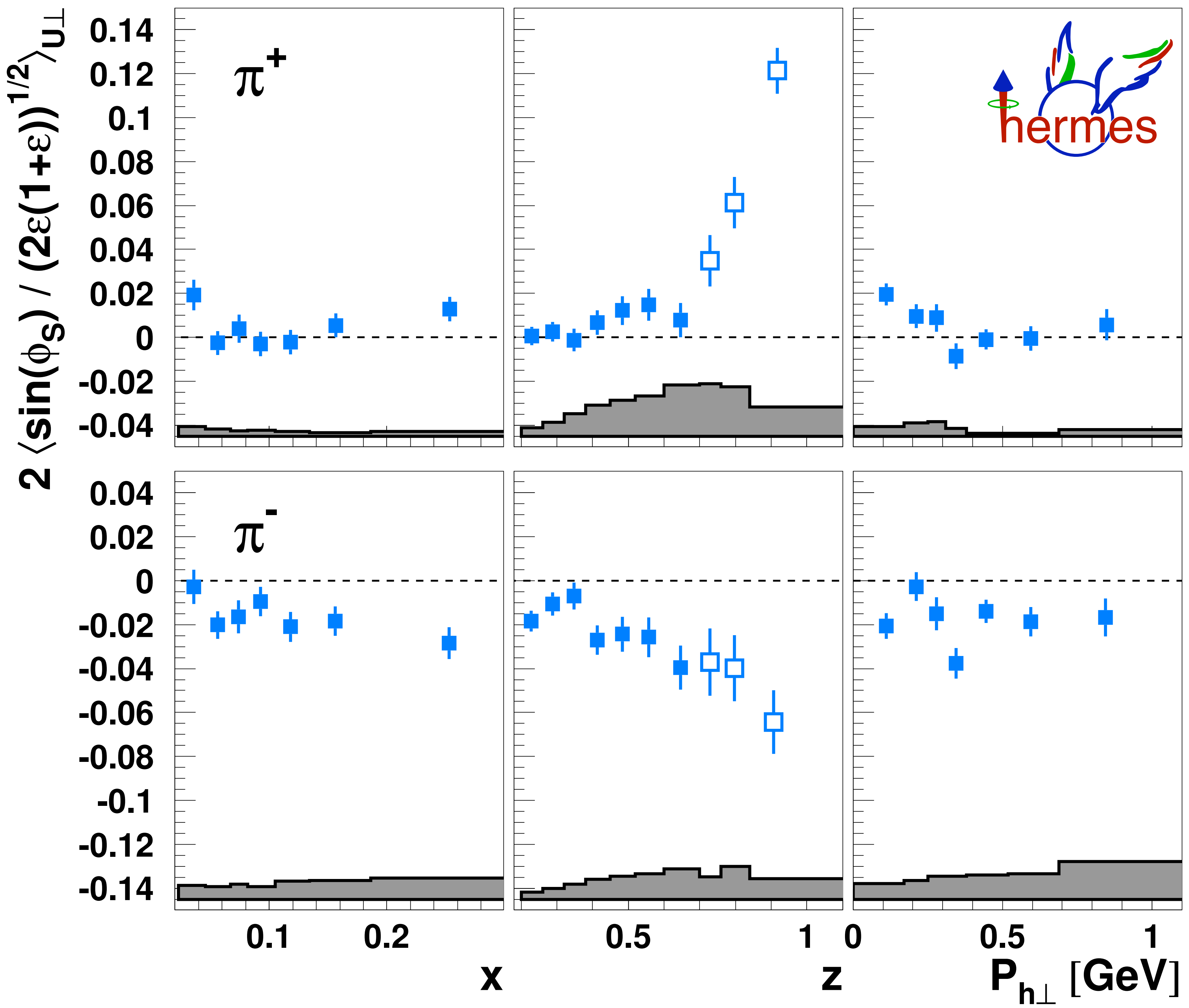
$$
\begin{aligned}
\propto \quad & \left(\mathbf{x f_T^{\perp} D_1} - \frac{\mathbf{M_h}}{\mathbf{M}} \mathbf{h_1} \frac{\mathbf{\tilde{H}}}{\mathbf{z}} \right) \\
& - \mathcal{W}(\mathbf{p_T}, \mathbf{k_T}, \mathbf{P_{h\perp}}) \left[\left(\mathbf{x h_T H_1^{\perp}} + \frac{\mathbf{M_h}}{\mathbf{M}} \mathbf{g_{1T}} \frac{\mathbf{\tilde{G}^{\perp}}}{\mathbf{z}} \right) \right. \\
& \qquad \left. - \left(\mathbf{x h_T^{\perp} H_1^{\perp}} - \frac{\mathbf{M_h}}{\mathbf{M}} \mathbf{f_{1T}^{\perp}} \frac{\mathbf{\tilde{D}^{\perp}}}{\mathbf{z}} \right) \right]
\end{aligned}
$$

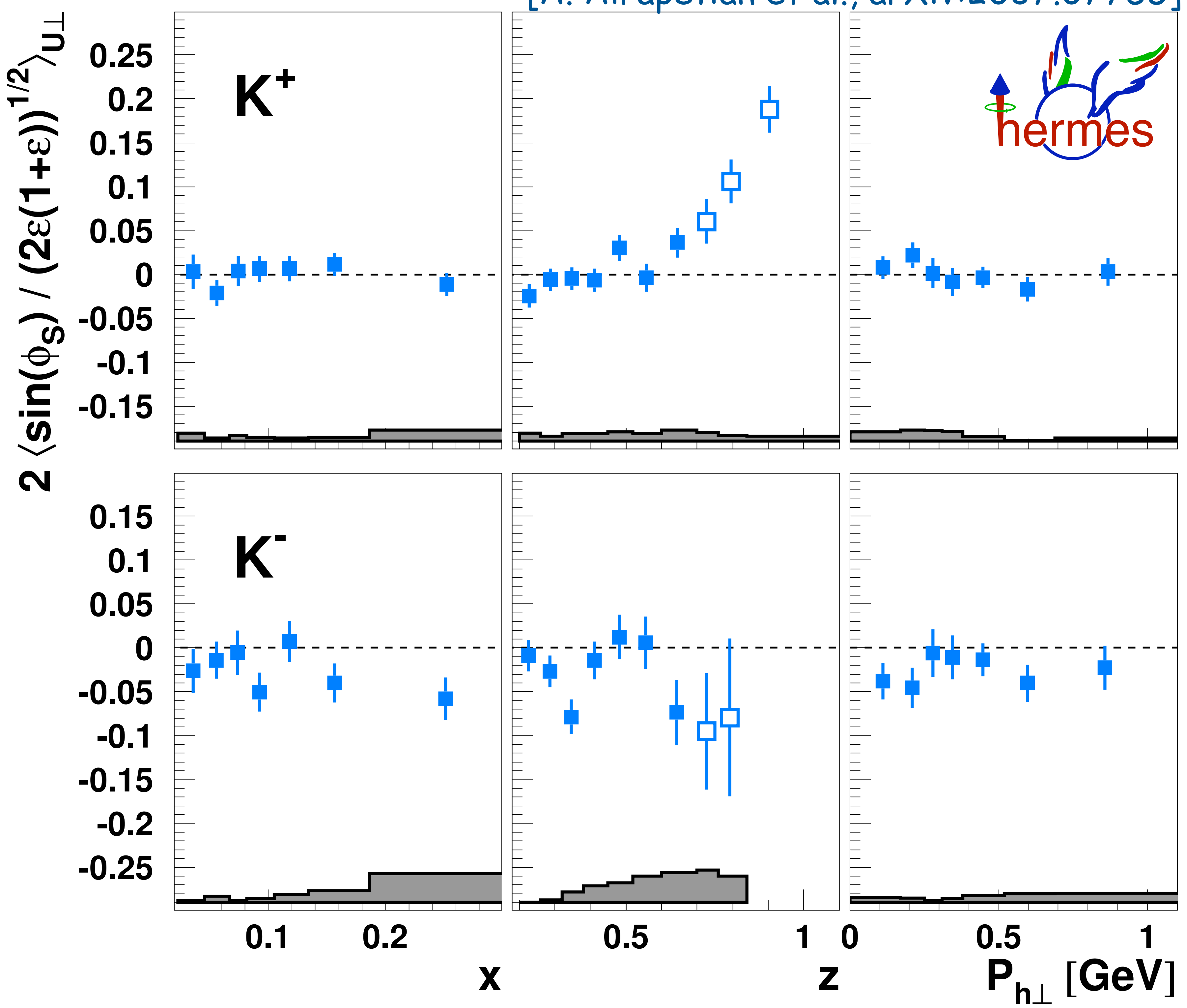
- non-vanishing collinear limit:

$$
F_{UT}^{\sin(\phi_S)}(x, Q^2, z) = \int d^2\mathbf{P}_{h\perp} \, F_{UT}^{\sin(\phi_S)}(x, Q^2, z, P_{h\perp}) = -x \frac{2M_h}{Q} \sum_q e_q^2 \, h_1^q \frac{\boxed{\tilde{H}^q(z)}}{z}
$$

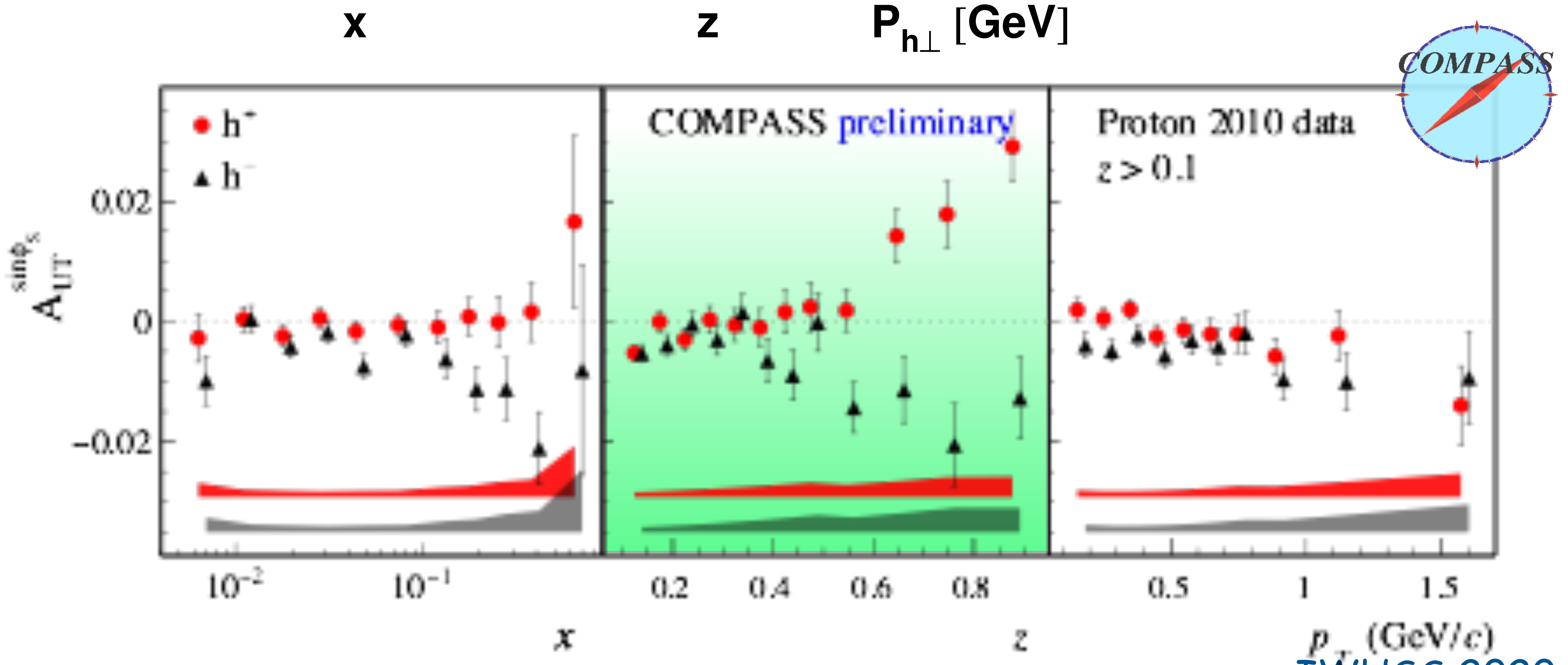
subleading twist III - $\langle\sin(\phi_S)\rangle_{UT}$

[A. Airapetian et al., arXiv:2007.07755]





- clearly non-zero asymmetries
- opposite sign for charged pions (Collins-like behavior)
- striking z dependence and in particular magnitude
- similar observation at COMPASS



conclusions

- 1st round of SIDIS measurements coming to an end
- various indications of flavor-& spin-dependent transverse momentum
- transversity is non-zero and quite sizable
  - d-quark transversity difficult to access with only proton targets -> COMPASS d-transversity run
- Sivers and chiral-even worm-gear function also clearly non-zero
- no sign for non-zero pretzelosity
- data on chiral-odd worm-gear not yet conclusive
- various sizable twist-3 effects seen, often in conflict with WW-type approximations
- new round of measurements coming up including remaining d-transversity at COMPASS as well as measurements at JLab12 and future EIC

☛ Marco Contalbrigo (next)
☛ Patrizia Rossi (Tue)
☛ Haiyan Gao (Tue)
☛ Harut Avagyan (Tue)

conclusions

- 1st round of SIDIS measurements coming to an end
- various indications of flavor-& spin-dependent transverse momentum
- transversity is non-zero and quite sizable
  - d-quark transversity difficult to access with only proton targets -> COMPASS d-transversity run
- Sivers and chiral-even worm-gear function also clearly non-zero
- no sign for non-zero pretzelosity
- data on chiral-odd worm-gear not yet conclusive
- various sizable twist-3 effects seen, often in conflict with WW-type approximations
- new round of measurements coming up including remaining d-transversity at COMPASS as well as measurements at JLab12 and future EIC

a big THANKS! to the organizers for bringing us together here, even if only virtually backup