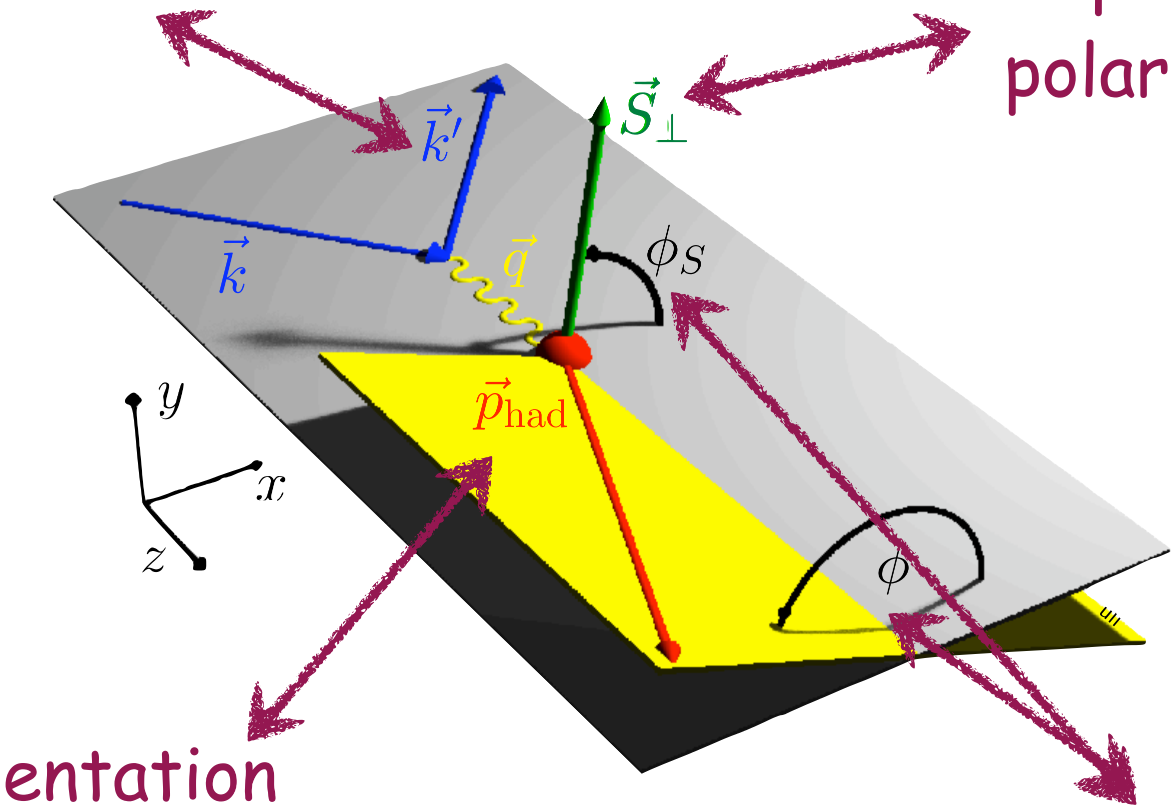
19th International Conference on Hadron Spectroscopy and Structure in memoriam Simon Eidelman (HADRON2021)
Mexico City (virtual) — July 26 to 31, 2021



parton kinematics

parton polarization

fragmentation kinematics

FF selector

Overview of recent HERMES results on transverse-momentum-dependent spin asymmetries in semi-inclusive DIS

Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Spin-momentum structure of the nucleon

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

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

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

Spin-momentum structure of the nucleon

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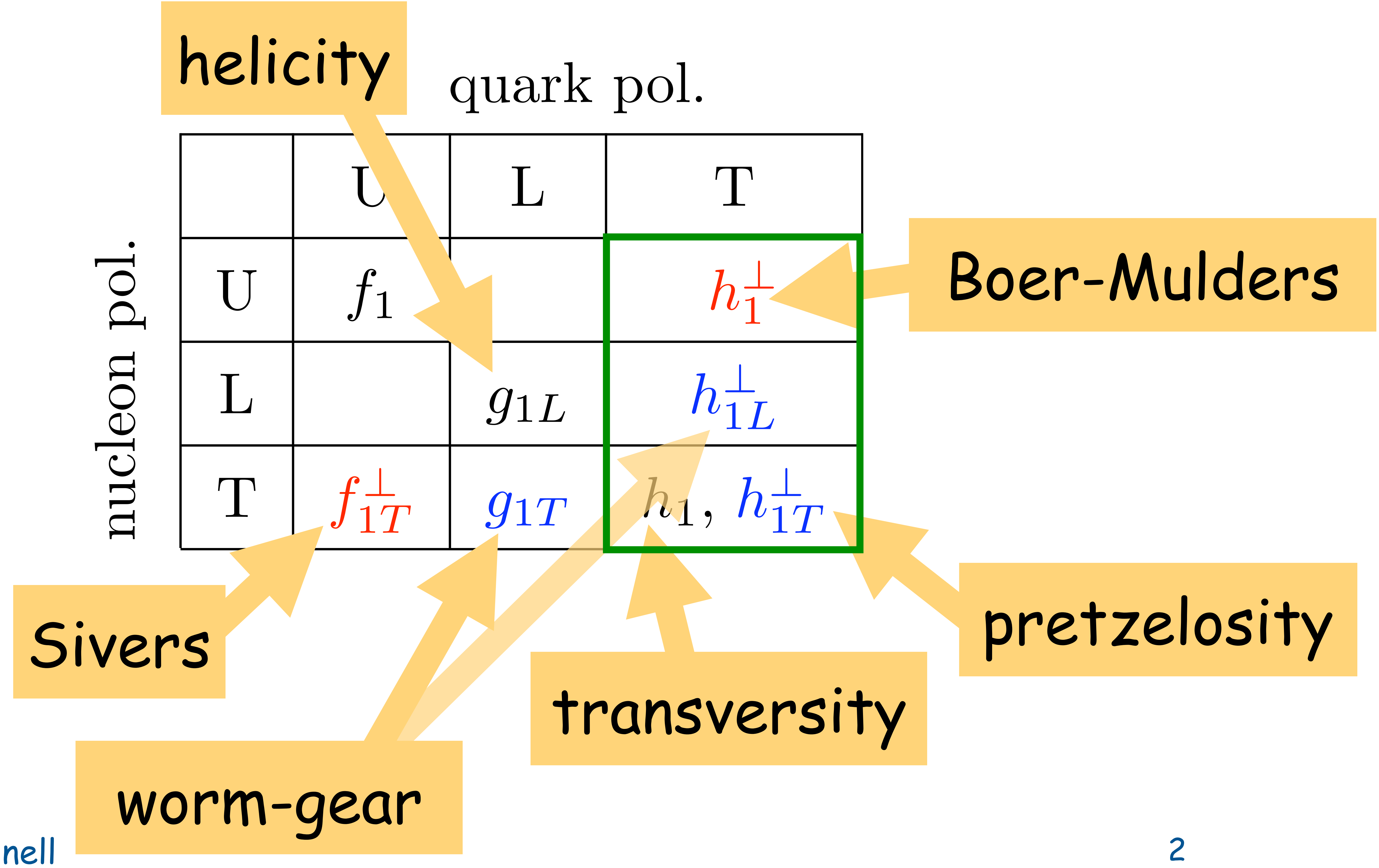

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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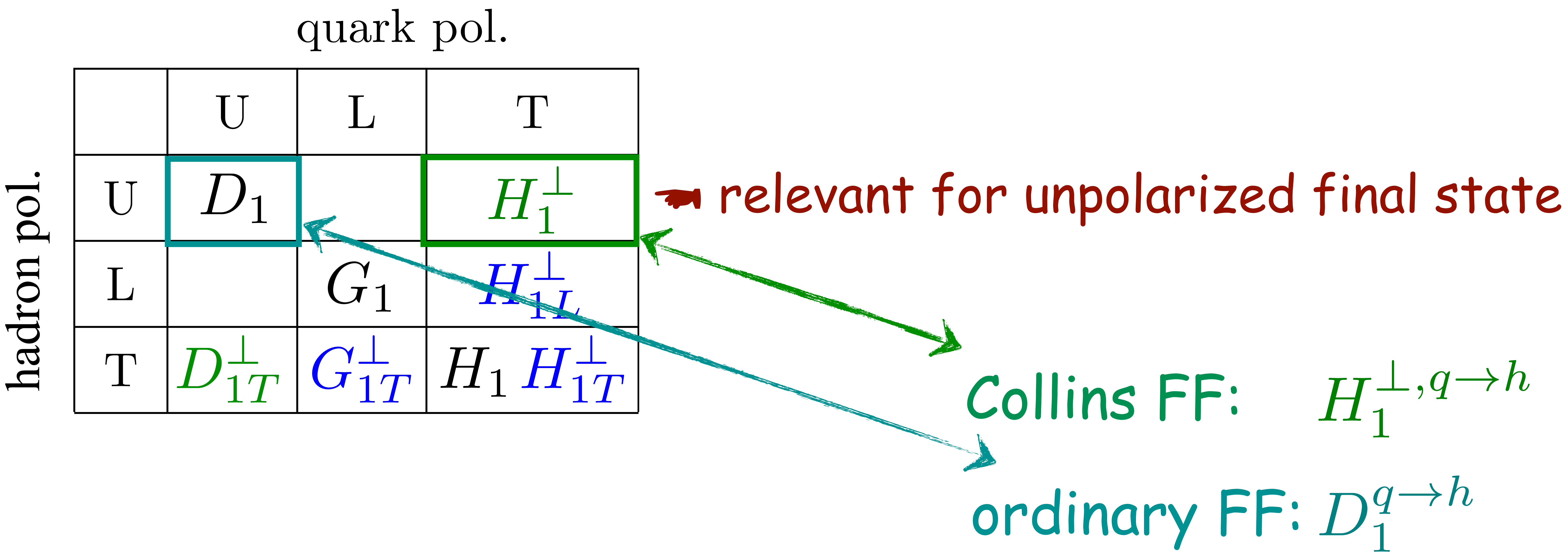
hadron pol.	U	D_1		$H_1^\perp$
	L		G_1	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☛ relevant for unpolarized final state

TMDs in hadronization



quark pol.

hadron pol.

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

☛ relevant for unpolarized final state

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

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

TMDs in hadronization

quark pol.

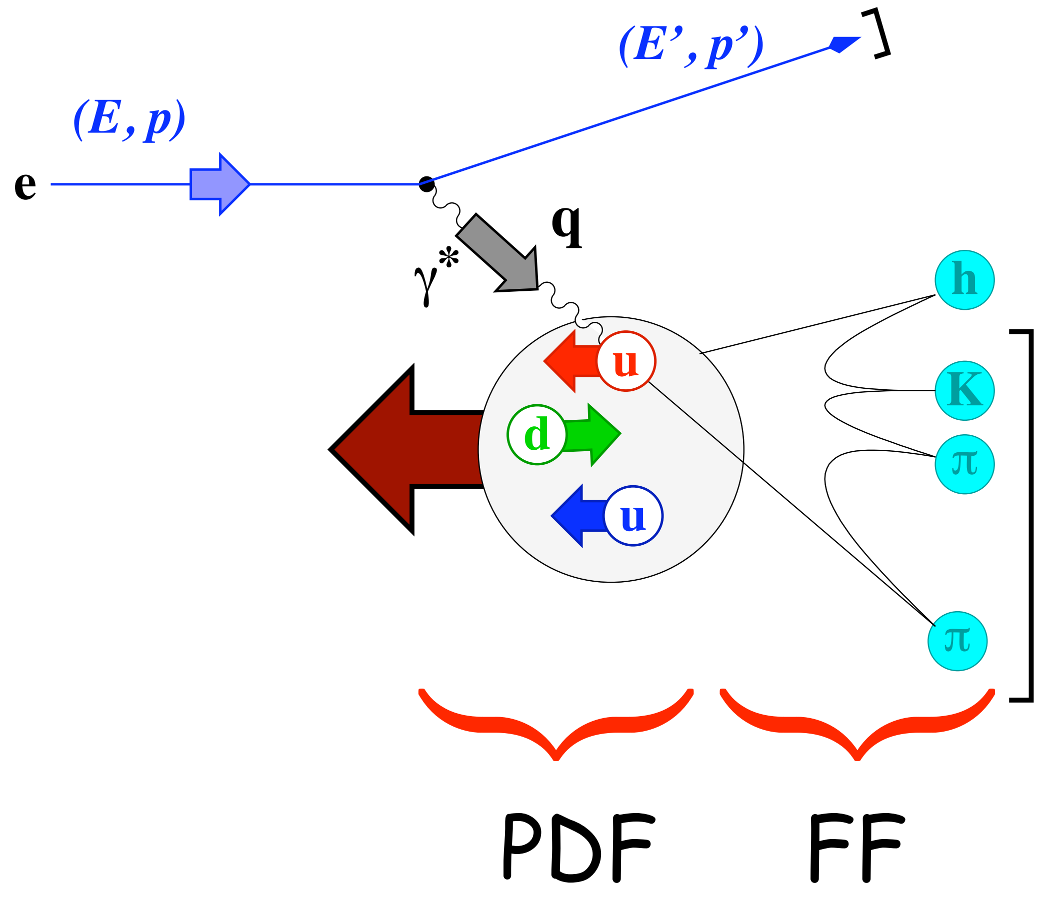
hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
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



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

in SIDIS*) couple PDFs to:

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

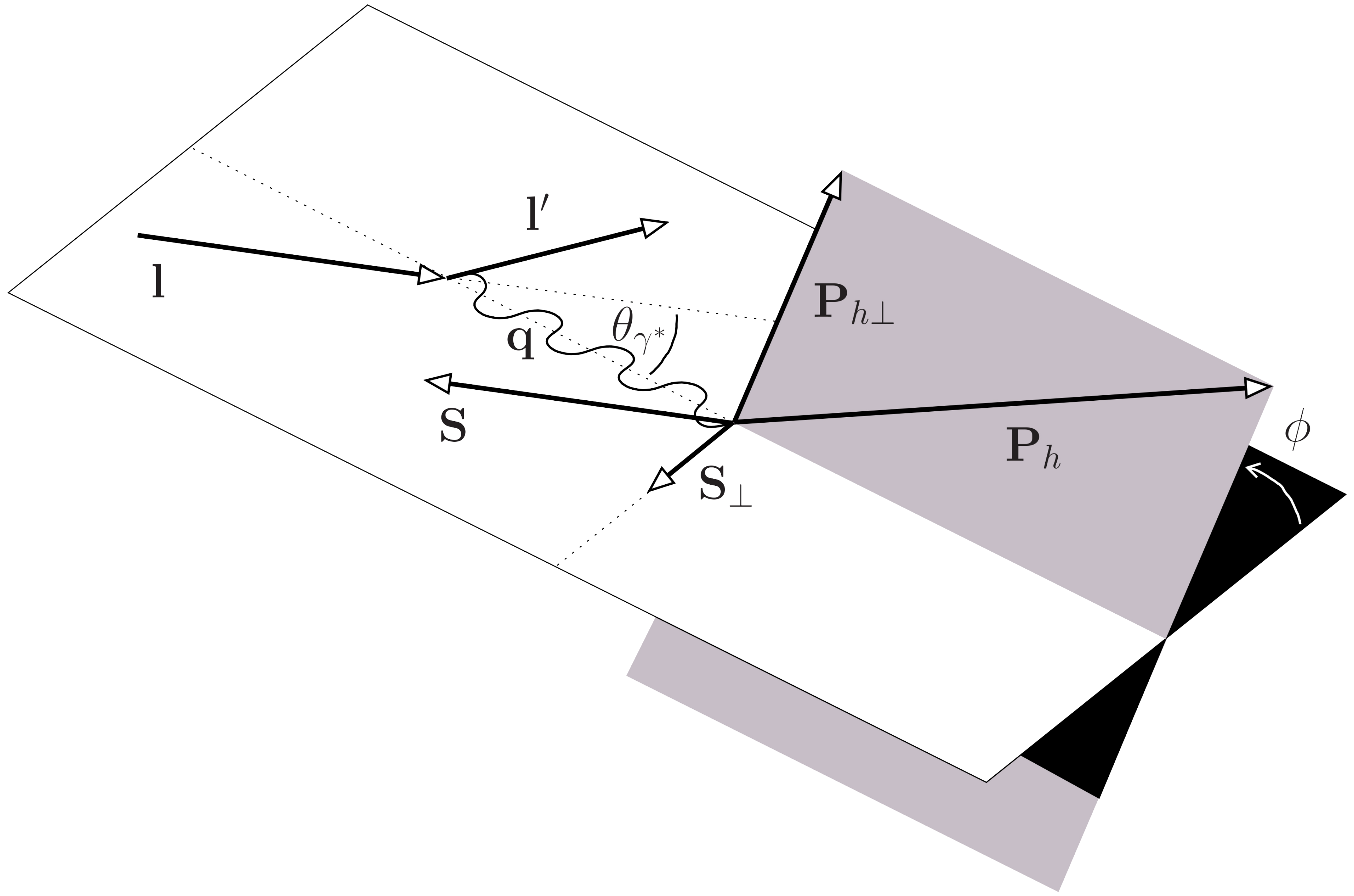
ordinary FF: $D_1^{q\to h}$

➟ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

semi-inclusive DIS

- excluding transverse polarization:



$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,{\color{red}F_{LL}^h}$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,{\color{blue}F_{LL}^{h,\cos\phi}} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

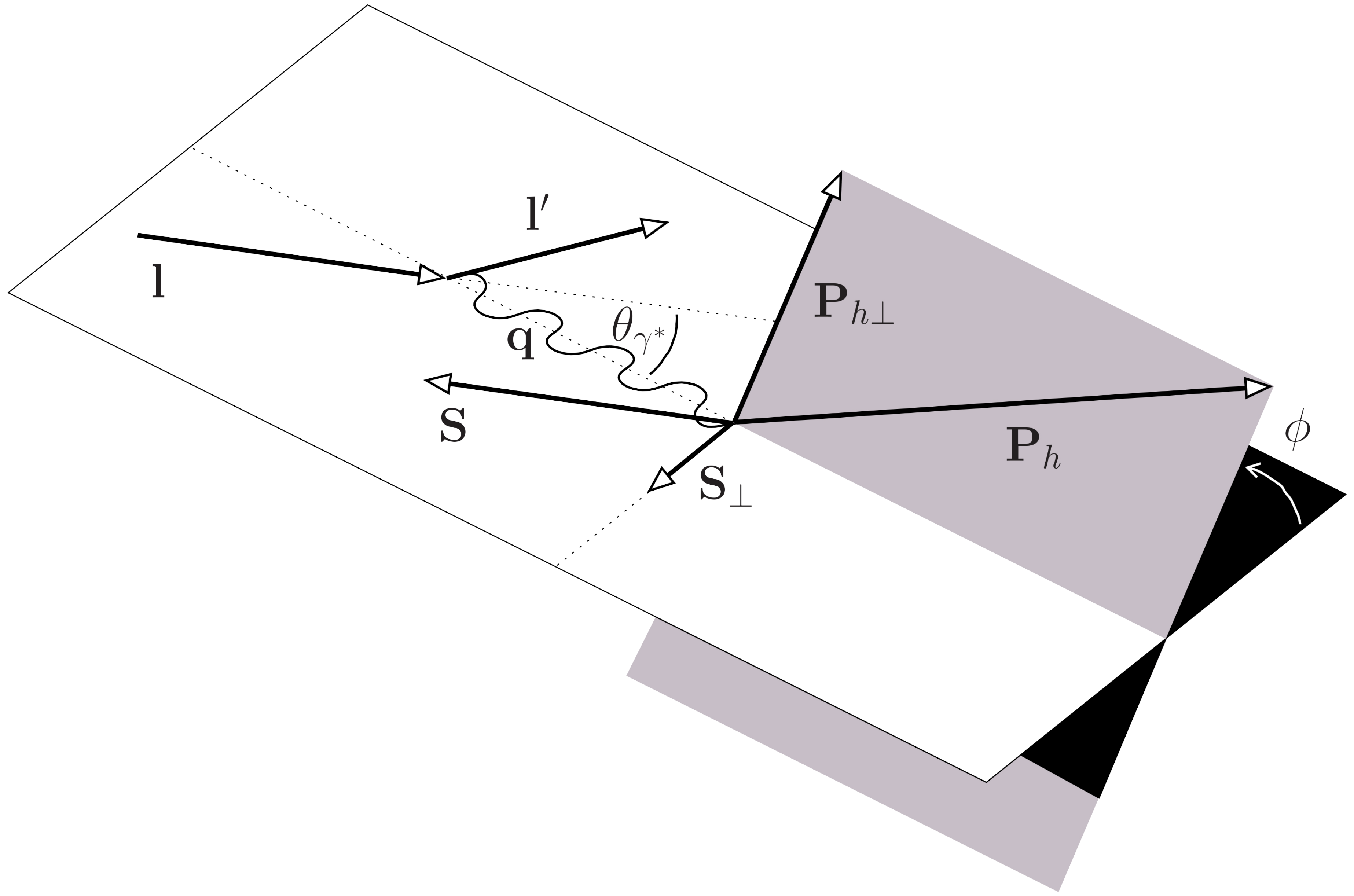
$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi\ \Big\}$$

$$F_{XY}^{h,\mathrm{mod}} = F_{XY}^{h,\mathrm{mod}}(x,Q^2,z,P_{h\perp})$$

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS



- excluding transverse polarization:

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F^h_{UU,T}+\epsilon F^h_{UU,L}+\lambda\Lambda\sqrt{1-\epsilon^2}F^h_{LL}$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F^{h,\sin\phi}_{LU}+\Lambda\sqrt{1+\epsilon}\,F^{h,\sin\phi}_{UL}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F^{h,\cos\phi}_{LL}+\sqrt{1+\epsilon}\,F^{h,\cos\phi}_{UU}\right]\cos\phi$$

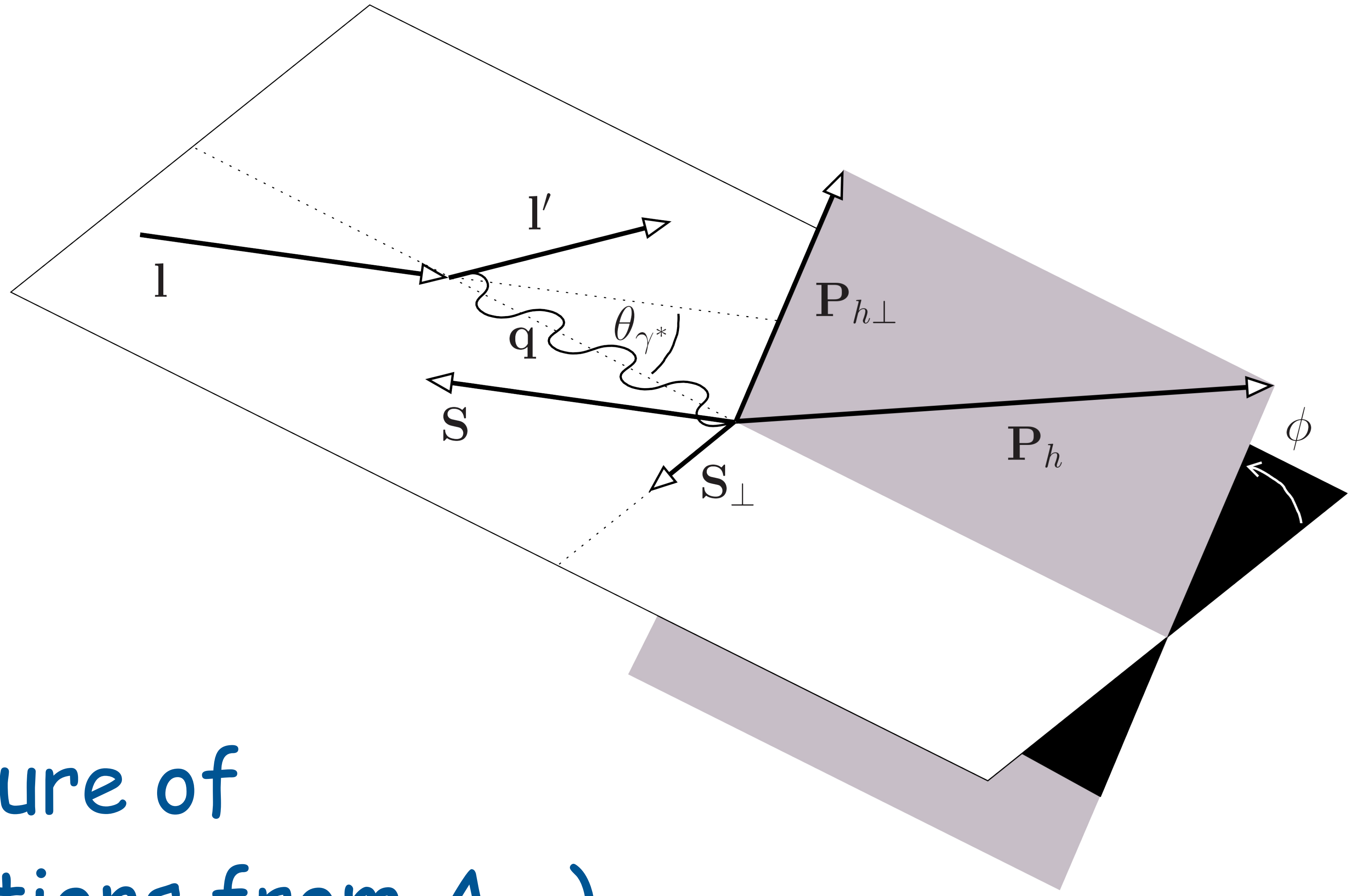
$$+\Lambda\epsilon\,F^{h,\sin 2\phi}_{UL}\sin 2\phi+\epsilon\,F^{h,\cos 2\phi}_{UU}\cos 2\phi\ \Big\}$$

- double-spin asymmetry:

$$A^h_{LL}\equiv\frac{\sigma^h_{++}-\sigma^h_{+-}+\sigma^h_{--}-\sigma^h_{-+}}{\sigma^h_{++}+\sigma^h_{+-}+\sigma^h_{--}+\sigma^h_{-+}}$$

semi-inclusive DIS

- in experiment extract instead $A_{||}$ which differs from A_{LL} in the way the polarization is measured:
  - A_{LL}: along virtual-photon direction
  - $A_{||}$: along beam direction (results in small admixture of transverse target polarization and thus contributions from A_{LT})
- $A_{||}$ related to virtual-photon-nucleon asymmetry A_1



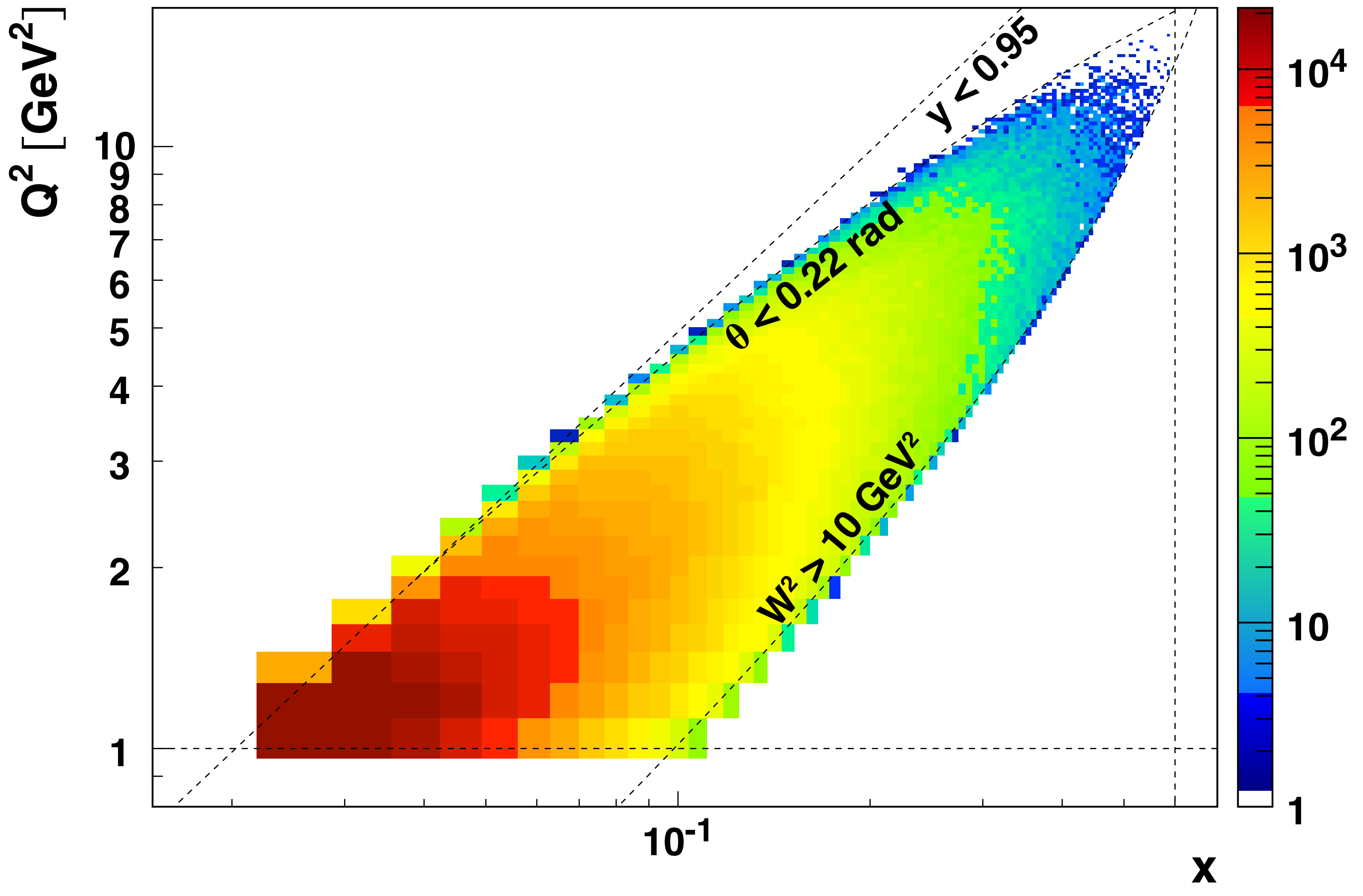
$$\boxed{A_1^h = \frac{1}{D(1+\eta\gamma)} A_{\|}^h}$$

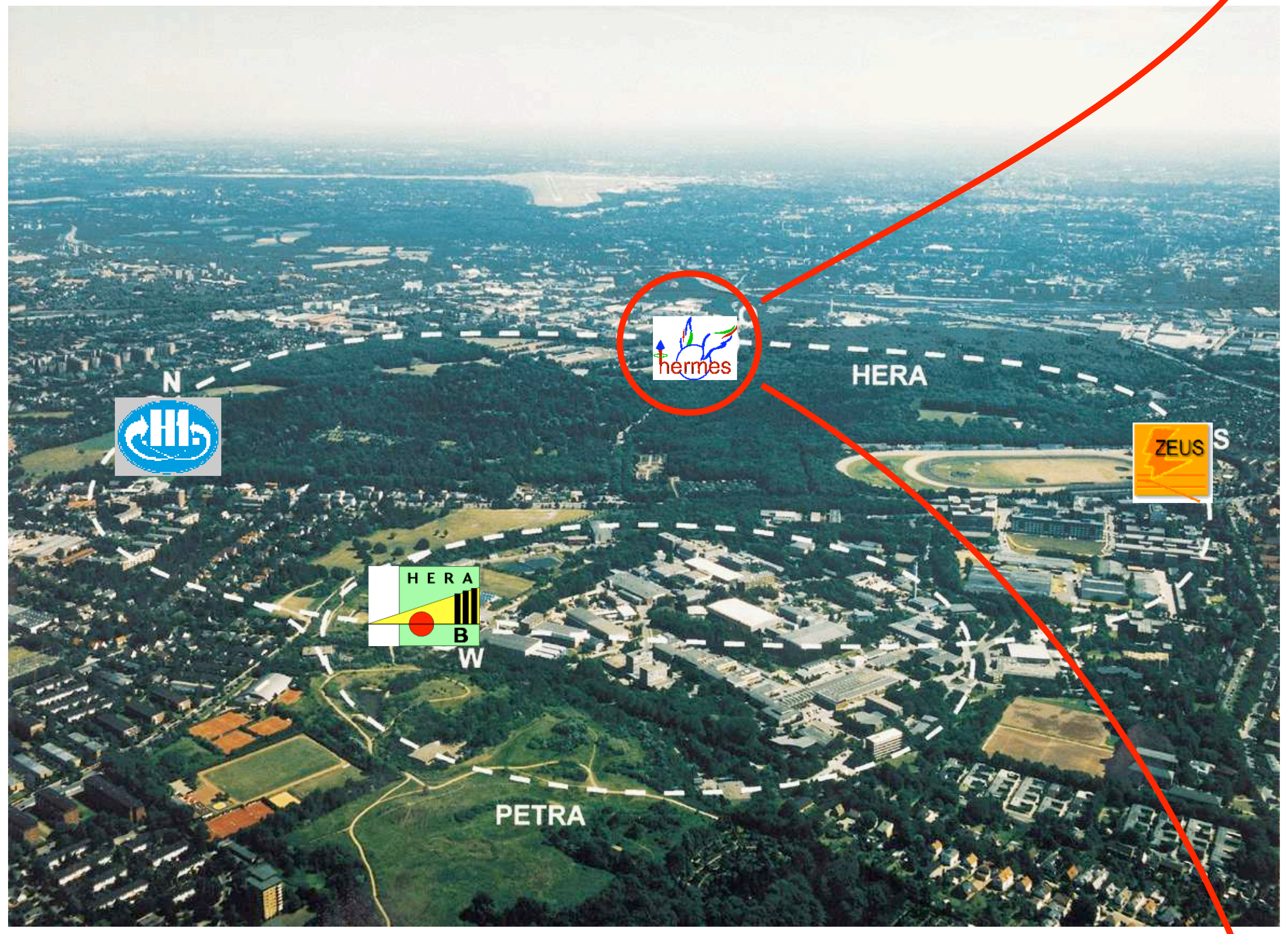
$$D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

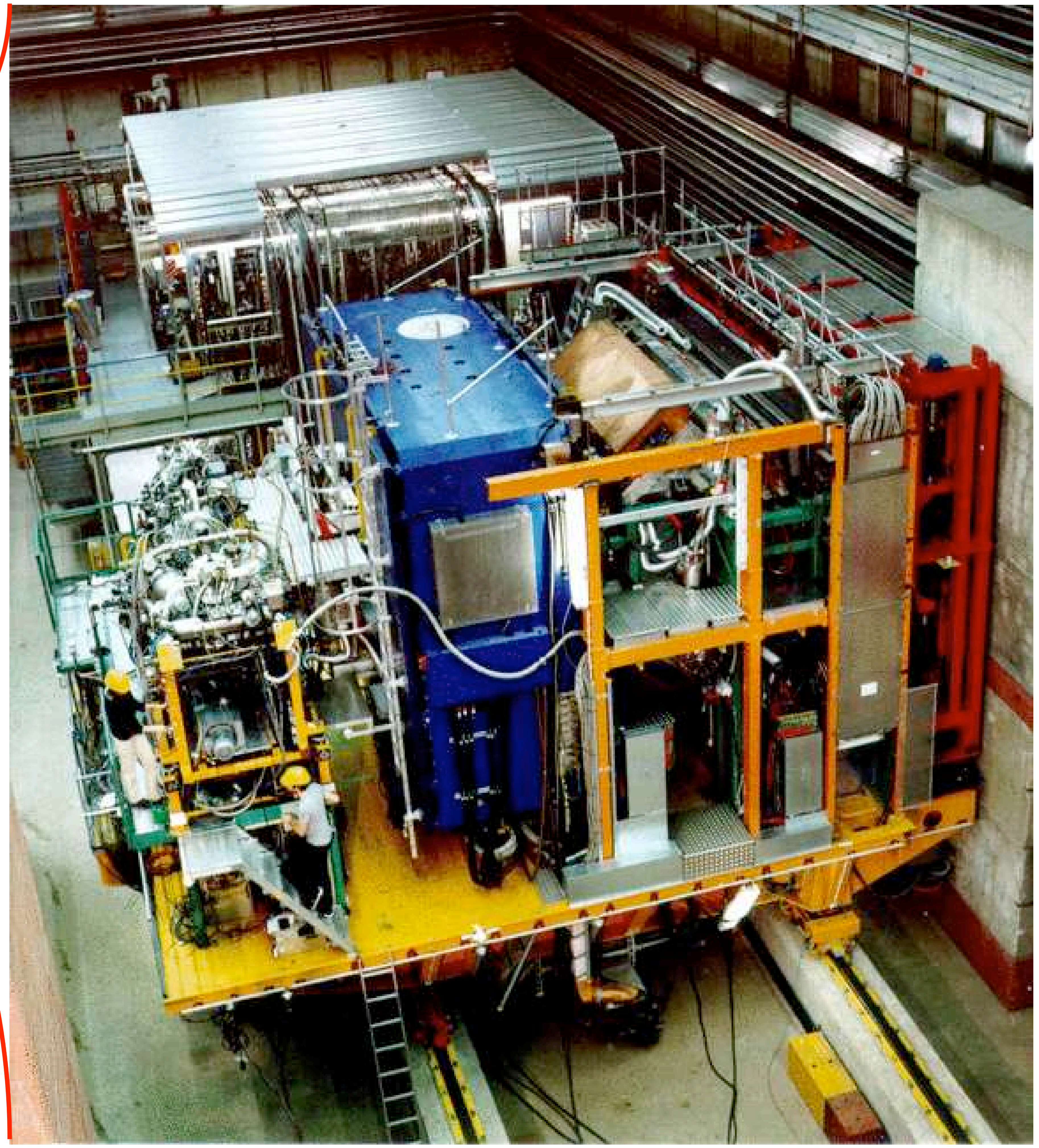
$$\eta = \frac{\epsilon\gamma y}{1-(1-y)\,\epsilon}$$

HERMES (†2007) @ DESY

27.6 GeV polarized e^{+}/e^{-} beam scattered off ...



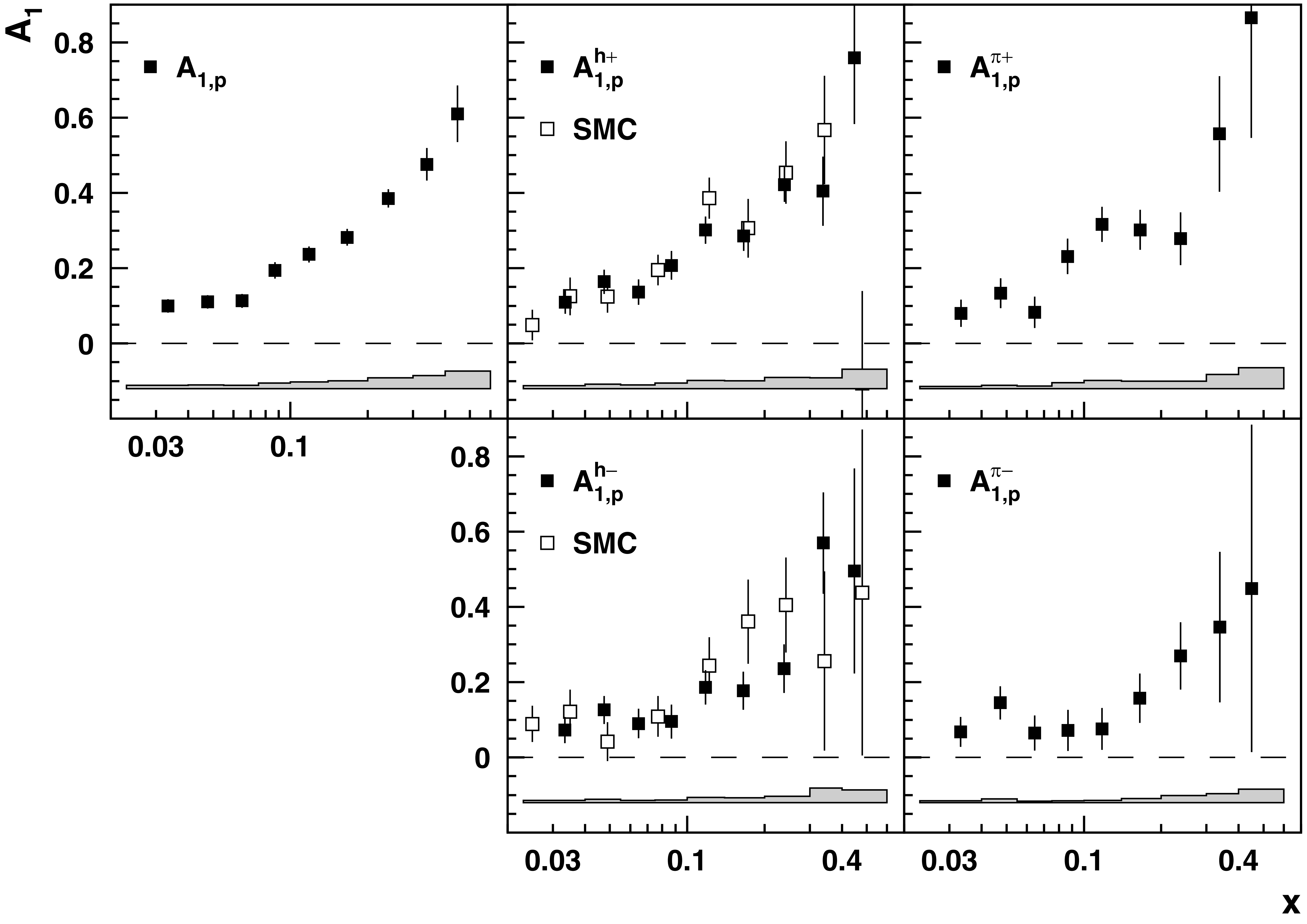




- ☑ unpolarized (H, D, He,..., Xe) as well as
- ☑ transversely (H) or longitudinally (H, D, He) polarized **pure gas targets**
- ☑ particle ID (incl. dual-radiator RICH) for efficient **e/pi/K/p separation**

previous HERMES analysis

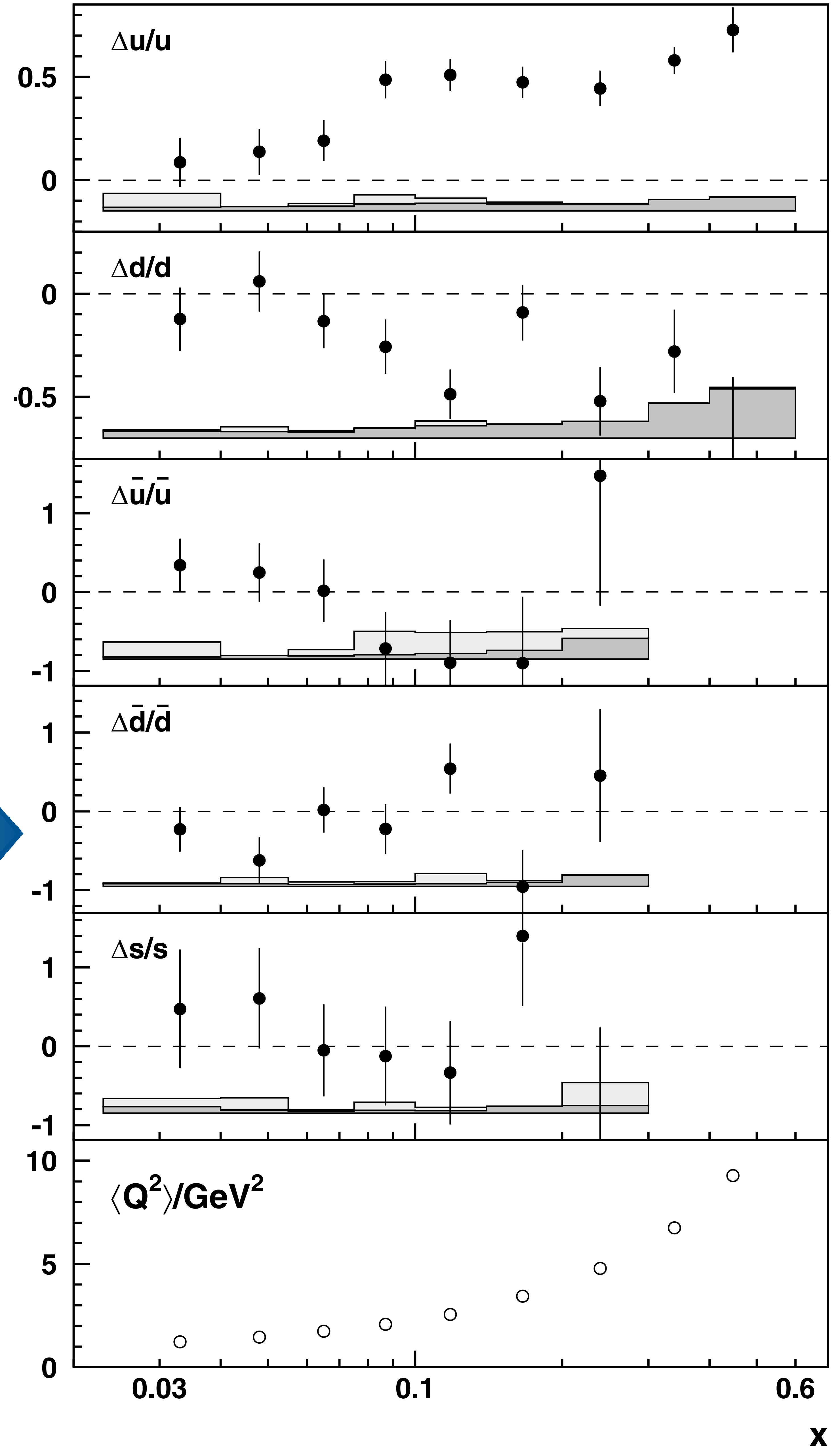
- (semi-) inclusive asymmetries used for LO extraction of helicity PDFs



Monte

Carlo

PHYSICAL REVIEW D **71,** 012003 (2005)



re-analysis of double-spin asymmetries

- revisited [PRD 71 (2005) 012003] A_1 analysis at HERMES in order to
  - exploit slightly larger data set (less restrictive momentum range)
  - **provide $A_{\parallel}$ in addition to A_1**

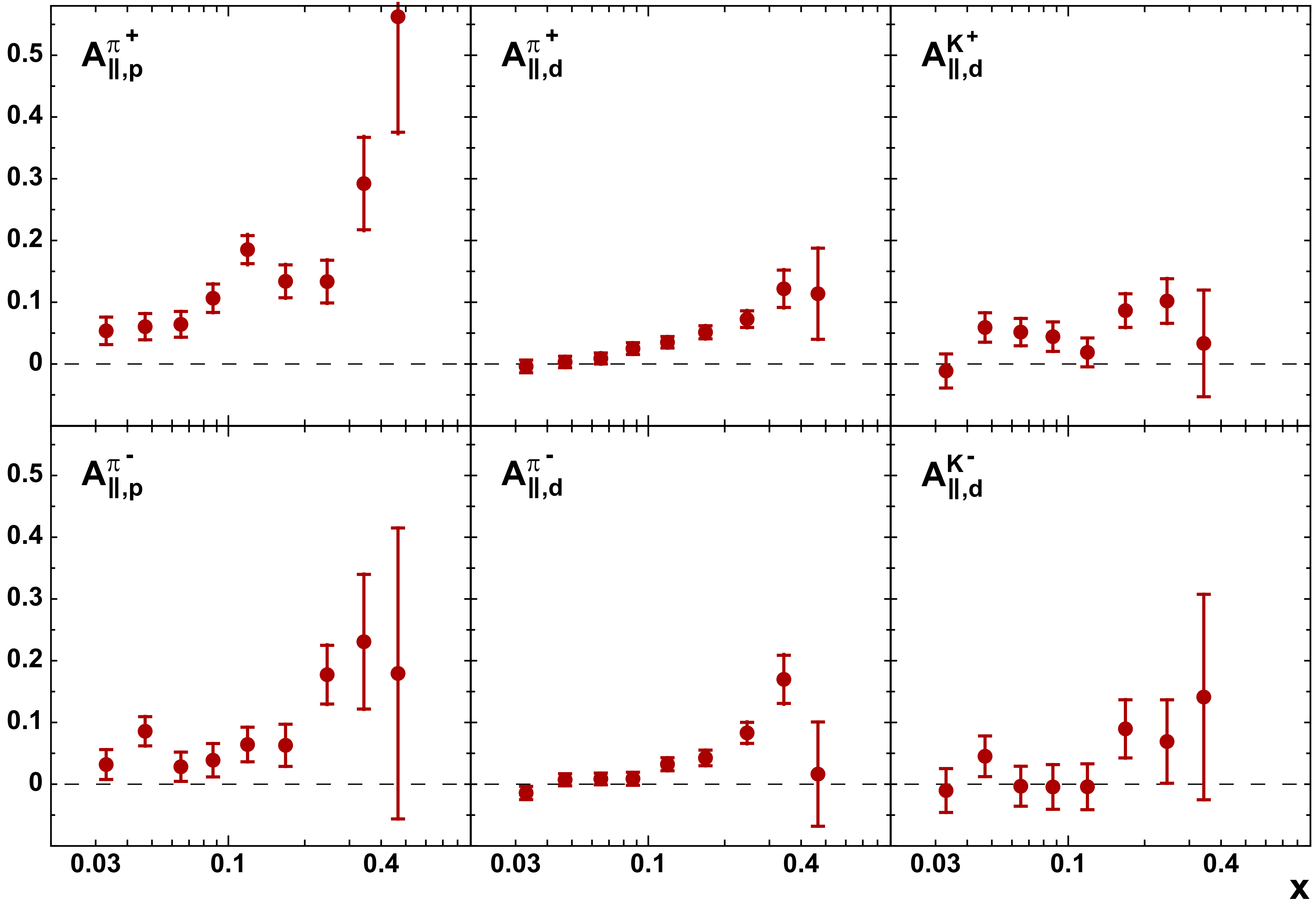
$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_{\parallel}^h \qquad\qquad D = \frac{1-(1-y)\epsilon}{1 \boxed{+\epsilon R}}$$

R (ratio of longitudinal-to-transverse cross-sec'n) still to be measured!
[only available for inclusive DIS data, e.g., used in g_1 SF measurements]

  - correct for D-state admixture (deuteron case) on asymmetry level
  - correct better for azimuthal asymmetries coupling to acceptance
  - **look at multi-dimensional (x, z, $P_{h\perp}$) dependences**
  - **extract twist-3 cosine modulations**

x dependence of $A_{||}$

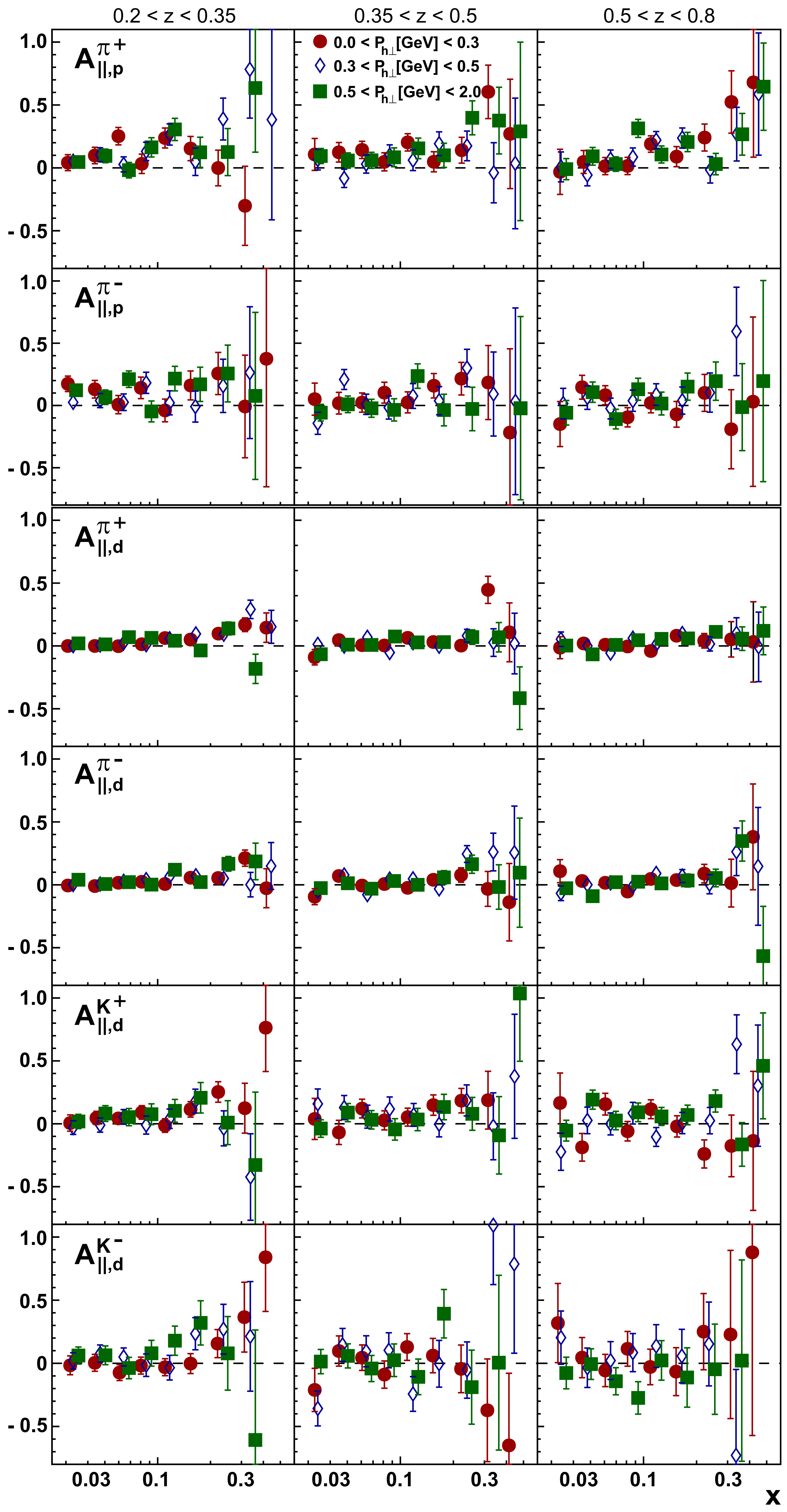
[HERMES, PRD 99 (2019) 112001]



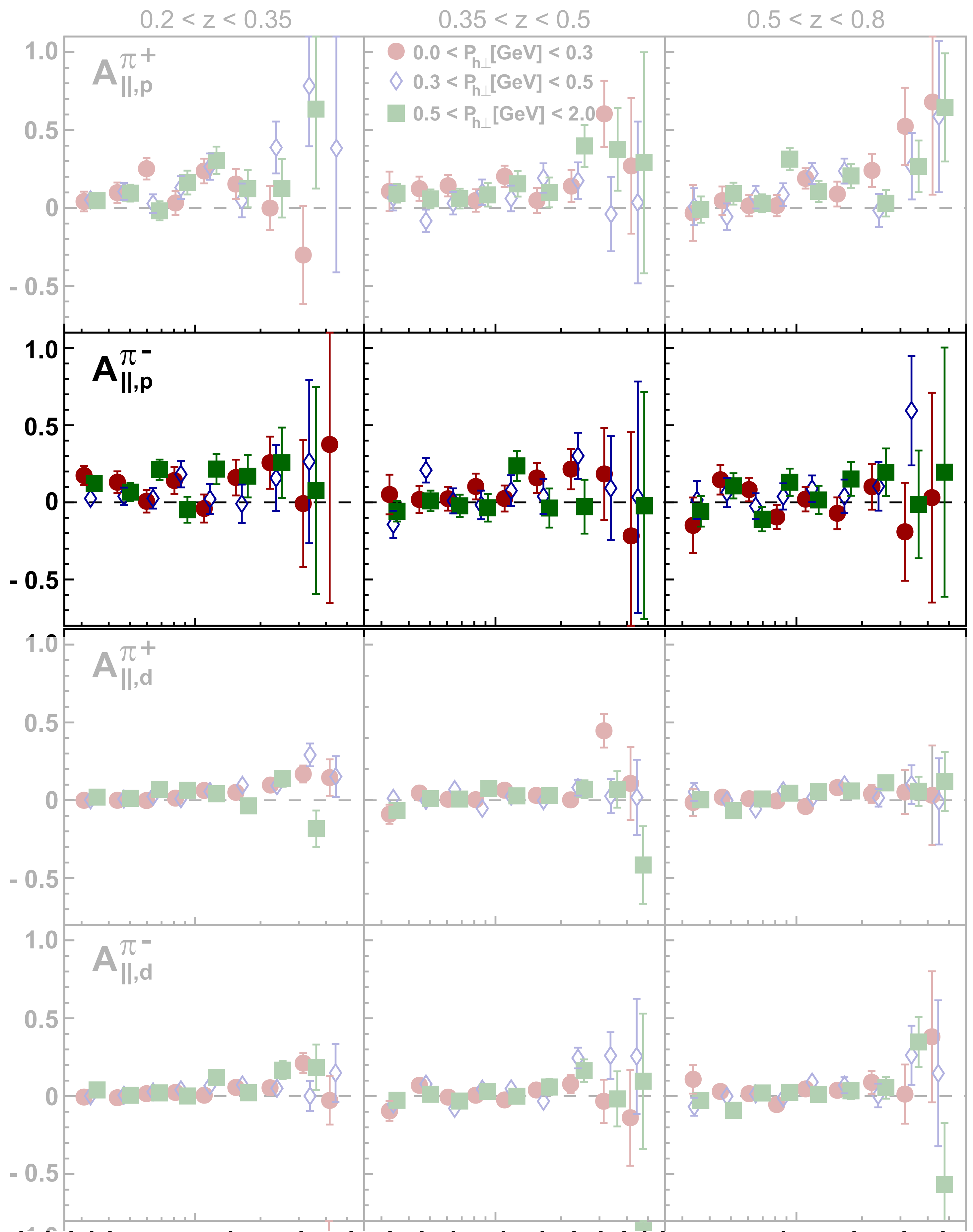
- ☑ fully consistent with previous HERMES publication [PRD 71 (2005) 012003]

3-dimensional binning

- first-ever 3d binning provides transverse-momentum dependence

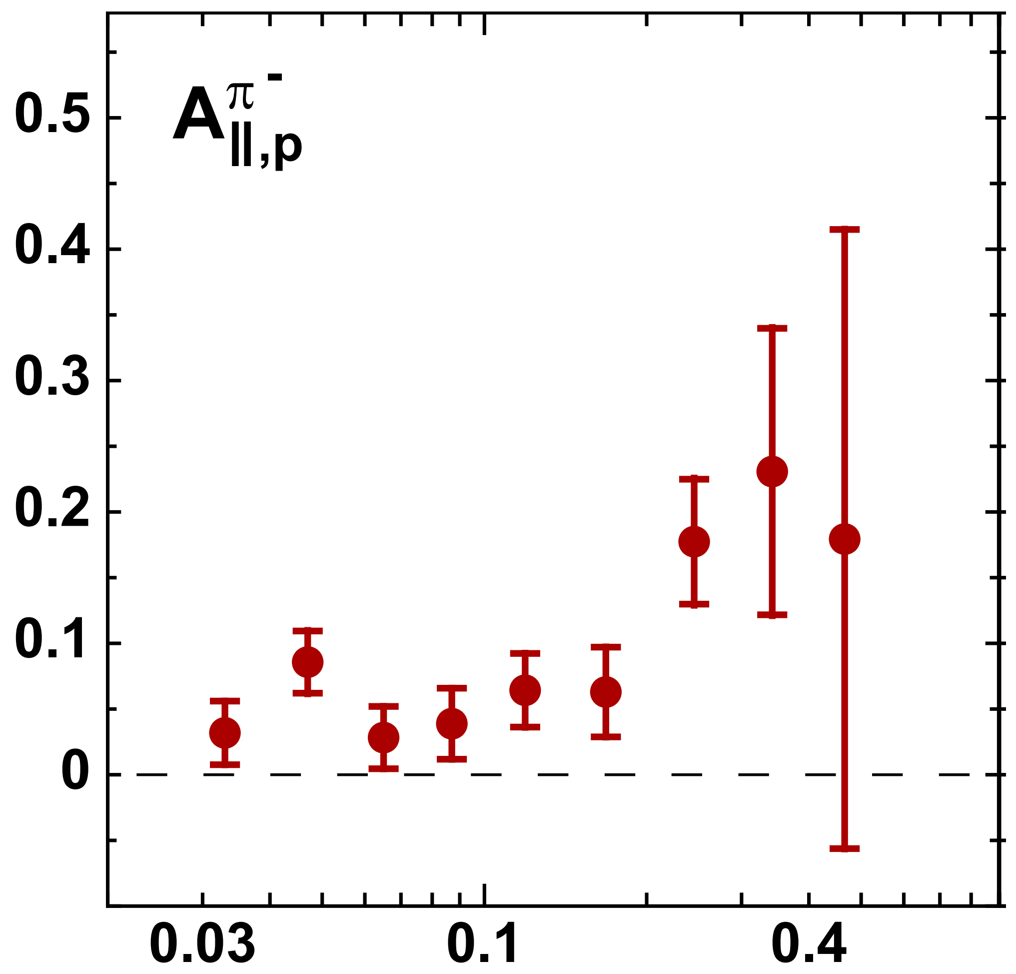


3-dimensional binning

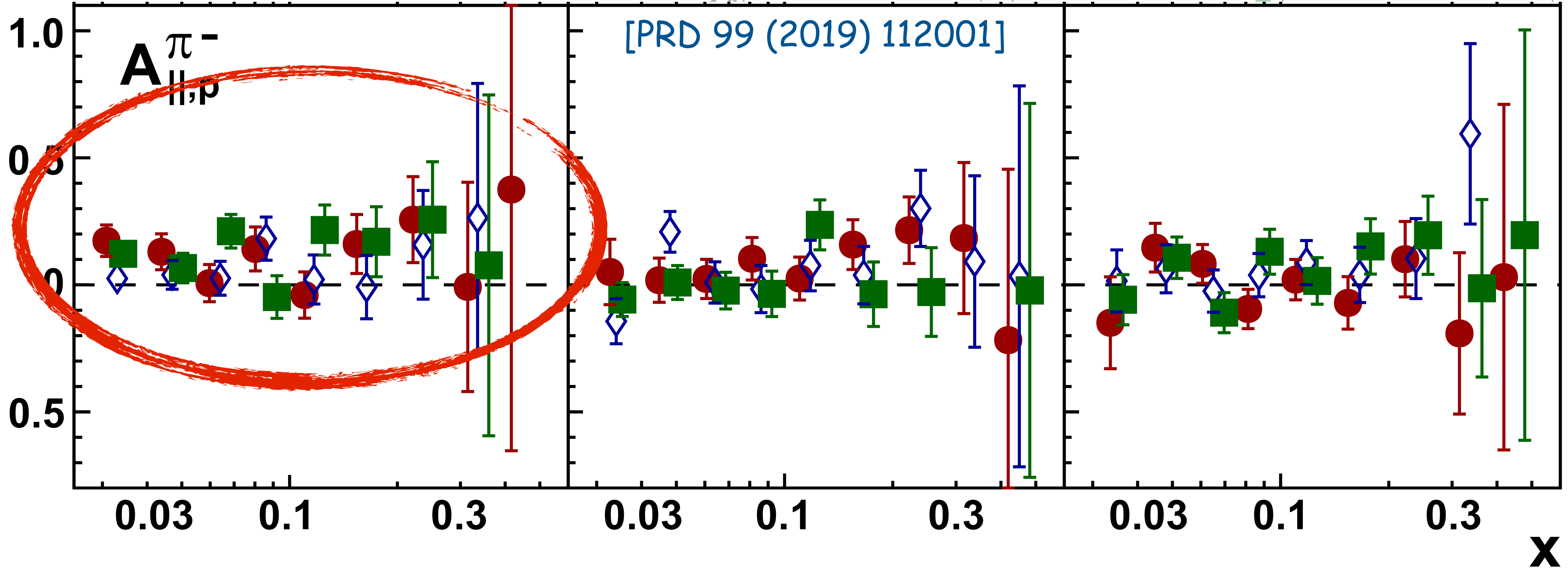


- first-ever 3d binning provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - **π^-** asymmetries mainly coming from **low-z** region where **disfavored fragmentation** large and thus **sensitivity** to the large **positive up-quark polarization**

1d



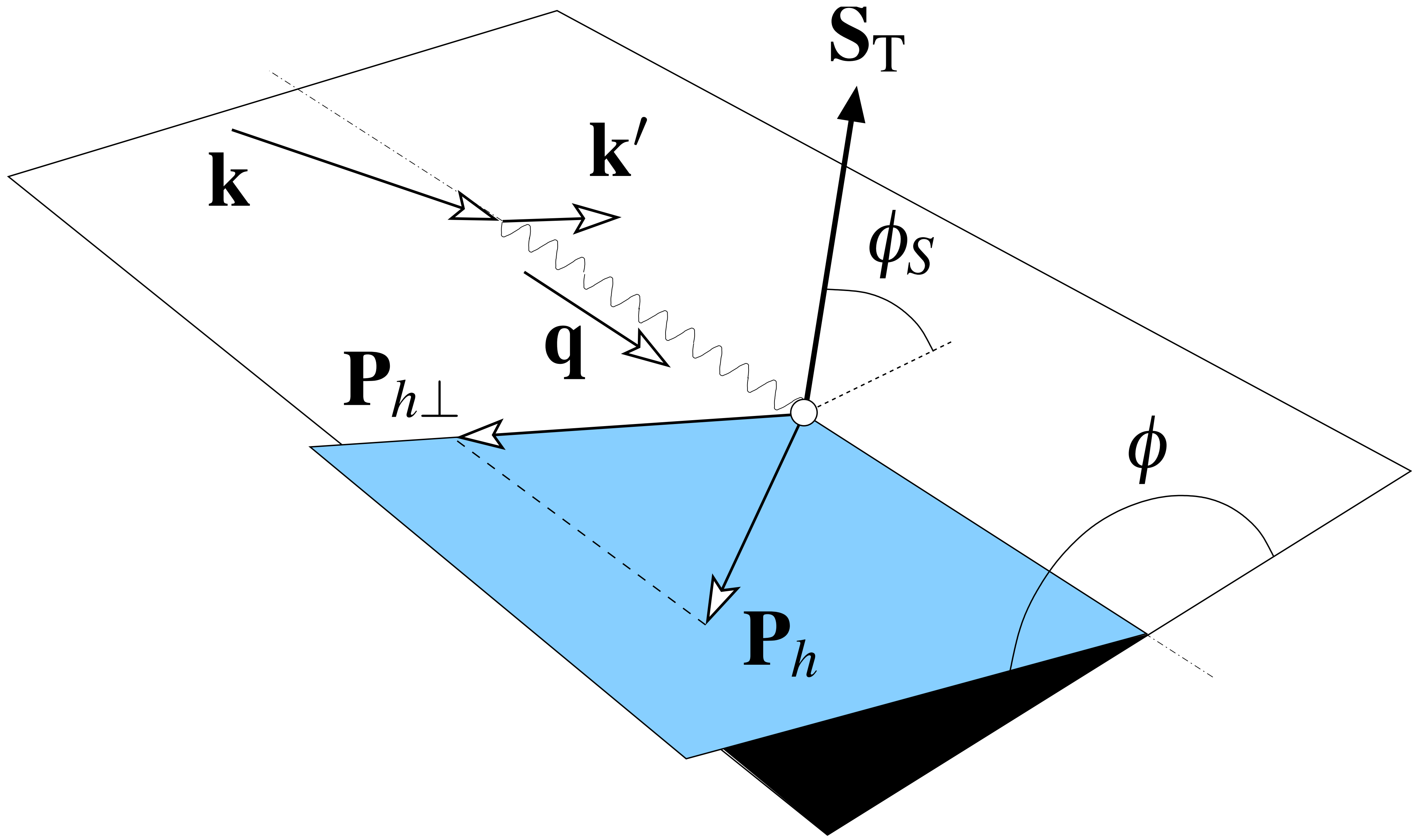
3d



[PRD 99 (2019) 112001]

semi-inclusive DIS

- with **transverse** target polarization:



$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi\,\mathrm{d}\phi_s} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Bigg\{F_{UU,T}^h + \epsilon F_{UU,L}^h + \text{terms not involving transv. polarization}$$

$$+ S_T\left[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)}\right)\sin(\phi-\phi_s)\right.$$

$$+ \epsilon\, F_{UT}^{h,\sin(\phi+\phi_s)}\sin(\phi+\phi_s) + \epsilon\, F_{UT}^{h,\sin(3\phi-\phi_s)}\sin(3\phi-\phi_s)$$

$$\left.+ \sqrt{2\,\epsilon(1+\epsilon)}\,F_{UT}^{h,\sin\phi_s}\sin\phi_s + \sqrt{2\,\epsilon(1+\epsilon)}\,F_{UT}^{h,\sin(2\phi-\phi_s)}\sin(2\phi-\phi_s)\right]$$

$$+ S_T\lambda\left[\sqrt{1-\epsilon^2}\,F_{LT}^{h,\cos(\phi-\phi_s)}\cos(\phi-\phi_s)\right.$$

$$\left.+ \sqrt{2\,\epsilon(1-\epsilon)}\,F_{LT}^{h,\cos\phi_s}\cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\,F_{LT}^{h,\cos(2\phi-\phi_s)}\cos(2\phi-\phi_s)\right]\Bigg\}$$

semi-inclusive DIS

- with **transverse** target polarization:

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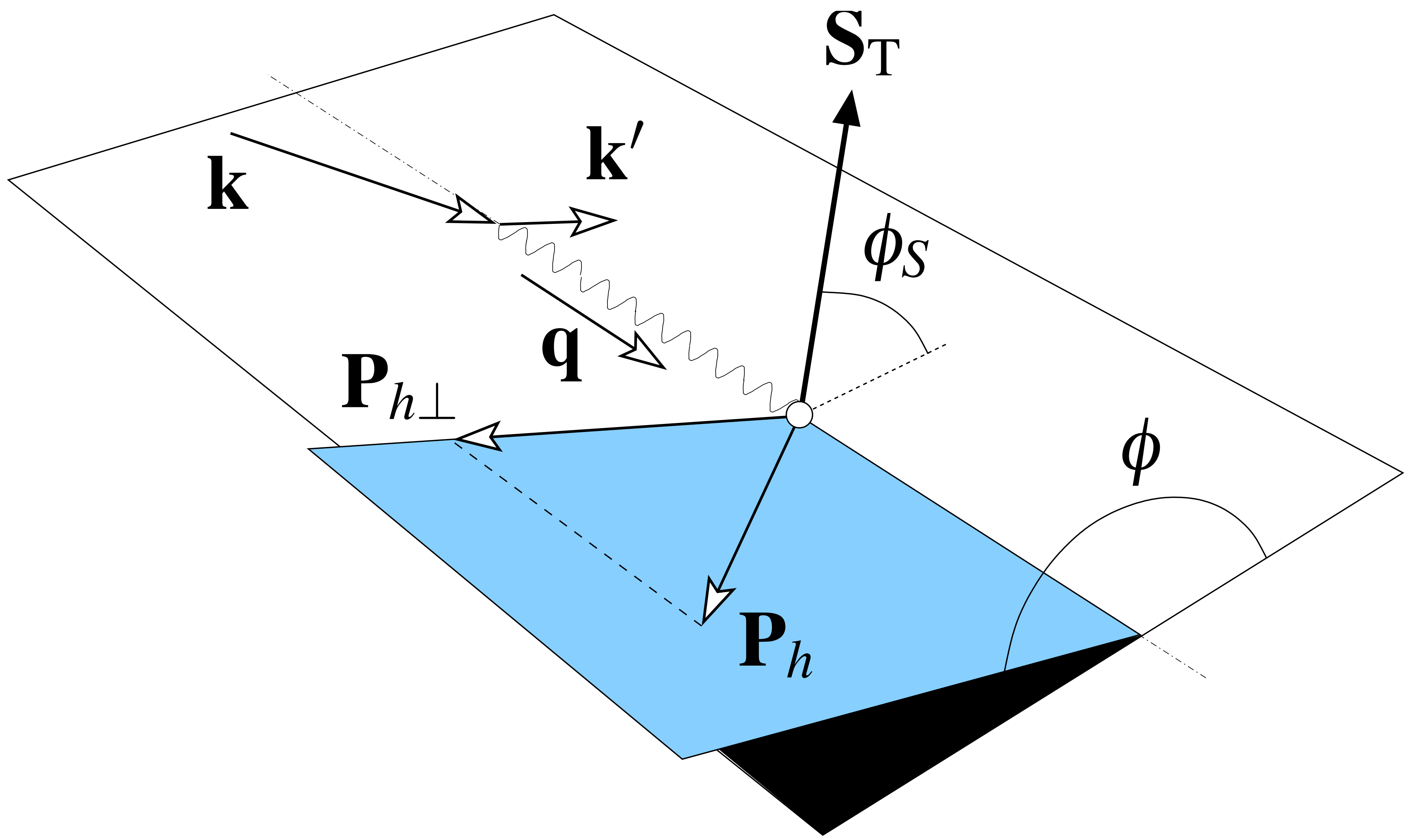
$$+ S_T \left[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi-\phi_s) \right.$$

$$+ \epsilon\, F_{UT}^{h,\sin(\phi+\phi_s)} \sin(\phi+\phi_s) + \epsilon\, F_{UT}^{h,\sin(3\phi-\phi_s)} \sin(3\phi-\phi_s)$$

$$\left. + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin\phi_s} \sin\phi_s + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin(2\phi-\phi_s)} \sin(2\phi-\phi_s) \right]$$

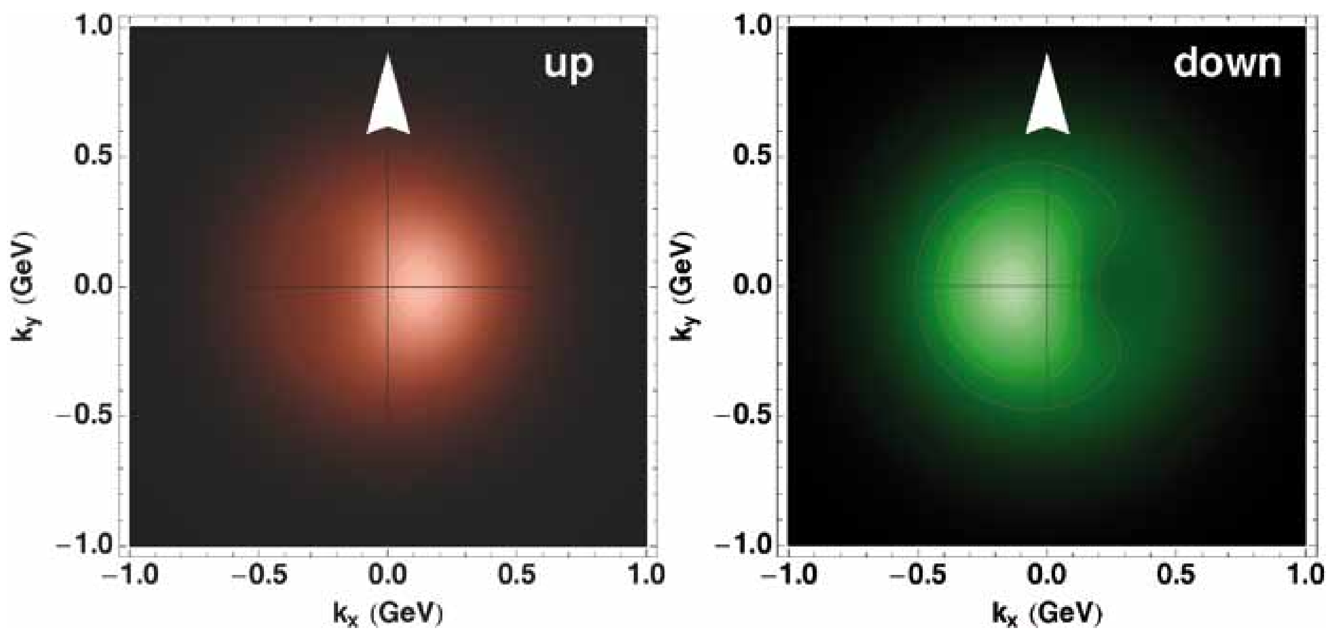
$$+ S_T\lambda \left[\sqrt{1-\epsilon^2}\, F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi-\phi_s) \right.$$

$$\left. + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi-\phi_s) \right] \Big\}$$



Sivers amplitudes for pions

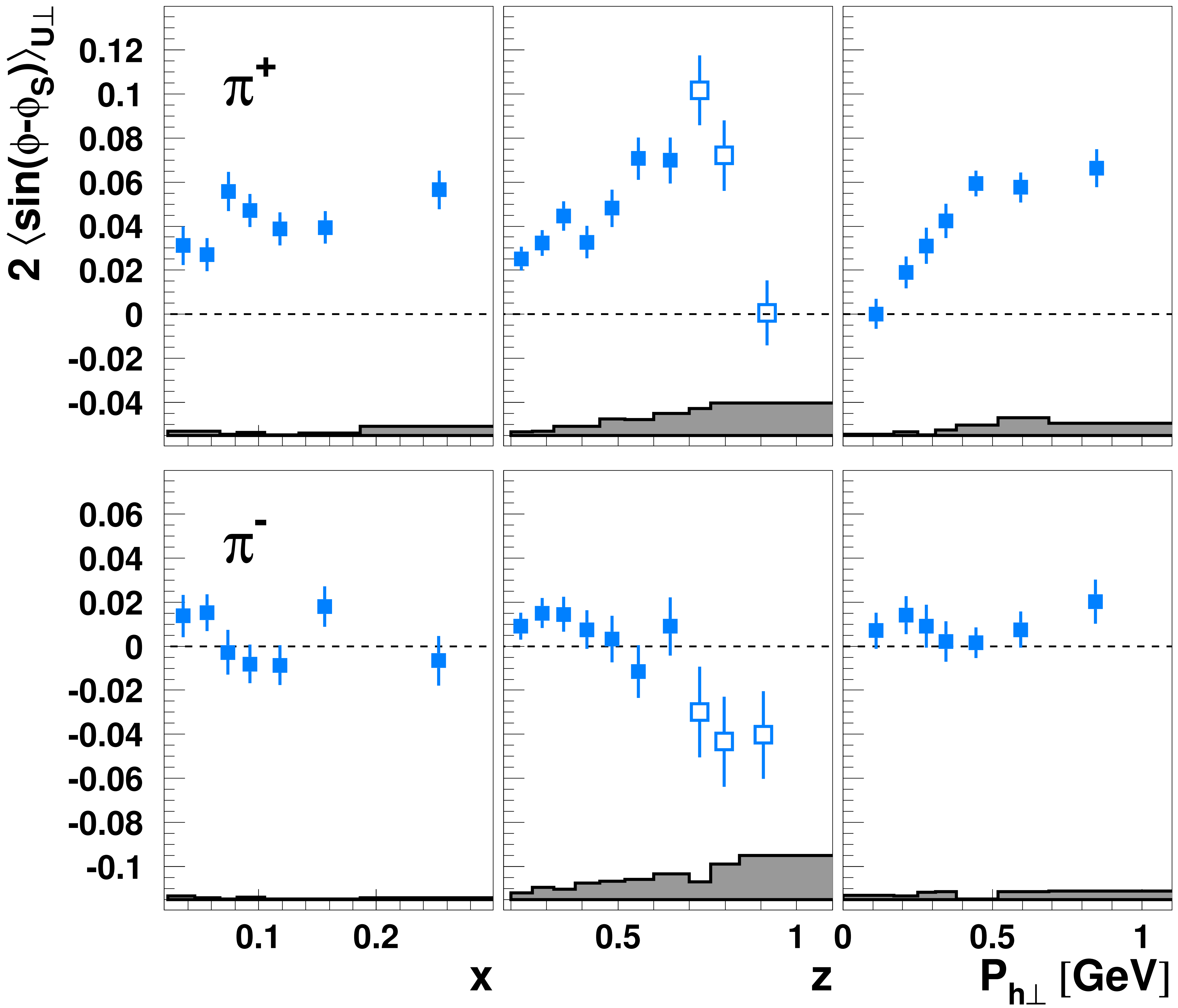
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

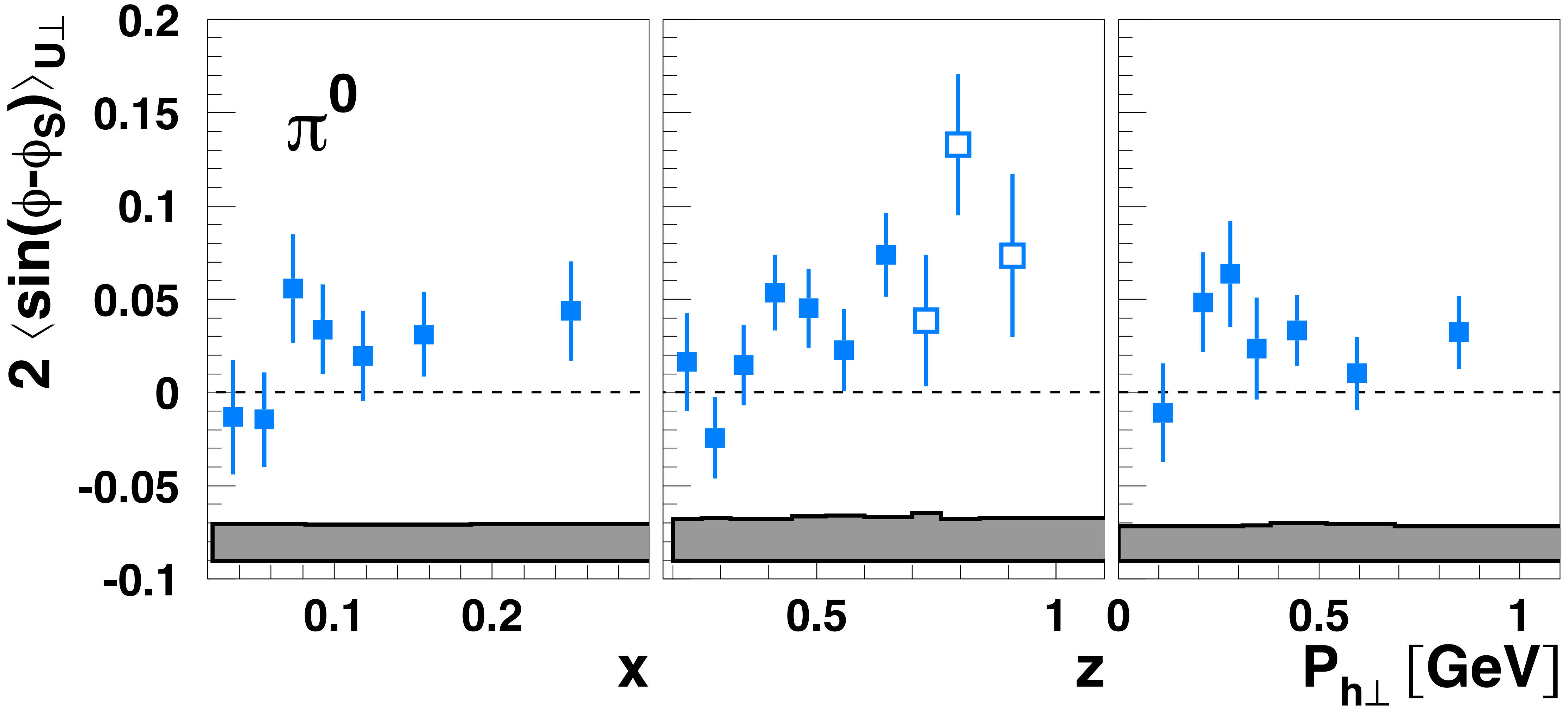


[A. Bacchetta et al.]

- Sivers TMD probes correlation between nucleon spin and parton transverse momentum
- previous HERMES results focused on z < 0.7

[HERMES, JHEP12(2020)010]





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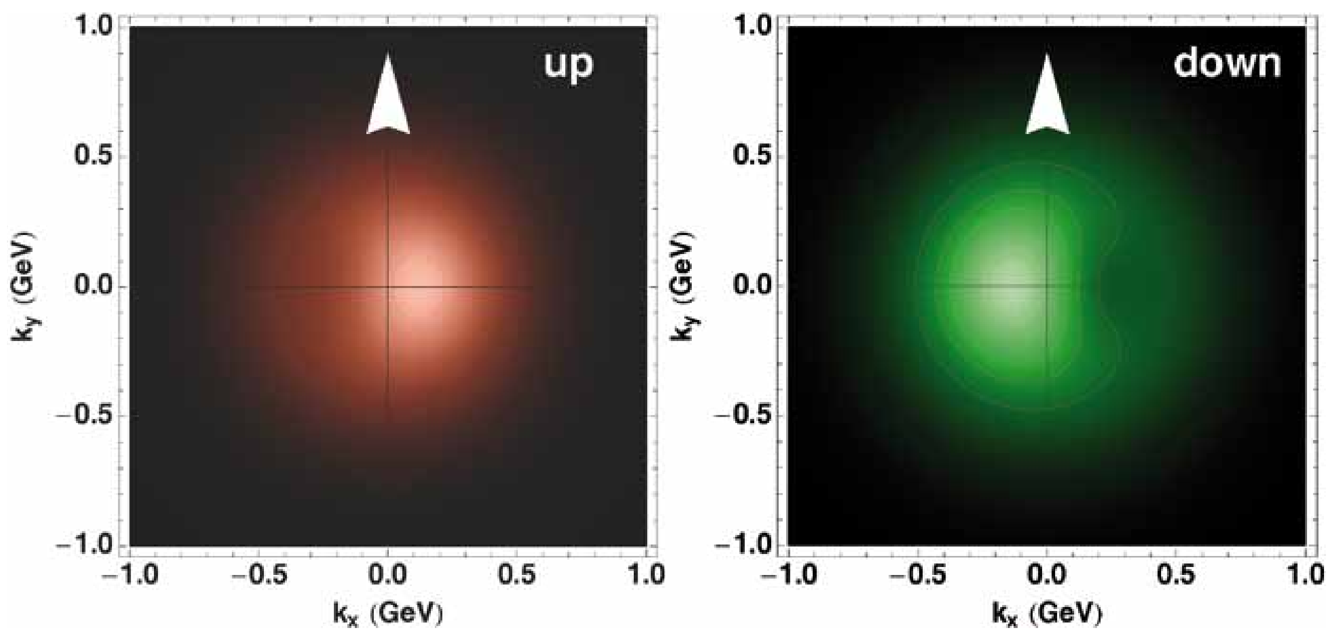
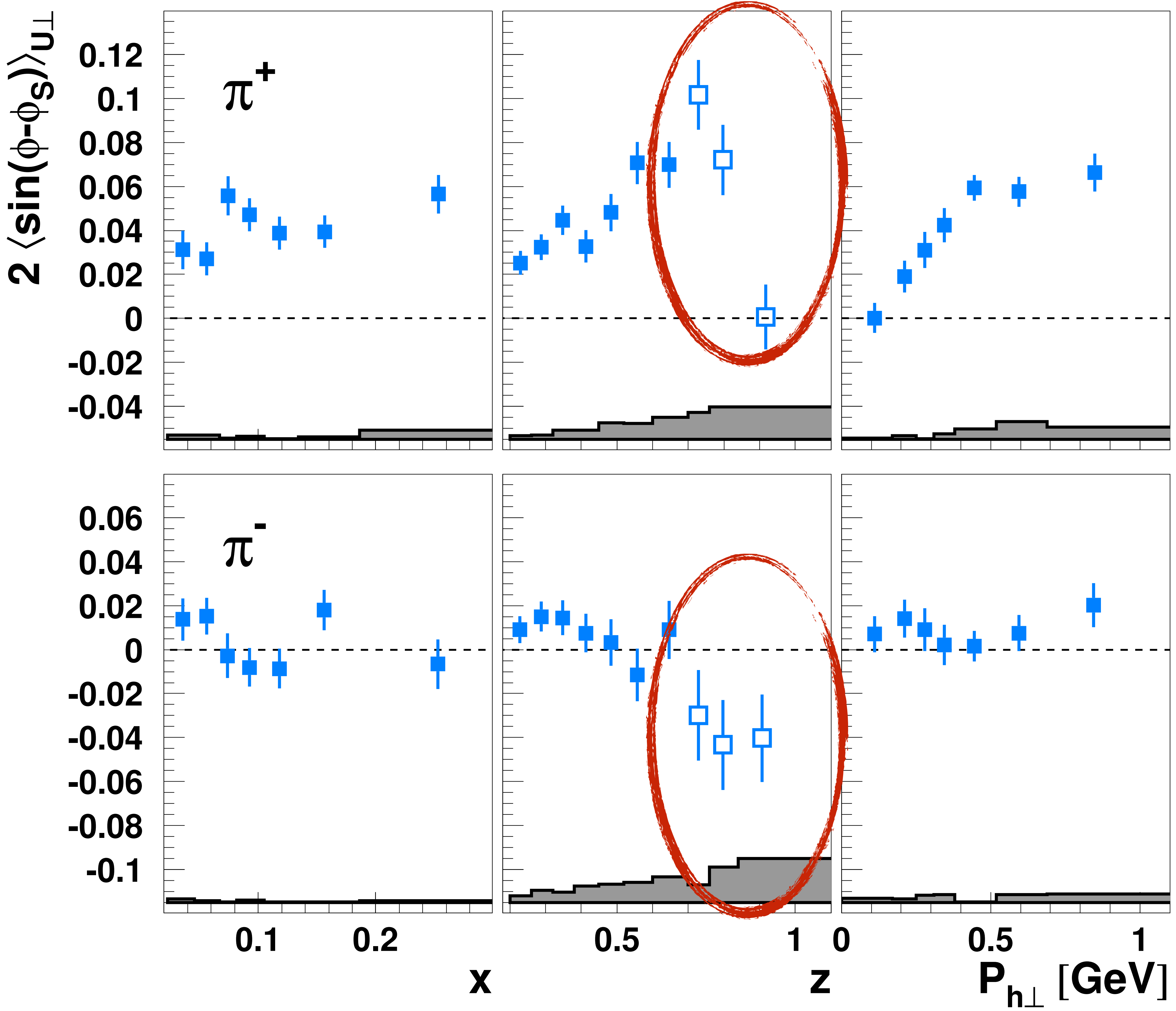
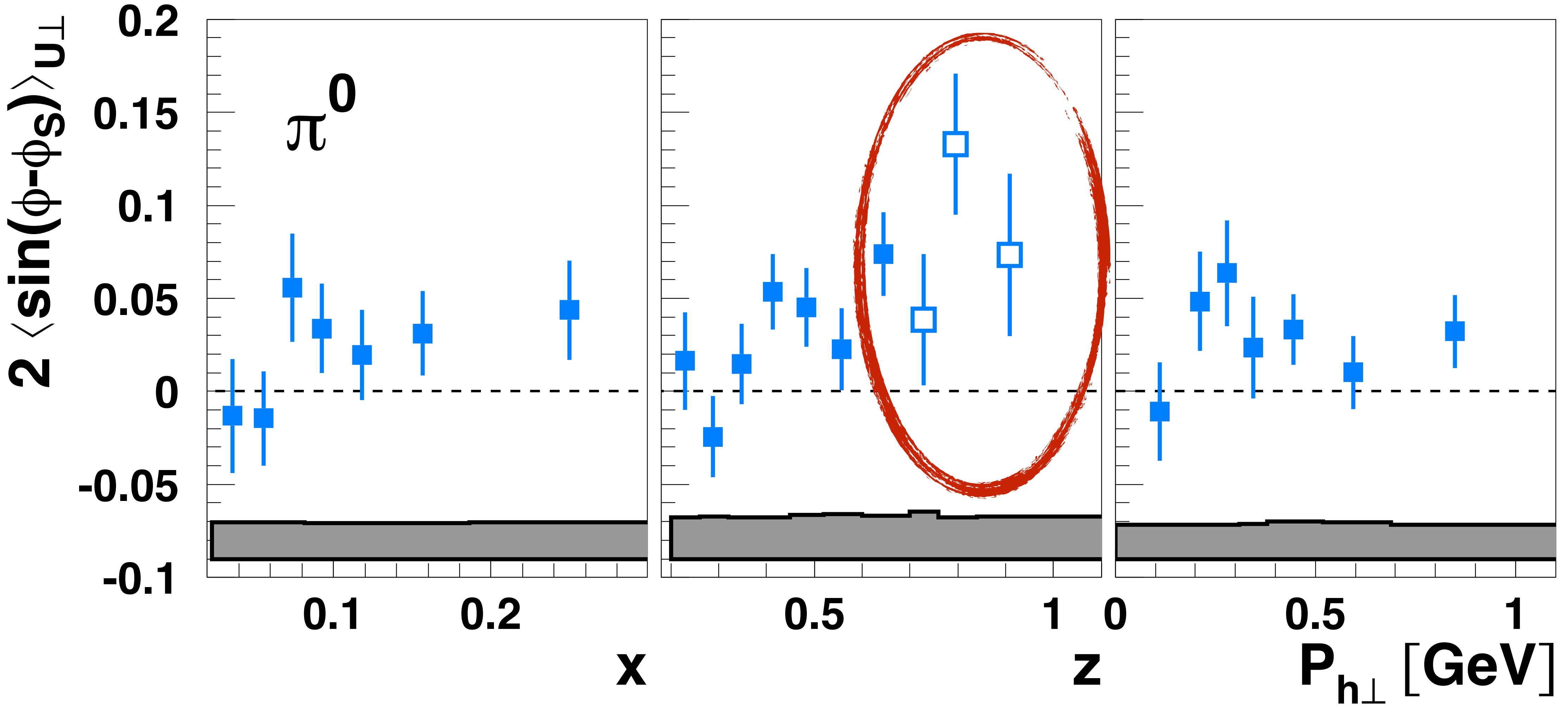


[A. Bacchetta et al.]

- Sivers TMD probes correlation between nucleon spin and parton transverse momentum
- previous HERMES results focused on z < 0.7
- high-z data probes transition region towards exclusive meson production but also **increased sensitivity to struck quark's flavor**

[HERMES, JHEP12(2020)010]





Sivers amplitudes
pions vs. (anti)protons

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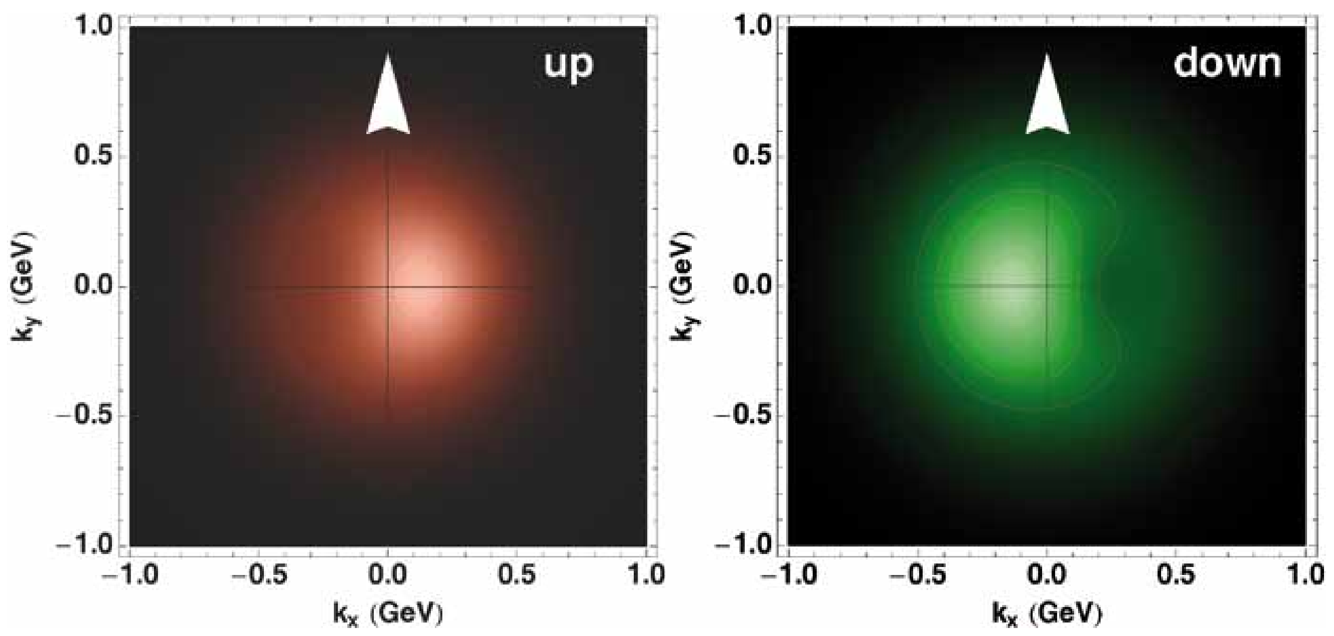
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



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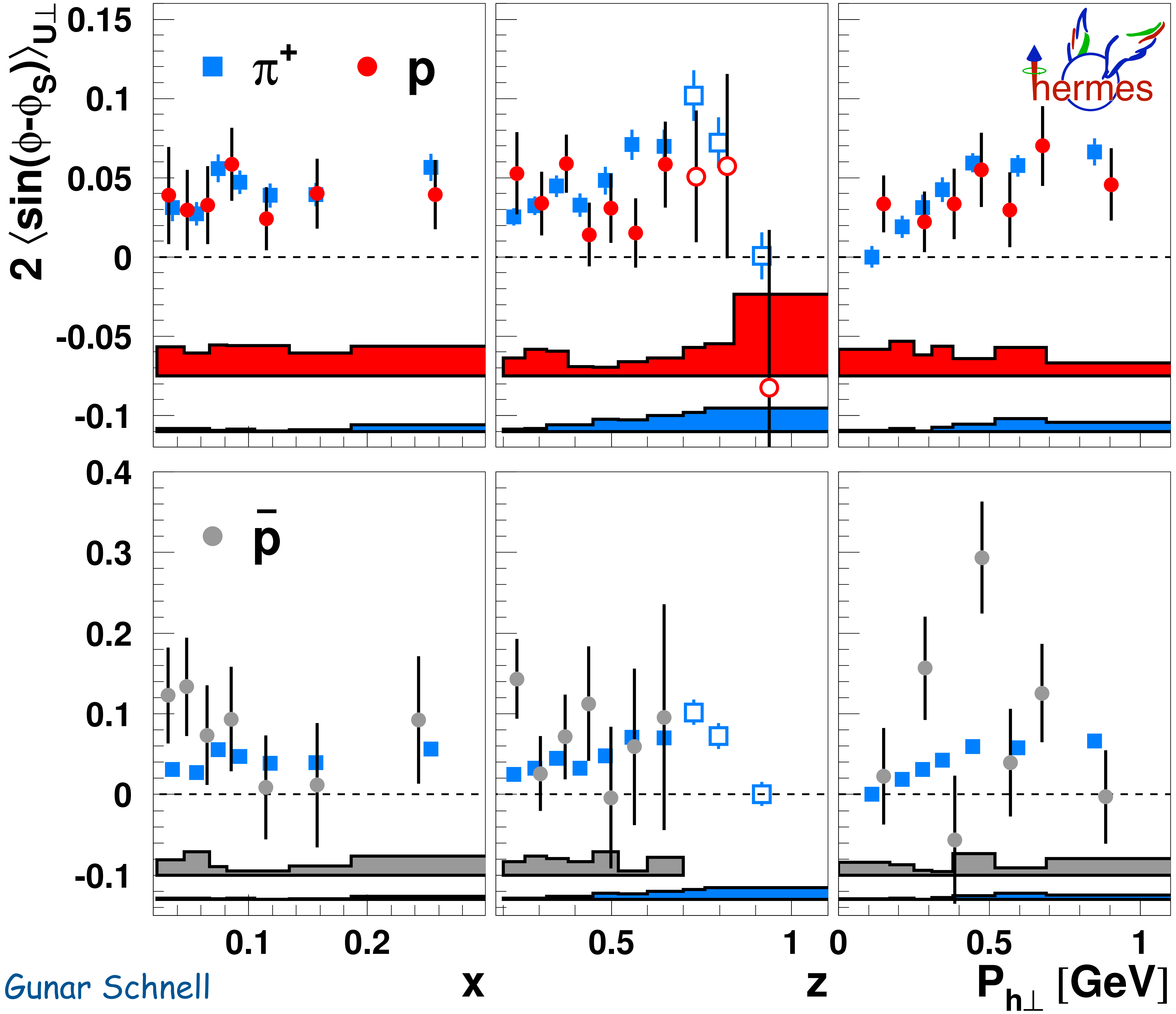

- first-ever results for protons and anti-protons

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pions vs. (anti)protons

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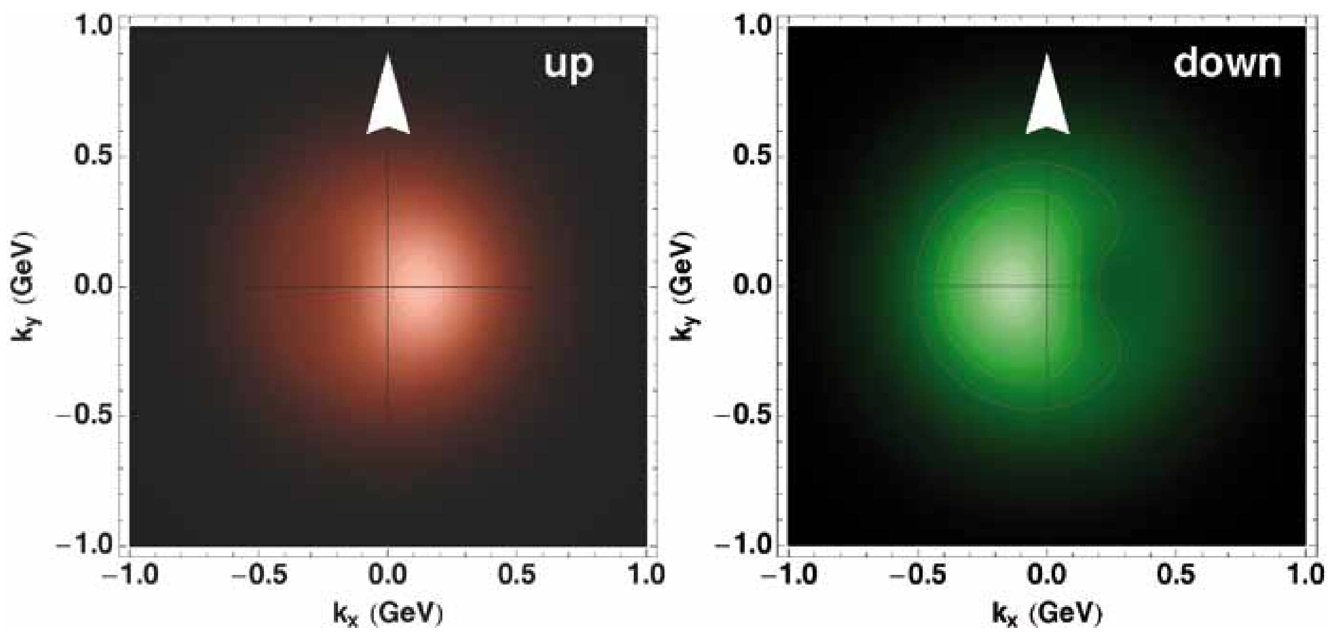

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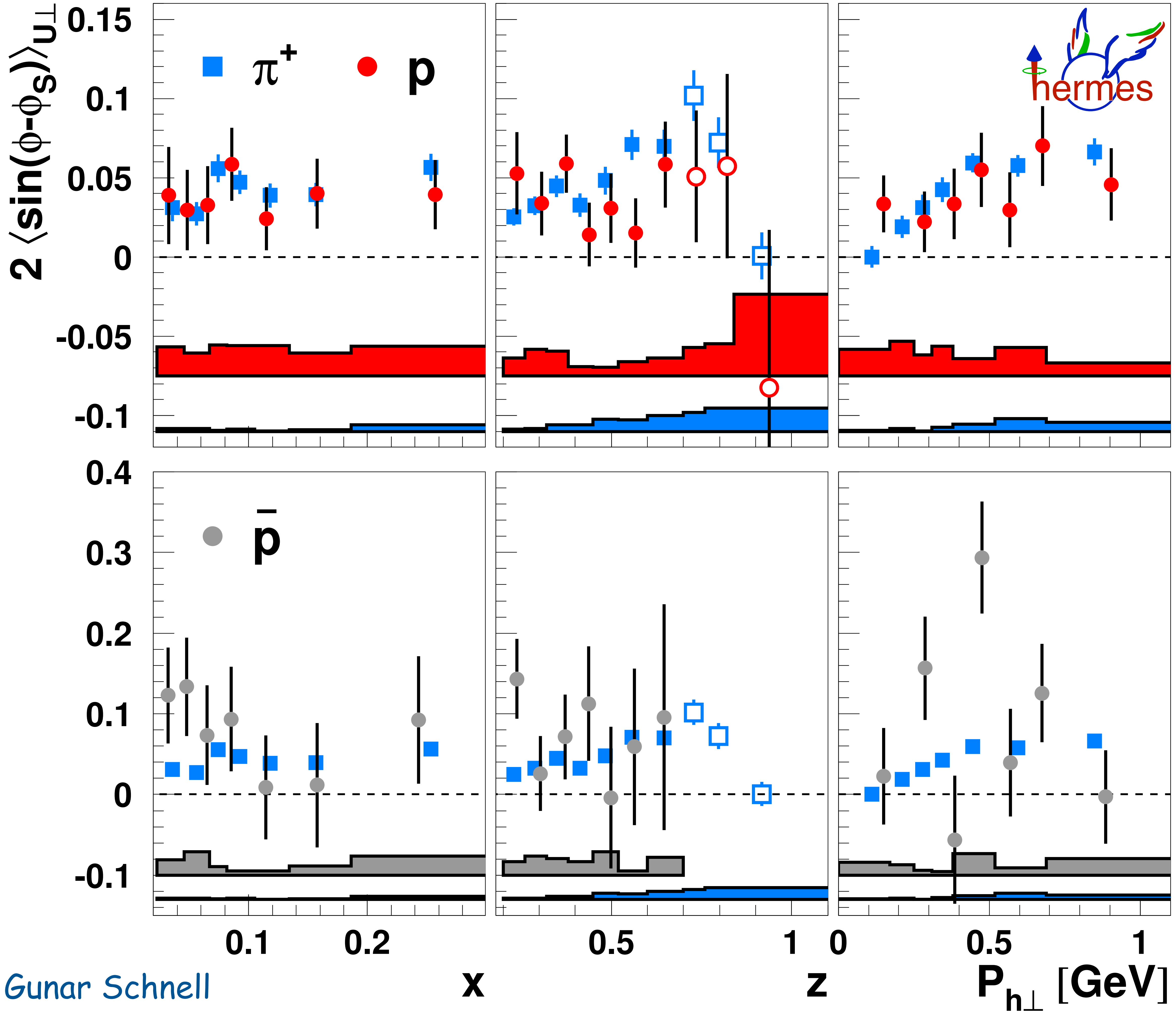
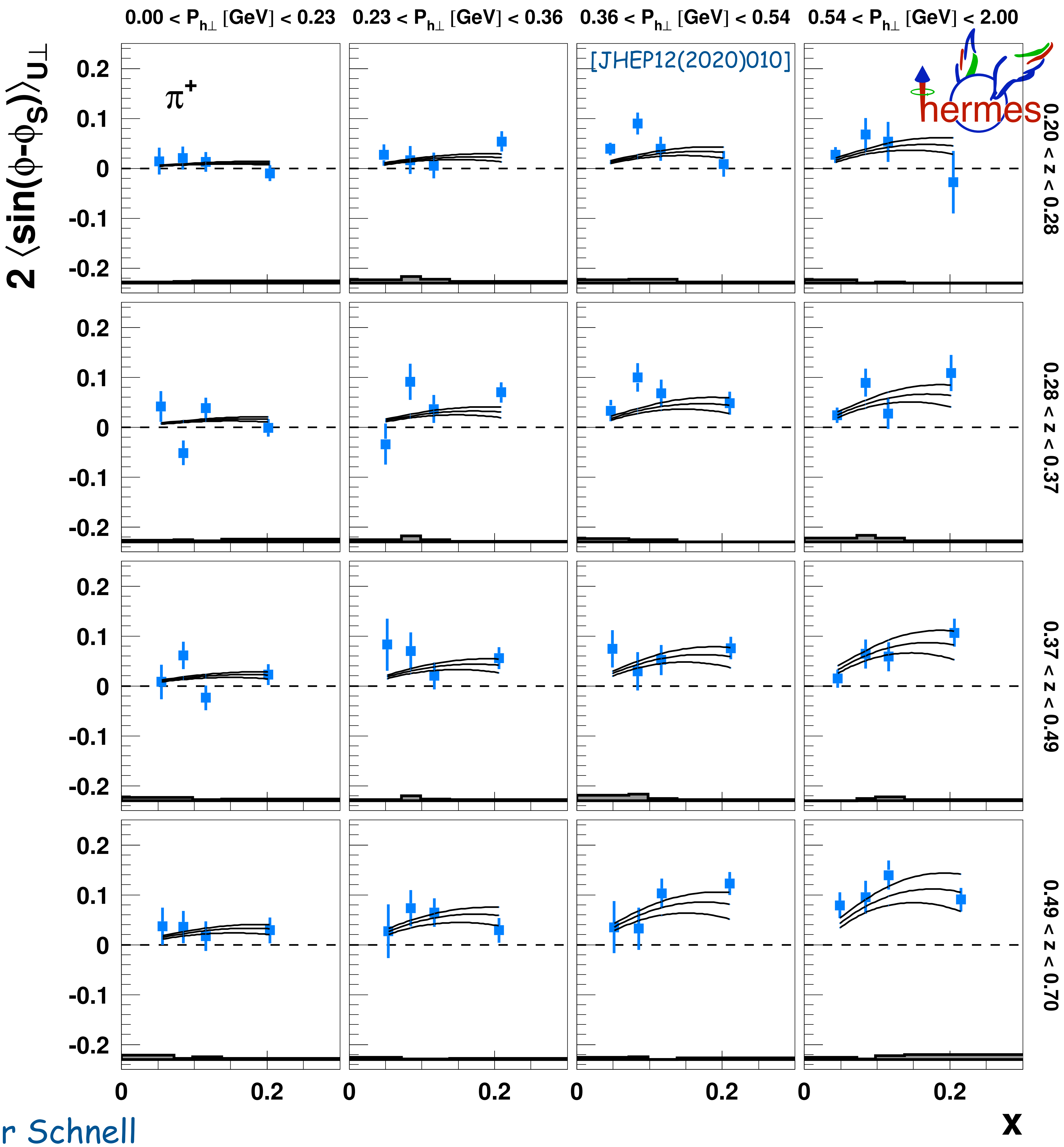


- first-ever results for protons and anti-protons
- similar-magnitude asymmetries for (anti)protons and pions
  ➥consequence of u-quark dominance in both cases?

	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



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

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U	f_1		$h_1^\perp$
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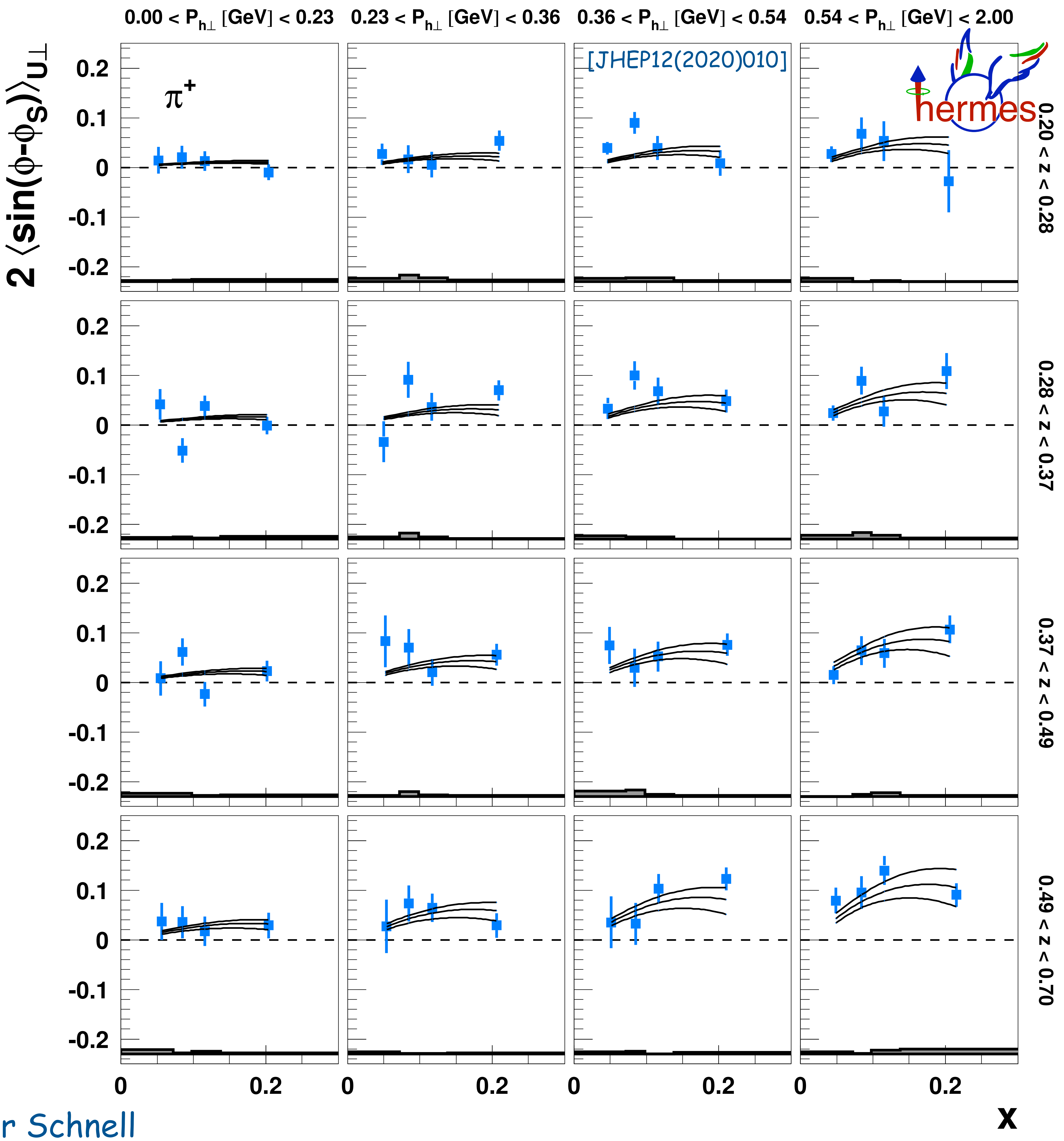
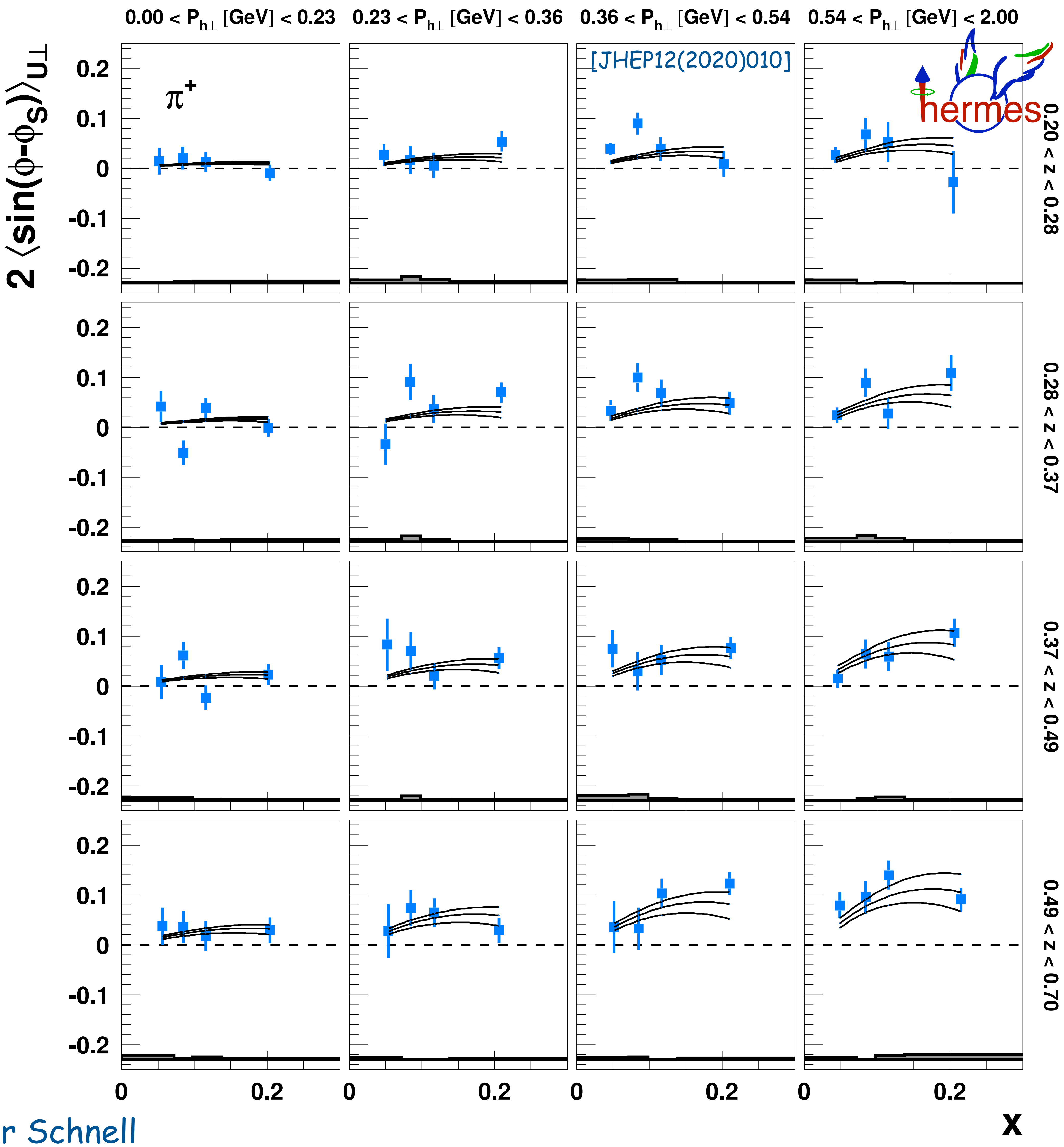
Sivers amplitudes multi-dimensional analysis



- 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

	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



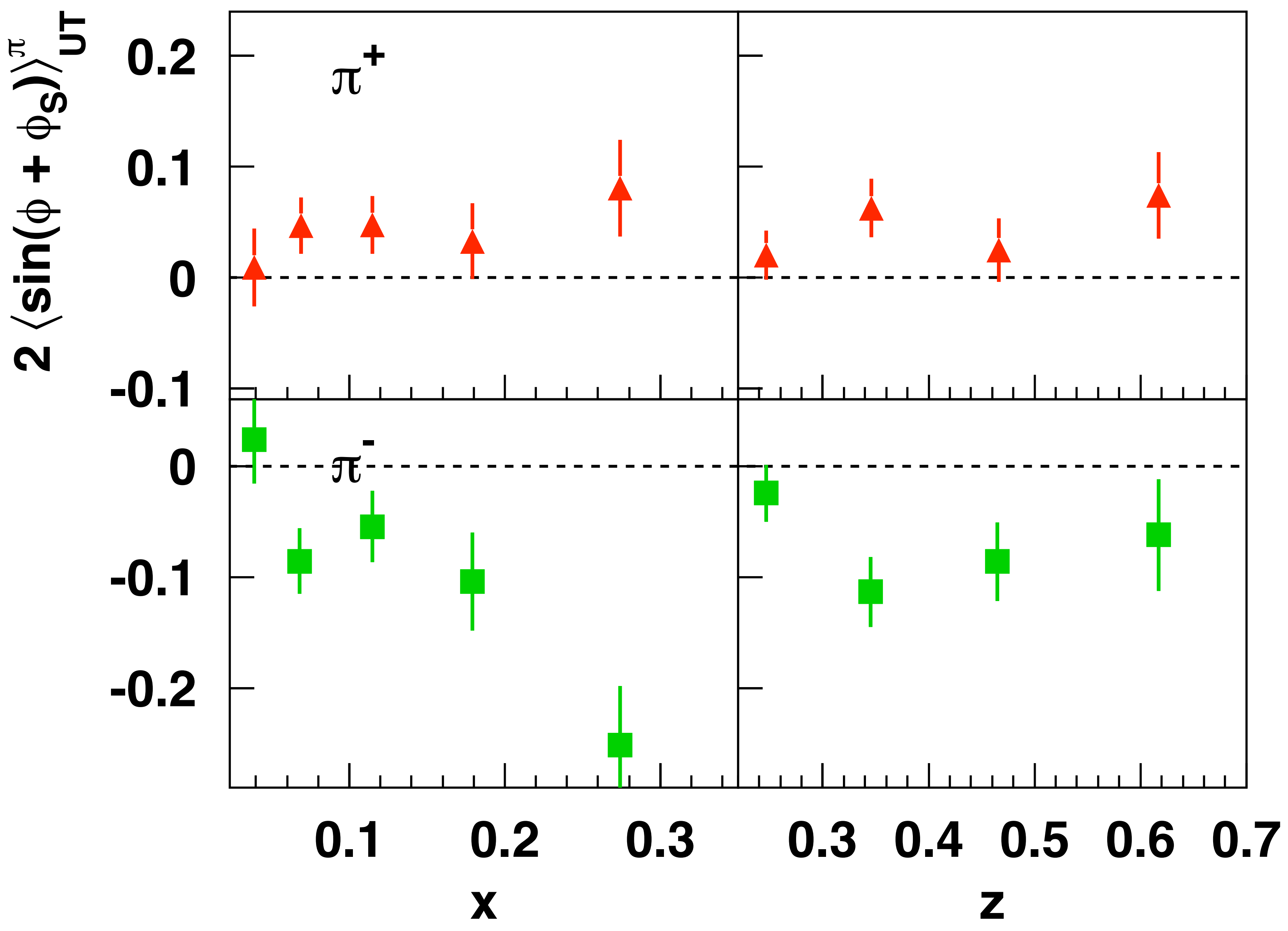
- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
  - reduced systematics
  - disentangle correlations
  - isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology*)

*) see, e.g., backup slides or supplemental material of JHEP12(2020)0210

	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)

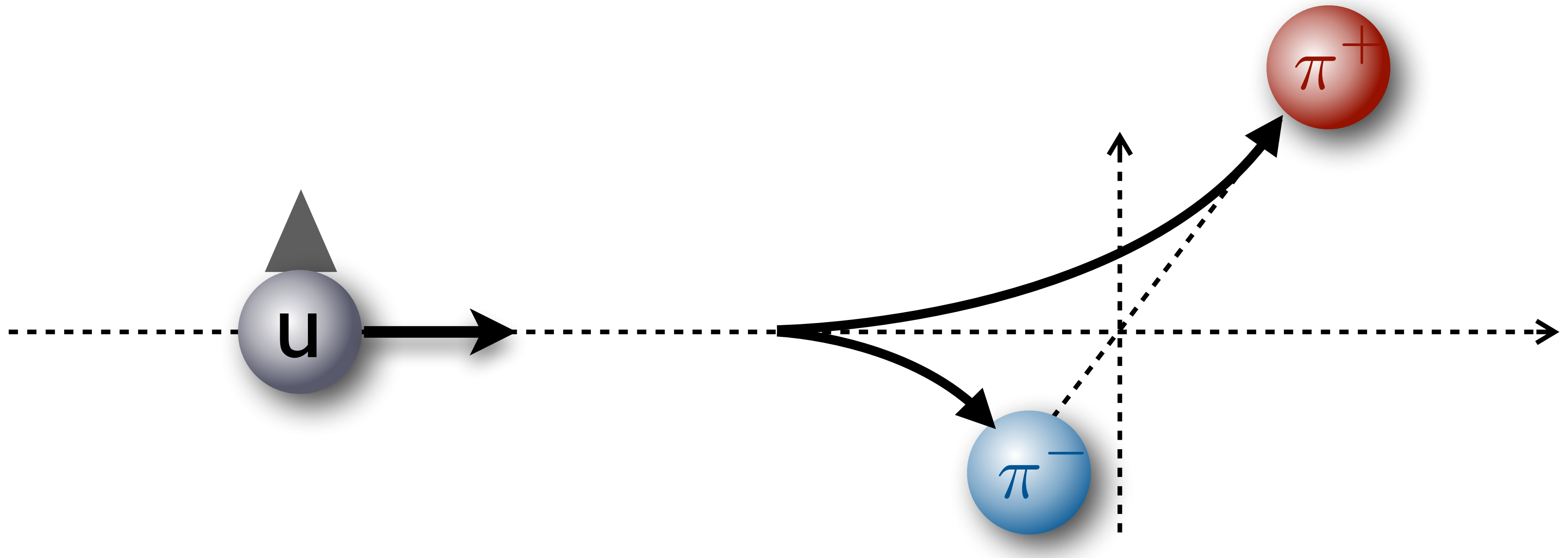
[HERMES, PRL 94 (2005) 012002]



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



Collins amplitudes

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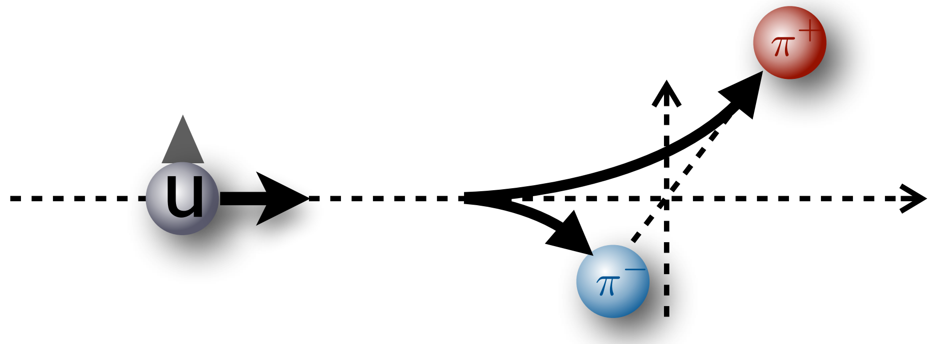
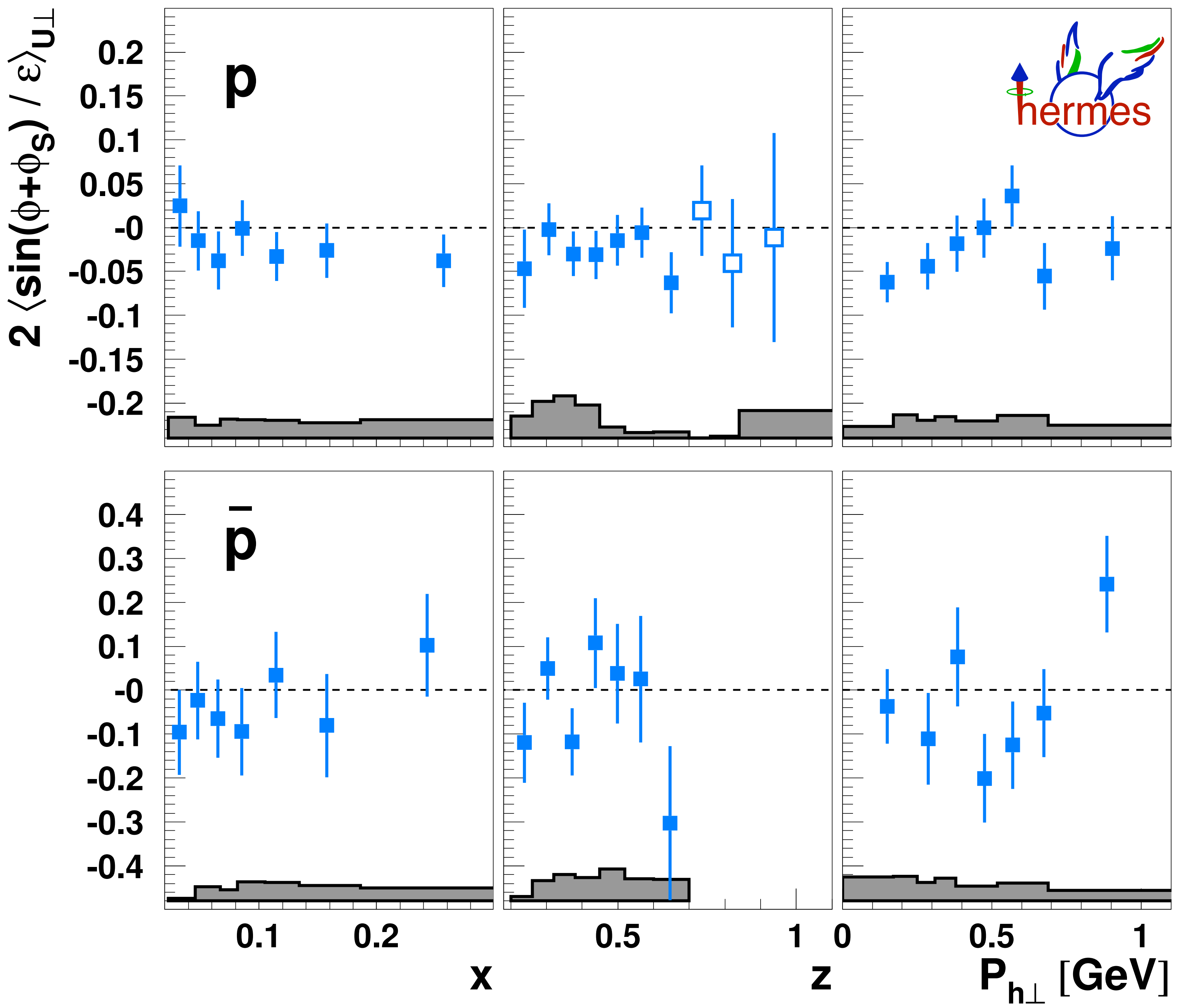


[HERMES, JHEP12(2020)010]



- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?

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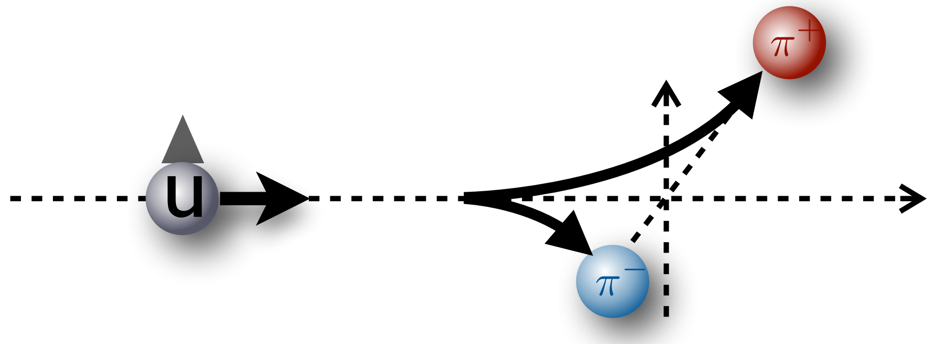

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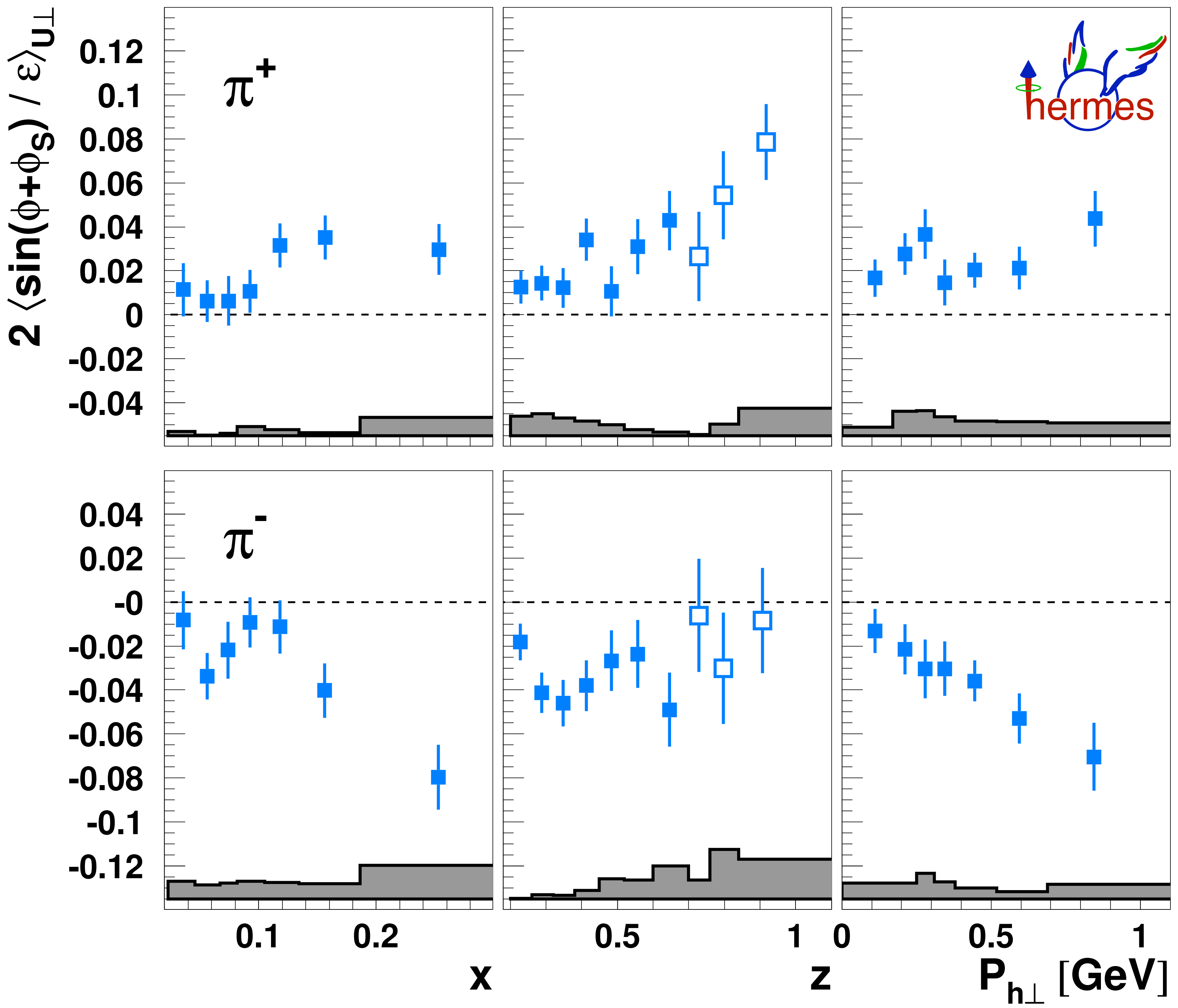

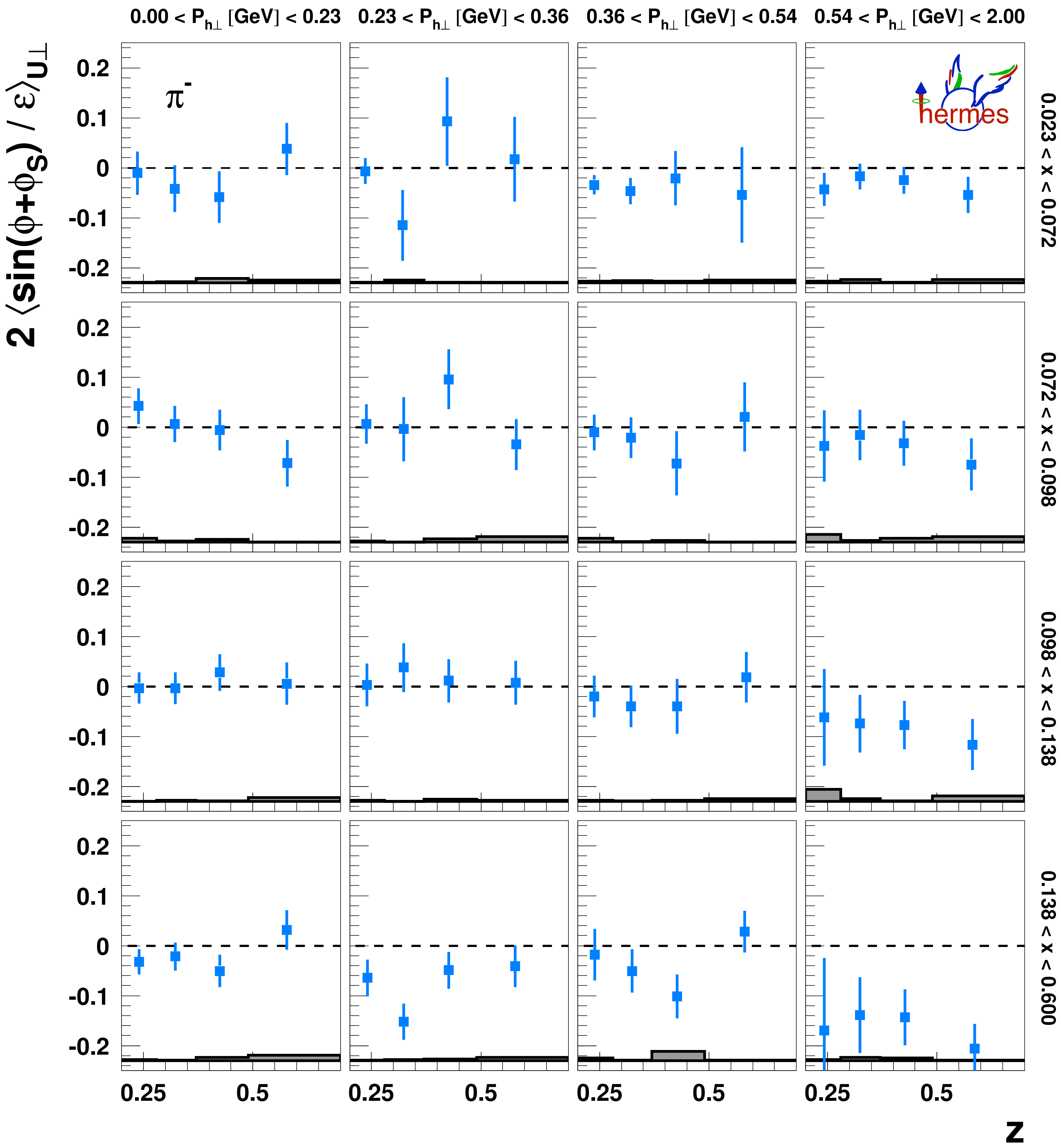

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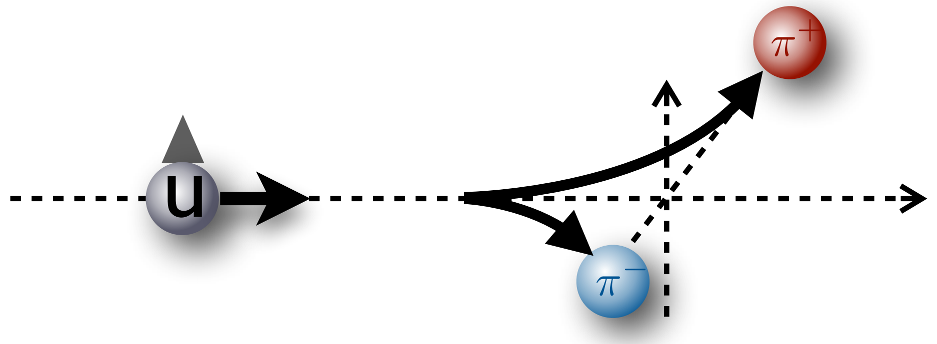

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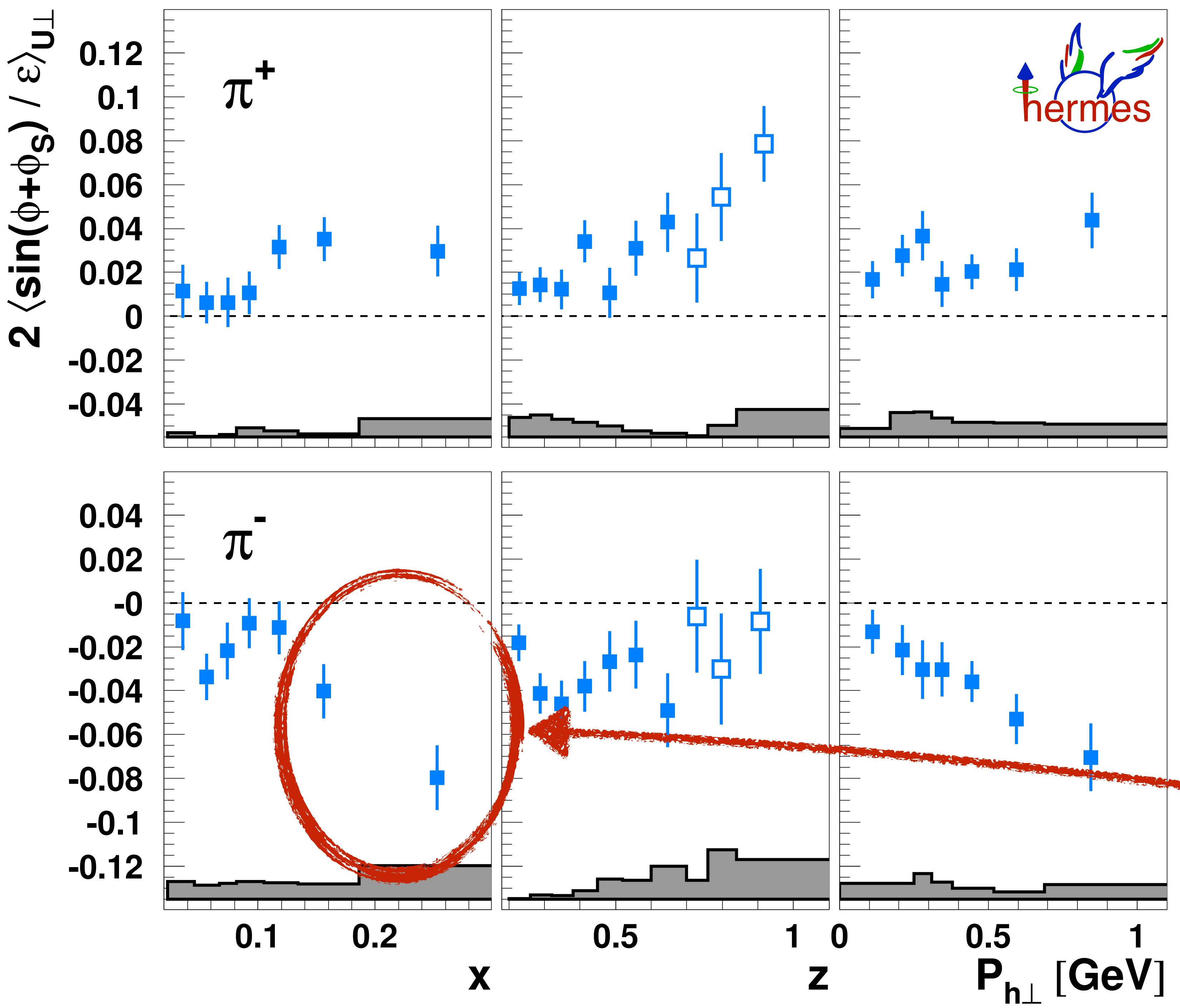

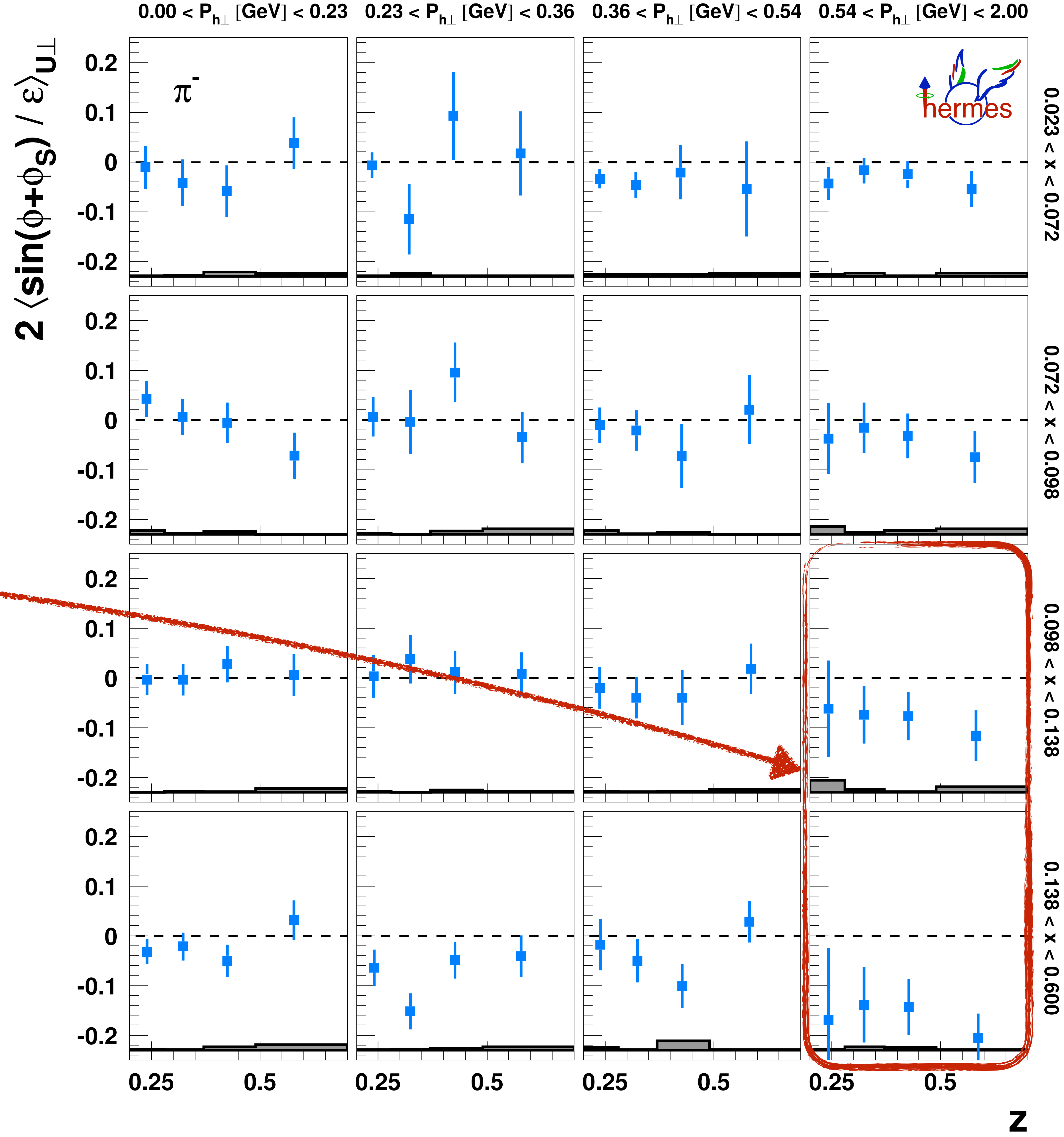

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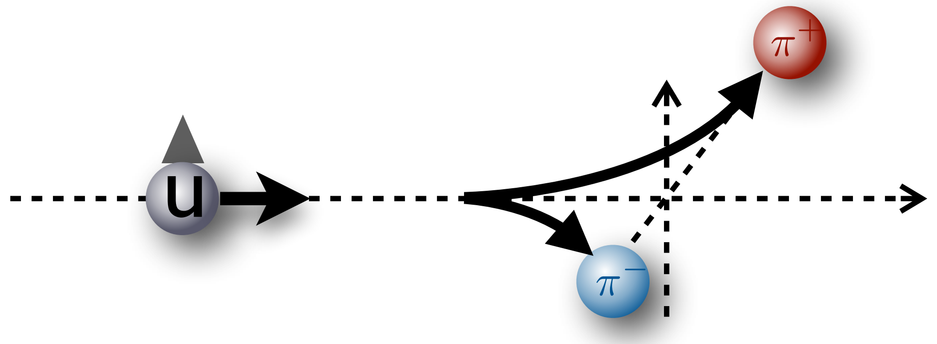
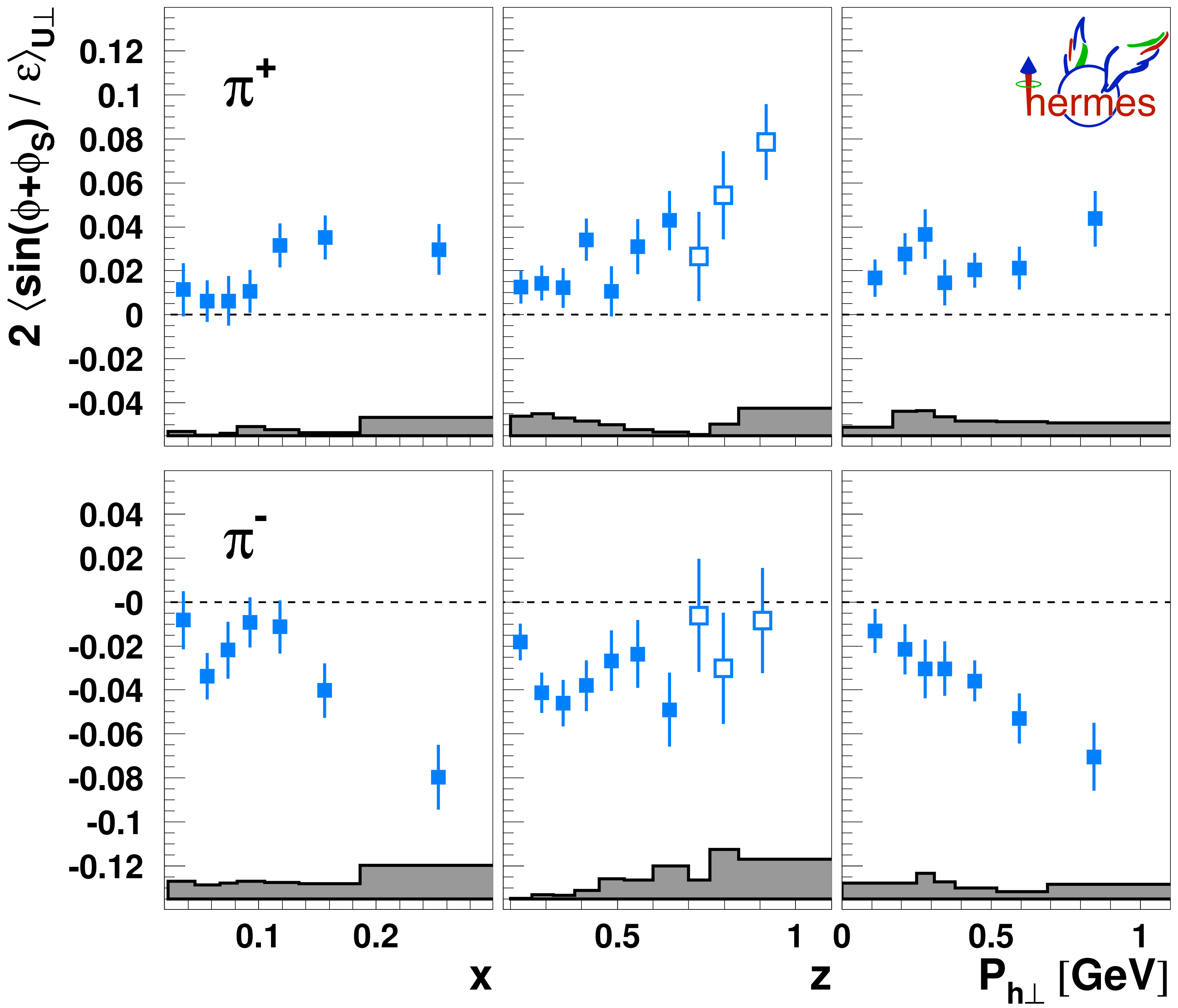
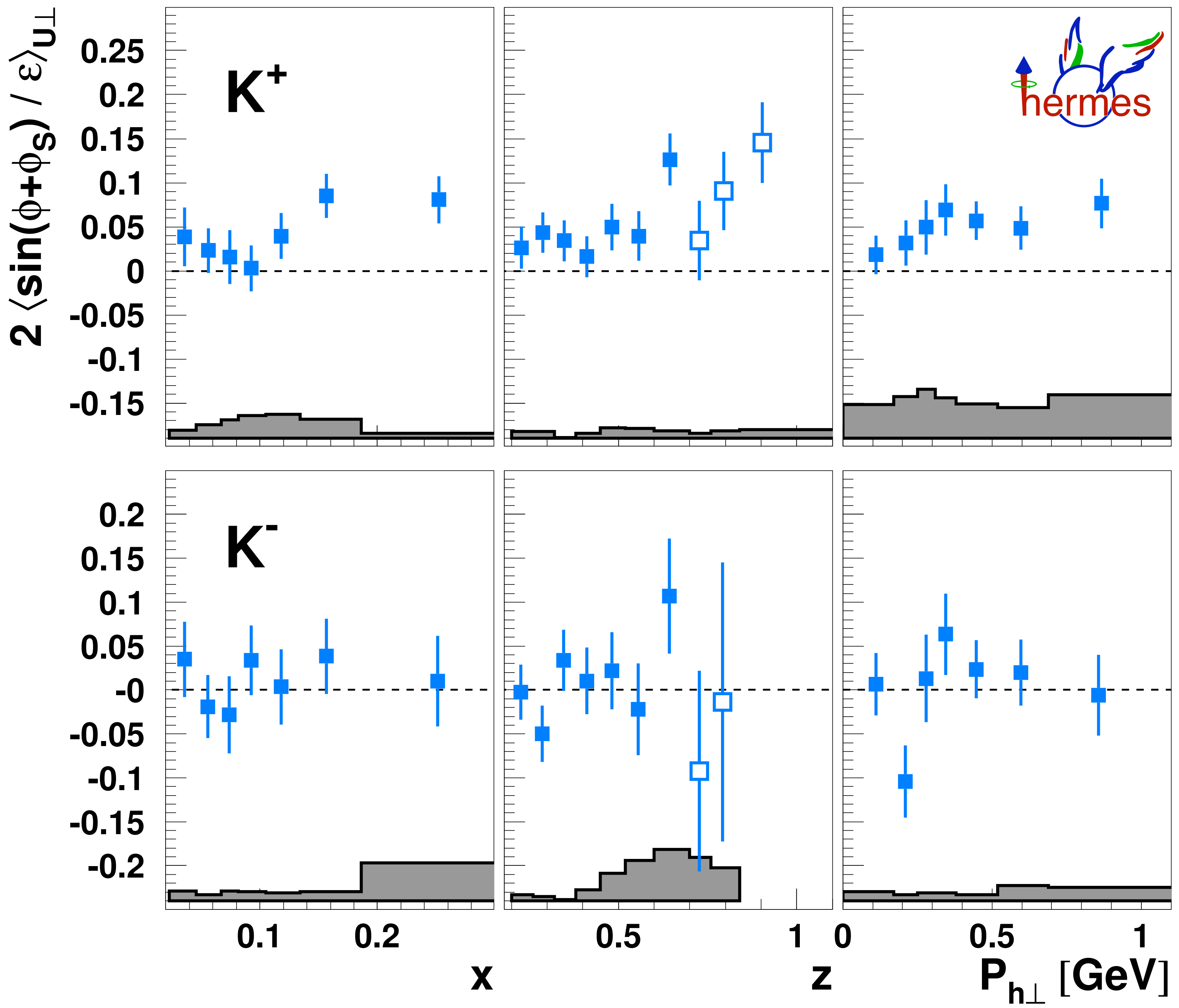


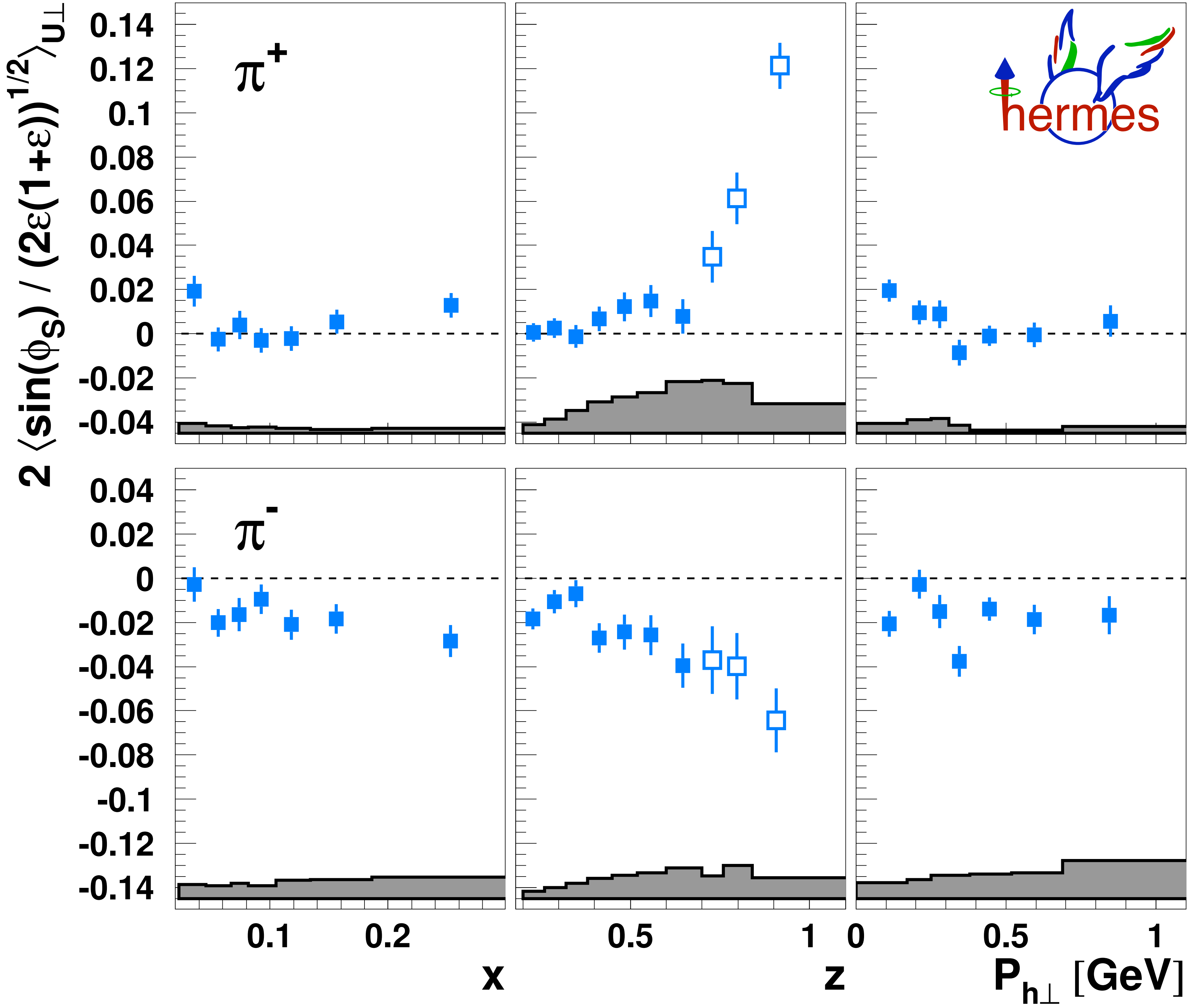

[HERMES, JHEP12(2020)010]


[HERMES, JHEP12(2020)010]

- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**
- **high-z region** probes transition region to exclusive domain (with increasing amplitudes for positive pions and kaons)

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

[HERMES, JHEP12(2020)010]



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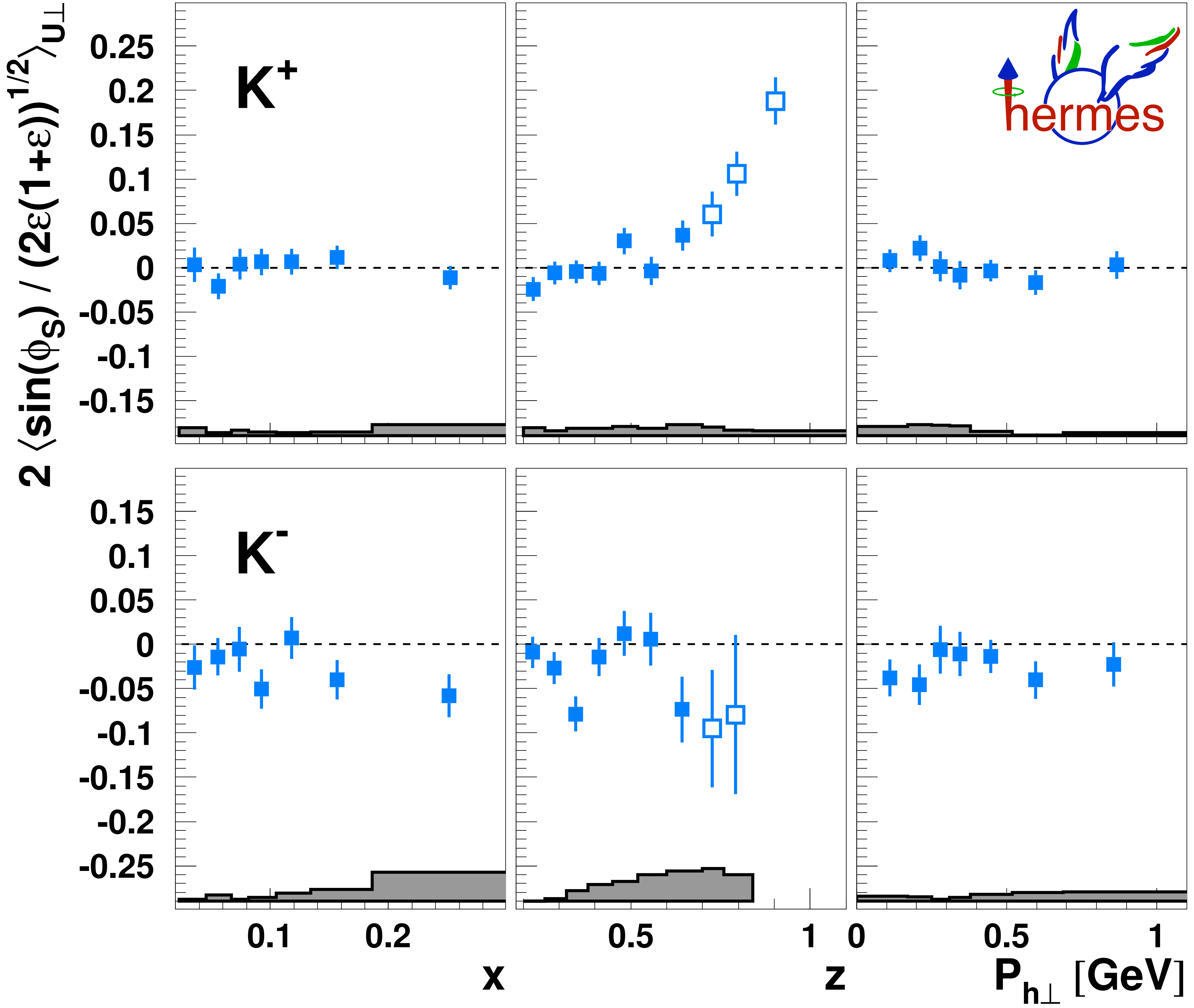
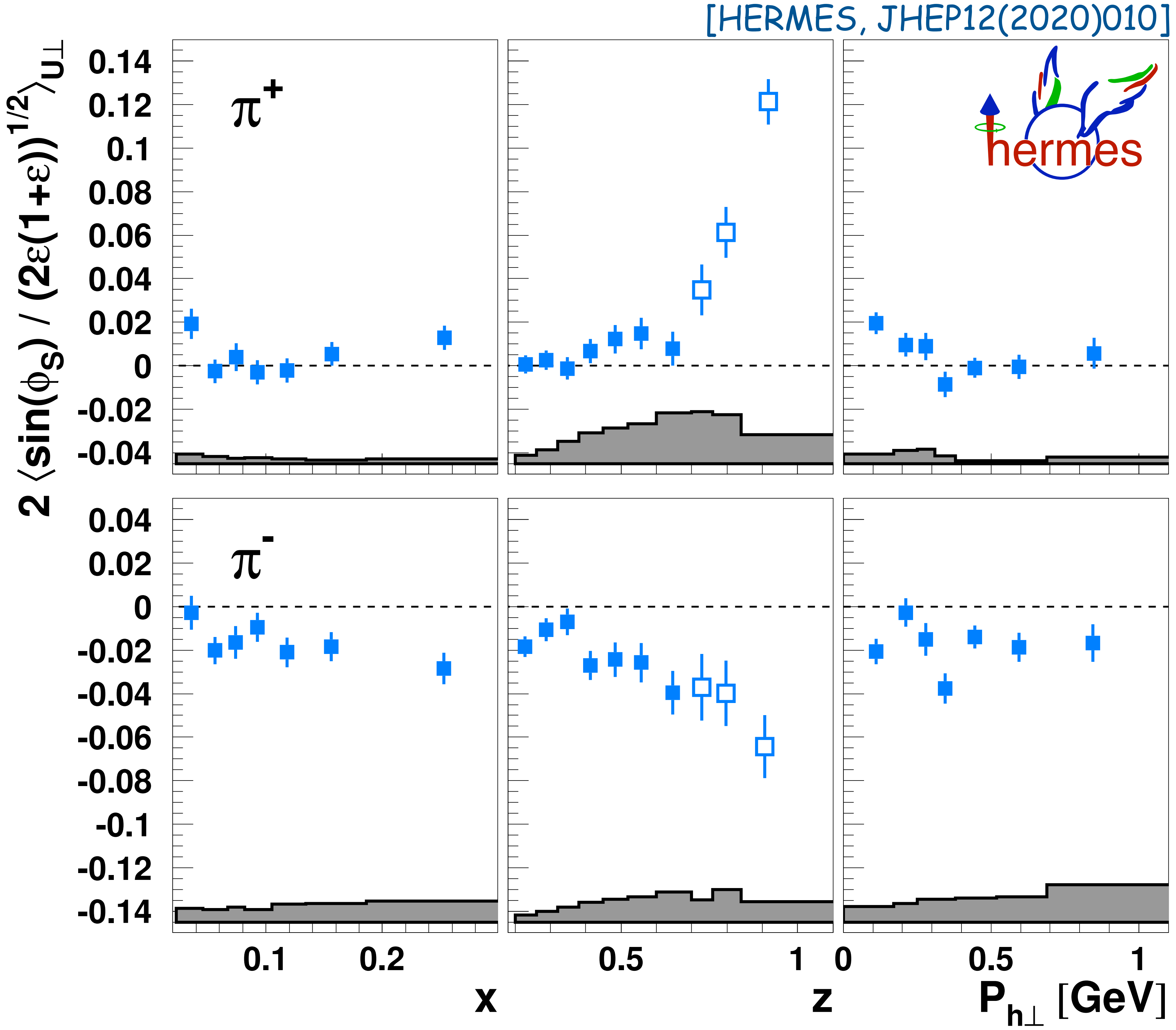


[JHEP12(2020)010]

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

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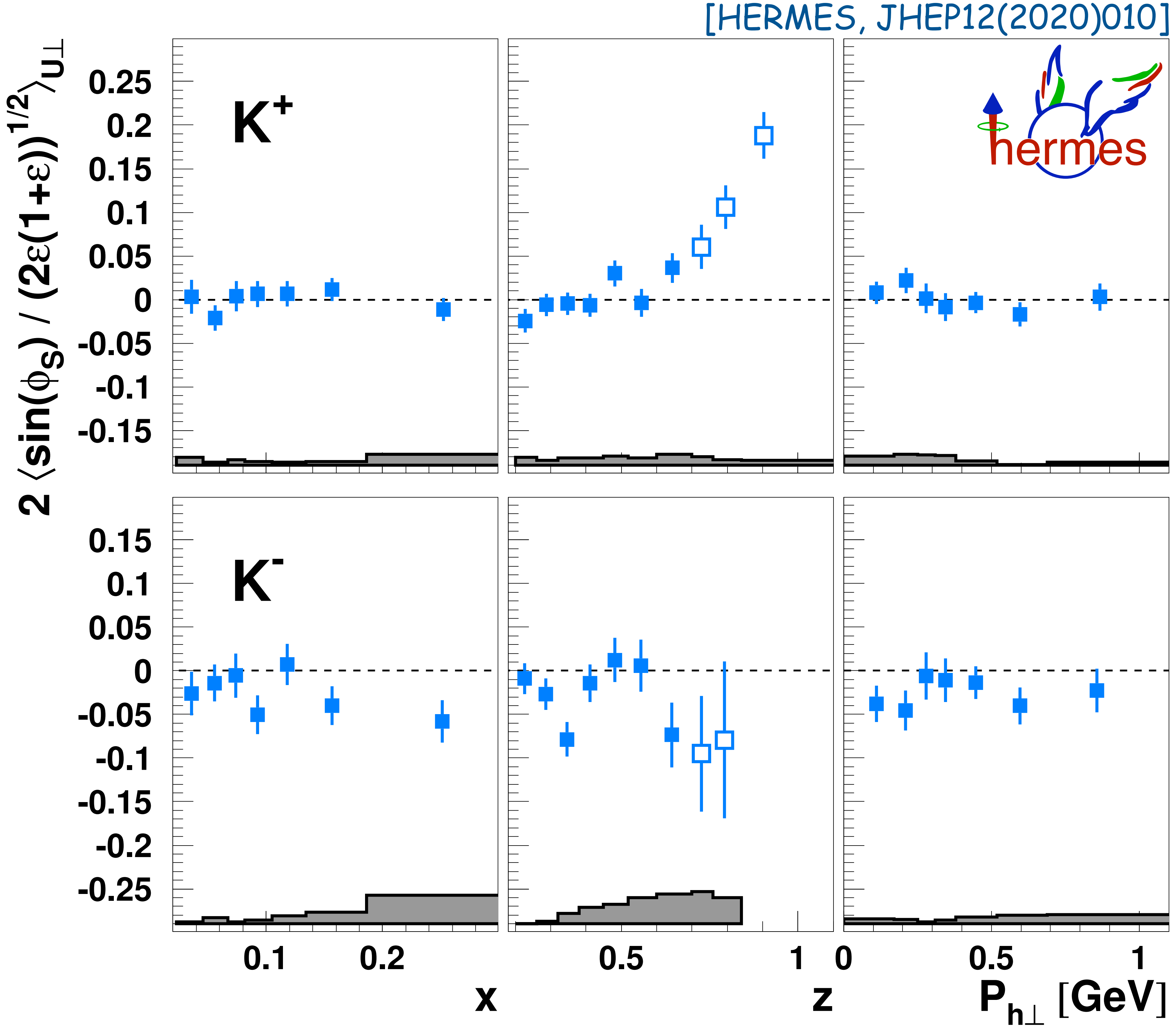
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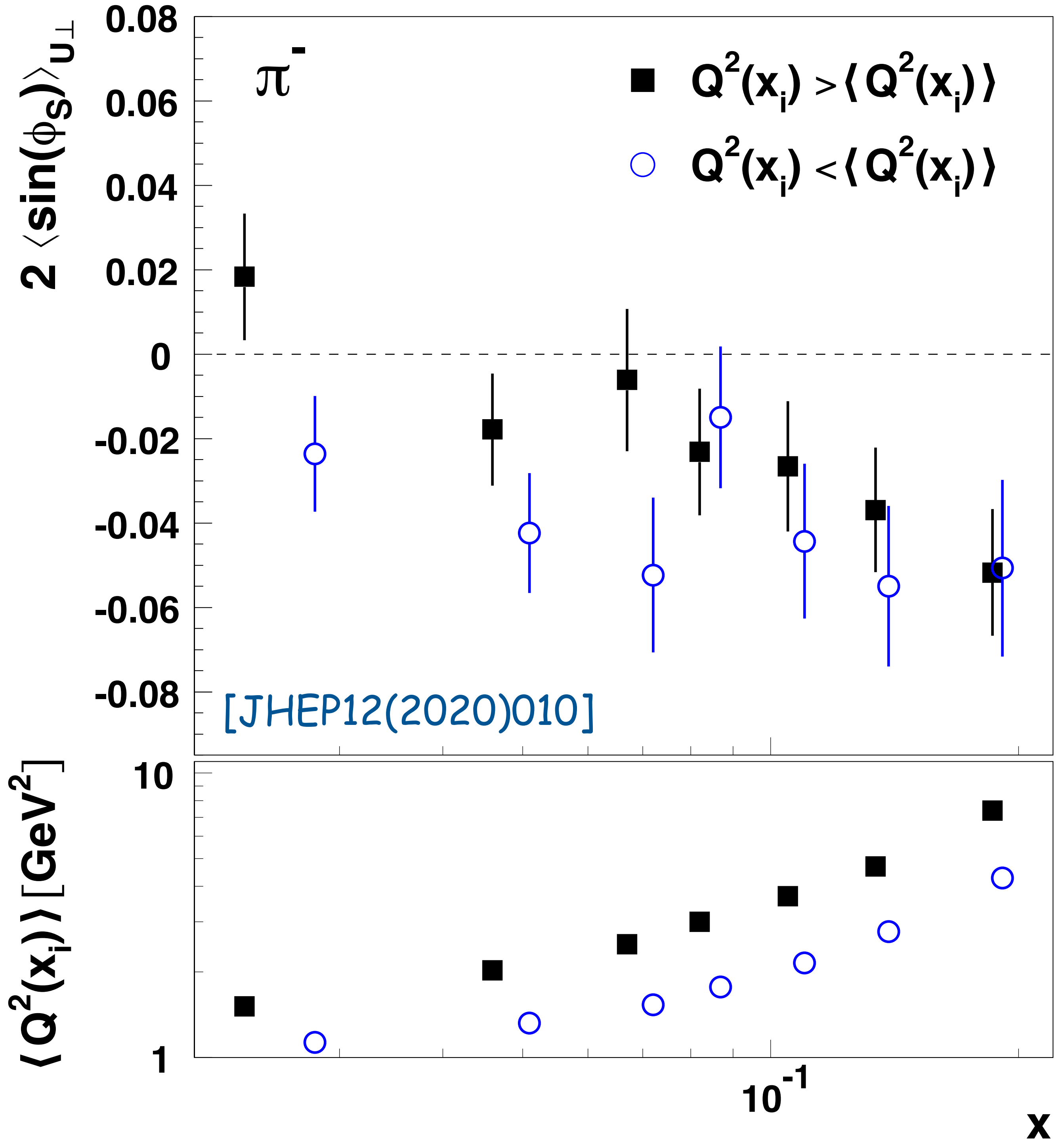
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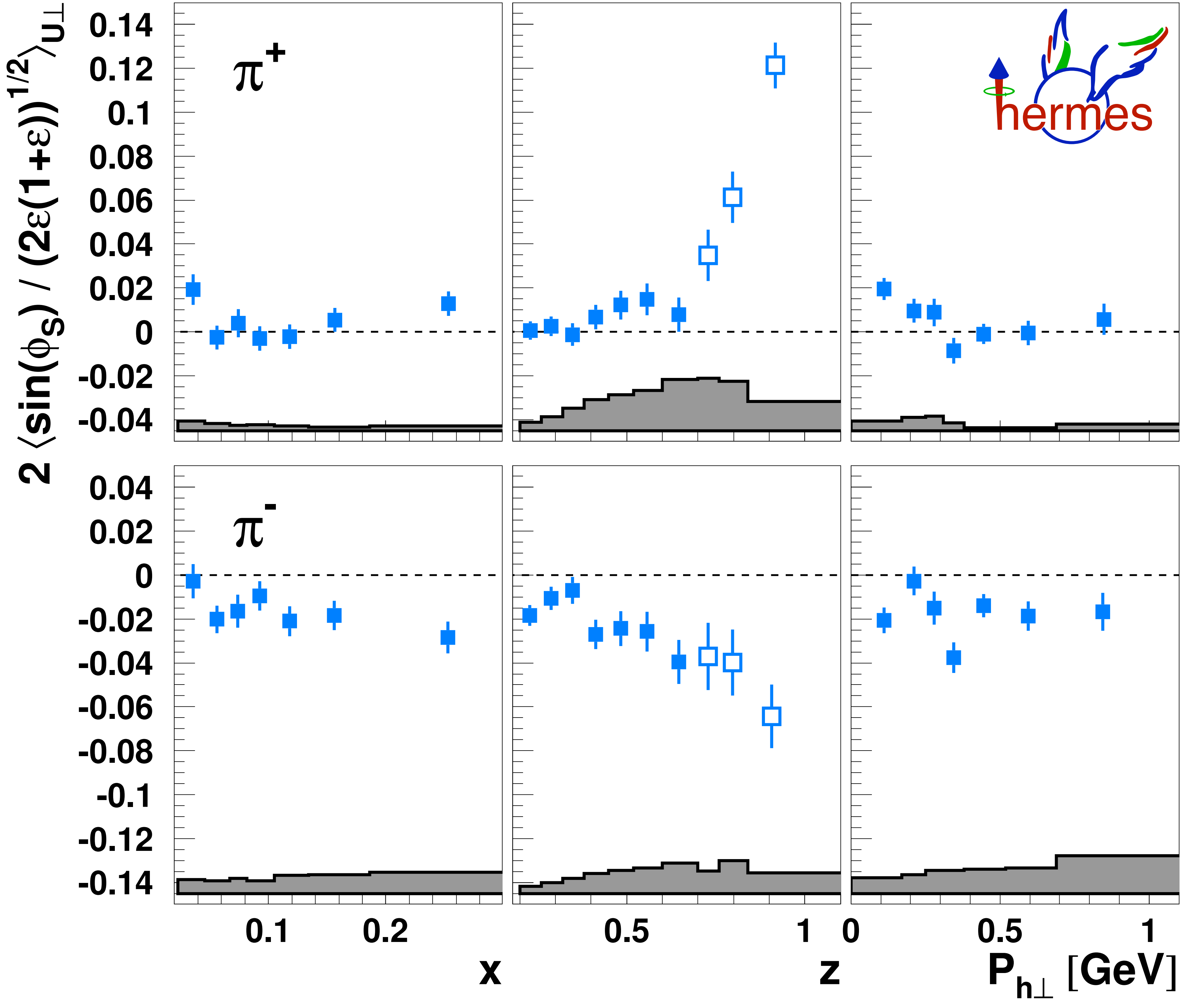
subleading twist — $\langle \sin(\phi_S) \rangle_{UT}$



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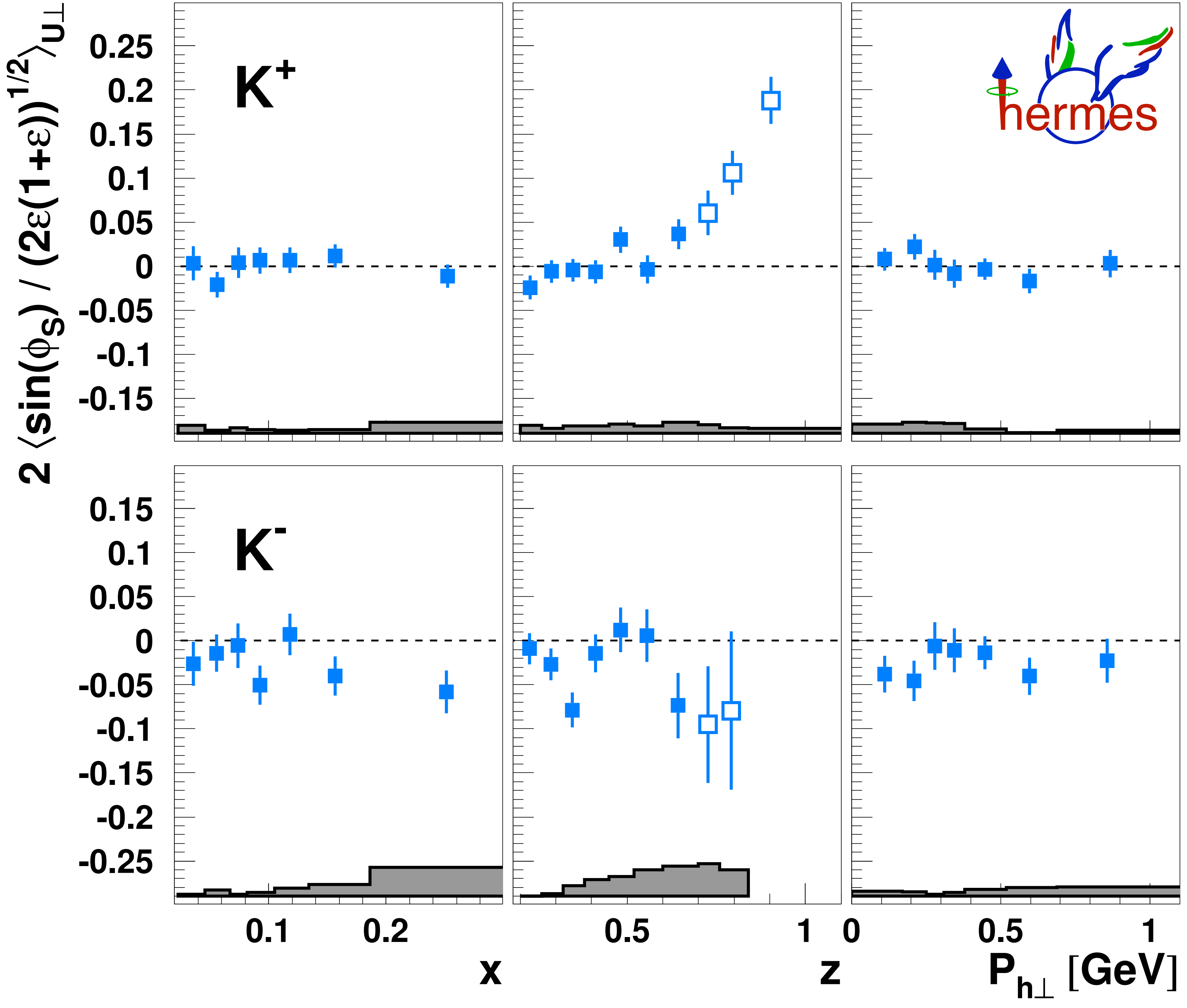

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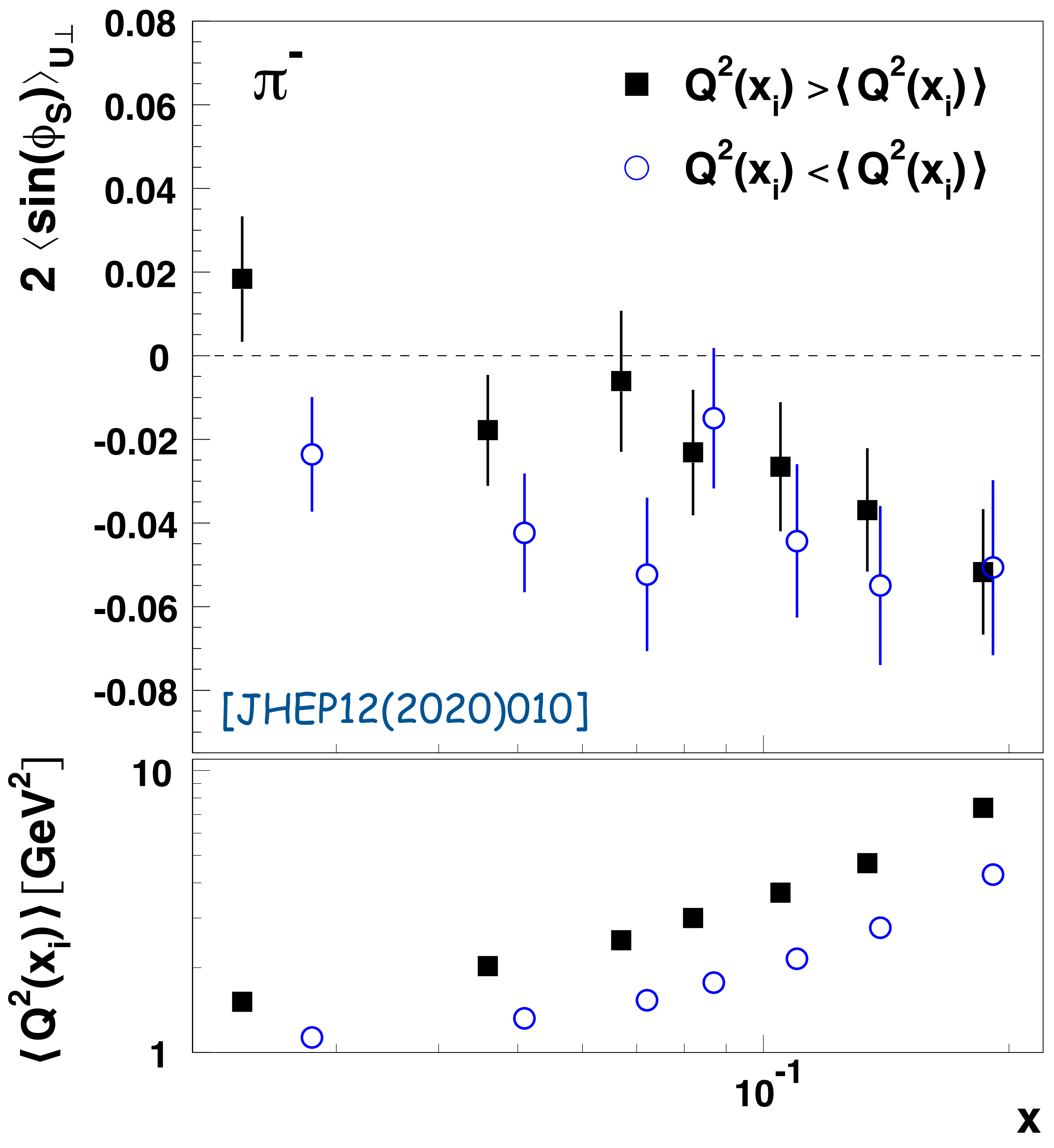
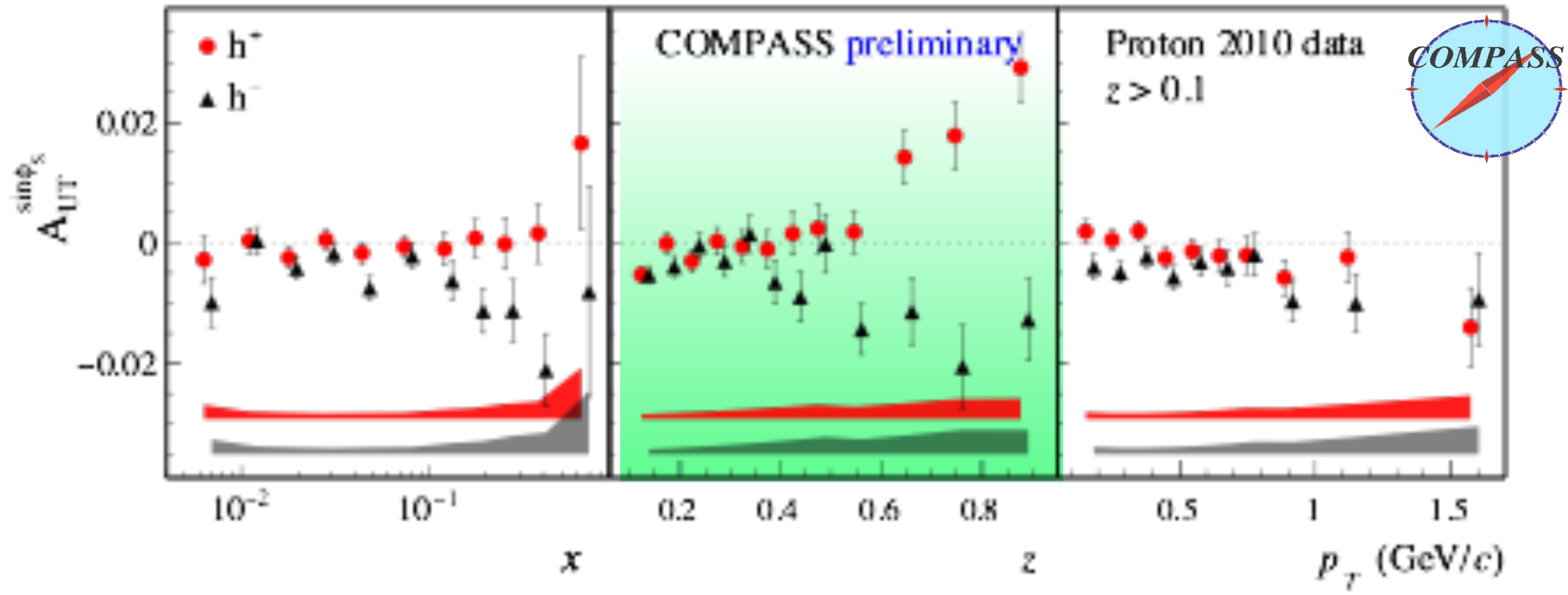
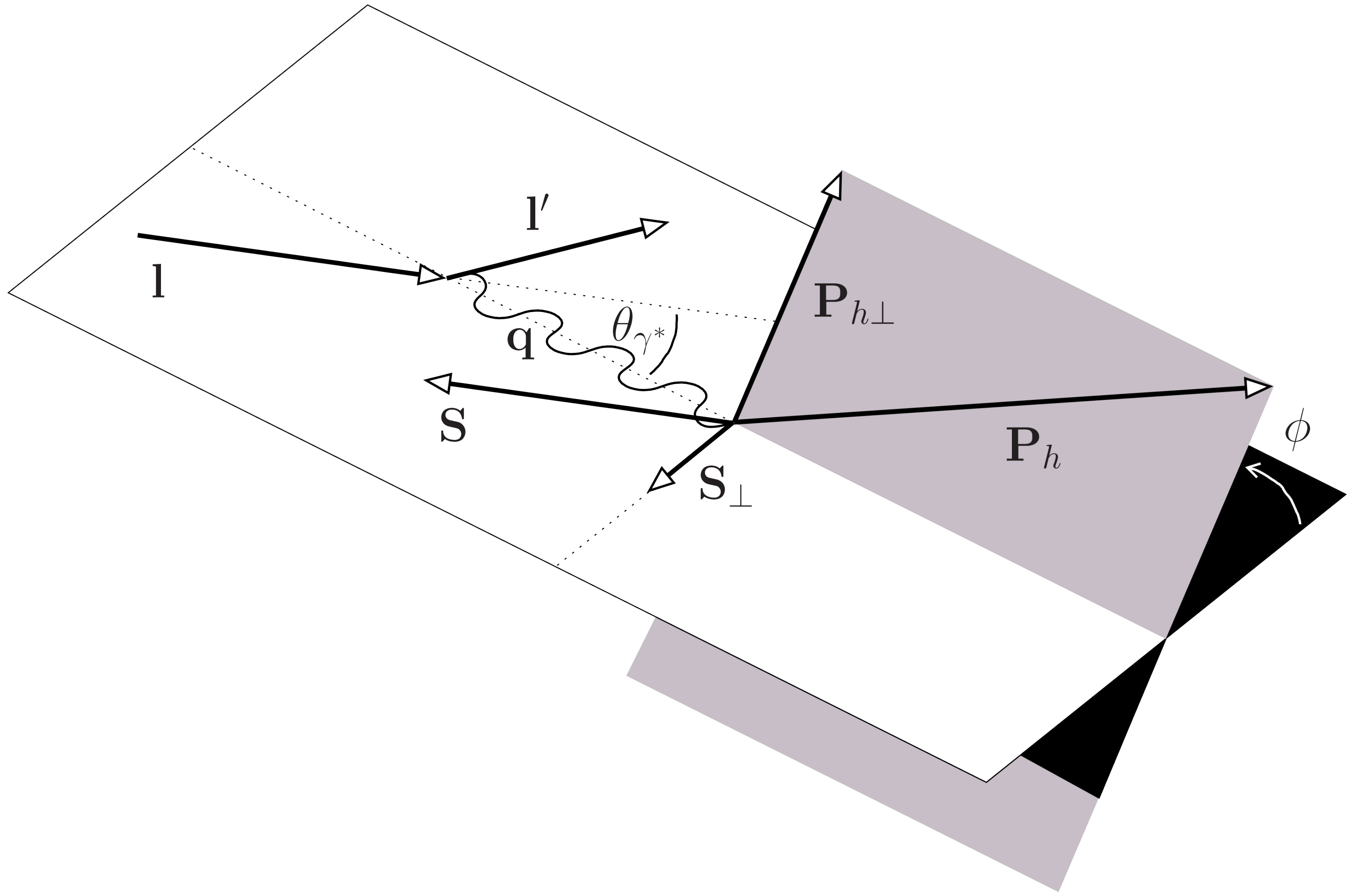


[JHEP12(2020)010]

- clearly non-zero asymmetries with opposite sign for charged pions (Collins-like behavior)
- striking z dependence and in particular magnitude
- hint of Q suppression
- similar z behaviour seen at COMPASS



semi-inclusive DIS



- excluding transverse polarization:

$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}F_{LL}^h$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \Big\}$$

- single-spin asymmetry:

$$A_{LU}^h \equiv \frac{\sigma_{+-}^h + \sigma_{++}^h - \sigma_{-+}^h - \sigma_{--}^h}{\sigma_{+-}^h + \sigma_{++}^h + \sigma_{-+}^h + \sigma_{--}^h}$$

beam-helicity asymmetry

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

- 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

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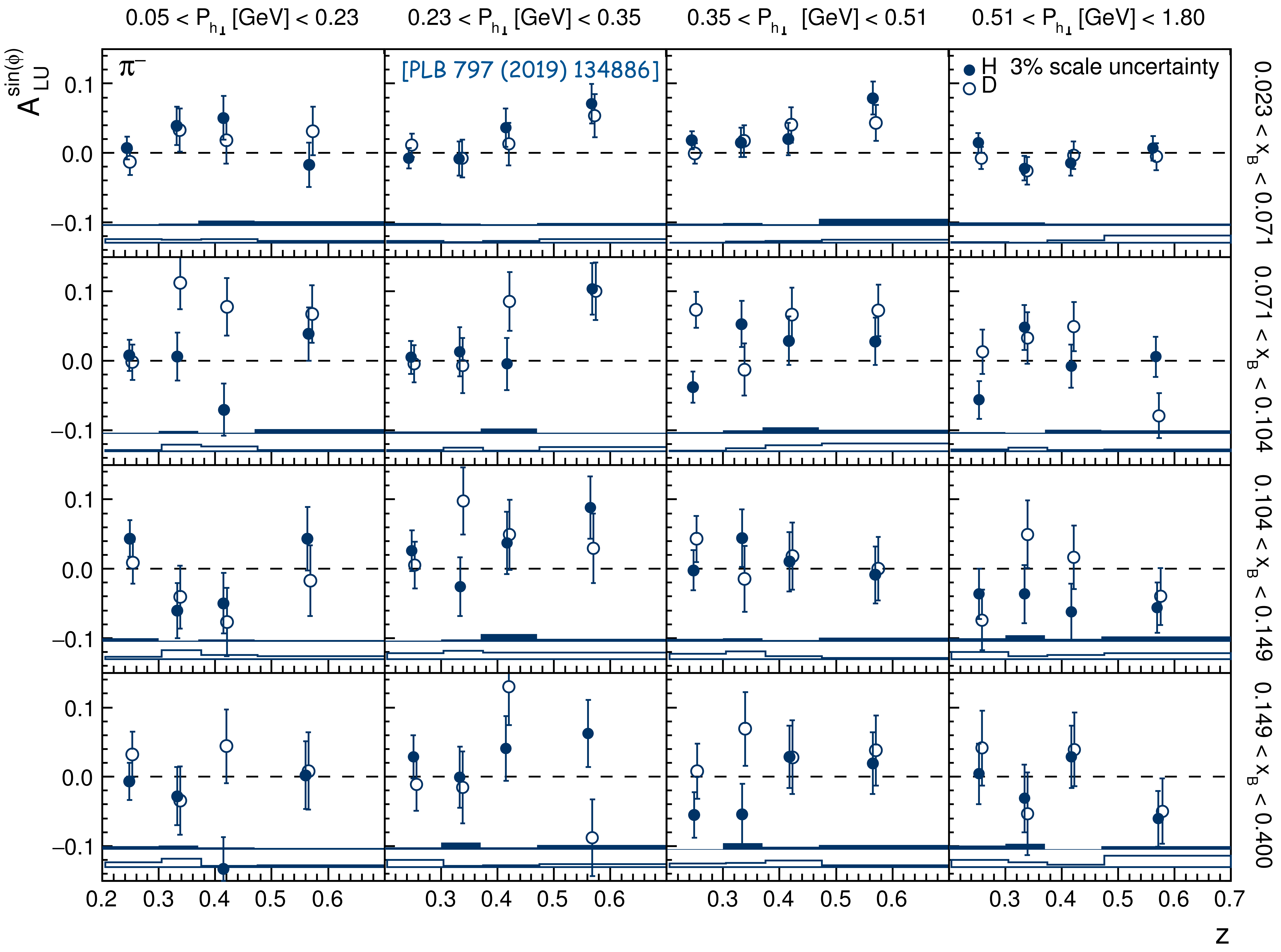
- little known about naive-T-odd $g^\perp$; singled out in A_{LU} in jet production
- large unpolarized f_1, coupled to interaction-dependent FF
- twist-3 e survives integration over $P_{h\perp}$; here coupled to Collins FF
  - e linked to the pion–nucleon σ-term
  - interpreted as color force (from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

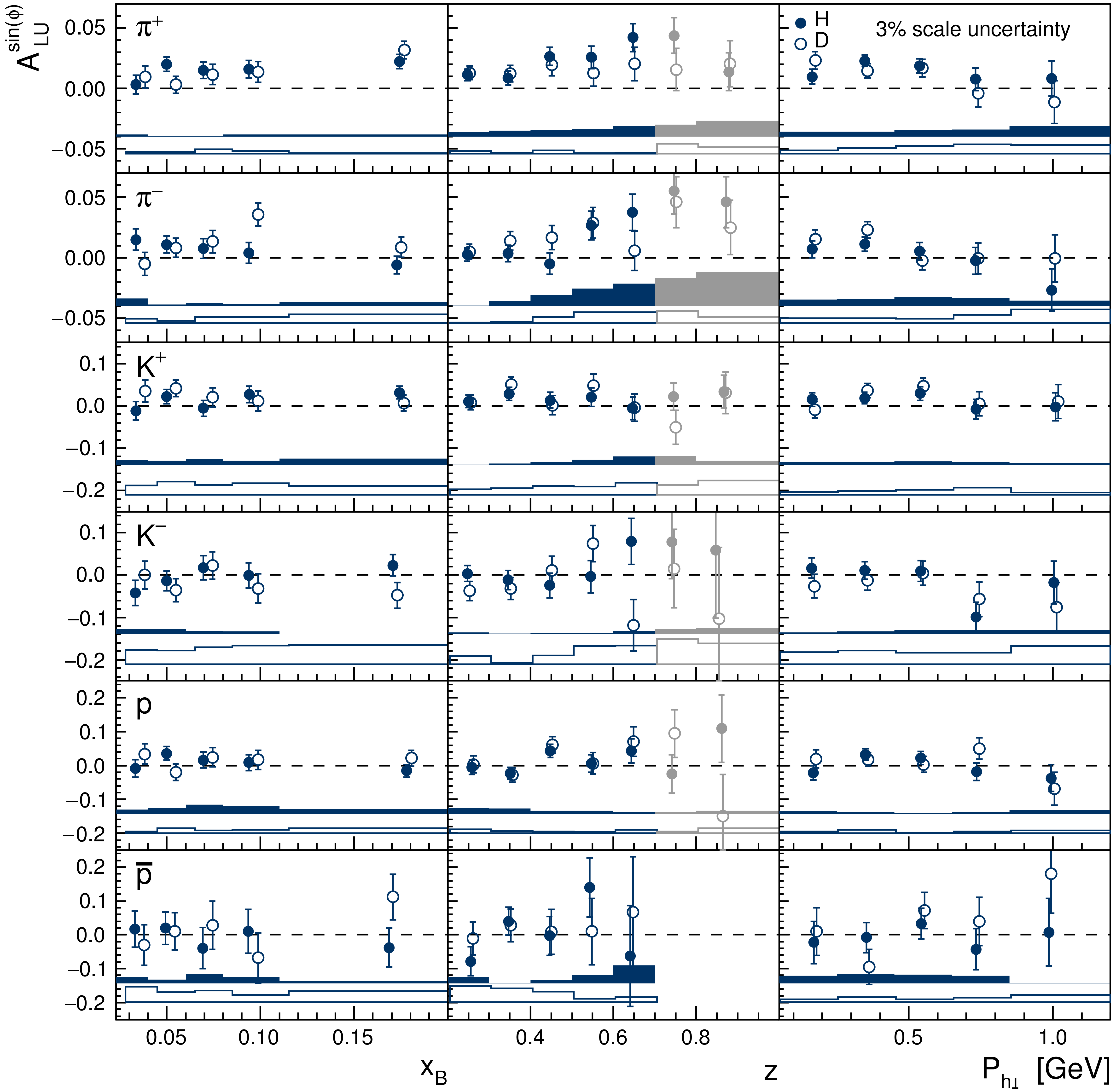
3d beam-helicity asymmetry for π⁻



most comprehensive presentation, for discussion use 1d binning

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

[HERMES, PLB 797 (2019) 134886]



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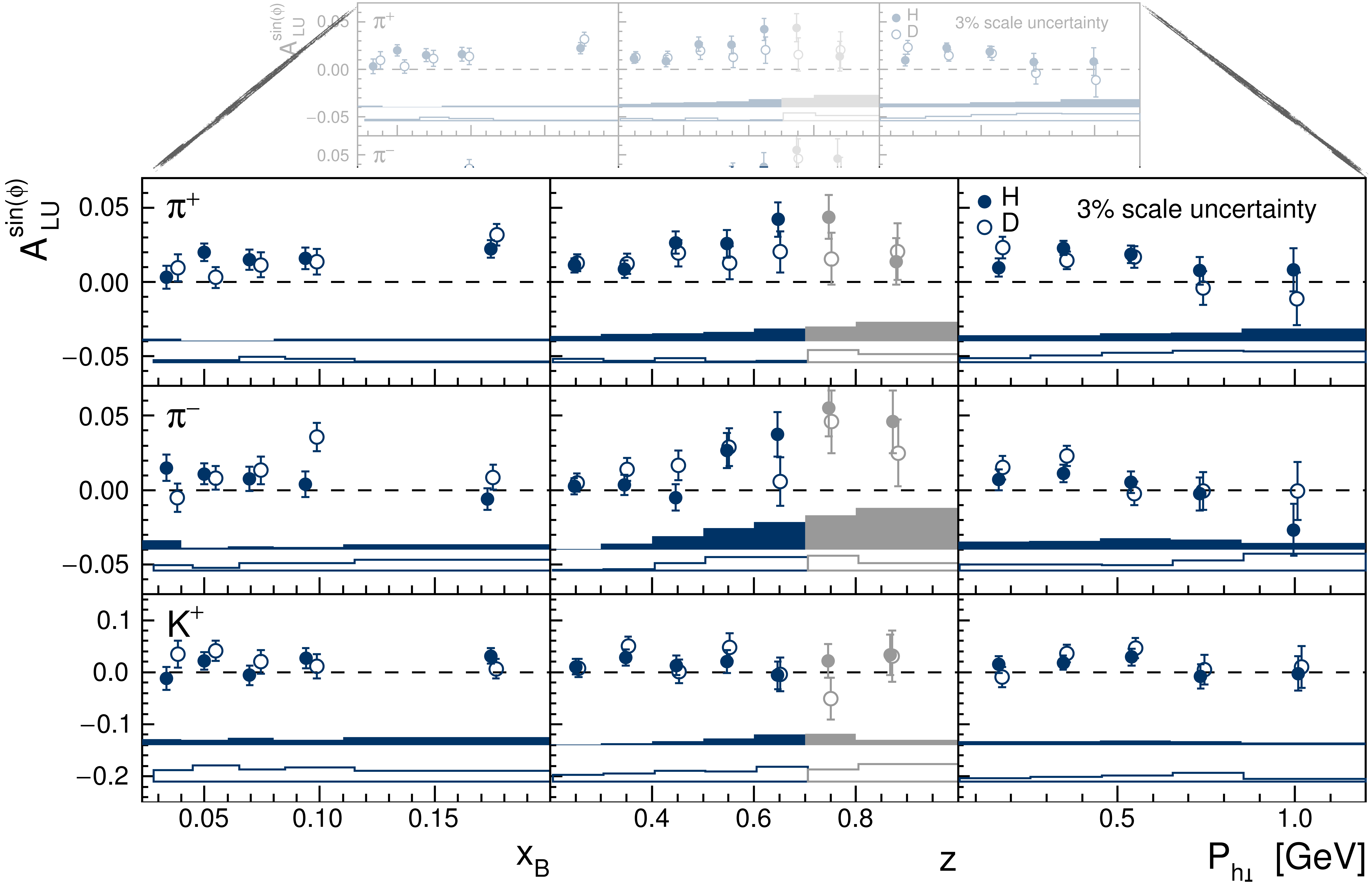

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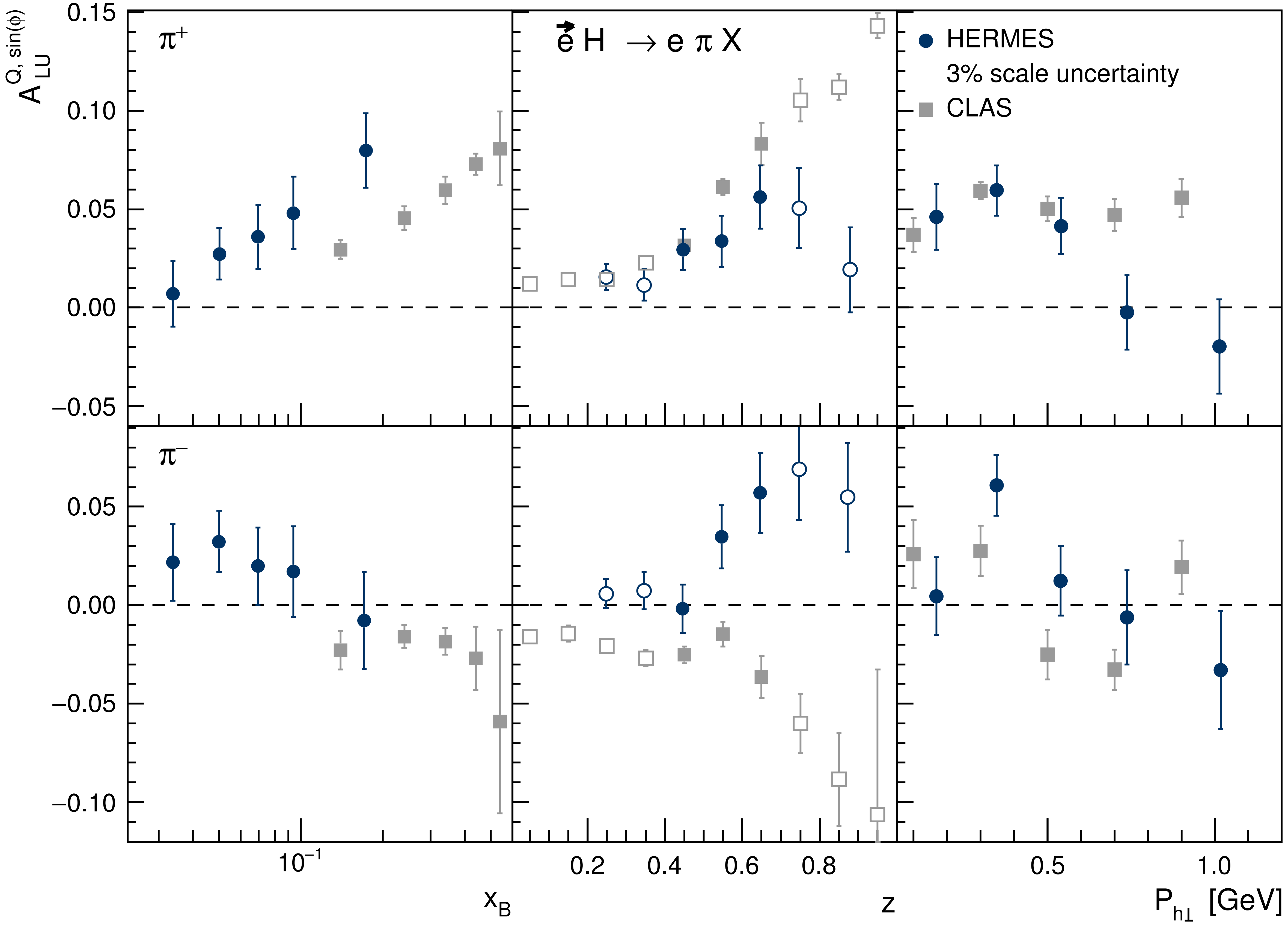

- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed

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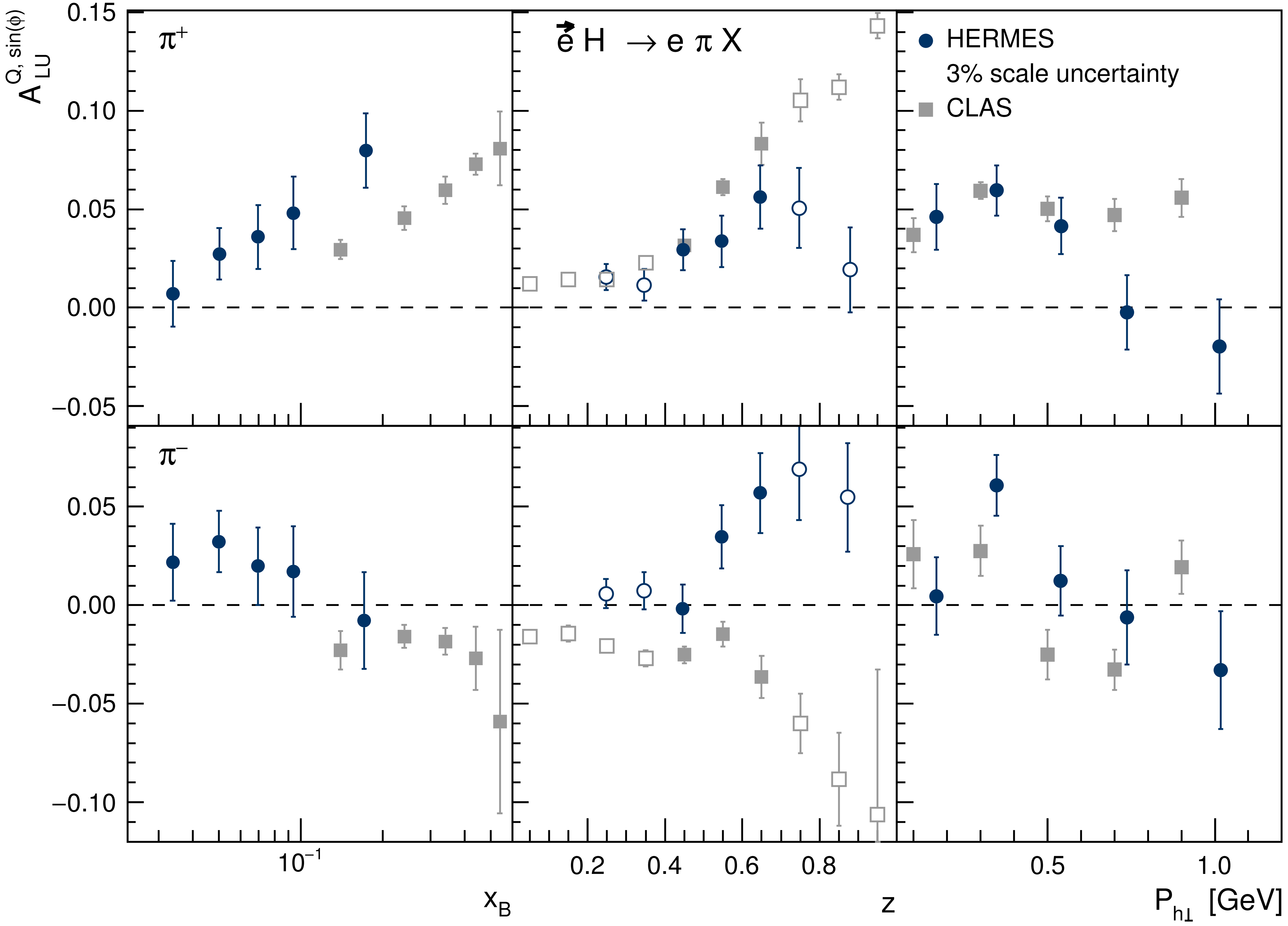

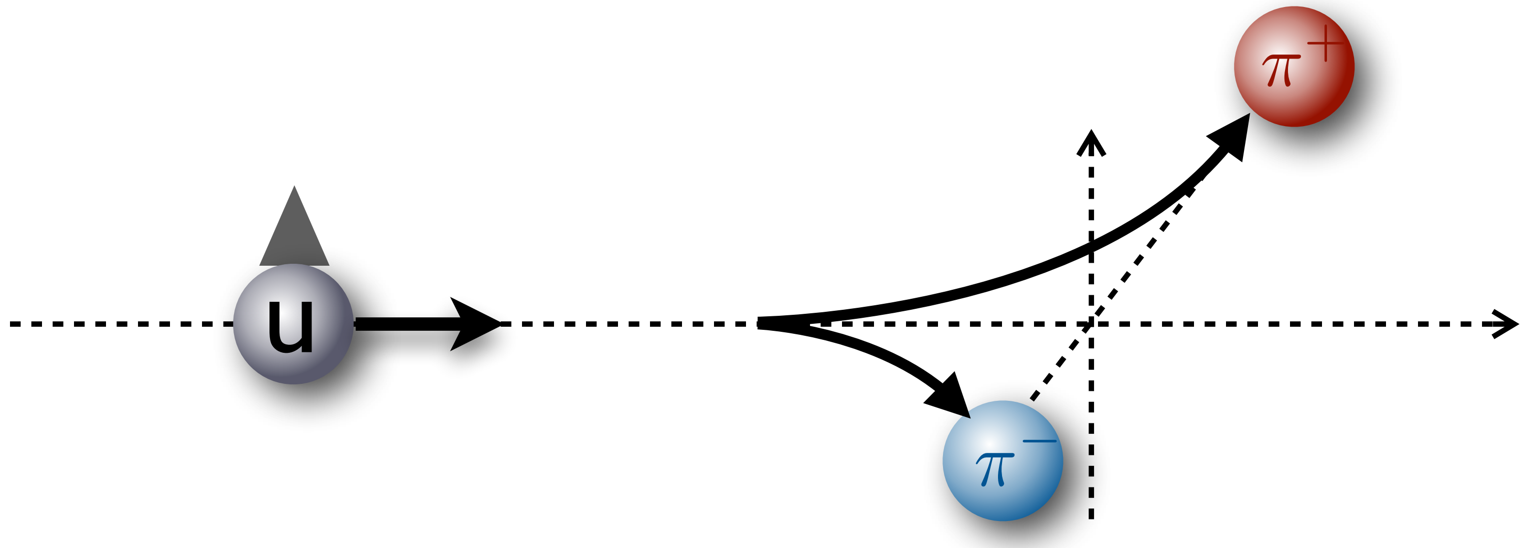

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- CLAS more sensitive to e(x) ⊗ Collins term due to higher x probed?

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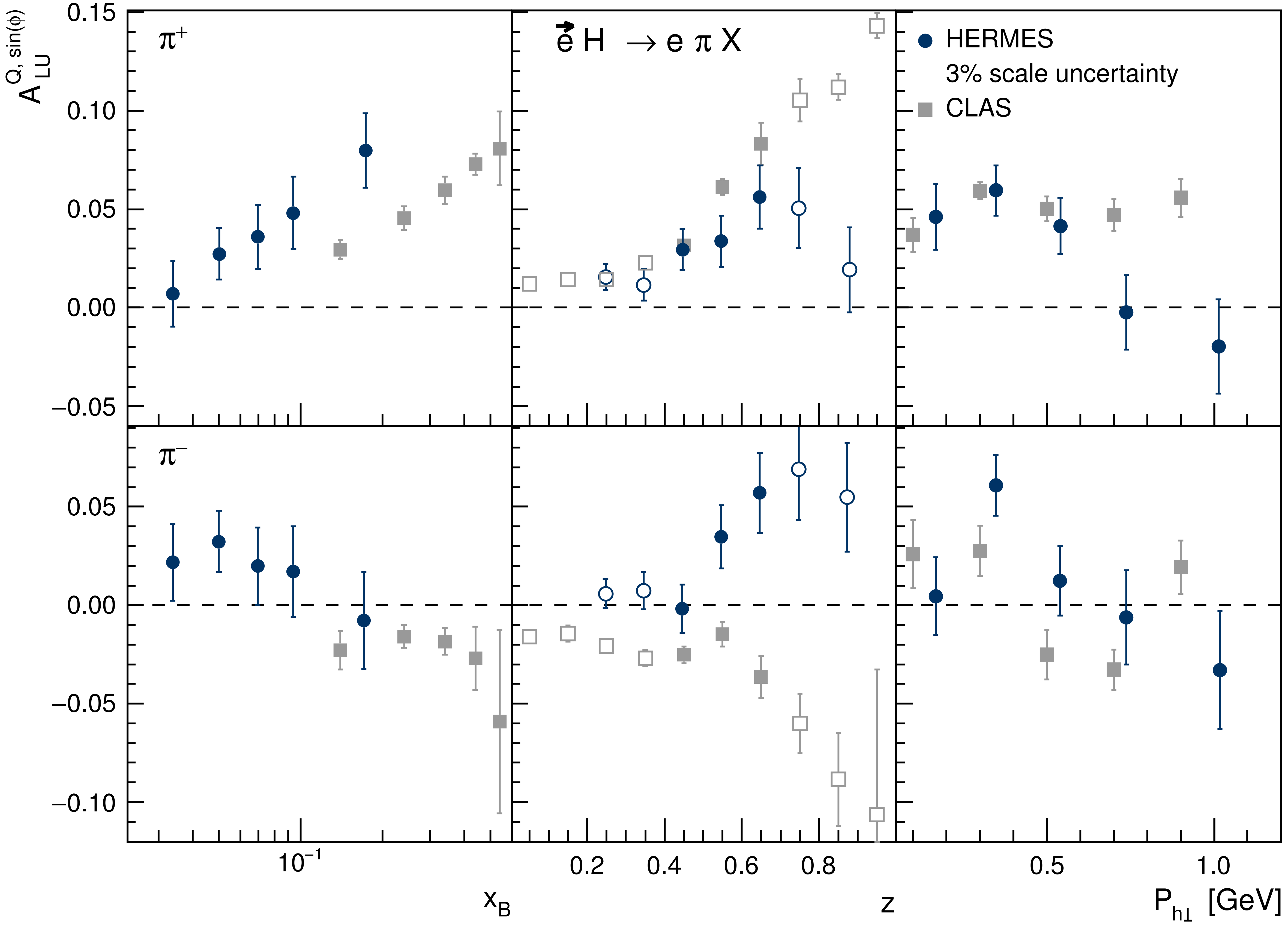

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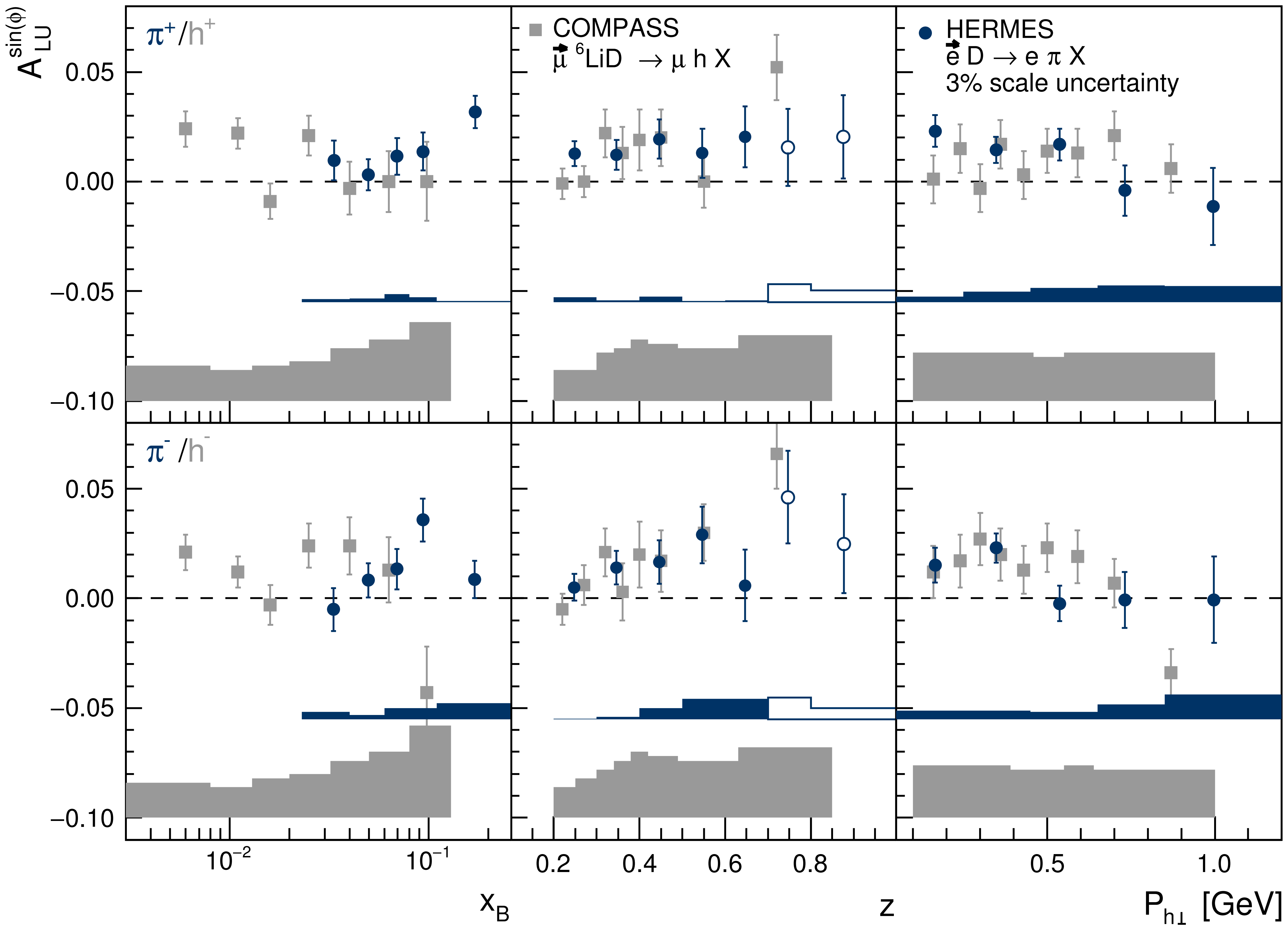

- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x) ⊗ Collins term due to higher x probed?
- consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets

conclusions

- HERMES continues producing results long after its shut down
- latest publications provide 3-dimensional presentations of longitudinal and transverse SSA and DSA
  - completes the TMD analyses of single-hadron production
  - multi-d analyses not only important to reduce experimental systematics but also to permit the isolation of the phase space of interest
  - several significant leading-twist spin-momentum correlations (Sivers, Collins, worm-gear) and surprising twist-3 effects
  - by now, **basically all asymmetries** (except one: A_{UL}) extracted simultaneously in **three or even four dimensions** — a rich data set on transverse-momentum distributions
- complementary to data from other facilities

backup slides

double-spin asymmetry $A_{||}$

$$A_{\parallel}^{h} \equiv \frac{C_{\phi}^{h}}{f_D} \left[\frac{L_{\rightrightarrows} N^{h}_{\rightleftarrows} - L_{\rightleftarrows} N^{h}_{\rightrightarrows}}{L_{P,\rightrightarrows} N^{h}_{\rightleftarrows} + L_{P,\rightleftarrows} N^{h}_{\rightrightarrows}} \right]_{\mathrm{B}}$$

double-spin asymmetry $A_{||}$

azimuthal correction

$$A_{\parallel}^{h} \equiv \frac{C_{\phi}^{h}}{f_D}\left[\frac{L_{\rightrightarrows} N^{h}_{\rightleftarrows} - L_{\rightleftarrows} N^{h}_{\rightrightarrows}}{L_{P,\rightrightarrows} N^{h}_{\rightleftarrows} + L_{P,\rightleftarrows} N^{h}_{\rightrightarrows}}\right]_{\mathrm{B}}$$

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nucleon-in-nucleus **depolarization** factor (0.926 for deuteron due to D-state admixture)

double-spin asymmetry $A_{||}$

azimuthal correction

luminosities

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nucleon-in-nucleus **depolarization** factor (0.926 for deuteron due to D-state admixture)

polarization-weighted luminosities

unfolded for QED radiation to Born level

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- dominated by statistical uncertainties

double-spin asymmetry $A_{||}$

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- dominated by statistical uncertainties
- main systematics arise from
  - polarization measurements [6.6% for hydrogen, 5.7% for deuterium)
  - azimuthal correction [O(few %)]

azimuthal-asymmetry corrections

measured

“polarized Cahn” effect etc.

$$\tilde{A}_{\|}^{h}(x,Q^2,z,P_{h\perp}) = \frac{\int \mathrm{d}\phi\ \sigma_{\|}^{h}\left(x,Q^2,z,P_{h\perp},\phi\right)\ \xi(\phi)}{\int \mathrm{d}\phi\ \sigma_{UU}^{h}\left(x,Q^2,z,P_{h\perp},\phi\right)\ \xi(\phi)}$$

Boer-Mulders and Cahn effects etc.

azimuthal
acceptance

- both numerator and in particular denominator ϕ dependent
  - in theory integrated out
  - in praxis, detector acceptance also ϕ dependent
  - convolution of physics & acceptance leads to bias in normalization of asymmetries

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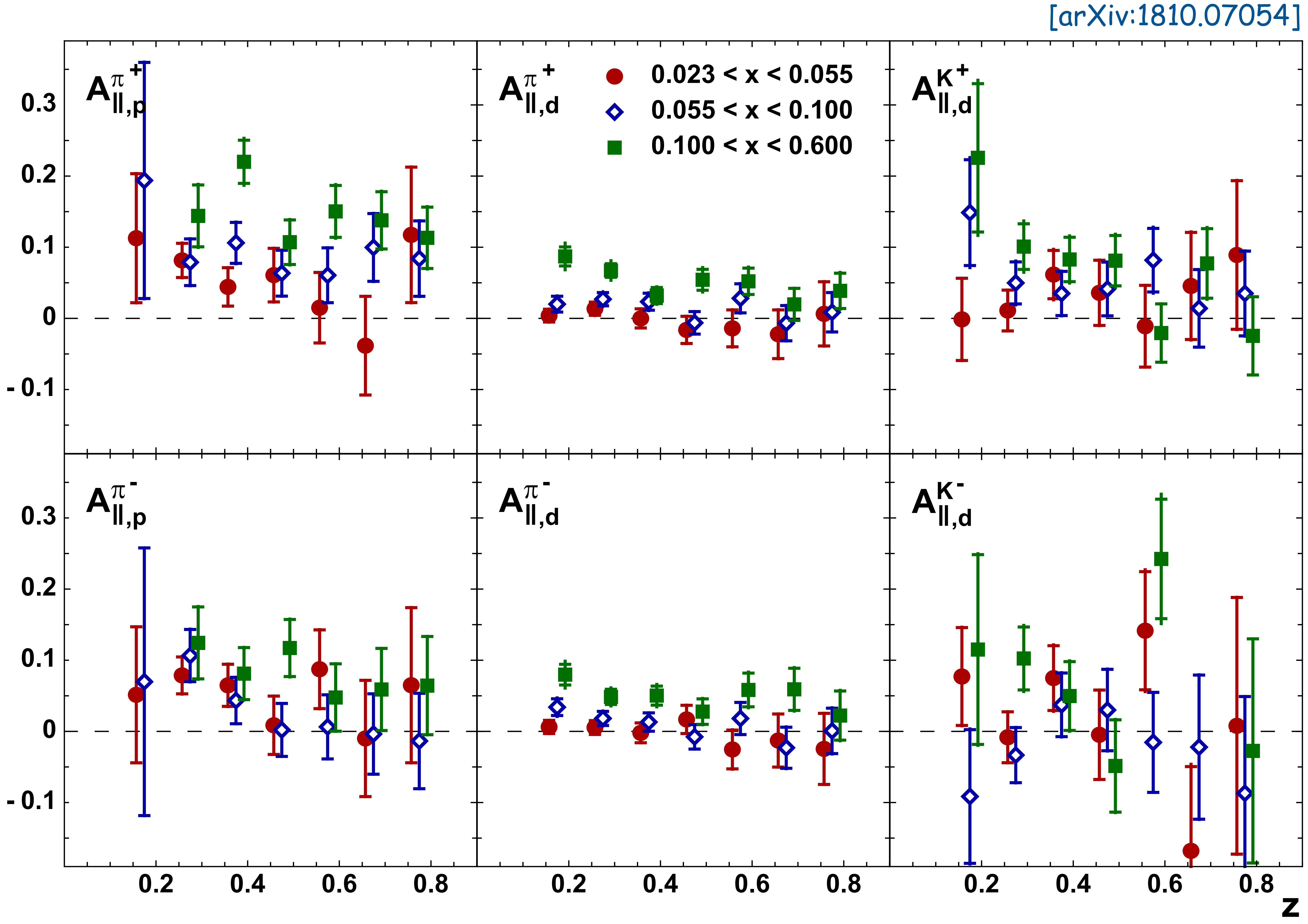
azimuthal acceptance

- both numerator and in particular denominator ϕ dependent
  - in theory integrated out
  - in praxis, detector acceptance also ϕ dependent
  - convolution of physics & acceptance leads to bias in normalization of asymmetries
- implement data-driven model for azimuthal modulations [PRD 87 (2013) 012010] into MC ☛ extract correction factor & apply to data

z dependence of $A_{||}$ (three x ranges)

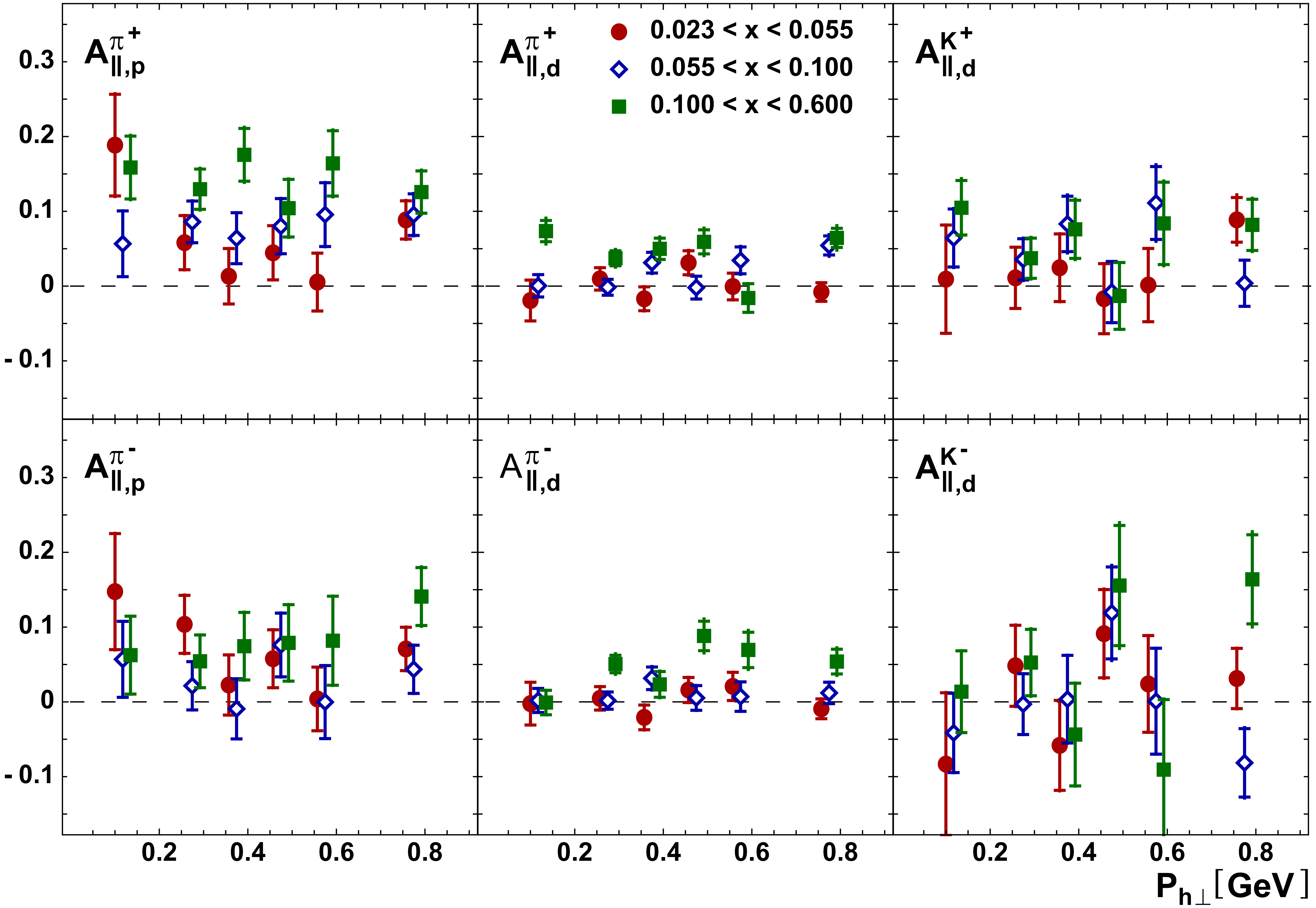
- in general, no strong z-dependence visible



$P_{h\perp}$ dependence of $A_{||}$ (three x ranges)

- no strong dependence (beyond on x)

[arXiv:1810.07054]



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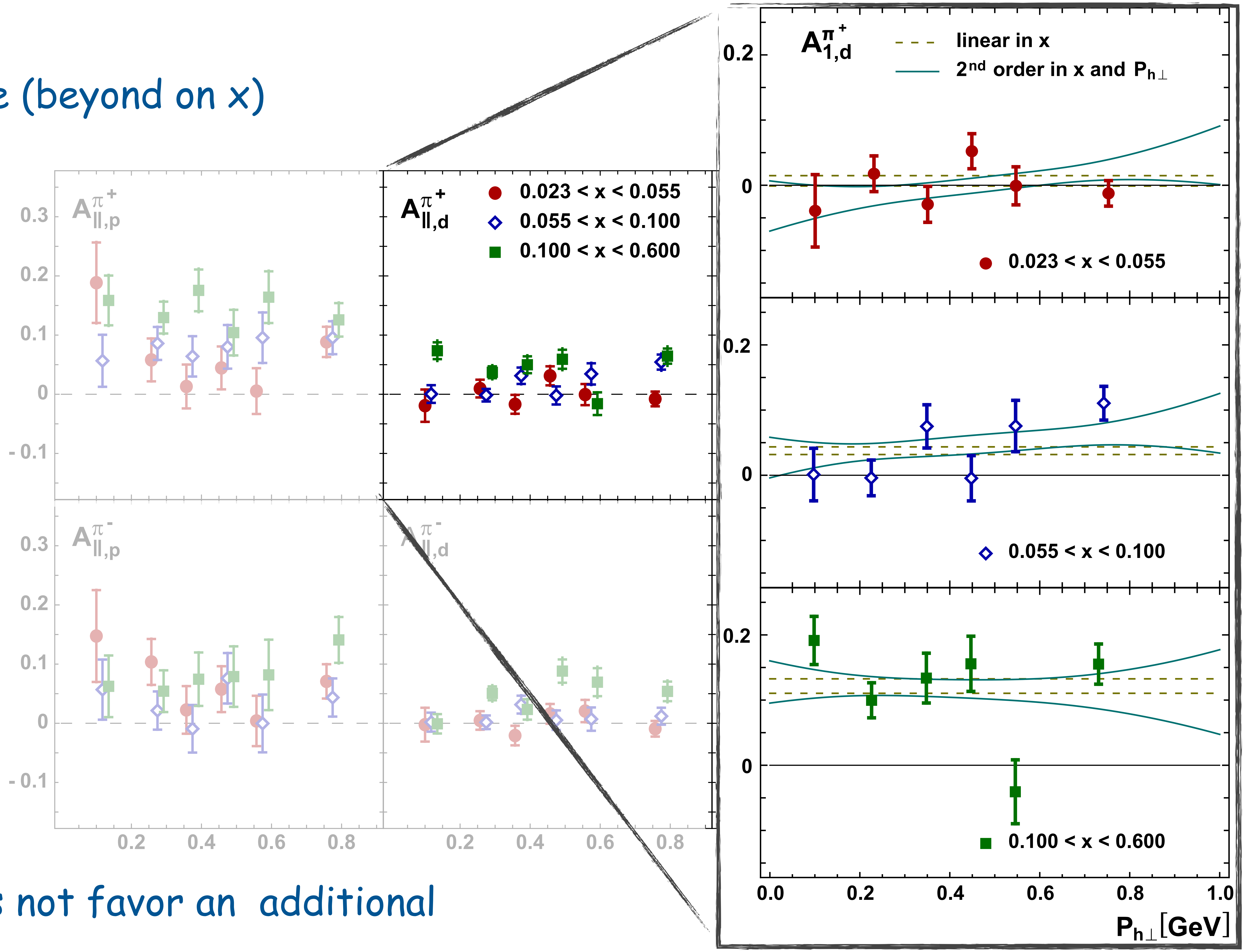

- also fit to A_1 fit does not favor an additional dependence on $P_{h\perp}$

hadron-charge difference asymmetries

$$A_1^{h^+-h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$

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- at leading-order and leading-twist, assuming charge conjugation symmetry for fragmentation functions:

$$A_{1,d}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{g_1^{u_v}+g_1^{d_v}}{f_1^{u_v}+f_1^{d_v}}$$

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- assuming also isospin symmetry in fragmentation:

$$A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

hadron-charge difference asymmetries

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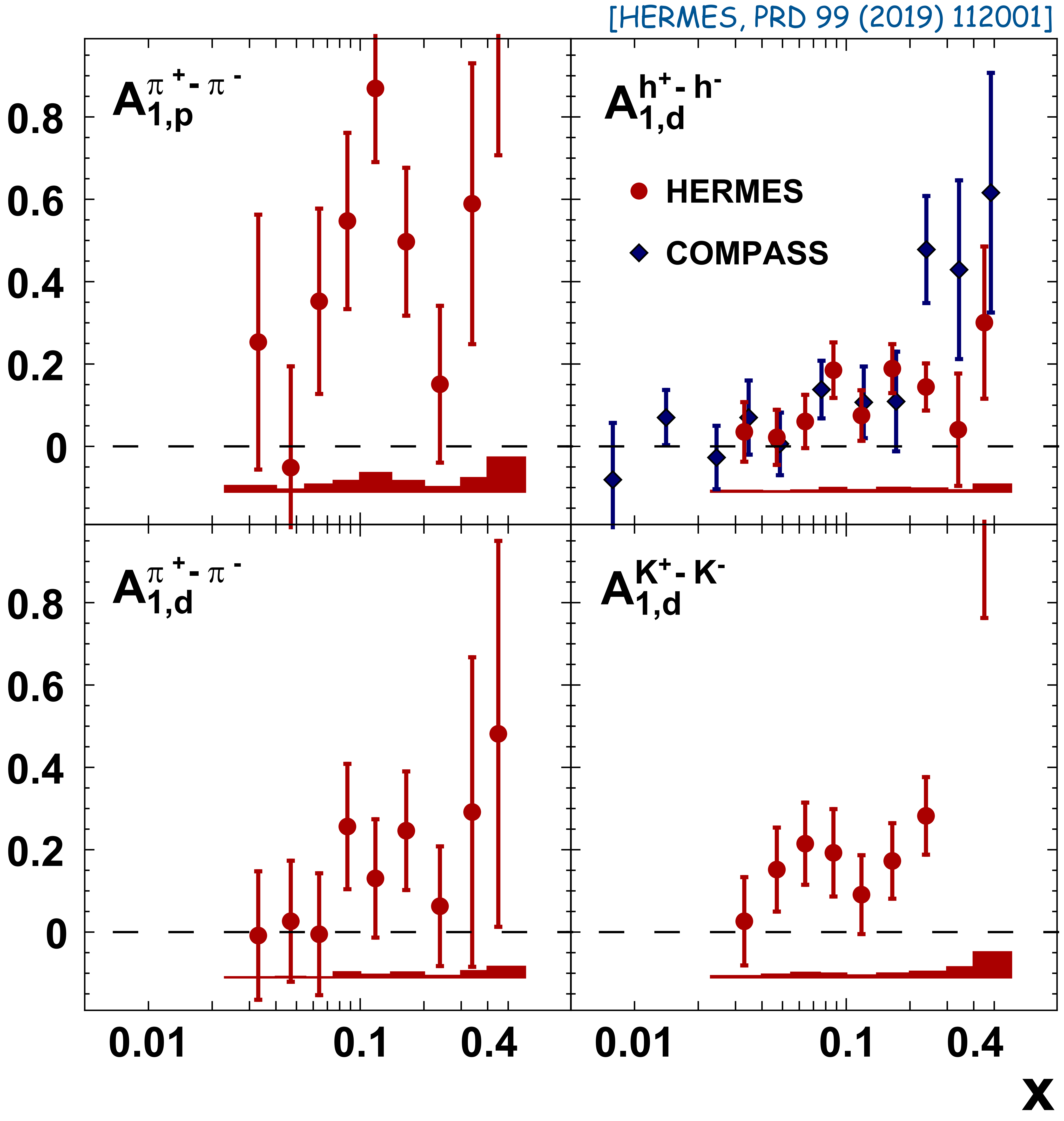
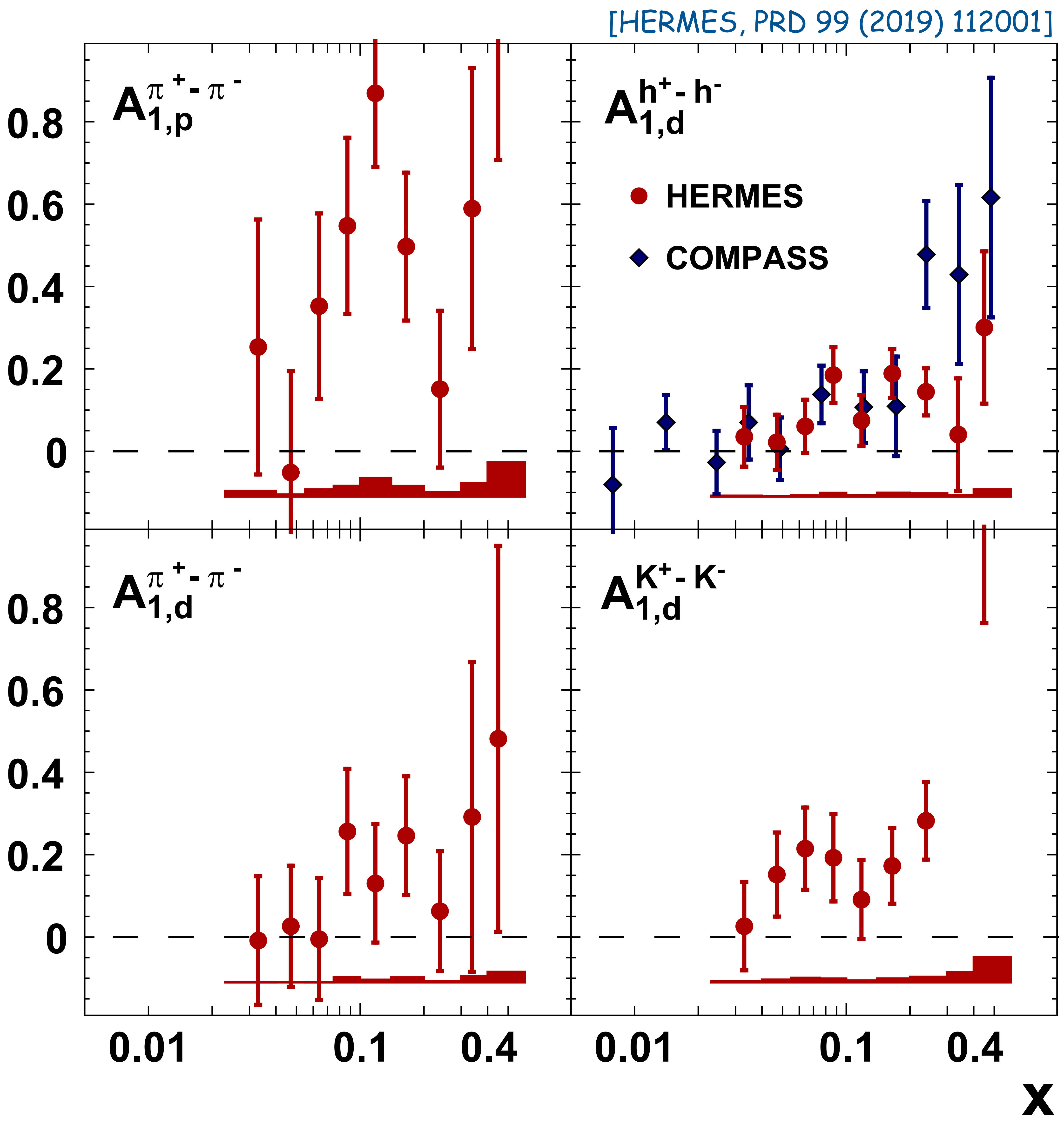
- can be used to extract valence helicity distributions

hadron-charge difference asymmetries

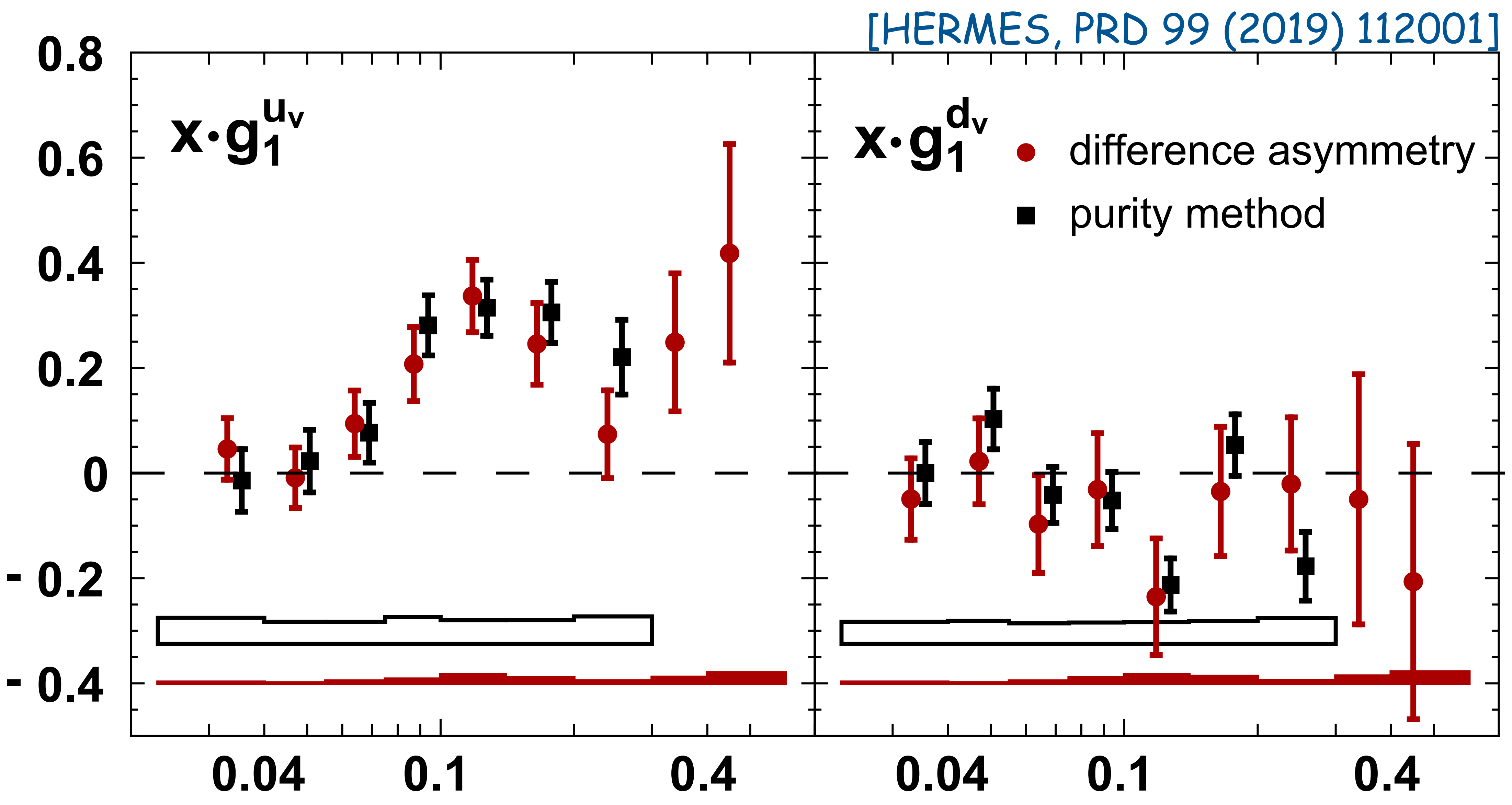


- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS

hadron-charge difference asymmetries

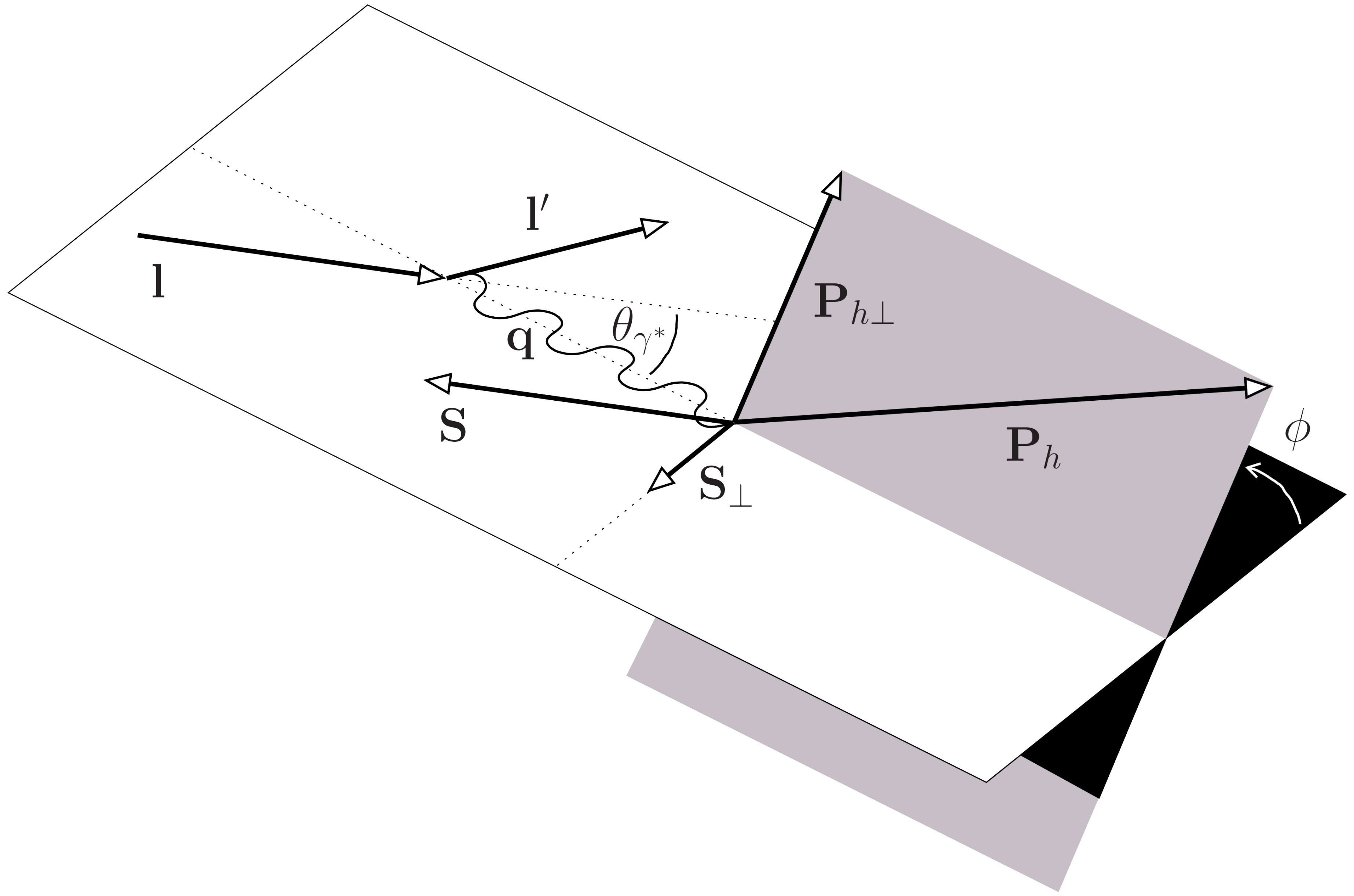


- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS
- valence distributions consistent with JETSET-based extraction:



semi-inclusive DIS

- excluding transverse polarization:



$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi\ \Big\}$$

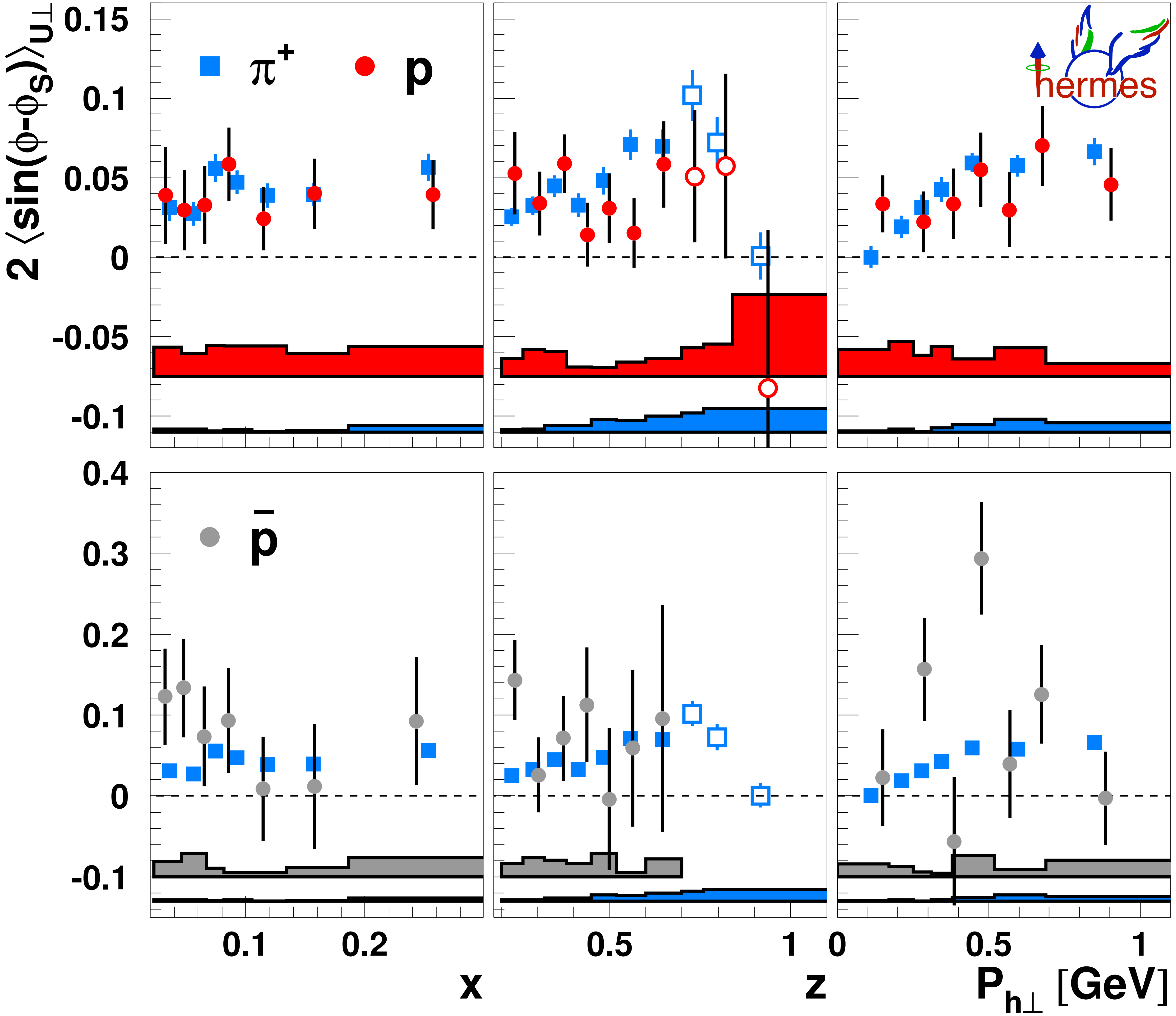
$$F_{XY}^{h,\mathrm{mod}} = F_{XY}^{h,\mathrm{mod}}(x, Q^2, z, P_{h\perp})$$

Beam (λ) / Target (Λ)

helicities

	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. (anti)protons

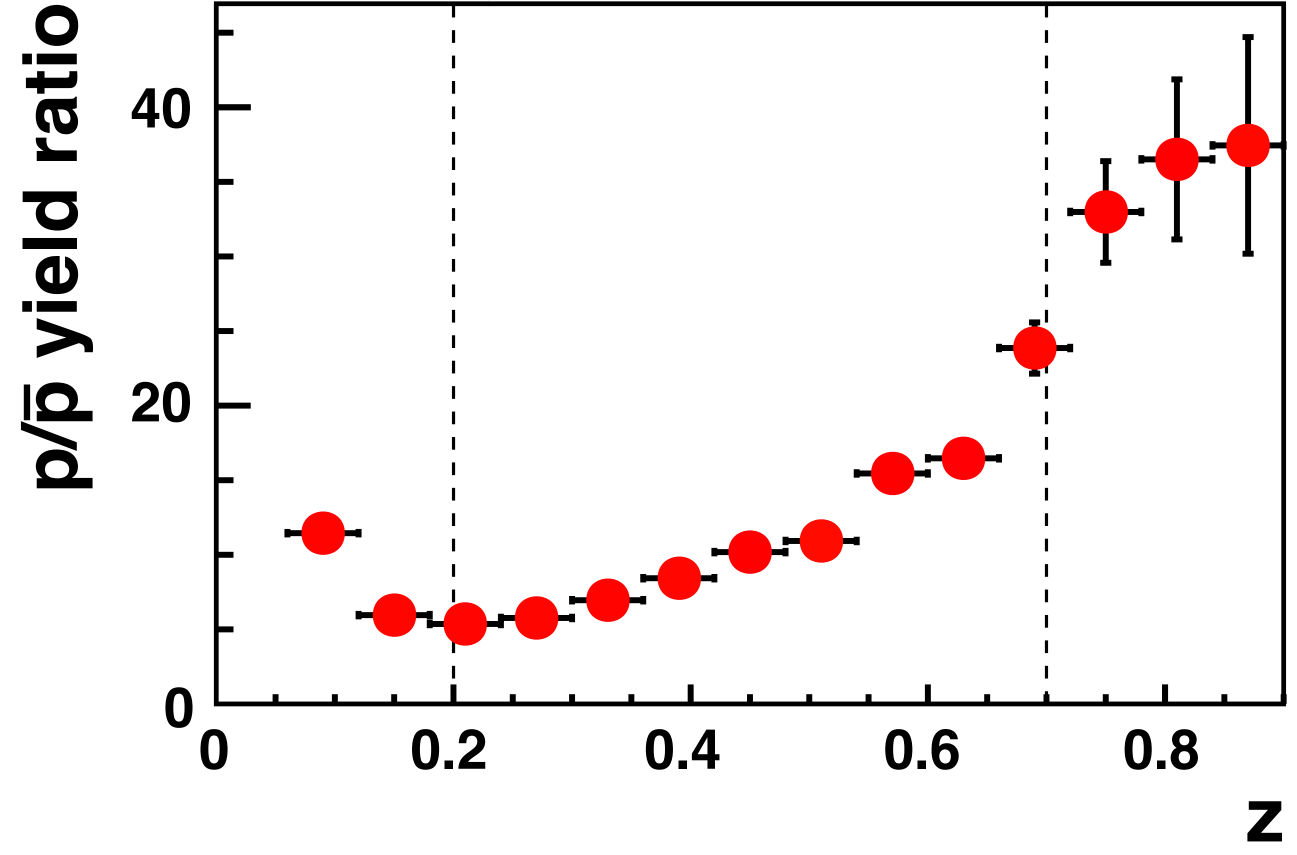


[A. Airapetian et al., JHEP12(2020)010]

similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

[A. Airapetian et al., JHEP12(2020)010]



possibly, onset of target fragmentation only at lower z

	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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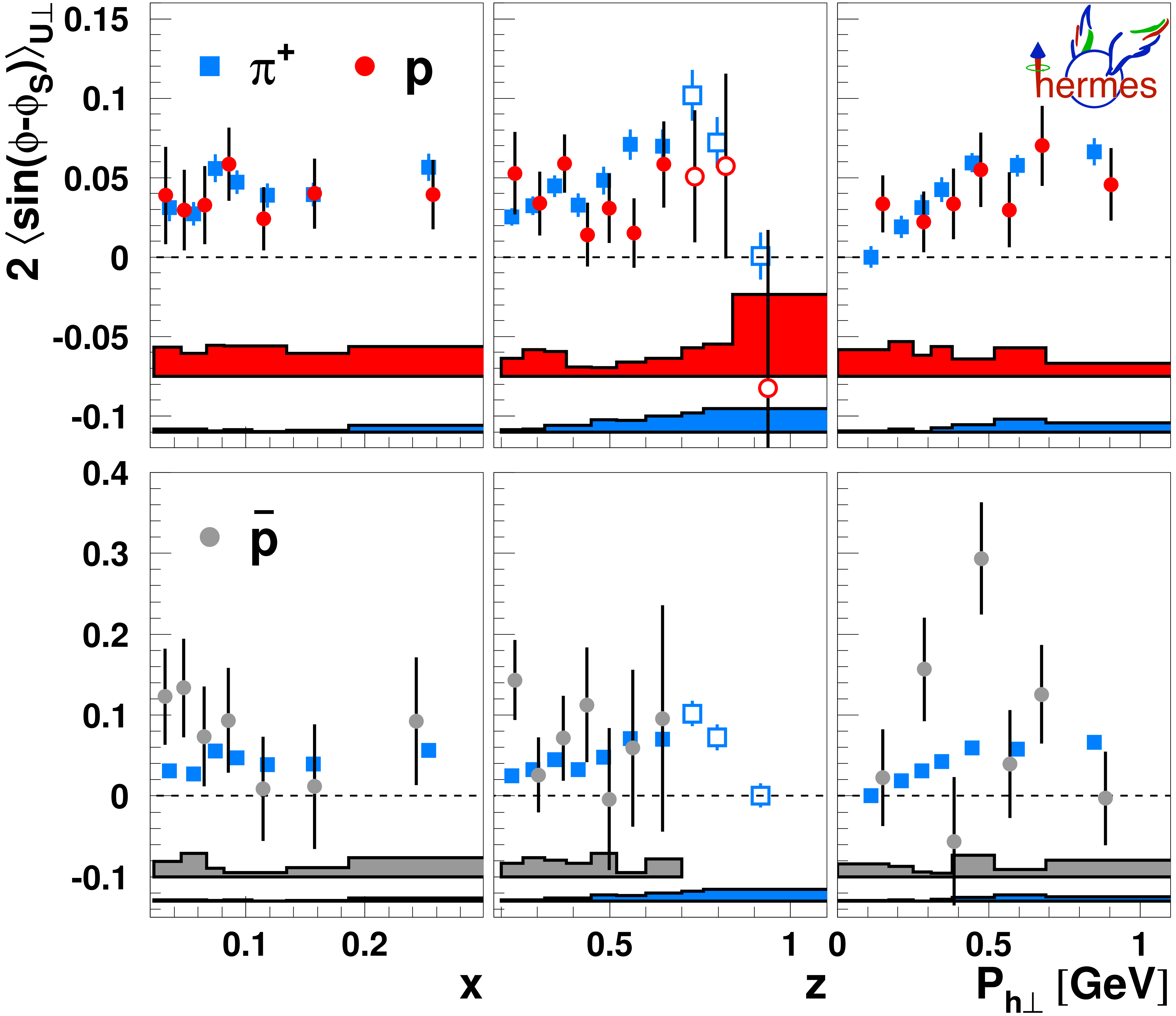

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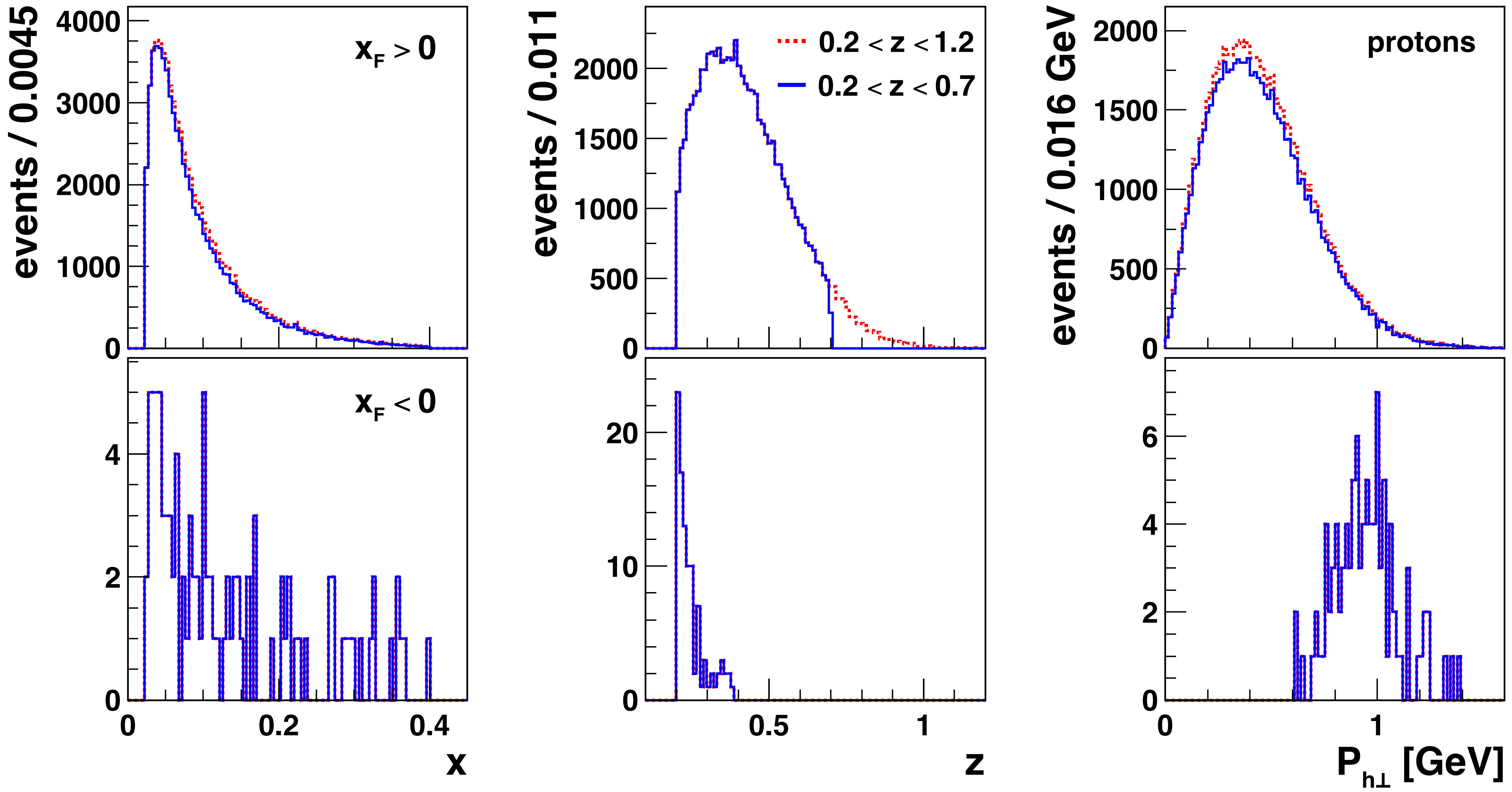

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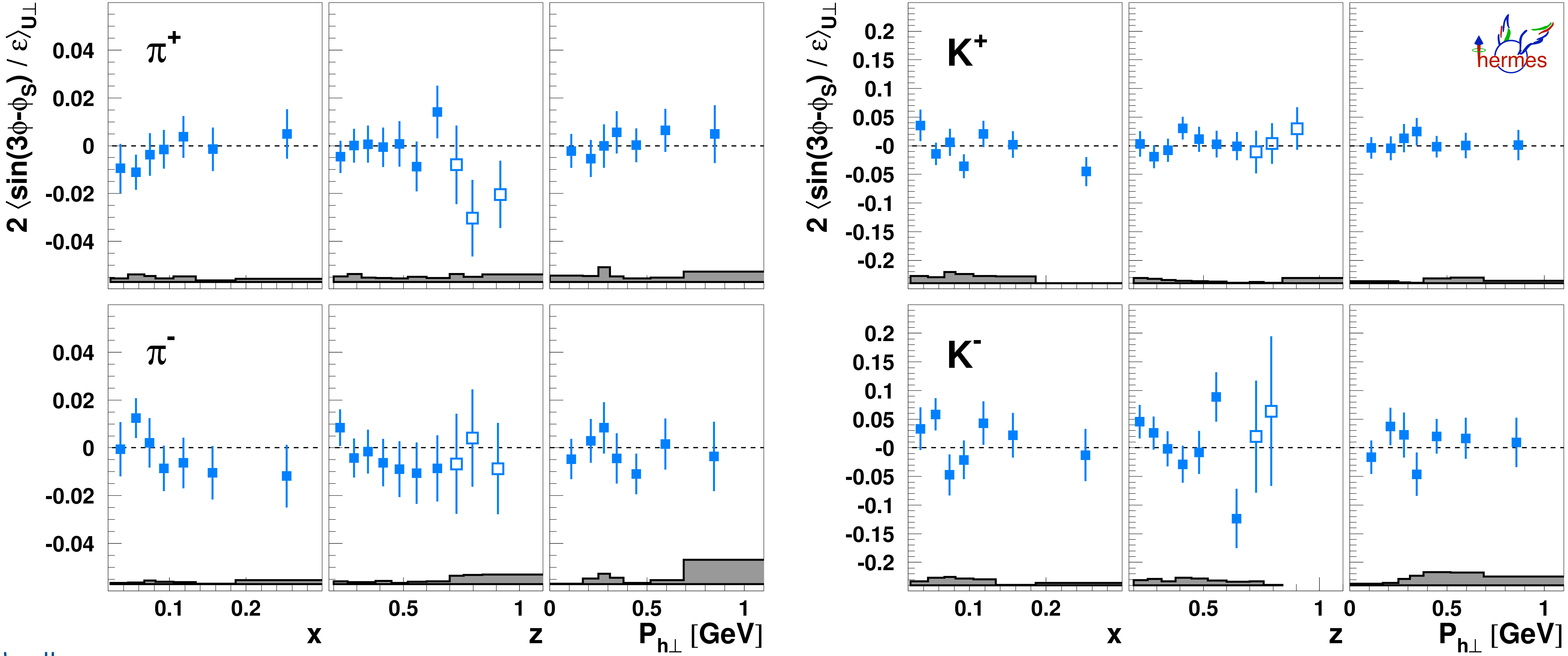
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Pretzelosity

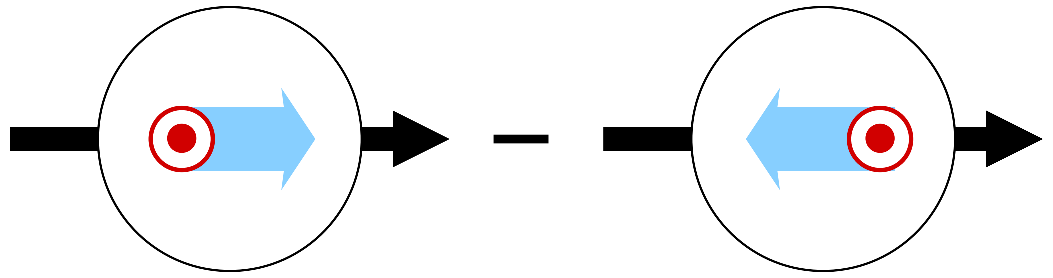
- chiral-odd ➥ needs Collins FF (or similar)
- ^{1}H, ^{2}H & ^{3}He data consistently small
- cancelations? pretzelosity=zero? or just the additional suppression by two powers of $P_{h\perp}$

[A. Airapetian et al., JHEP12(2020)010]

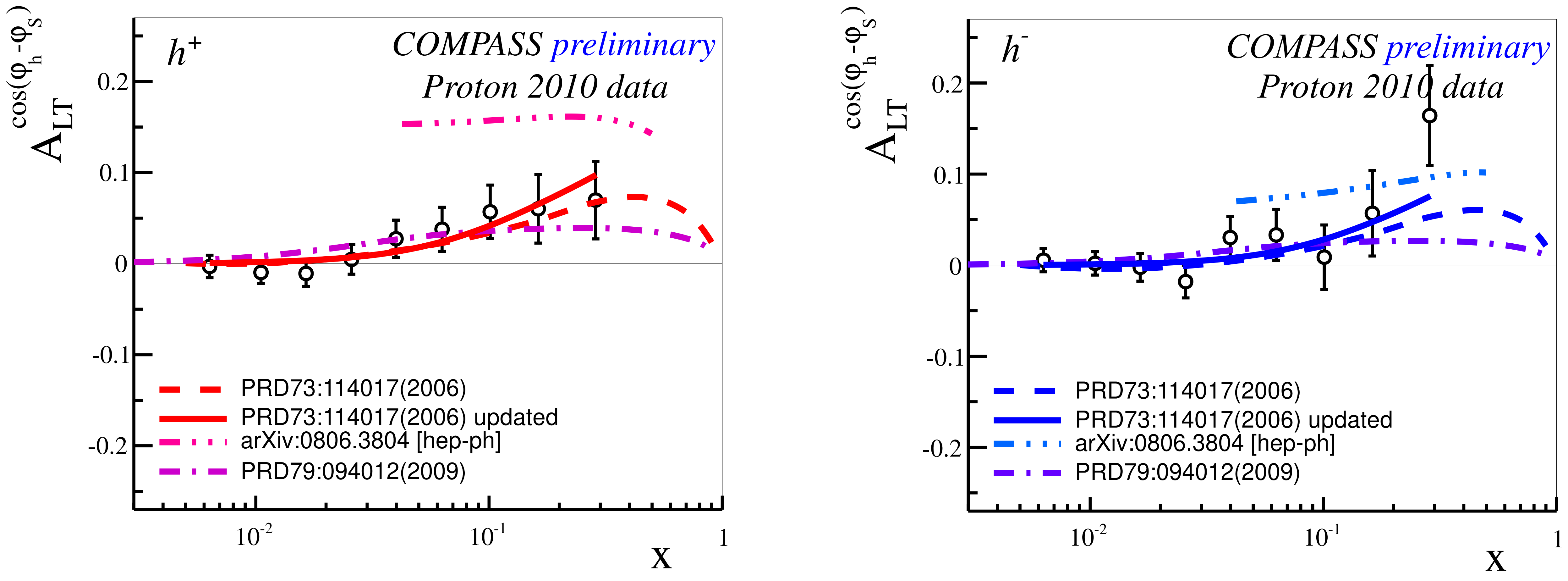


Worm-Gear II

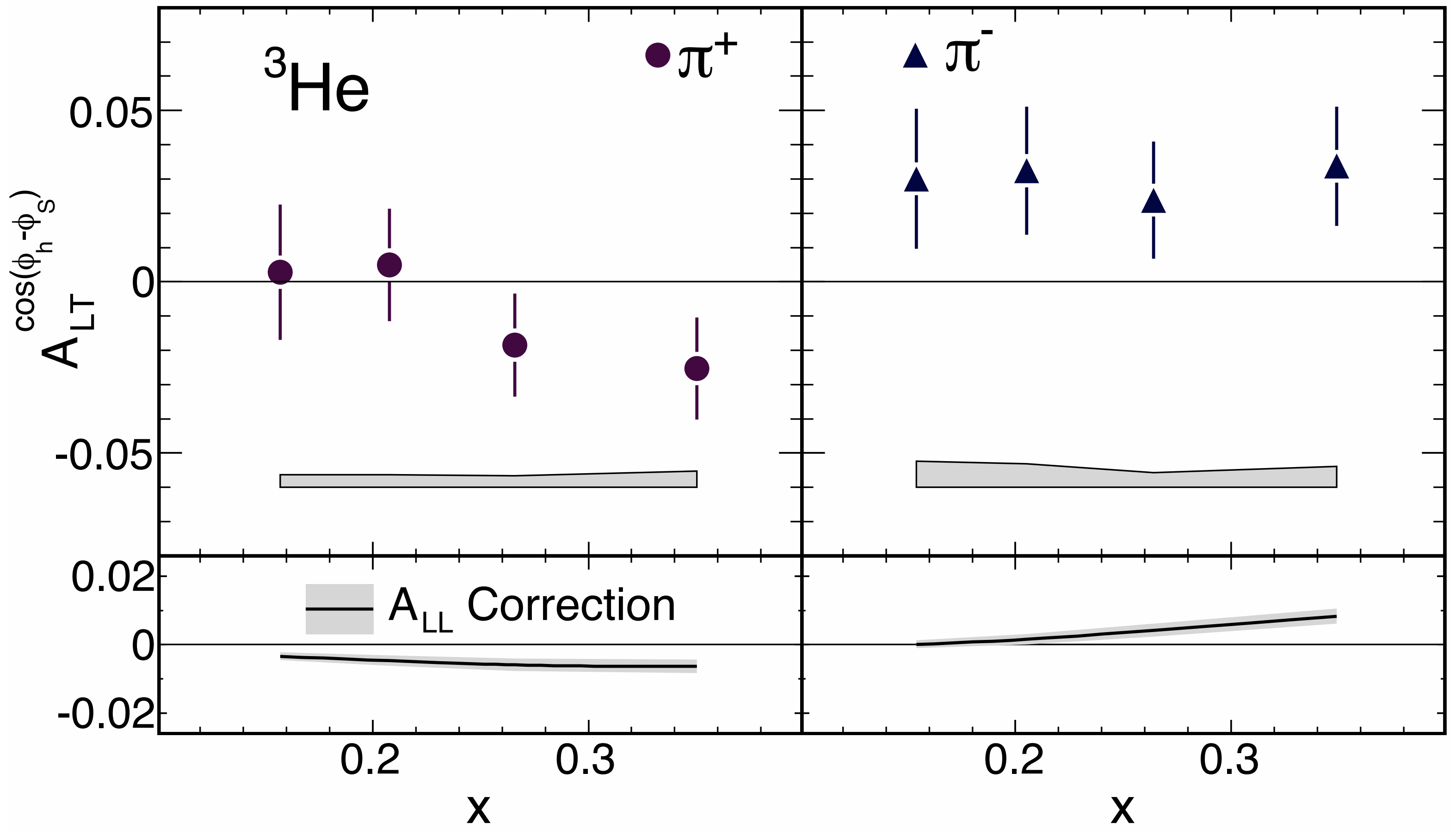
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



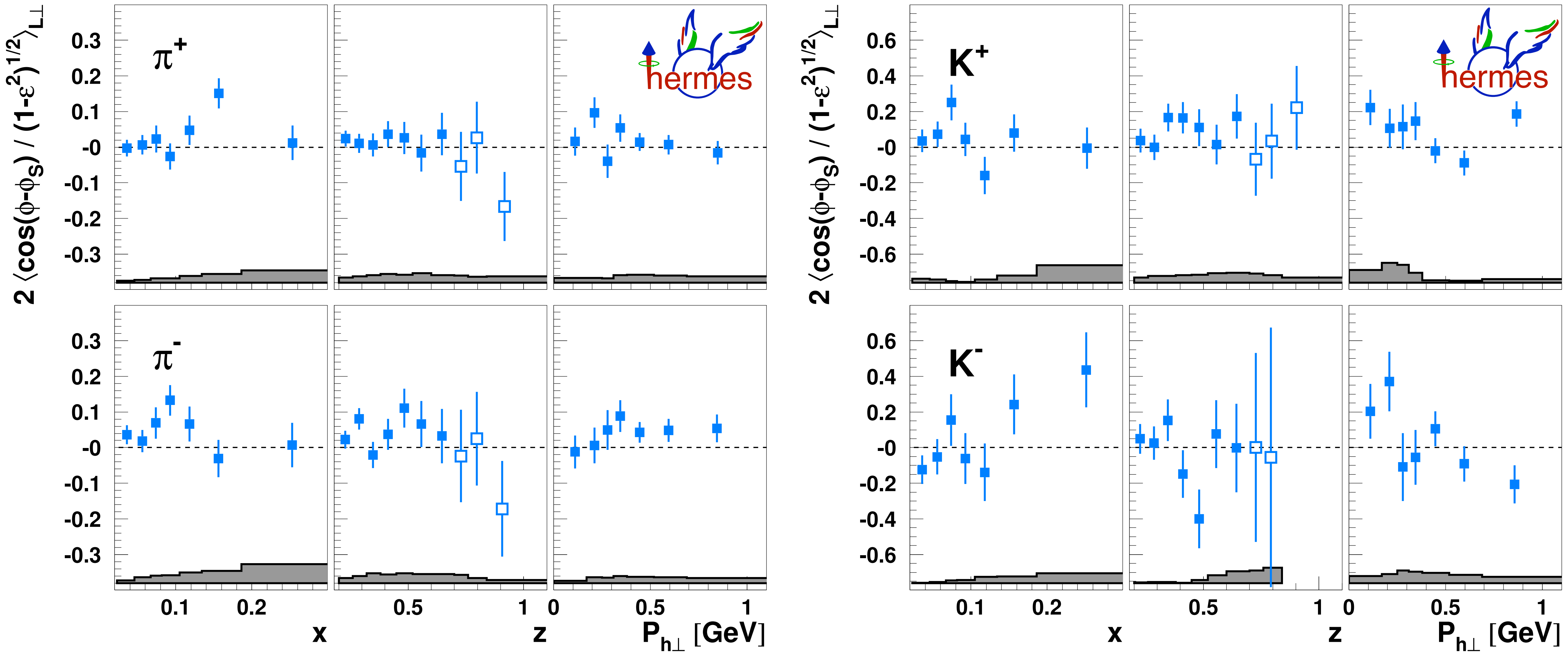
- chiral even, couples to D_1
- evidences from
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES



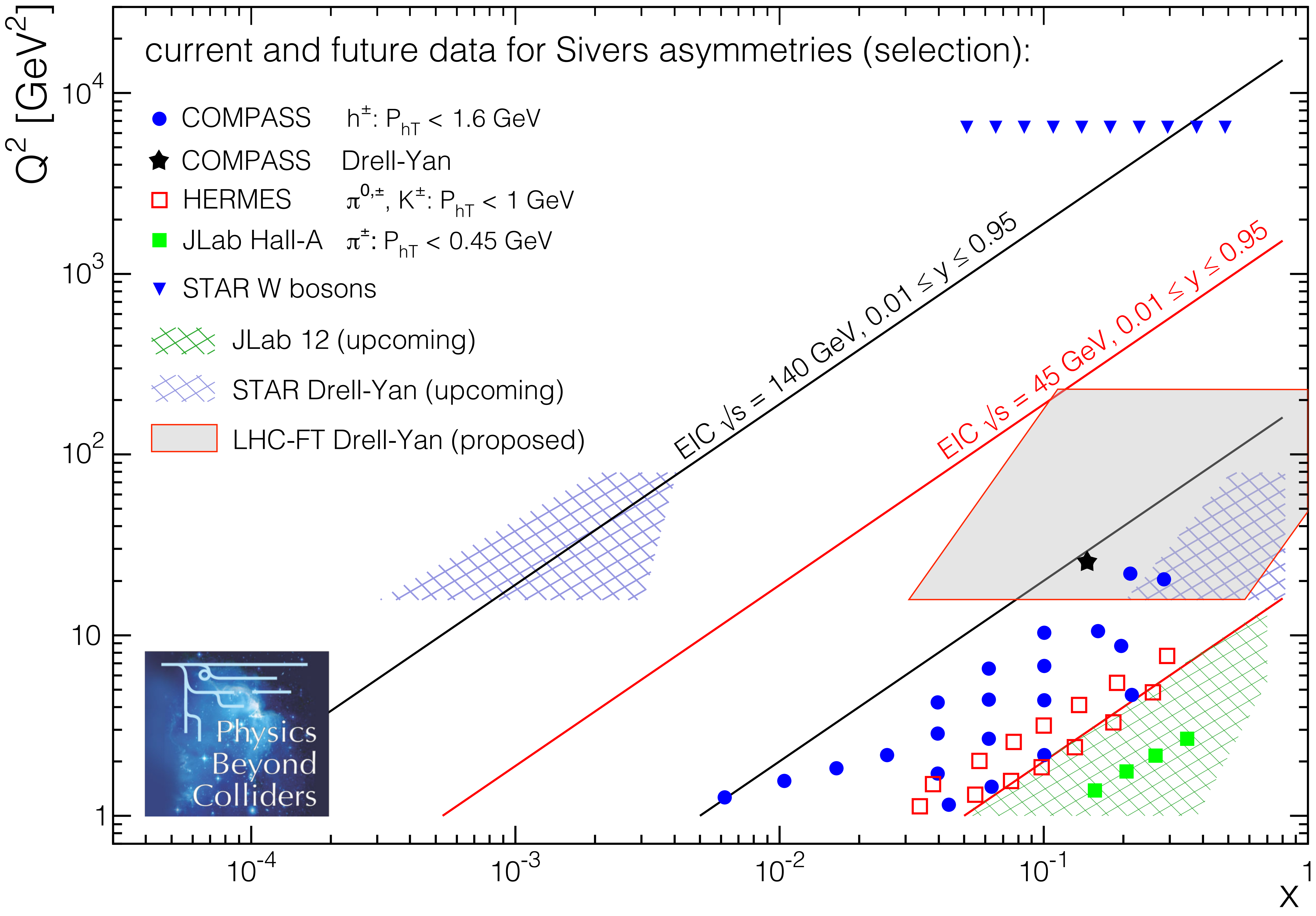
[PRL 108 (2012) 052001]



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



2d kinematic phase space



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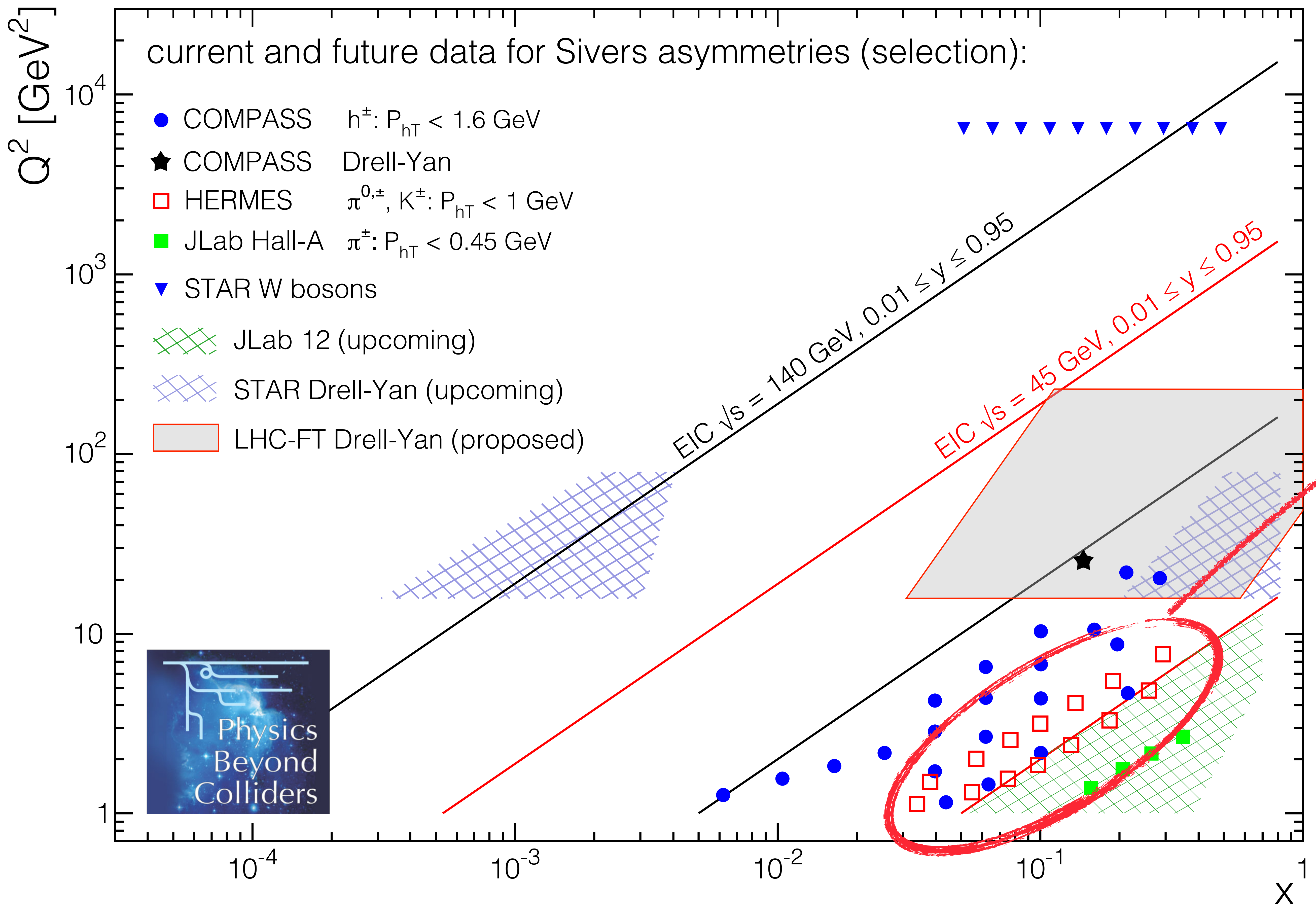
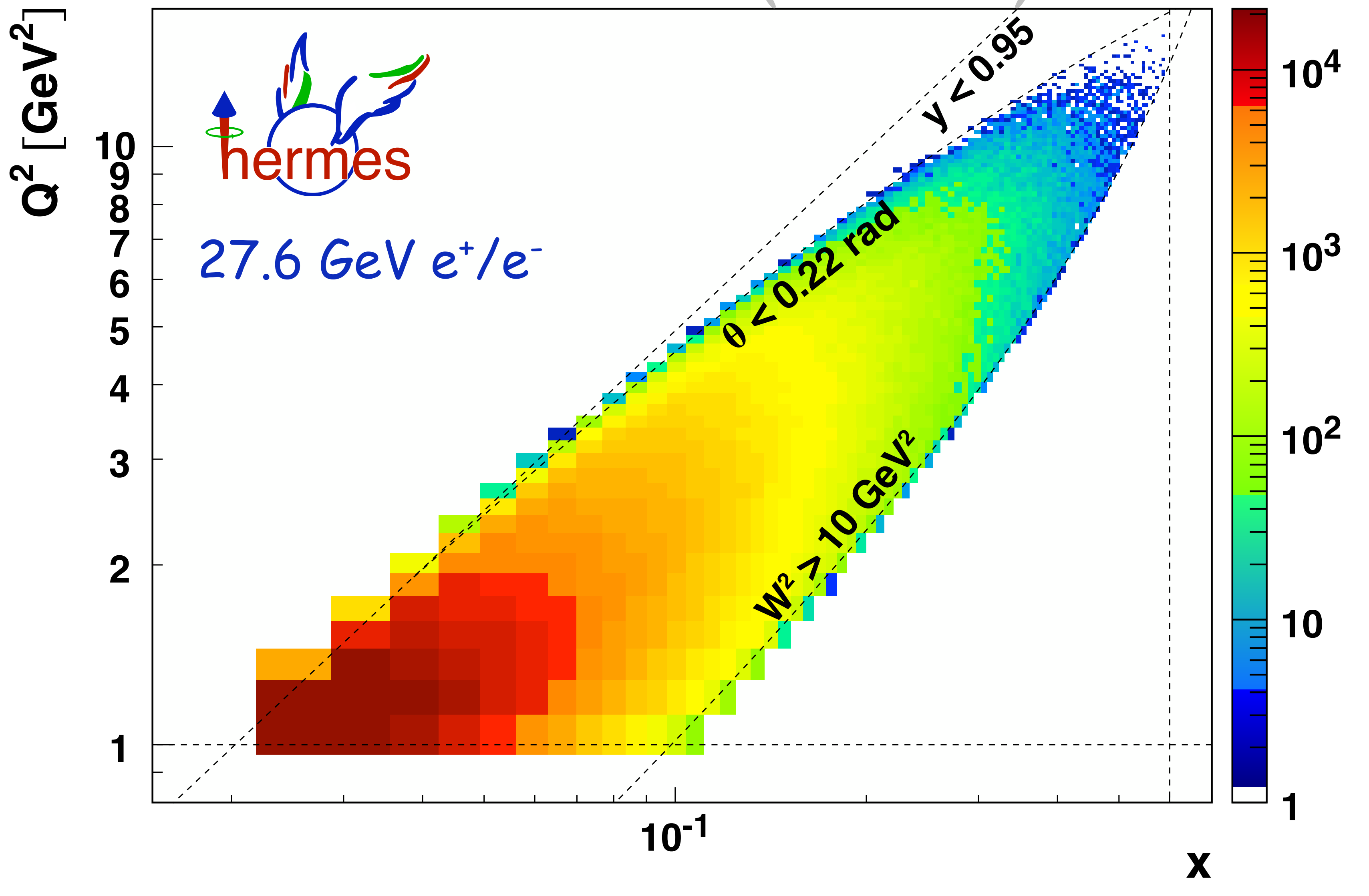
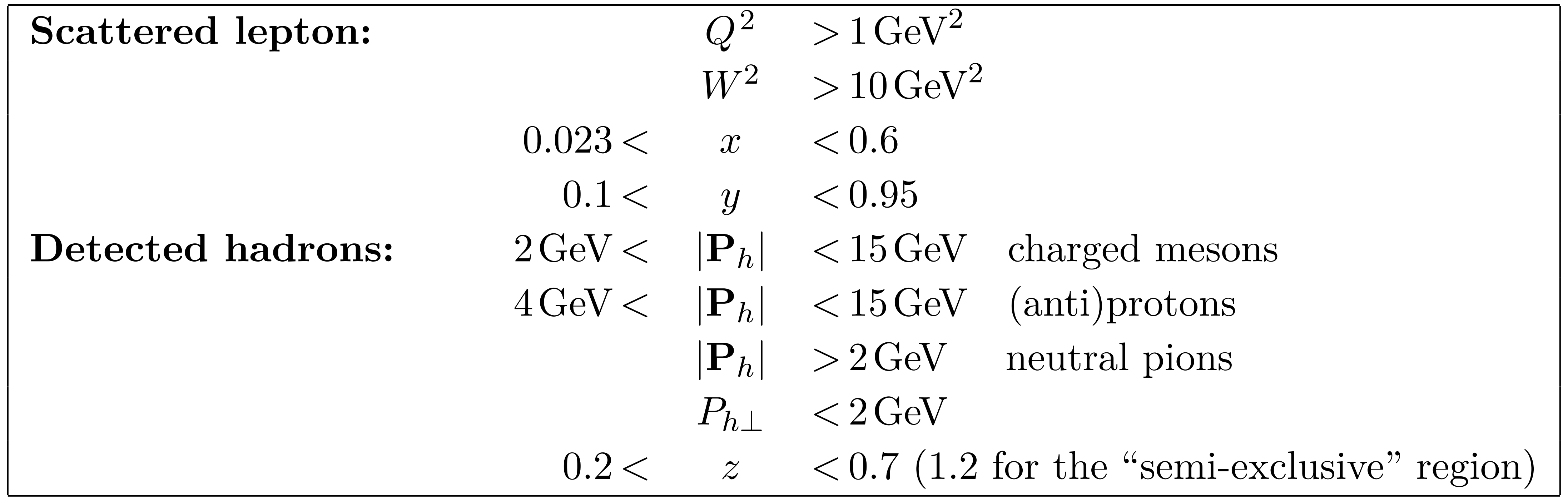


JHEP12(2020)010

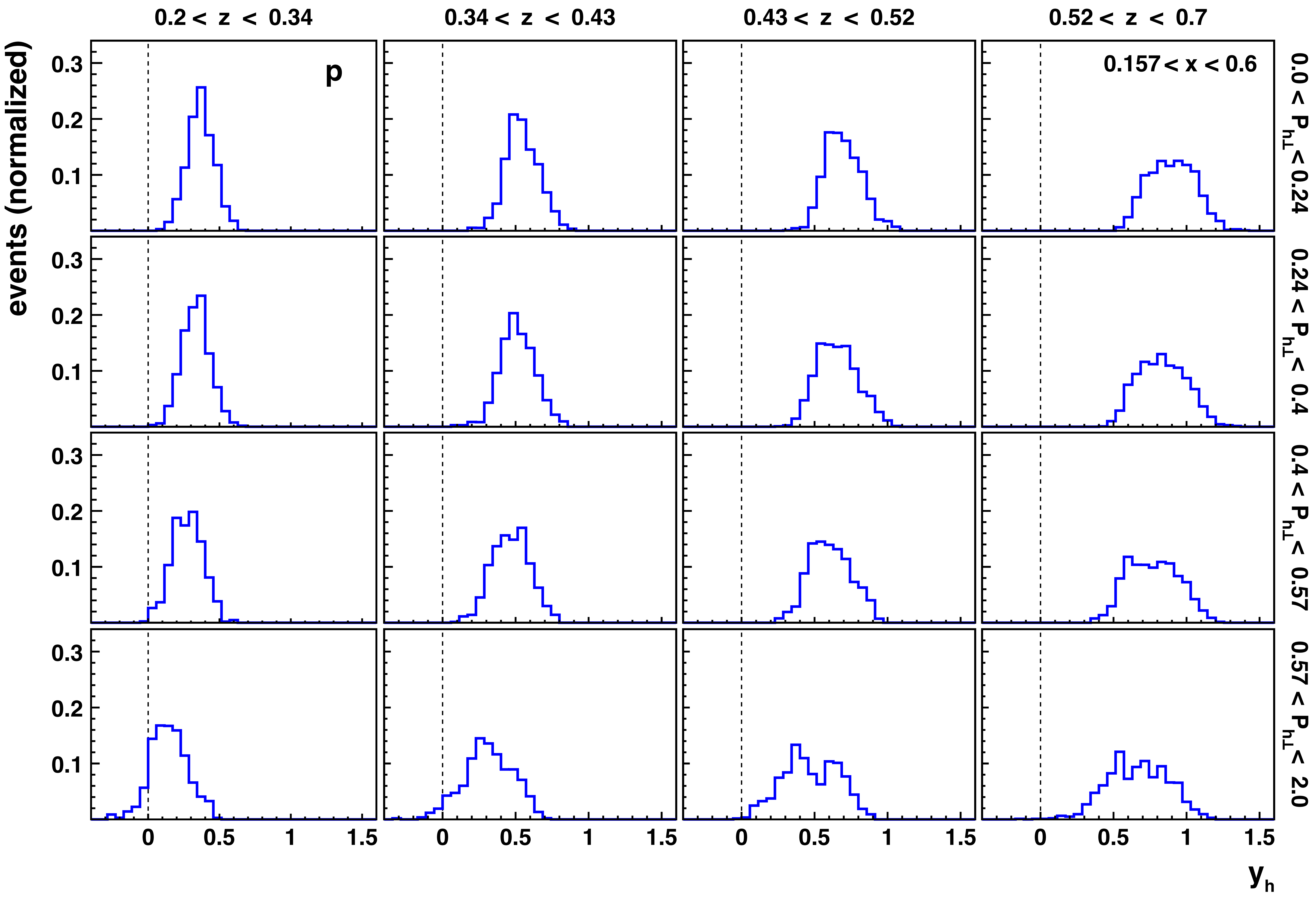




Scattered lepton:		Q^2	$> 1\,\mathrm{GeV}^2$	
		W^2	$> 10\,\mathrm{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	charged mesons
	$4\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\mathrm{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\mathrm{GeV}$	
	$0.2 <$	z	< 0.7 (1.2 for the “semi-exclusive” region)	

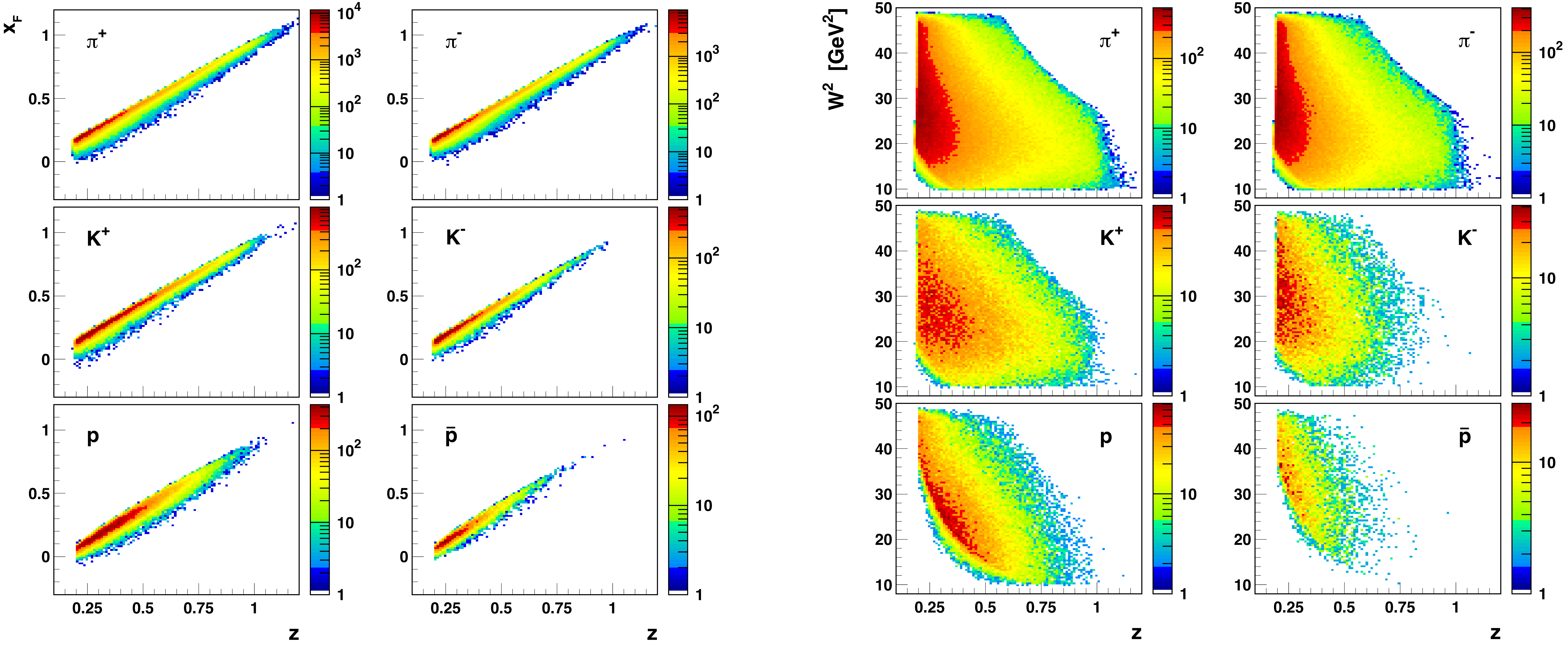
Table 3. Restrictions on selected kinematics variables. The upper limit on z of 1.2 applies only to the analysis of the z dependence.

hadron production at HERMES



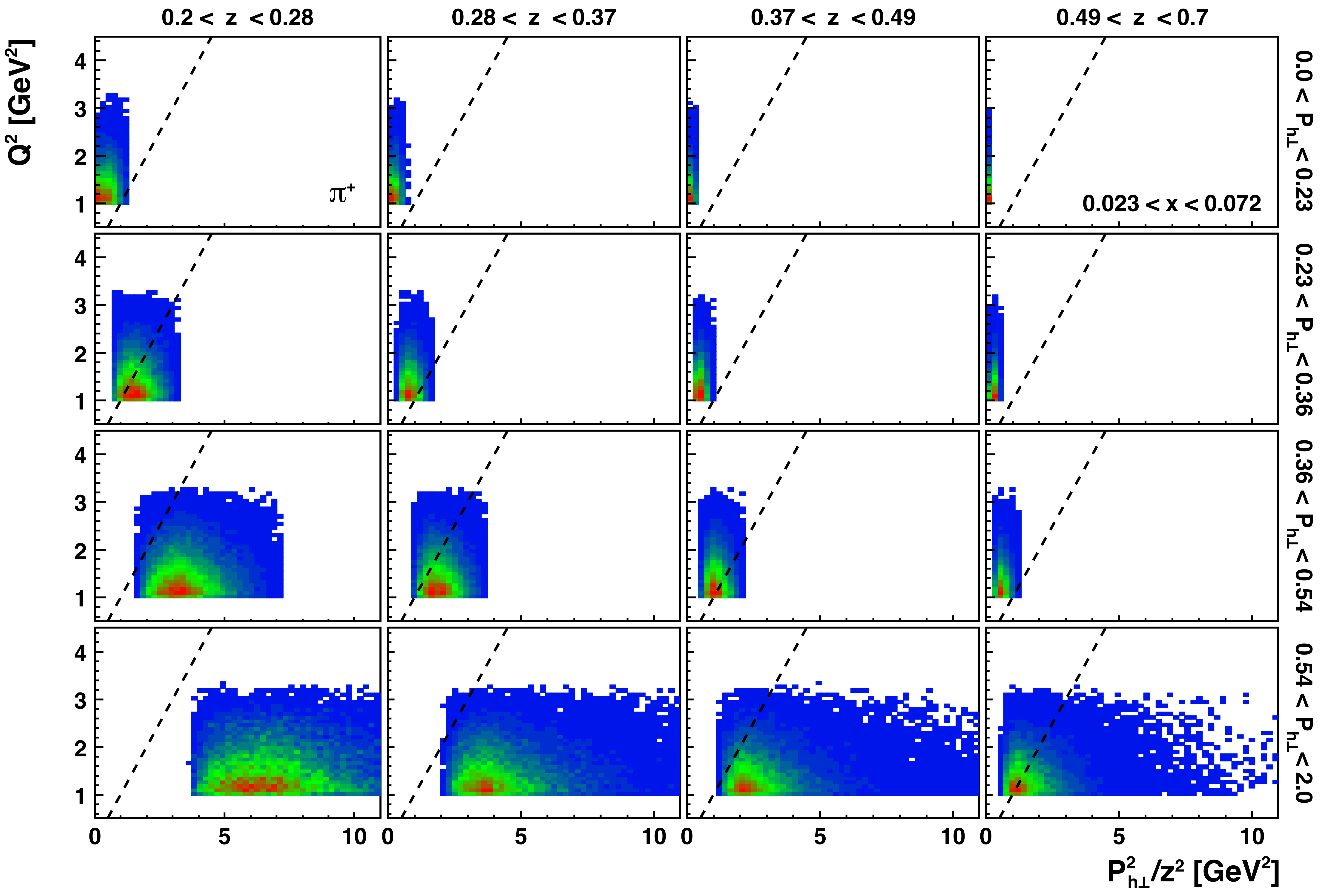
- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]
- rapidity distributions available for all kinematic bins (e.g., highest-x bin protons)

current vs. target fragmentation



TMD factorization: a 2-scale problem

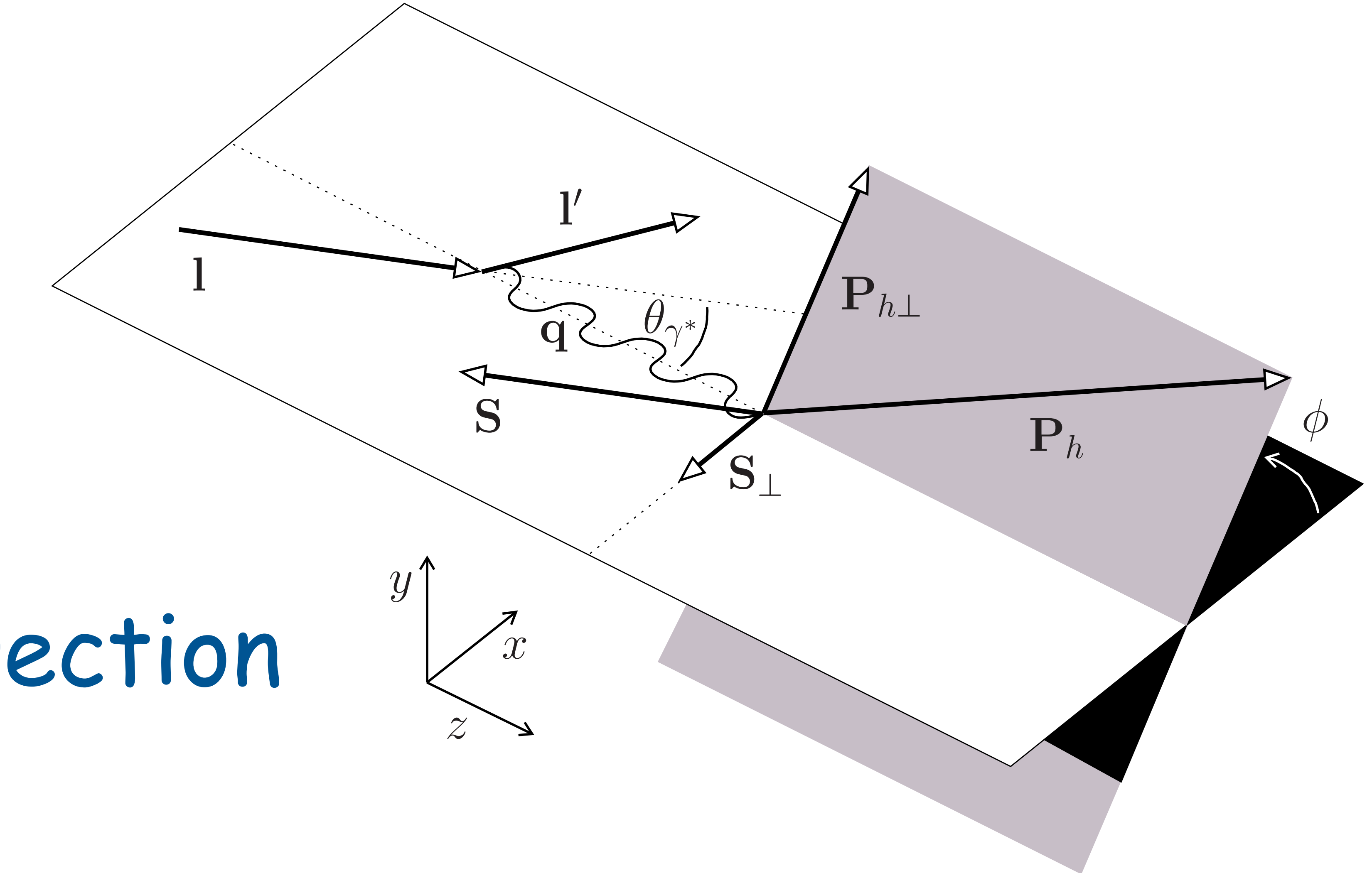
lowest x bin



- - - $Q^2 = P^2_{h\perp}/z^2$

all other x-bins included in the Supplemental Material of JHEP12(2020)010

Mixing of target polarizations



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

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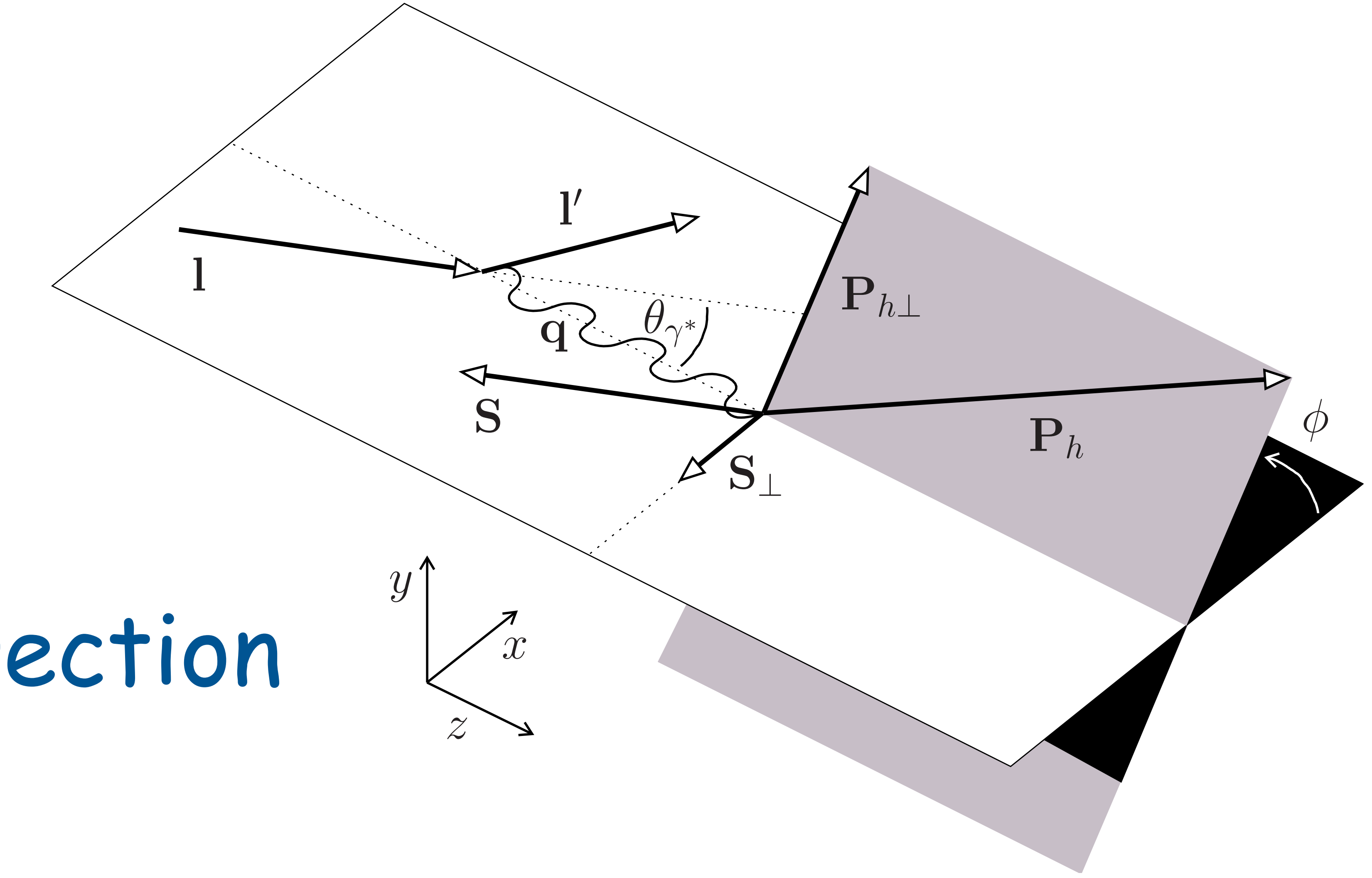

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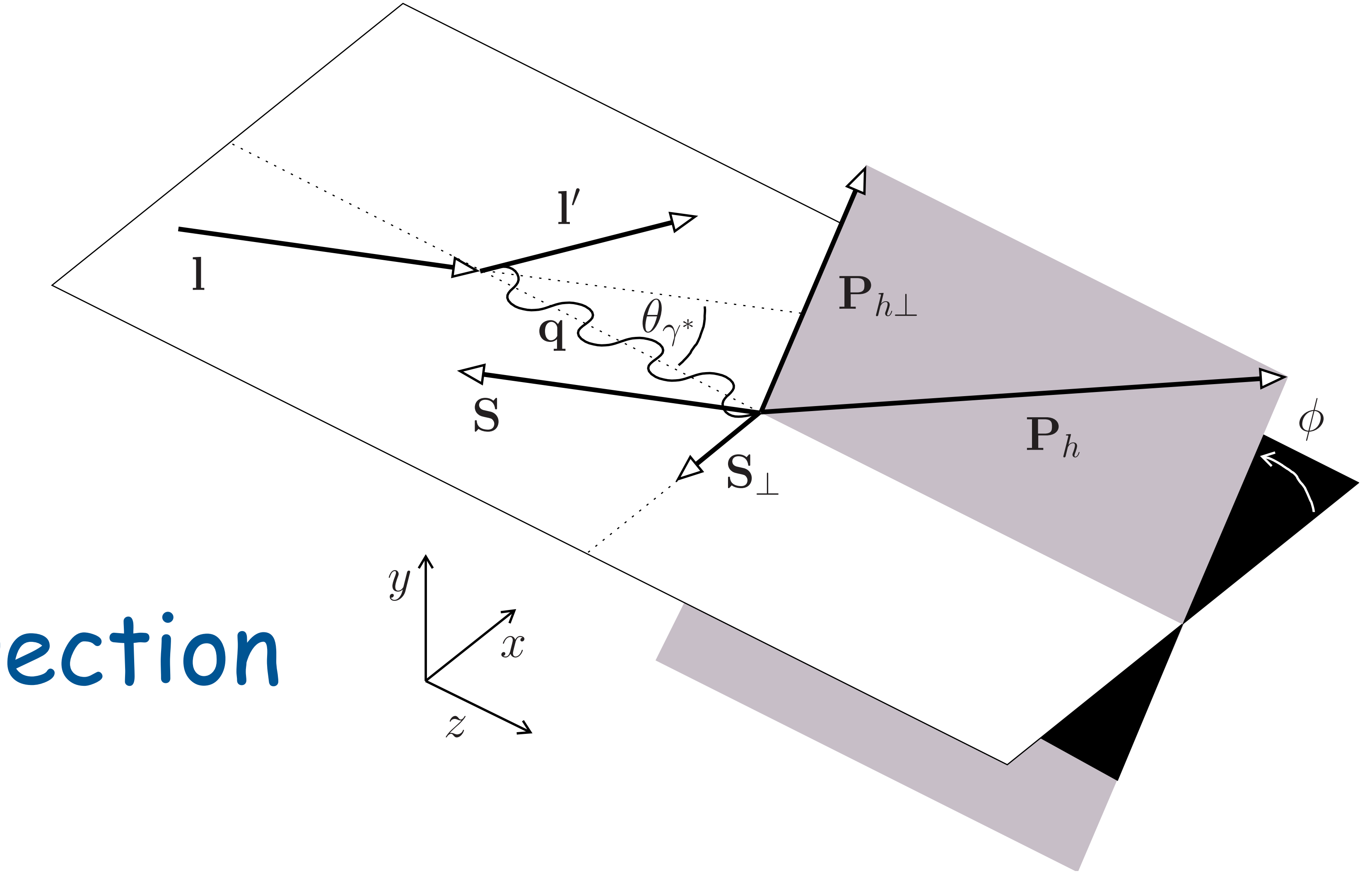
➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

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

Mixing of target polarizations



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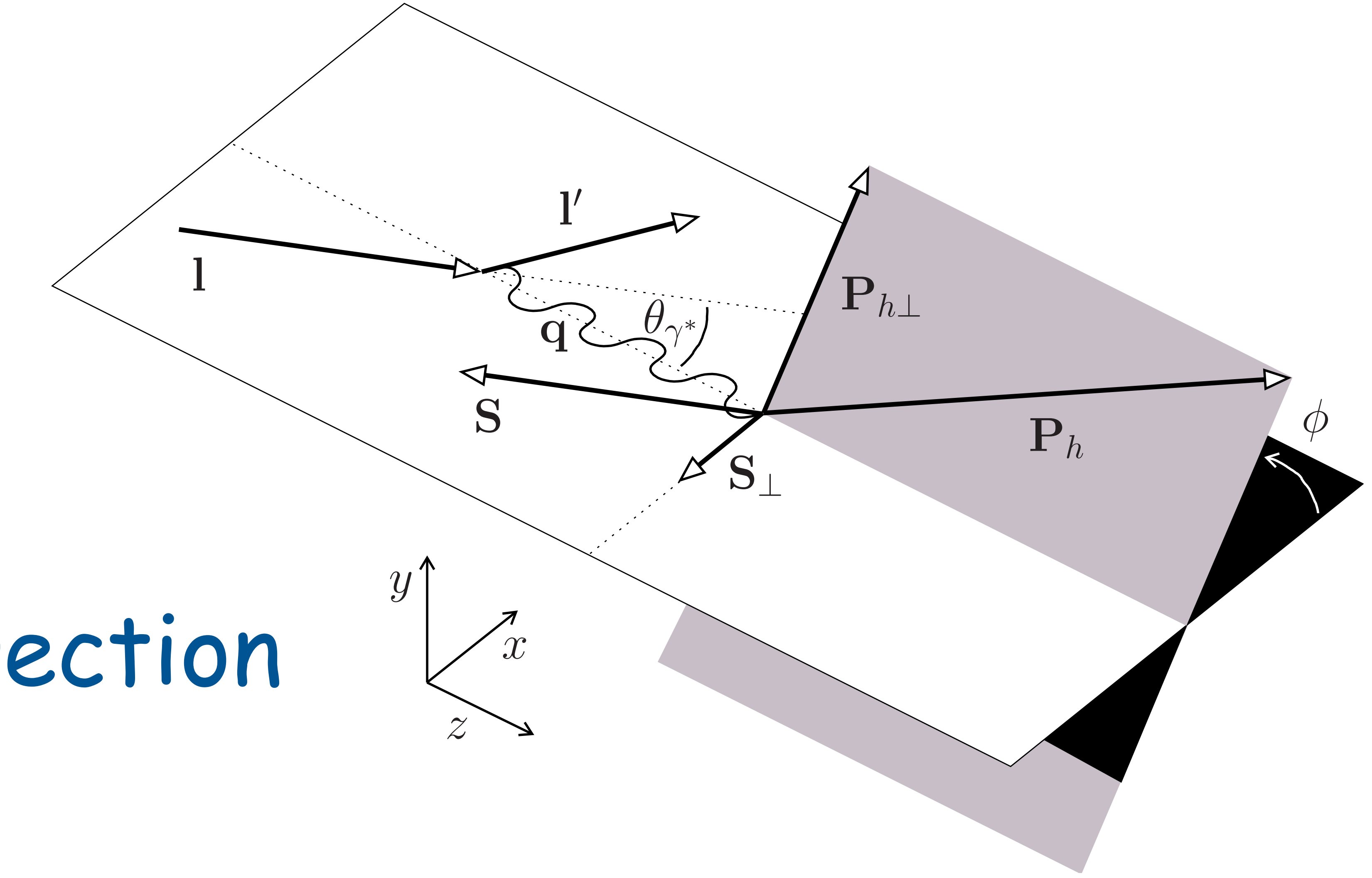
➡ need data on same target for both polarization orientations!

Mixing of target polarizations



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