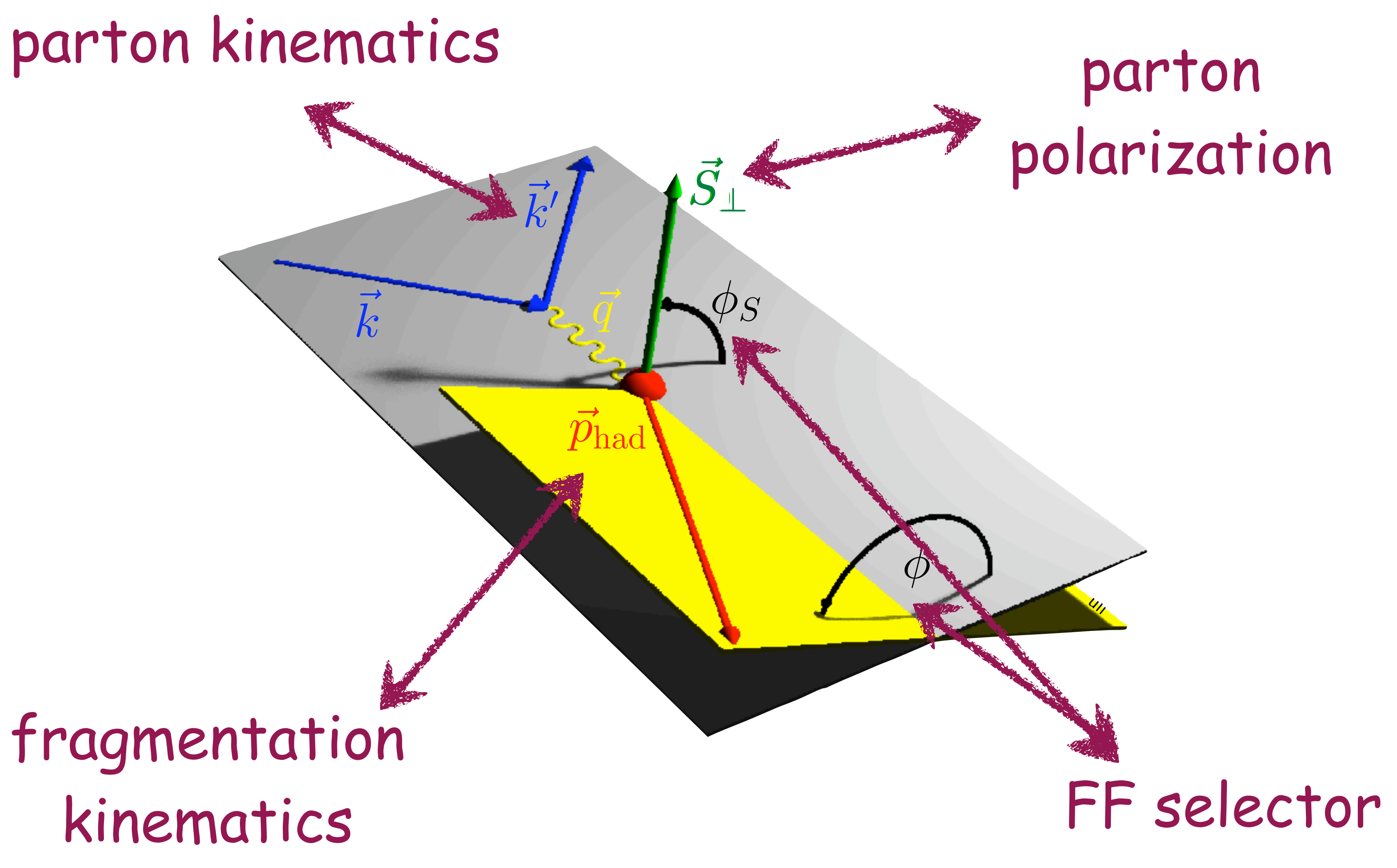


Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

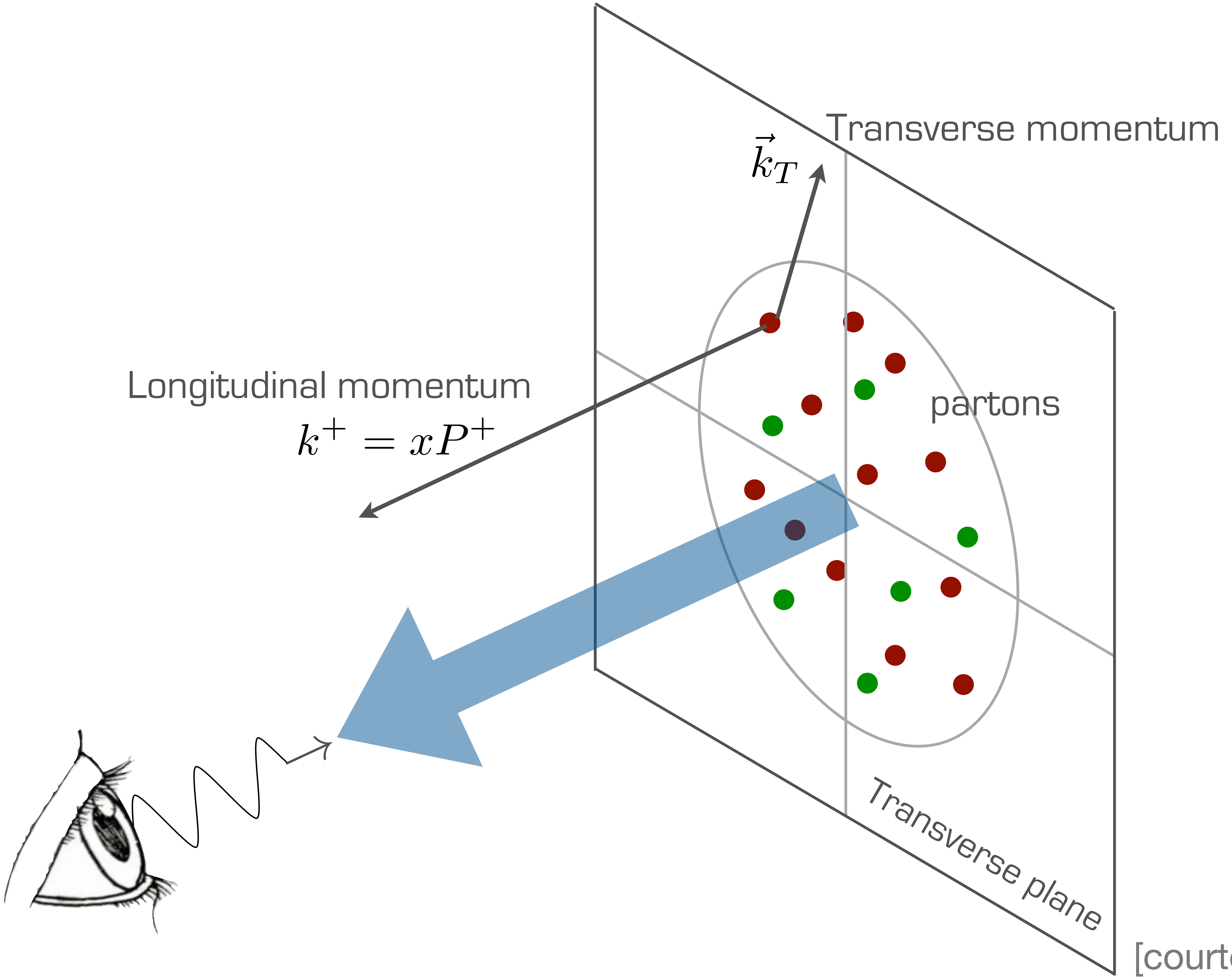
On behalf of the hermes Collaboration

Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Transverse-momentum distributions (TMDs)



[courtesy of A. Bacchetta, Pavia]

Spin-momentum structure of the nucleon

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

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\frac{1}{m}\,h_1^\perp + s^iS^ih_1$$
$$+ s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\frac{1}{m}\,h_{1L}^\perp\Big]$$

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
- last row those accessible with transverse target polarization

Spin-momentum structure of the nucleon

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

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

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

helicity

Boer-Mulders

Sivers

worm-gear

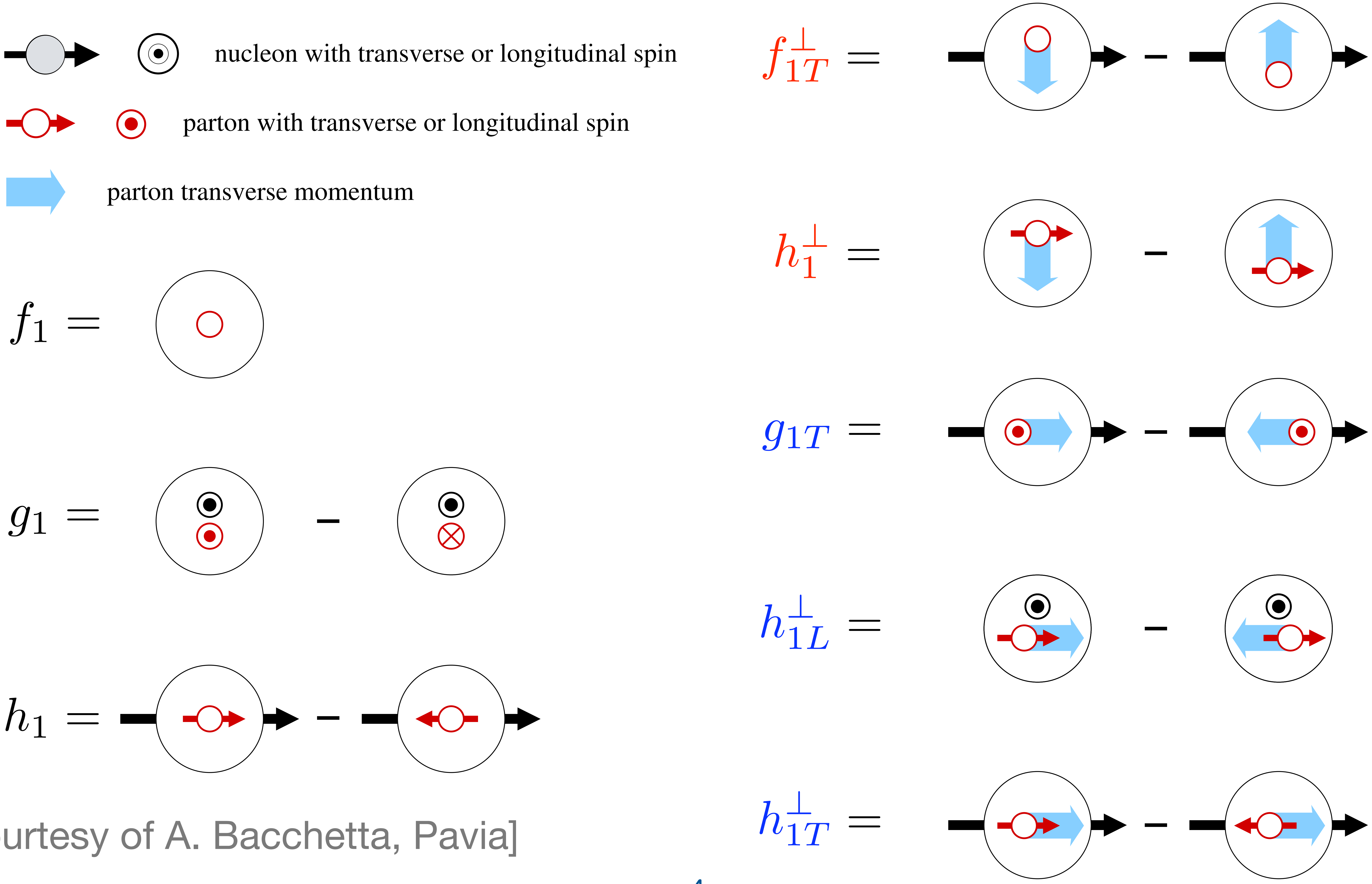
transversity

pretzelosity

- 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
- last row those accessible with transverse target polarization

TMDs - probabilistic interpretation

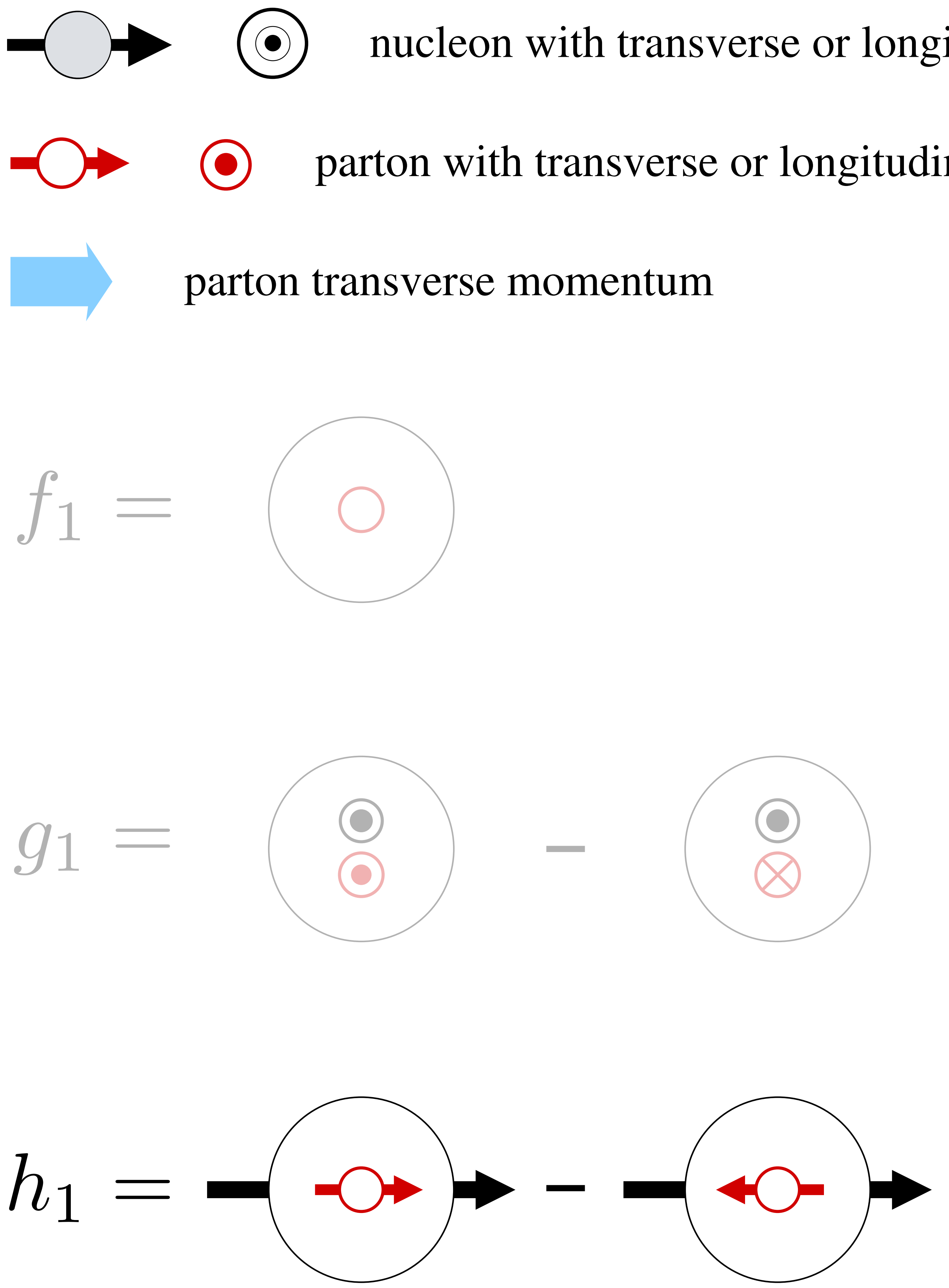
proton goes out of the screen / photon goes into the screen

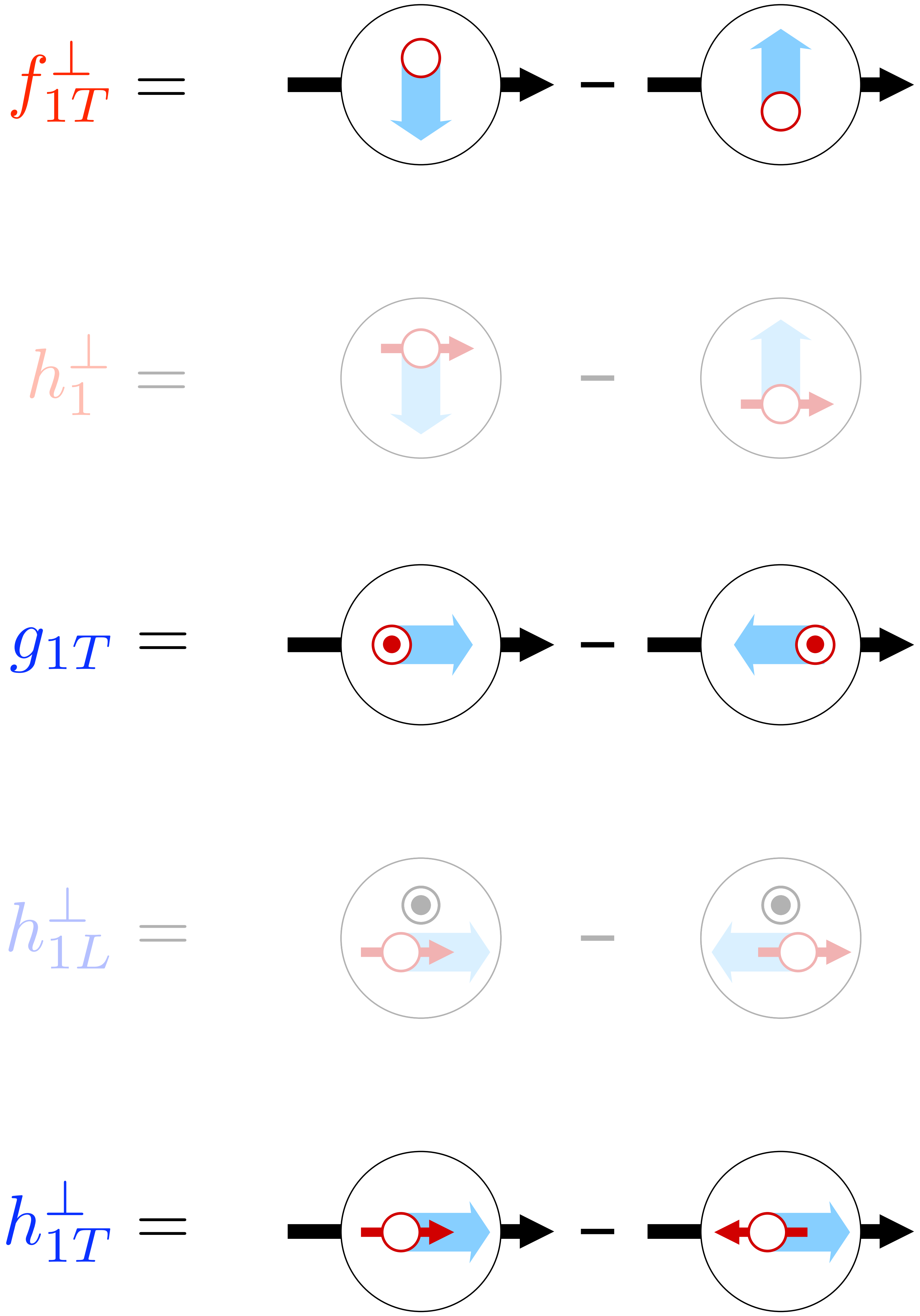


[courtesy of A. Bacchetta, Pavia]

TMDs - probabilistic interpretation

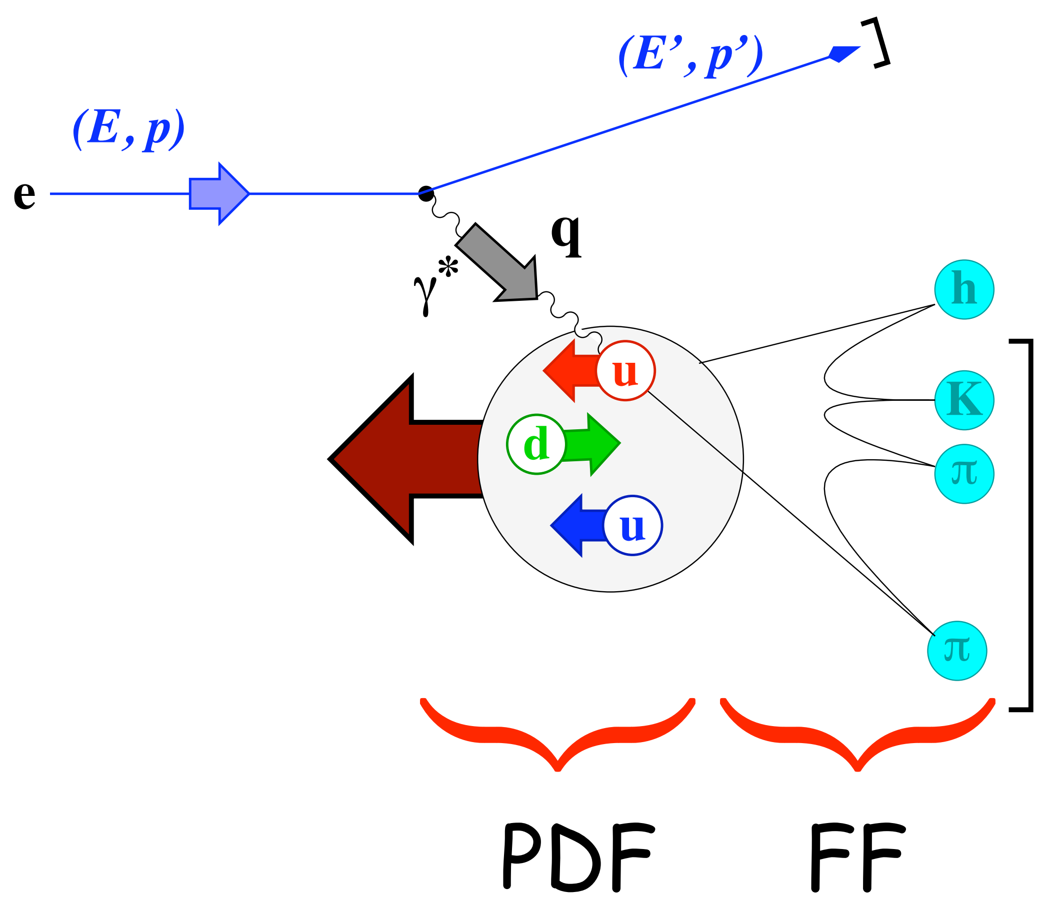
proton goes out of the screen / photon goes into the screen





[courtesy of A. Bacchetta, Pavia]

Probing TMDs in semi-inclusive DIS



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, $h_{1T}^\perp$

<u>in SIDIS*) couple PDFs to:</u>

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

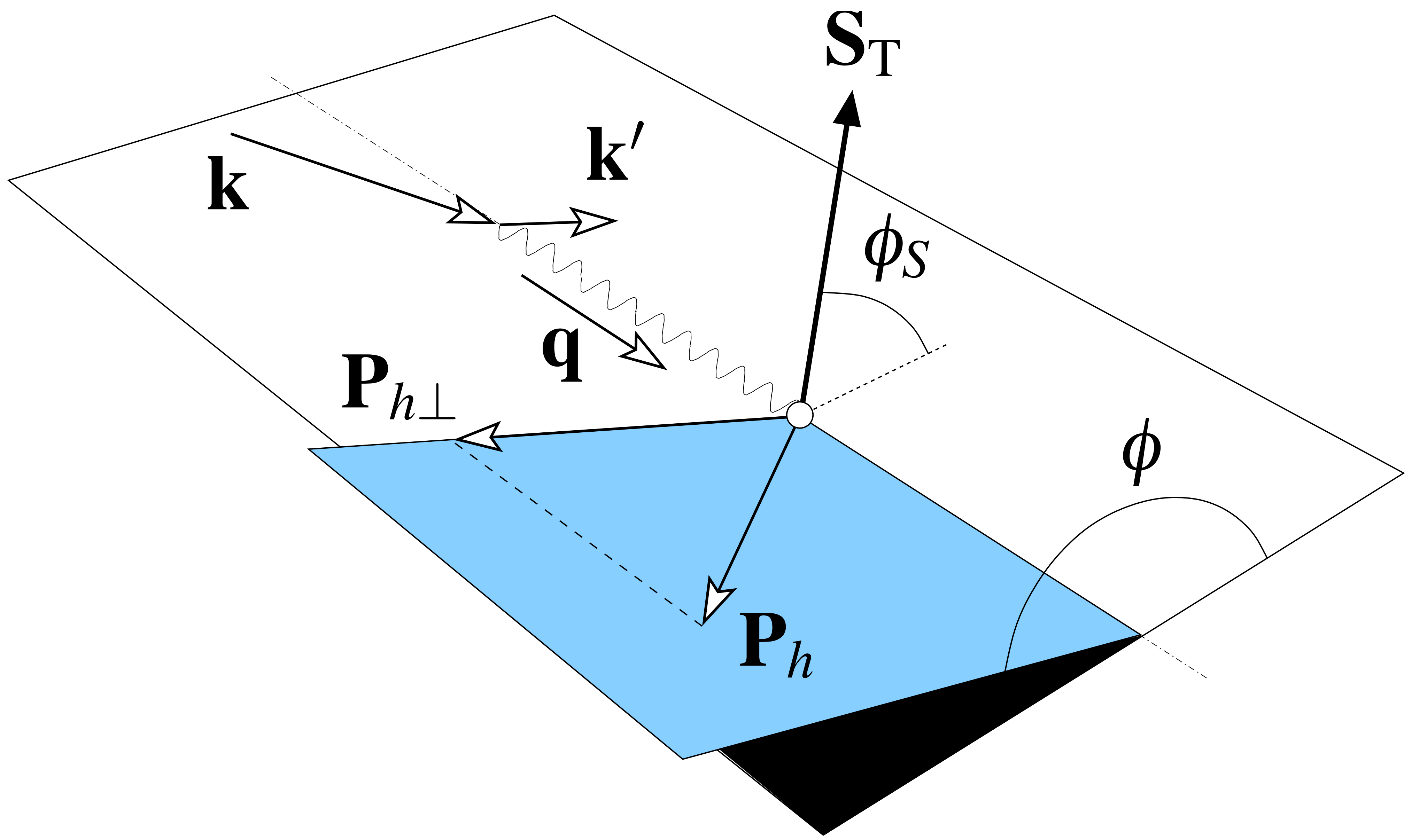
ordinary FF: $D_1^{q\to h}$

➟ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

Semi-inclusive DIS

- with **transverse** target polarization:



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

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

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

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

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

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

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

- with **transverse** target polarization:

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

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

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

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

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

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

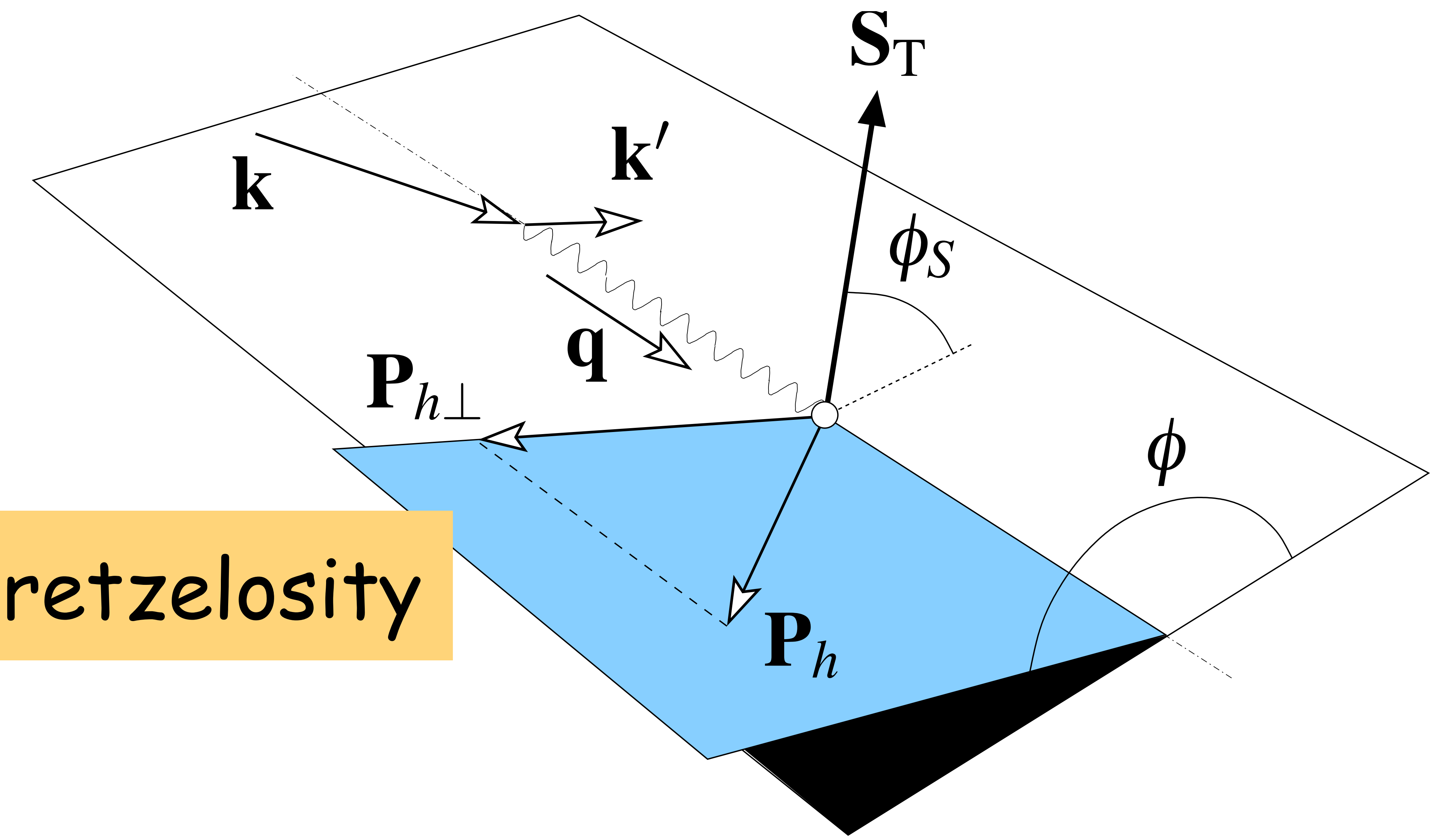
$$
+ \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi-\phi_s) \Big] \Big\}
$$

Sivers

pretzelosity

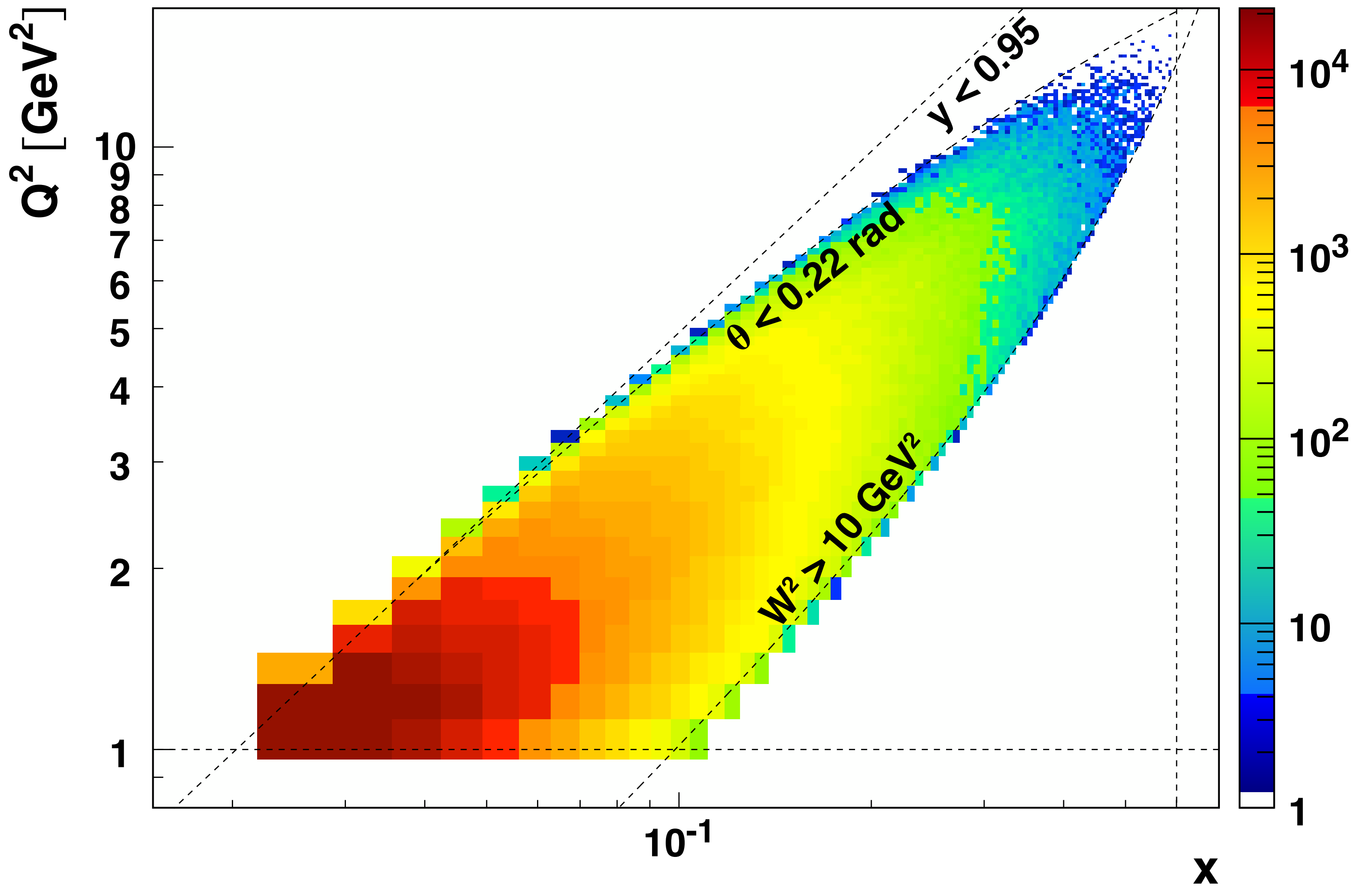
transversity

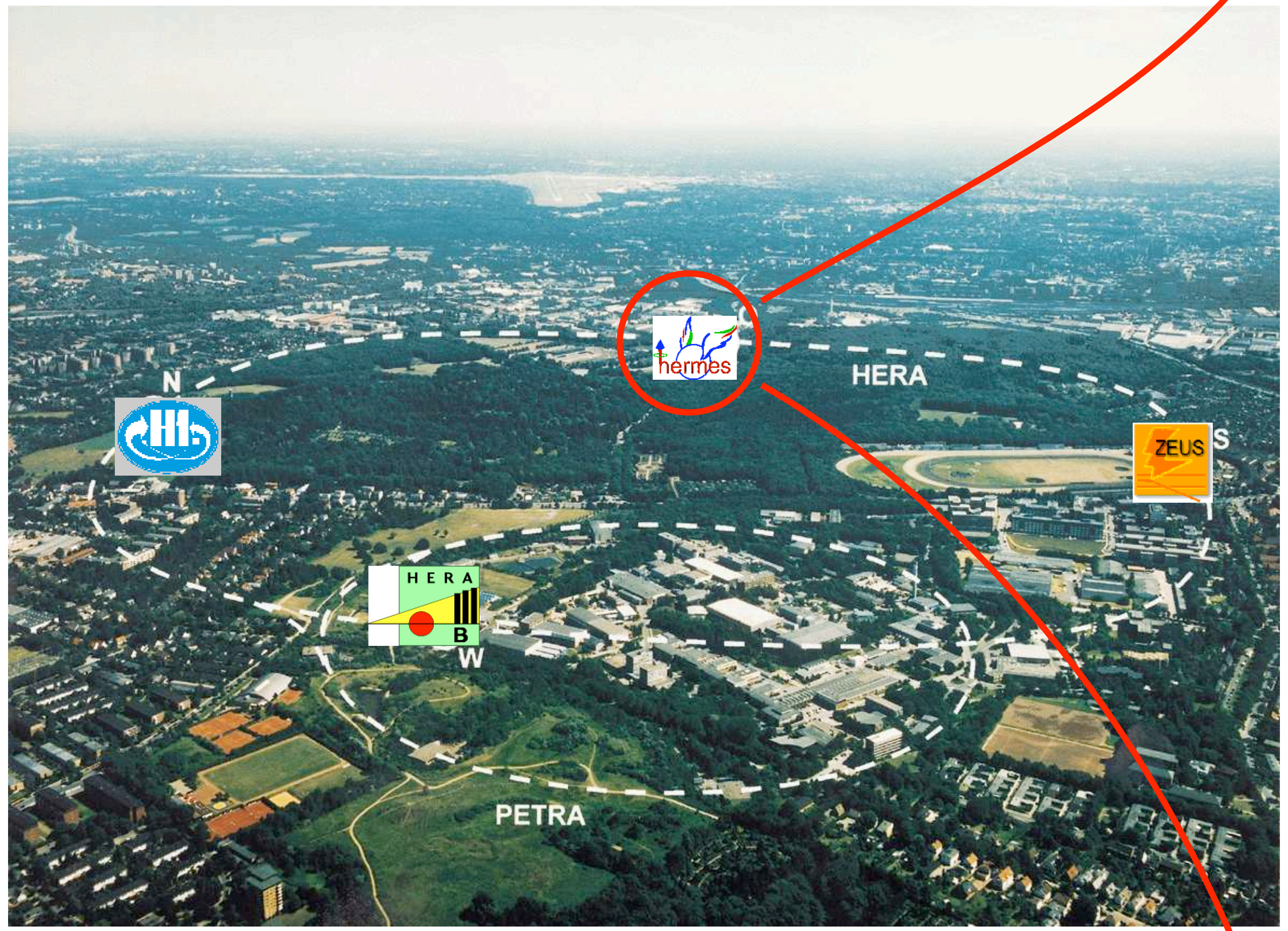
worm-gear

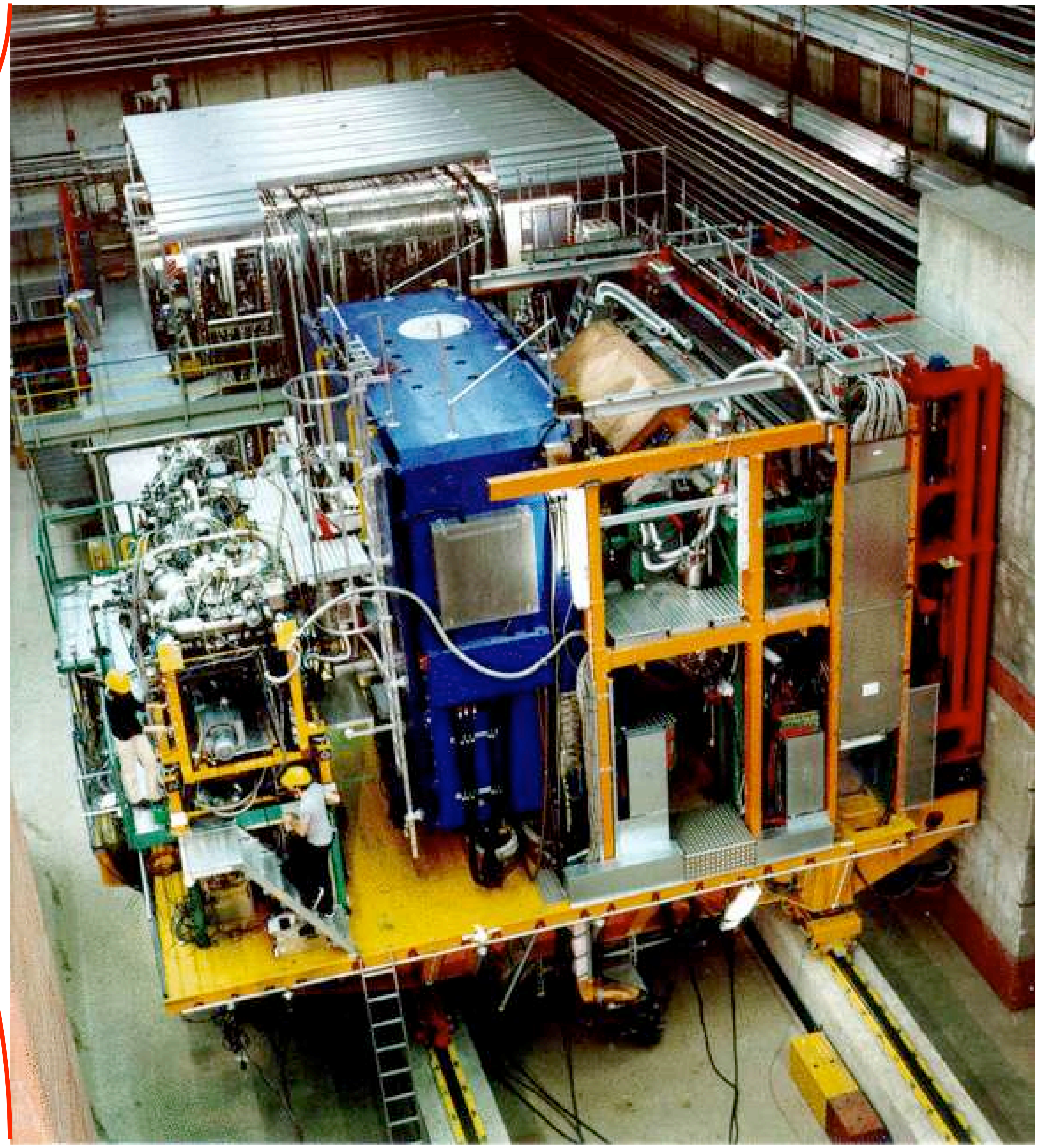


HERMES (1995-2007) @ DESY

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





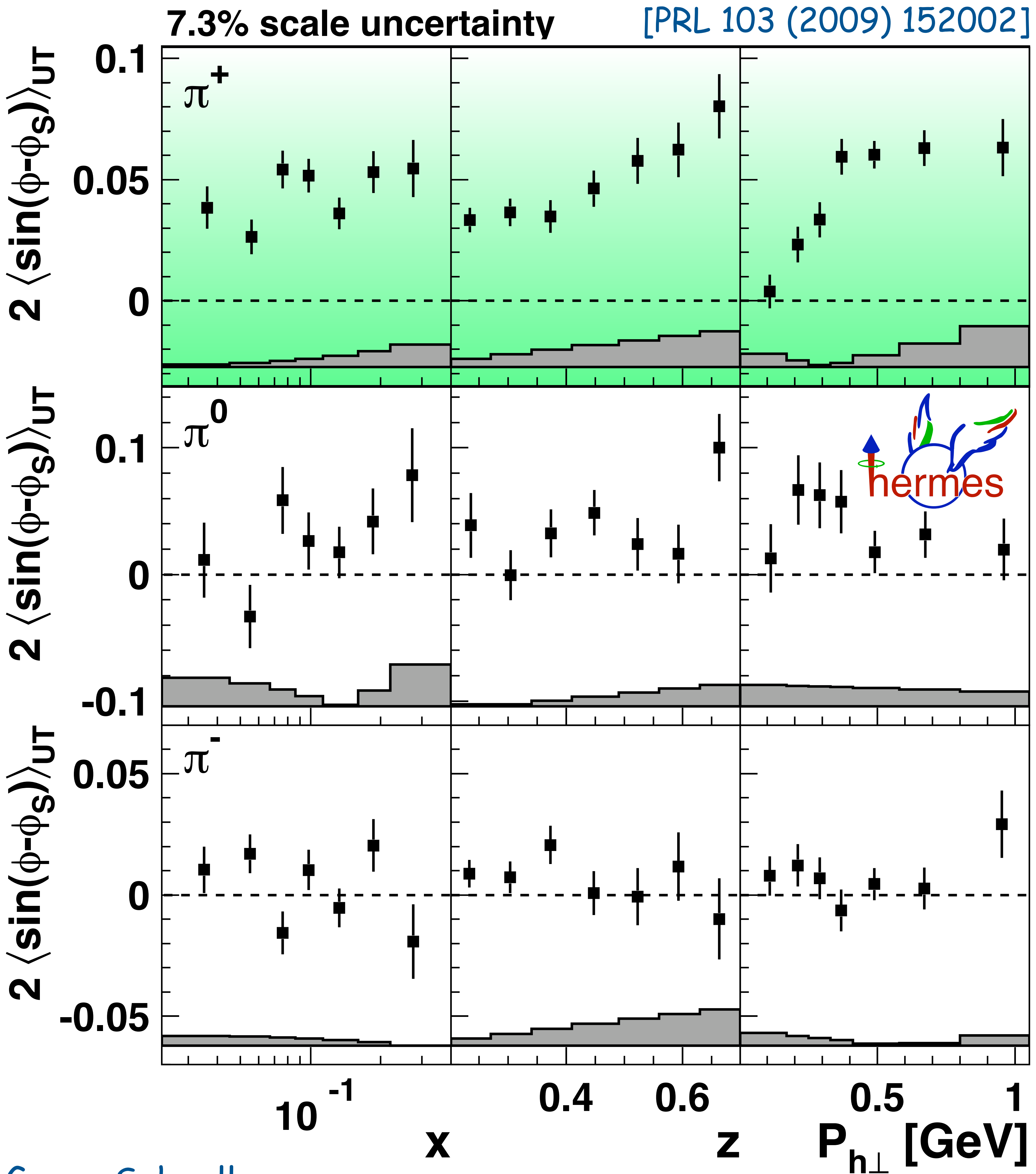


- unpolarized (H, D, He,..., Xe) as well as
- transversely (H) or longitudinally (H, D, He) polarized **pure gas targets**
- particle ID (incl. dual-radiator RICH) for efficient **e/pi/K/p separation**

	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

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



	U	L	T
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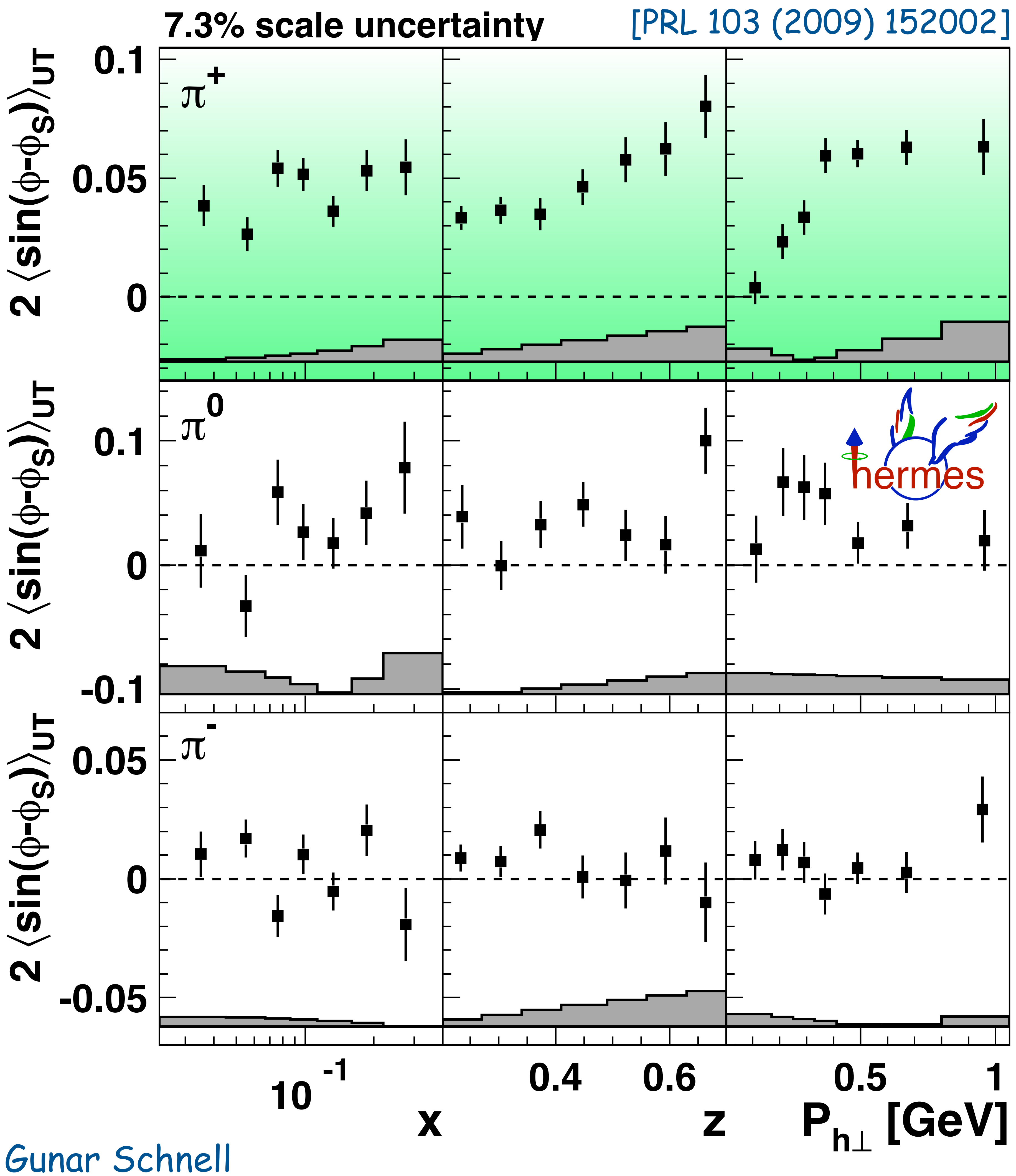

π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

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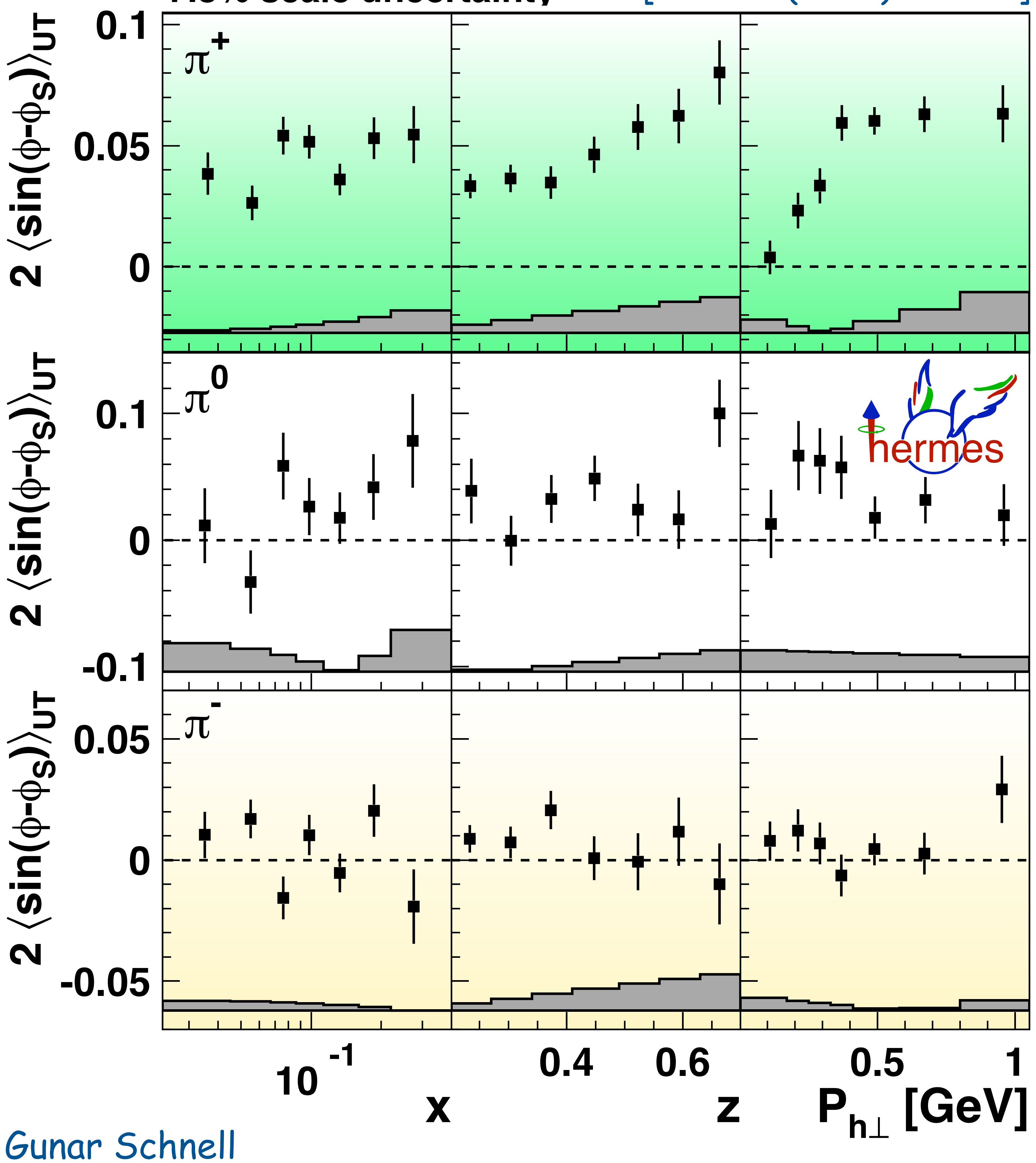
7.3% scale uncertainty [PRL 103 (2009) 152002]



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☛ u-quark Sivers DF < 0

☛ d-quark Sivers DF > 0 (cancelation for π^-)

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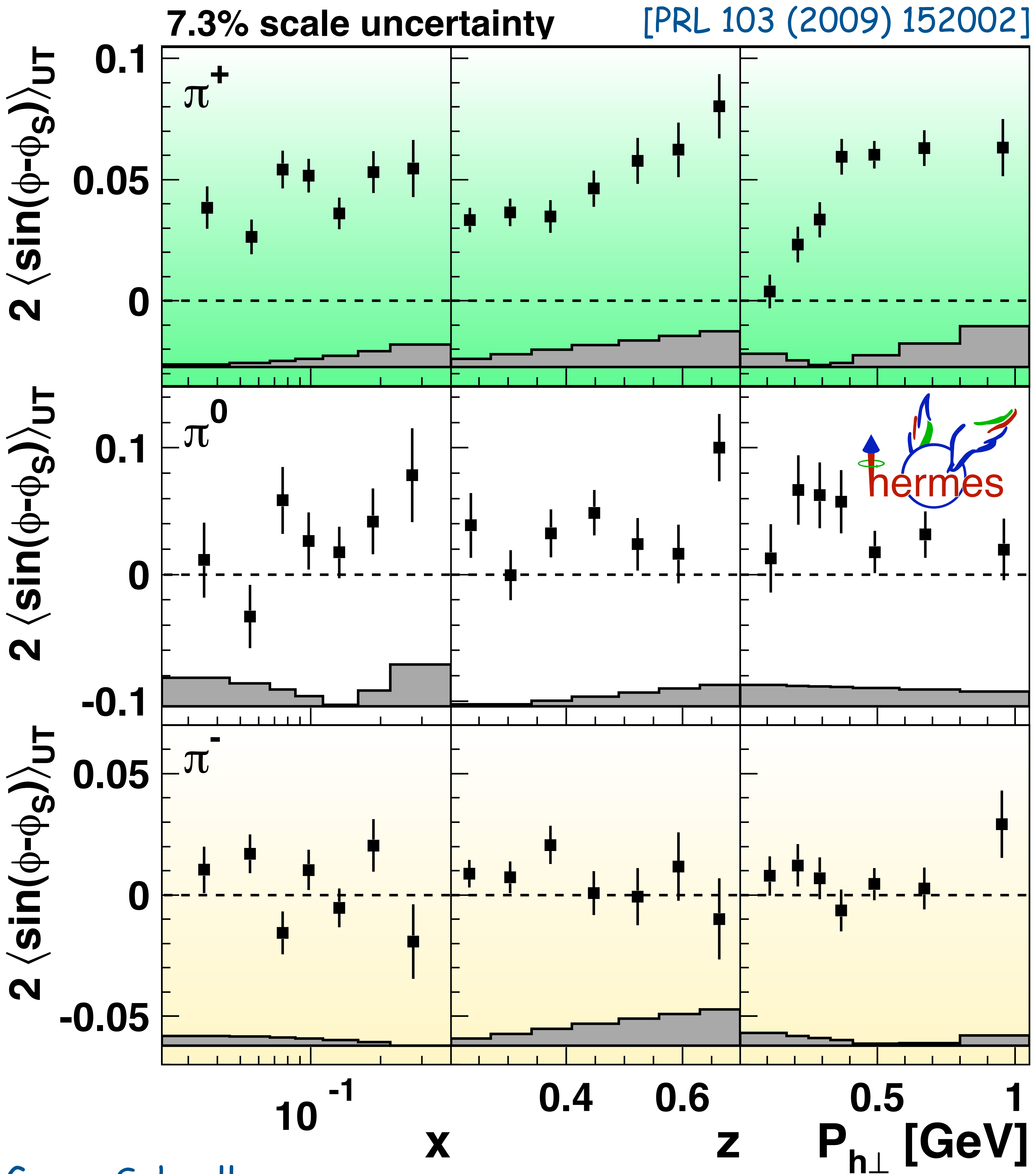
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

Sivers amplitudes for pions

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



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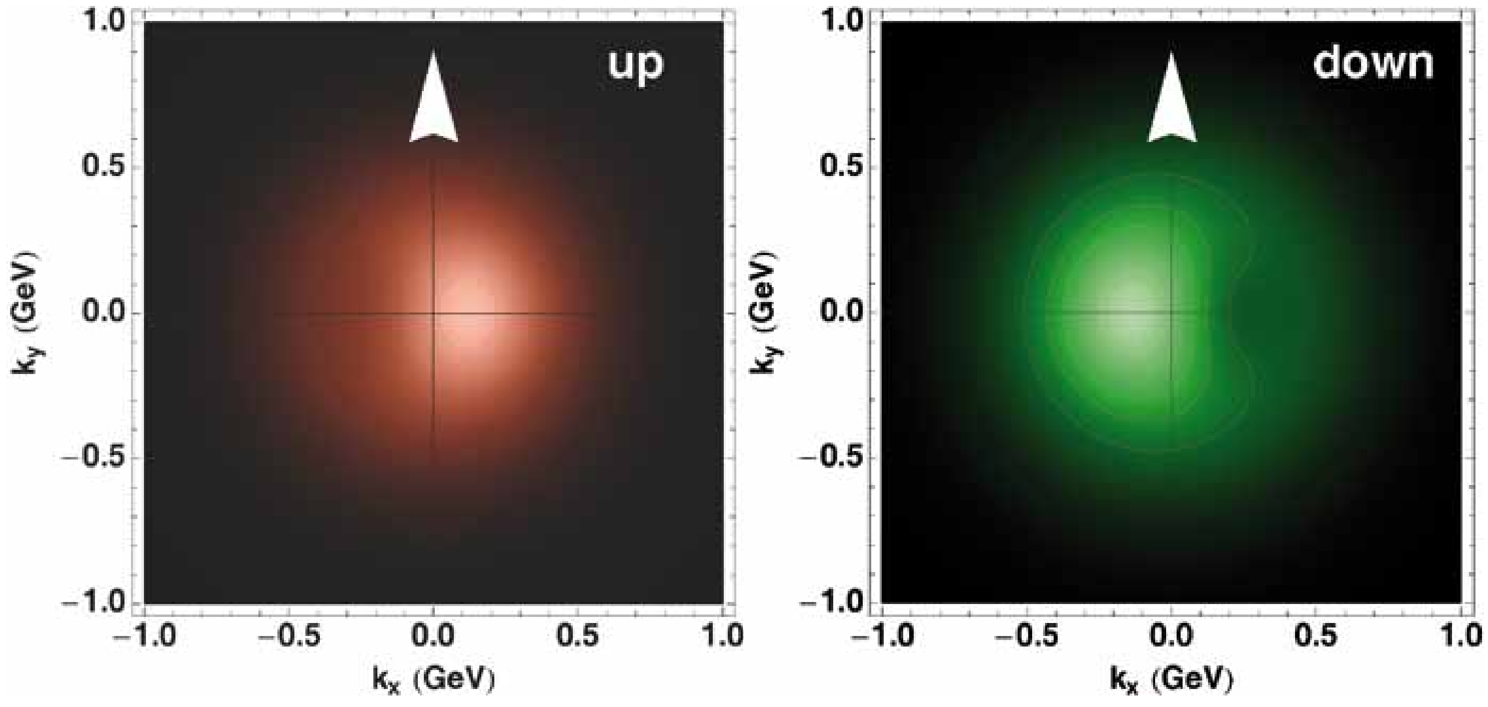

[A. Bacchetta et al.]

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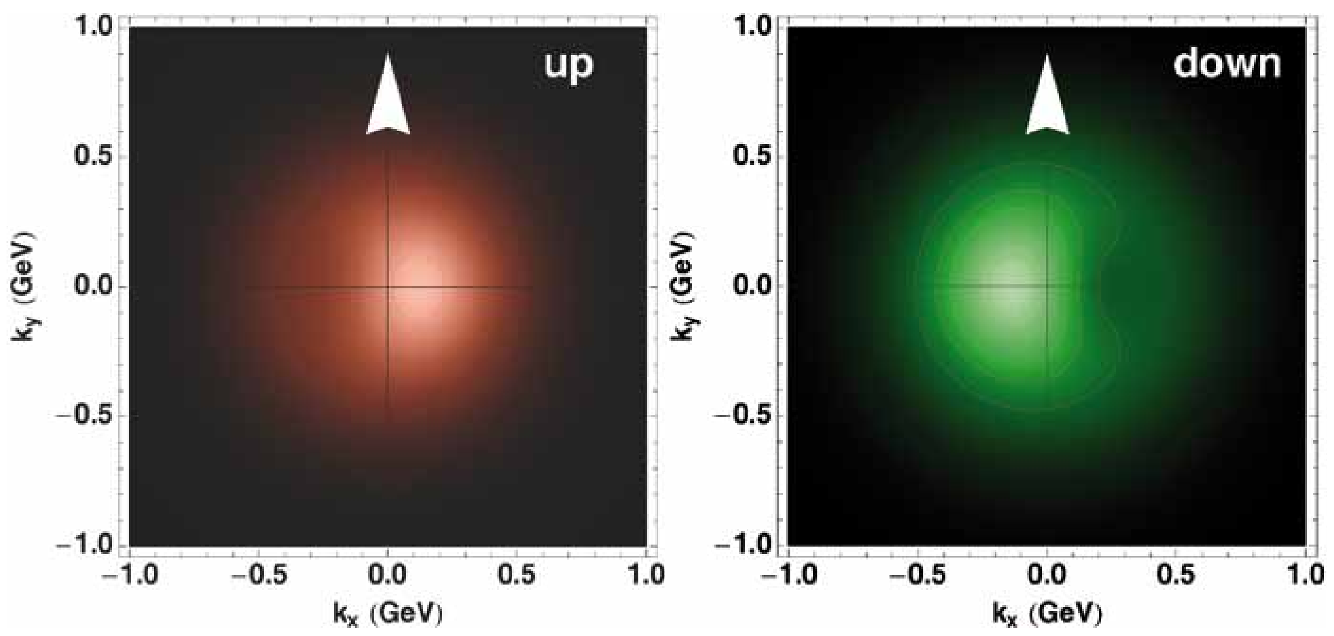
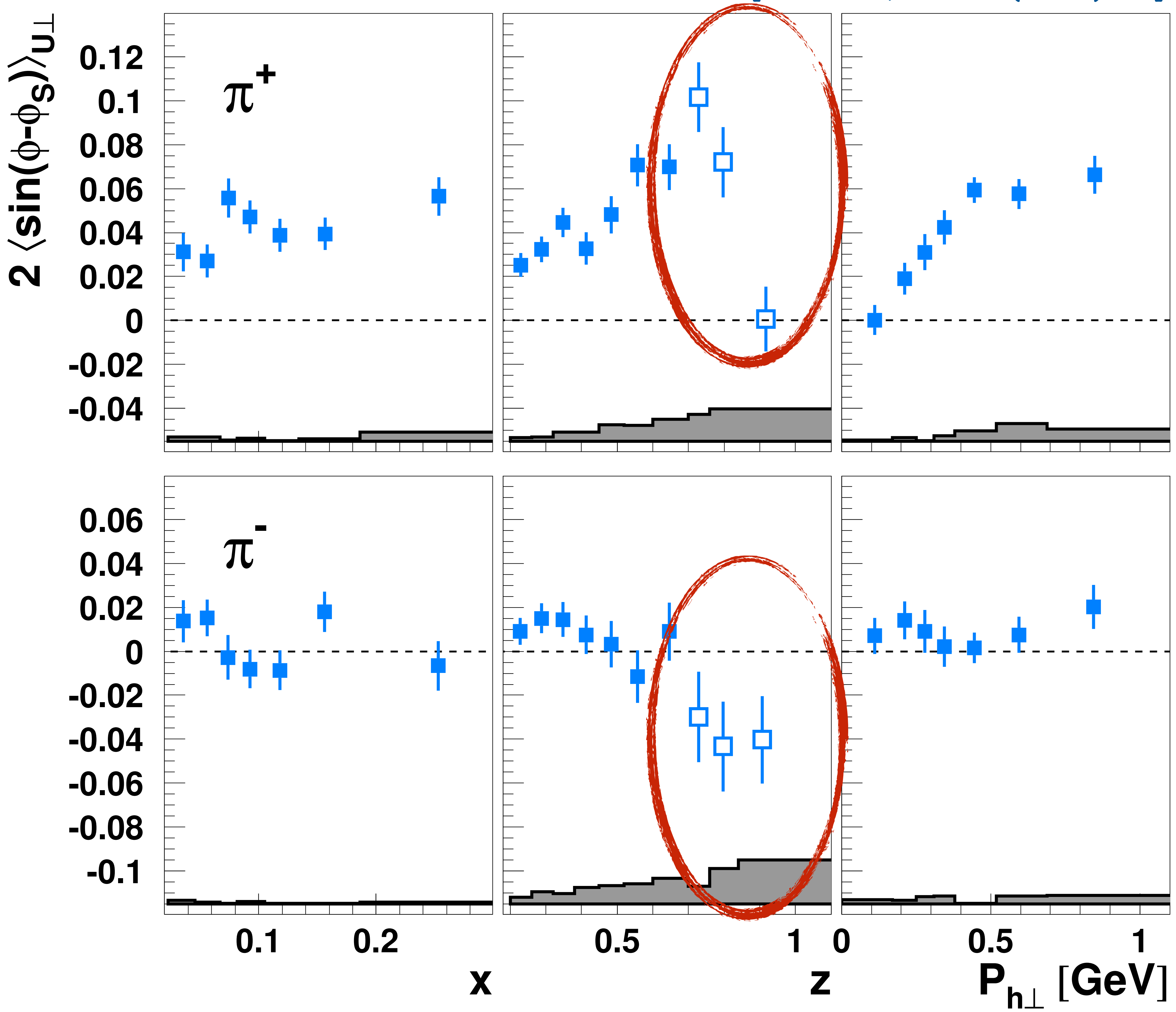


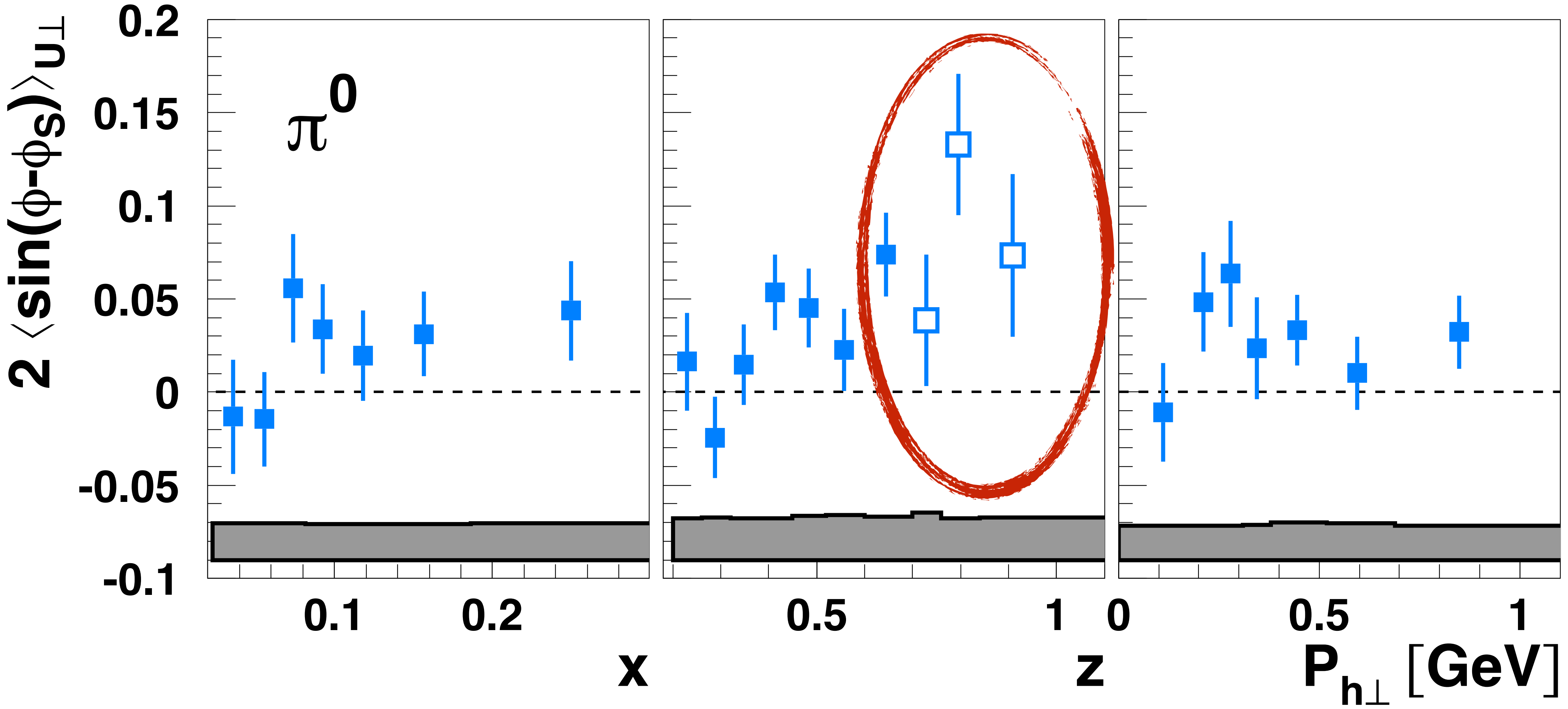
[A. Bacchetta et al.]

Sivers amplitudes for pions

- high-z data probes region with high sensitivity to flavor of struck quark

[HERMES, JHEP12(2020)010]





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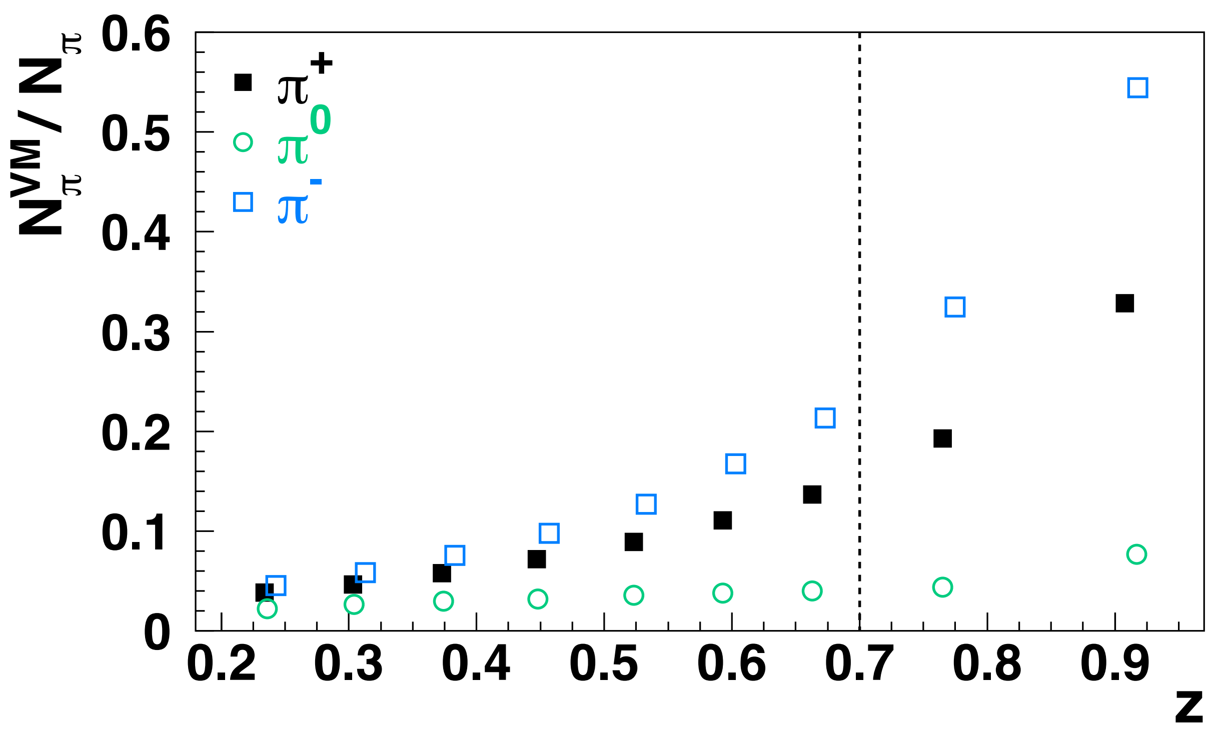
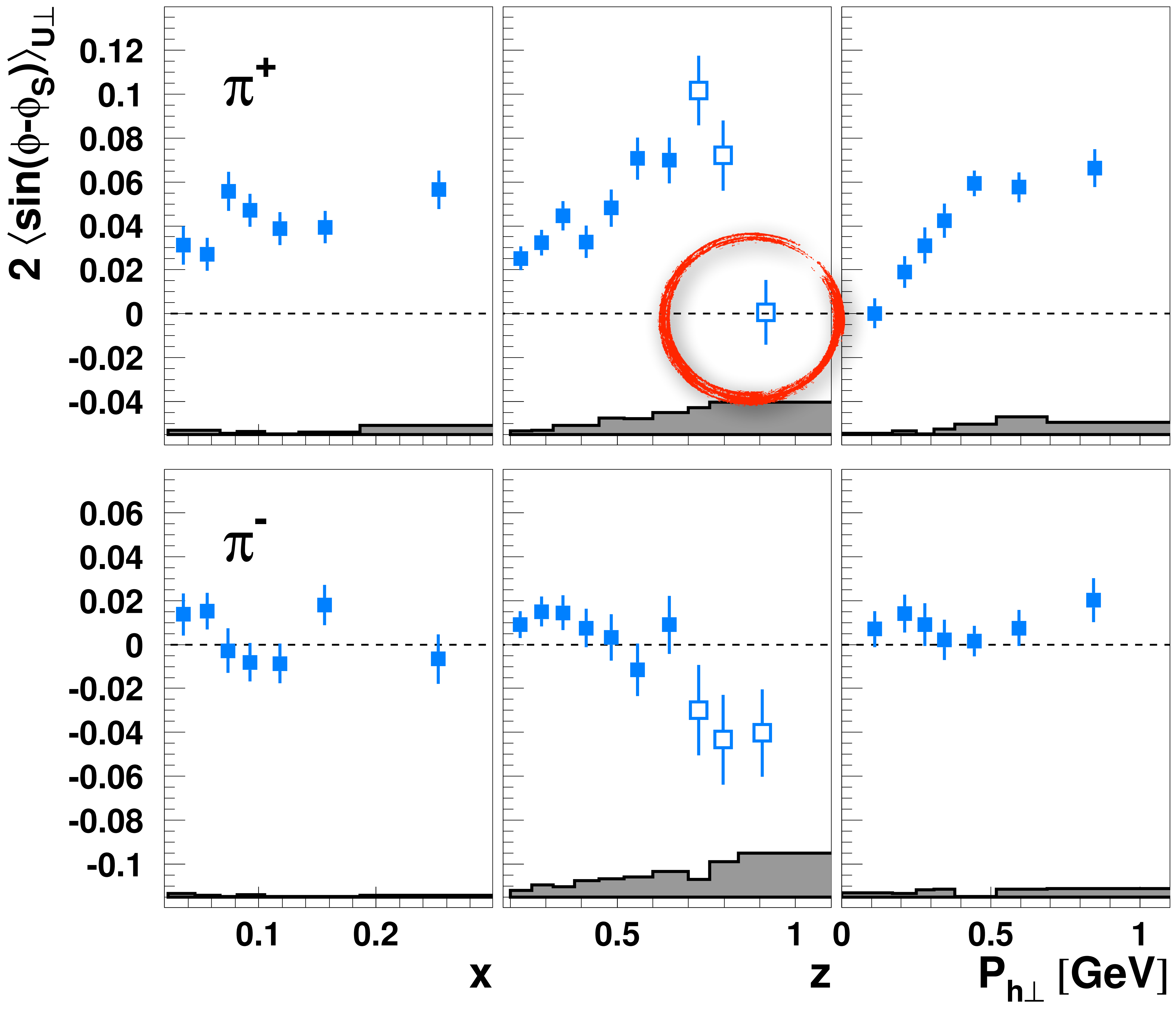
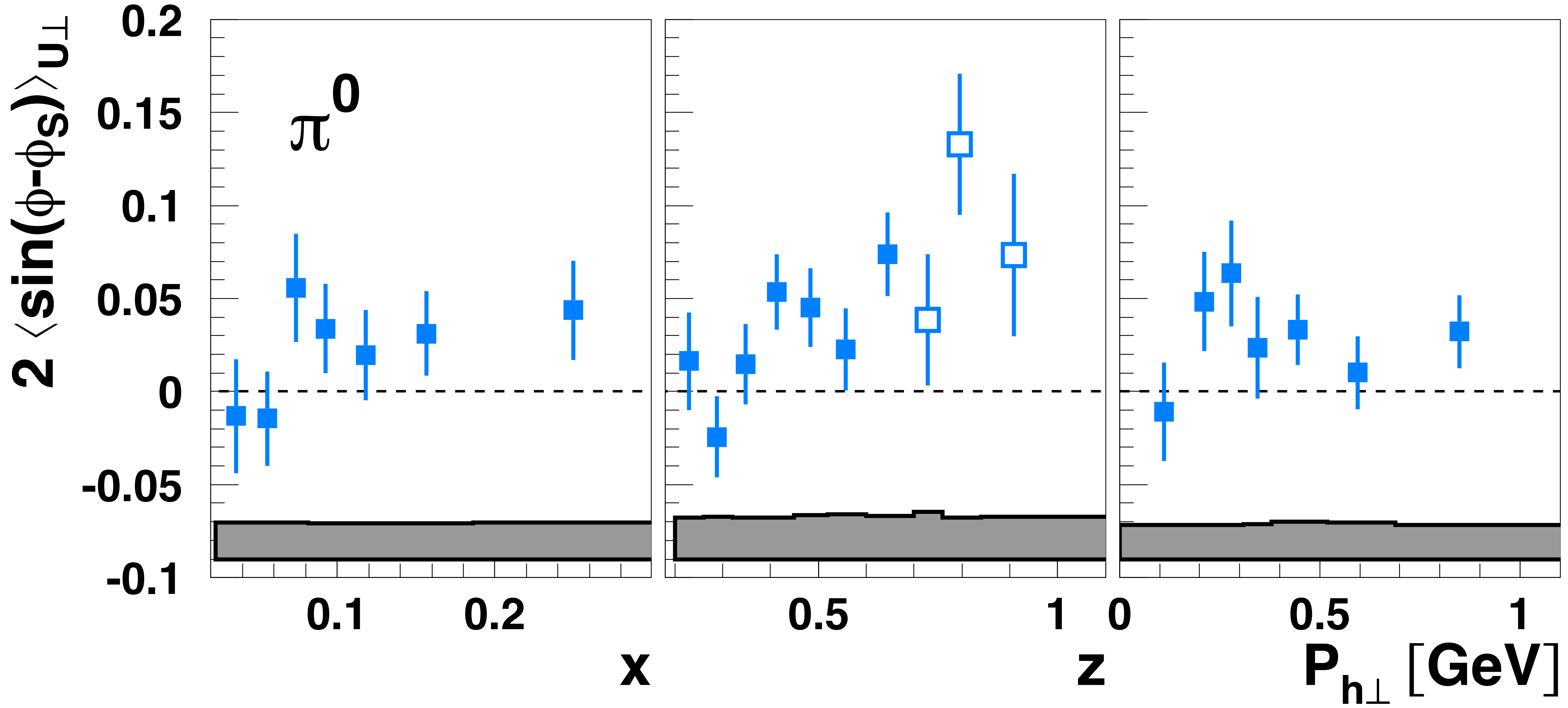


Sivers amplitudes for pions

- high-z data probes region with high sensitivity to flavor of struck quark
- … but also to contributions from exclusive vector-meson production
- only last z bin shows indication of sizeable ρ^0 contribution (decaying into charged pions)

[HERMES, JHEP12(2020)010]





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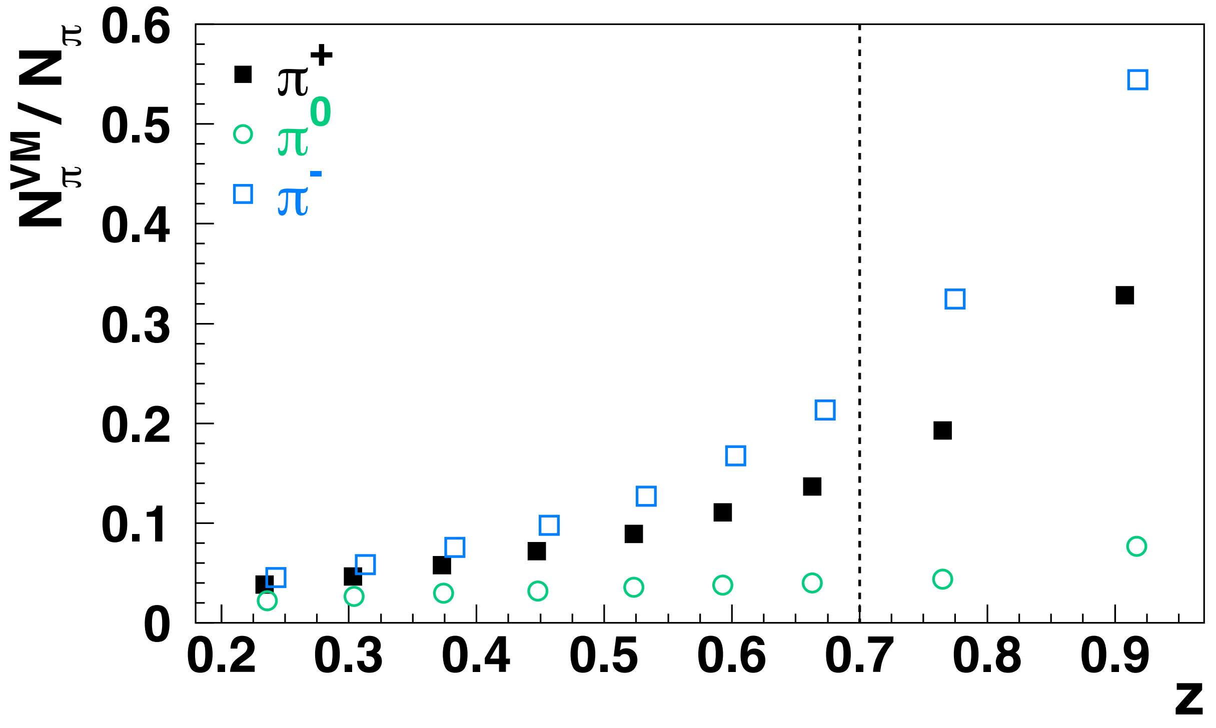
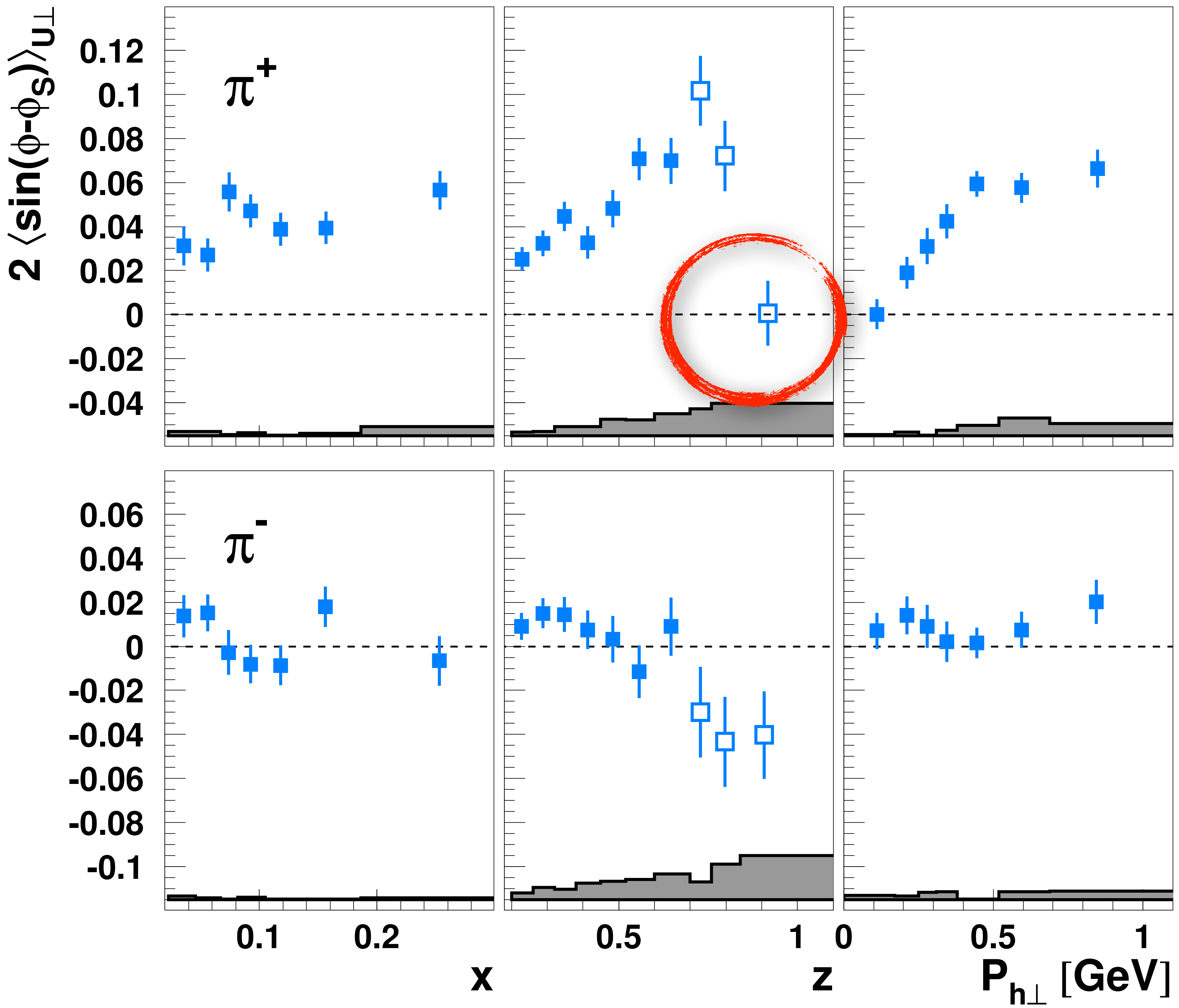
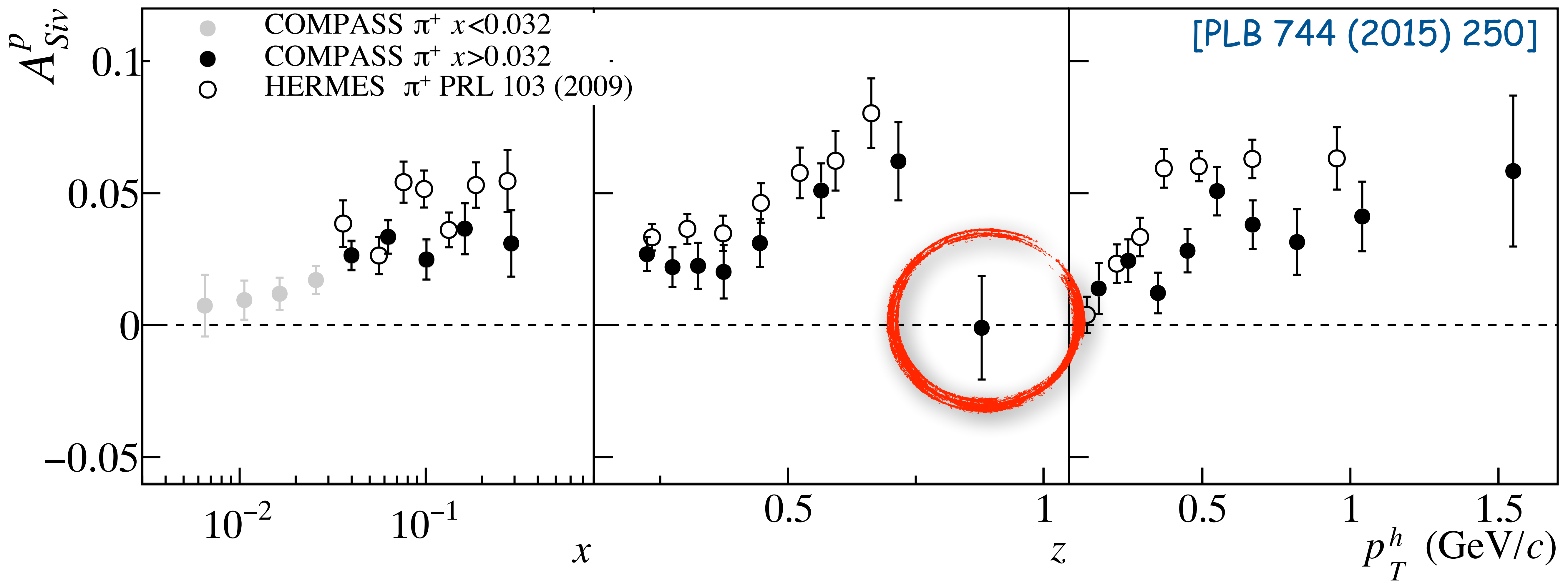


Sivers amplitudes for pions

- high-z data probes region with high sensitivity to flavor of struck quark
- … but also to contributions from exclusive vector-meson production
- only last z bin shows indication of sizeable ρ^0 contribution (decaying into charged pions)
- incidentally, similar drop of asymmetry at large z seen at COMPASS

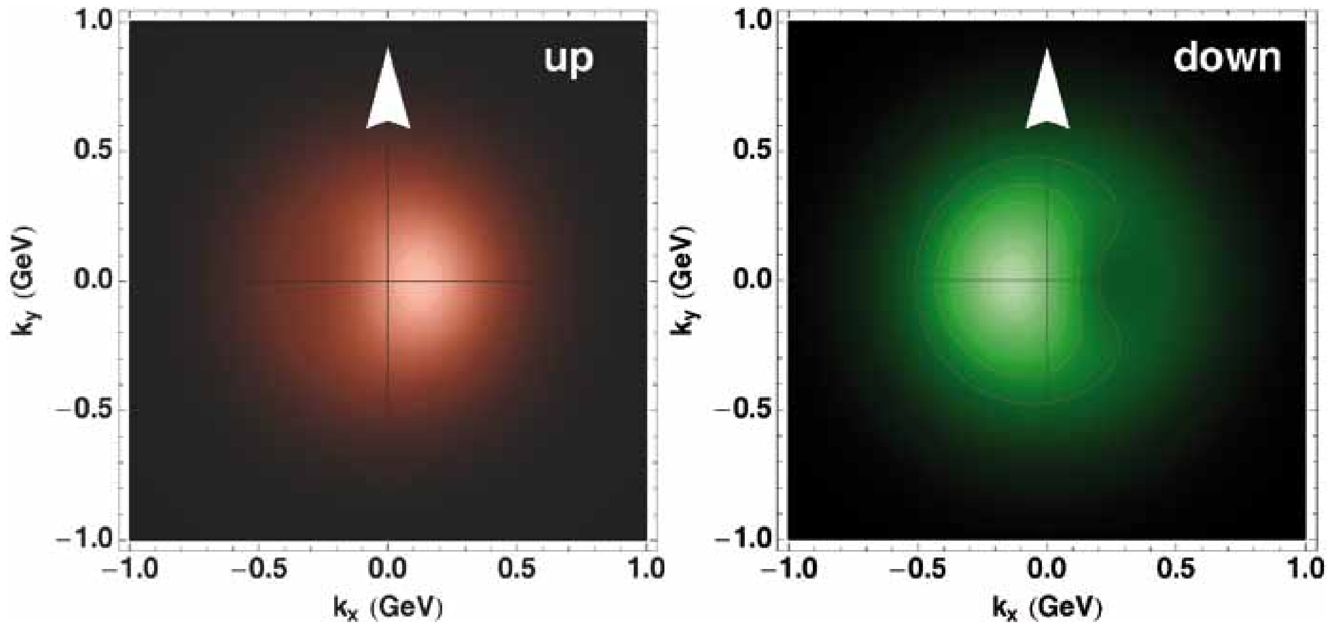
[HERMES, JHEP12(2020)010]





Sivers amplitudes
pions vs. kaons

	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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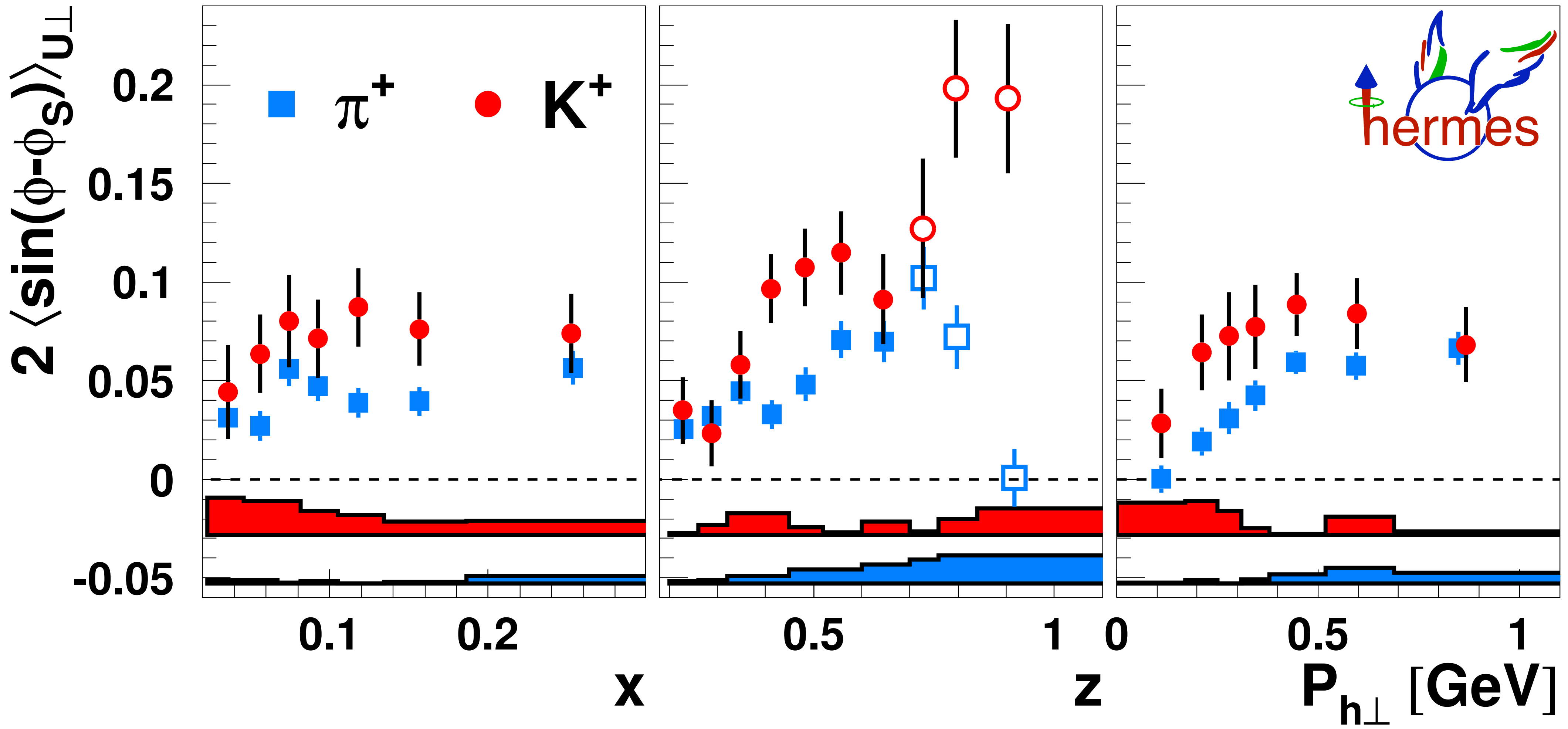
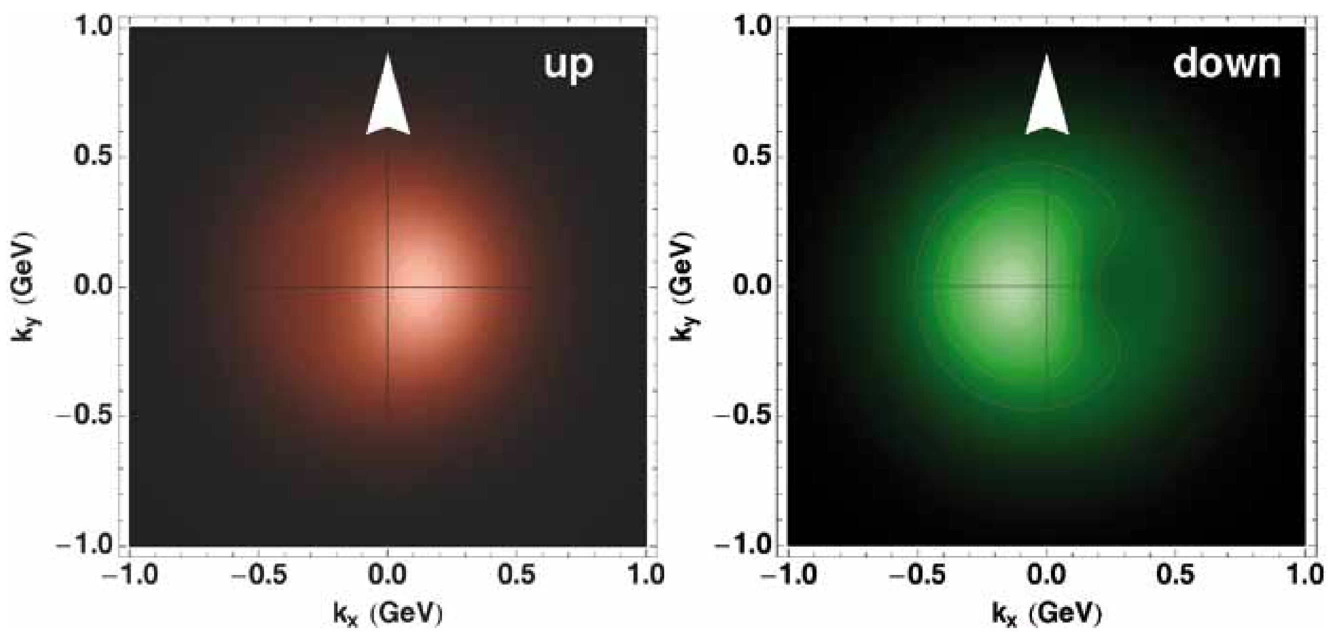


somewhat unexpected if dominated by scattering from u-quarks:

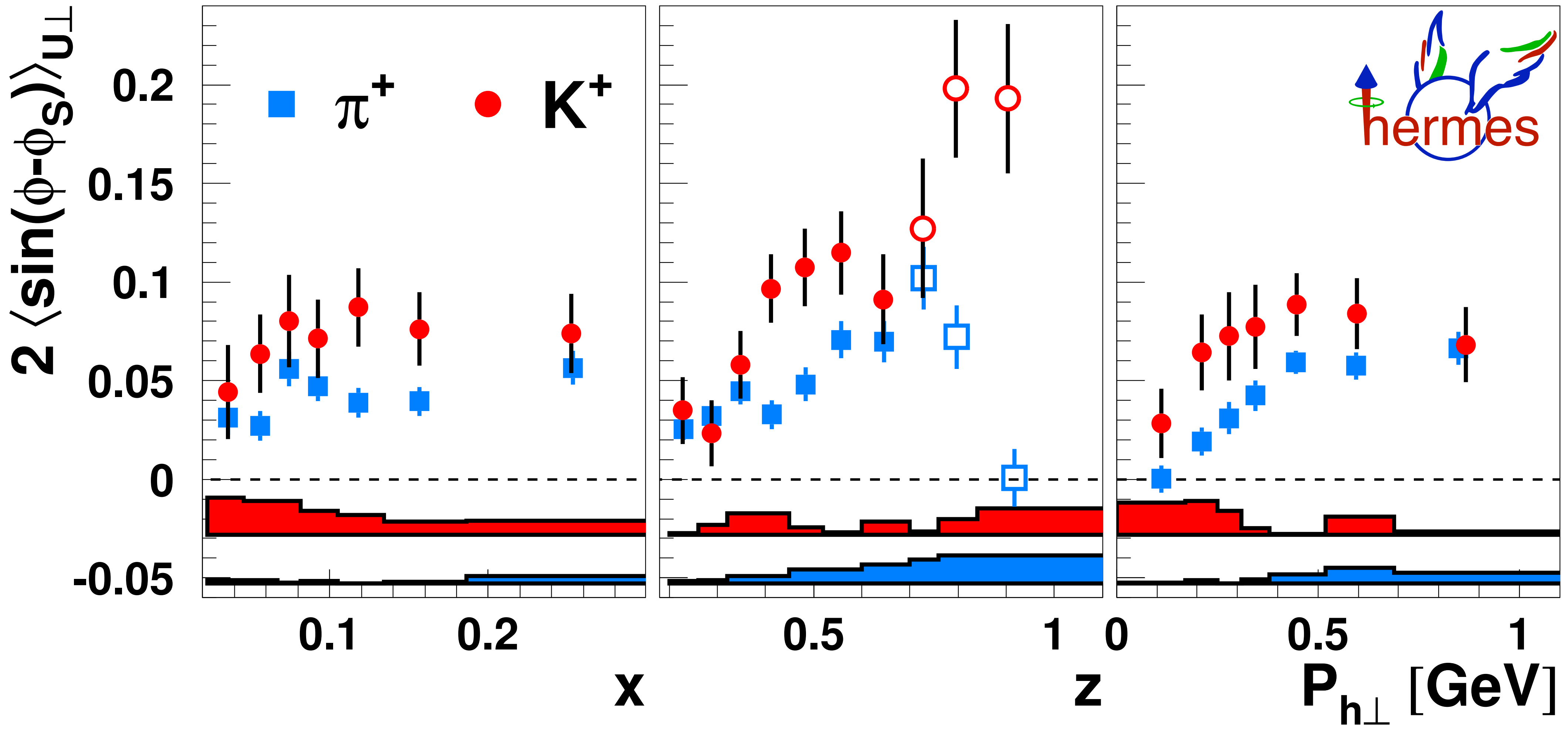
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$$

Sivers amplitudes
pions vs. kaons

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



[HERMES, JHEP12(2020)010]



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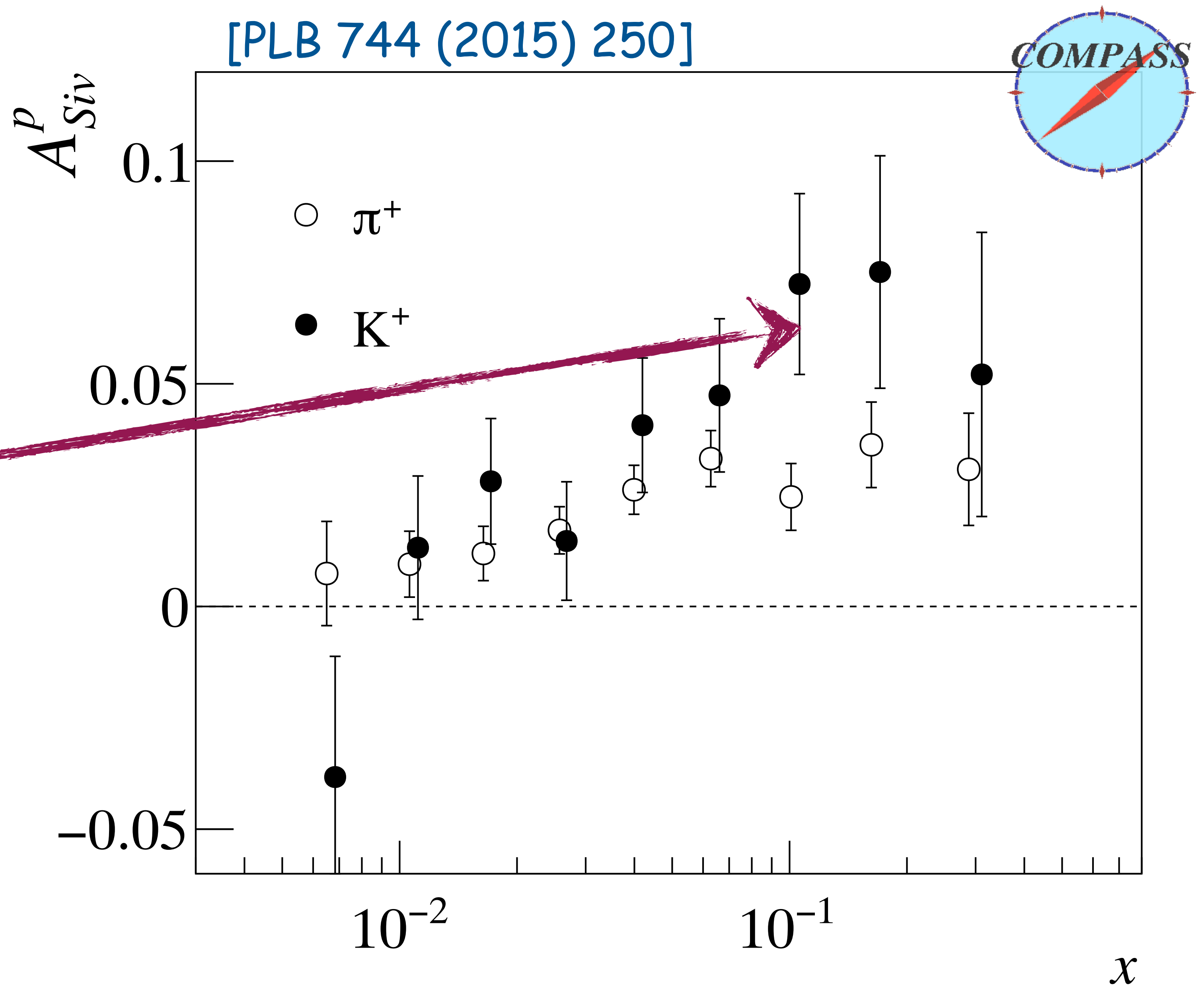
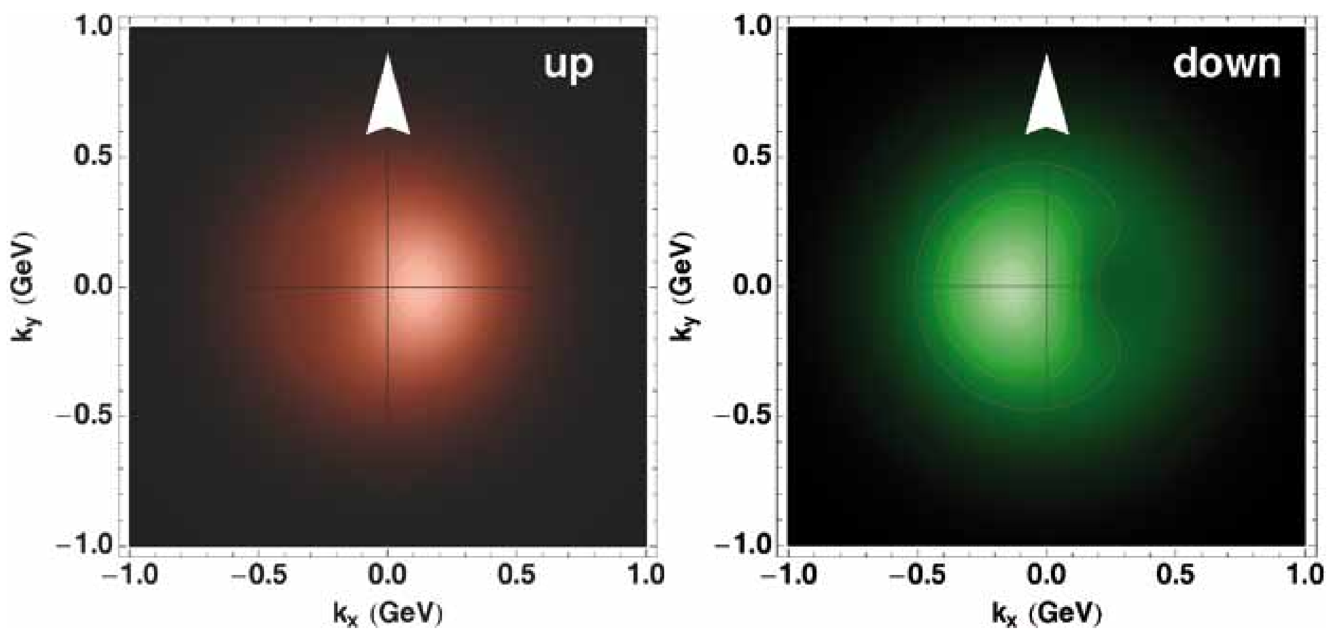
[PLB 744 (2015) 250]



larger amplitudes seen also by COMPASS

Sivers amplitudes
pions vs. kaons

	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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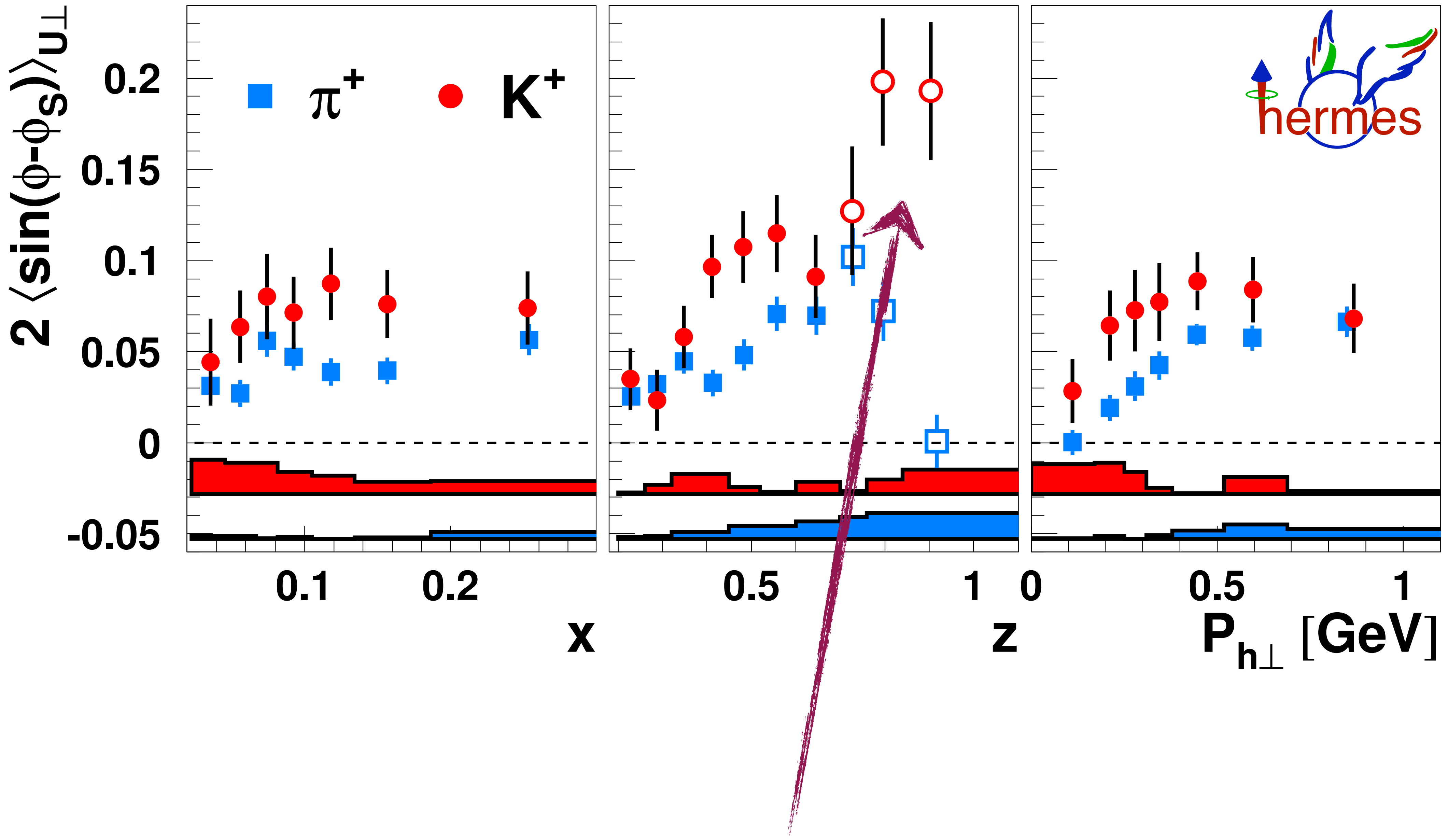
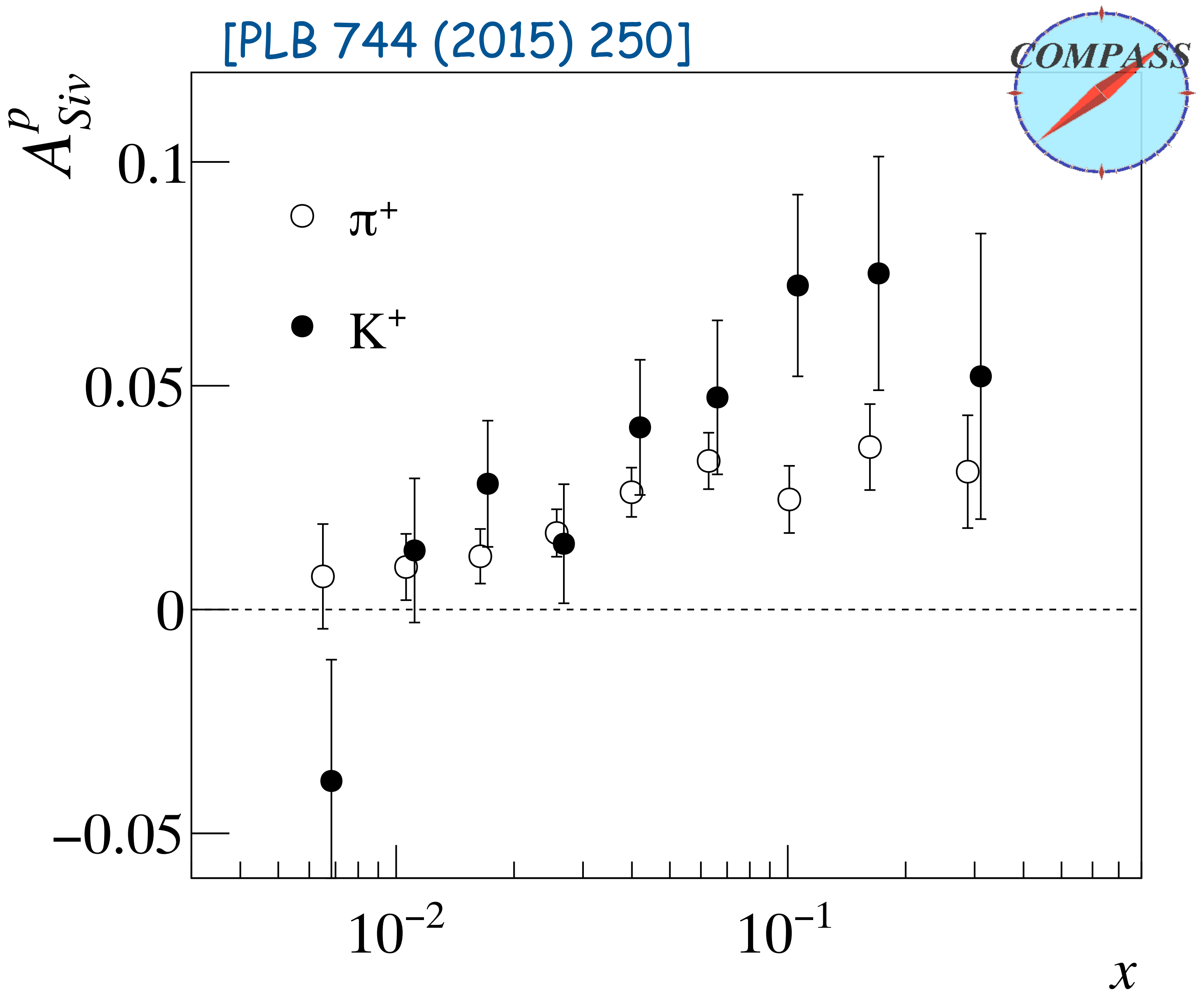


unlike the pion case, no drop at large z

somewhat unexpected if dominated by scattering from u-quarks:

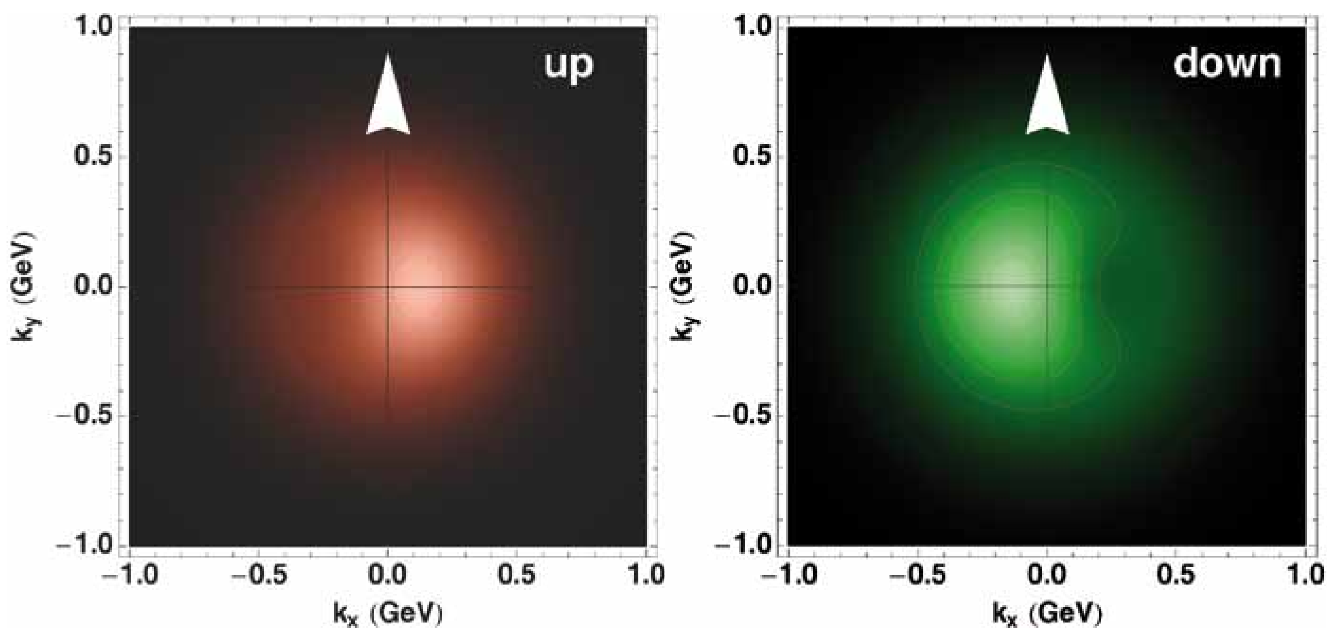
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$$

[PLB 744 (2015) 250]



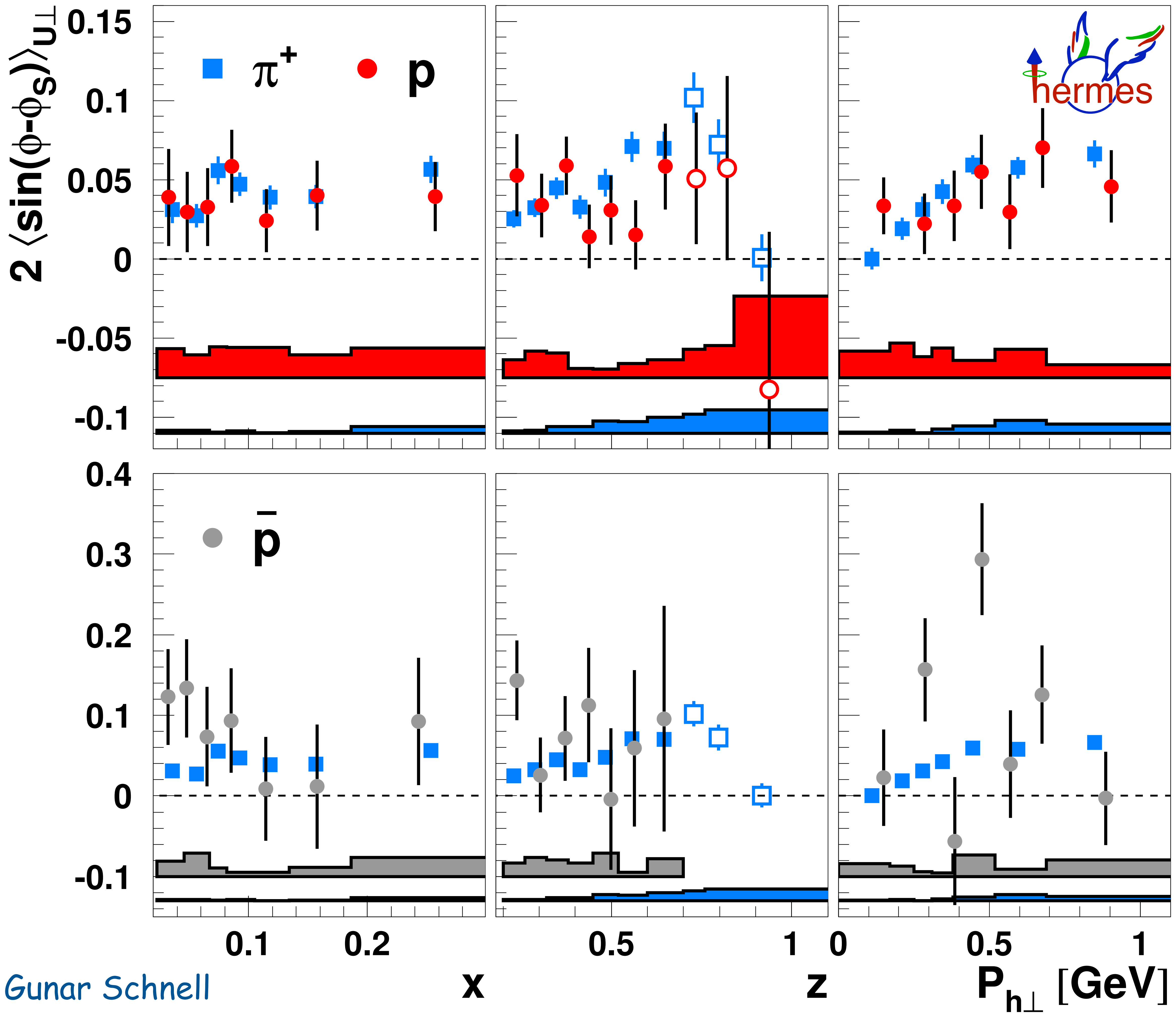
Sivers amplitudes
pions vs. (anti)protons

	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.]

[HERMES, JHEP12(2020)010]



- first-ever results for protons and anti-protons

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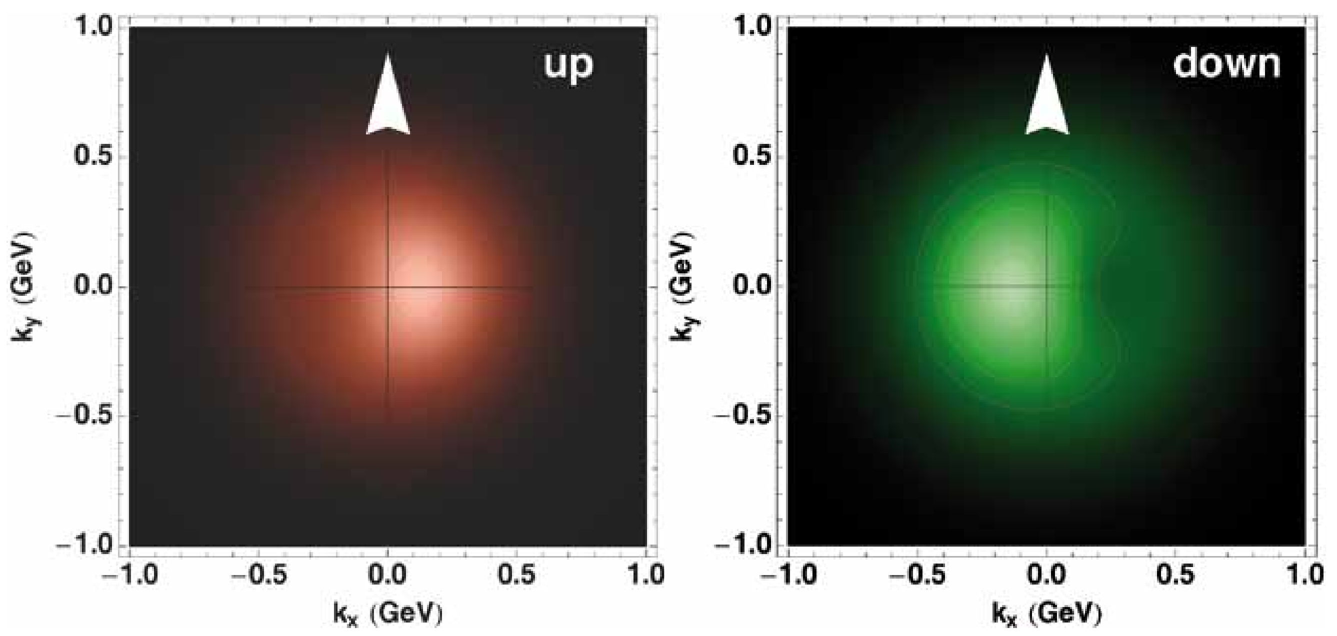

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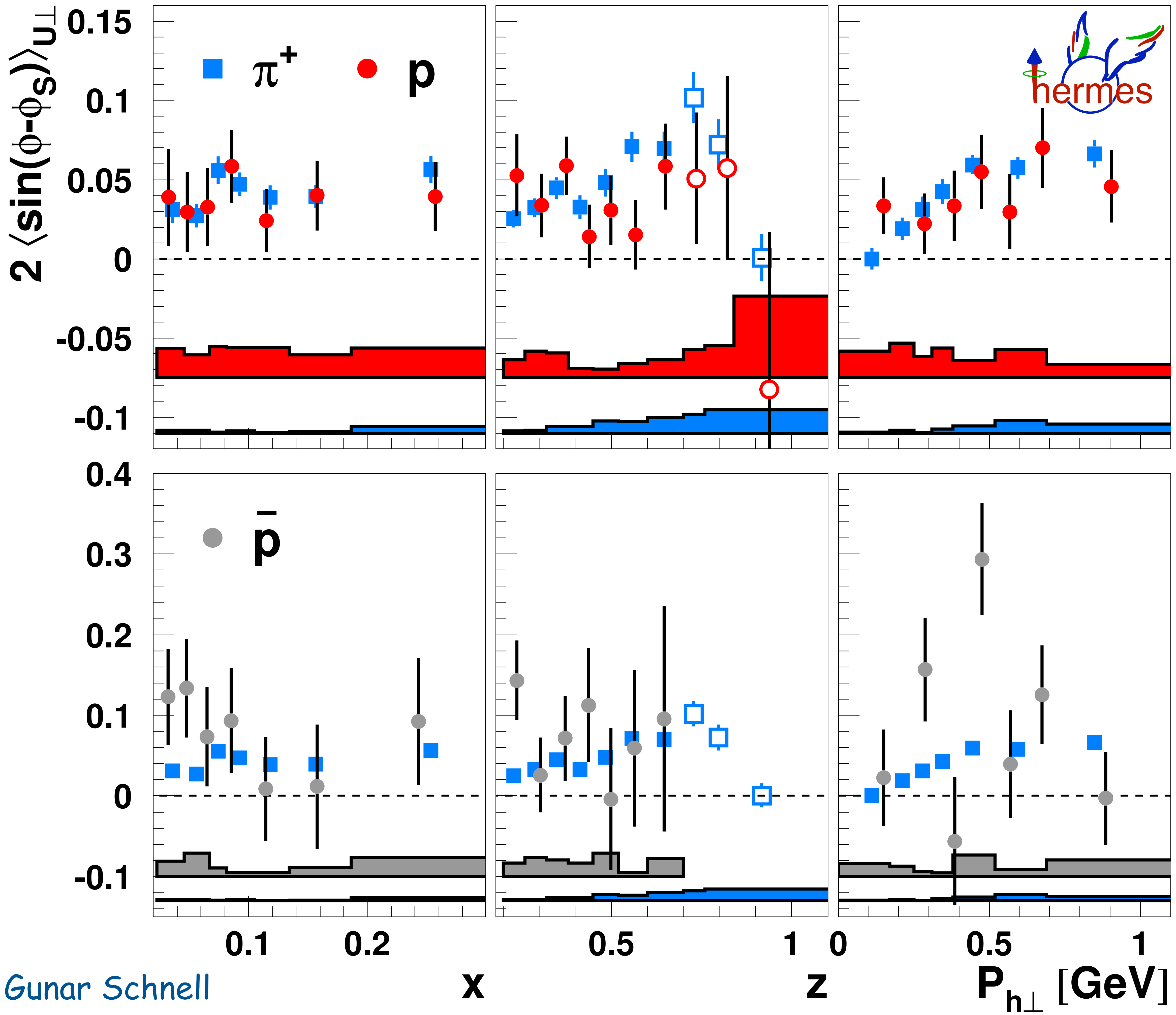

Sivers amplitudes
pions vs. (anti)protons

- 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
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L		g_{1L}	$h_{1L}^\perp$
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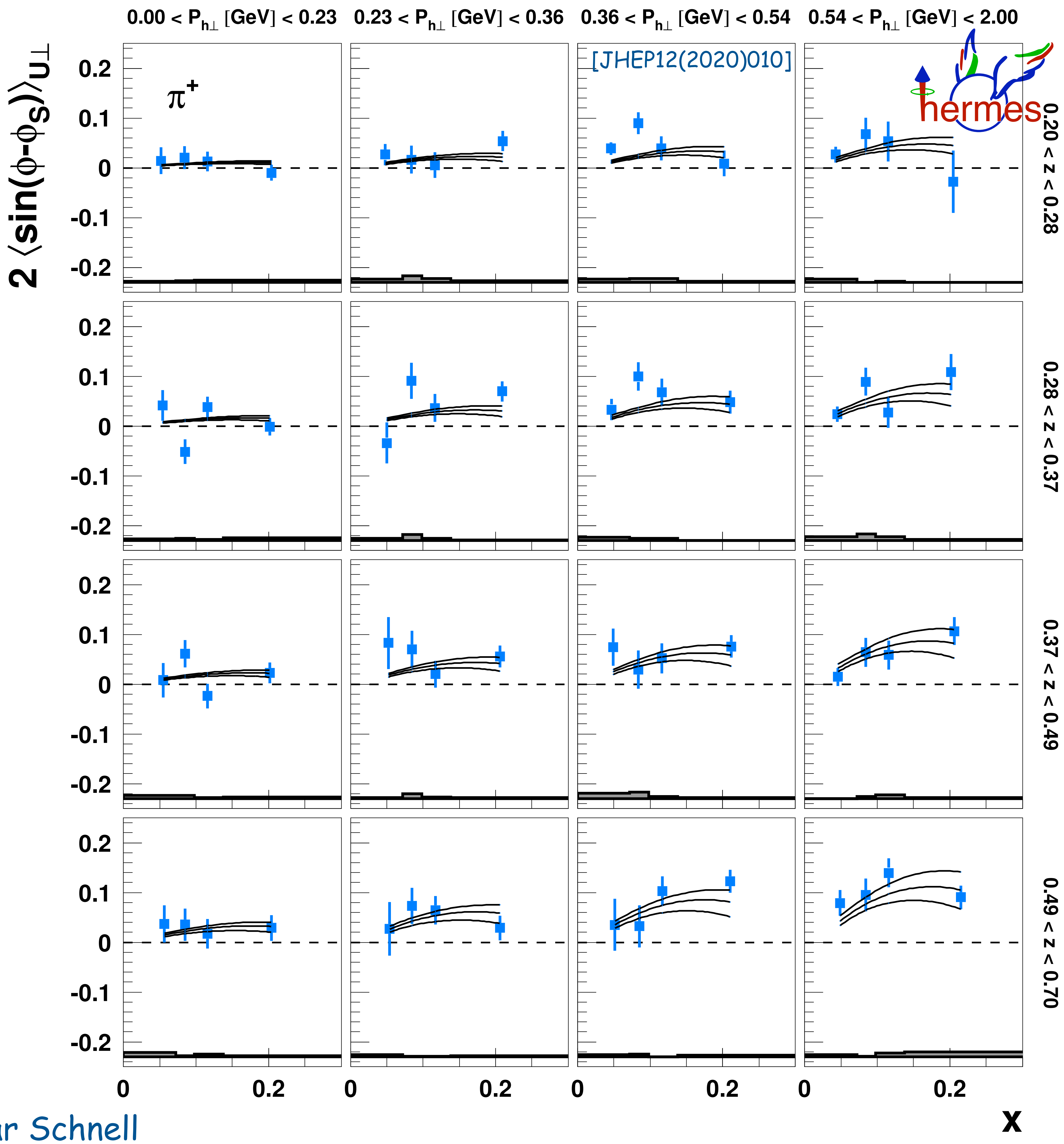
Sivers amplitudes multi-dimensional analysis



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

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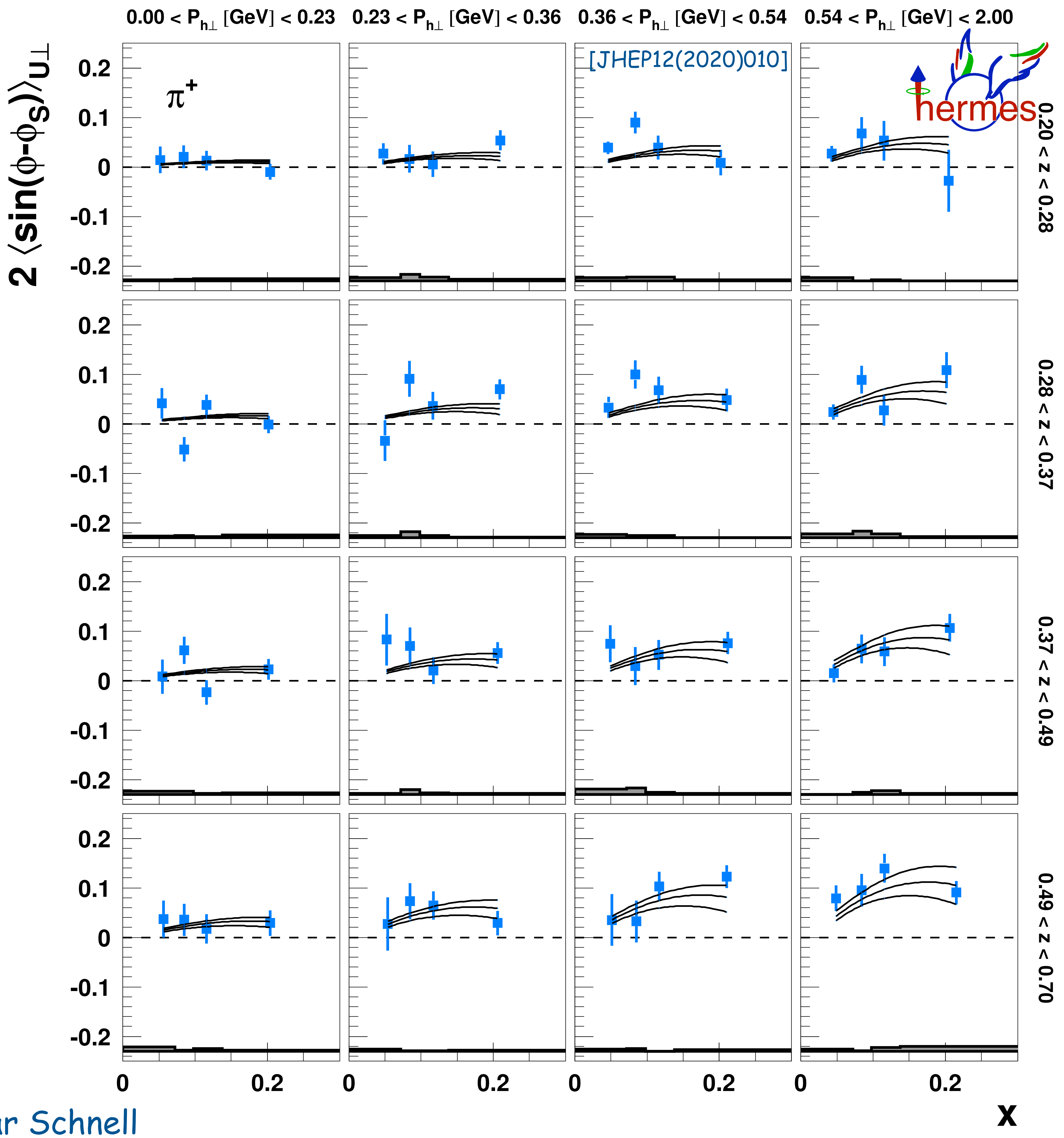

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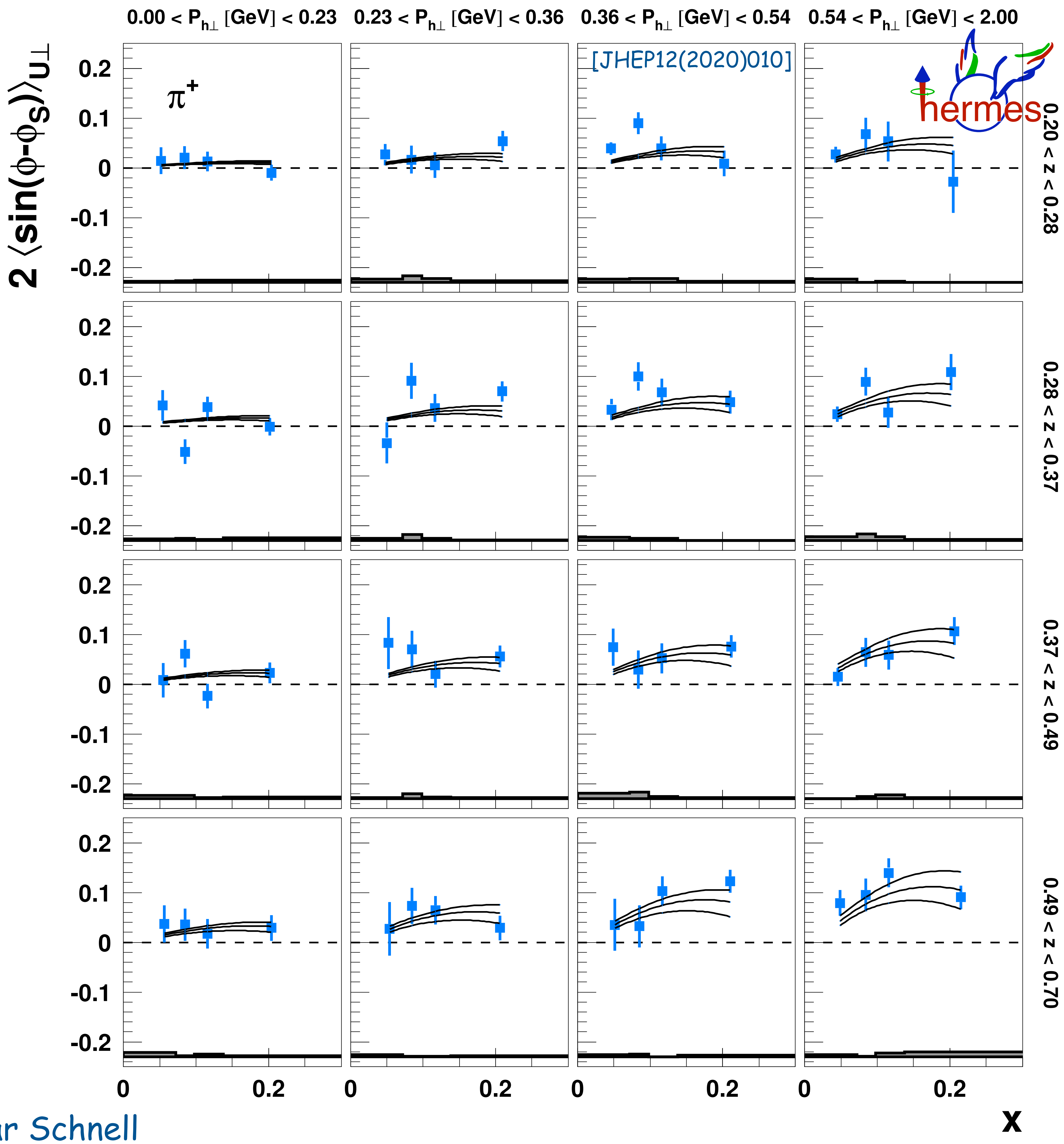
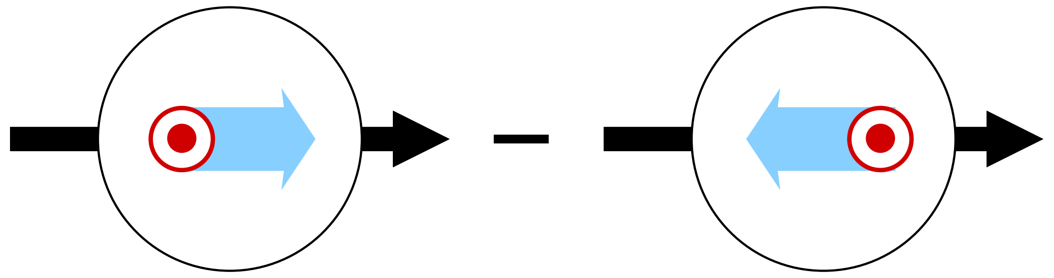


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
  - reduced systematics
  - disentangle correlations
  - isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distributions to guide phenomenology*)

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

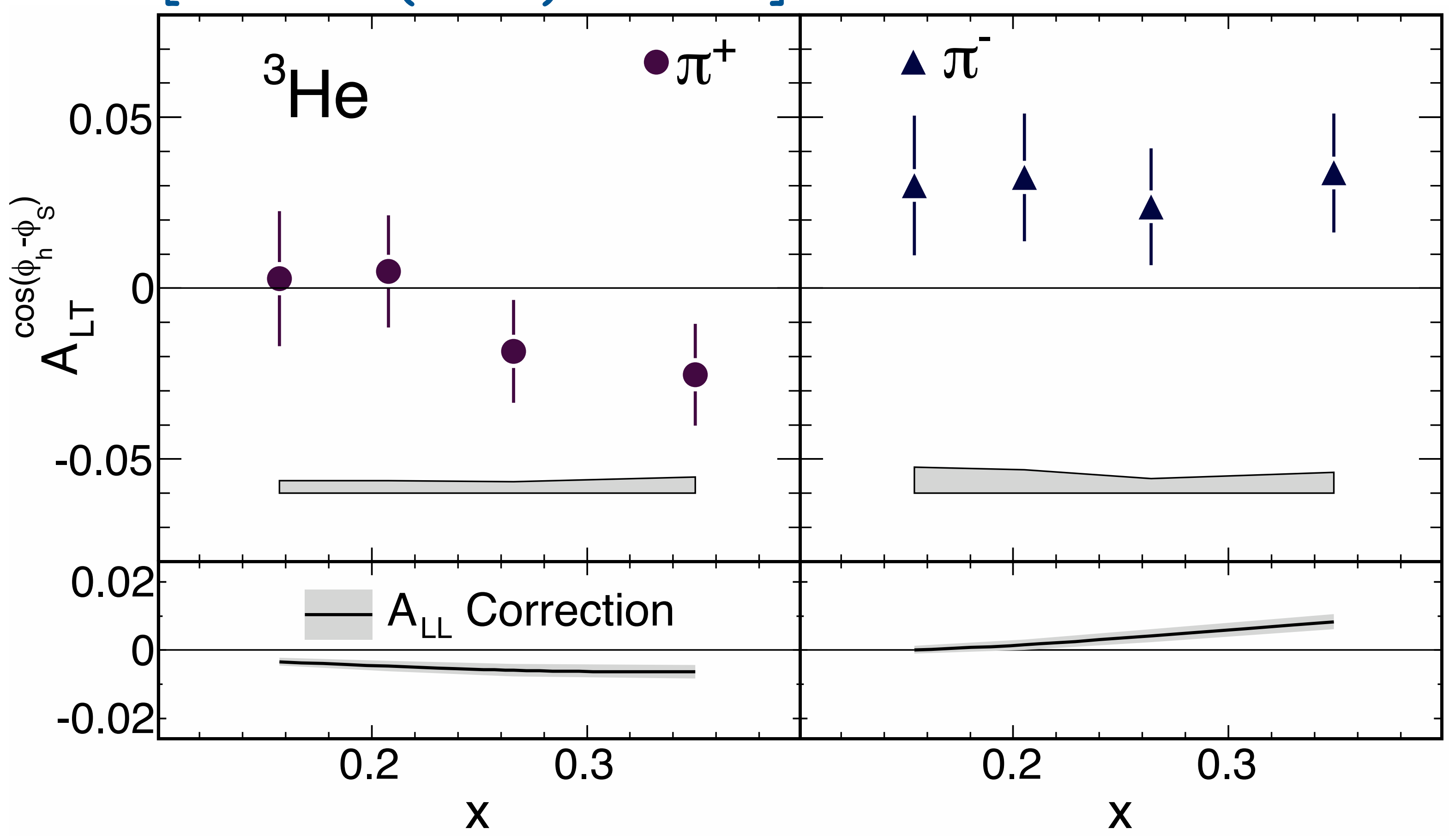
Worm-Gear II

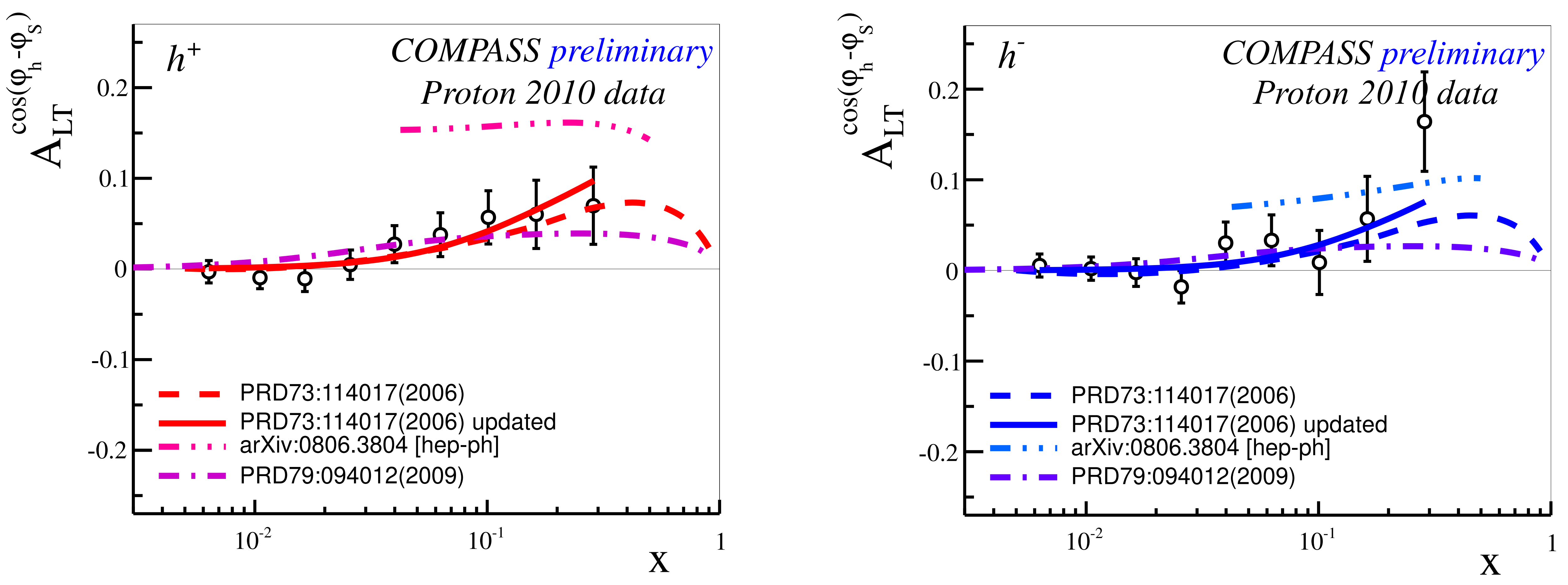
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



- quark-helicity asymmetry in transversely polarized nucleon
- evidences from
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

[PRL 108 (2012) 052001]





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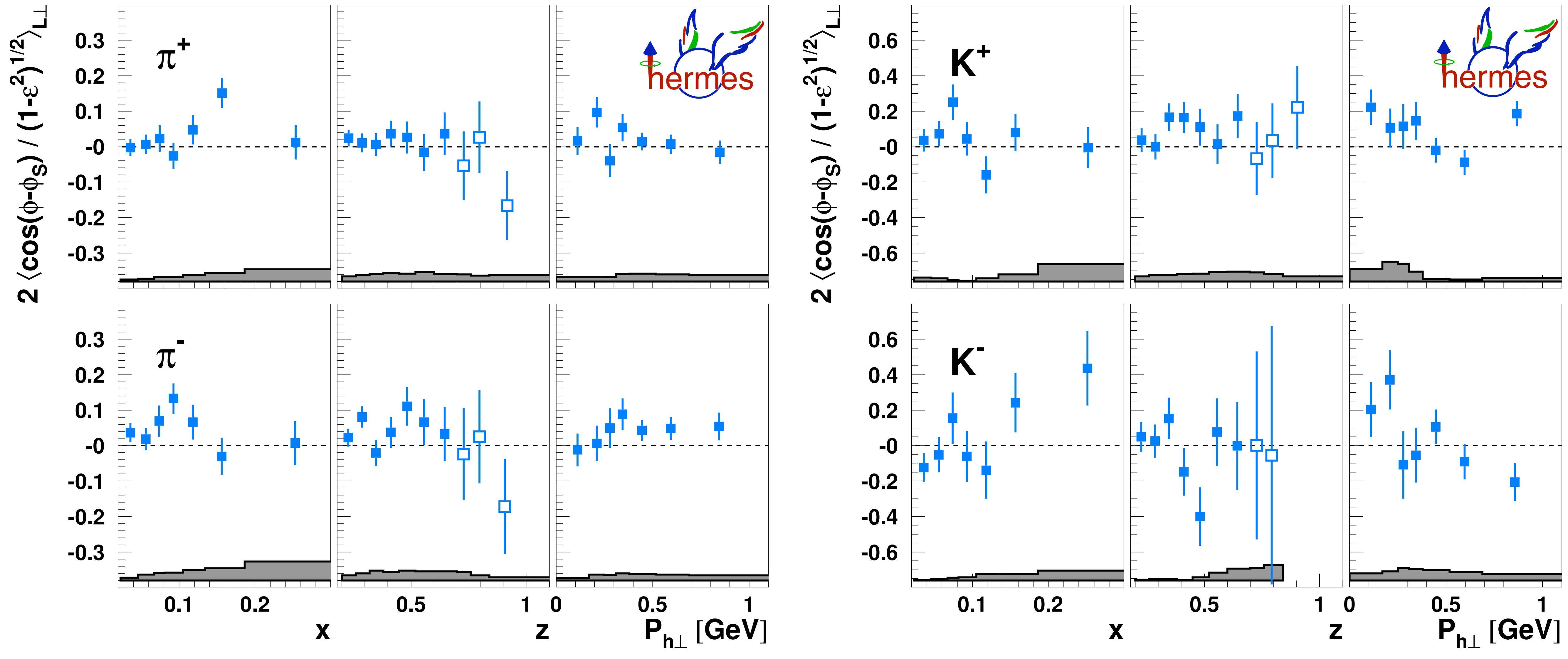

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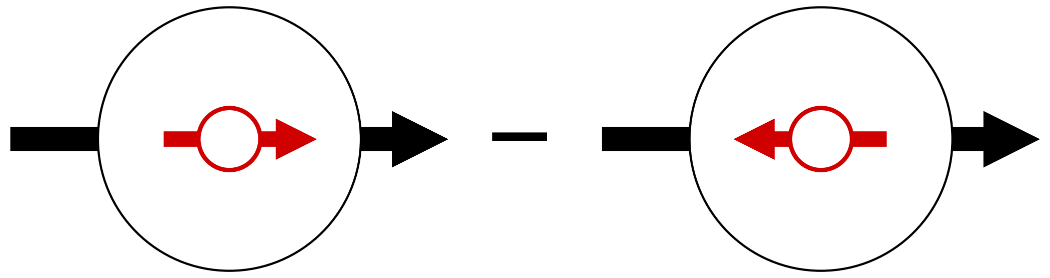
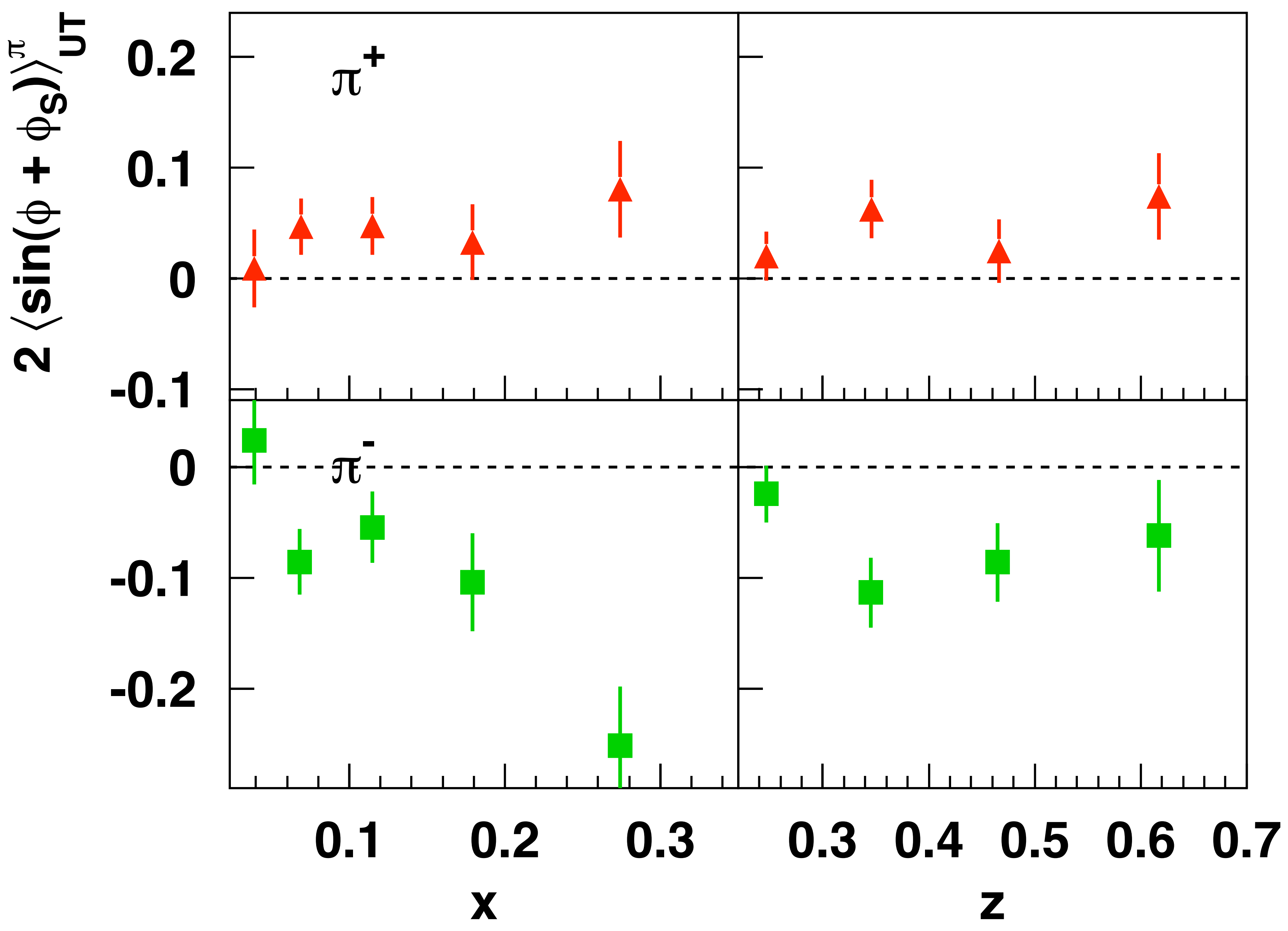


Transversity (Collins fragmentation)

[HERMES, PRL 94 (2005) 012002]



2005: first evidence from HERMES semi-inclusive DIS on proton

- significant in size and opposite in sign for charged pions
  - non-zero transversity!
  - non-zero Collins function!

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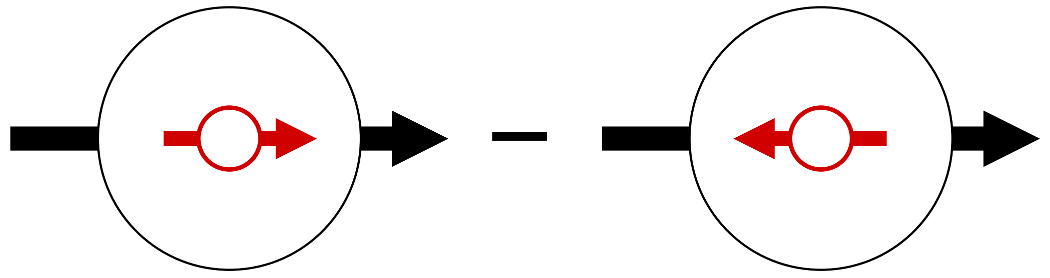

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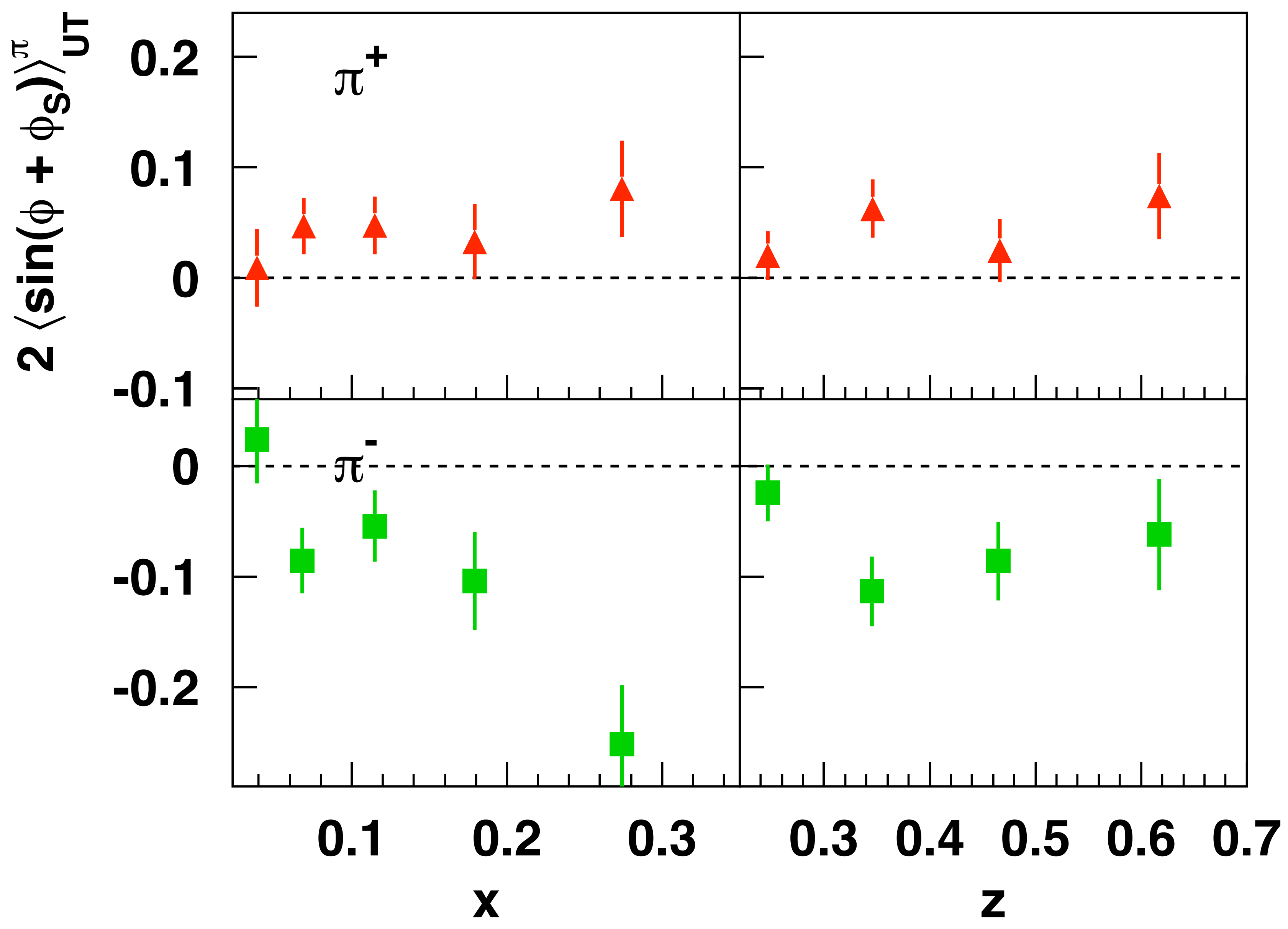

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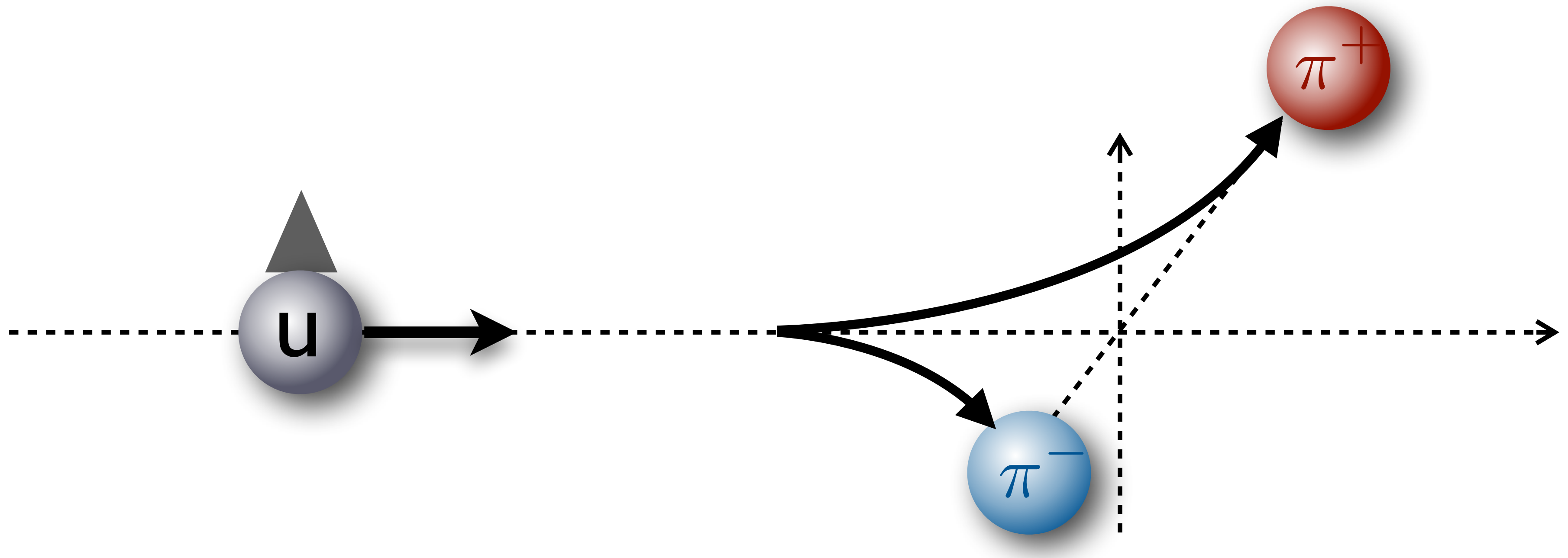
  - non-zero Collins function!
- **disfavored** Collins FF **large** and **opposite in sign** to favored one



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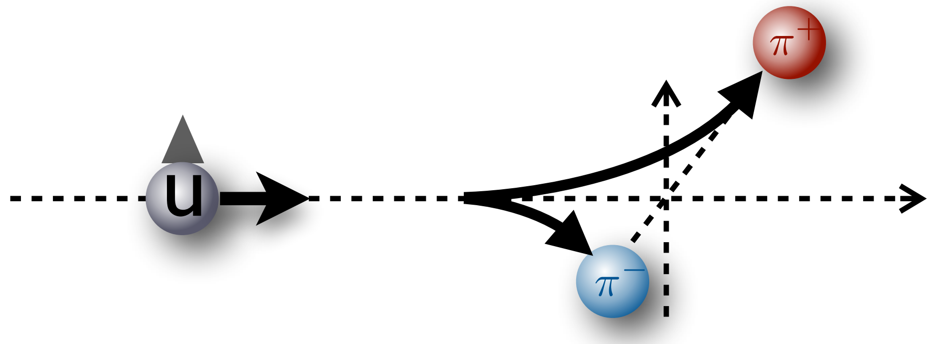

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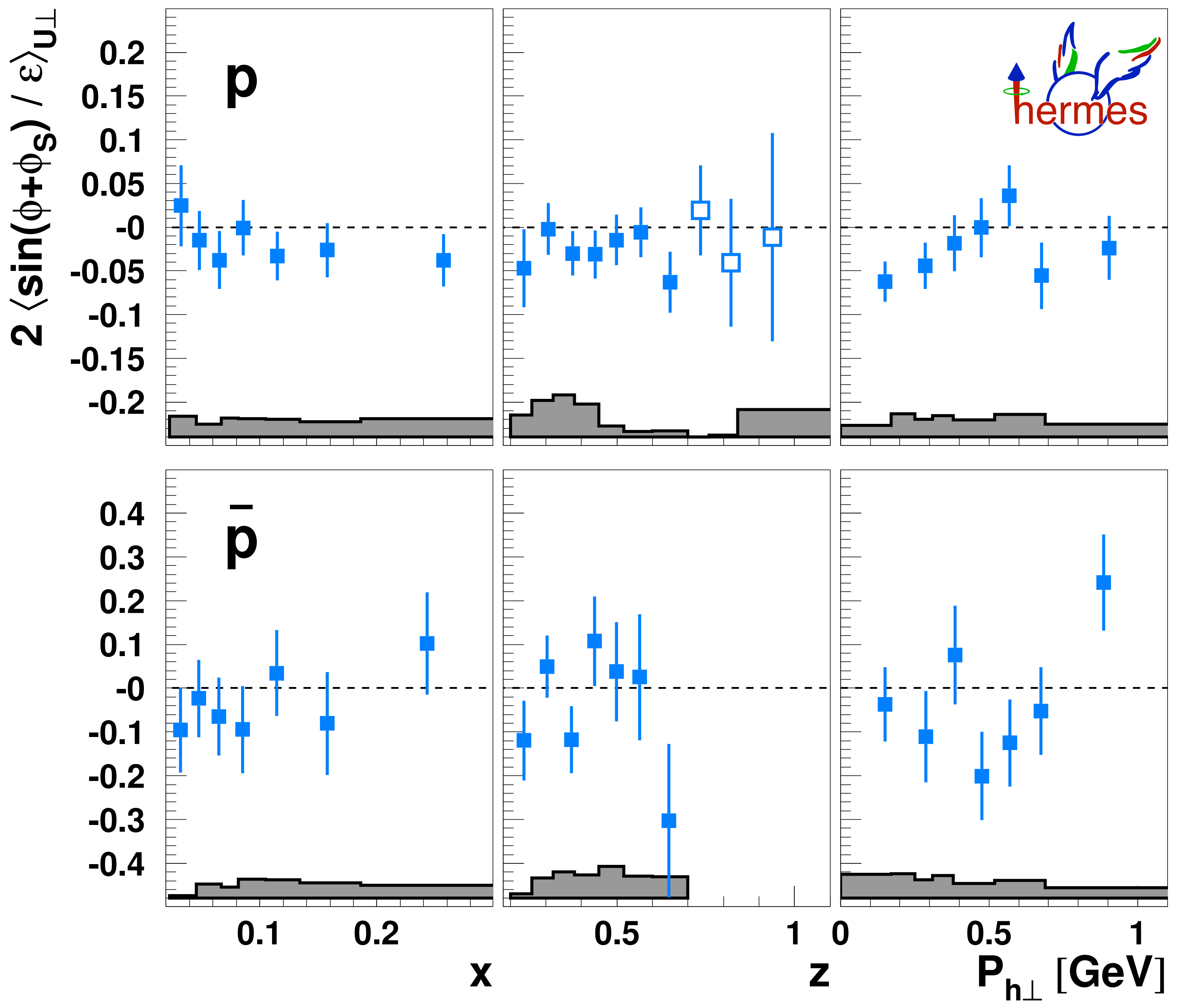

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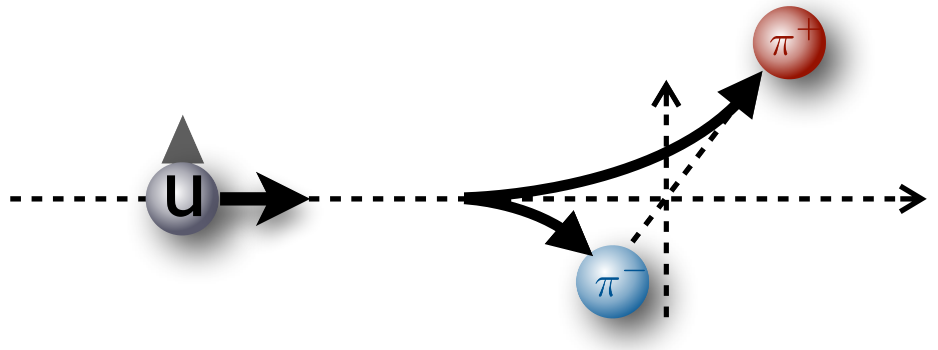

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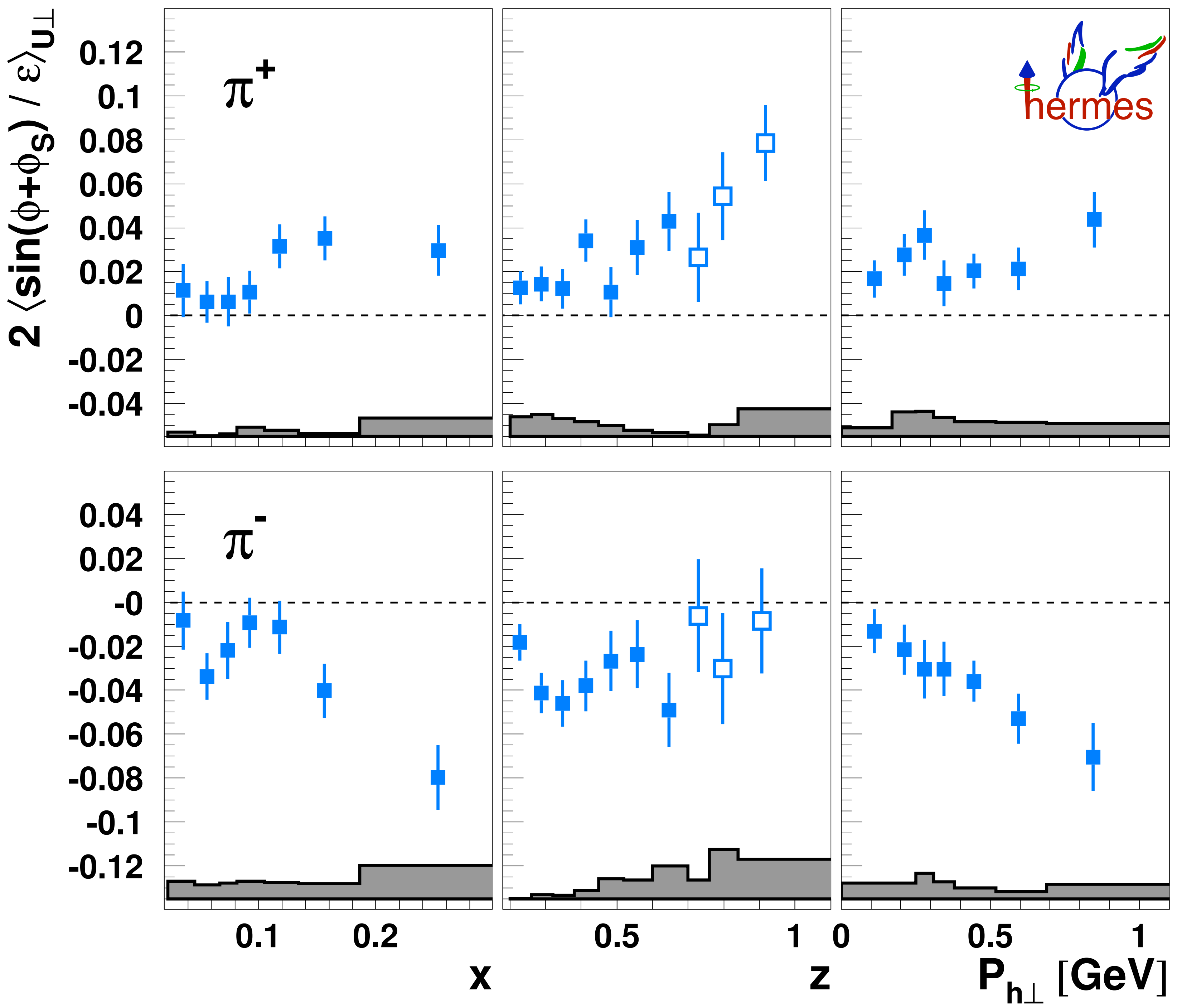

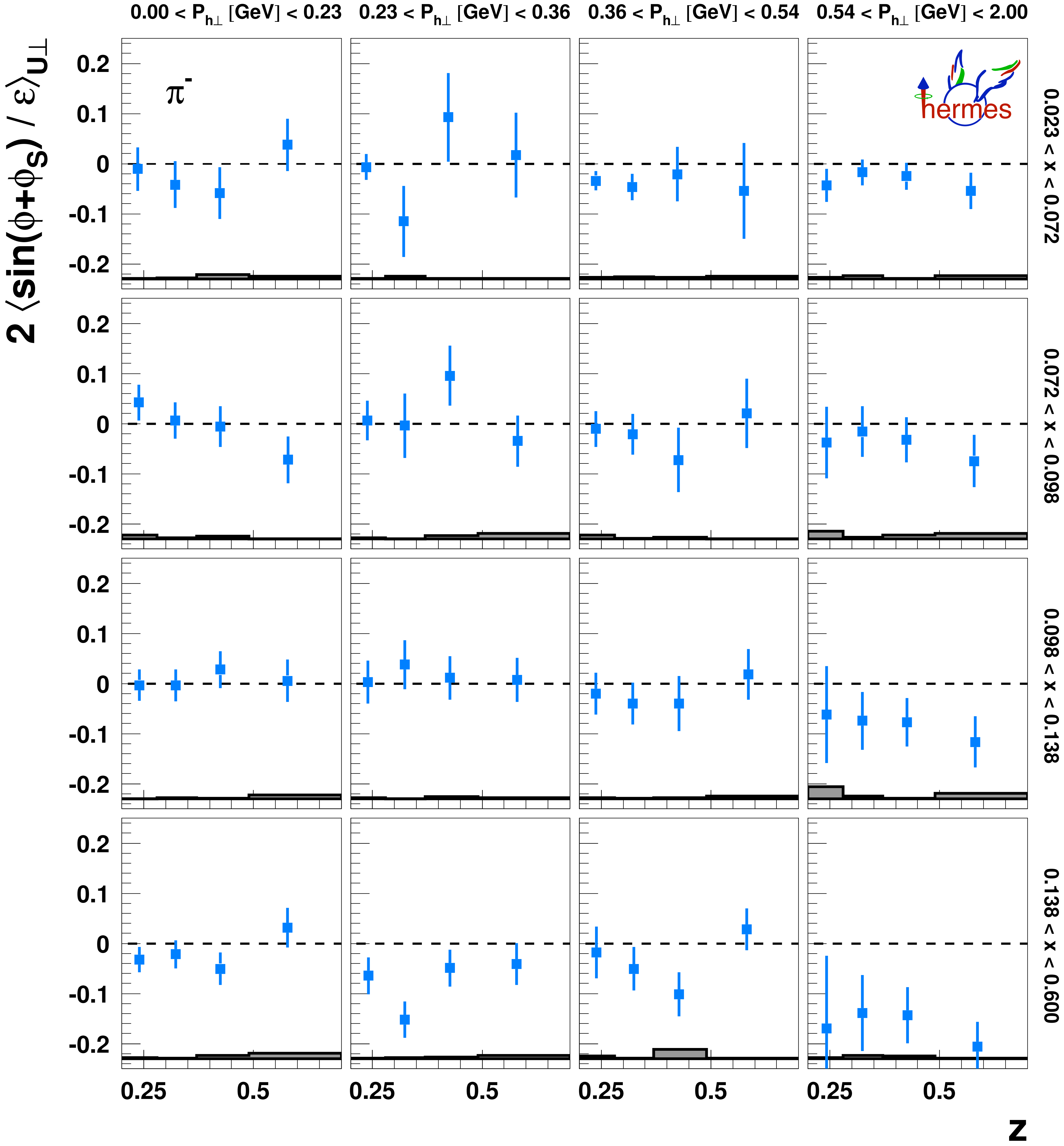

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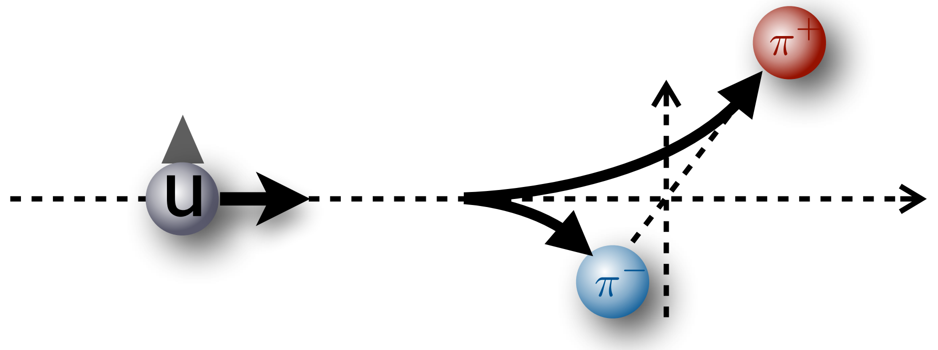

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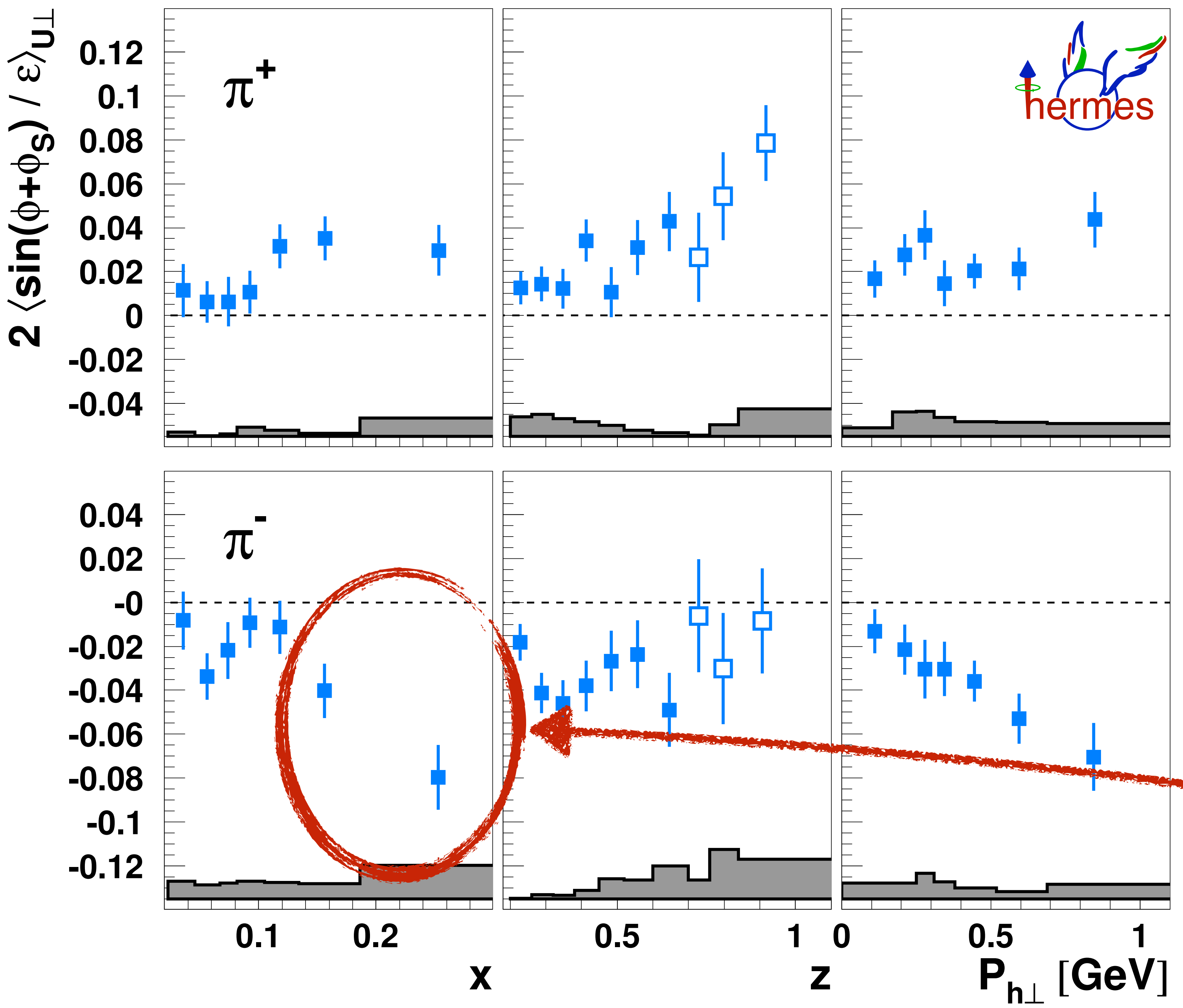

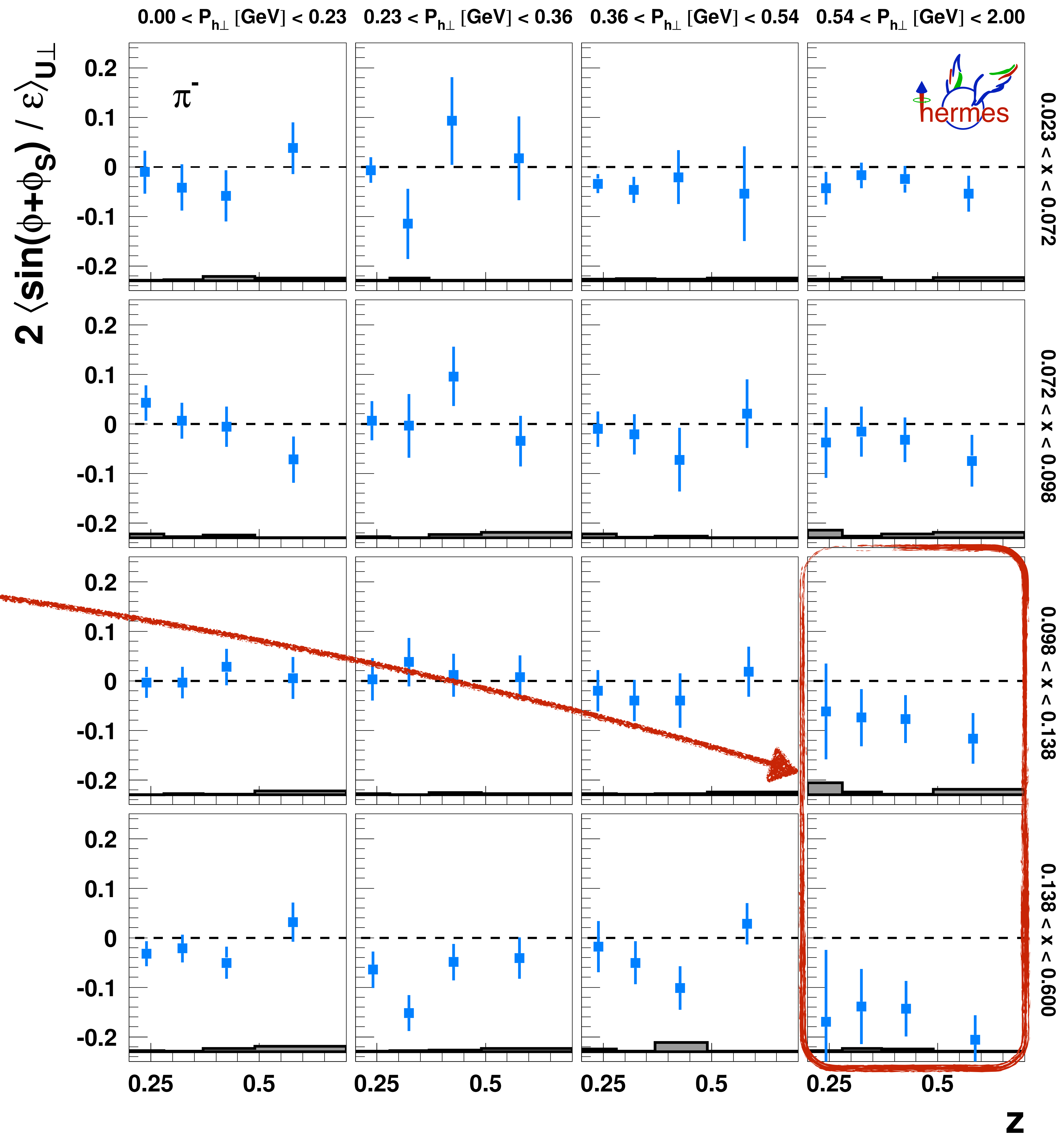

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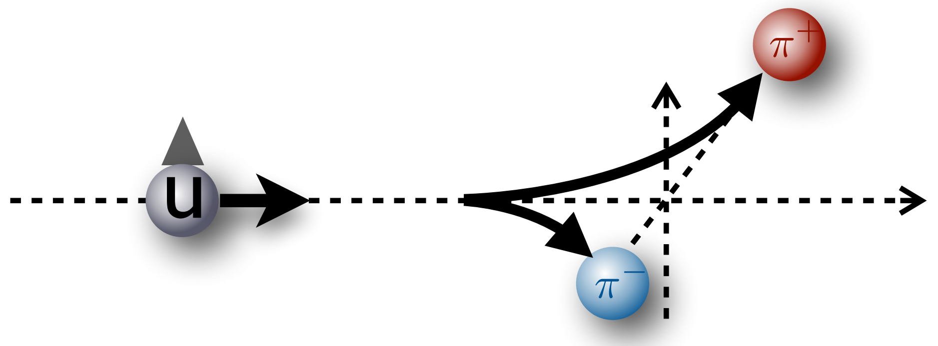
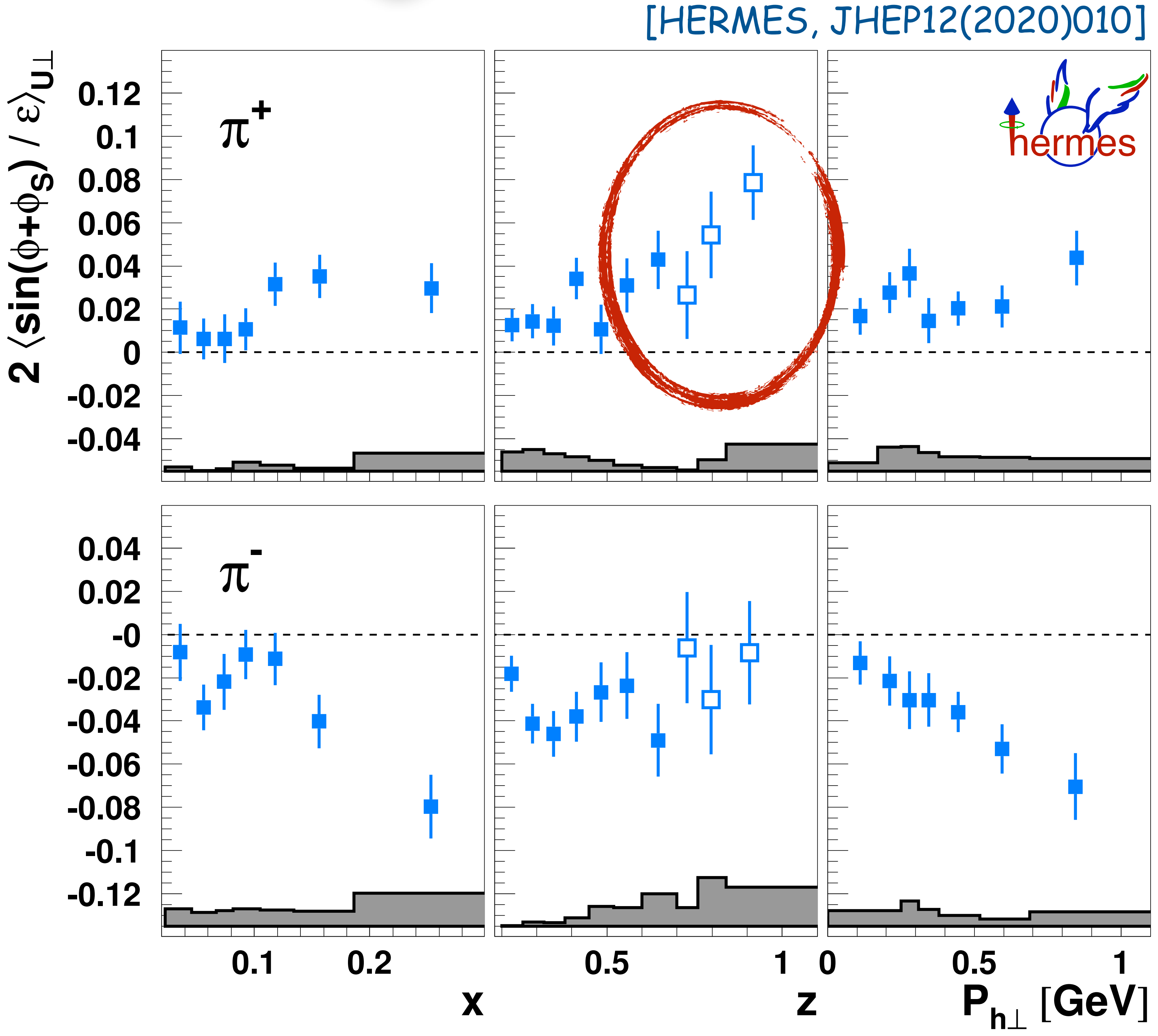
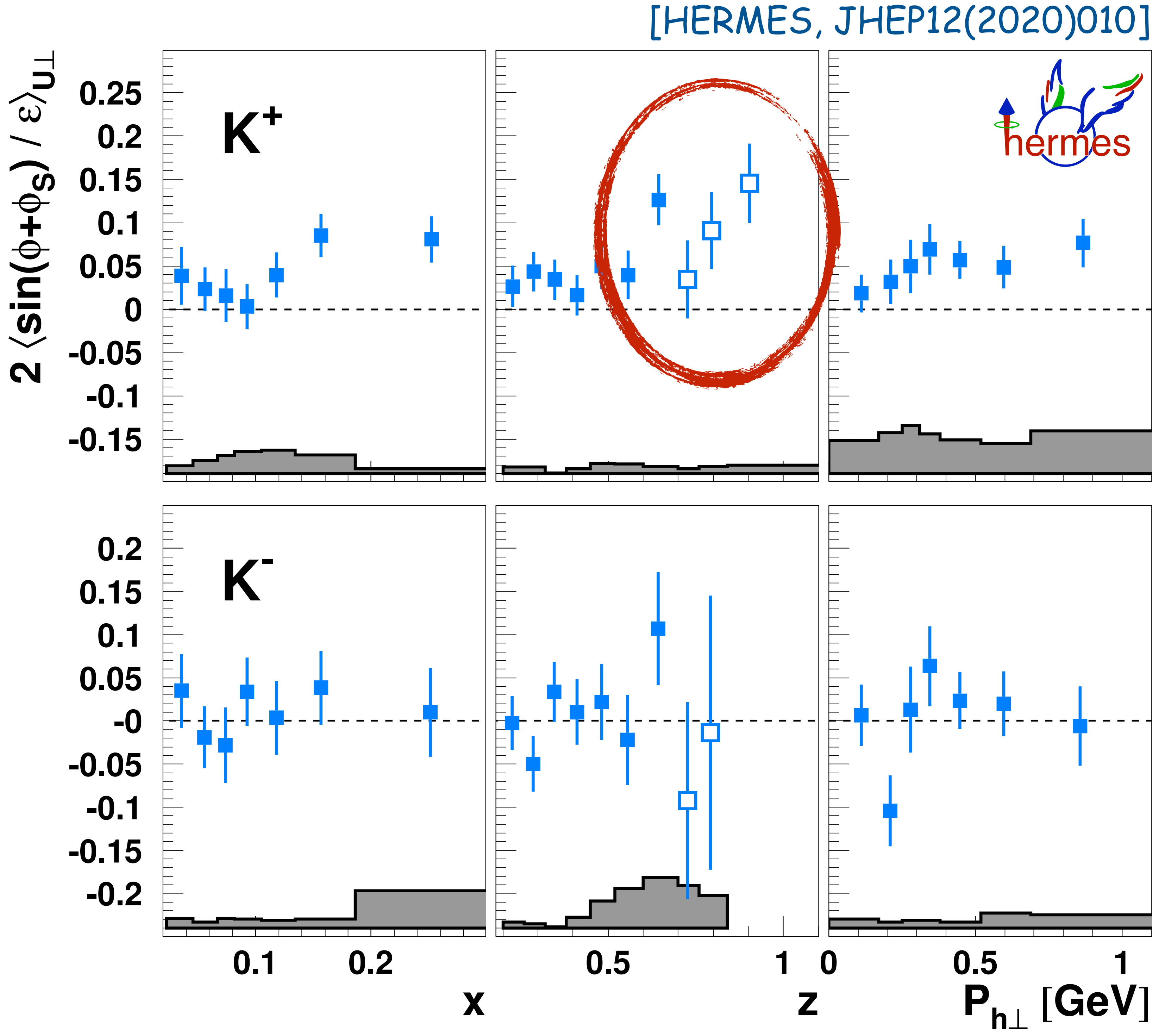






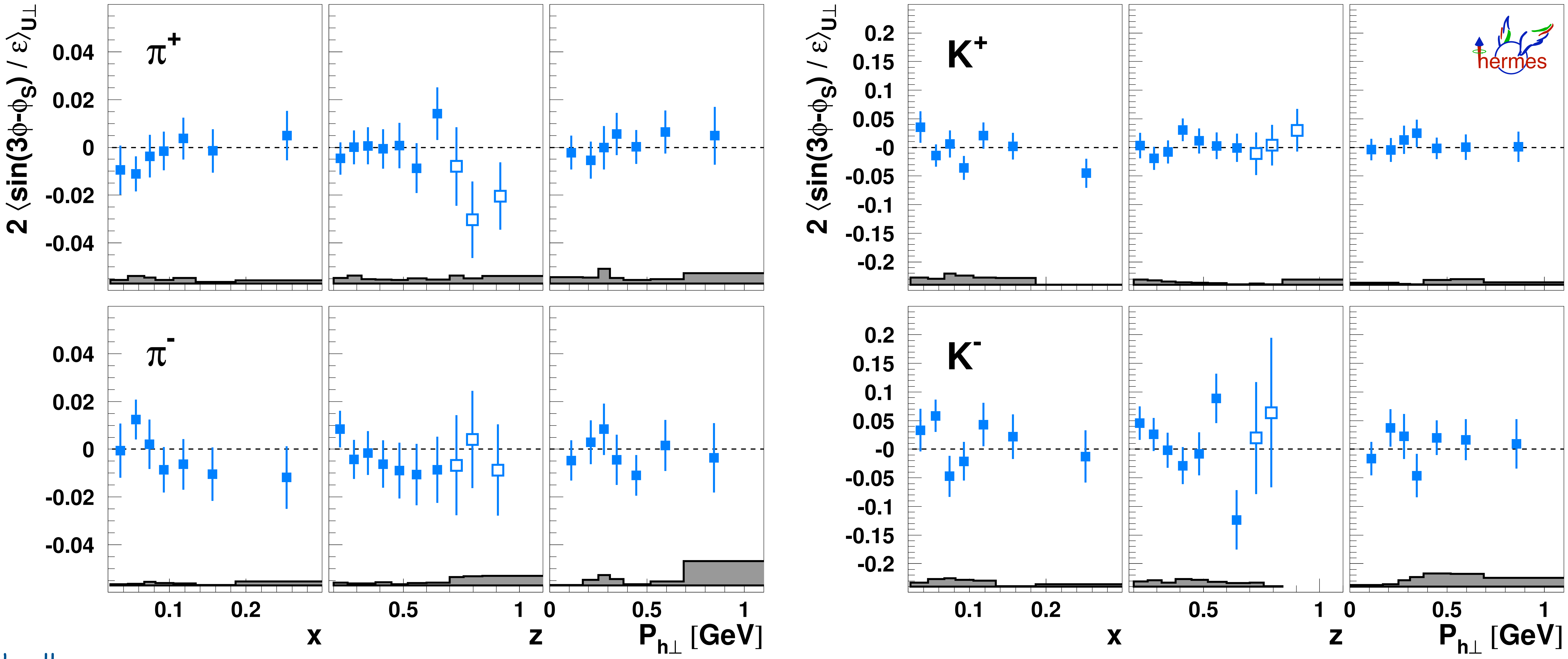
- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**
- **high-z region** probes region of increased flavour sensitivity of struck quark with increasing amplitudes for positive pions and kaons (but also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

Pretzelosity

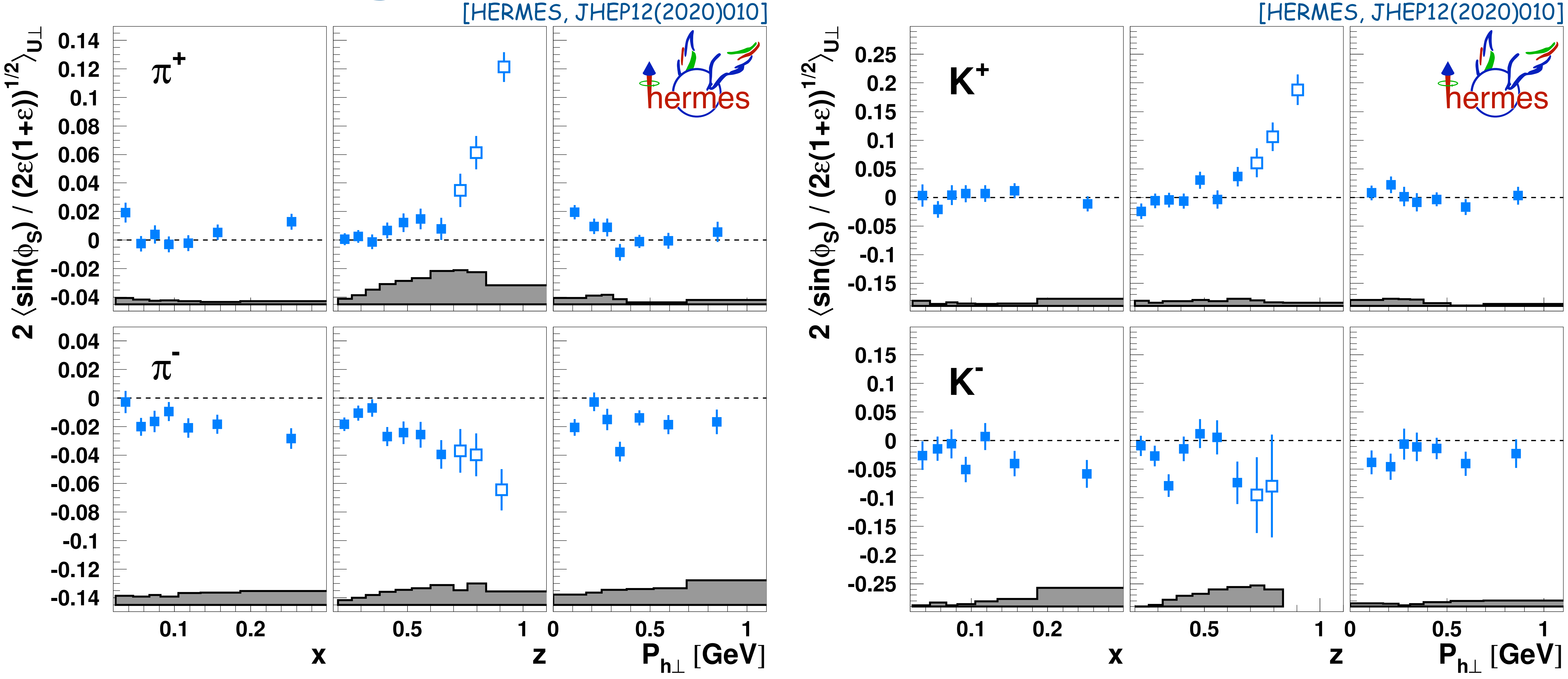
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

- quadrupole deformation in momentum space
- chiral-odd ➥ needs Collins FF (or similar)
- ^{1}H, ^{2}H & ^{3}He data from various experiments consistently small/vanishing
- cancelations? pretzelosity=zero? or just the additional general suppression of the asymmetry by two powers of $P_{h\perp}/M_N$

[HERMES, JHEP12(2020)010] [HERMES, JHEP12(2020)010]



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



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

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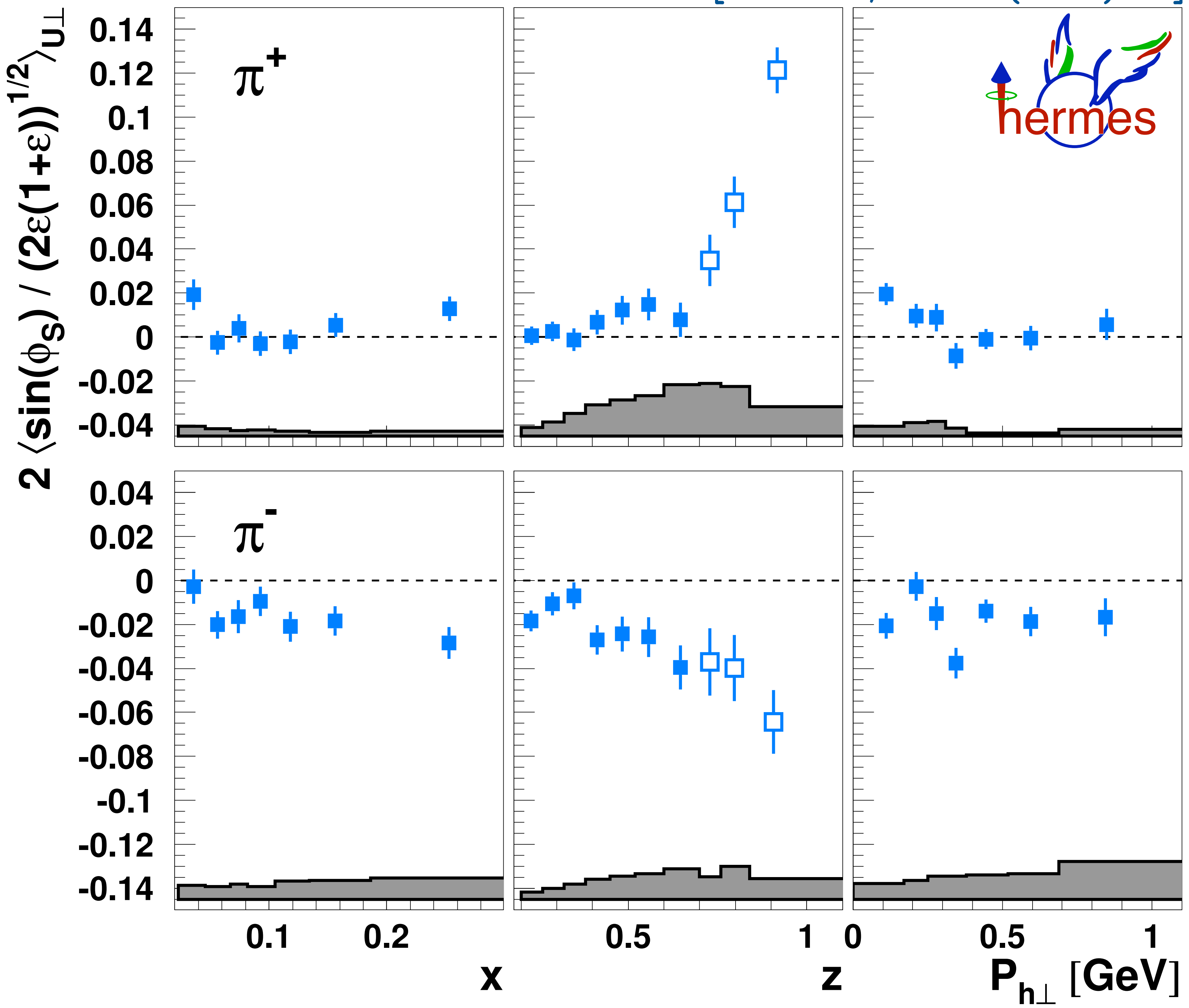

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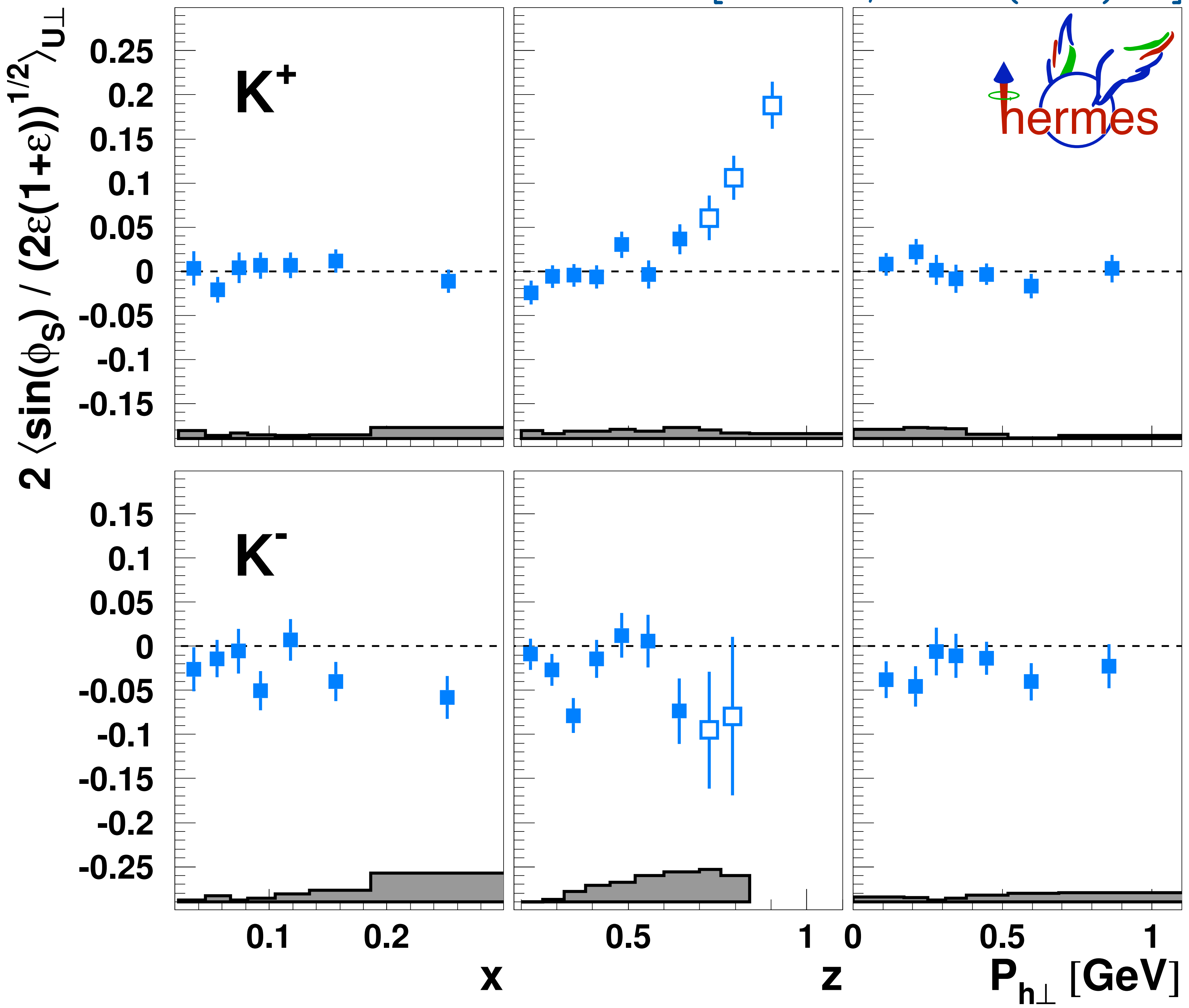

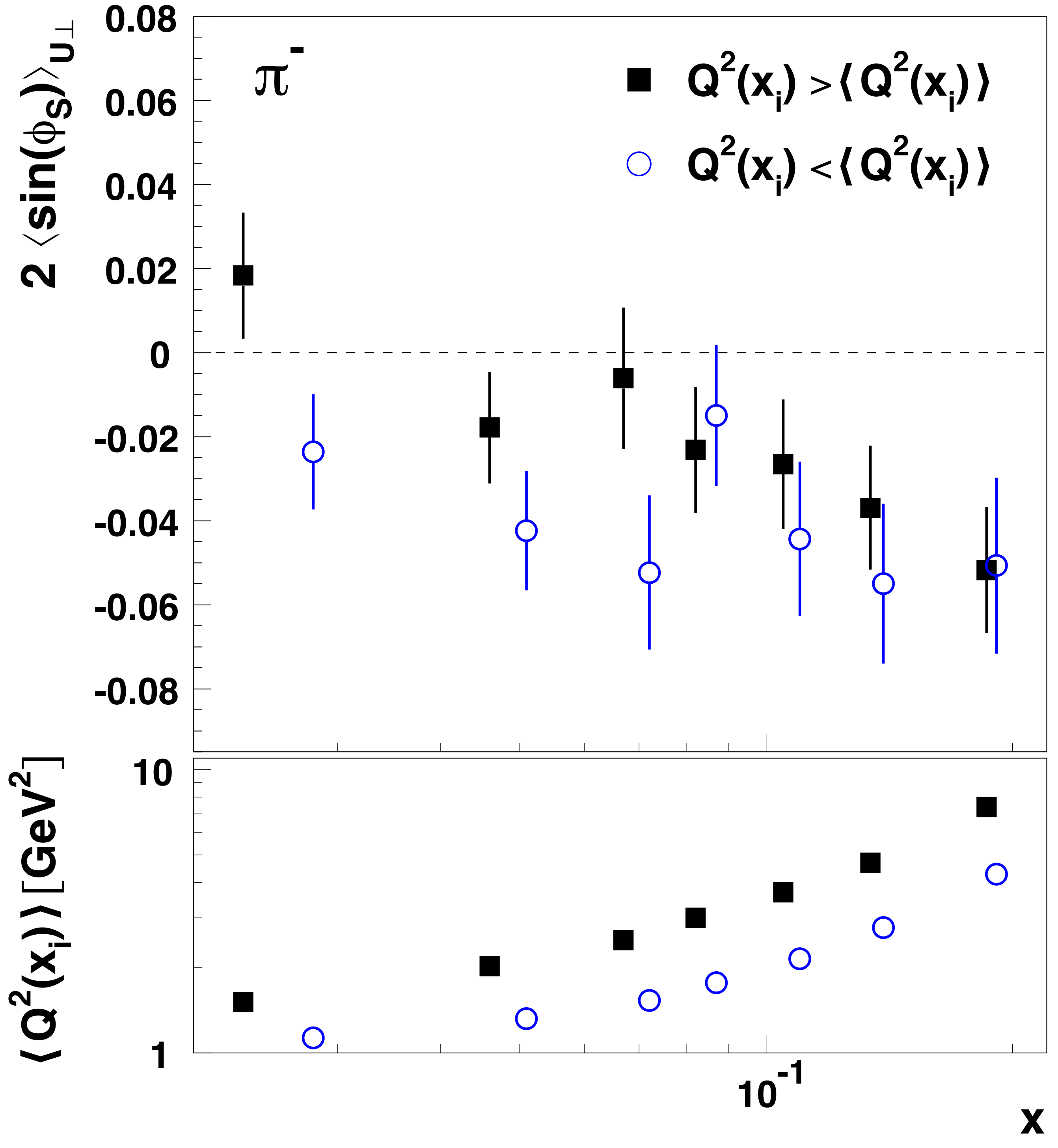

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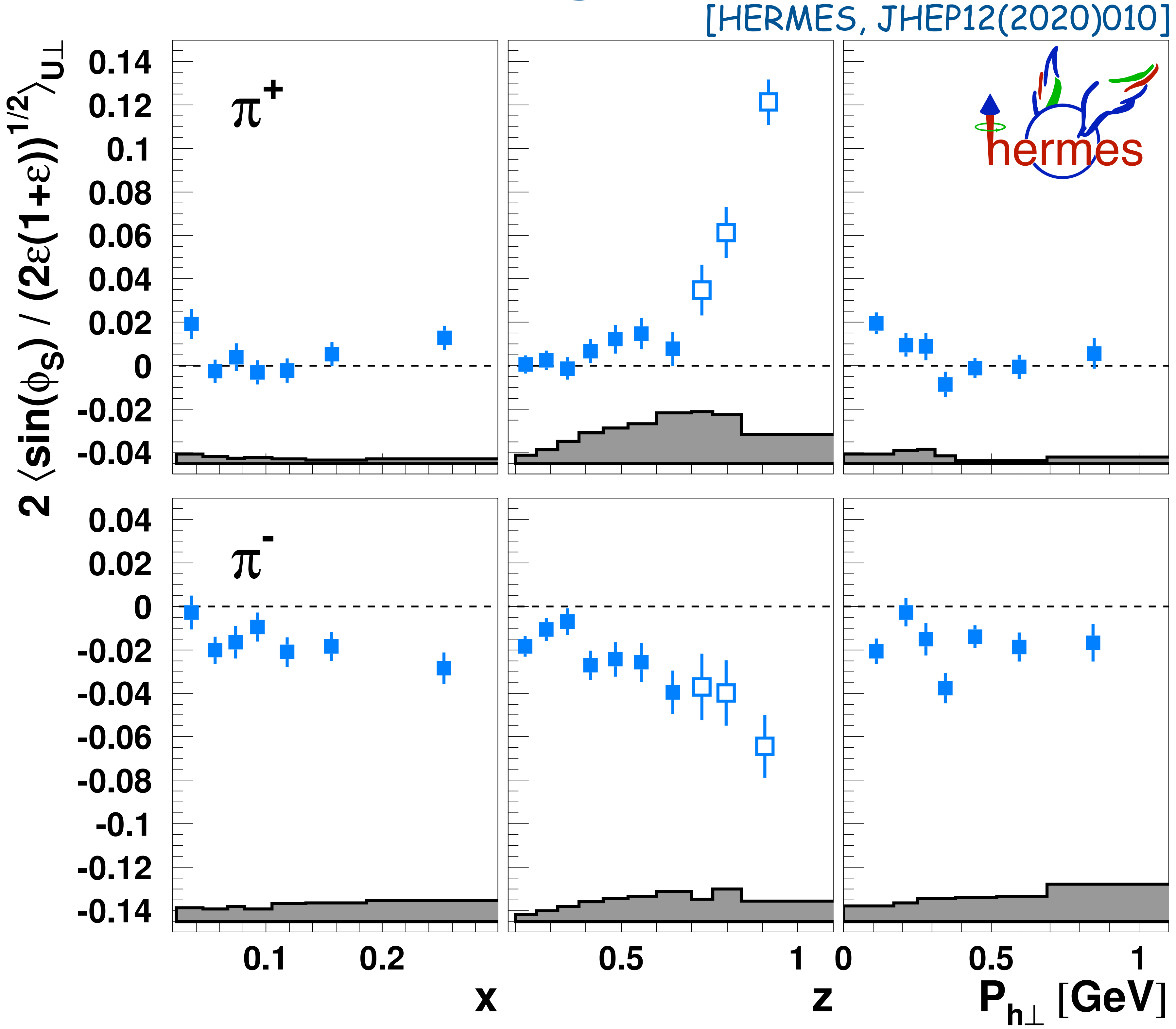
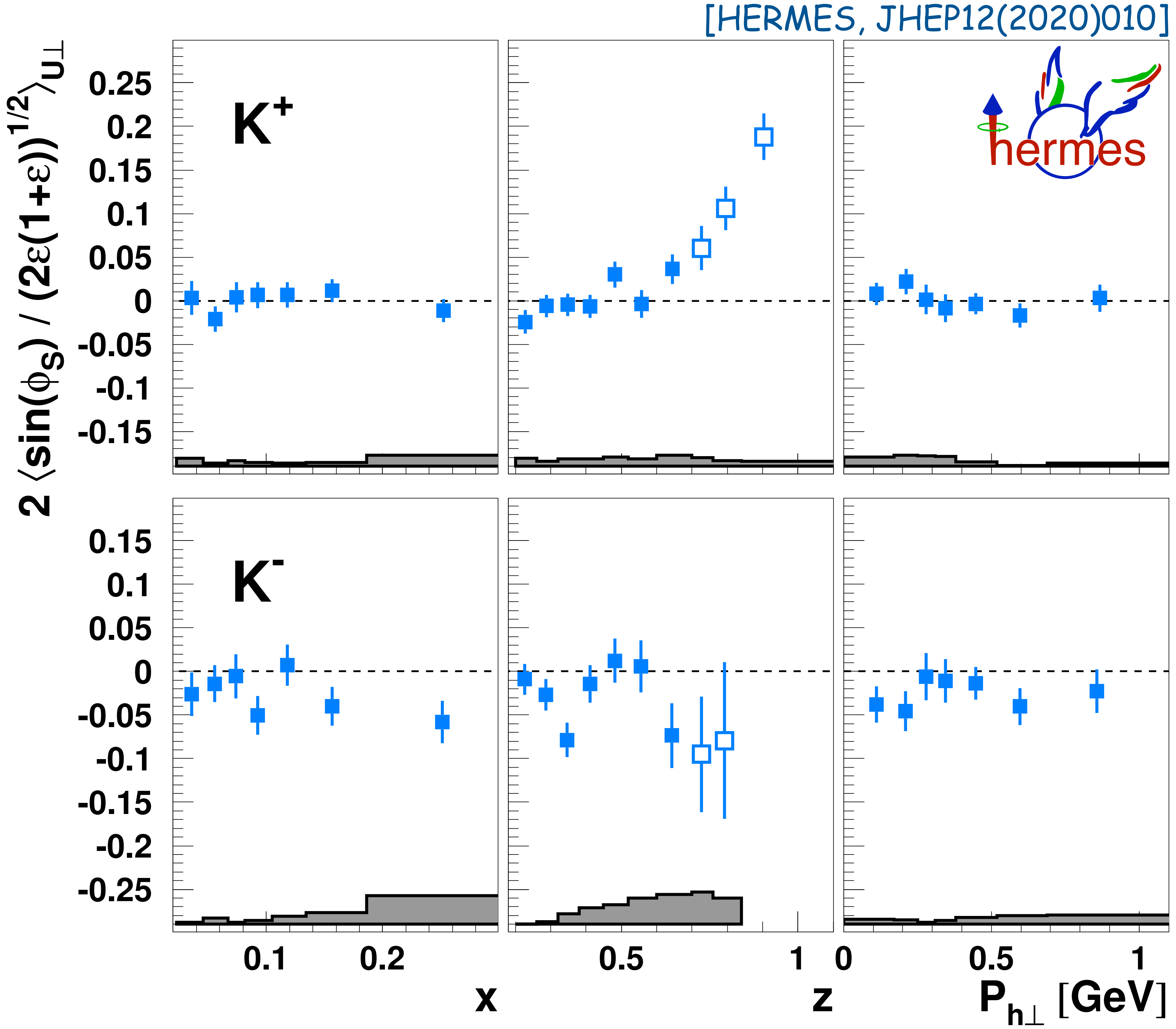
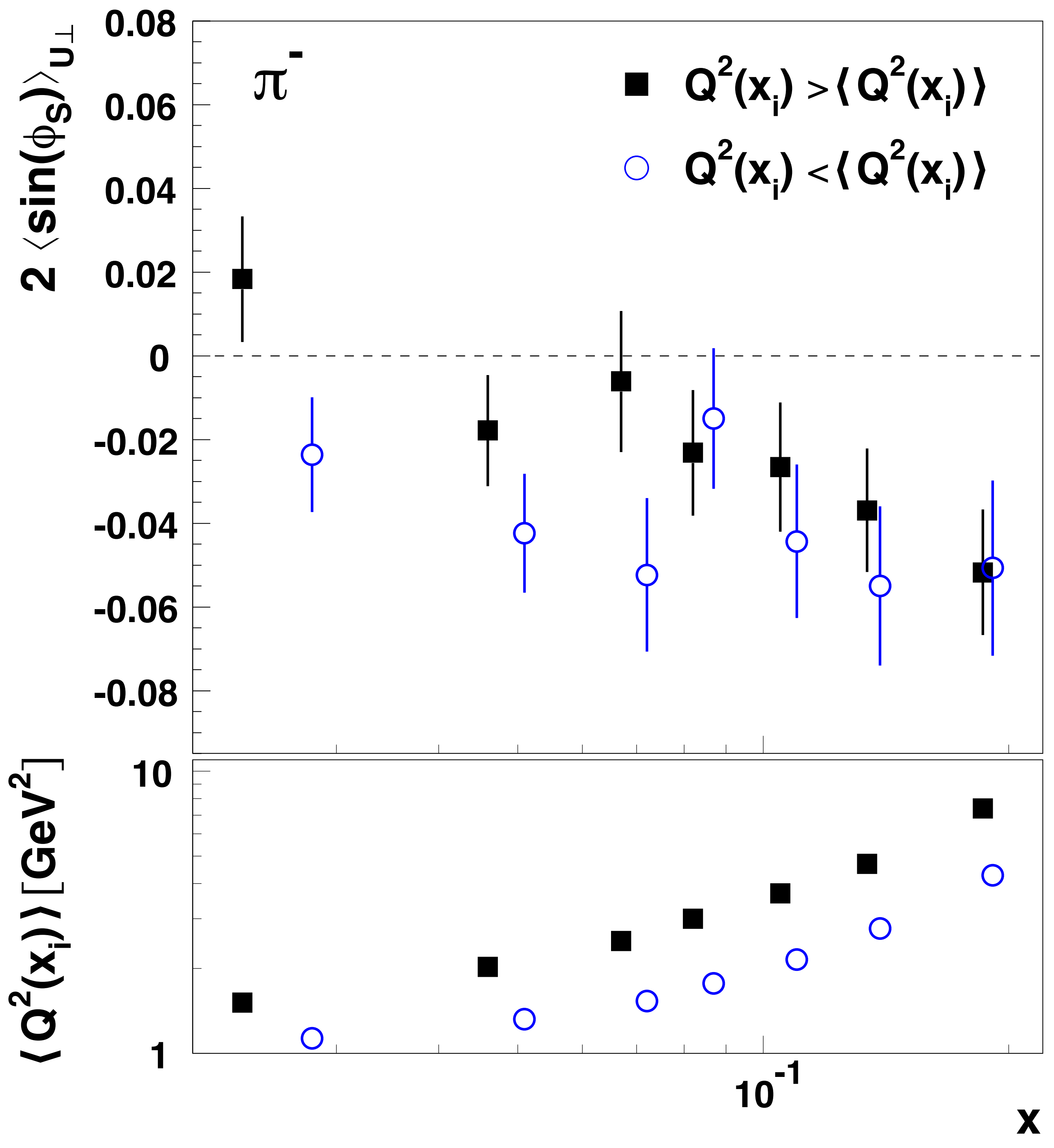
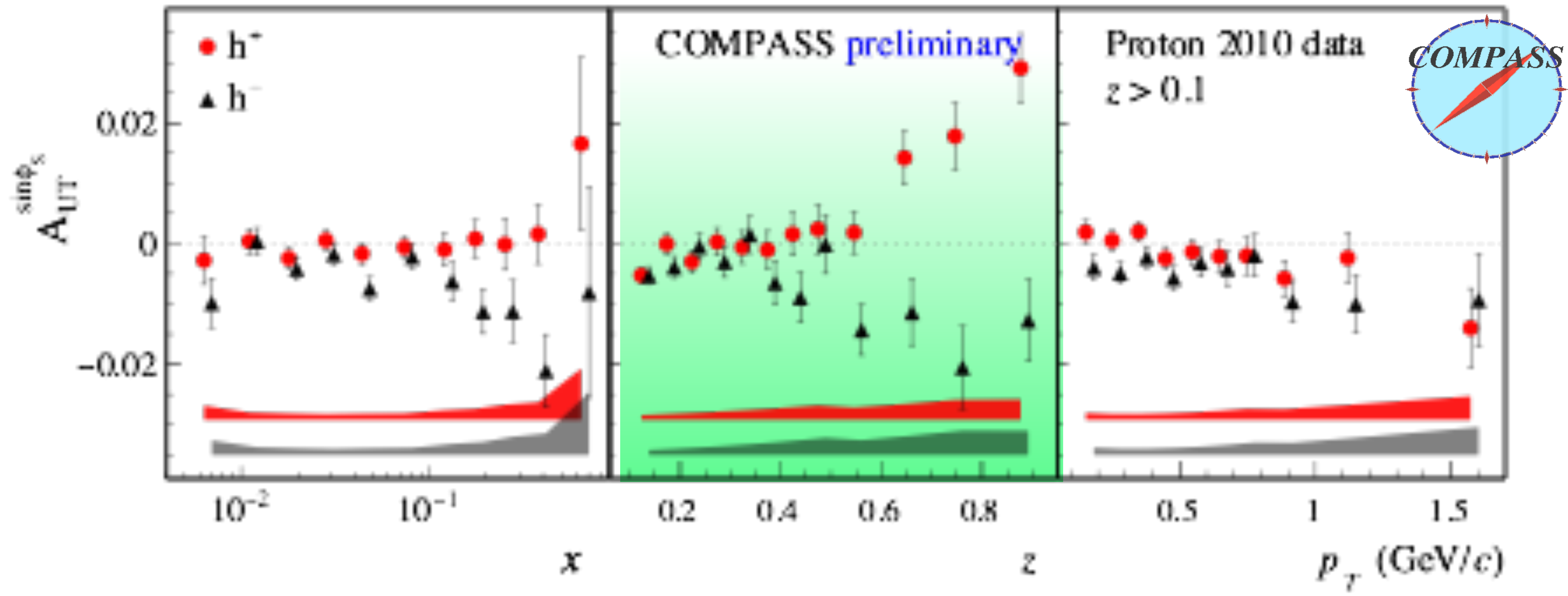






- clearly non-zero asymmetries with opposite sign for charged pions (Collins-like behaviour)
- striking z dependence and in particular magnitude
- hint of Q suppression
- similar z behaviour seen at COMPASS



Conclusions

- HERMES continues producing results long after its shut-down, latest publications providing 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) but no sign for pretzelosity => **clear dipole but no quadrupole deformations**
  - surprisingly **large 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

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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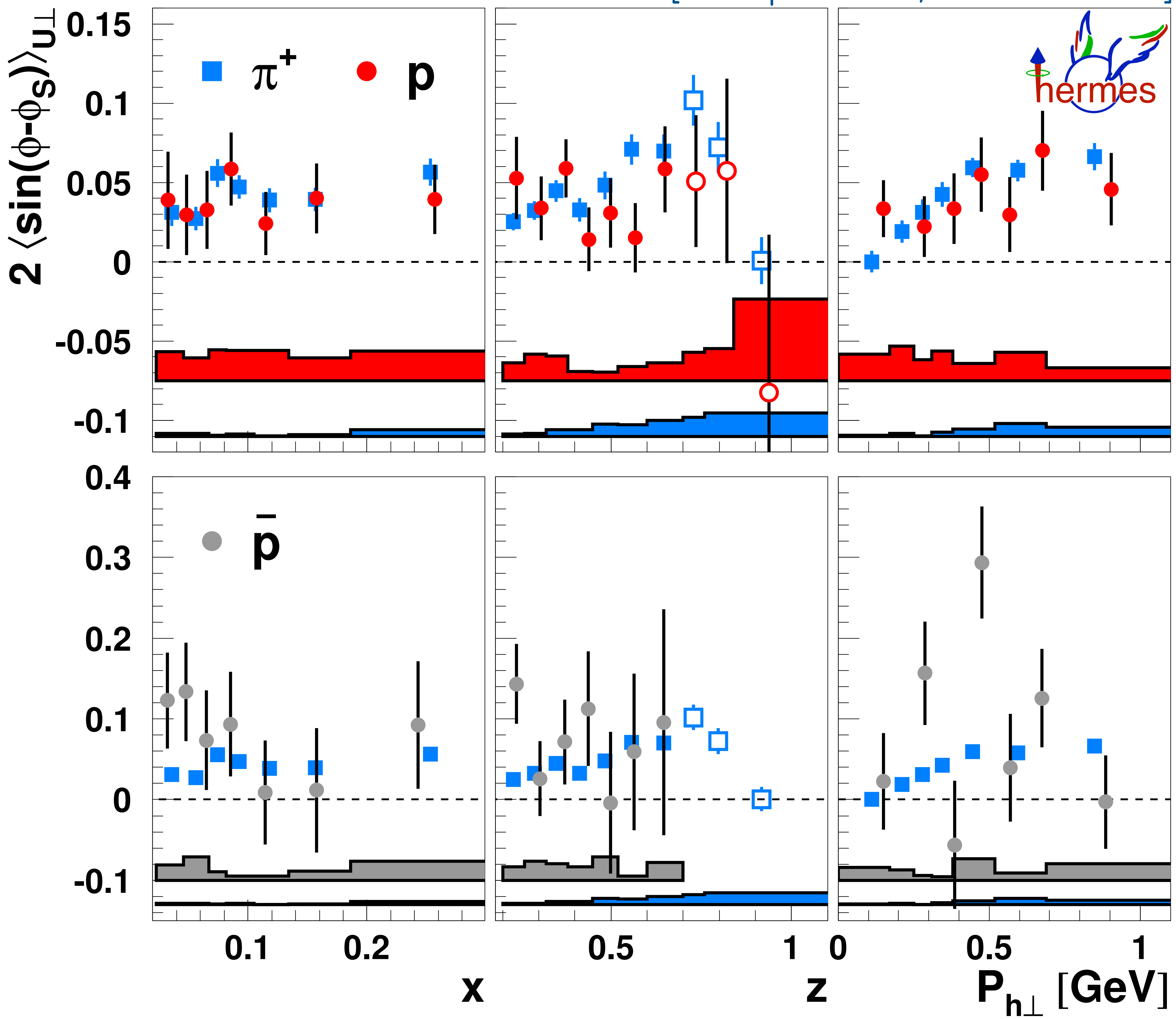
Sivers amplitudes
pions vs. (anti)protons

[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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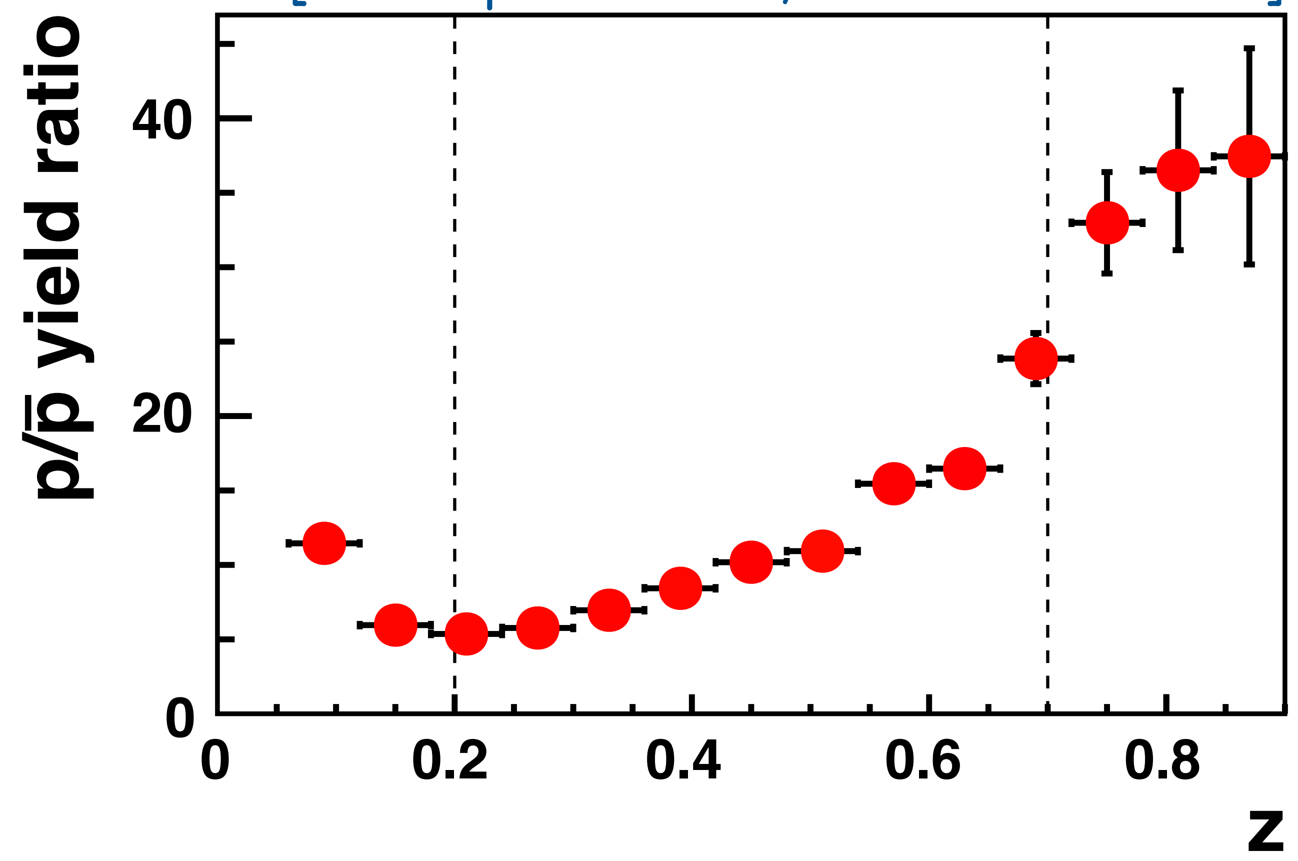

possibly, onset of target fragmentation only at lower z

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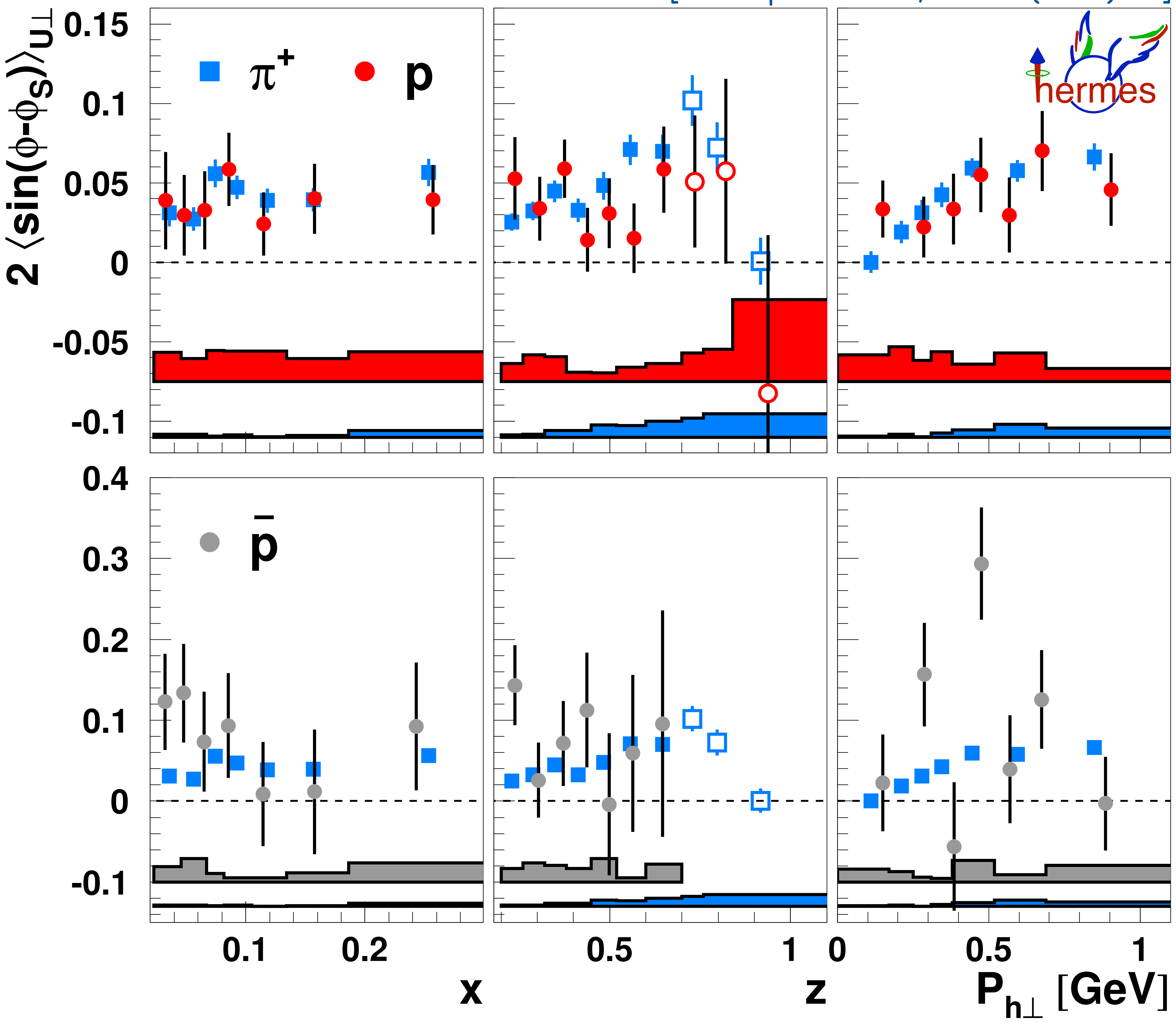

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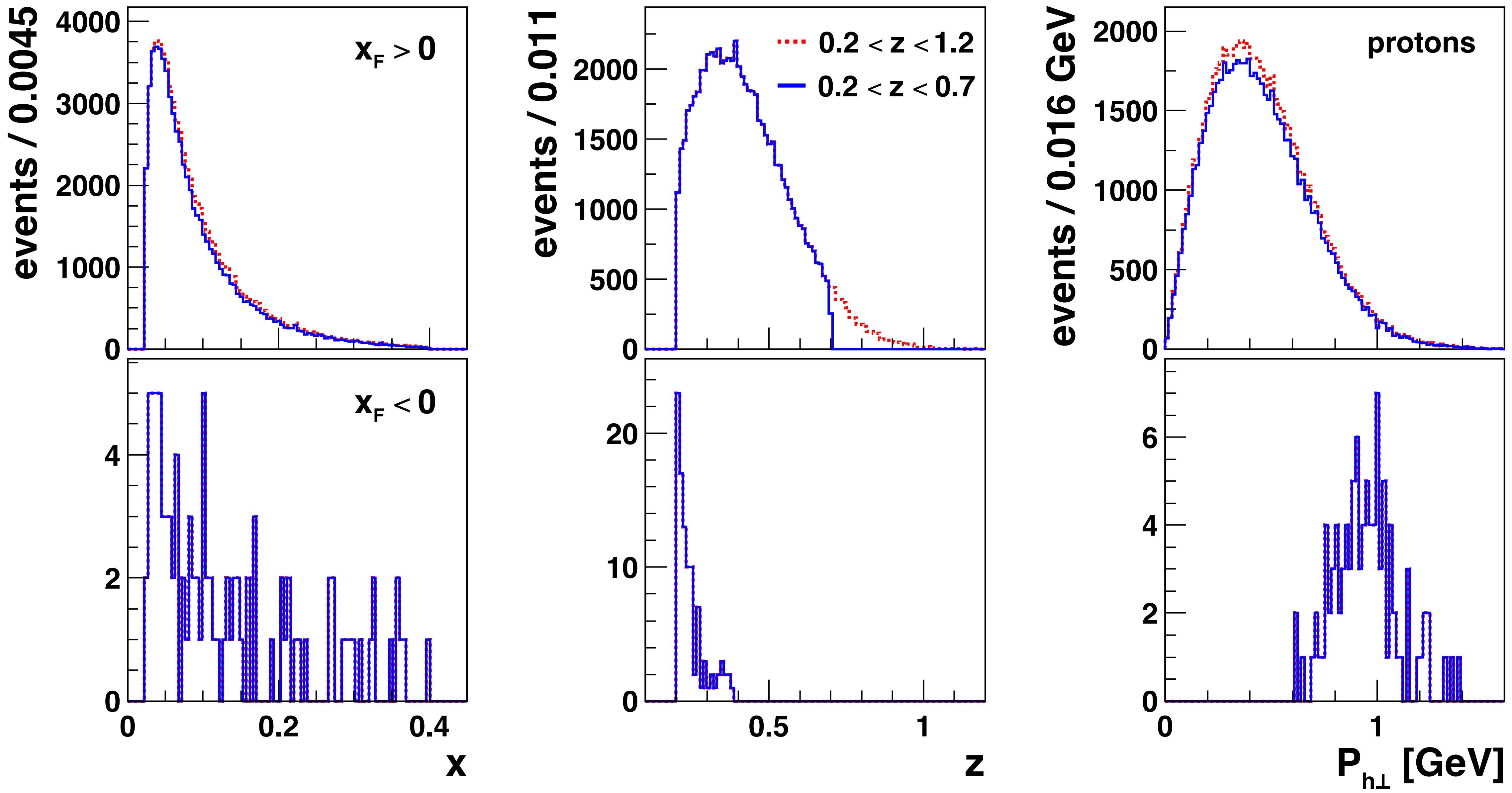

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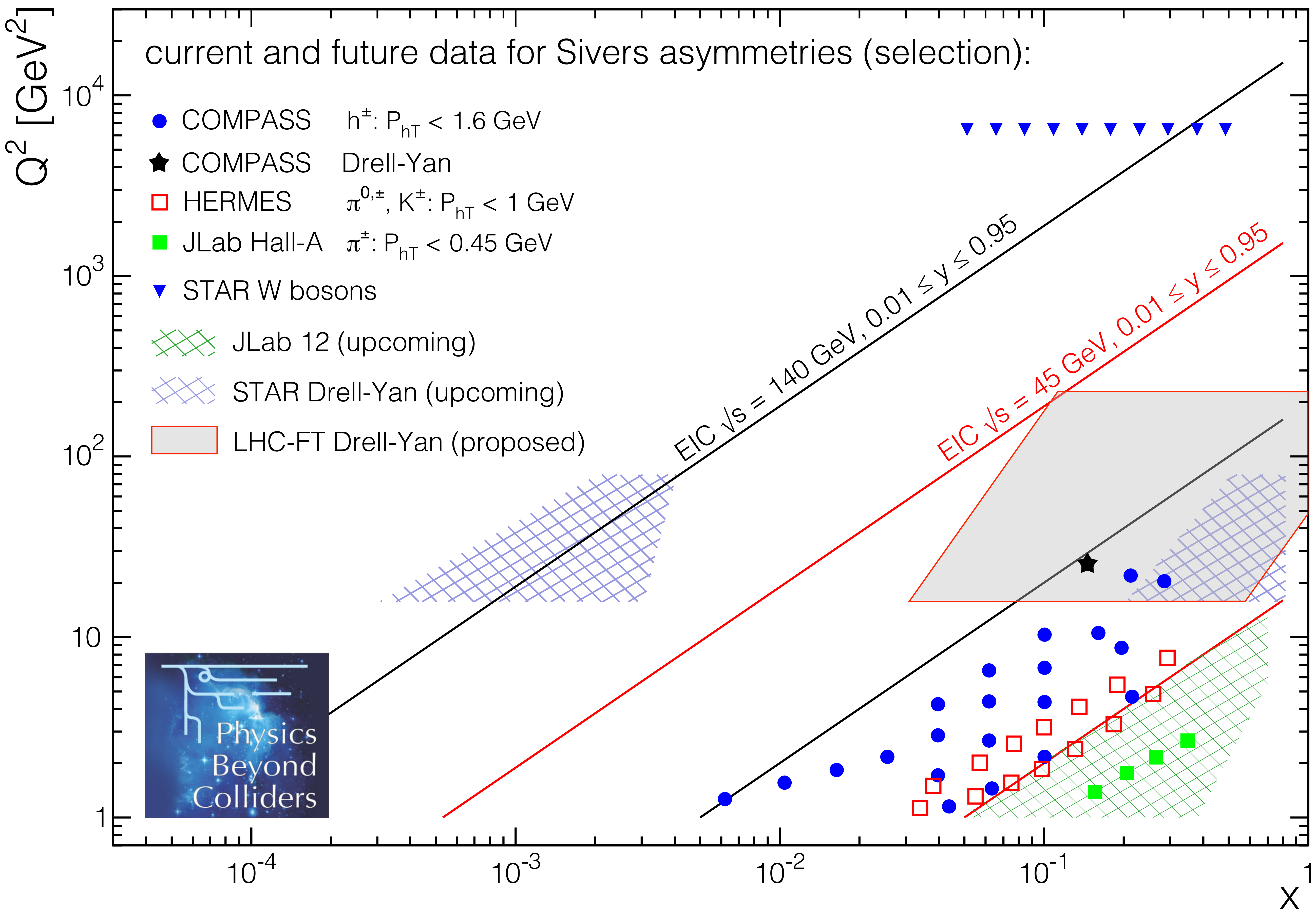
2d kinematic phase space



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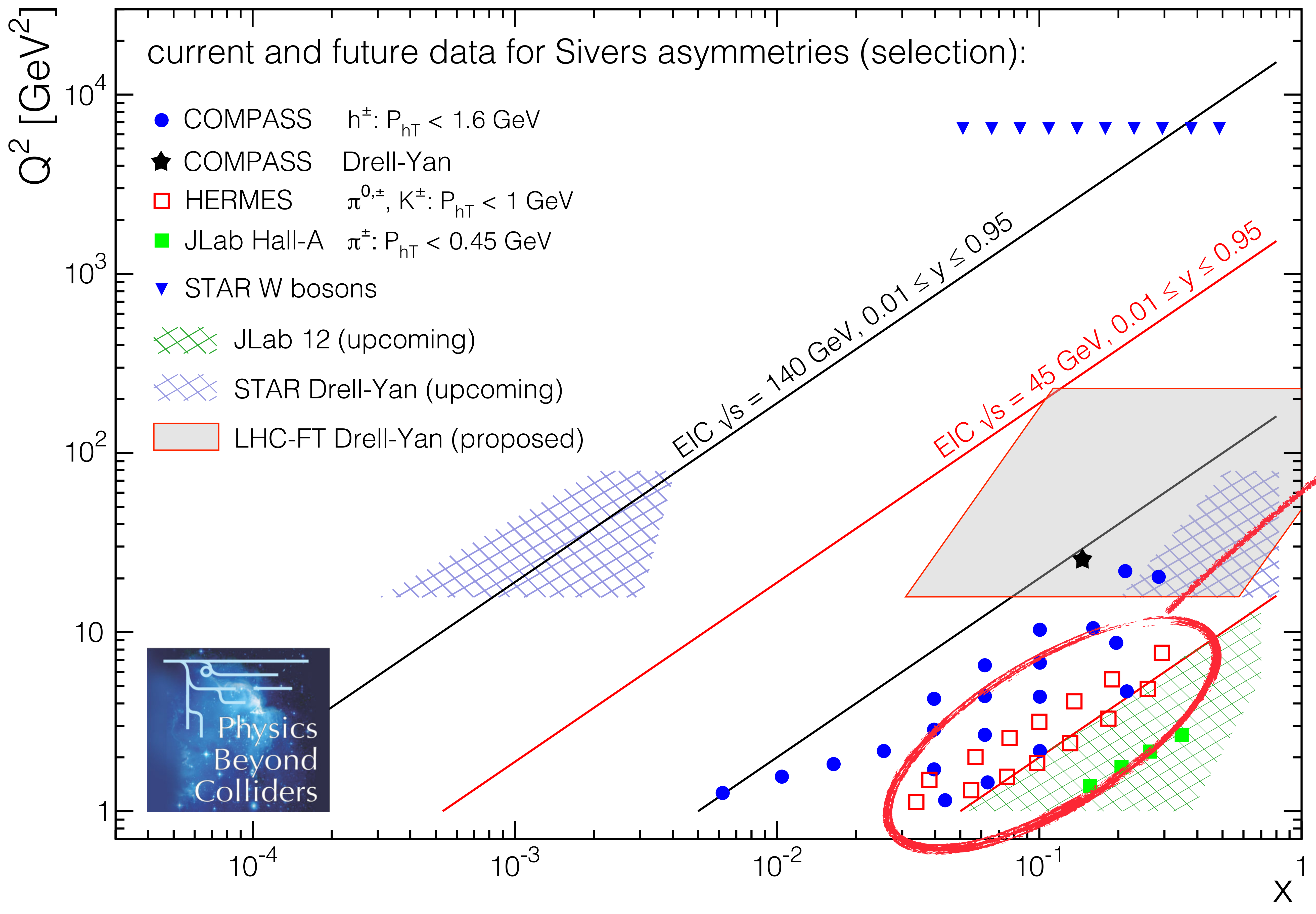
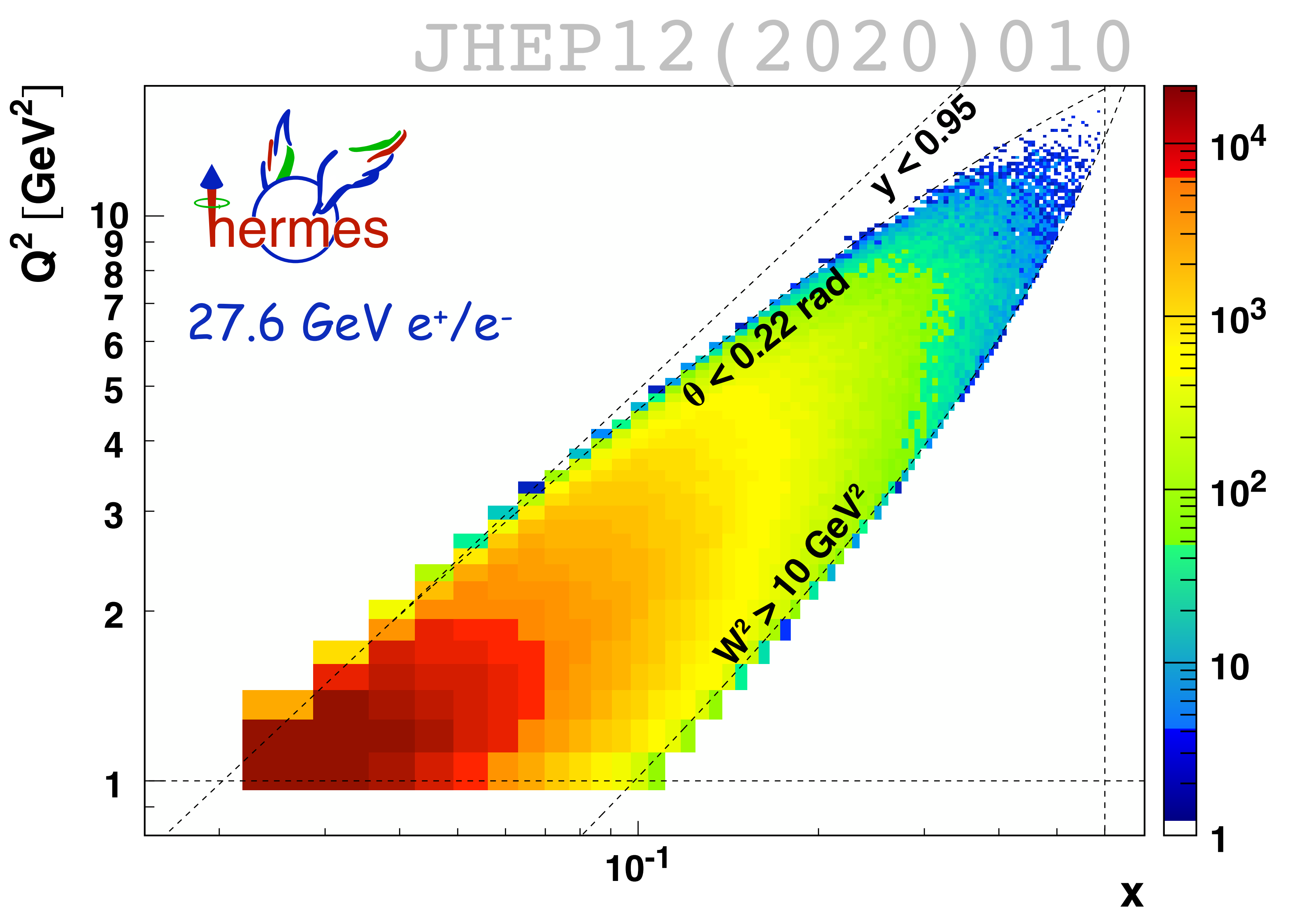
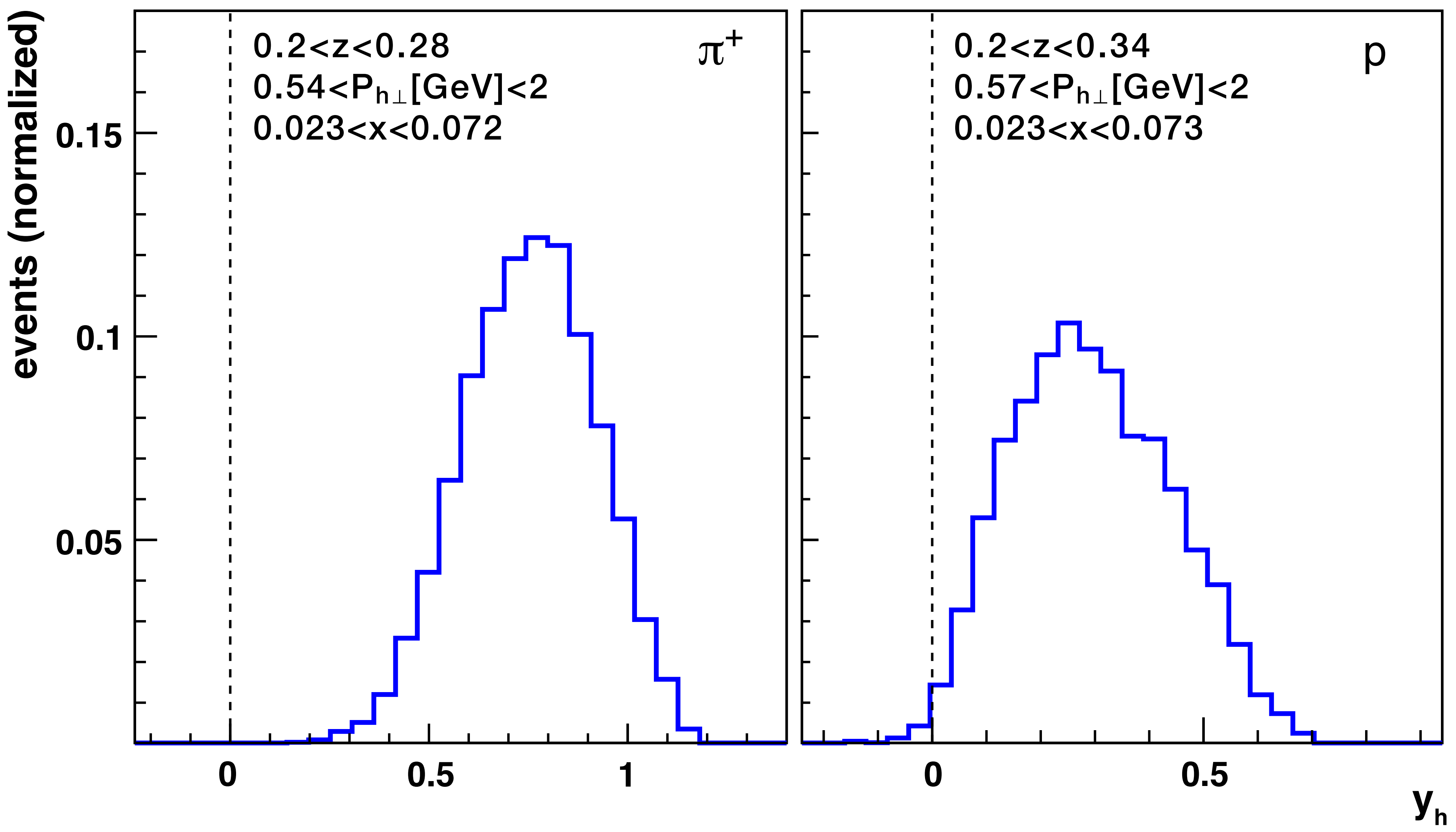


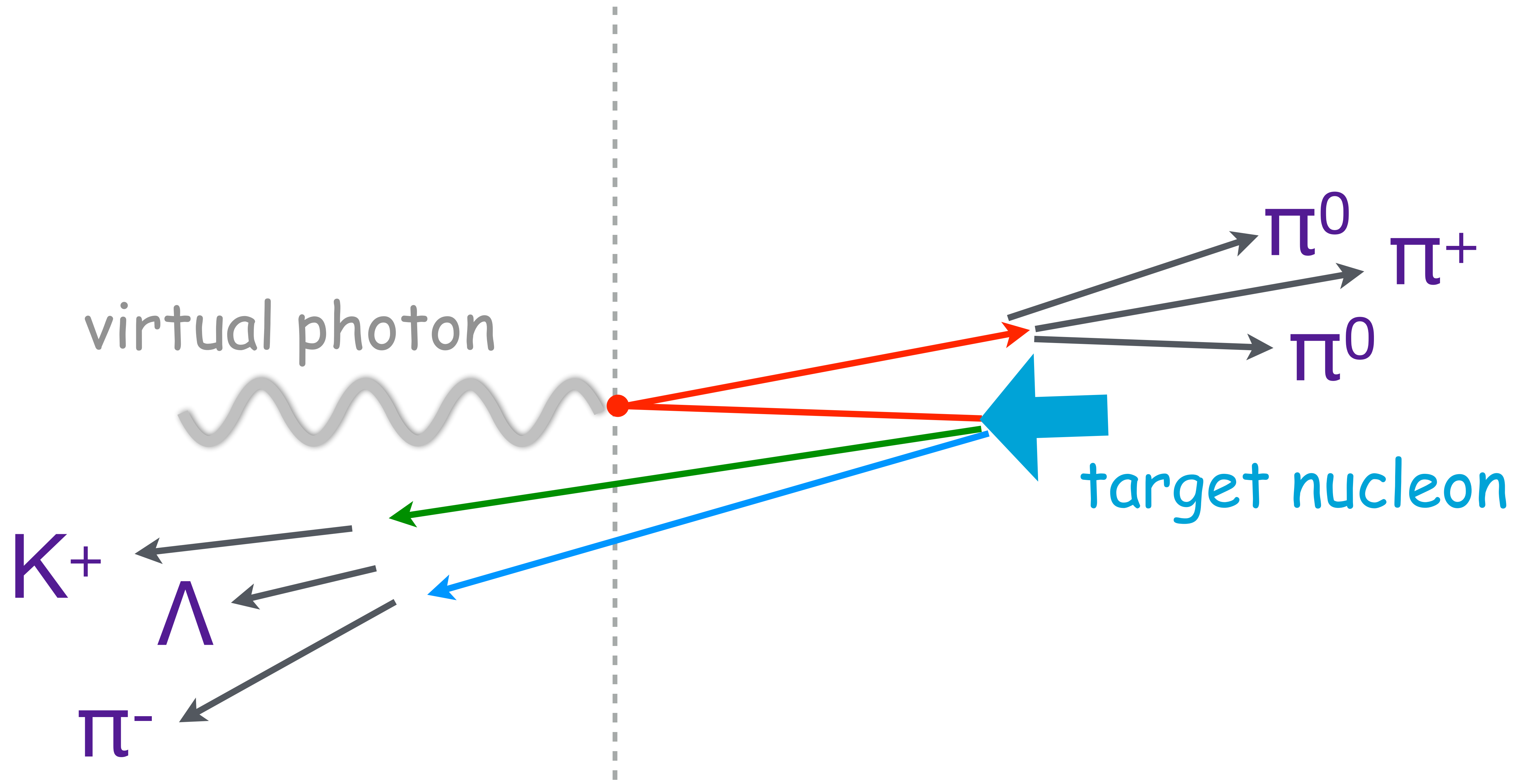


Scattered lepton:		Q^2	$> 1\,\mathrm{GeV}^2$	
		W^2	$> 10\,\mathrm{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	charged mesons
	$4\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\mathrm{GeV}$	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.

current vs. target fragmentation





$$y_h \equiv \frac{1}{2} \ln \frac{P_h^+}{P_h^-}$$

$P_h^\pm$ ... light-cone momenta

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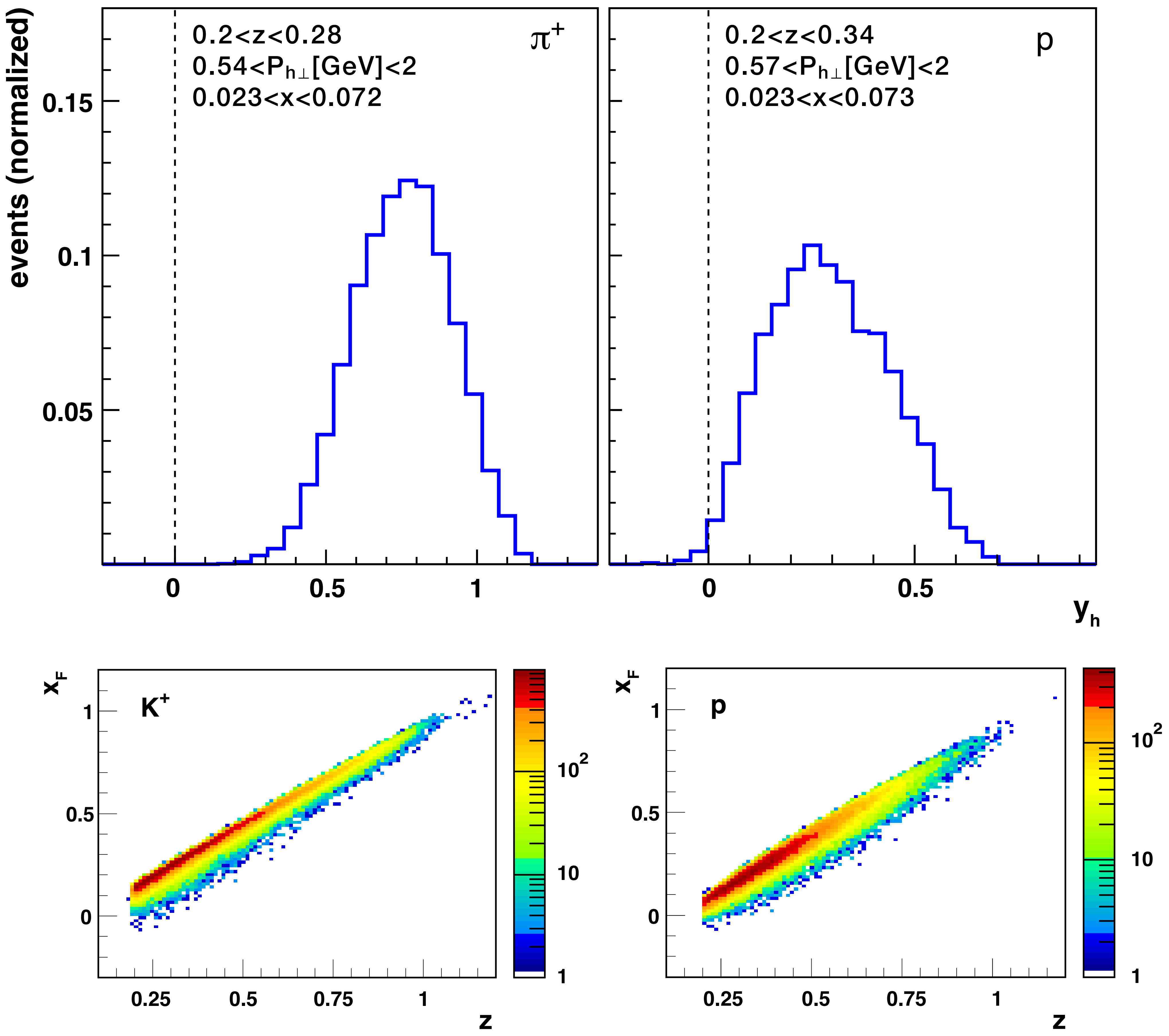
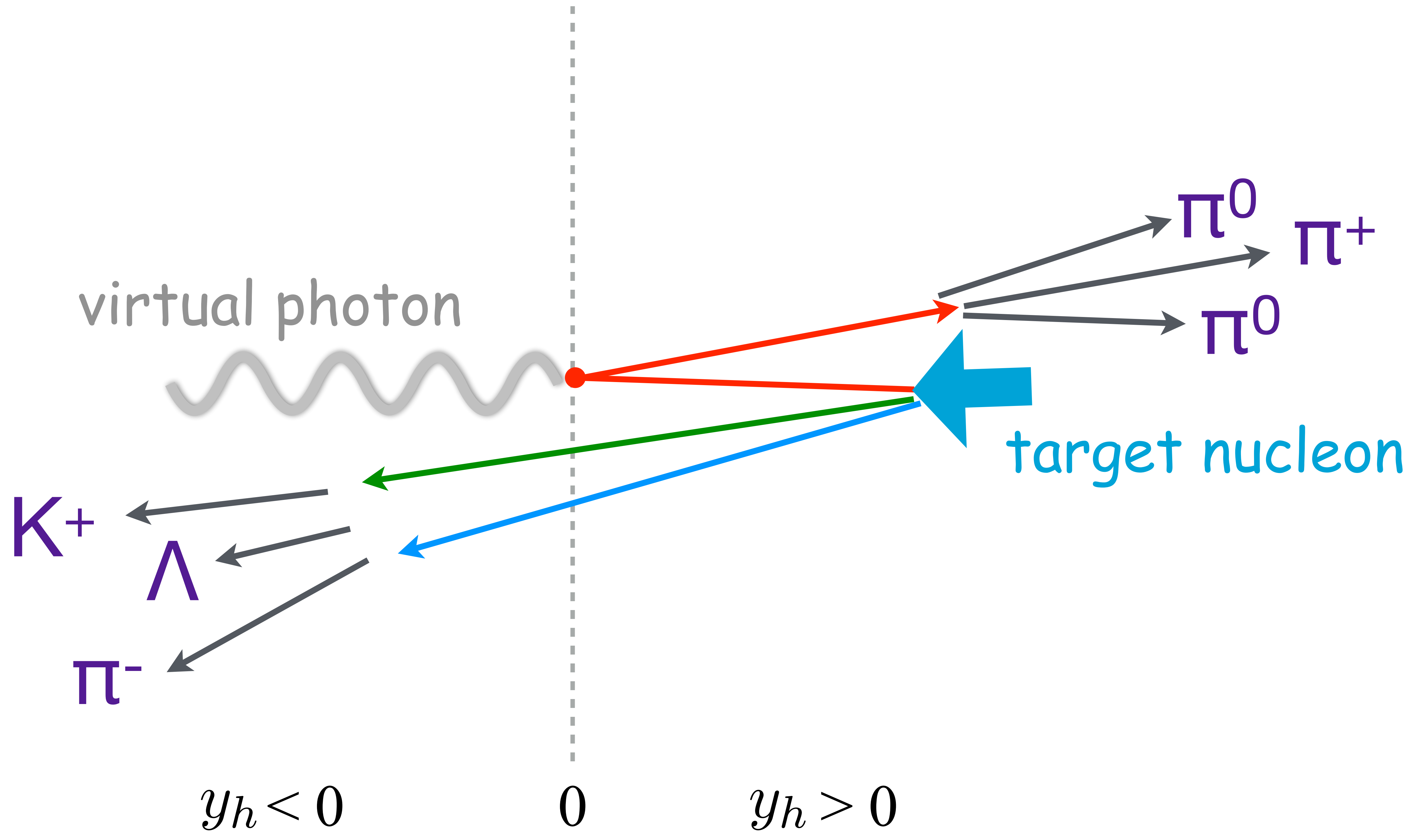


x_F ... Feynman x

selected hadrons at HERMES mainly forward-going in photon-nucleon c.m.s.

virtual-photon—nucleon c.m.s



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

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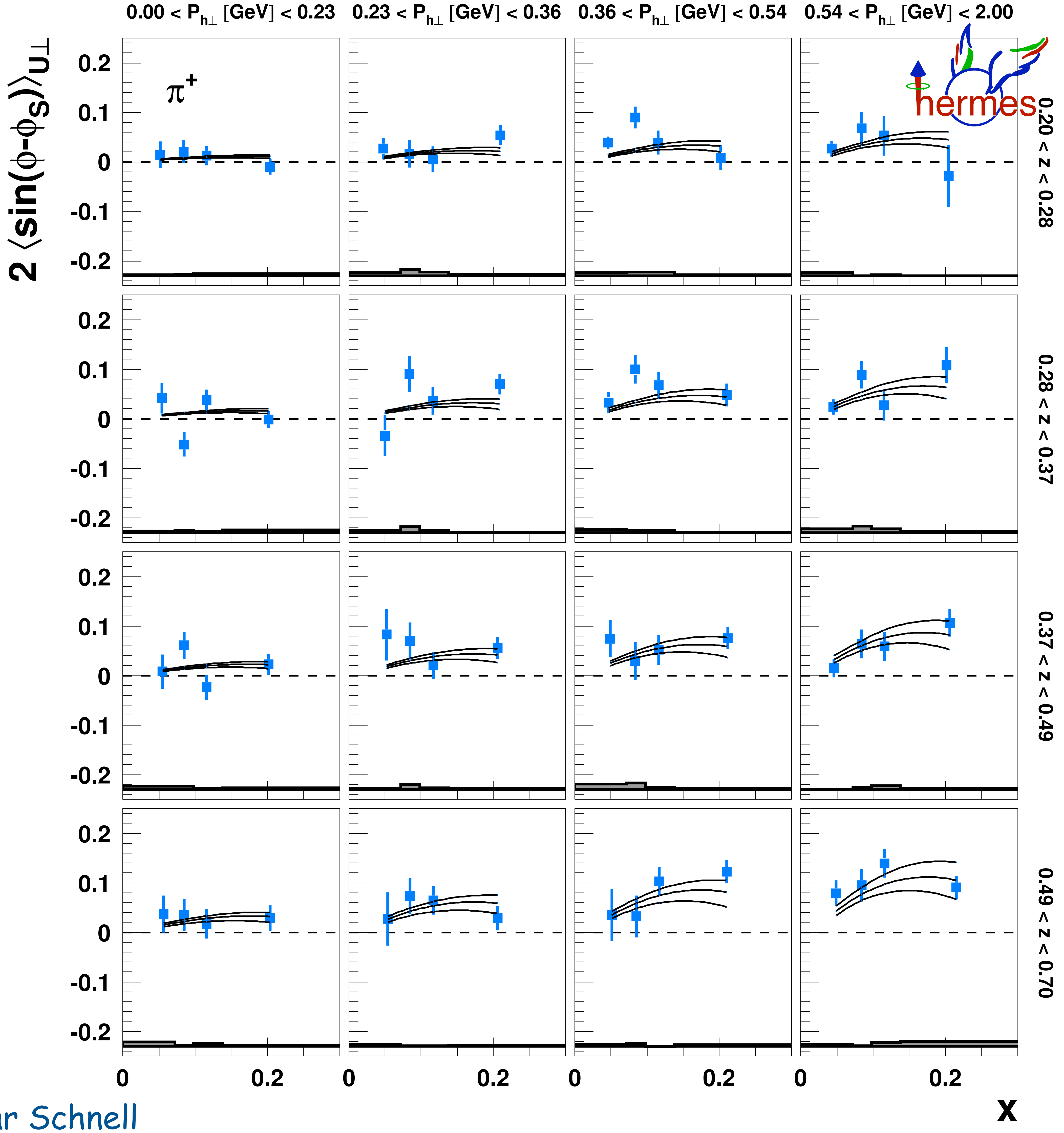
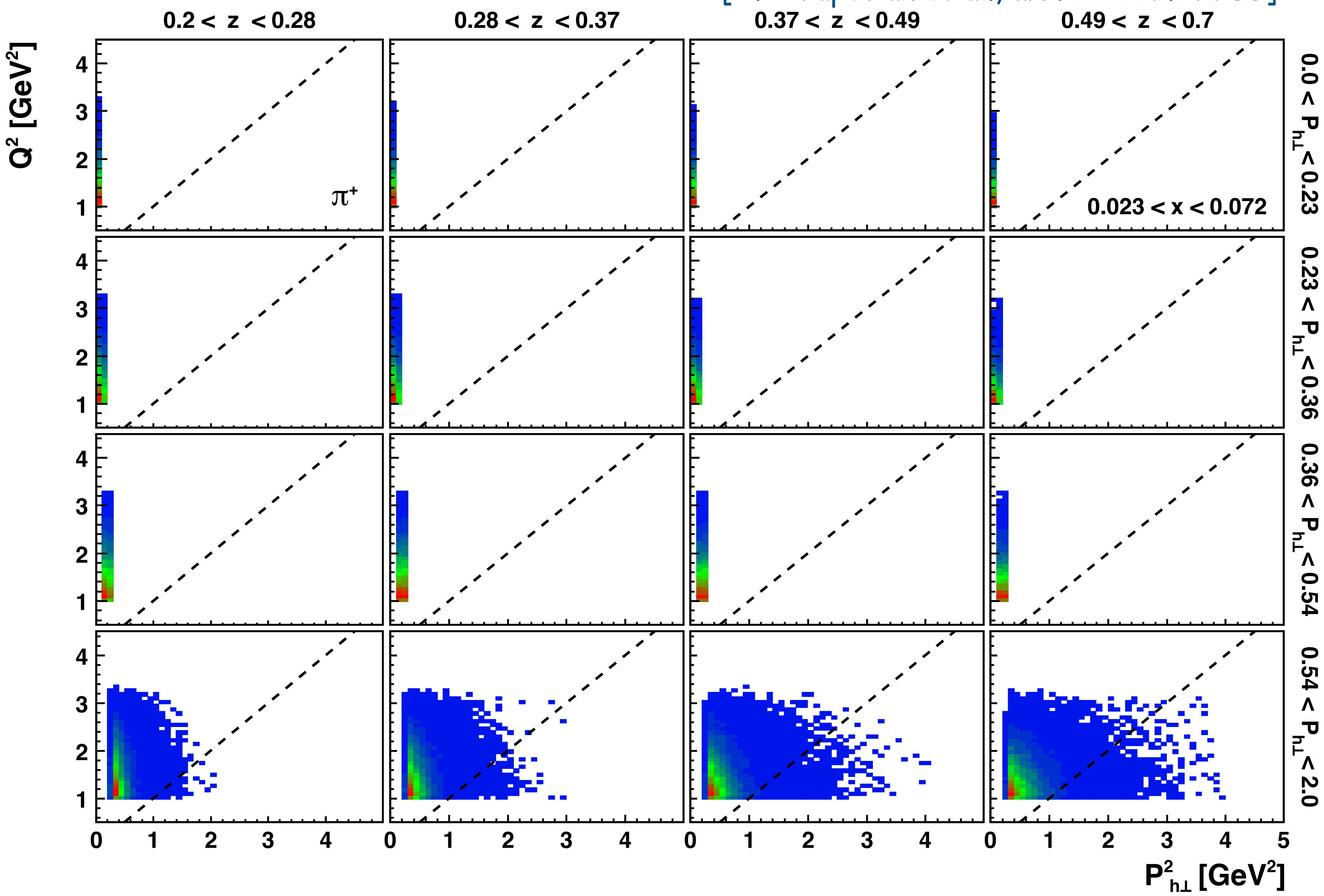


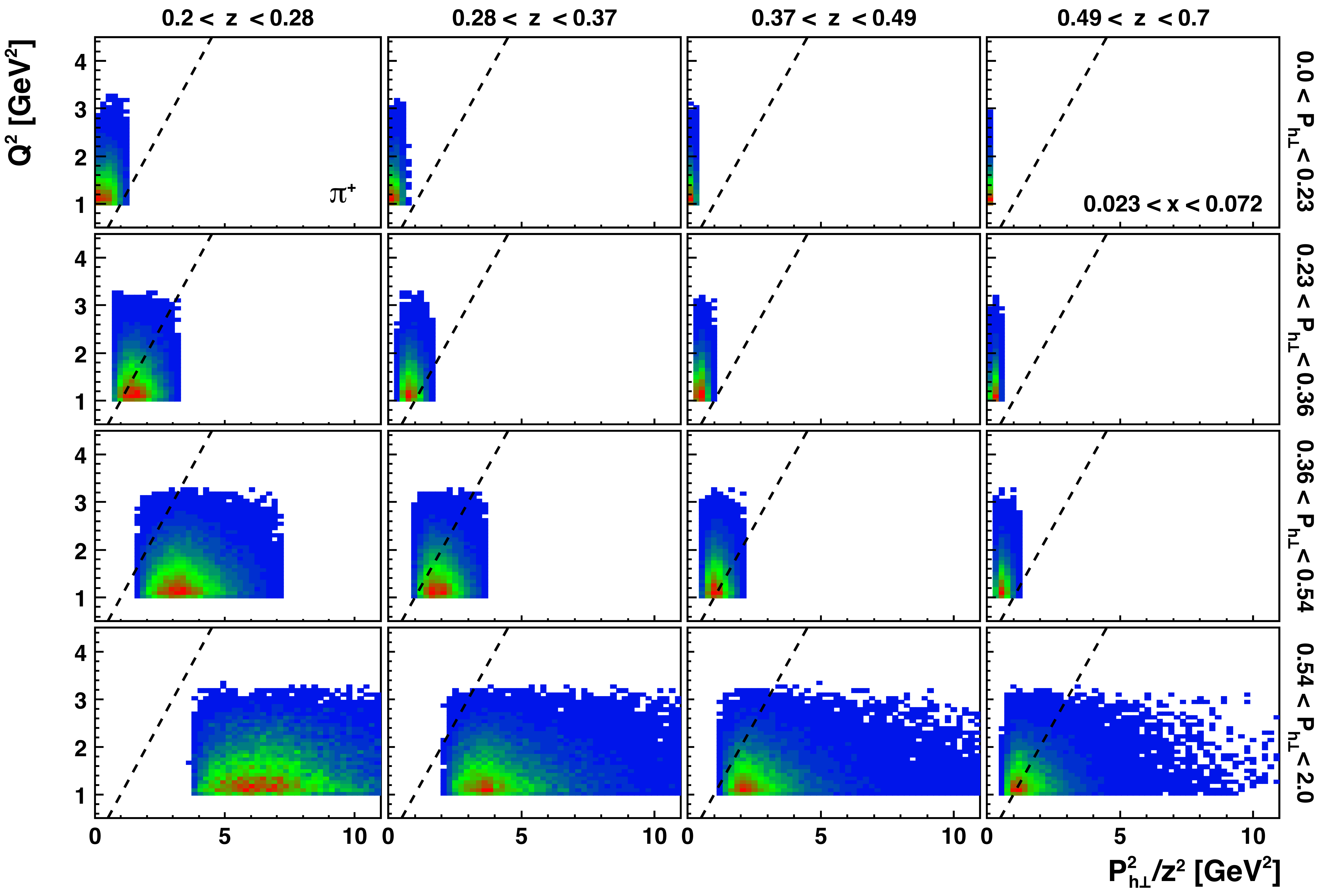
[A. Airapetian et al., arXiv:2007.07755]



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

TMD factorization: a 2-scale problem

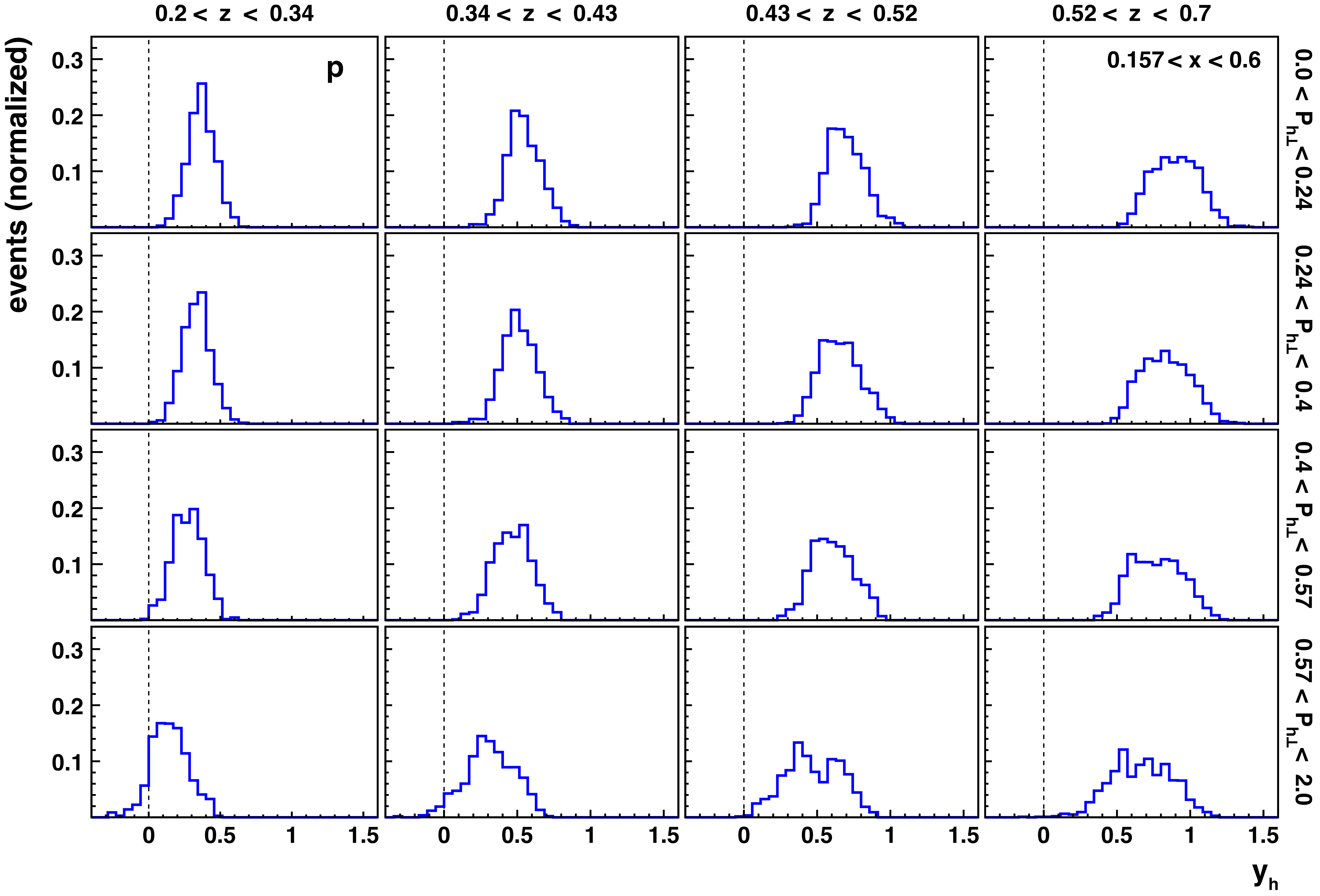
lowest x bin



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

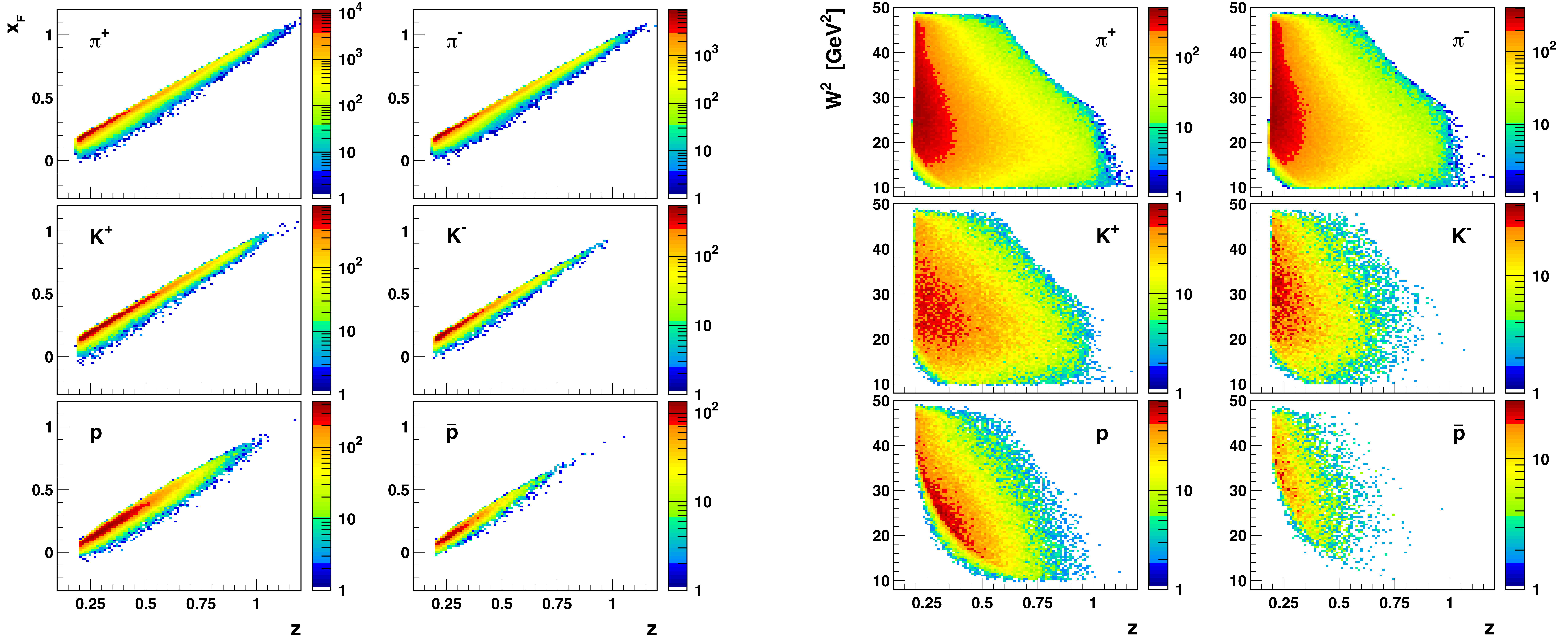
all other x-bins included in the Supplemental Material of JHEP12(2020)010

hadron production at HERMES

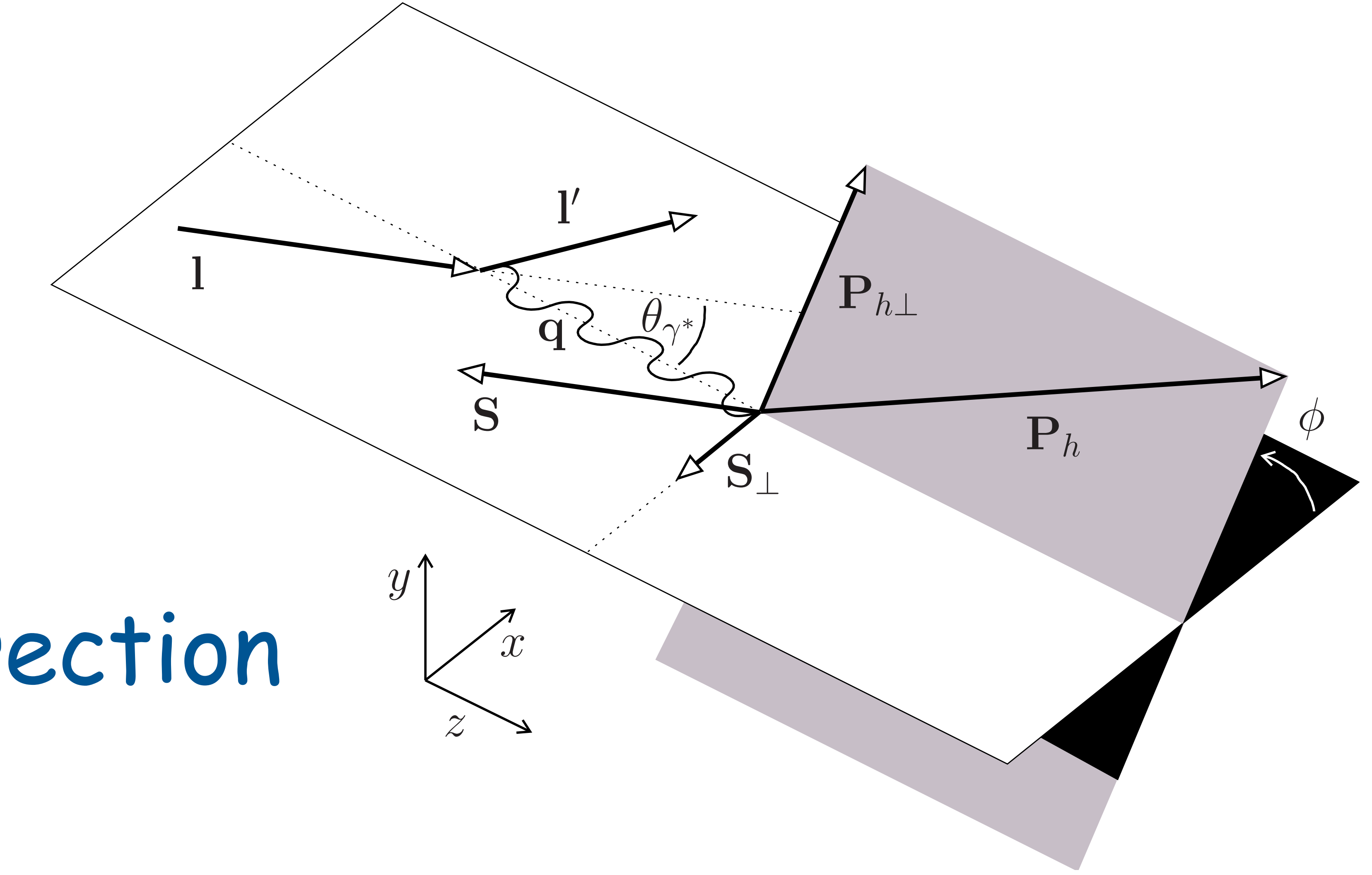


- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]
- rapidity distributions available for all kinematic bins (e.g., highest-x bin protons)

current vs. target fragmentation



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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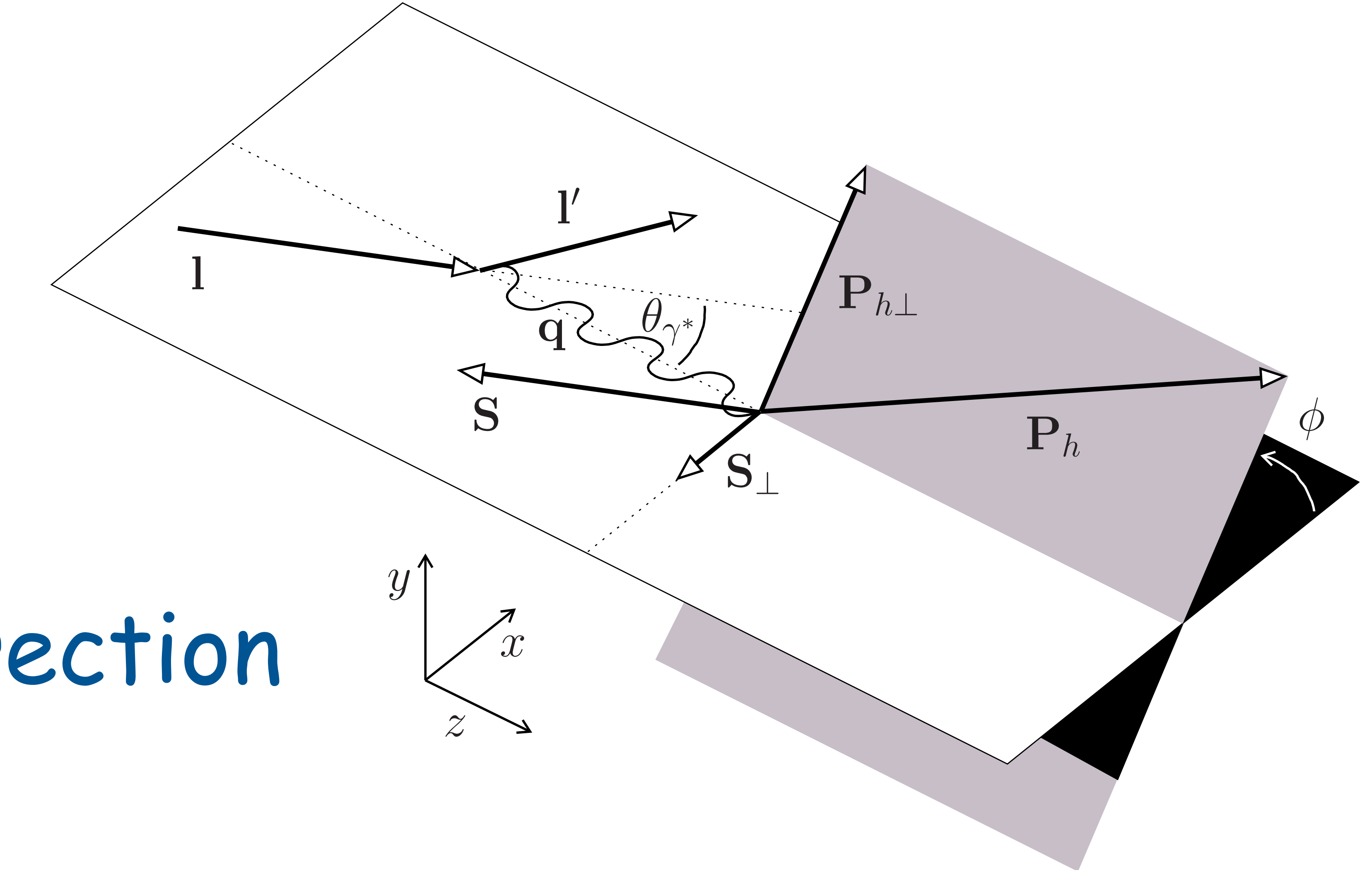

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➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

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

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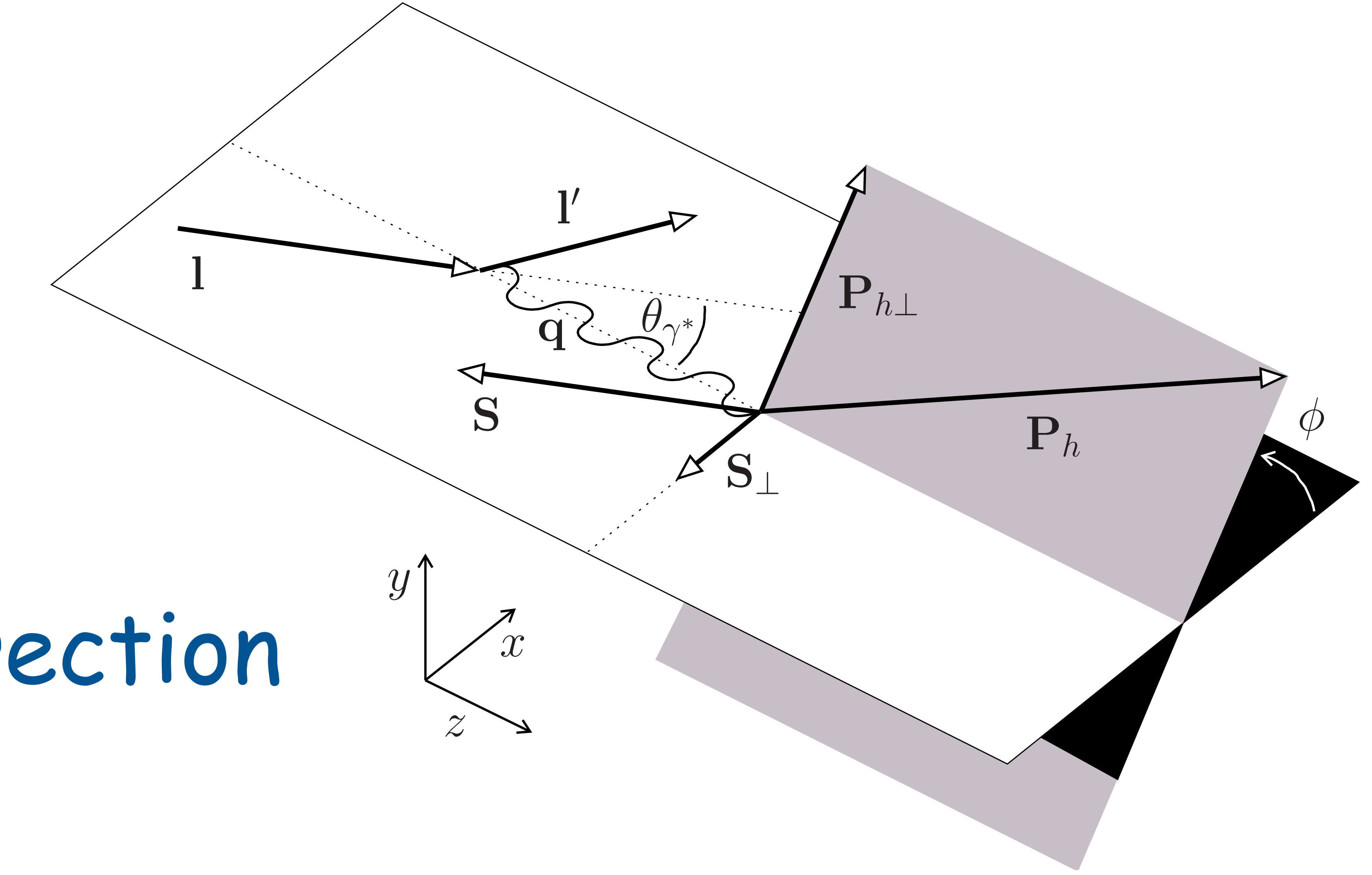

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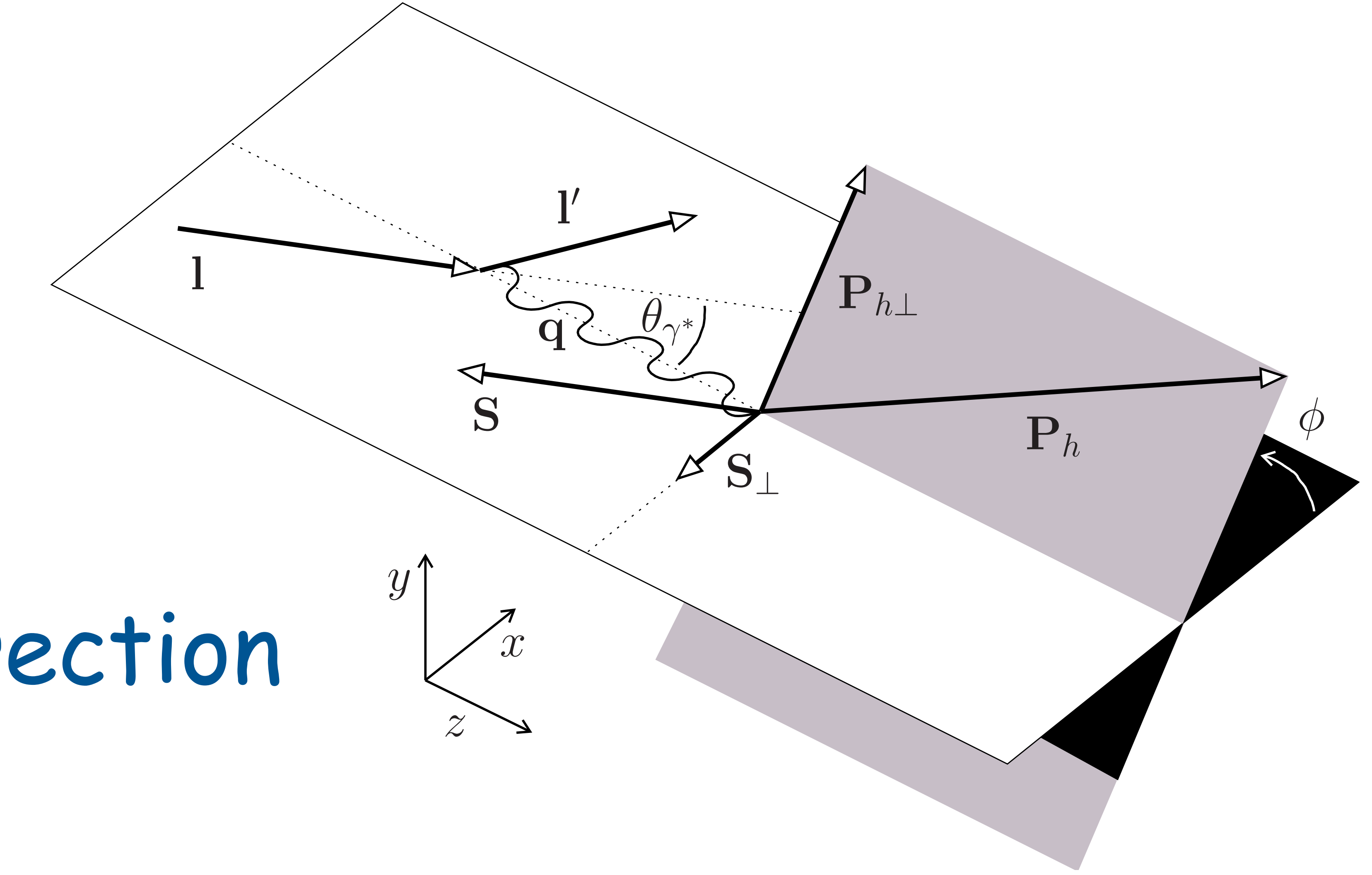
➡ need data on same target for both polarization orientations!

Mixing of target polarizations



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