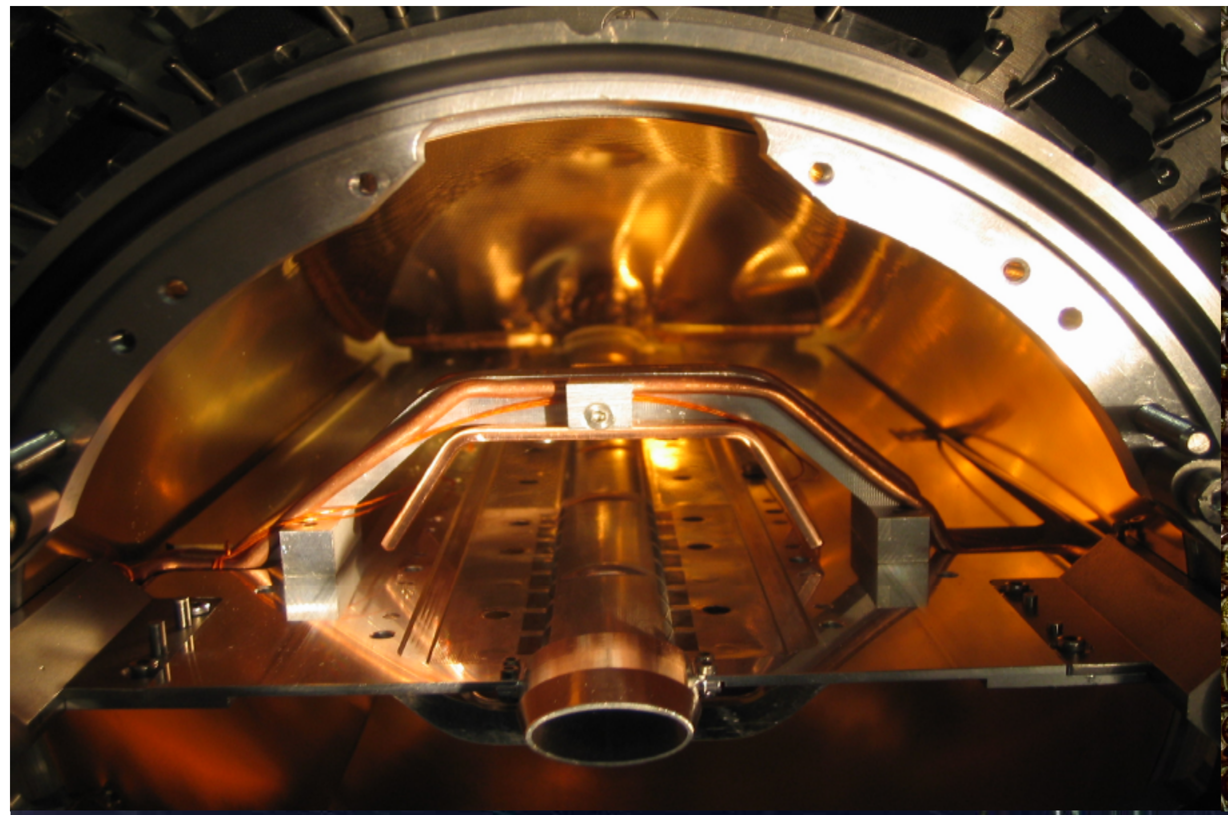
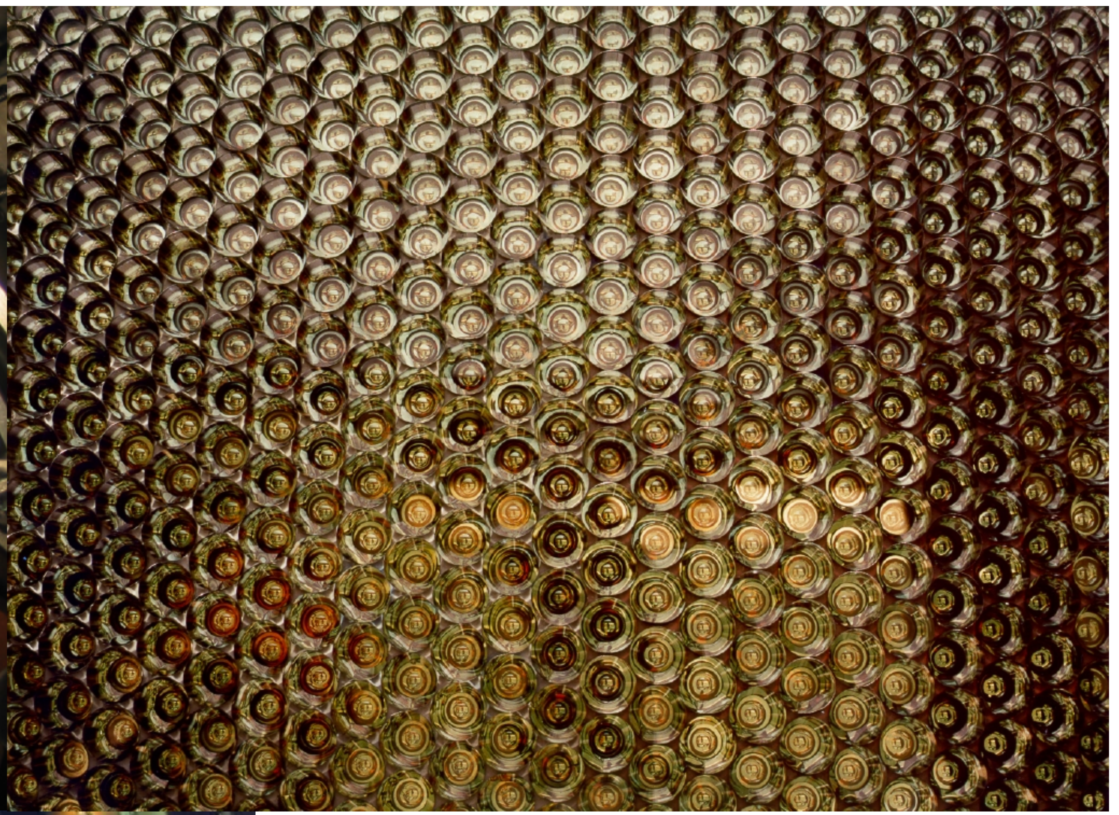
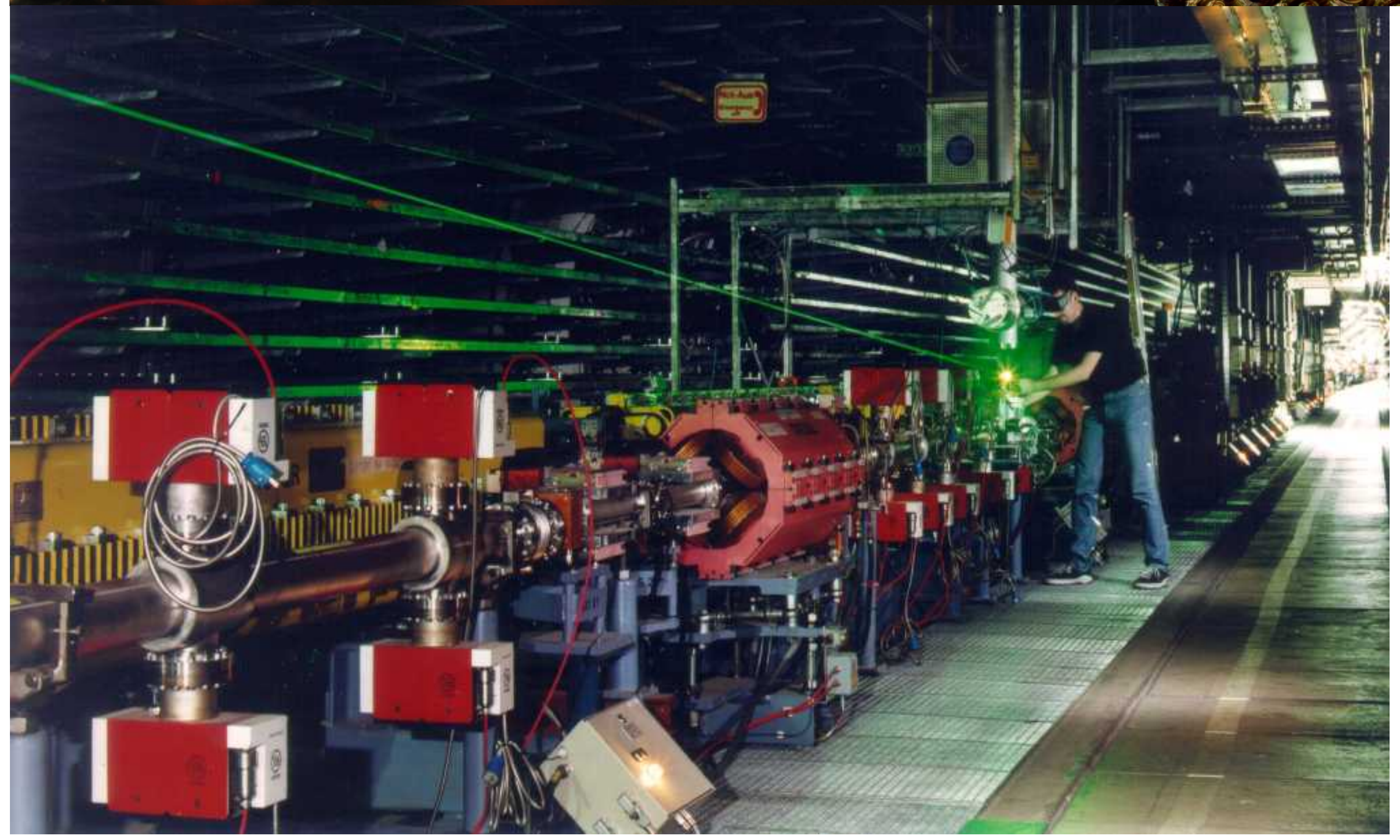
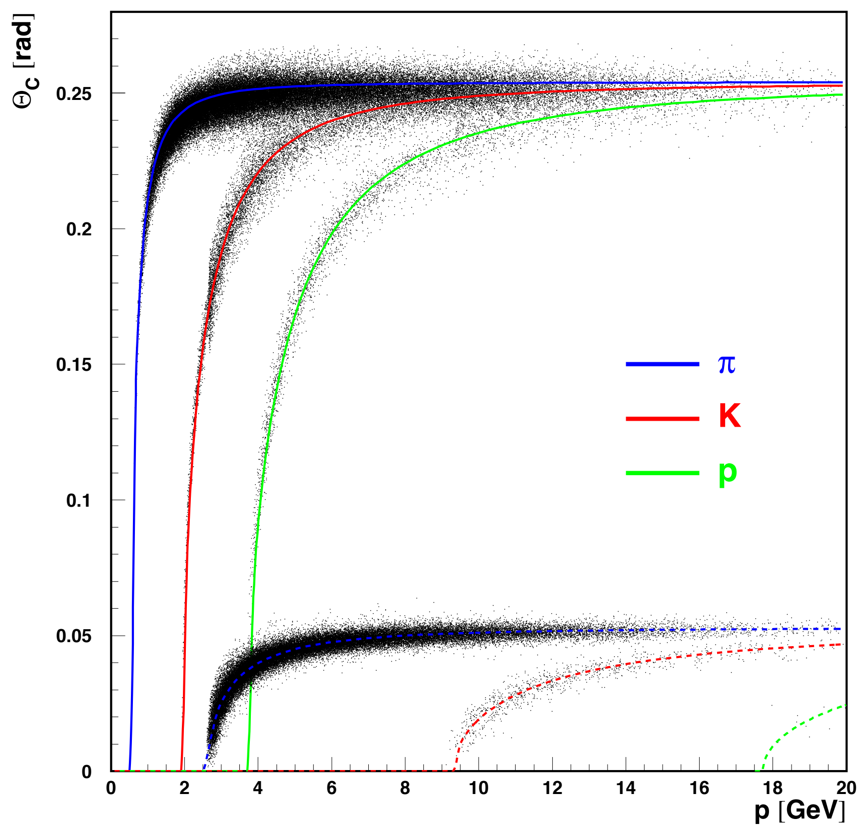
IWHSS 2022

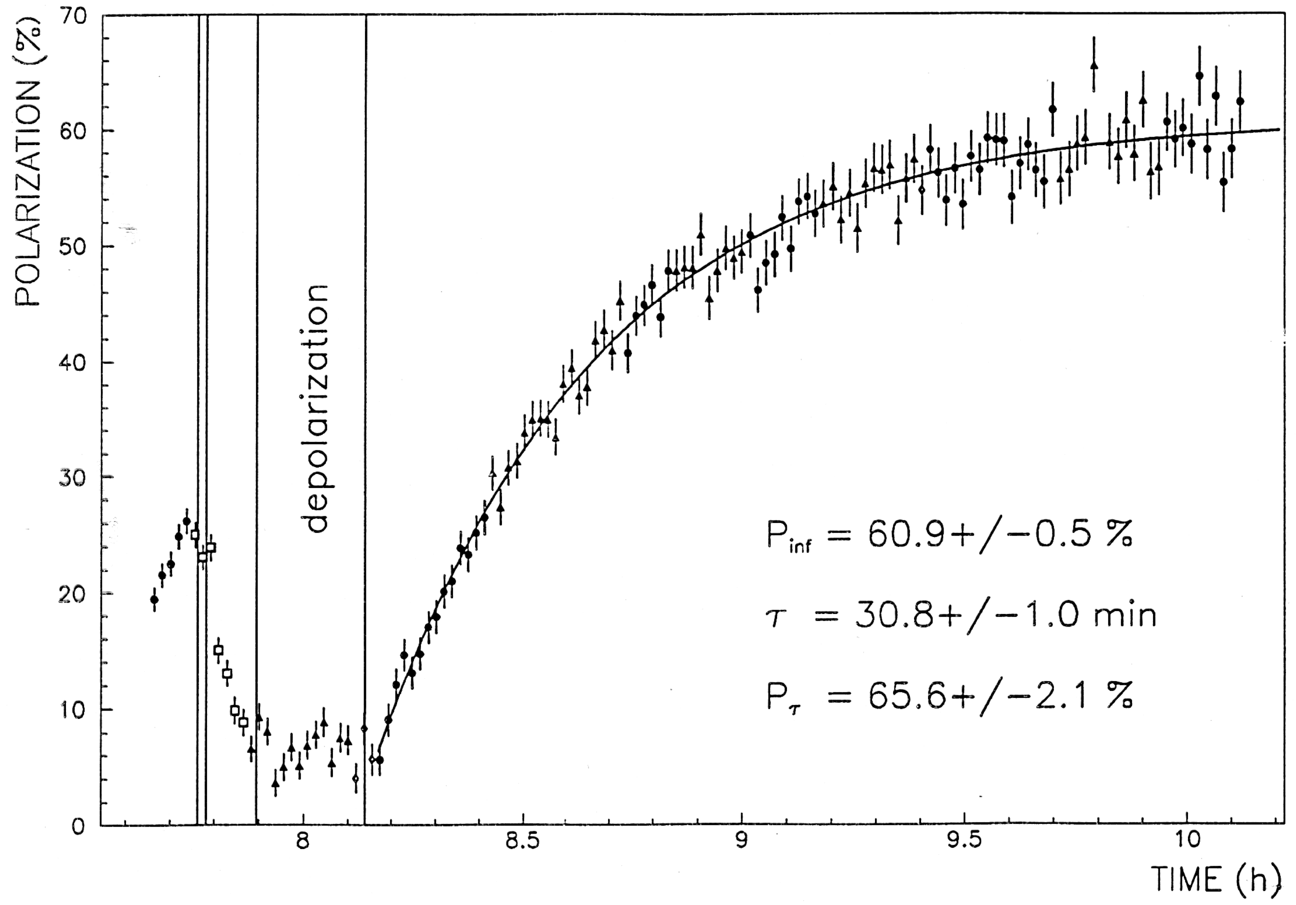
International Workshop on
Hadron Structure and Spectroscopy
CERN — August 29-31, 2022











hermes

HERMES view on the nucleon's spin & 3d structure

Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

[clipart.info]

2022 — so many anniversaries!

- 25 years of COMPASS approval
- 20 years of COMPASS data taking

[GetDrawings.com]

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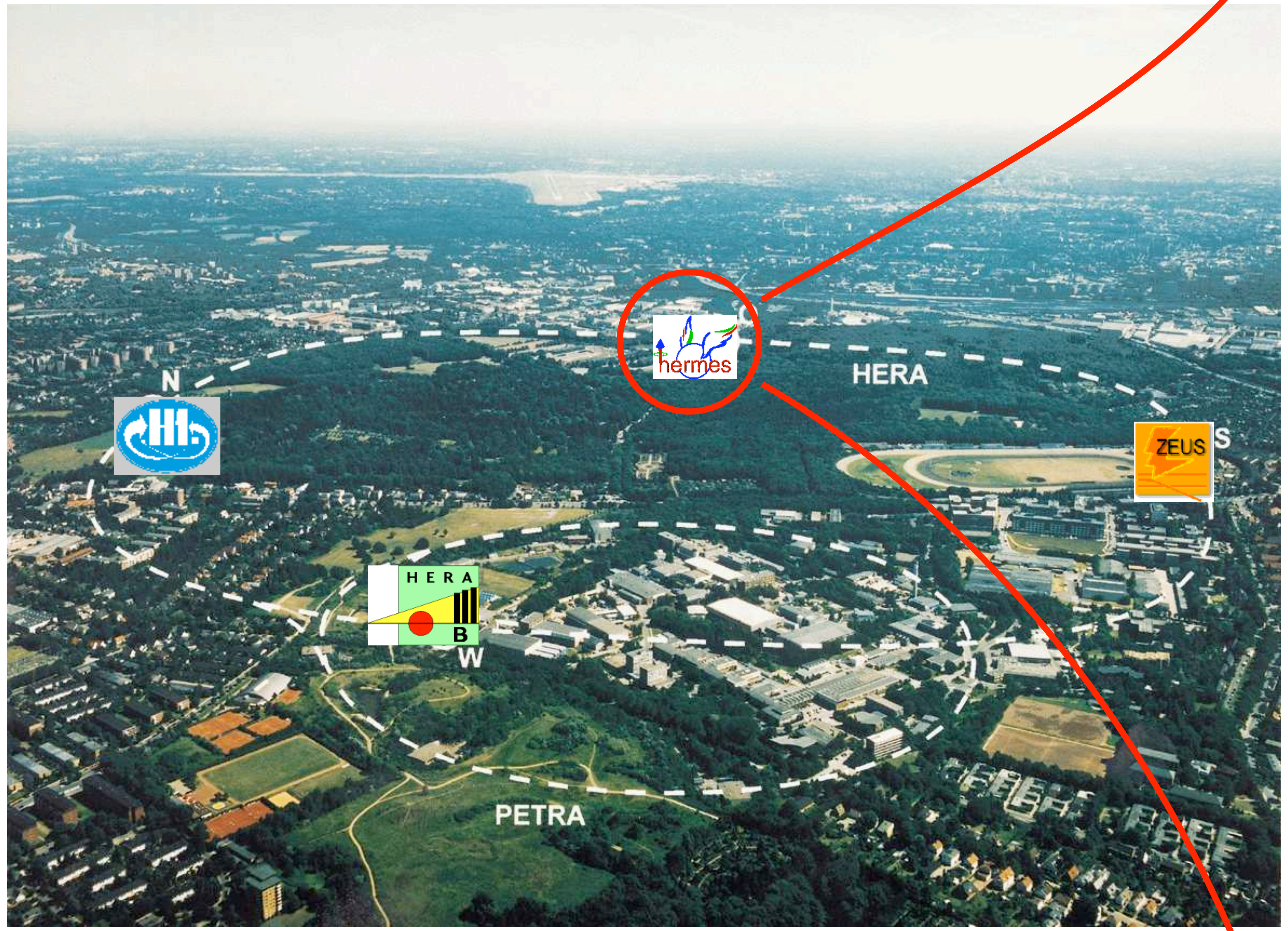
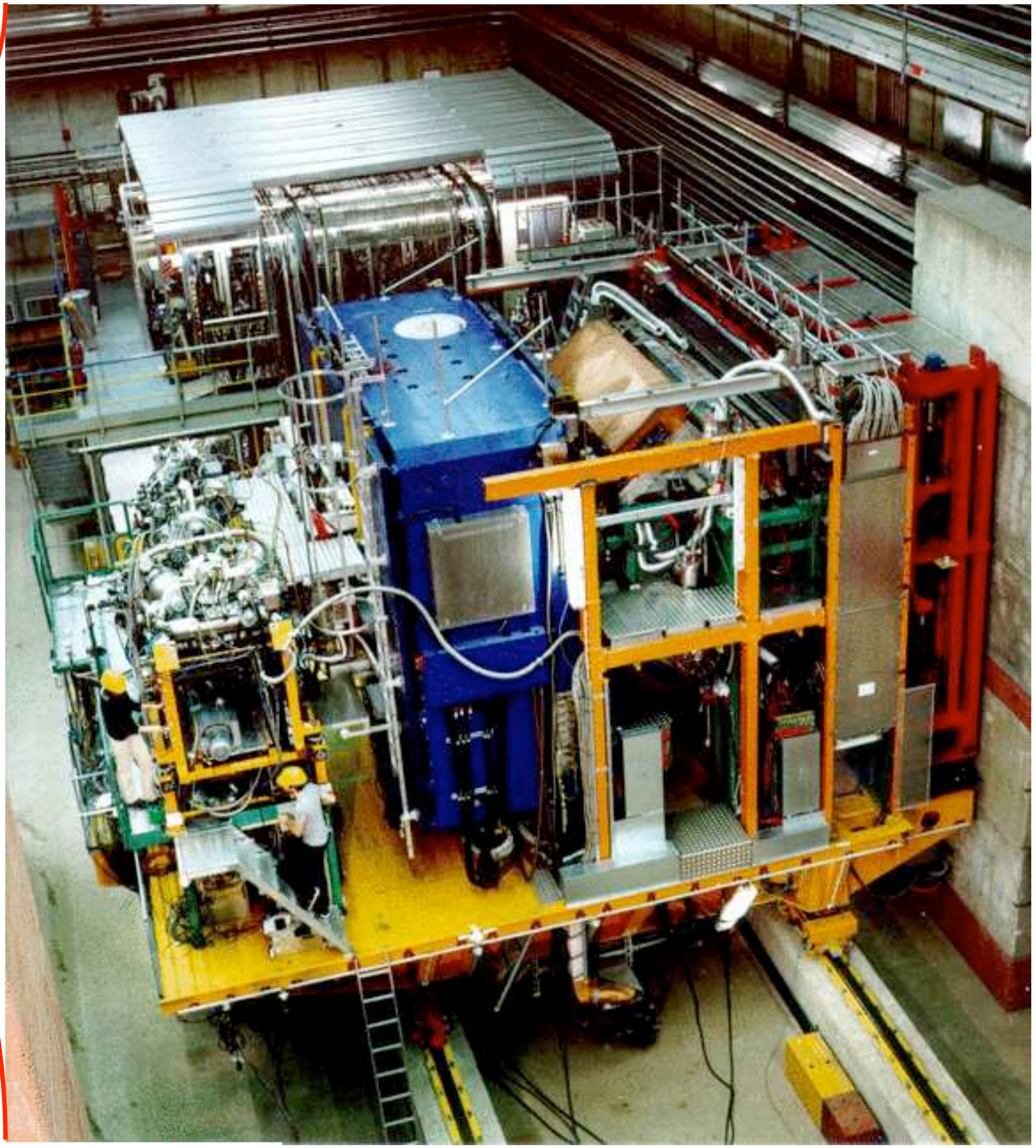
- 25 years of COMPASS approval
- 20 years of COMPASS data taking

- 35 years of spin crisis/puzzle
- 30 years of HERA and (conditional) HERMES approval
- 15 years of HERA shutdown

HERMES (1995-2007) @ HERA

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





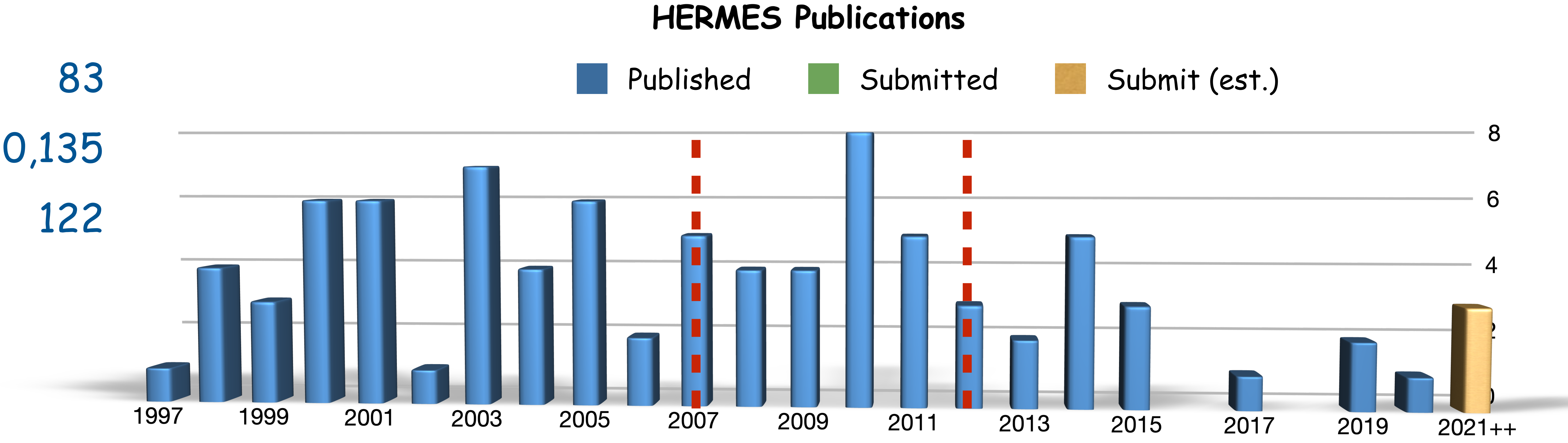
- unpolarized (H, D, He,..., Xe) as well as
- **transversely** (H) or
- **longitudinally** (H, D, He) polarized

pure gas targets

HERMES publication statistics (08/2022)

- Total number of published HERMES papers: 83
  - Total number of citations: 10,135
  - Average citations per paper: 122
  - **2 top-cite 500+** & 9 topcite 250+

  [inspirehep.net as of Aug. 28, 2022]



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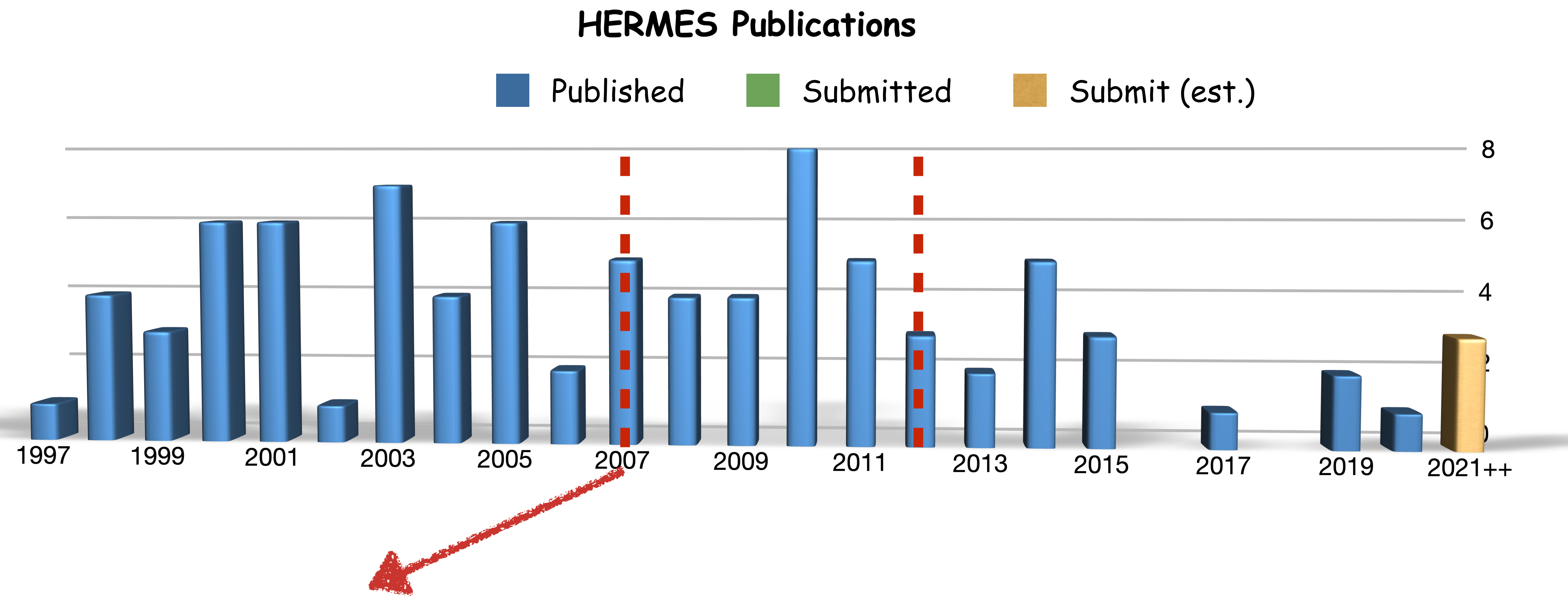

end of data taking

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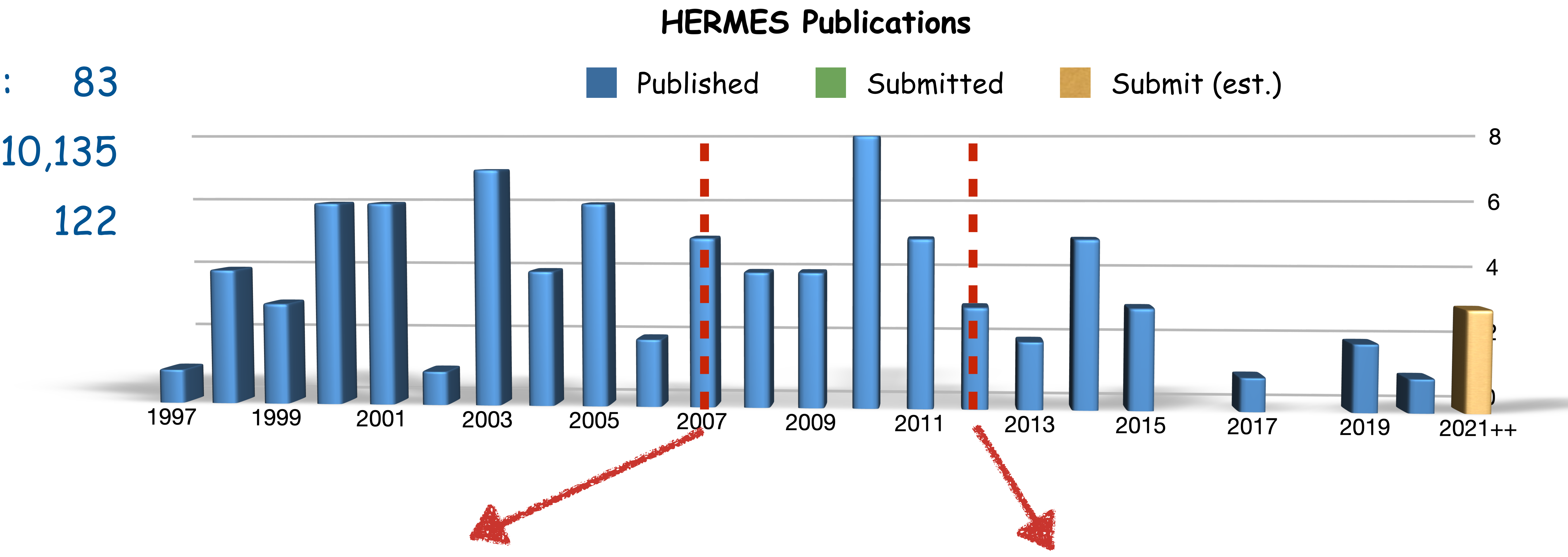

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official end of funding

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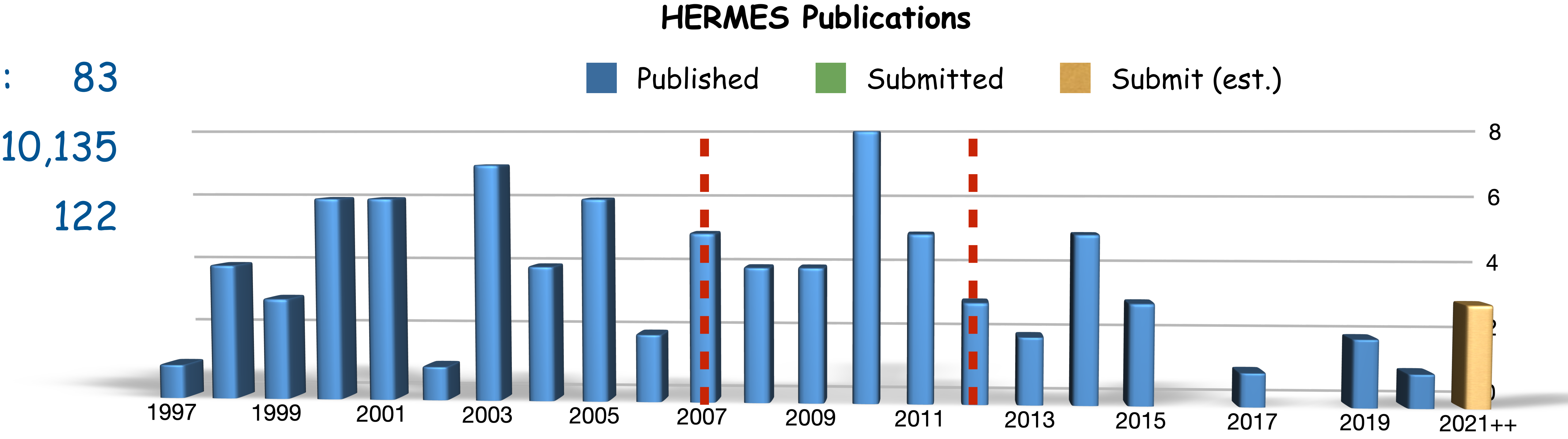
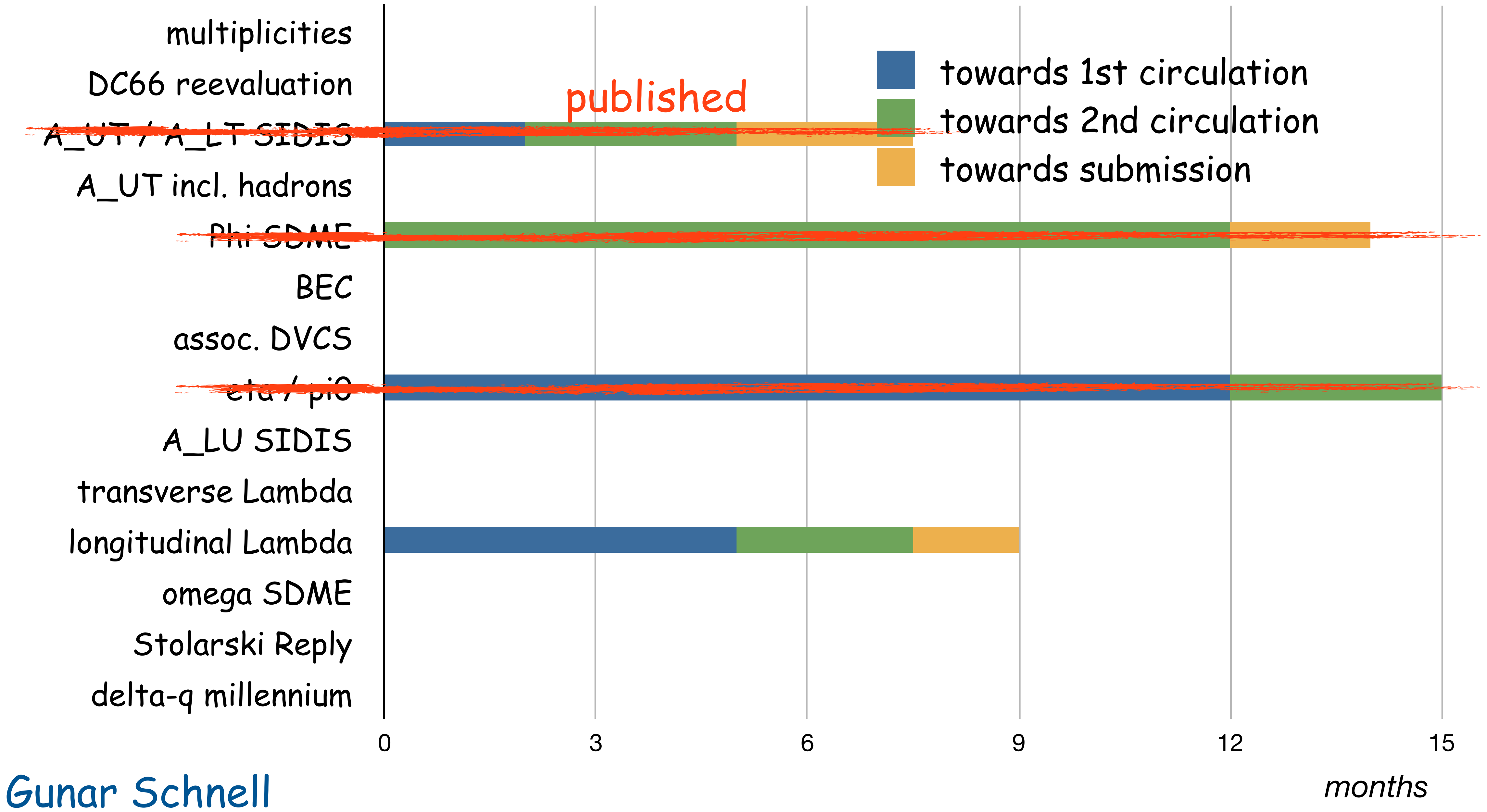
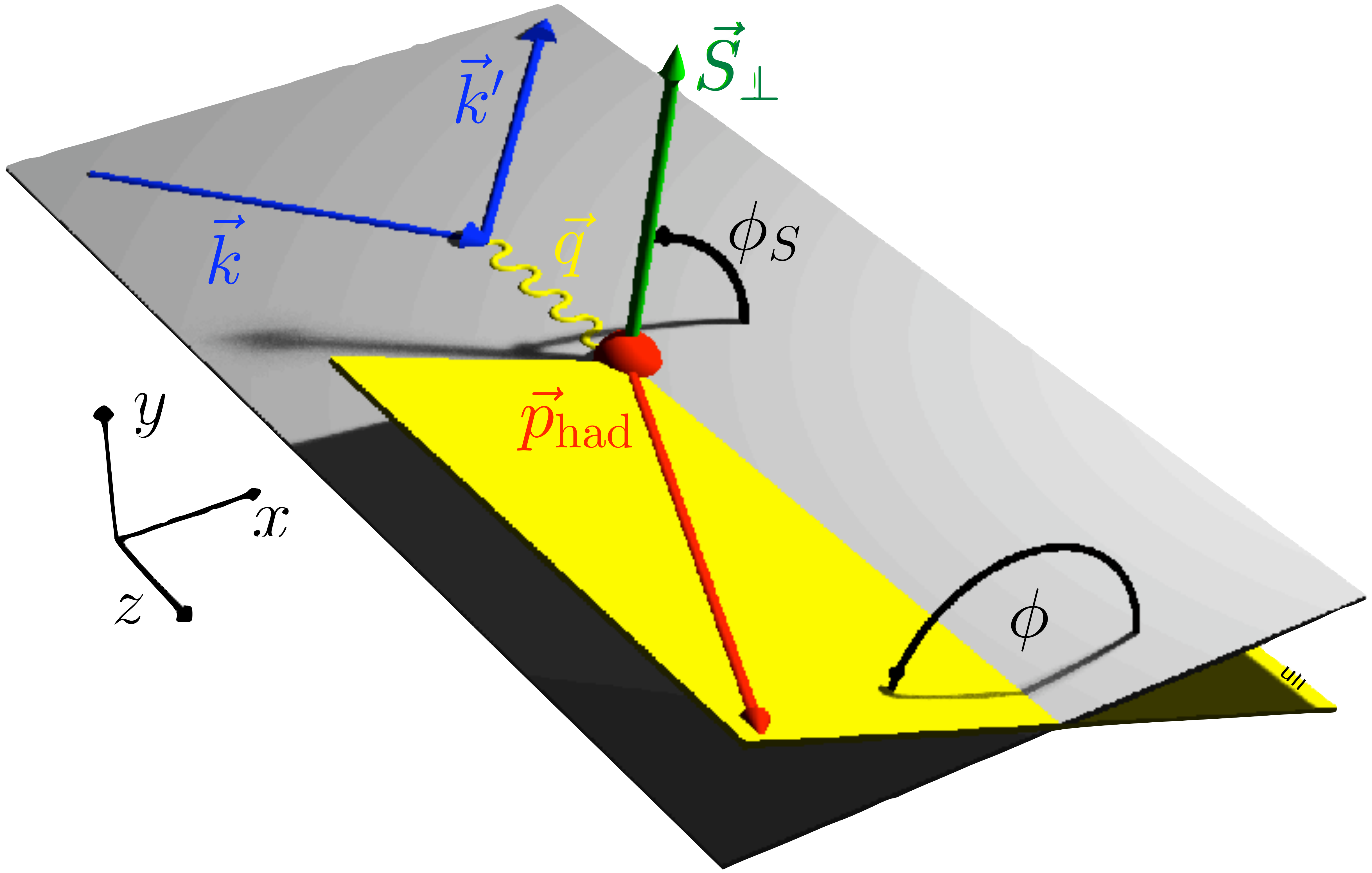


Publication schedule for **2012 priority** analyses (08/2022)



- despite tremendous drop in analysis manpower, almost all priority analyses identified finished
  - two analyses dropped
  - one still ongoing in advanced state
- at same time **new ideas**; partially already published, others … **waiting for manpower**
- only possible thanks to tremendous data-preservation efforts

semi-inclusive one-hadron production (ep→ehX)



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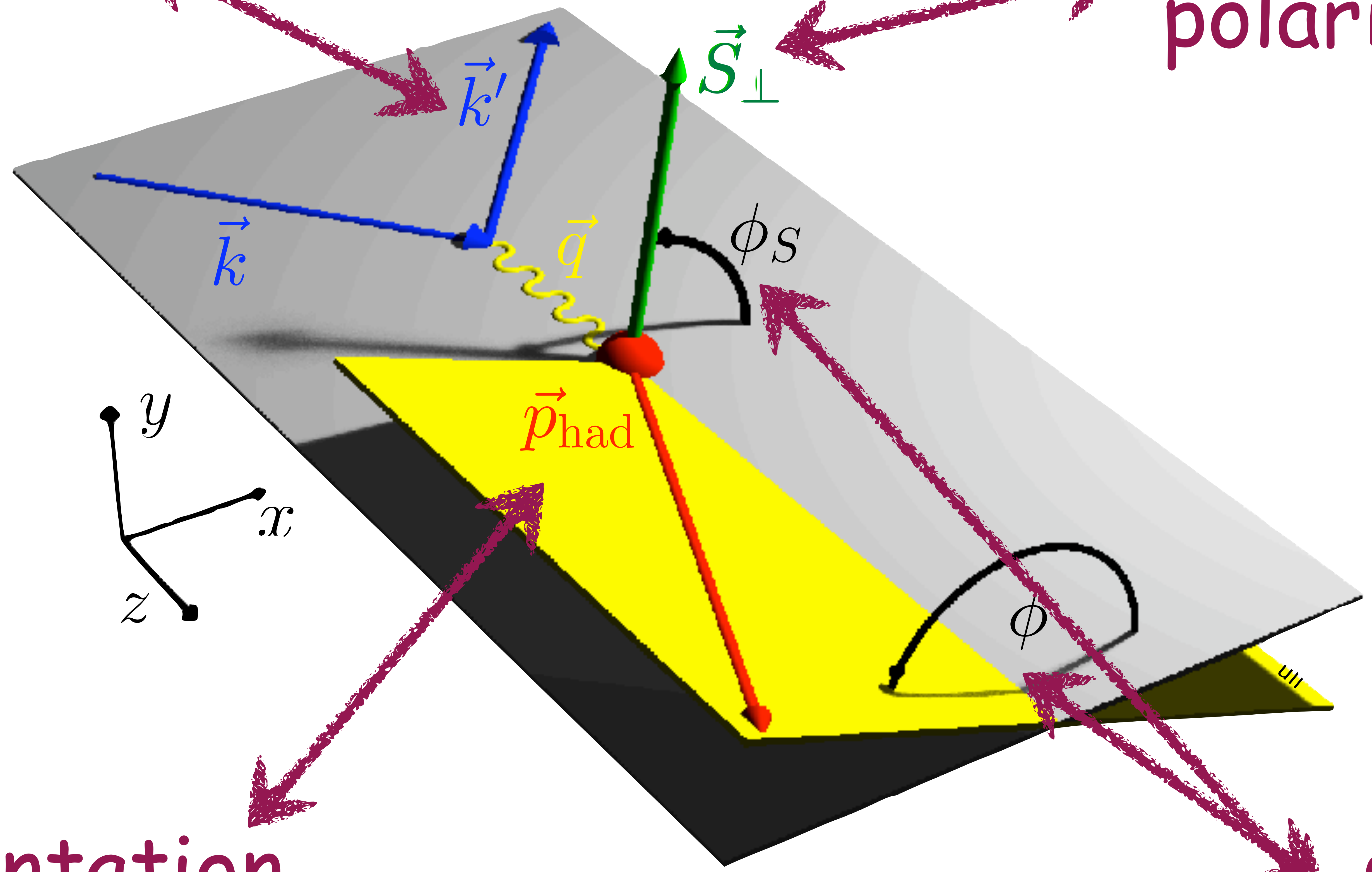


parton kinematics

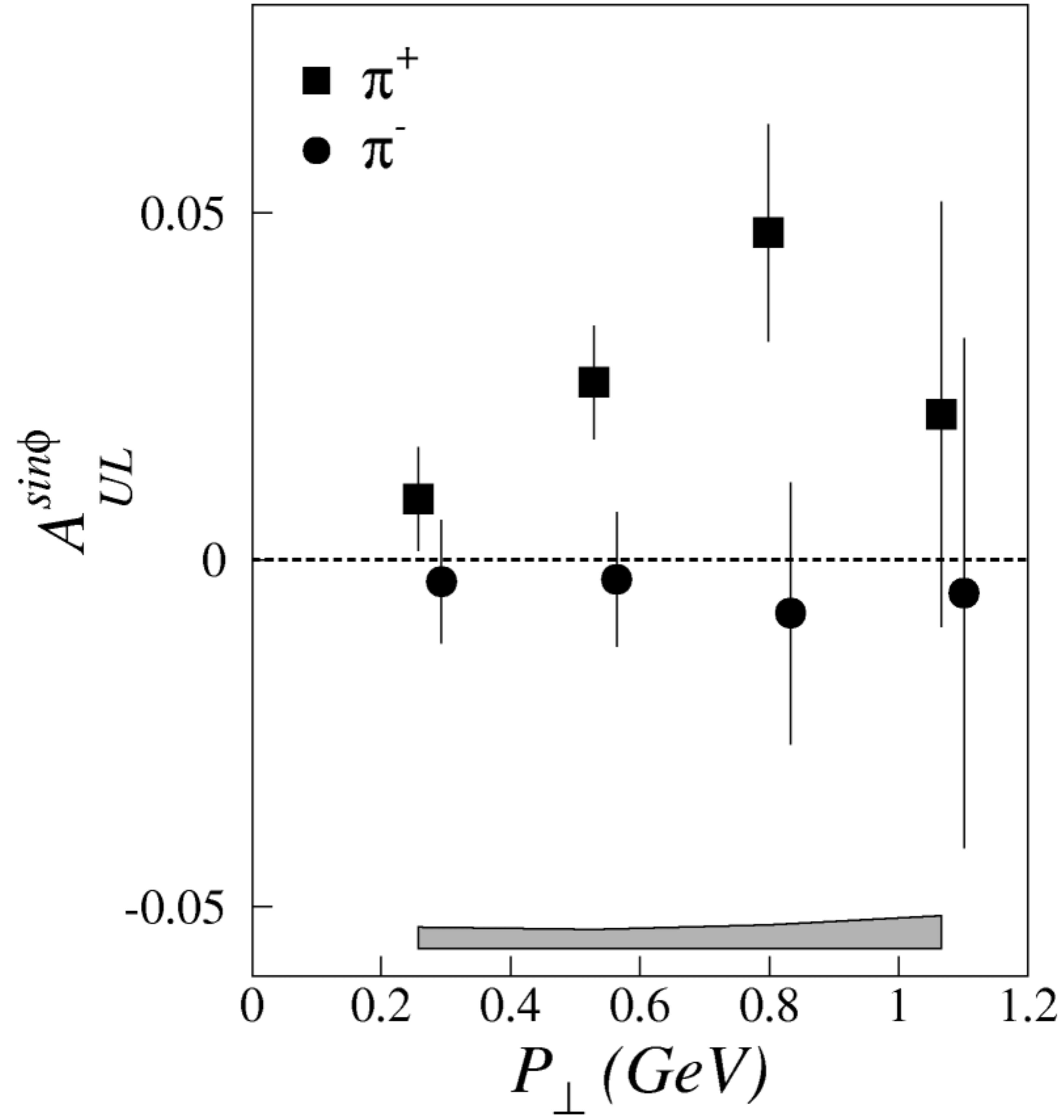
parton polarization

fragmentation kinematics

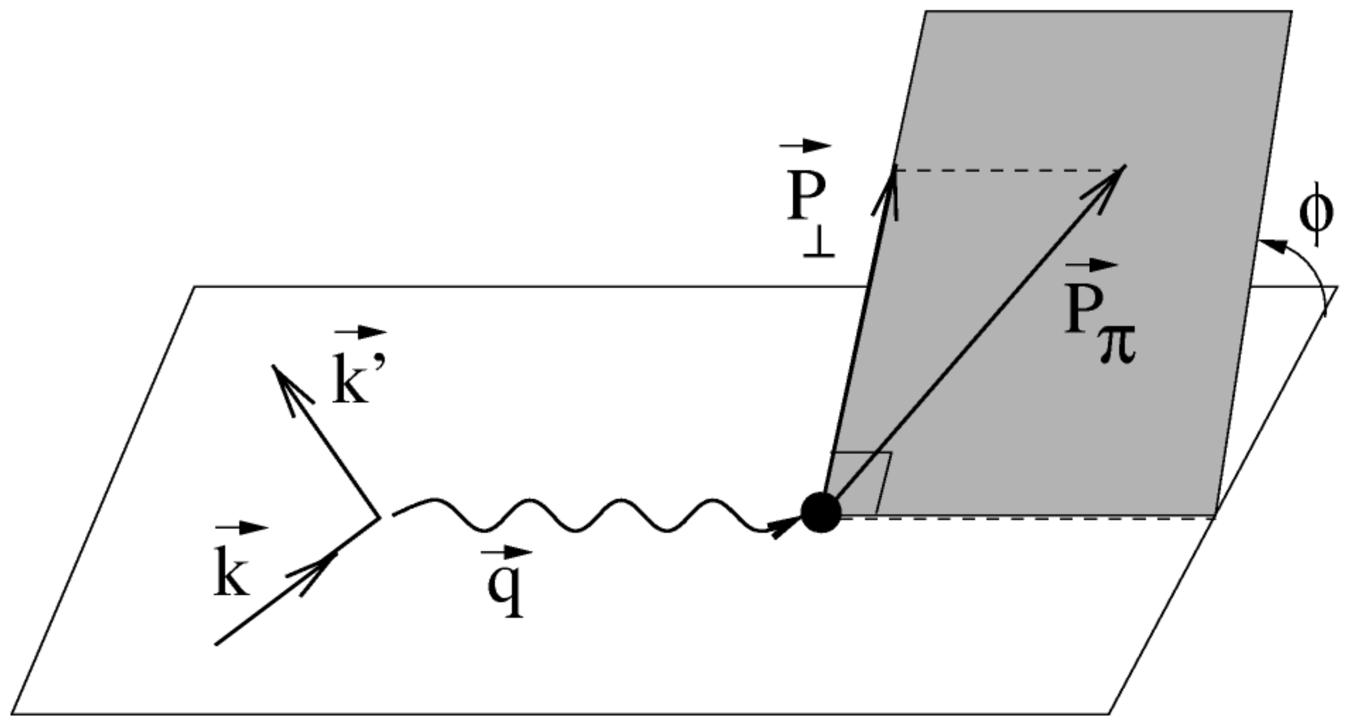
fragmentation fct. selector

VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction



$$A_{UL} = \frac{1}{|P_B|} \frac{N^{\rightarrow}(\phi) - N^{\leftarrow}(\phi)}{N^{\rightarrow}(\phi) + N^{\leftarrow}(\phi)}$$



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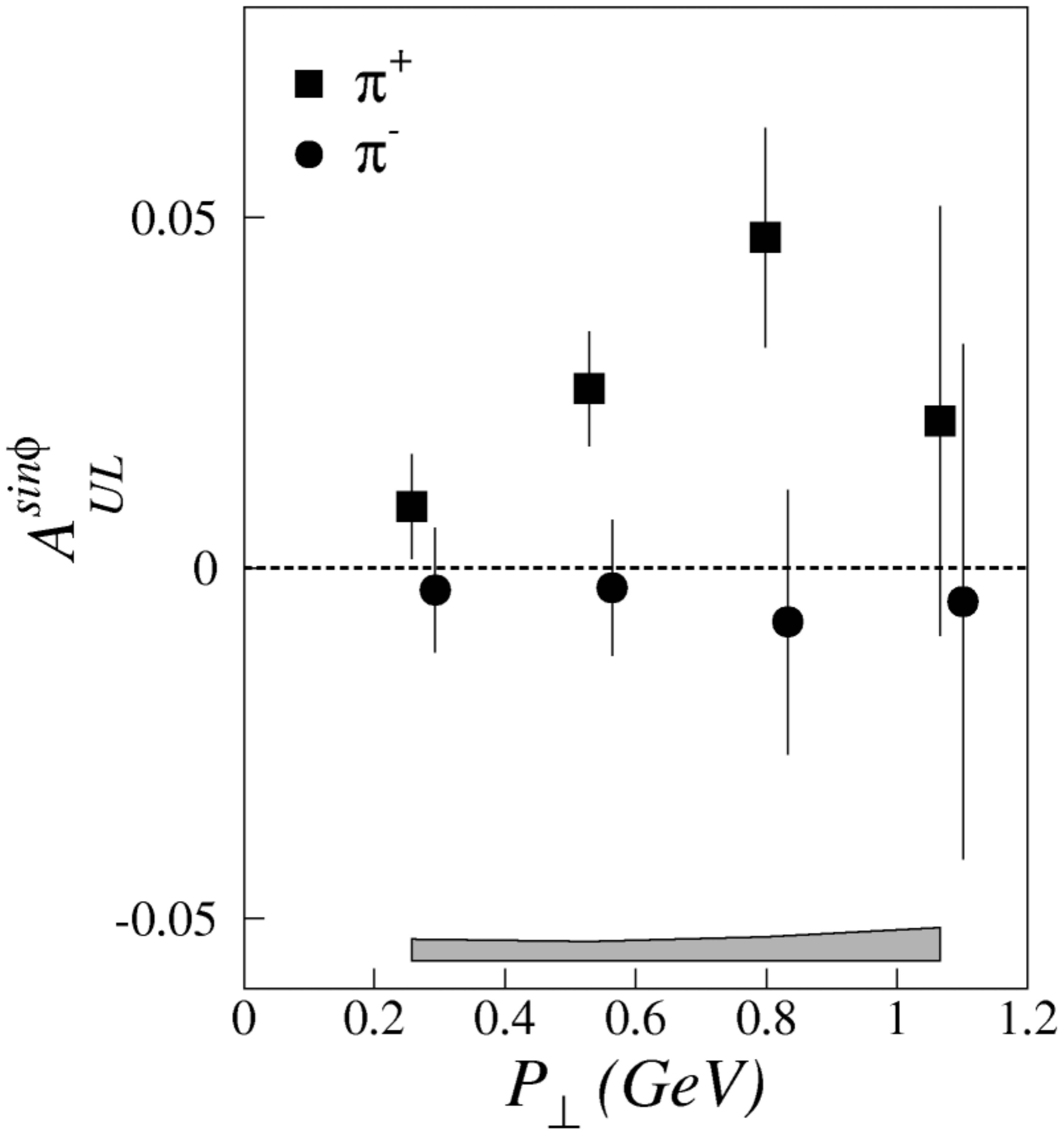

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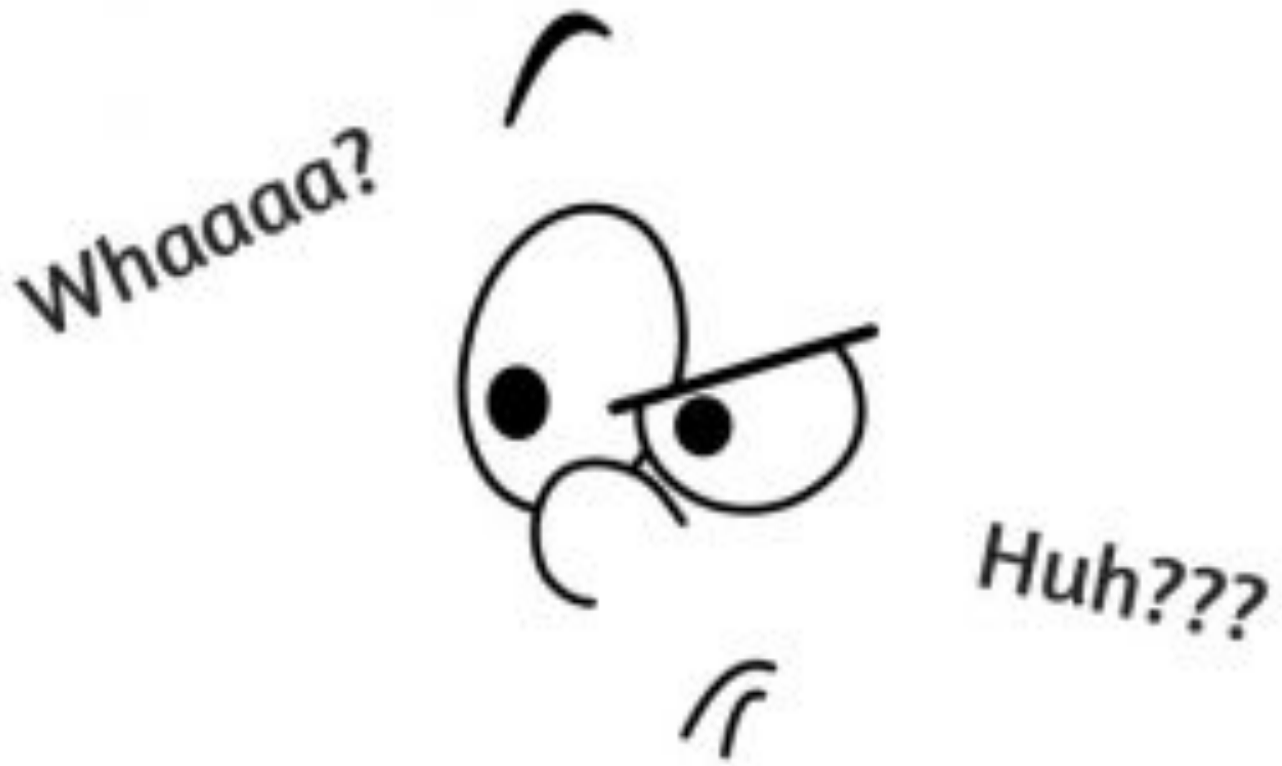
$\sim \sin\phi$?



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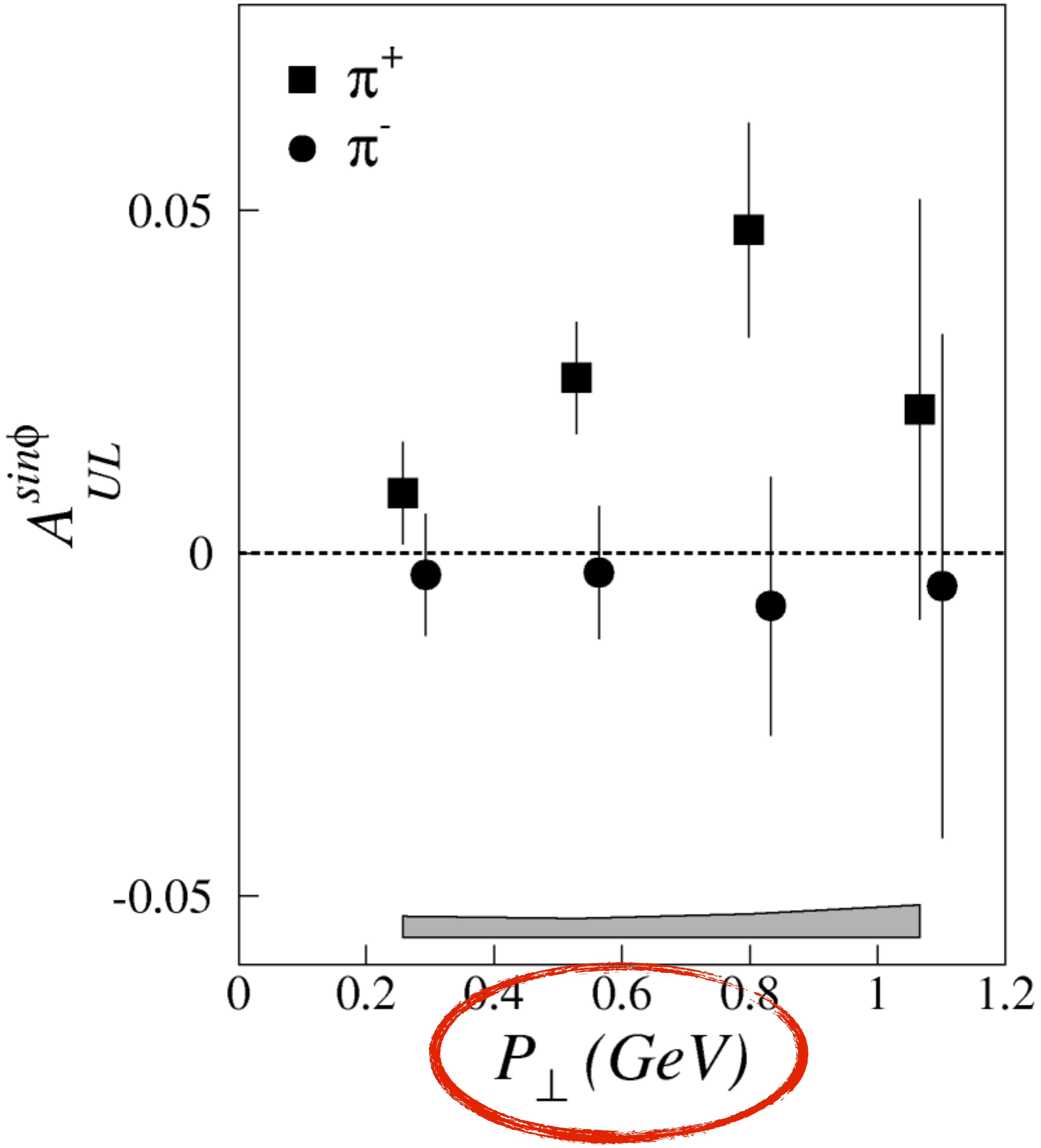

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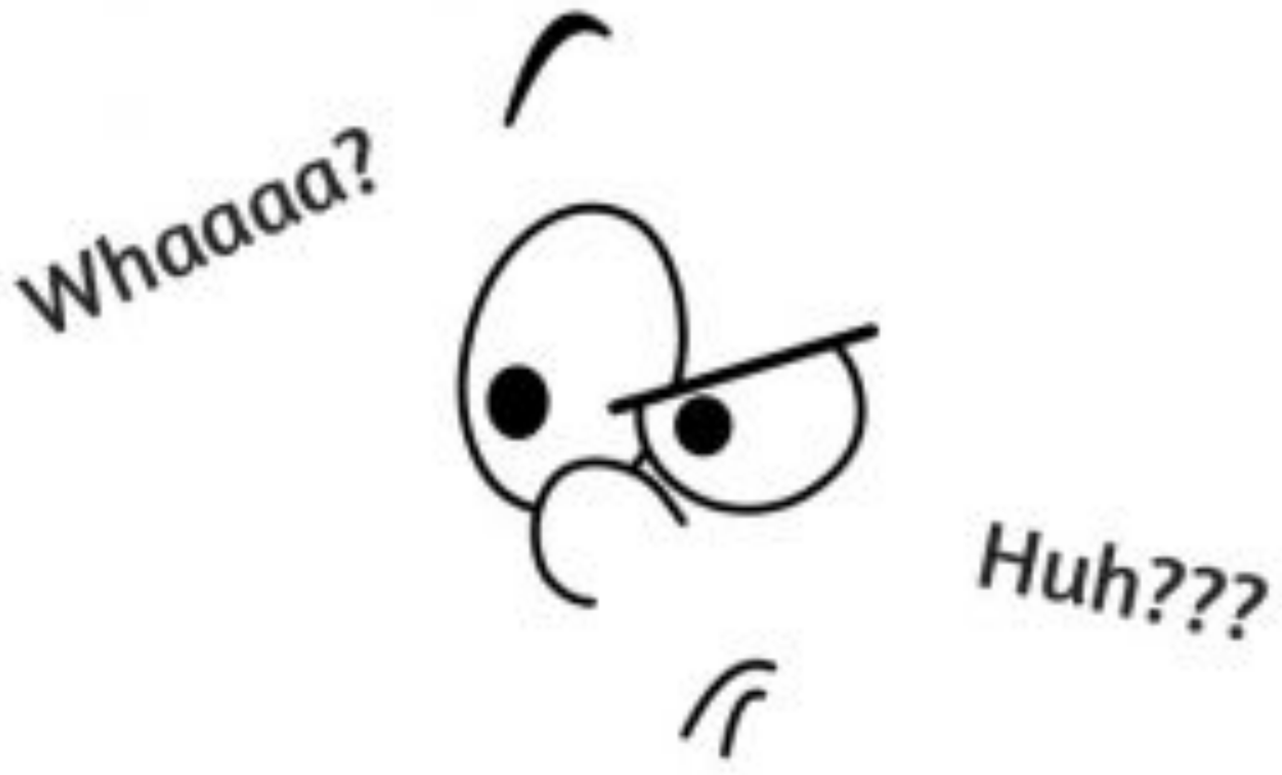
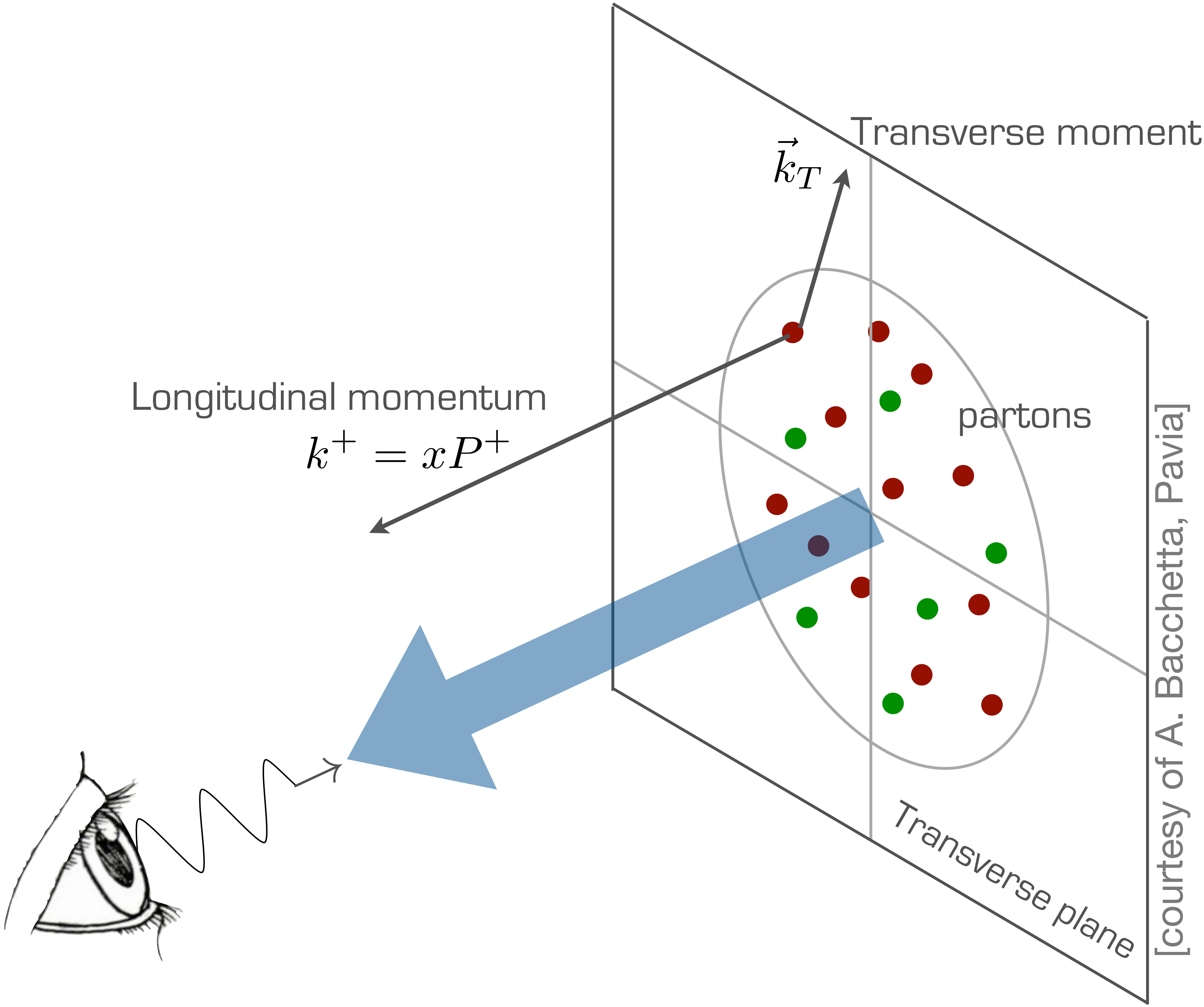


transverse-momentum distributions (TMDs)



[courtesy of A. Bacchetta, Pavia]

3d 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

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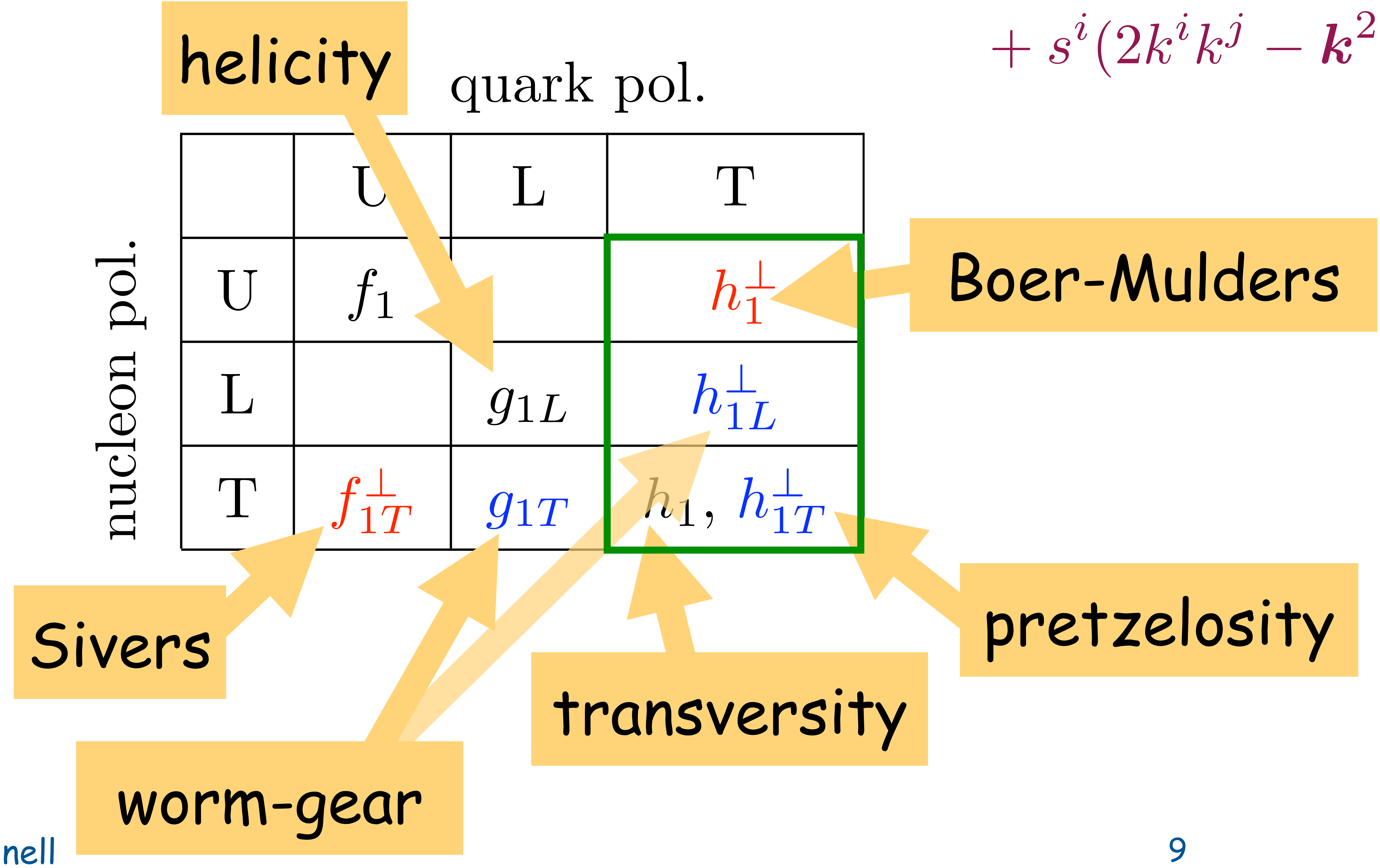

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L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
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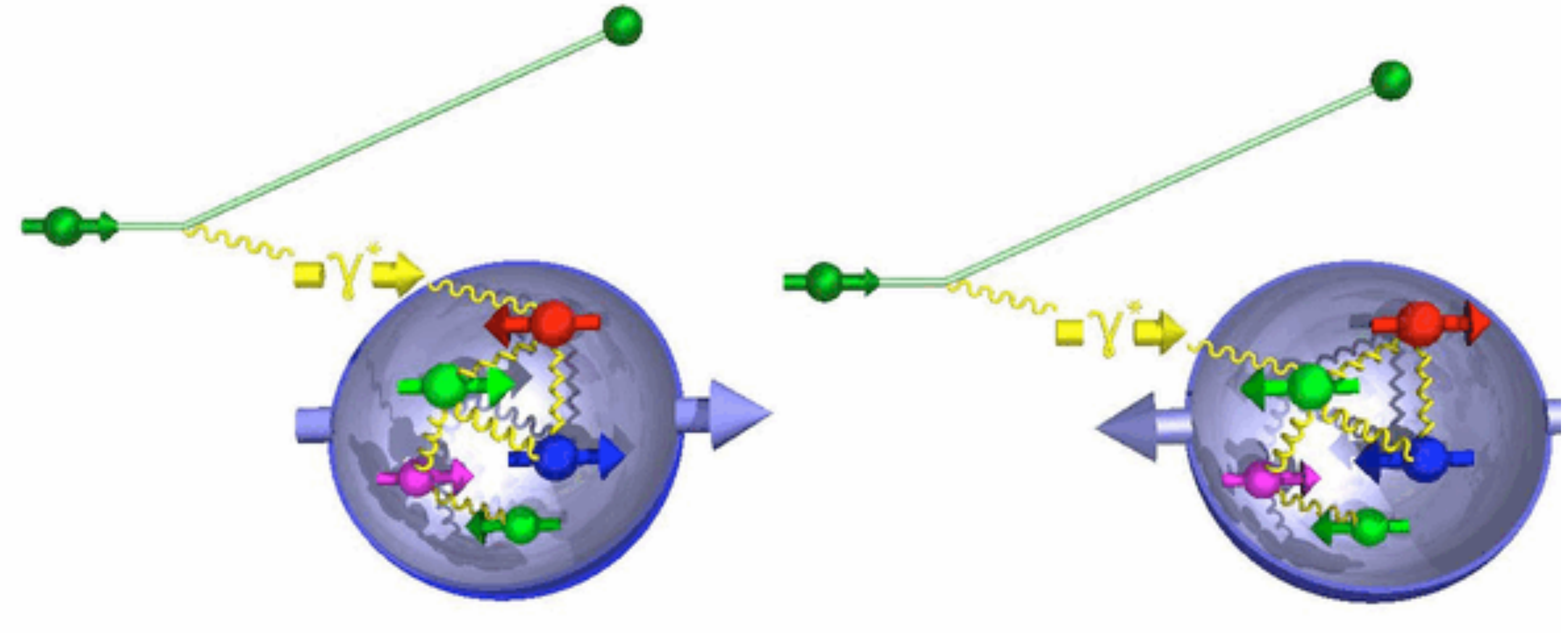
quark polarimetry

- unpolarized quarks: easy - “just” hit them (and count)

- longitudinally polarized quarks: use polarized beam



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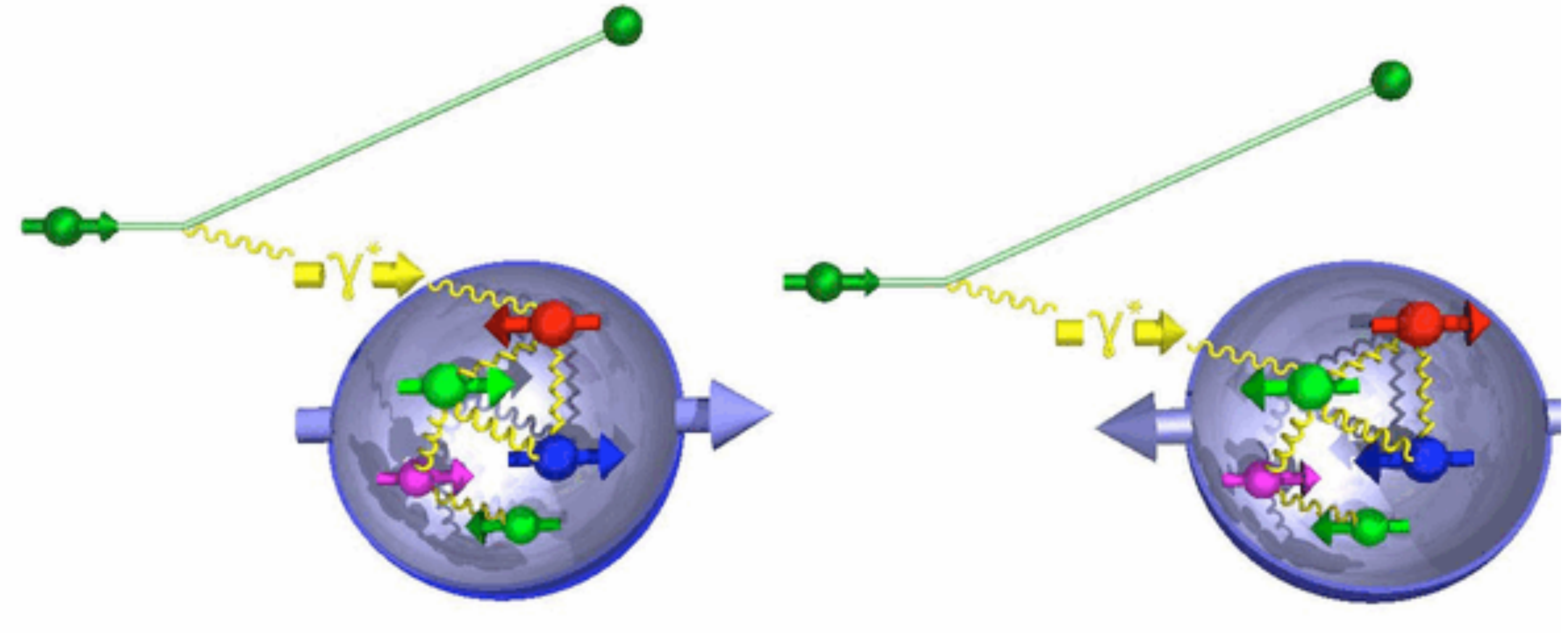
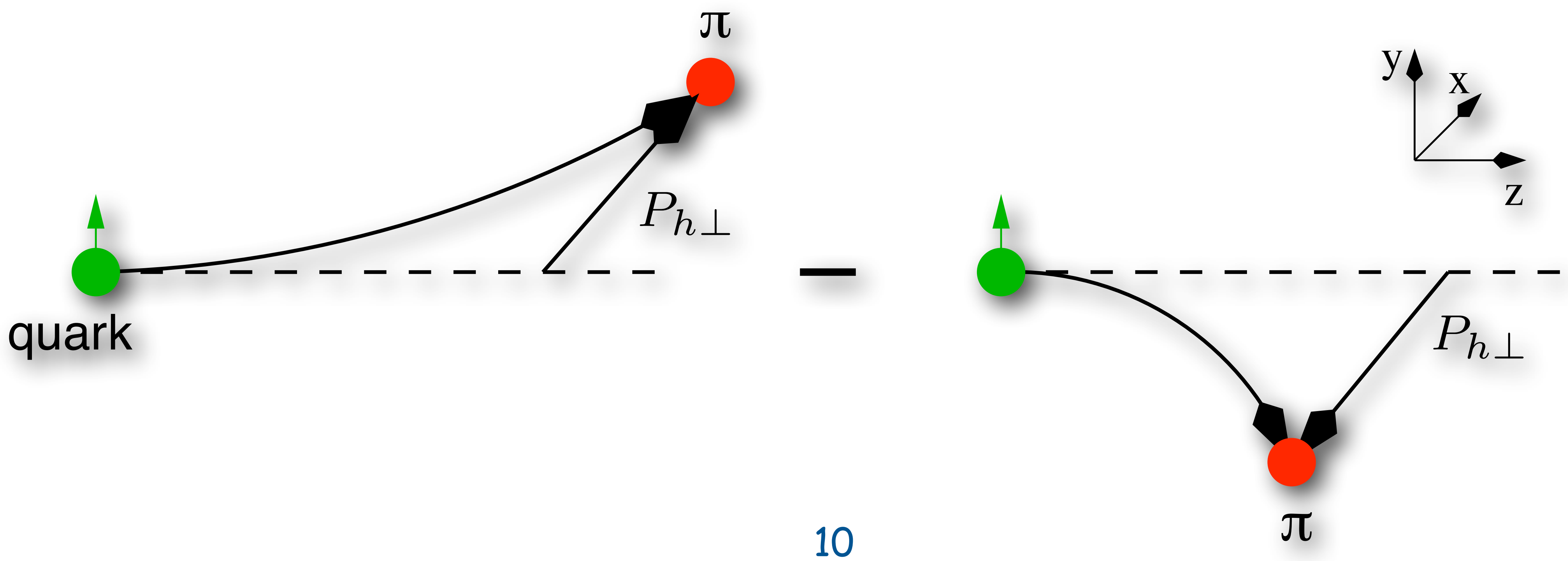


- transversely polarized quarks: need final-state polarimetry, e.g.



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

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hadron pol.

	U	L	T
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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: $D_1^{q\to h}$

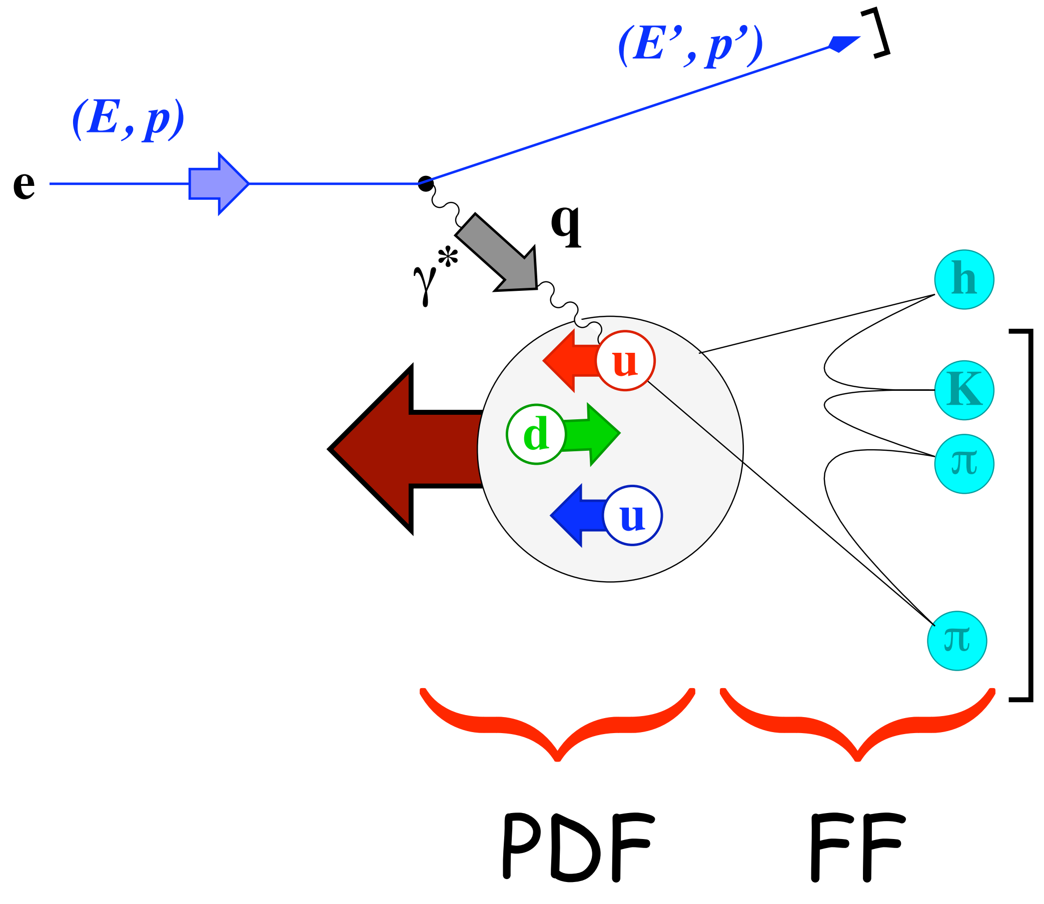
TMDs in hadronization

		quark pol.		
		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 $H_{1T}^\perp$

☚ relevant for unpolarized final state

$\}$ polarized final-state hadrons (e.g., hyperons)

probing TMDs in semi-inclusive DIS



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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:

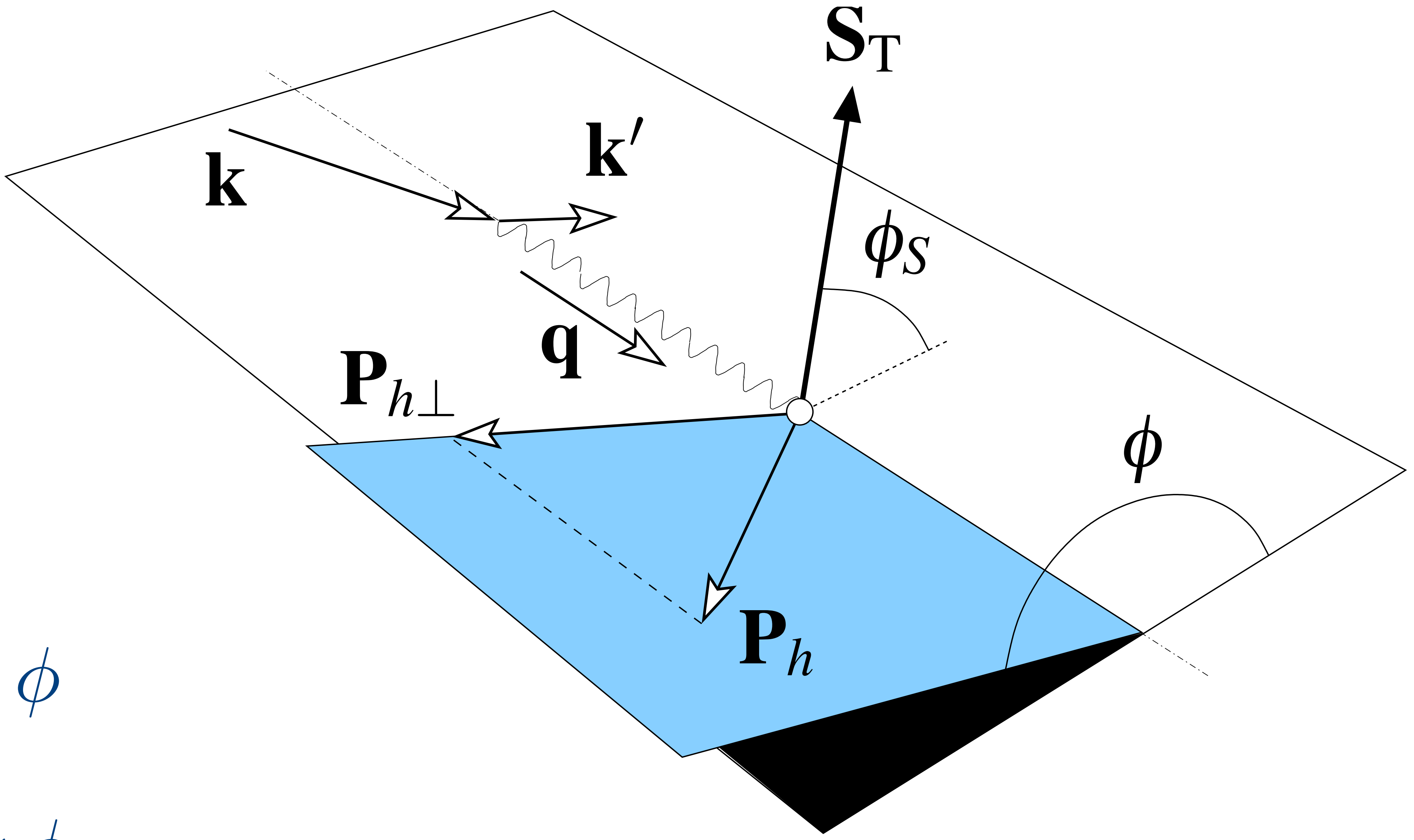
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



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

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

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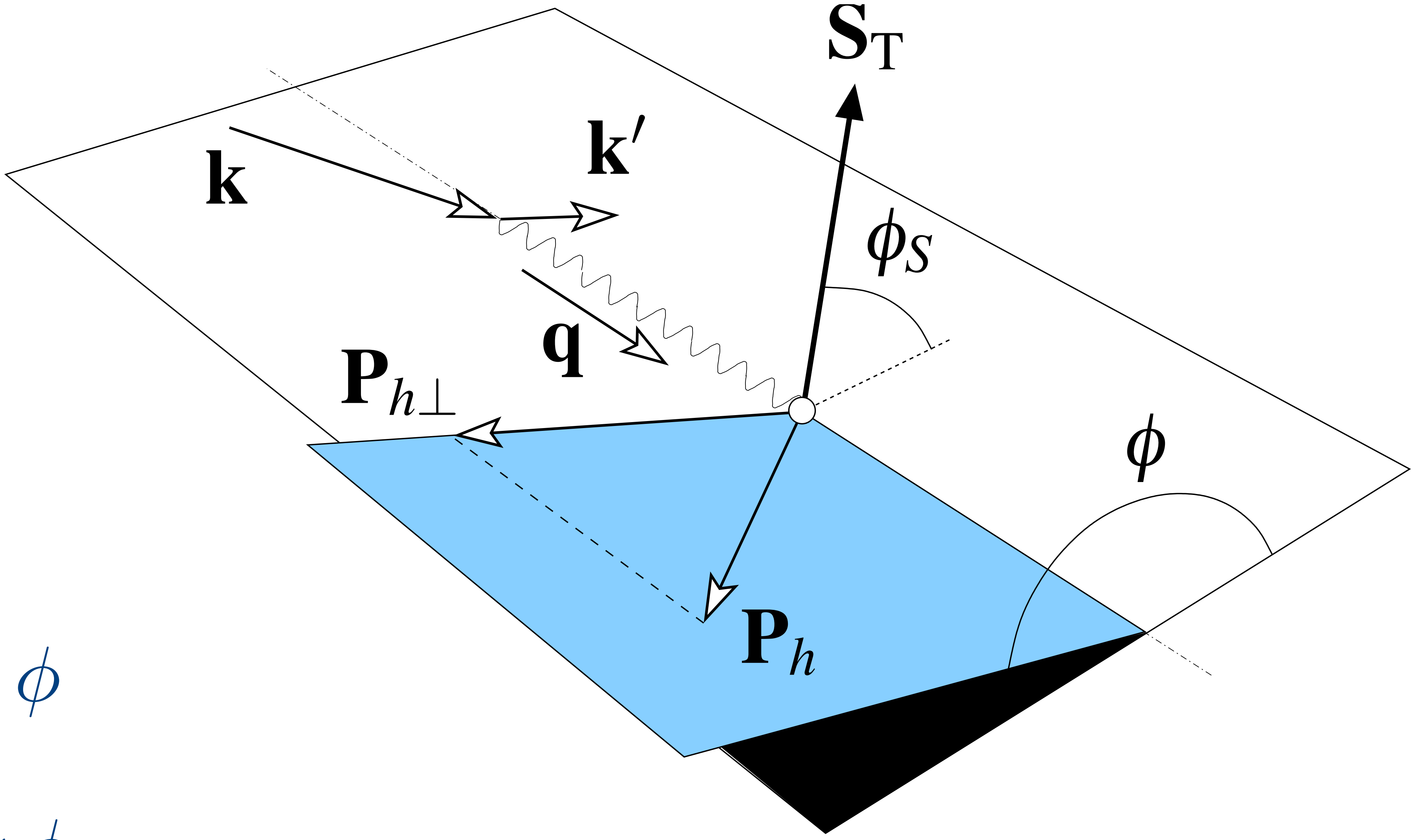

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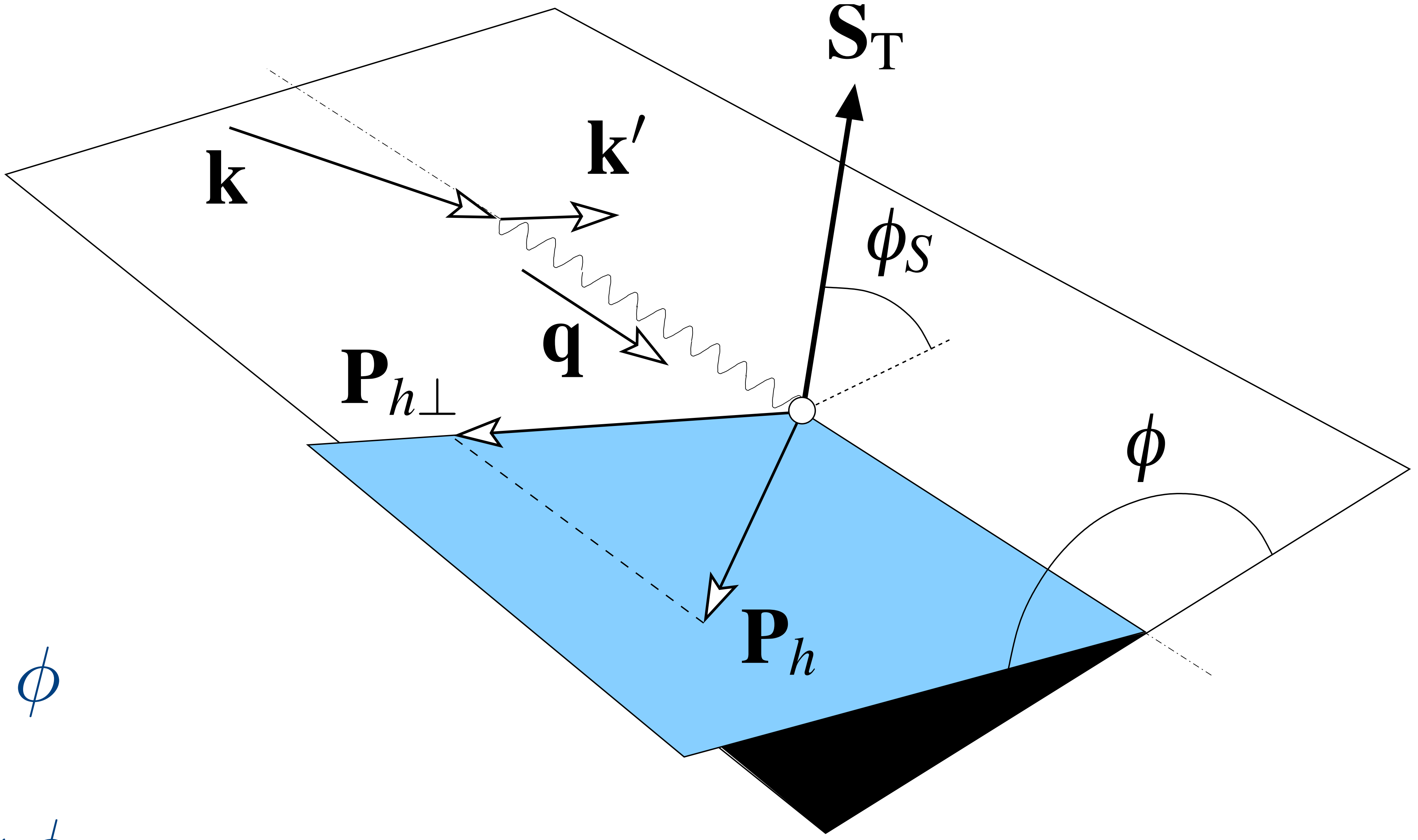

- double-spin asymmetry:

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

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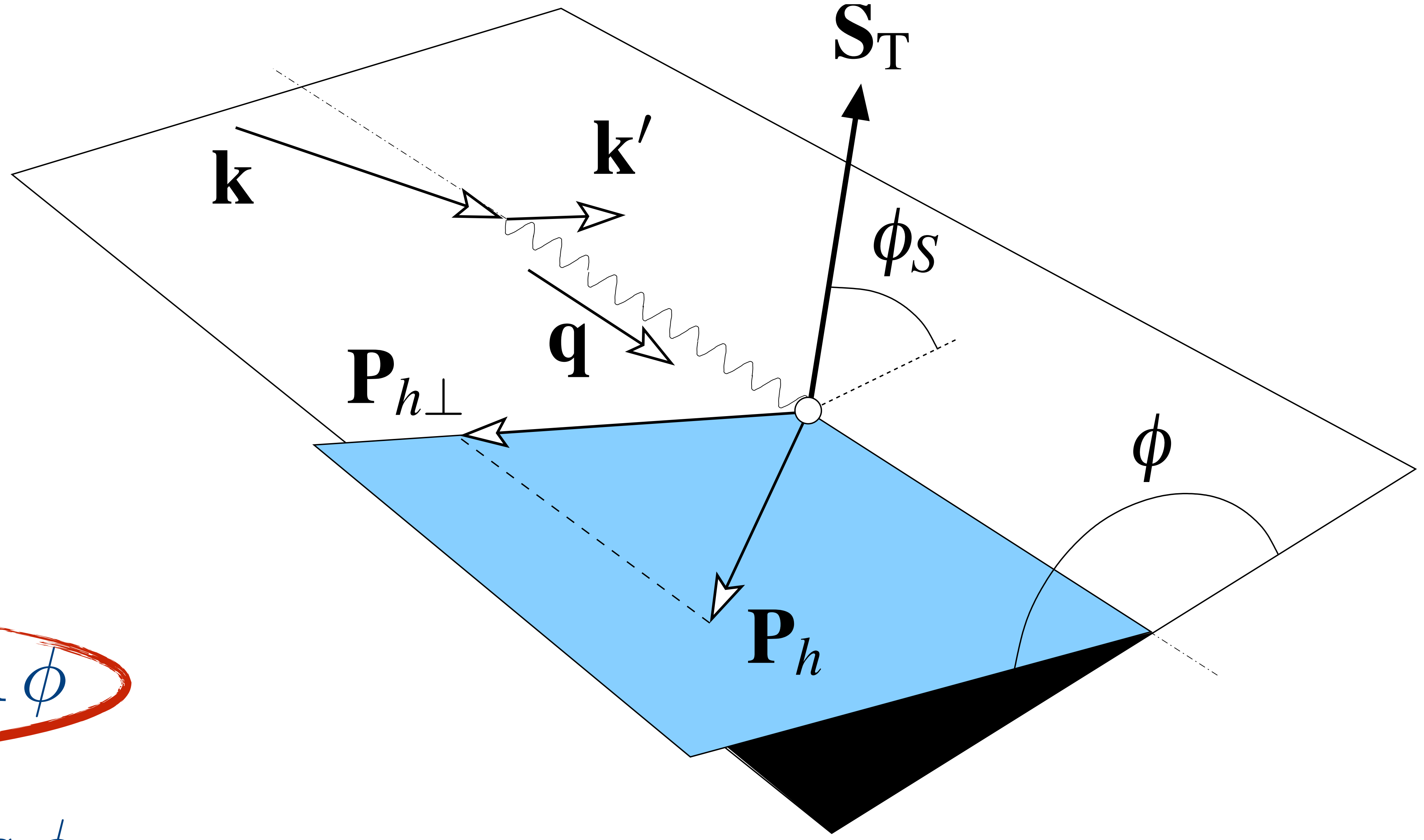

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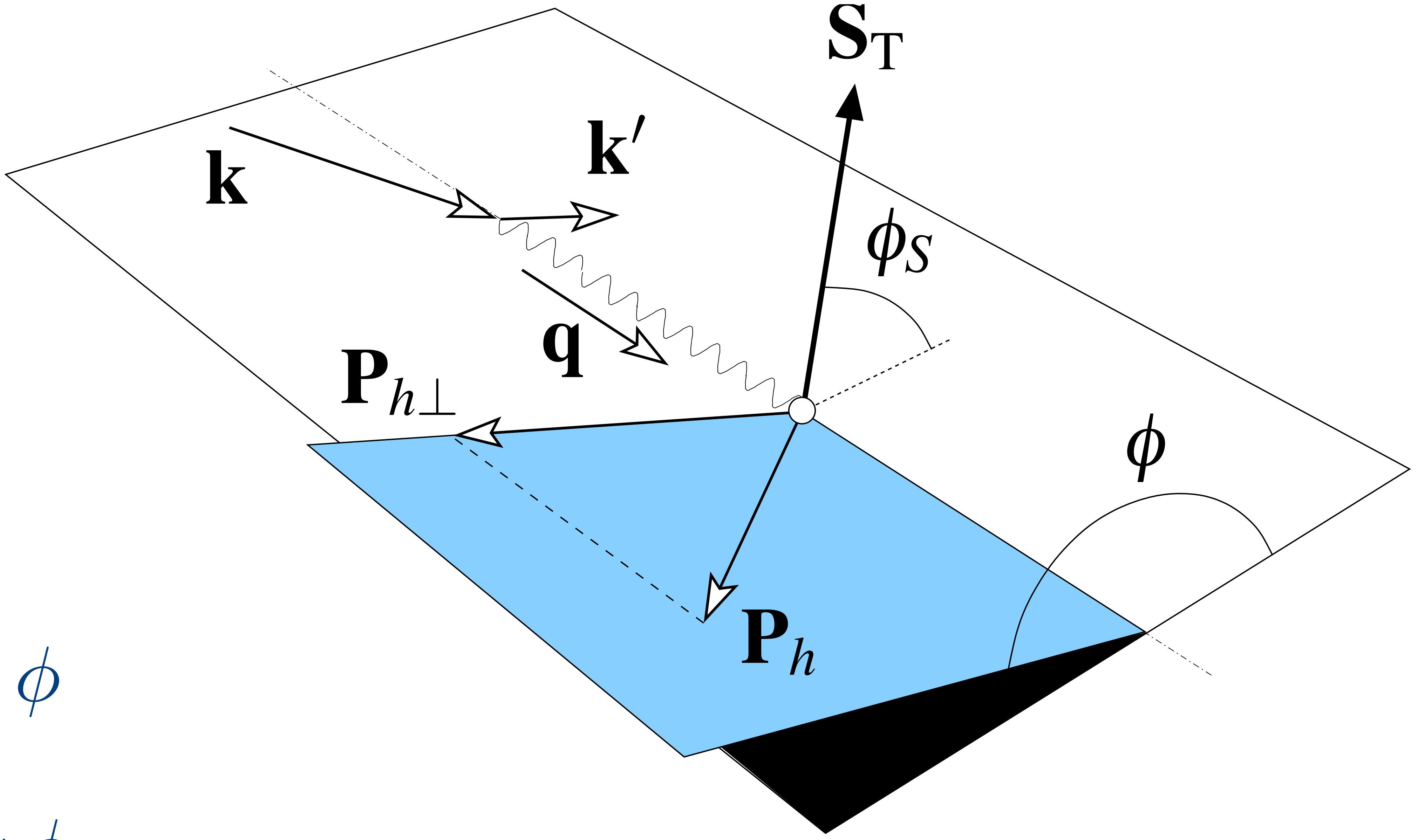

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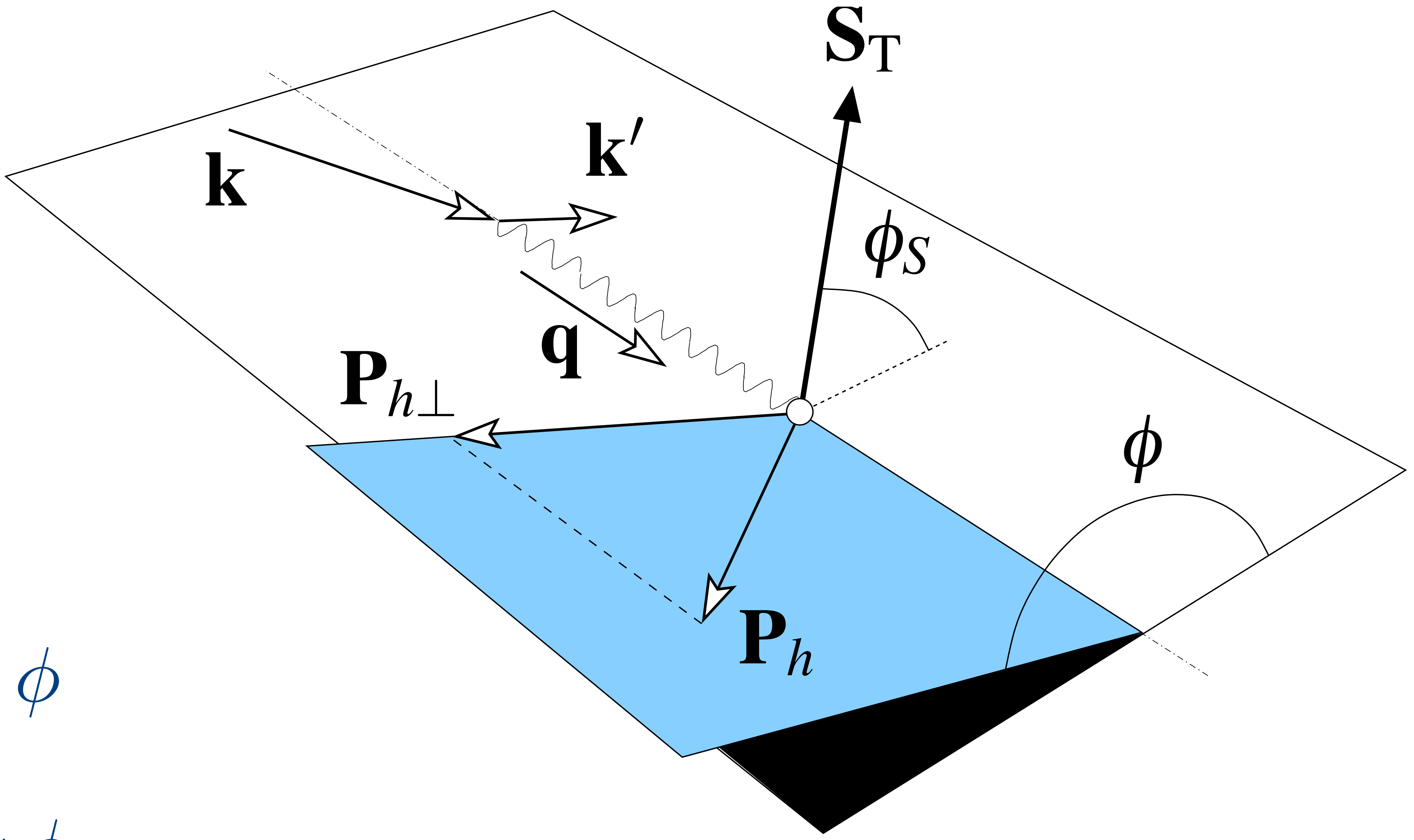
$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

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



- double-spin asymmetry:

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

semi-inclusive DIS

- excluding transverse polarization:

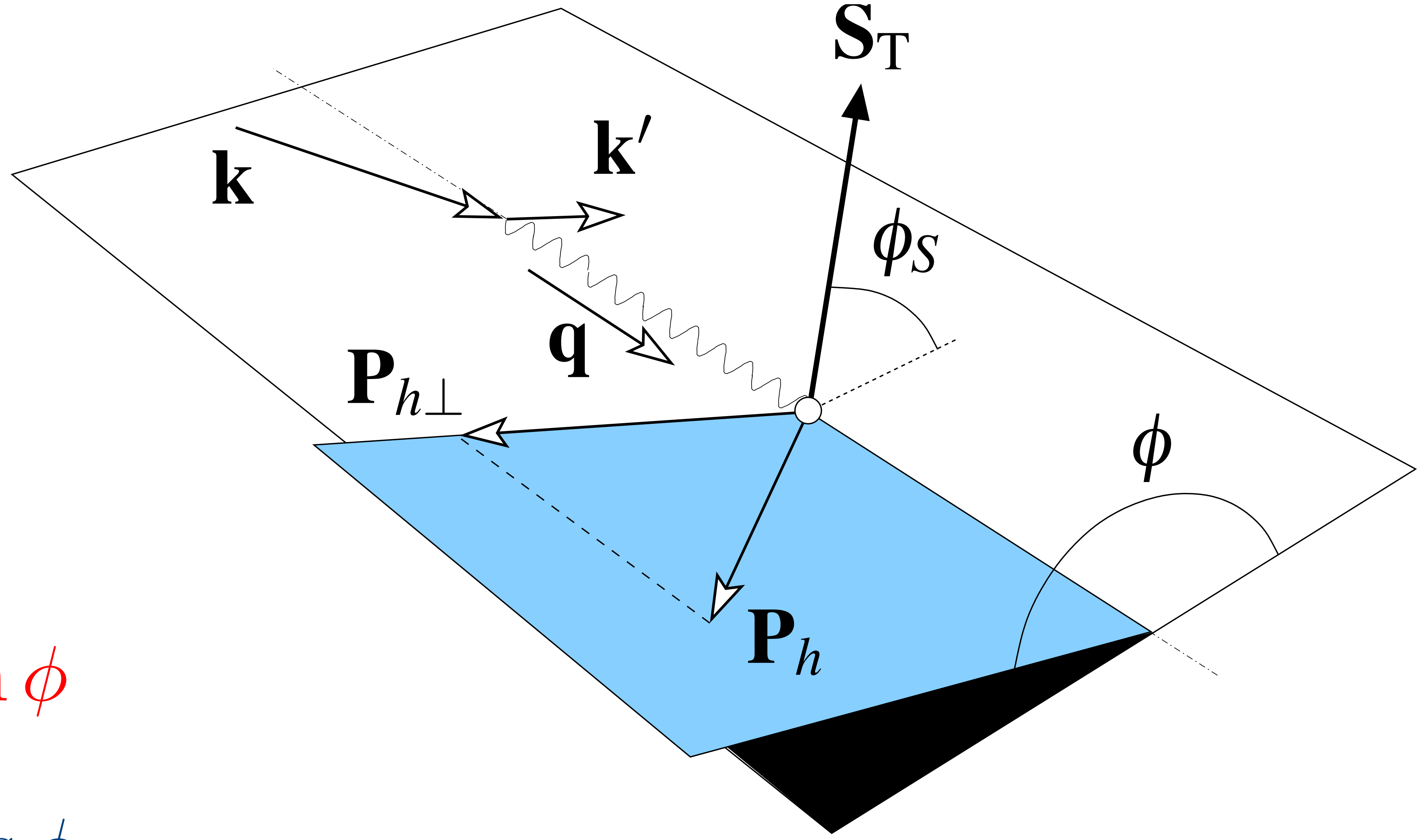
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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

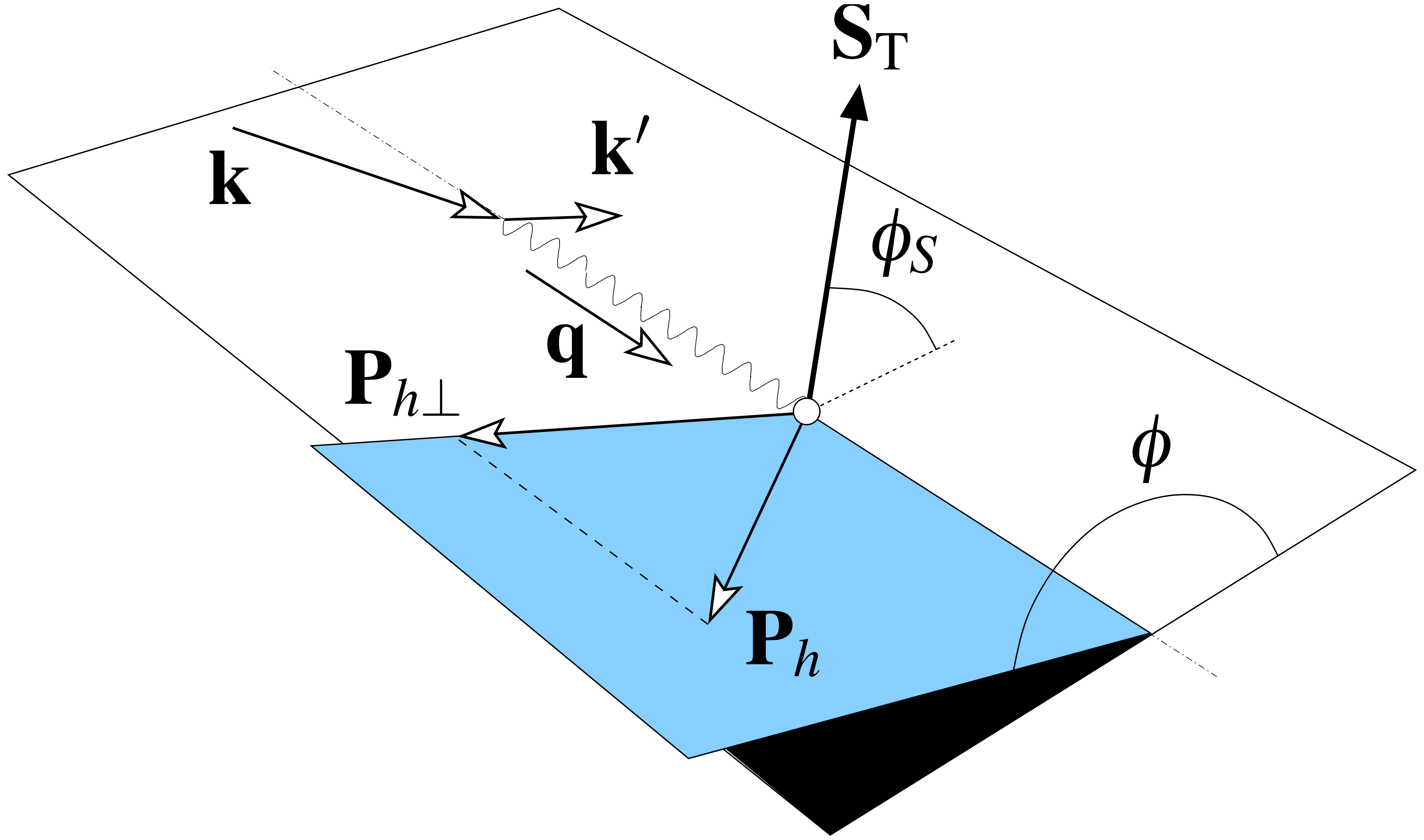


- single-spin asymmetry:
  - explicit angular dependence to be analyzed

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

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:

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

Sivers

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

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

pretzelosity

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

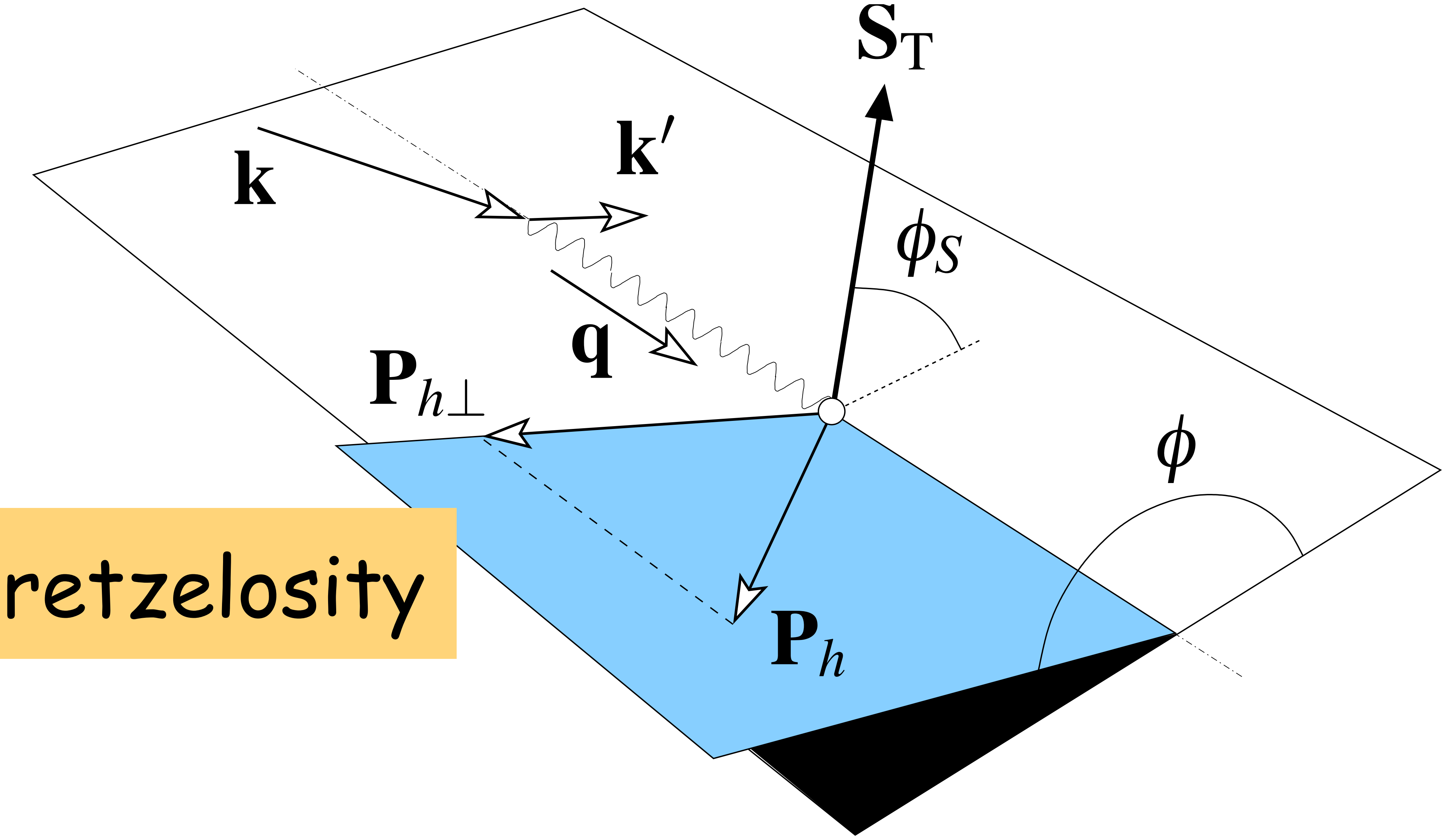
transversity

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

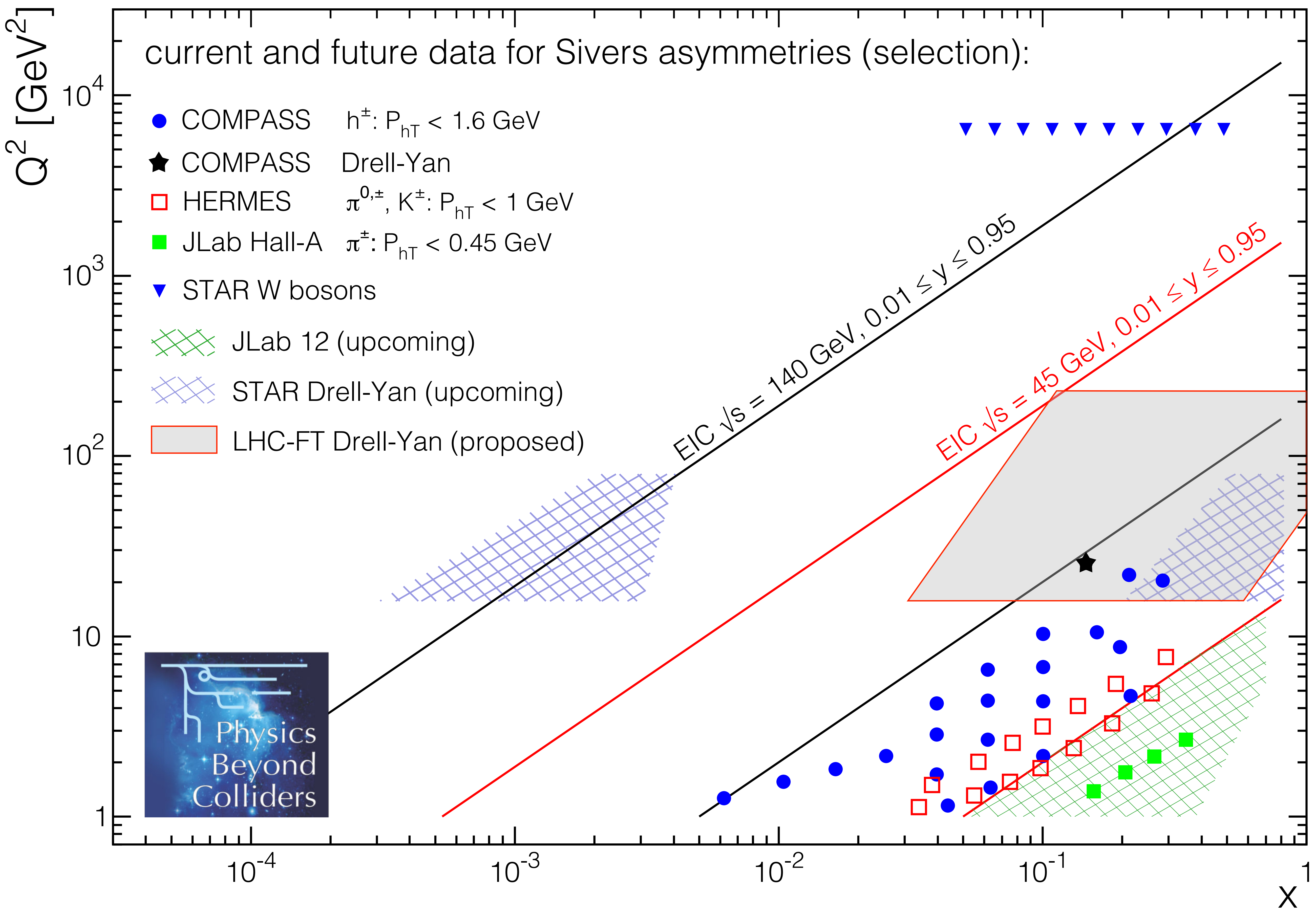
$$+\,S_T\lambda\left[\sqrt{1-\epsilon^2}\,F_{LT}^{h,\cos(\phi-\phi_s)}\cos(\phi-\phi_s)\right.$$

worm-gear

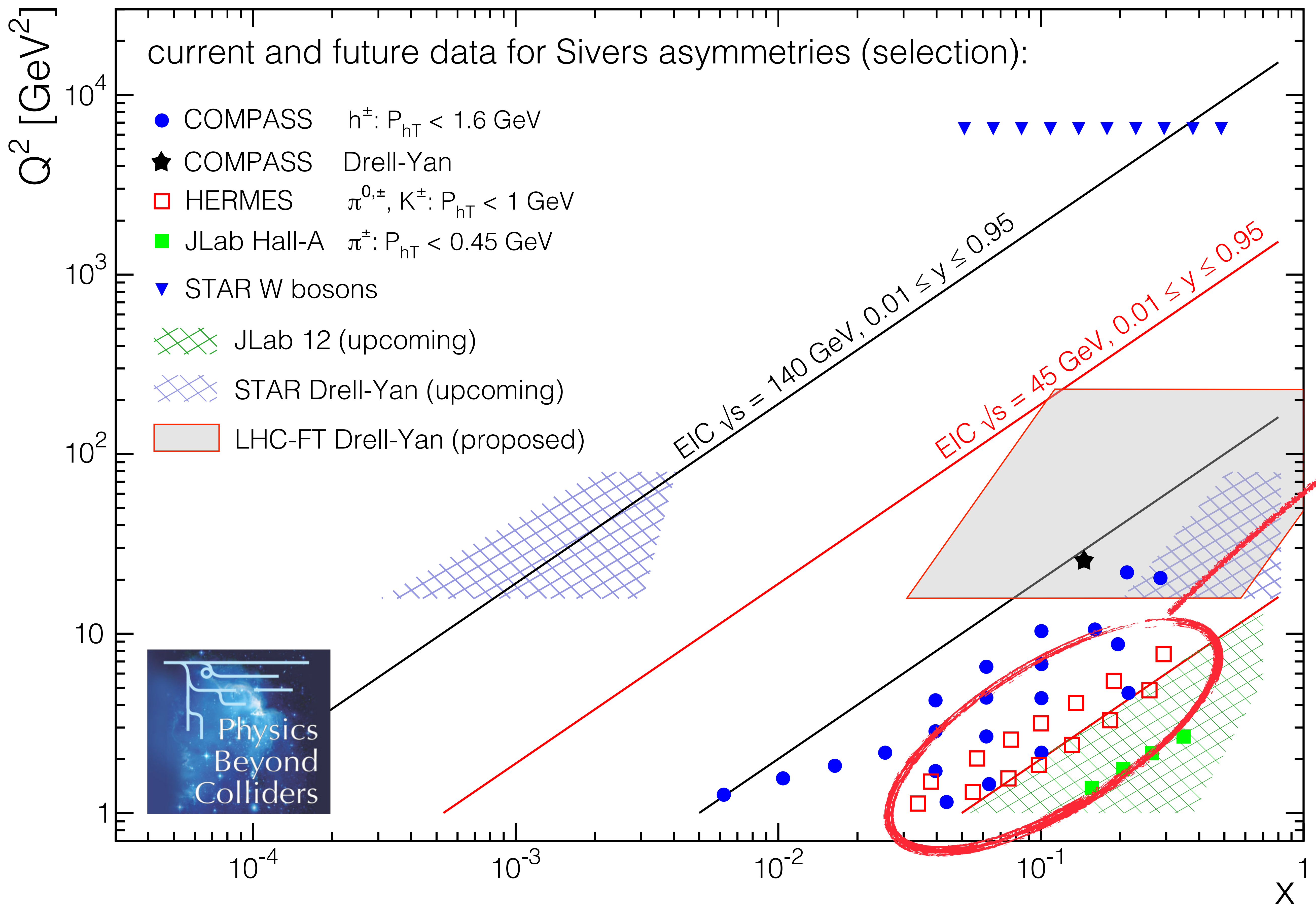
$$\left.+\sqrt{2\,\epsilon(1-\epsilon)}\,F_{LT}^{h,\cos\phi_s}\cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\,F_{LT}^{h,\cos(2\phi-\phi_s)}\cos(2\phi-\phi_s)\right]\Big\}$$



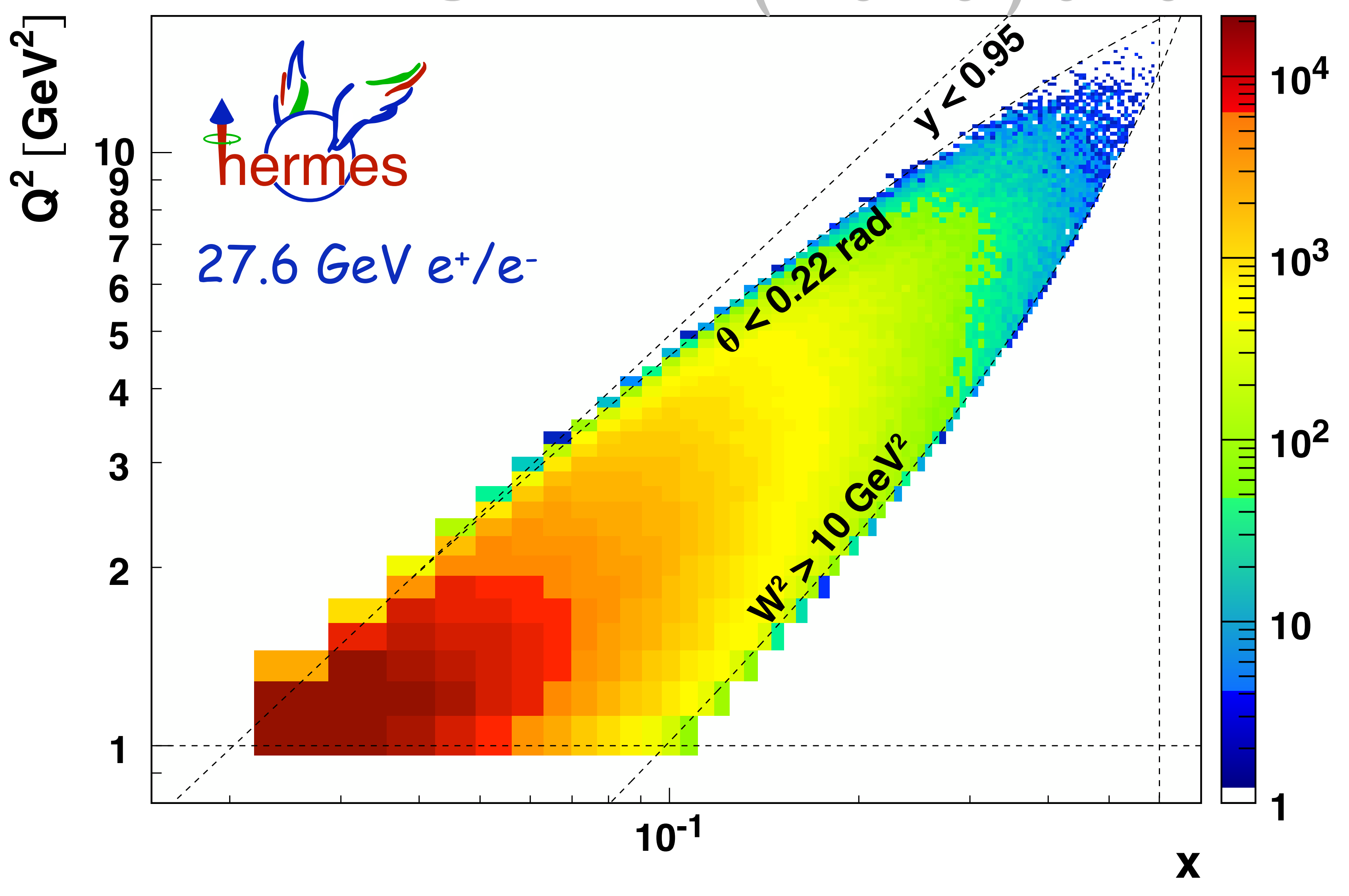
2d kinematic phase space



2d kinematic phase space



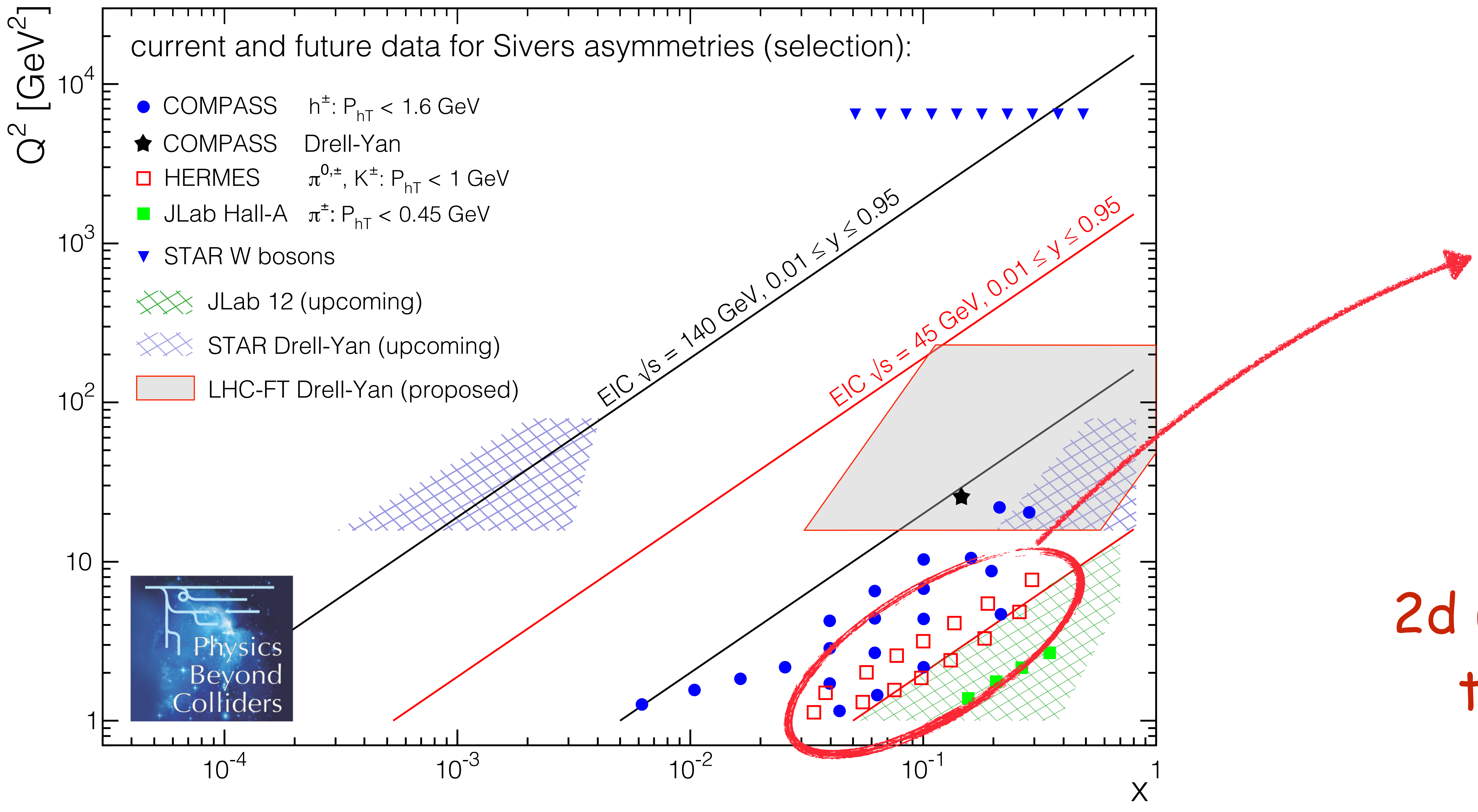
JHEP12(2020)010



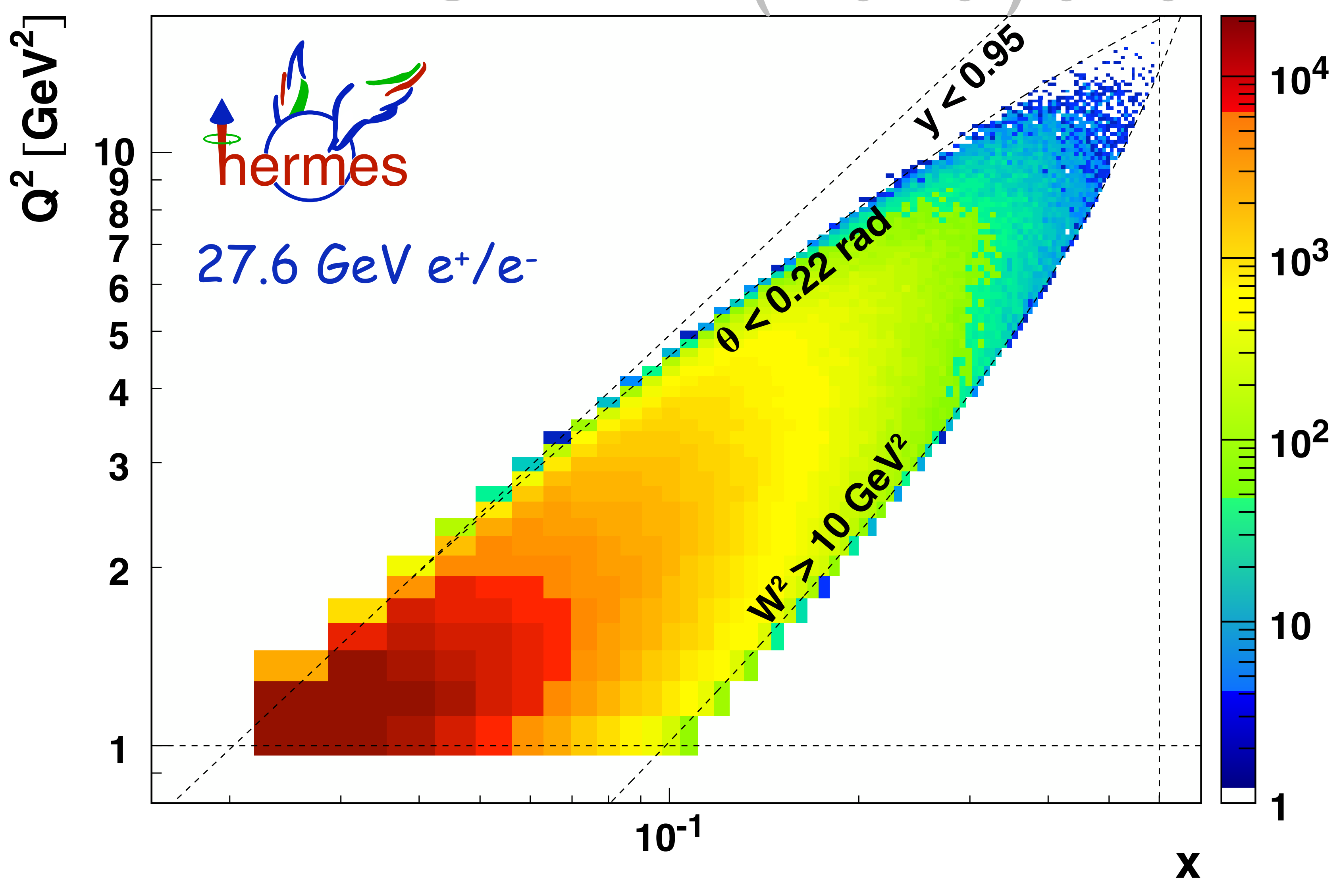
Scattered lepton:		Q^2	$> 1\,\mathrm{GeV}^2$	
		W^2	$> 10\,\mathrm{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\mathrm{GeV} <$	$\lvert \mathbf{P}_h \rvert$	$< 15\,\mathrm{GeV}$	charged mesons
	$4\,\mathrm{GeV} <$	$\lvert \mathbf{P}_h \rvert$	$< 15\,\mathrm{GeV}$	(anti)protons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

2d kinematic phase space

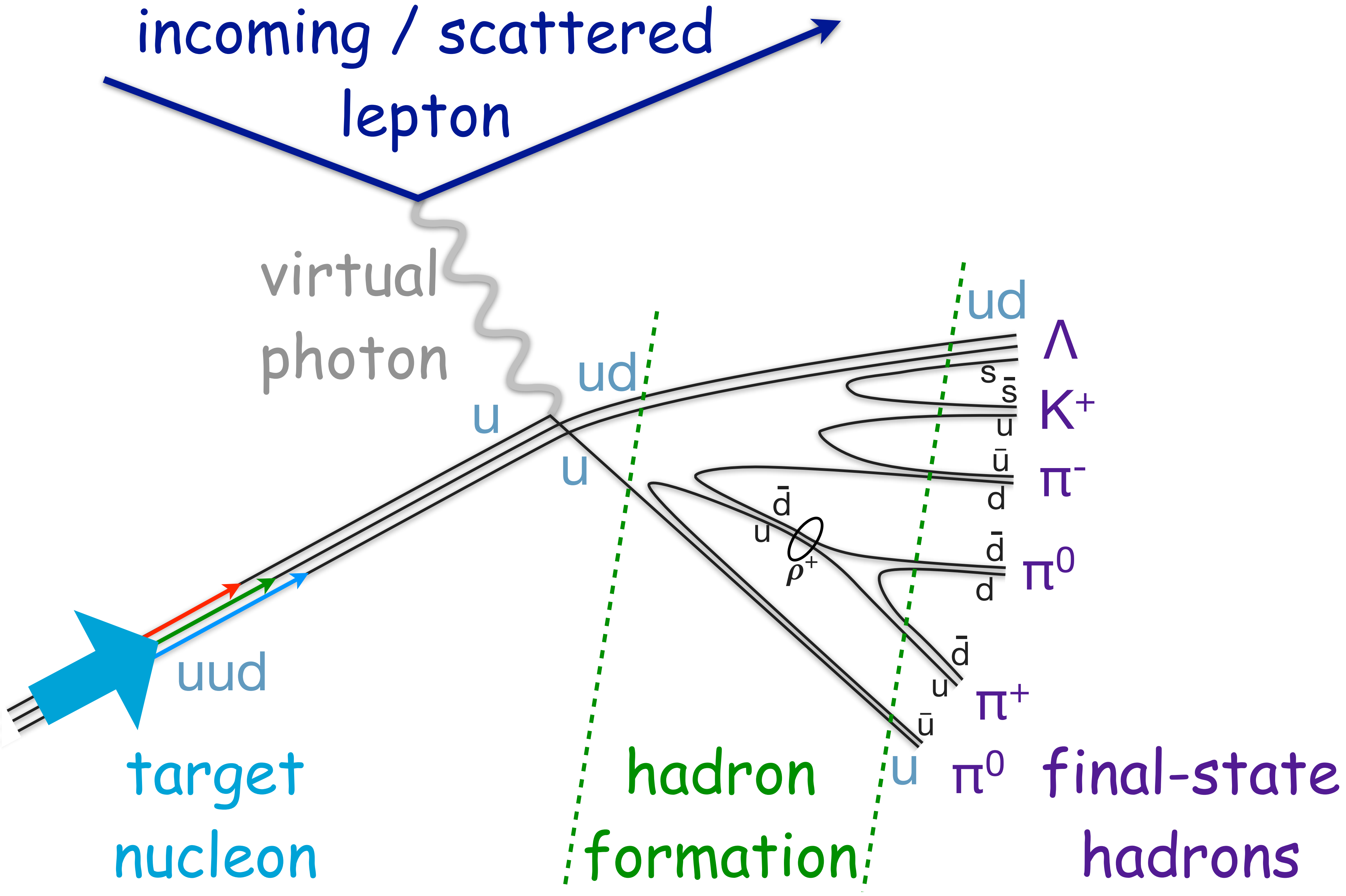


JHEP12(2020)010

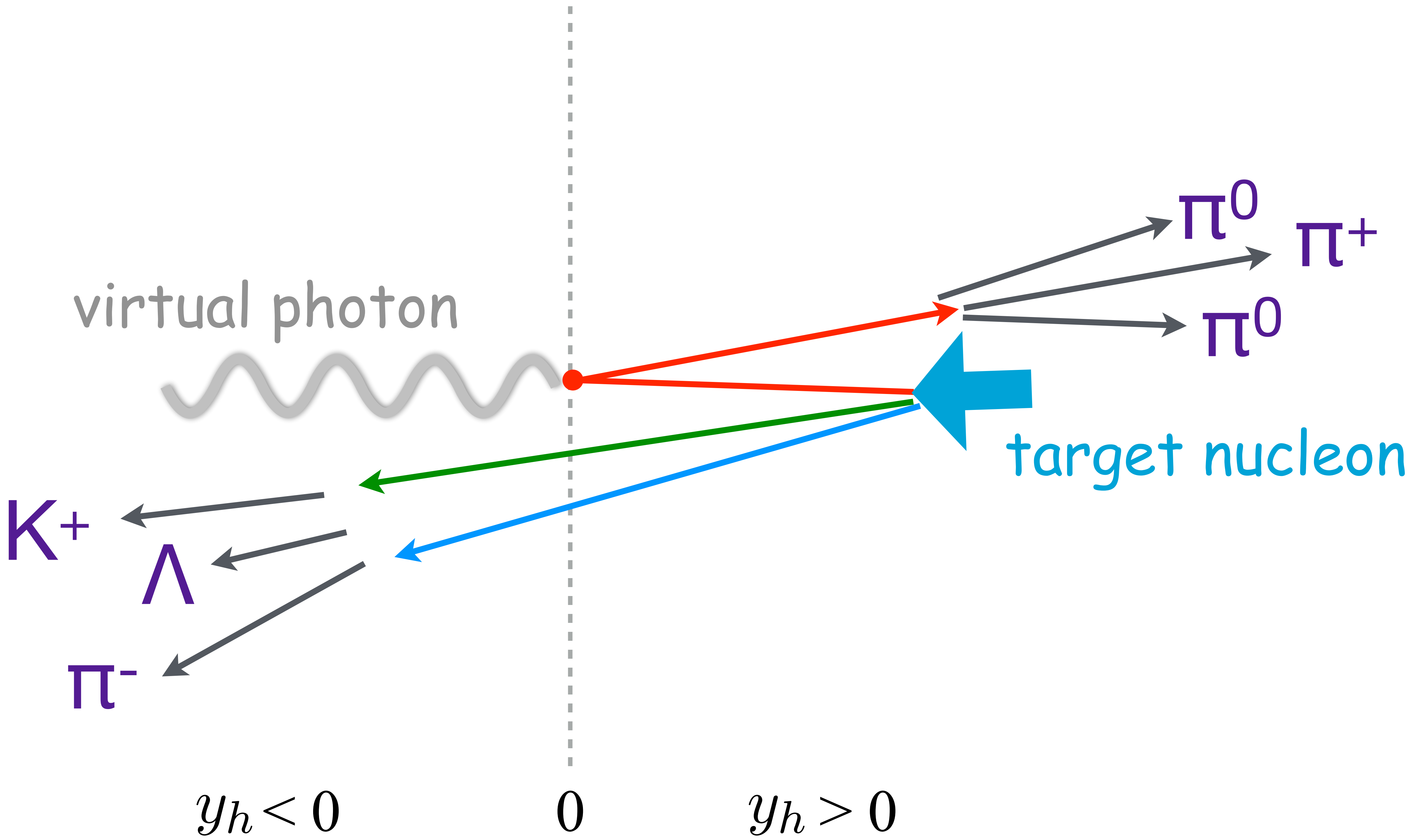


2d (x-Q^2) kinematic space not the only relevant one for SIDIS interpretation

current vs. target fragmentation



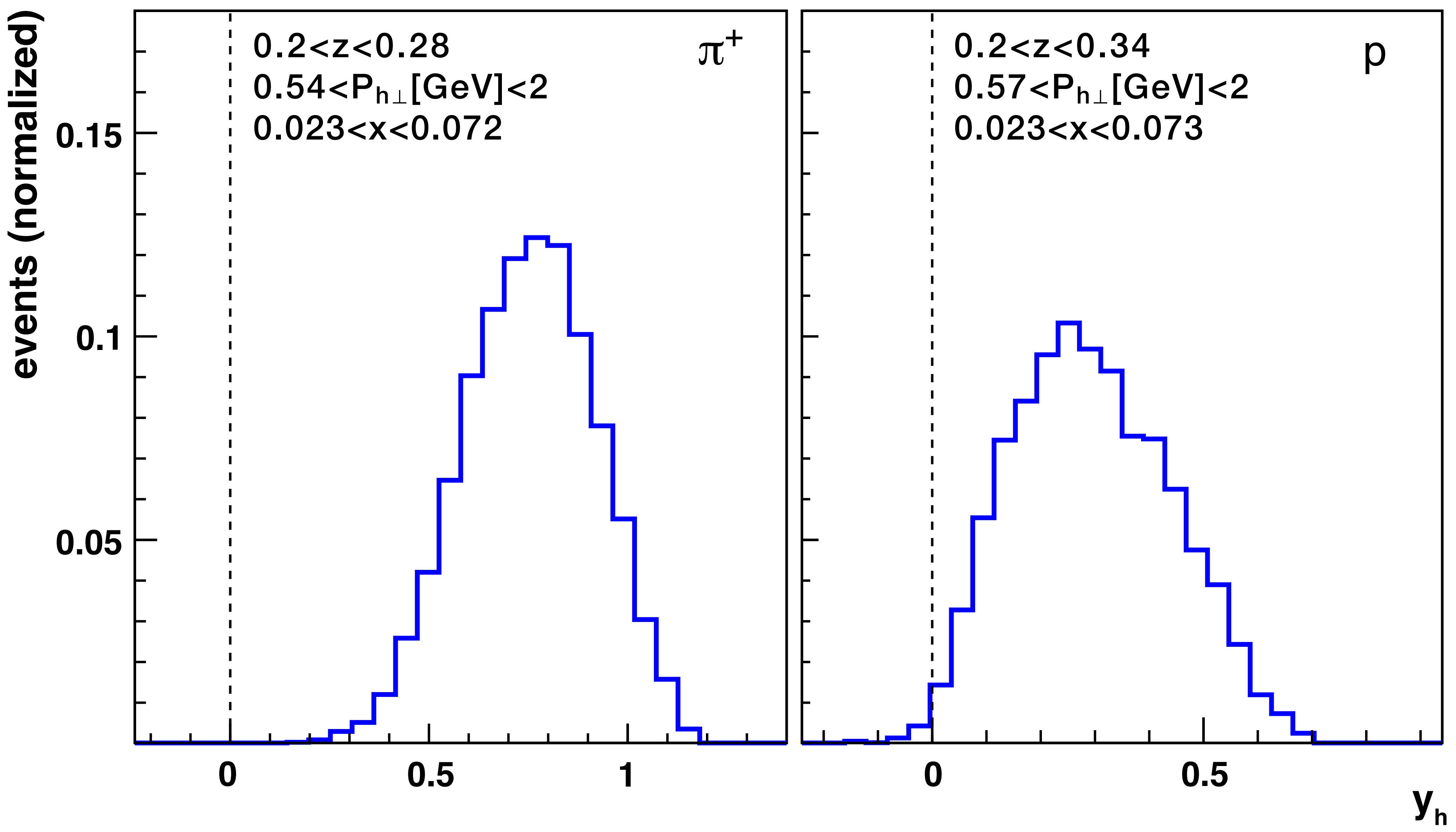
virtual-photon—nucleon c.m.s



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

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

current vs. target fragmentation



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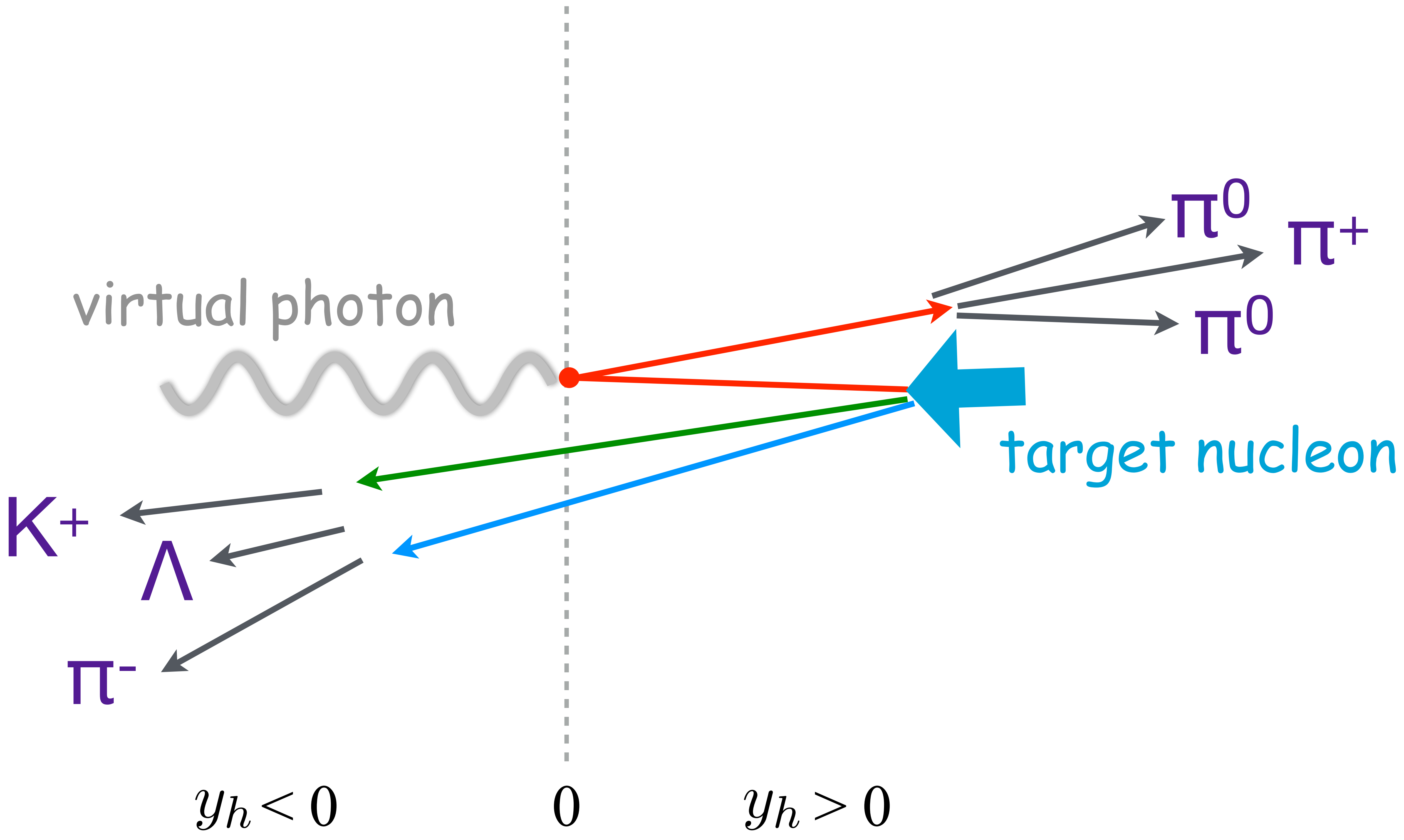

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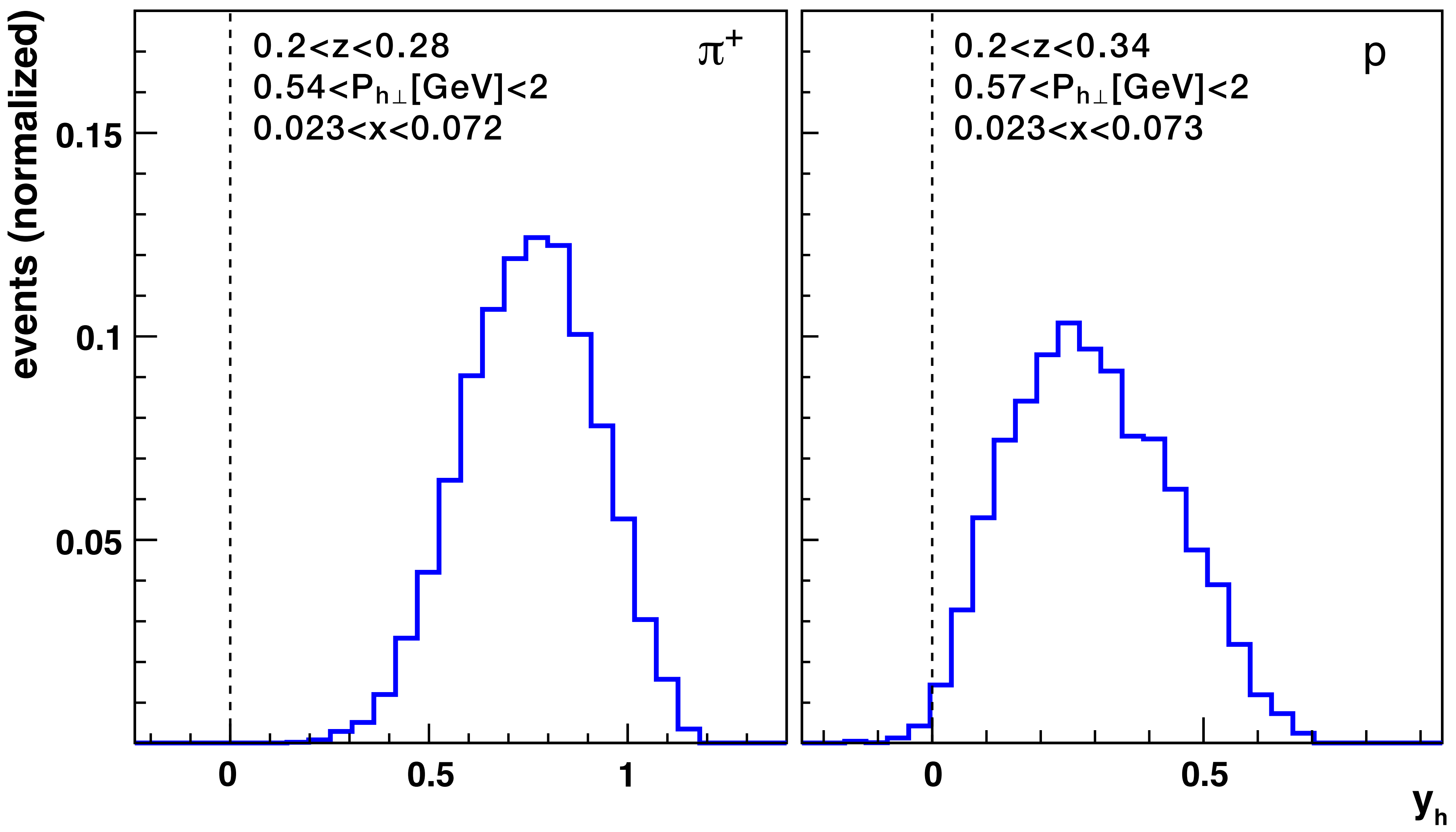
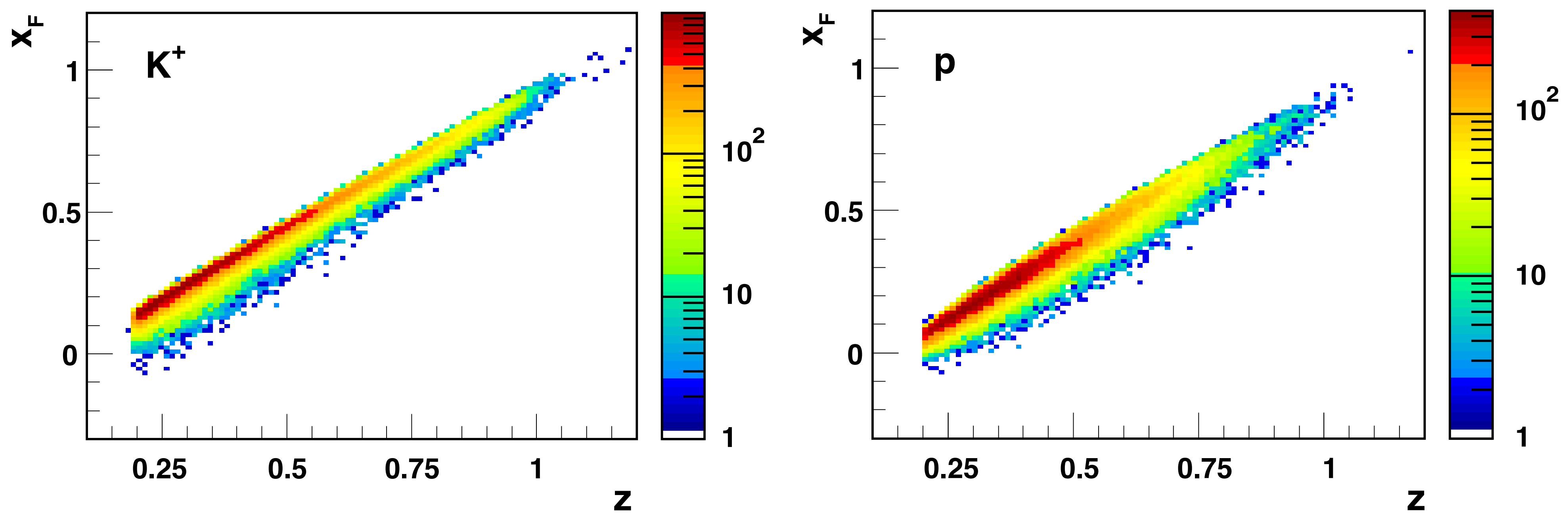
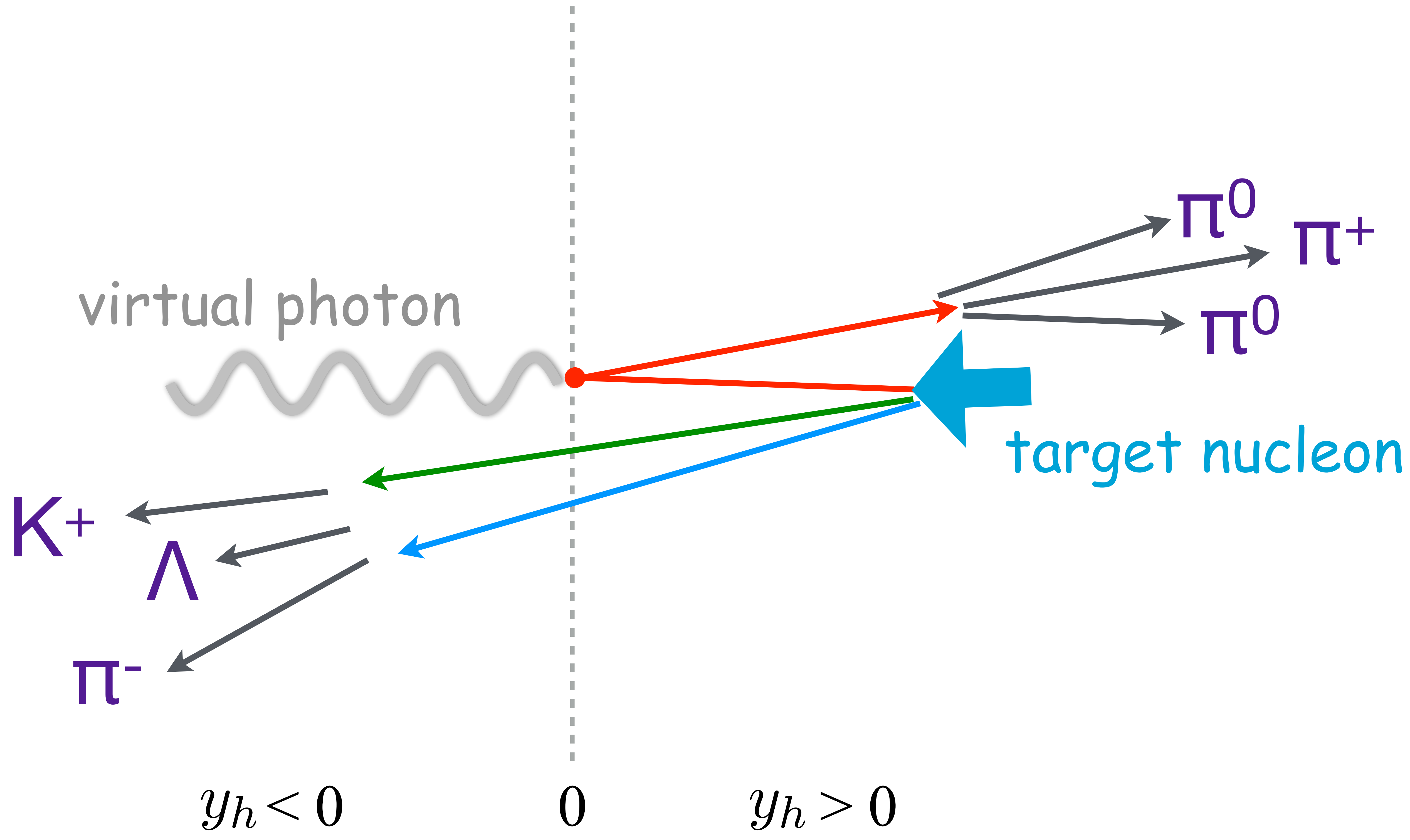




x_F ... Feynman x

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

virtual-photon—nucleon c.m.s



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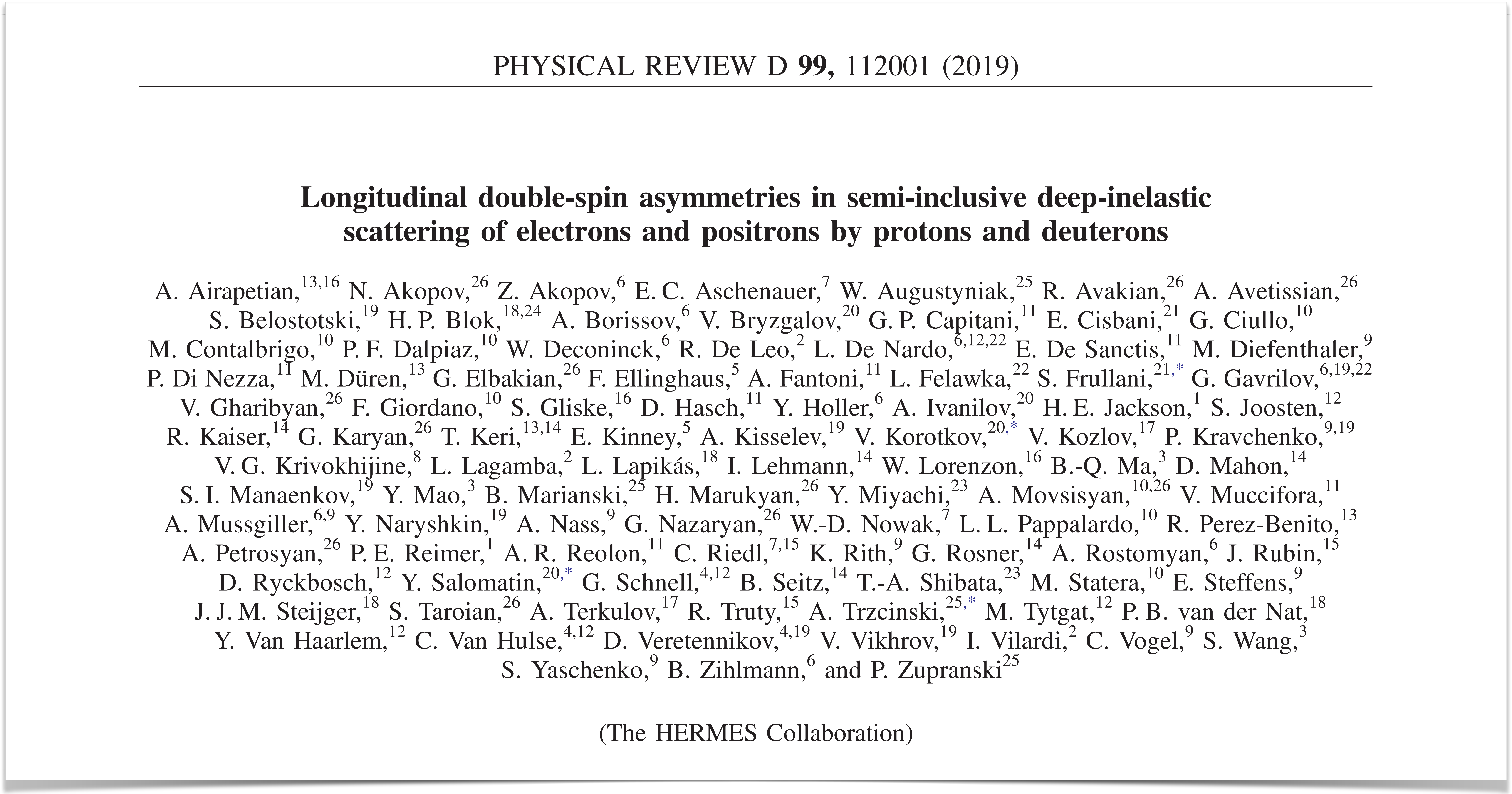

PHYSICAL REVIEW D **99,** 112001 (2019)

Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E. C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26] A. Avetissian,[26] S. Belostotski,[19] H. P. Blok,[18,24] A. Borissov,[6] V. Bryzgalov,[20] G. P. Capitani,[11] E. Cisbani,[21] G. Ciullo,[10] M. Contalbrigo,[10] P. F. Dalpiaz,[10] W. Deconinck,[6] R. De Leo,[2] L. De Nardo,[6,12,22] E. De Sanctis,[11] M. Diefenthaler,[9] P. Di Nezza,[11] M. Düren,[13] G. Elbakian,[26] F. Ellinghaus,[5] A. Fantoni,[11] L. Felawka,[22] S. Frullani,[21,*] G. Gavrilov,[6,19,22] V. Gharibyan,[26] F. Giordano,[10] S. Gliske,[16] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H. E. Jackson,[1] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[26] T. Keri,[13,14] E. Kinney,[5] A. Kisselev,[19] V. Korotkov,[20,*] V. Kozlov,[17] P. Kravchenko,[9,19] V. G. Krivokhijine,[8] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] W. Lorenzon,[16] B.-Q. Ma,[3] D. Mahon,[14] S. I. Manaenkov,[19] Y. Mao,[3] B. Marianski,[25] H. Marukyan,[26] Y. Miyachi,[23] A. Movsisyan,[10,26] V. Muccifora,[11] A. Mussgiller,[6,9] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L. L. Pappalardo,[10] R. Perez-Benito,[13] A. Petrosyan,[26] P. E. Reimer,[1] A. R. Reolon,[11] C. Riedl,[7,15] K. Rith,[9] G. Rosner,[14] A. Rostomyan,[6] J. Rubin,[15] D. Ryckbosch,[12] Y. Salomatin,[20,*] G. Schnell,[4,12] B. Seitz,[14] T.-A. Shibata,[23] M. Statera,[10] E. Steffens,[9] J. J. M. Steijger,[18] S. Taroian,[26] A. Terkulov,[17] R. Truty,[15] A. Trzcinski,[25,*] M. Tytgat,[12] P. B. van der Nat,[18] Y. Van Haarlem,[12] C. Van Hulse,[4,12] D. Veretennikov,[4,19] V. Vikhrov,[19] I. Vilardi,[2] C. Vogel,[9] S. Wang,[3] S. Yaschenko,[9] B. Zihlmann,[6] and P. Zupranski[25]

(The HERMES Collaboration)

re-analysis of longitudinal 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**

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

    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**

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  - correct better for azimuthal asymmetries coupling to acceptance
  - **look at multi-dimensional (x, z, $P_{h\perp}$) dependences**
  - **extract twist-3 cosine modulations … consistent with zero**

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

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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

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

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nucleon-in-nucleus
depolarization factor
(0.926 for deuteron due
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polarization-weighted
luminosities

double-spin asymmetry $A_{||}$

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luminosities

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

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

polarization-weighted luminosities

unfolded for QED radiation to Born level

double-spin asymmetry $A_{||}$

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

- dominated by statistical uncertainties

double-spin asymmetry $A_{||}$

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

- 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

azimuthal-asymmetry corrections

measured

"polarized Cahn" effect etc.

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

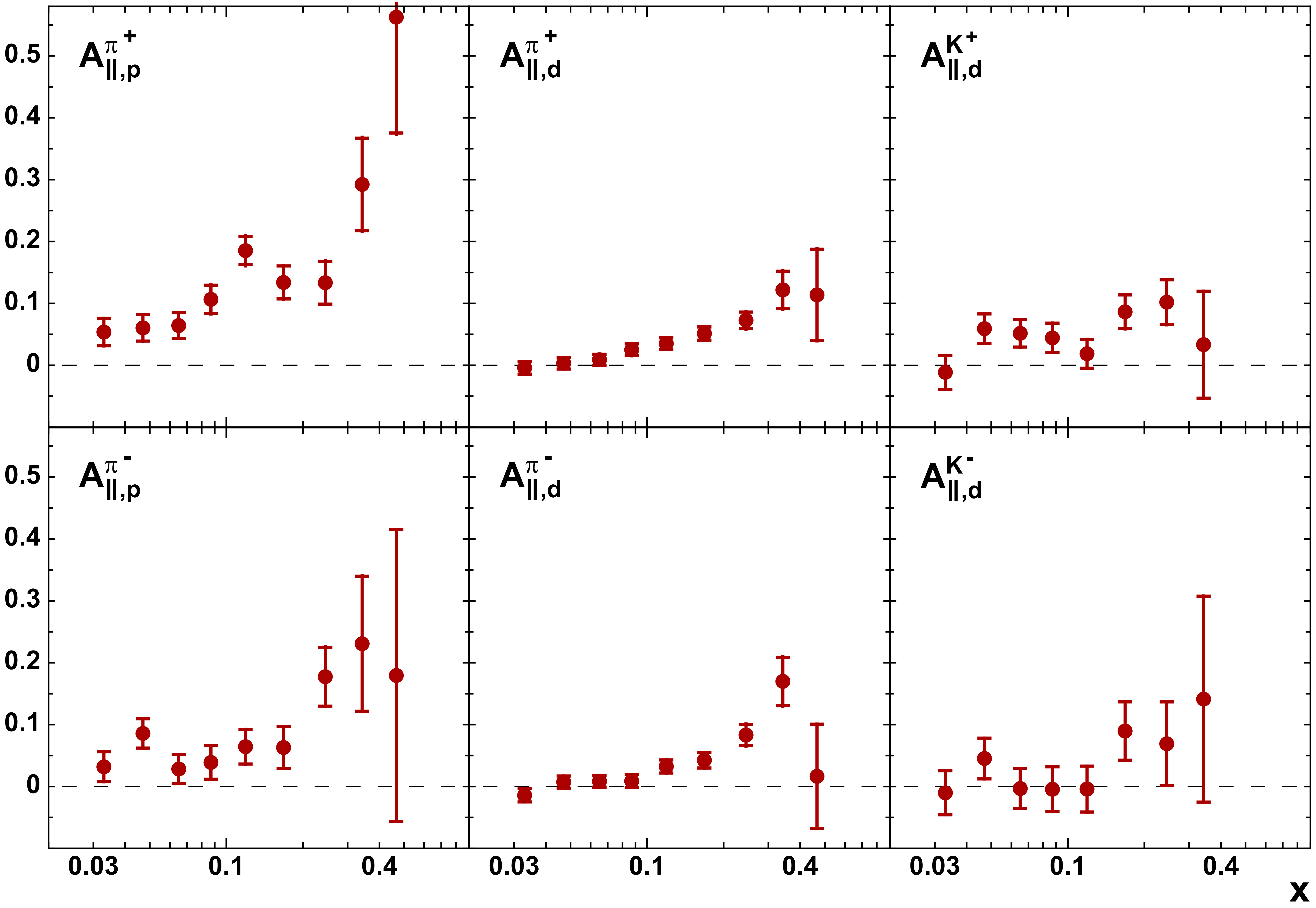
Boer-Mulders and Cahn effects etc.

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
- implemented data-driven model for azimuthal modulations [PRD 87 (2013) 012010] into MC
  ☞ extract correction factor & apply to data

x dependence of $A_{||}$

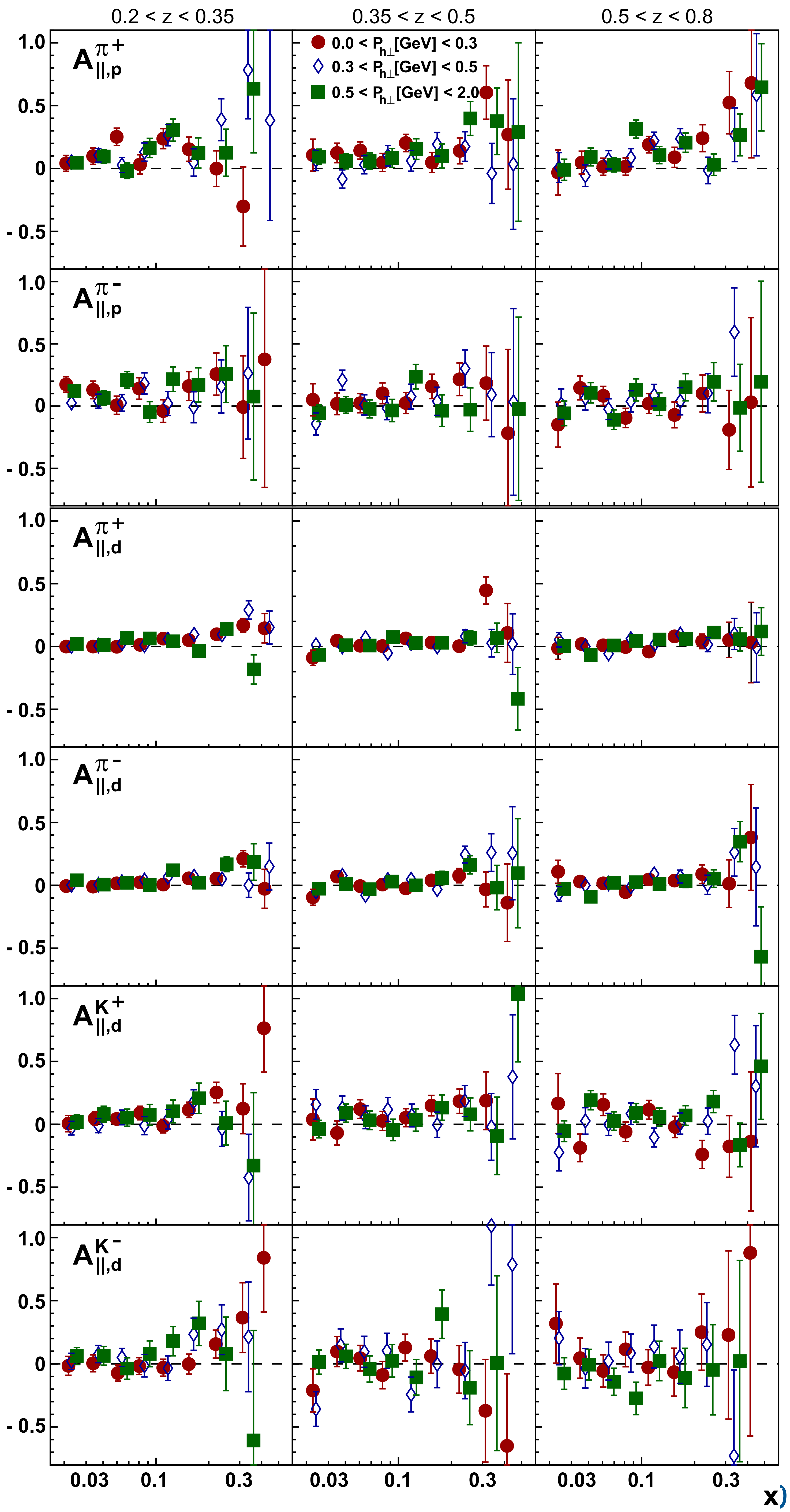
[HERMES, PRD 99 (2019) 112001]



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

3-dimensional binning

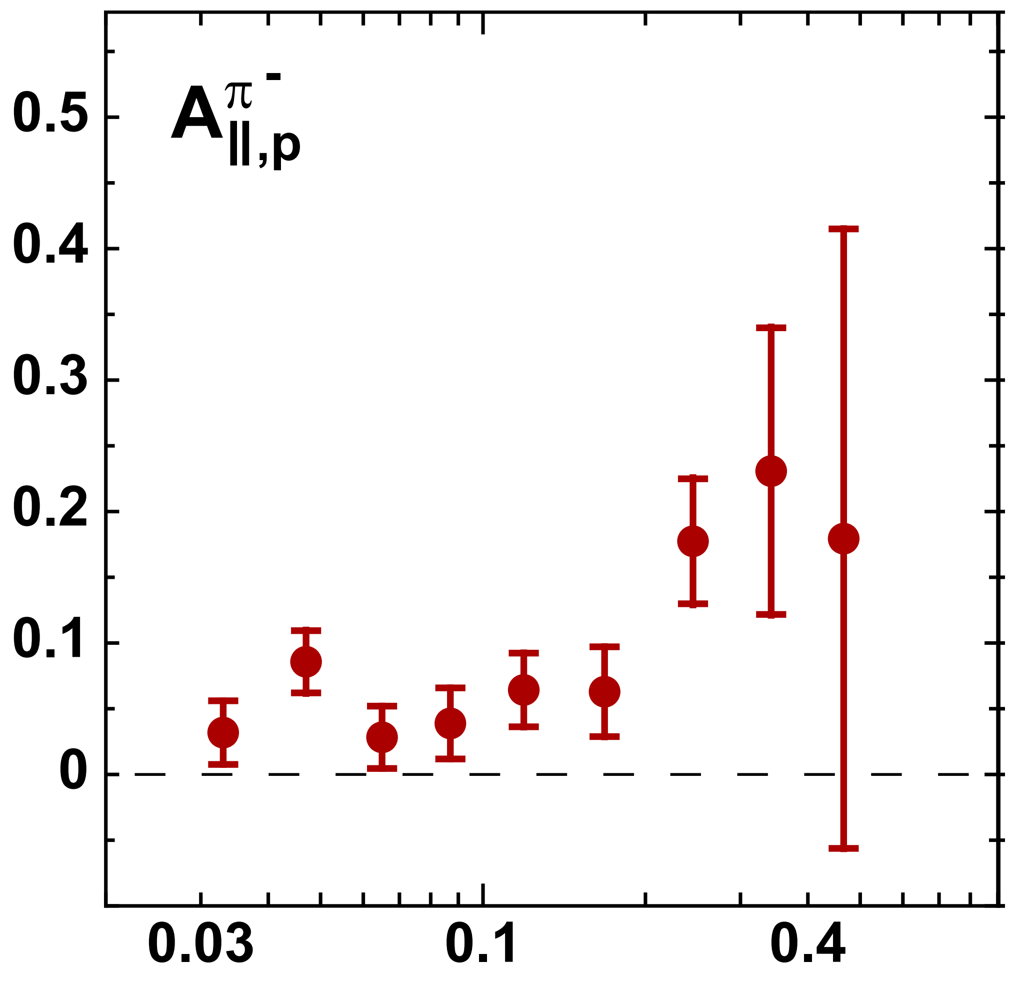
- **first-ever 3d binning** provides transverse-momentum dependence



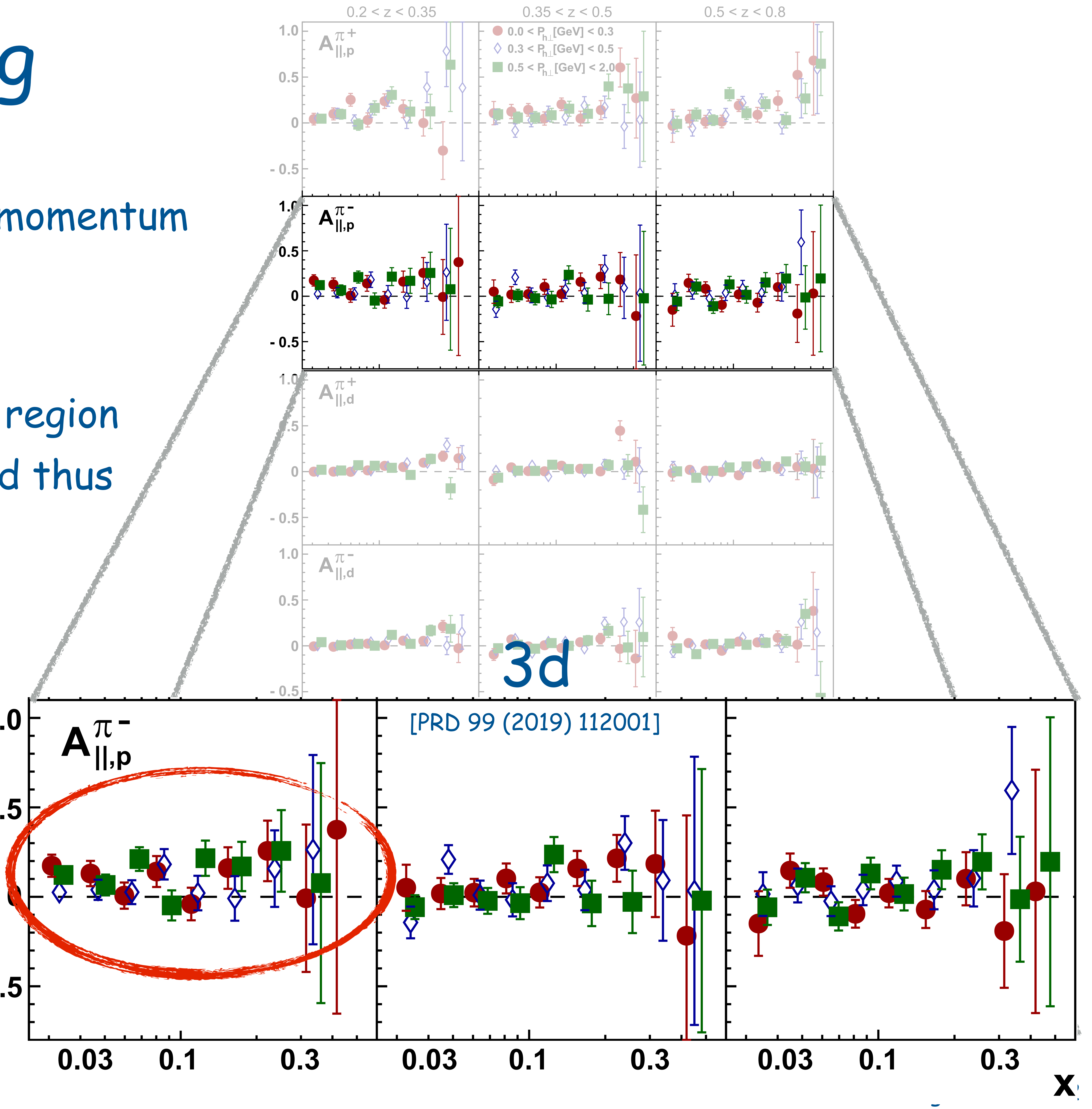
3-dimensional binning

- **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



hadron-charge difference asymmetries

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

hadron-charge difference asymmetries

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

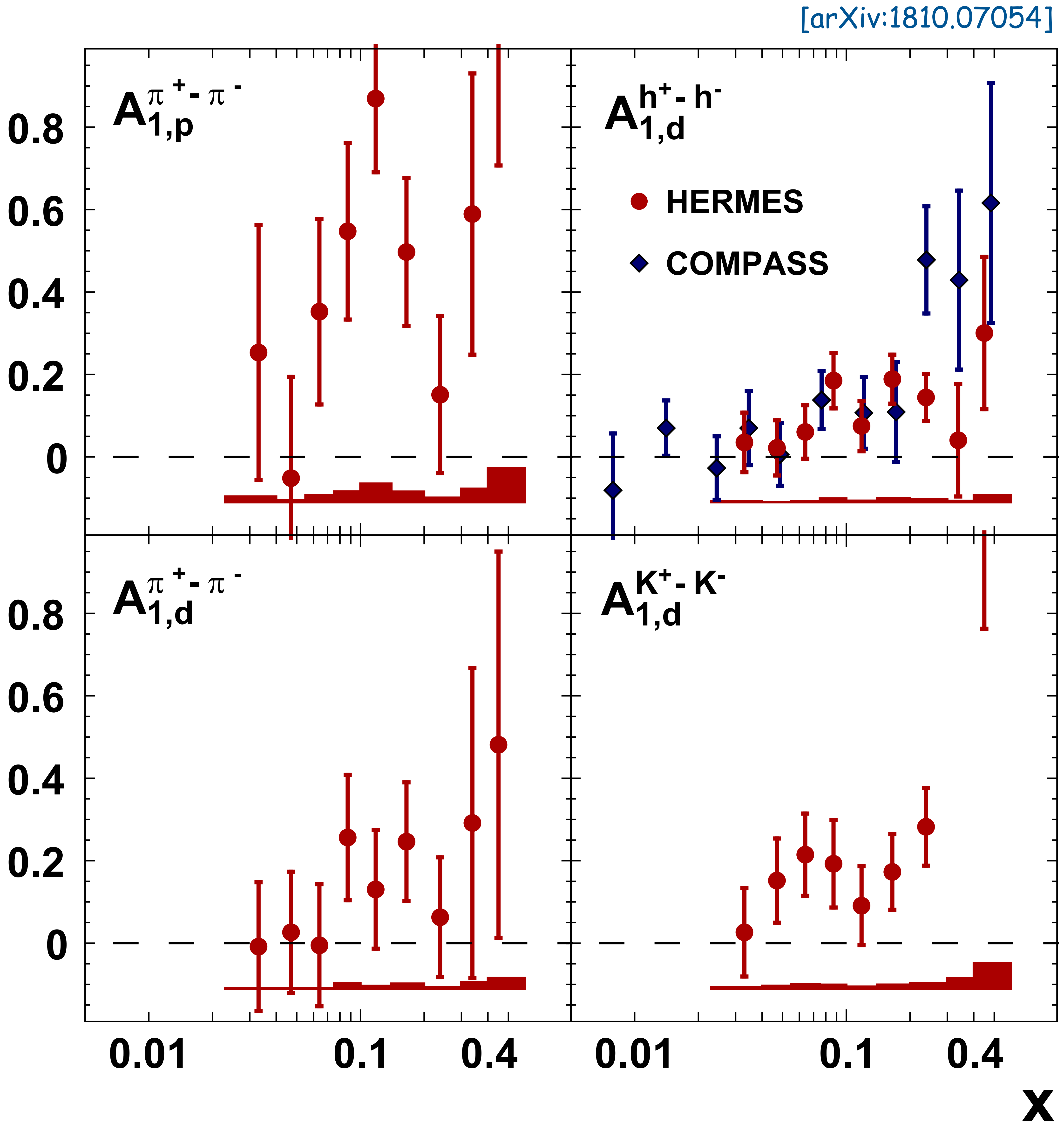
$$A_{1,d}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}$$

- assuming also isospin symmetry in fragmentation:

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

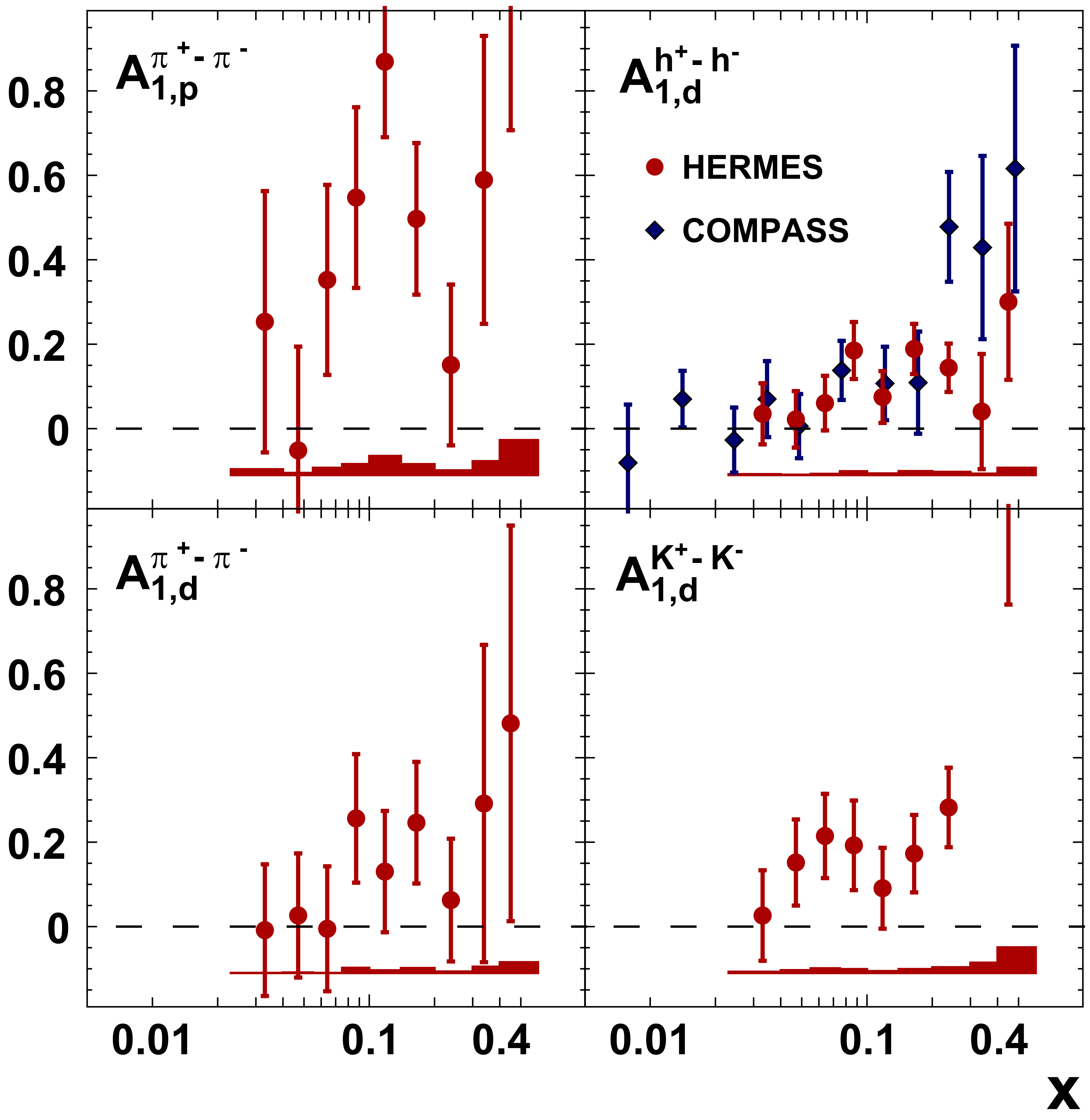
- can be used to extract valence helicity distributions

hadron-charge difference asymmetries

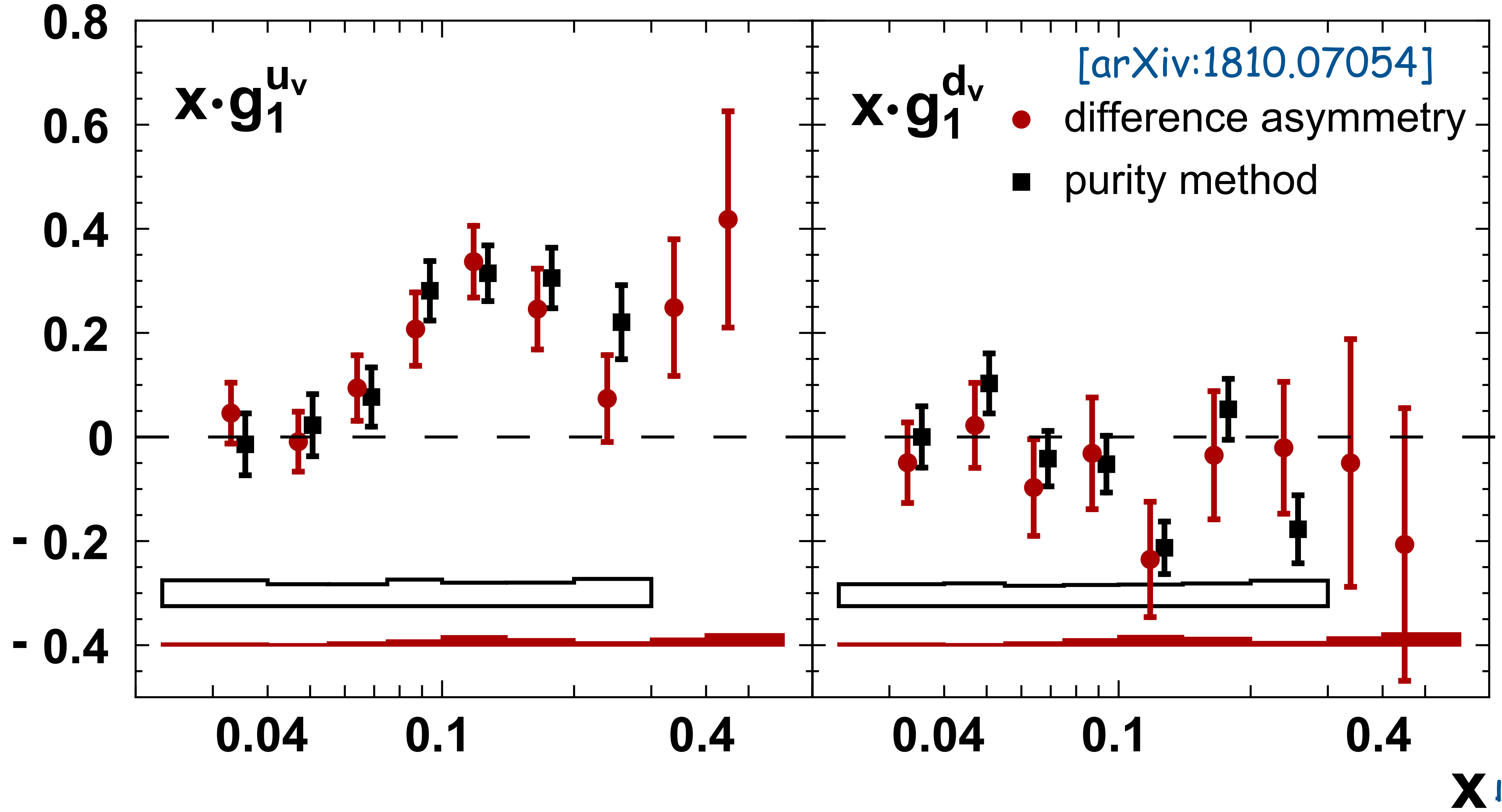


- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS

hadron-charge difference asymmetries


[arXiv:1810.07054]

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


[arXiv:1810.07054]

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JHEP12(2020)010

The HERMES Collaboration

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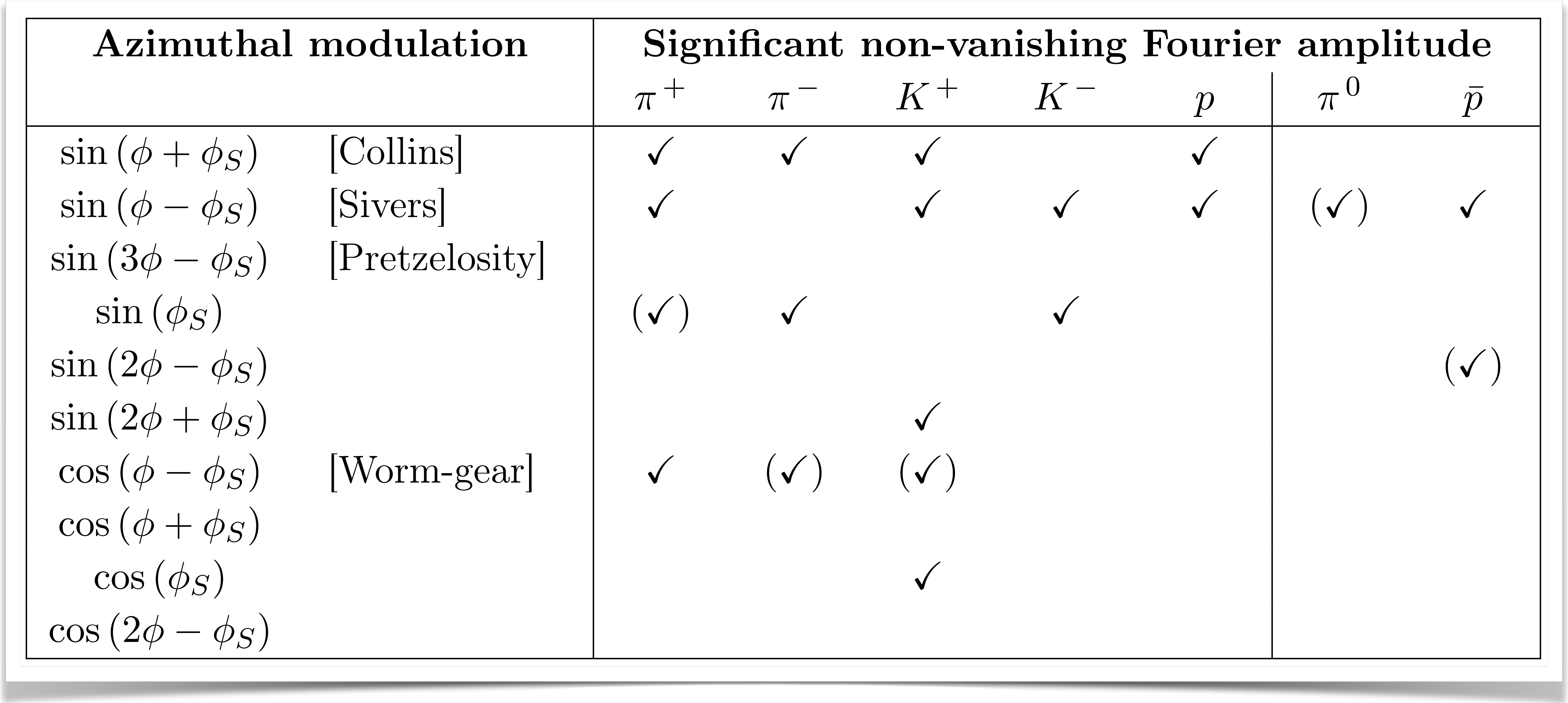

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$\sin(\phi-\phi_S)$	[Sivers]	✓		✓	✓	✓	(✓)	✓
$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

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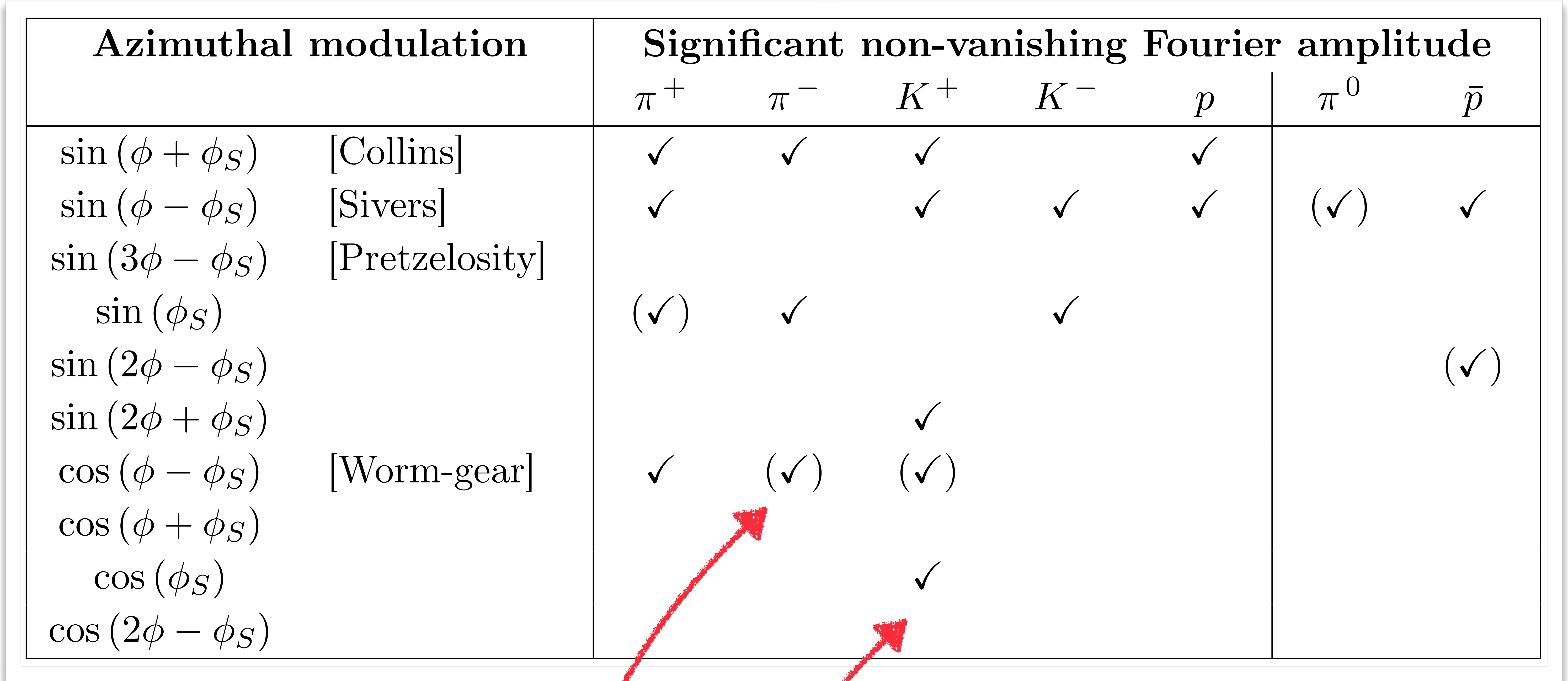

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$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

95%

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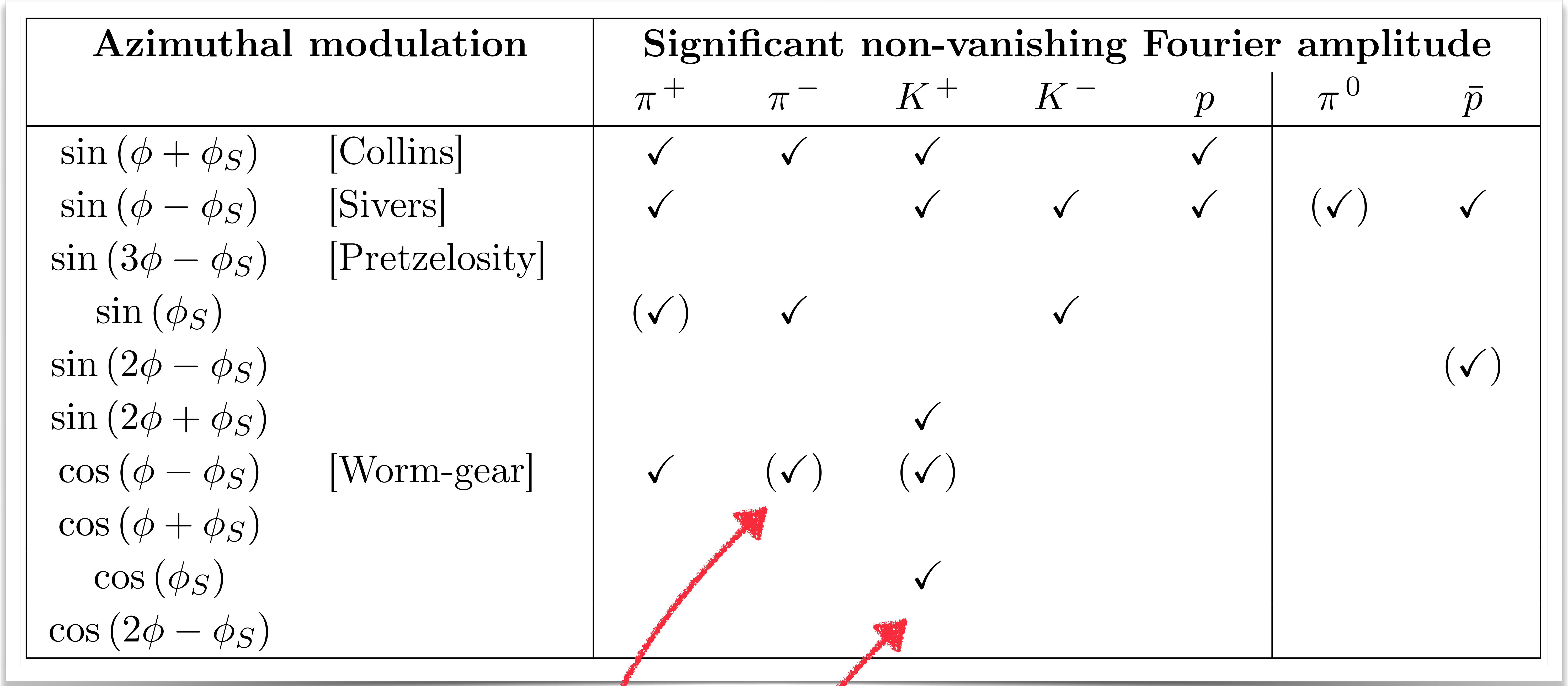
3d

1d



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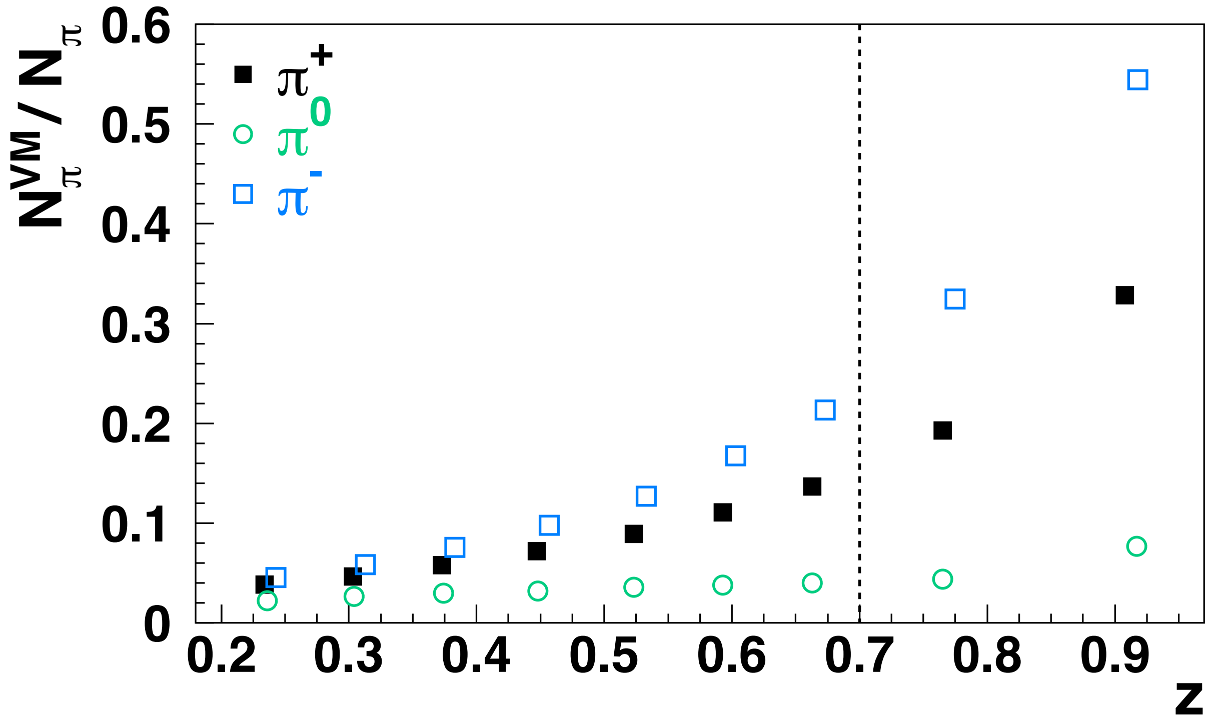
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

95%

Sivers amplitudes for pions

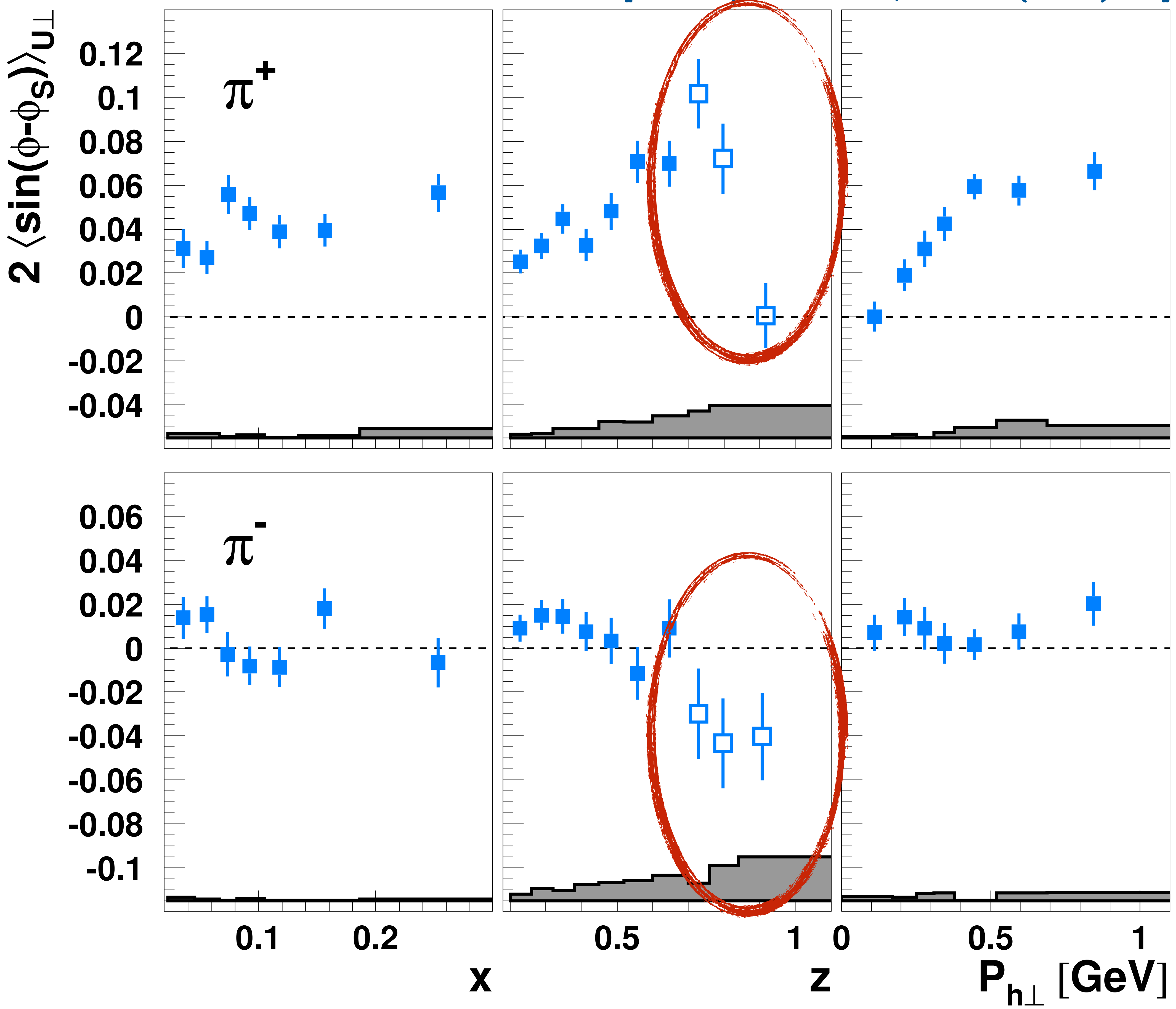
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

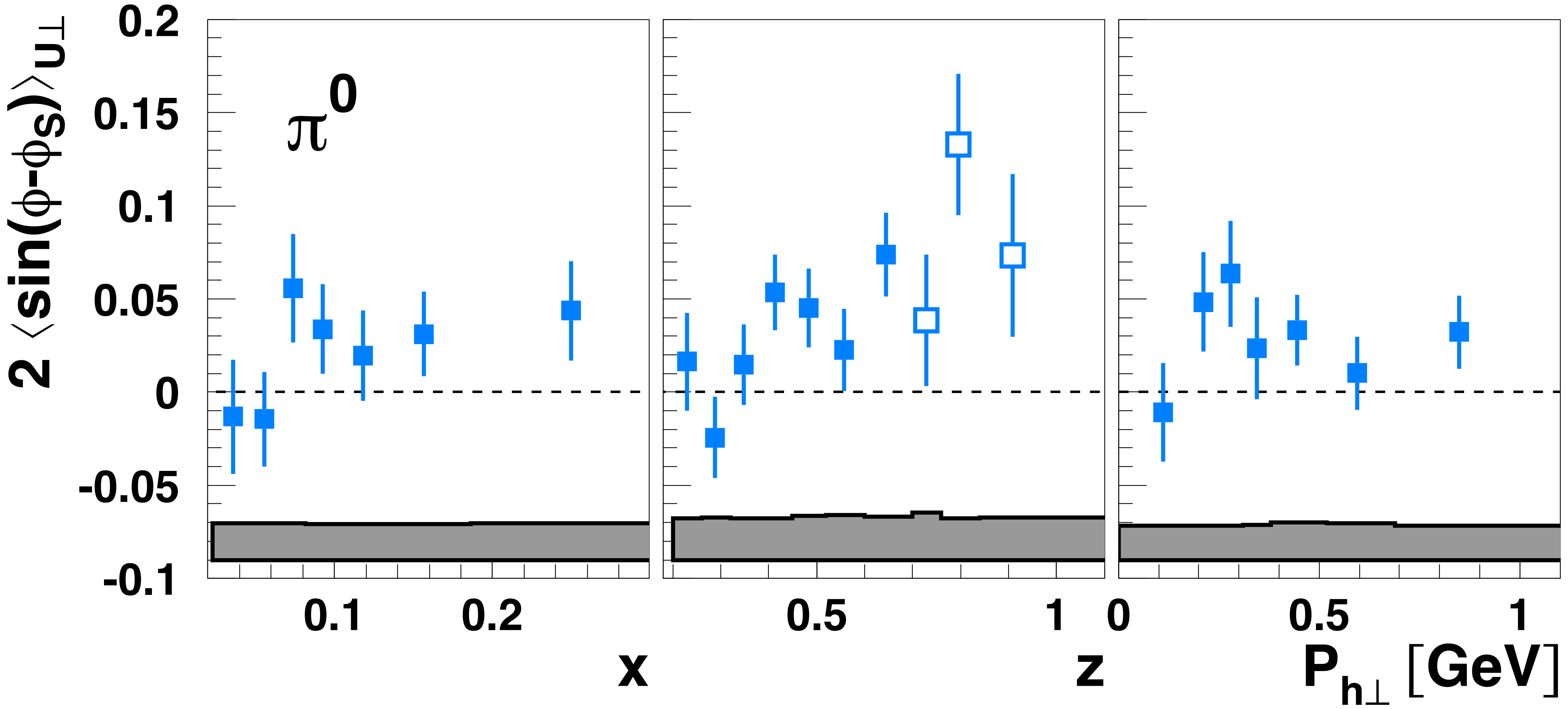


- **high-z data** probes region of **increased flavor sensitivity** to struck quark (but also where contributions from exclusive vector-meson production becomes significant)

  - only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)

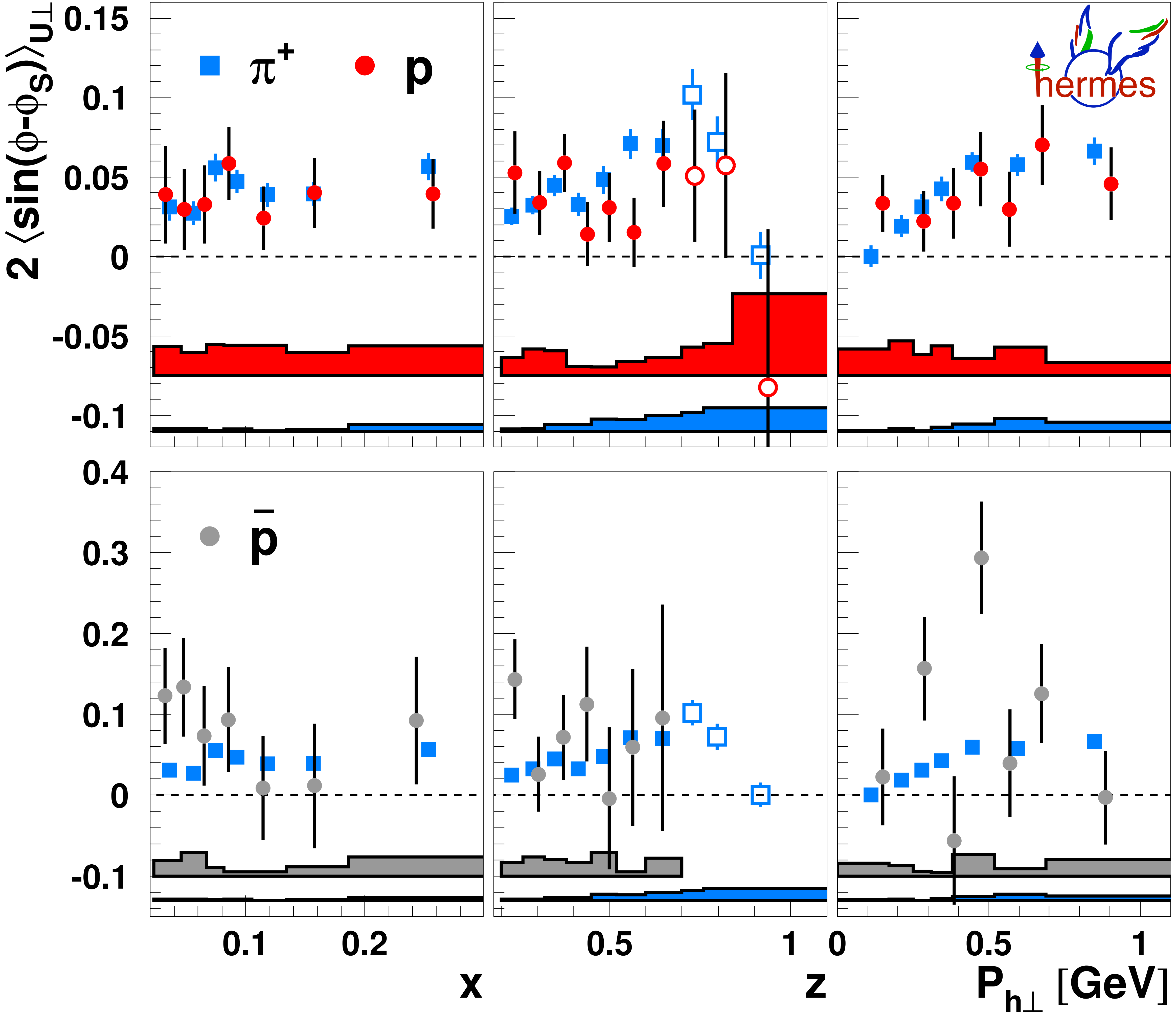
[A. Airapetian et al., JHEP12(2020)010]





	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?

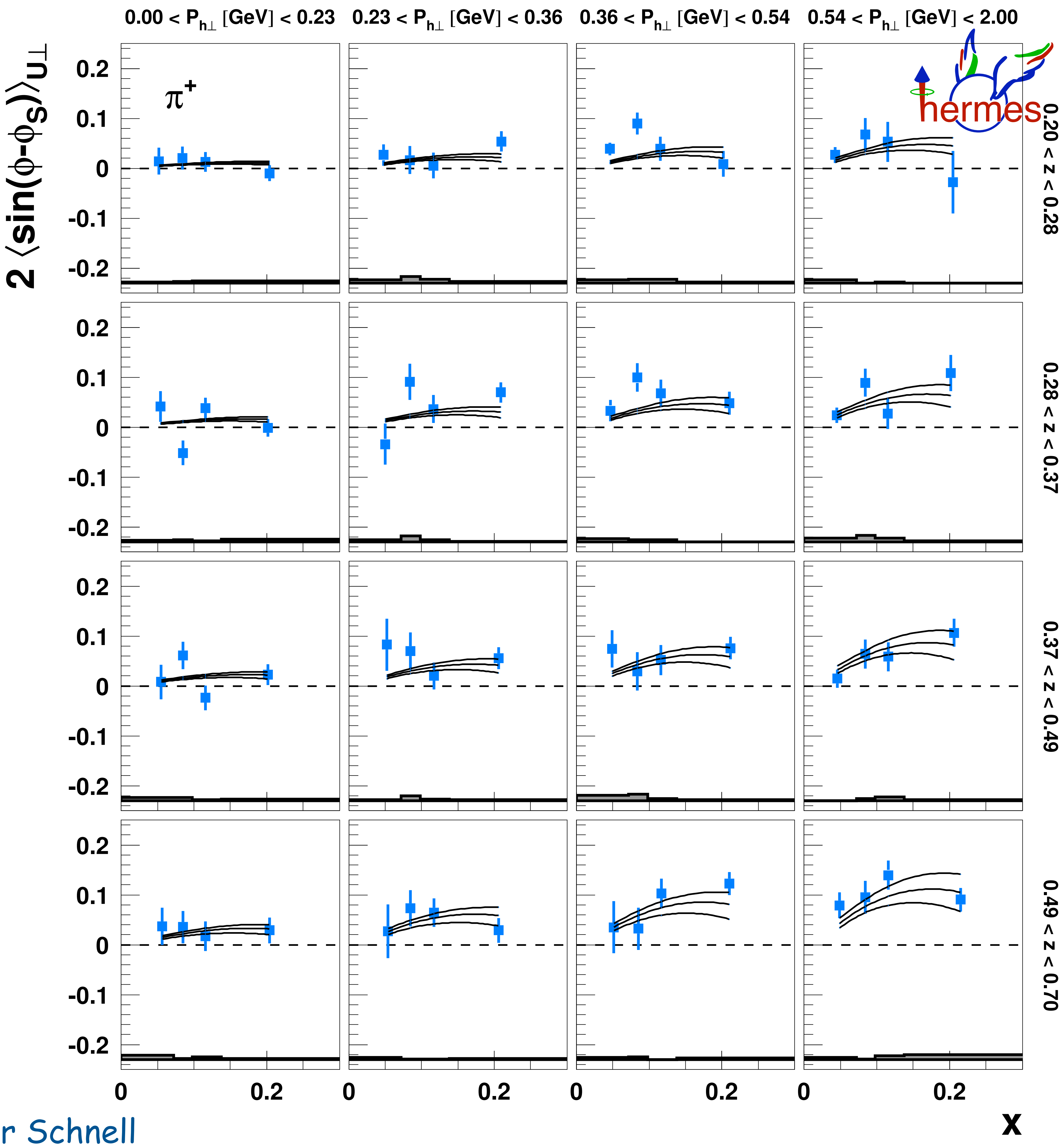
$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

$$\approx -\mathcal{C}\,\frac{f_{1T}^{\perp,u}(x,p_T^2)}{f_1^u(x,p_T^2)}$$

	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 multi-dimensional analysis

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



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

	U	L	T
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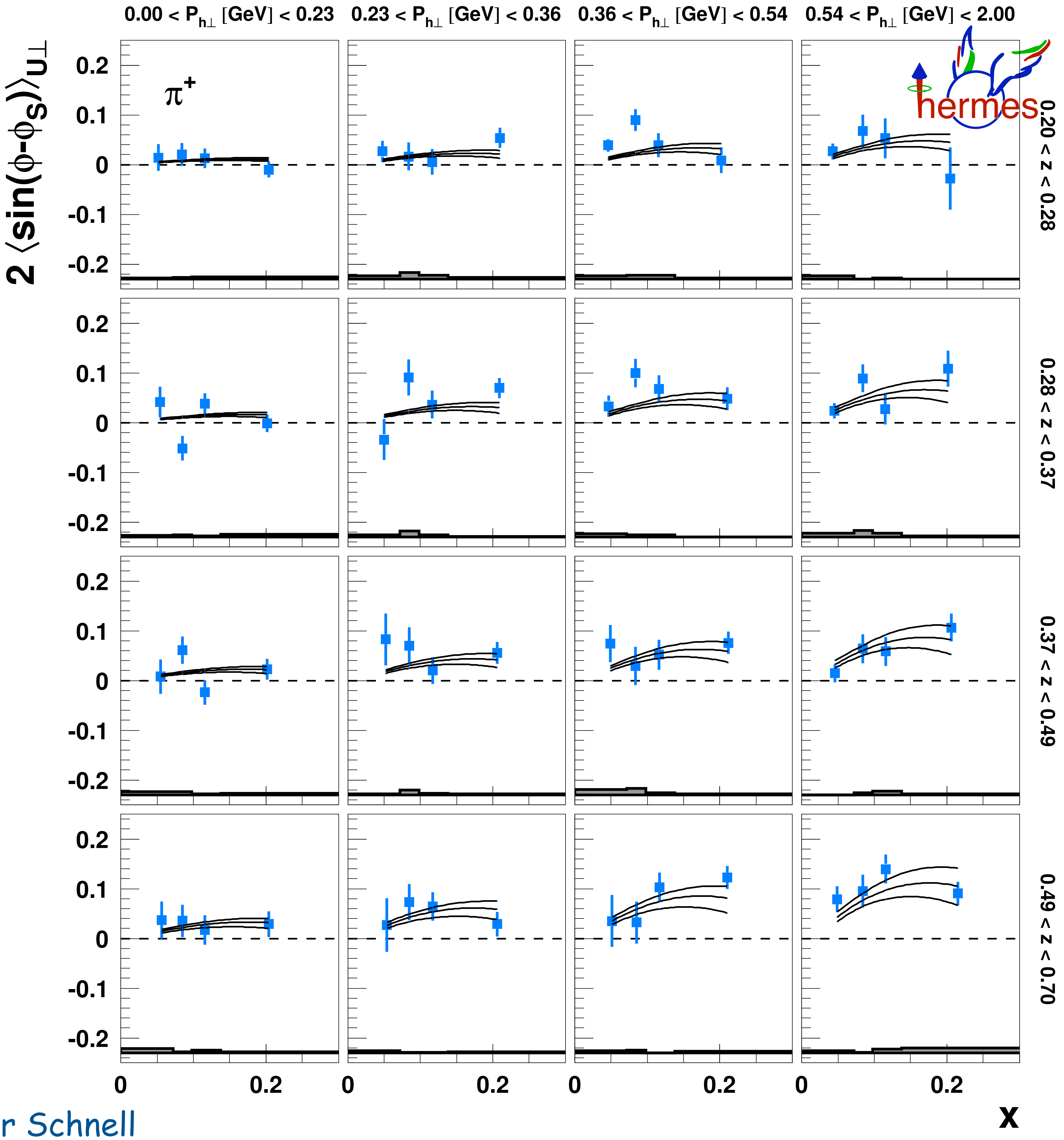

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

	U	L	T
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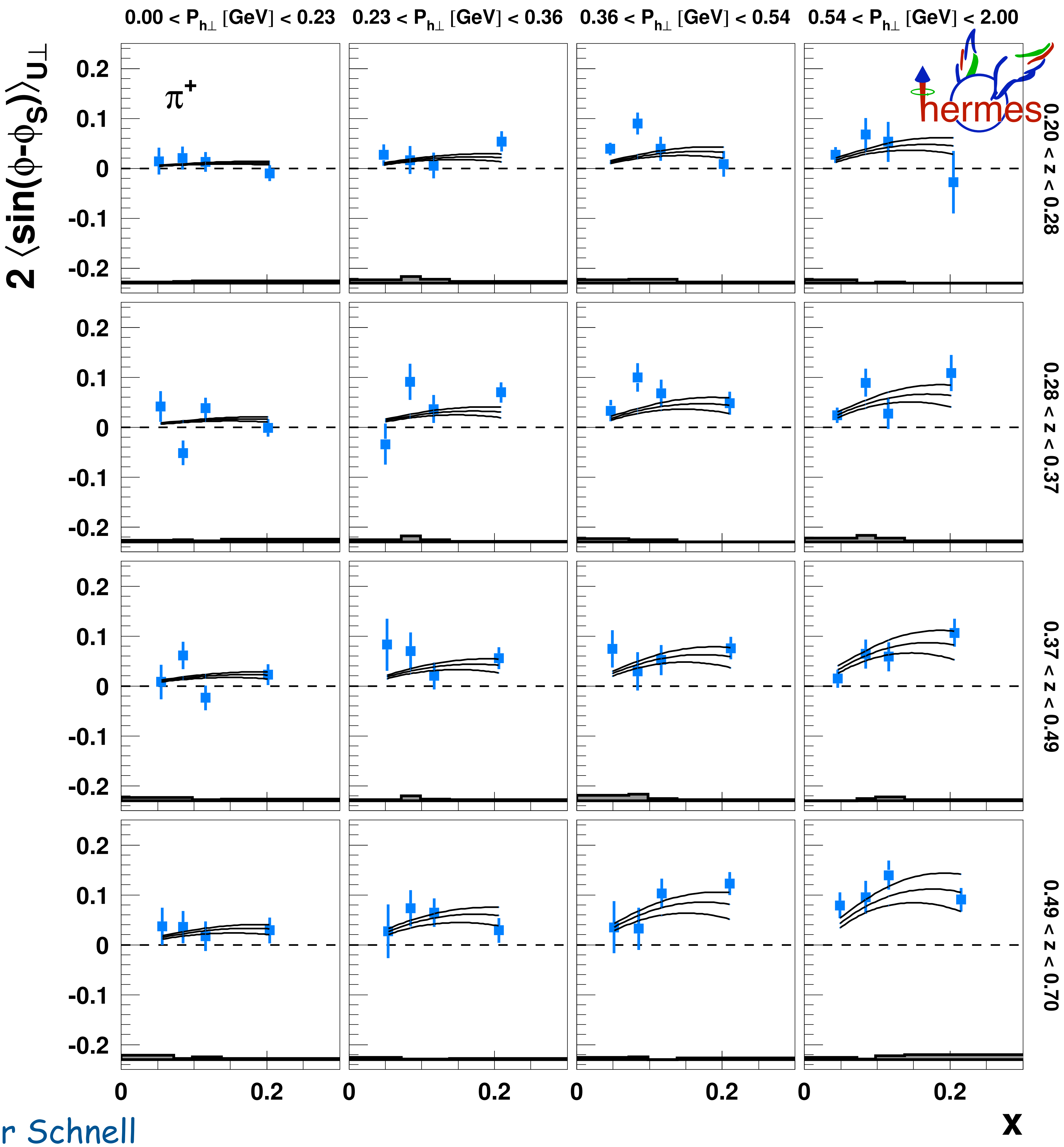
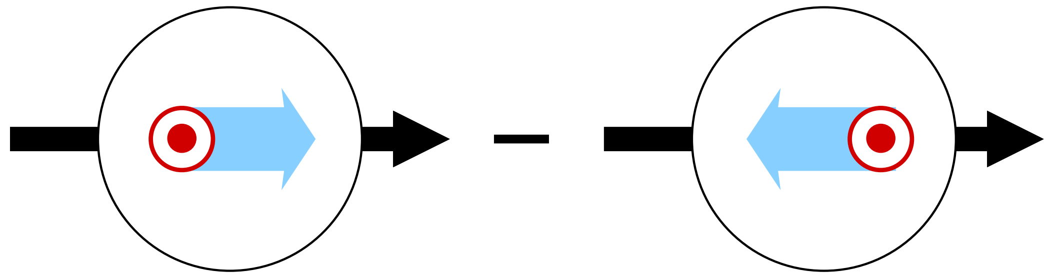


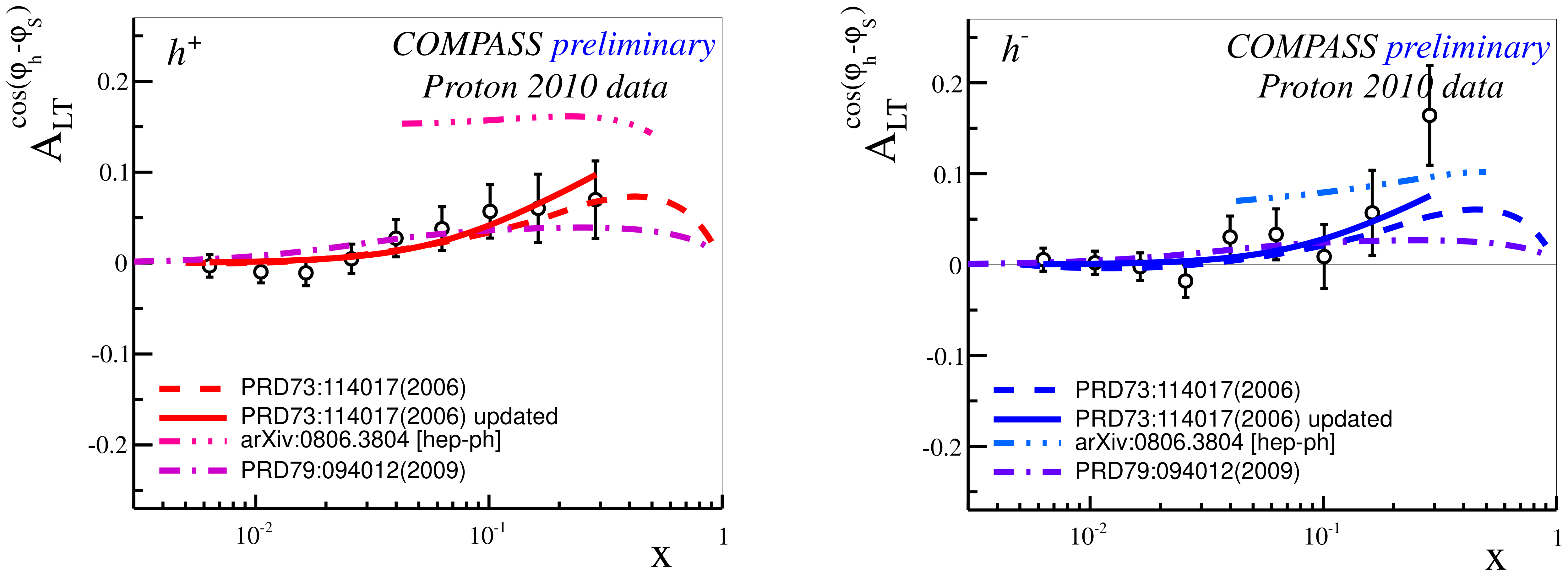
- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

worm-gear II

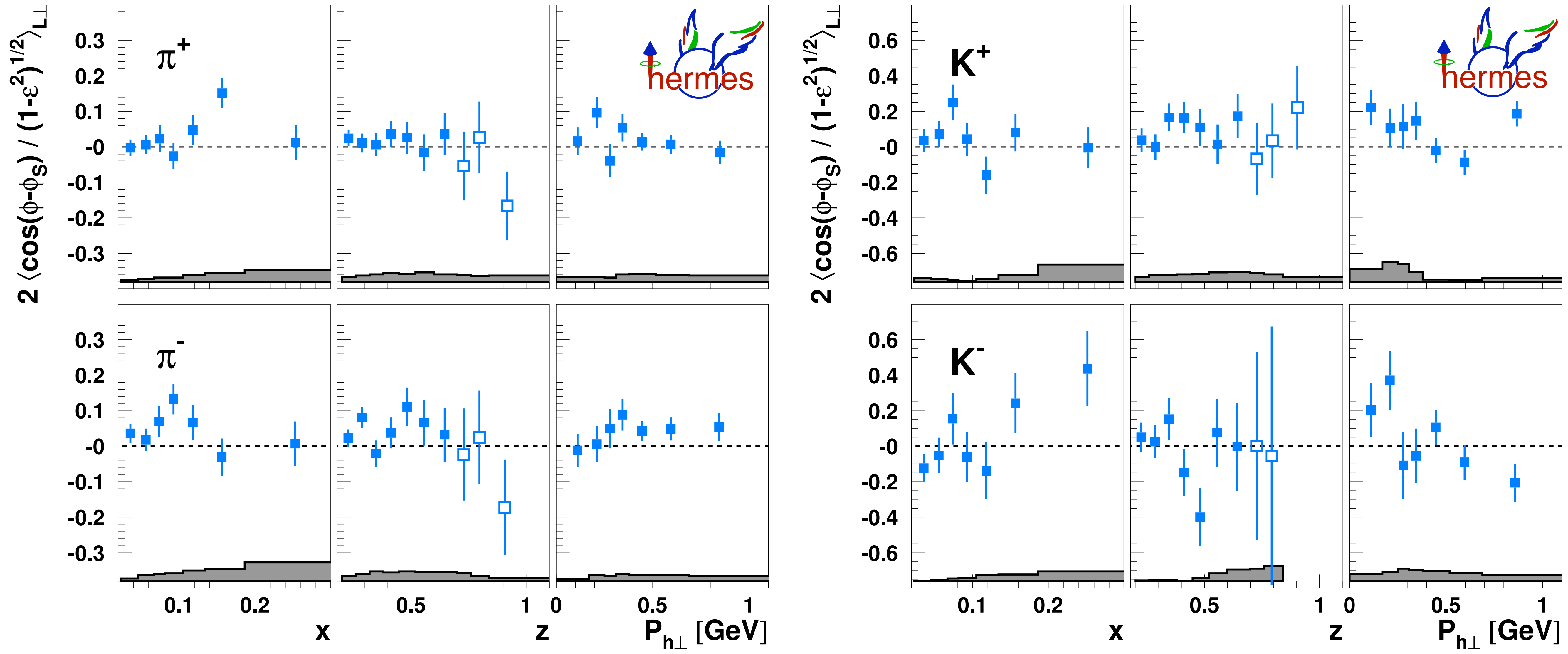
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



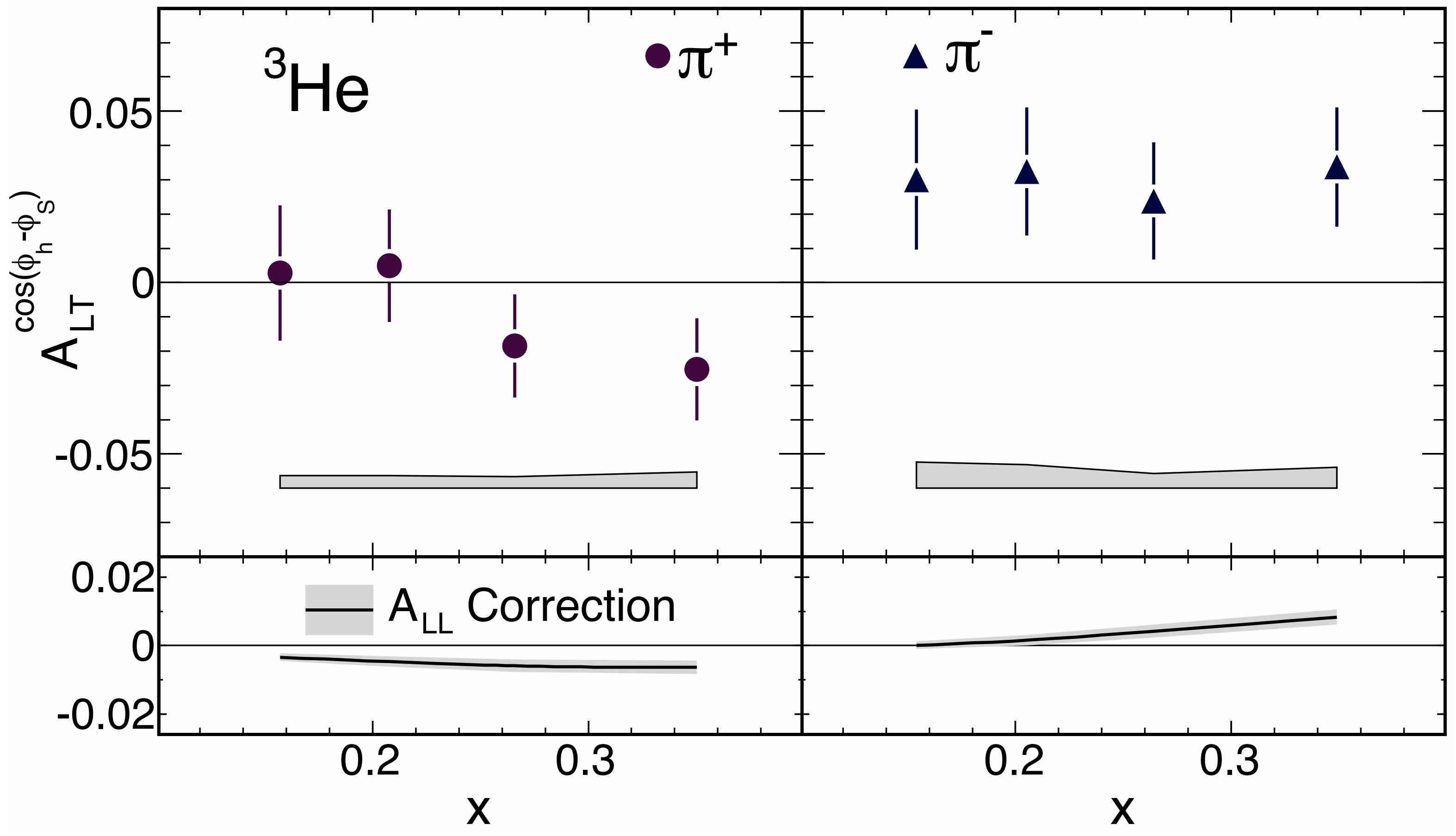
- quark-helicity asymmetry in transversely polarized nucleon
- evidences from
    - ³He target at JLab
    - H target at COMPASS & HERMES



[HERMES, JHEP12(2020)010]



[PRL 108 (2012) 052001]



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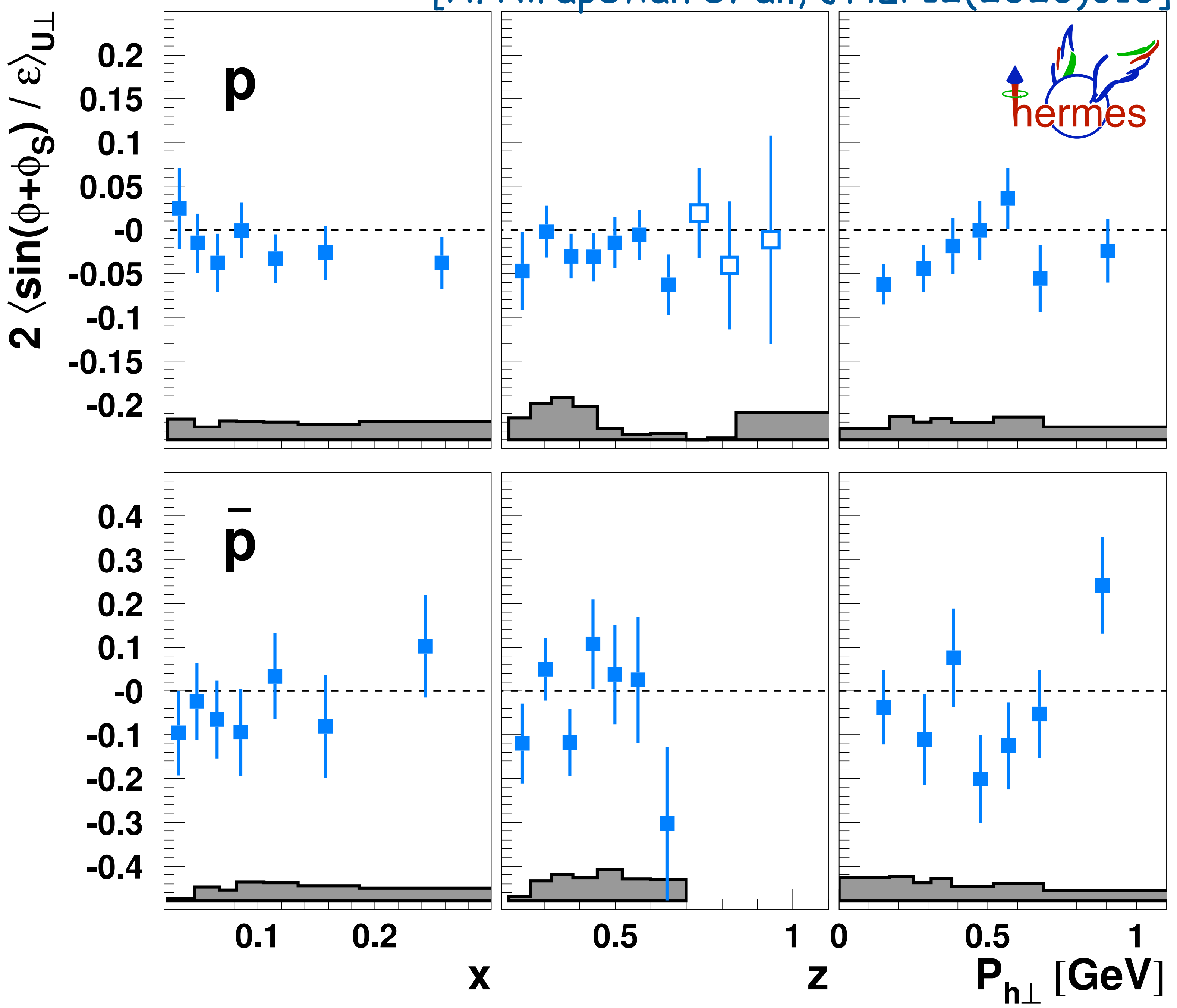
new HERMES results on Collins amplitudes



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

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

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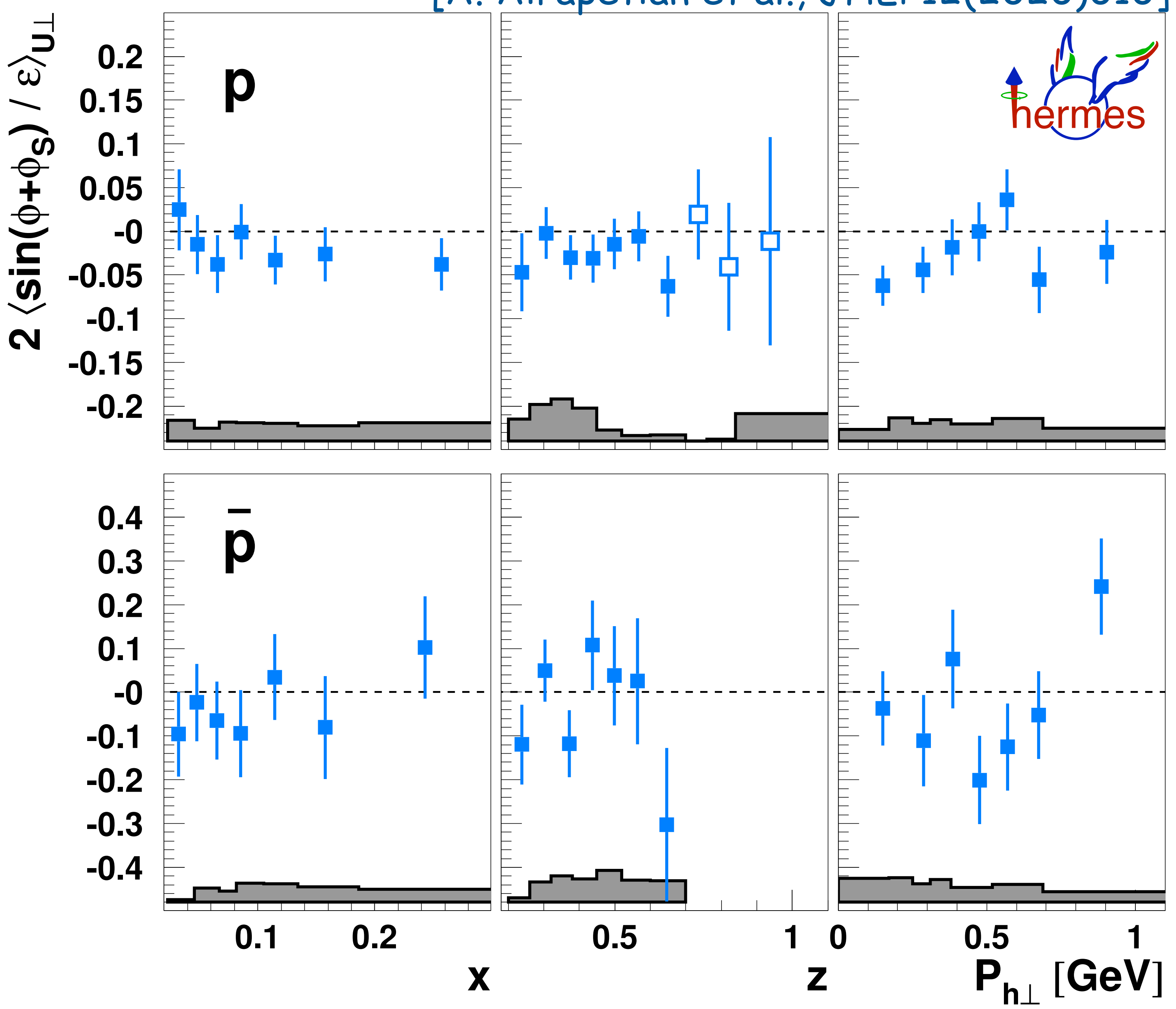

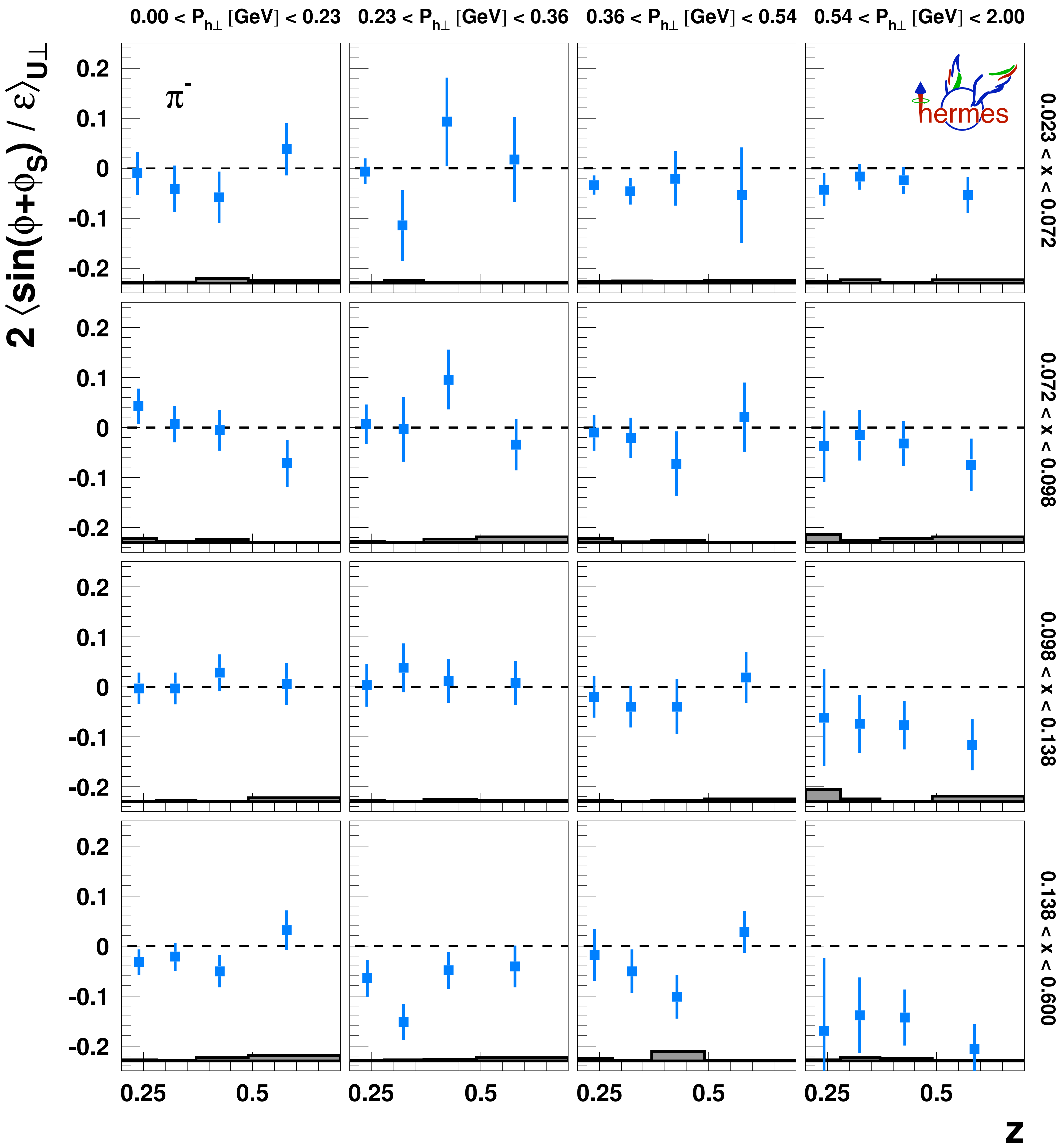

- first-ever results for **(anti-)protons** consistent with zero
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- analysis now **performed in 3d**, both including or not including kinematic “depolarization” prefactor

	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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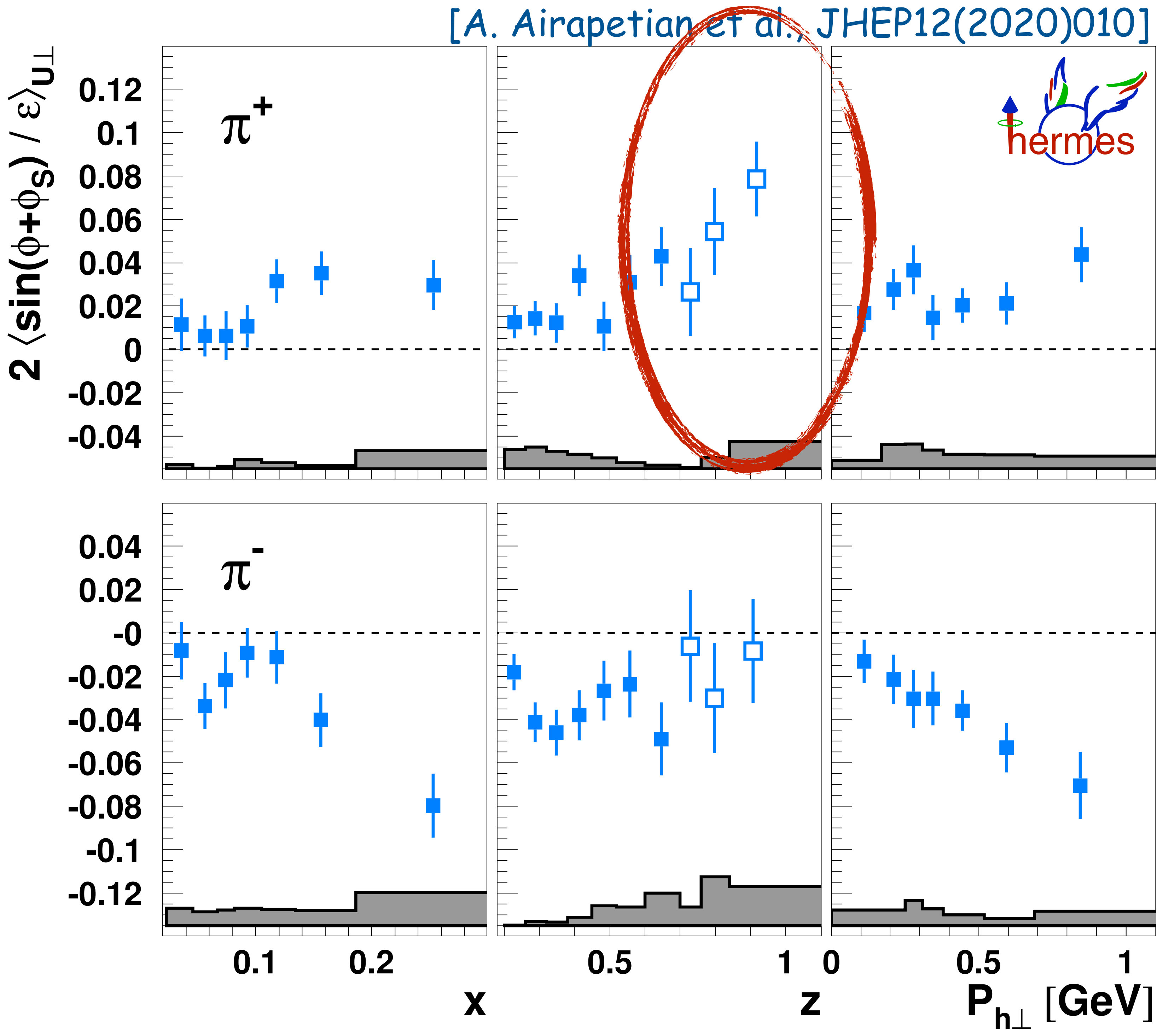
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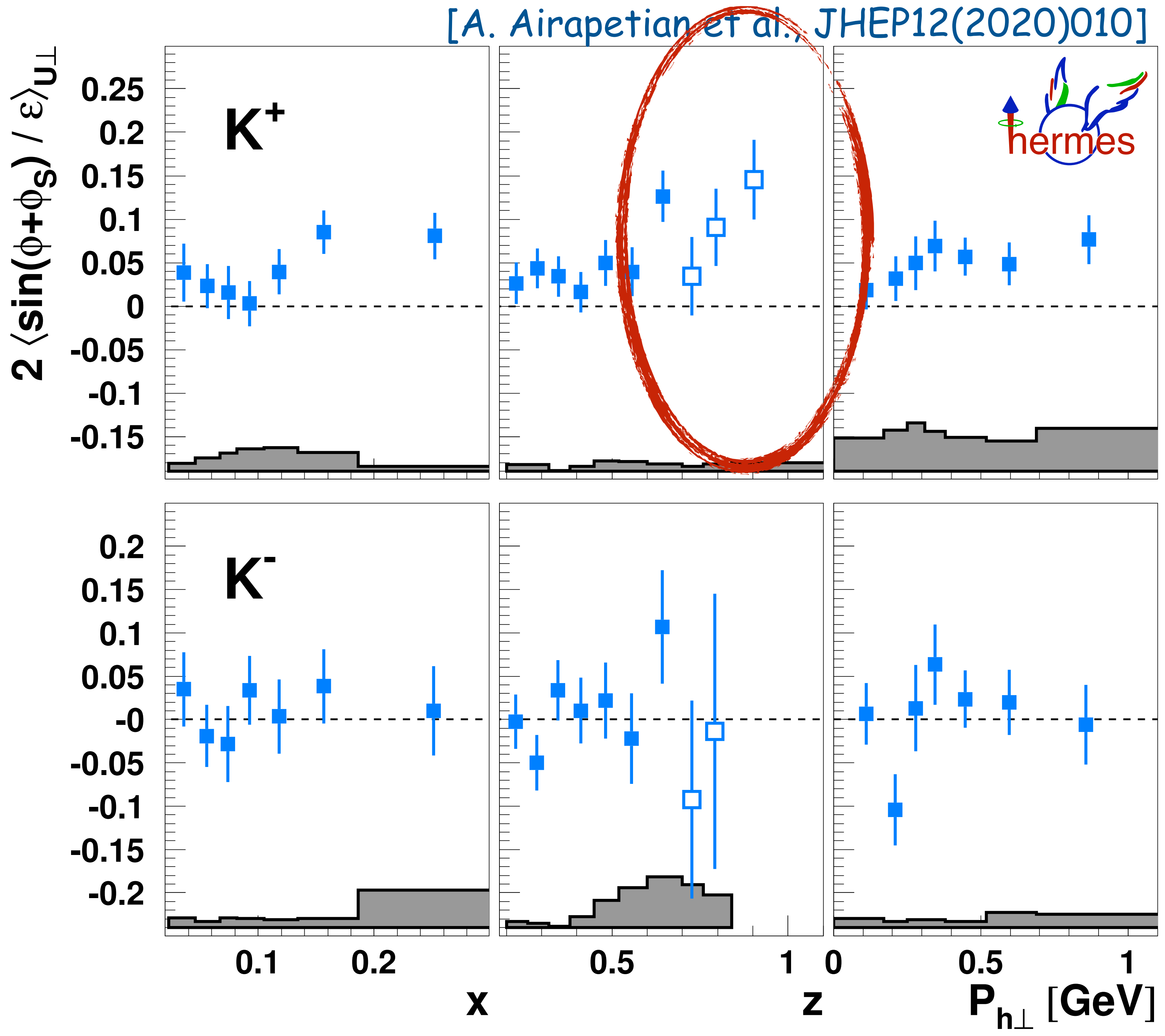
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- first-ever results for **(anti-)protons** consistent with zero
➥ vanishing Collins effect for (spin-1/2) baryons?

- analysis now **performed in 3d**, both including or not including kinematic “depolarization” prefactor

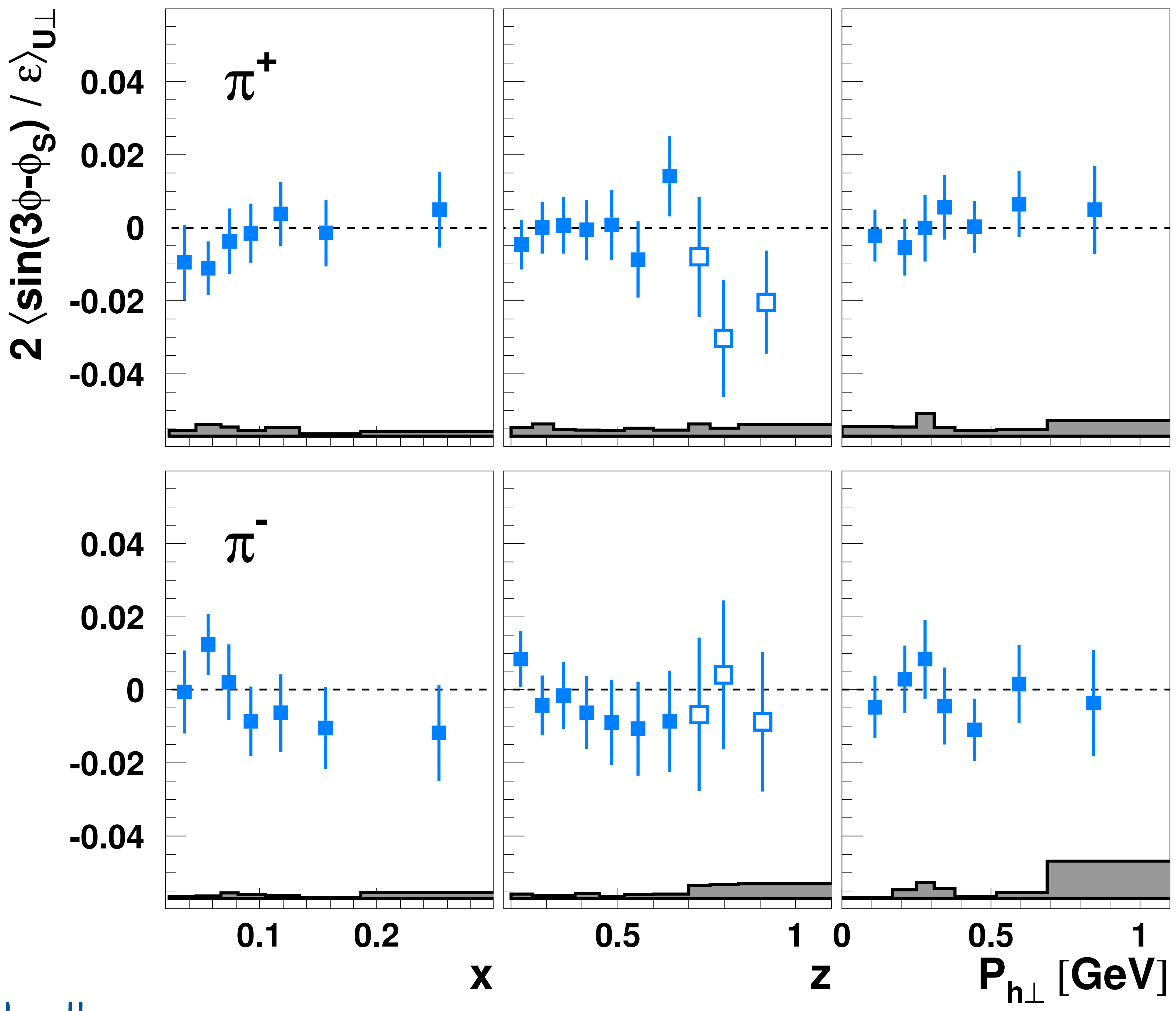
- **high-z region** with larger quark-flavour sensitivity, with **increasing amplitudes** for positive pions and kaons

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

Pretzelosity

- 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]



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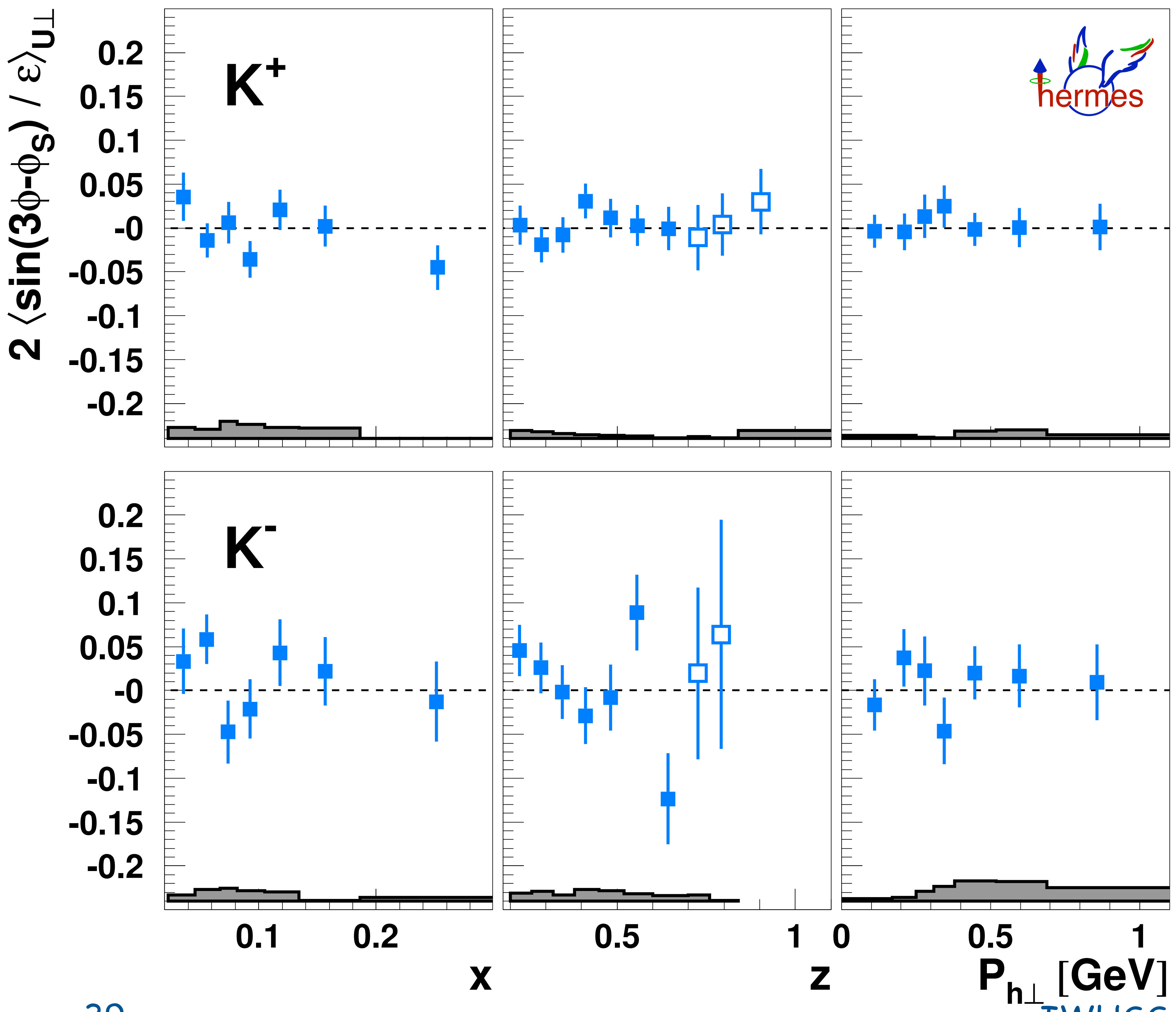
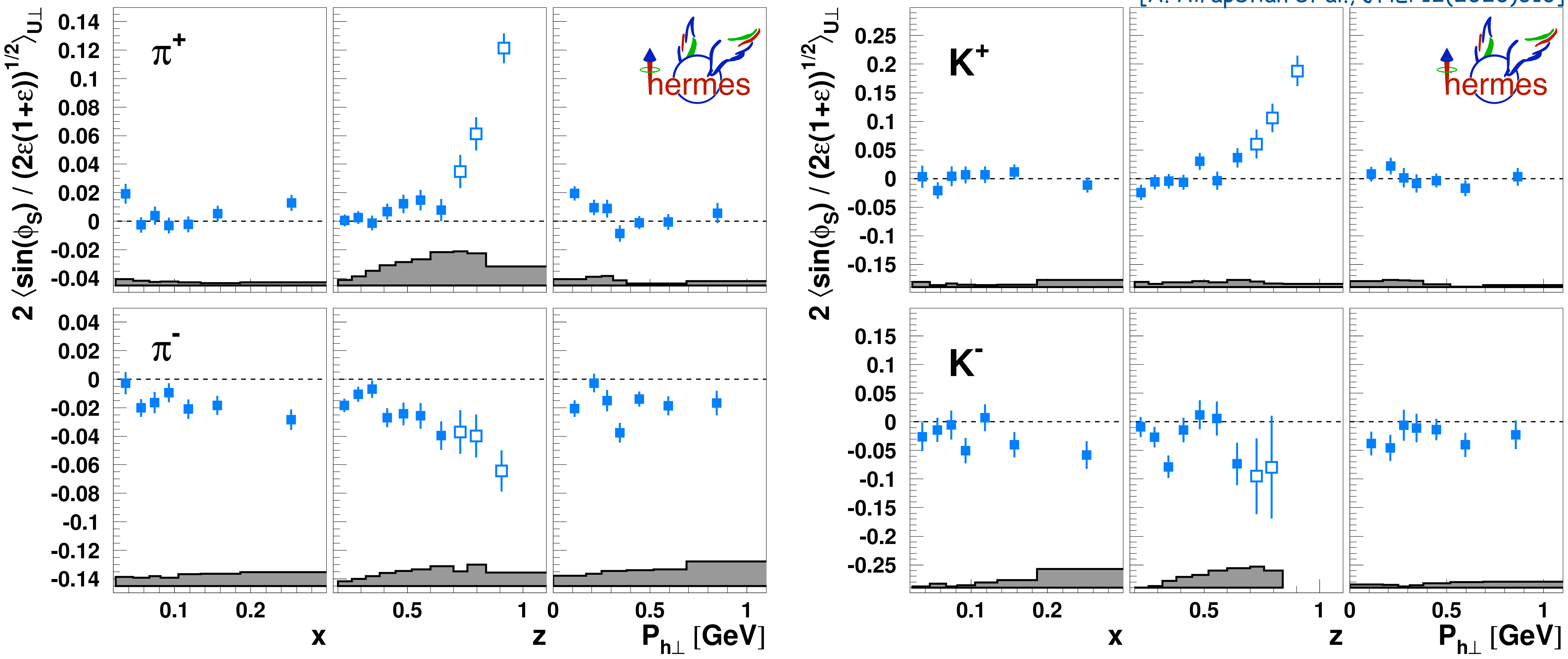
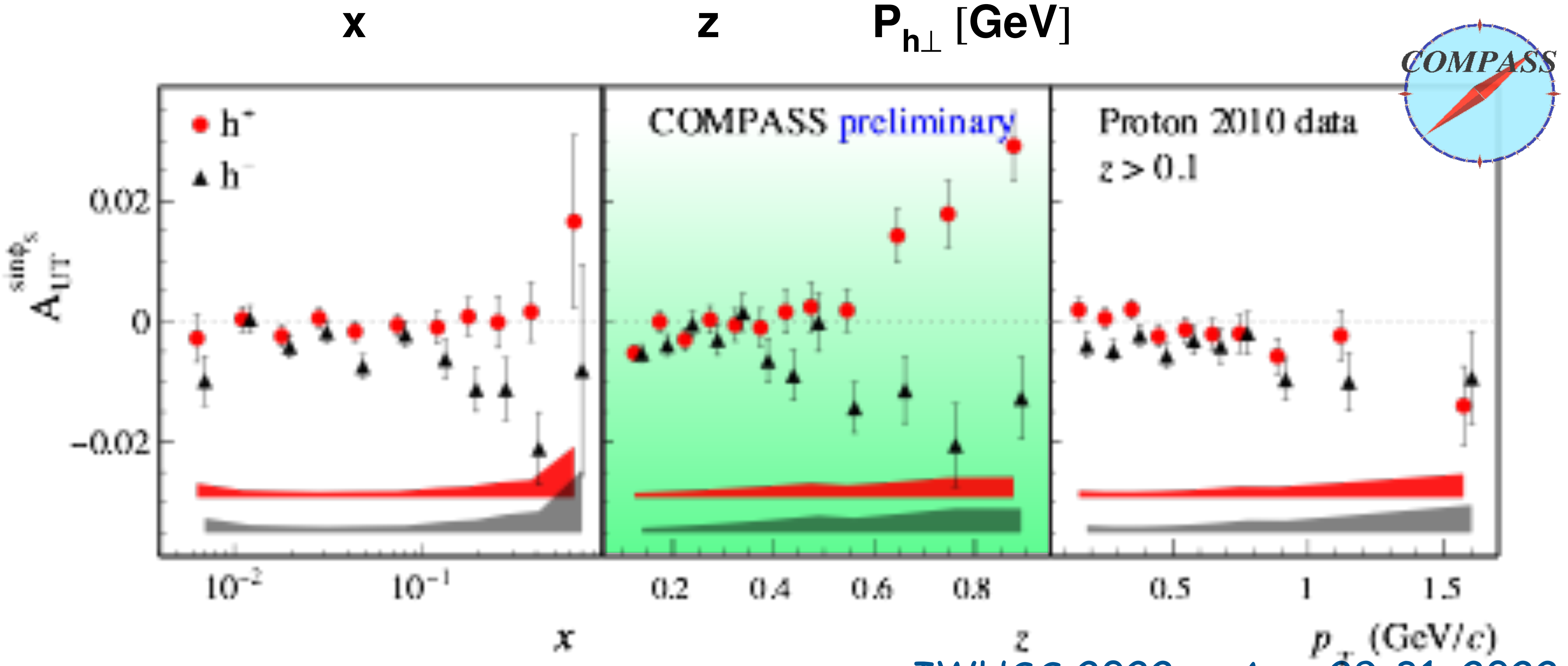


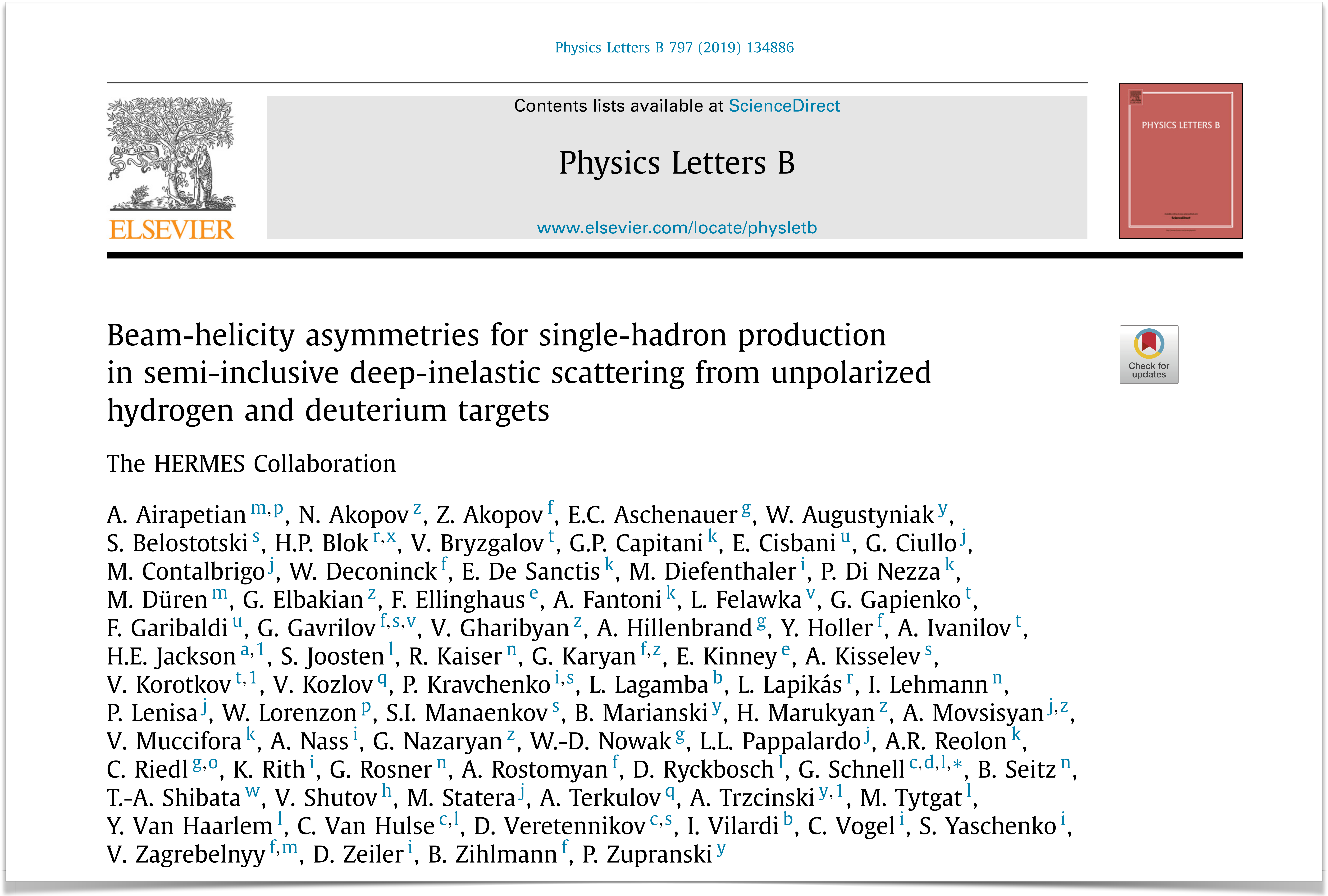
surprises: subleading twist, e.g., $\langle\sin(\phi_S)\rangle_{UT}$

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



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





Physics Letters B 797 (2019) 134886

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Physics Letters B

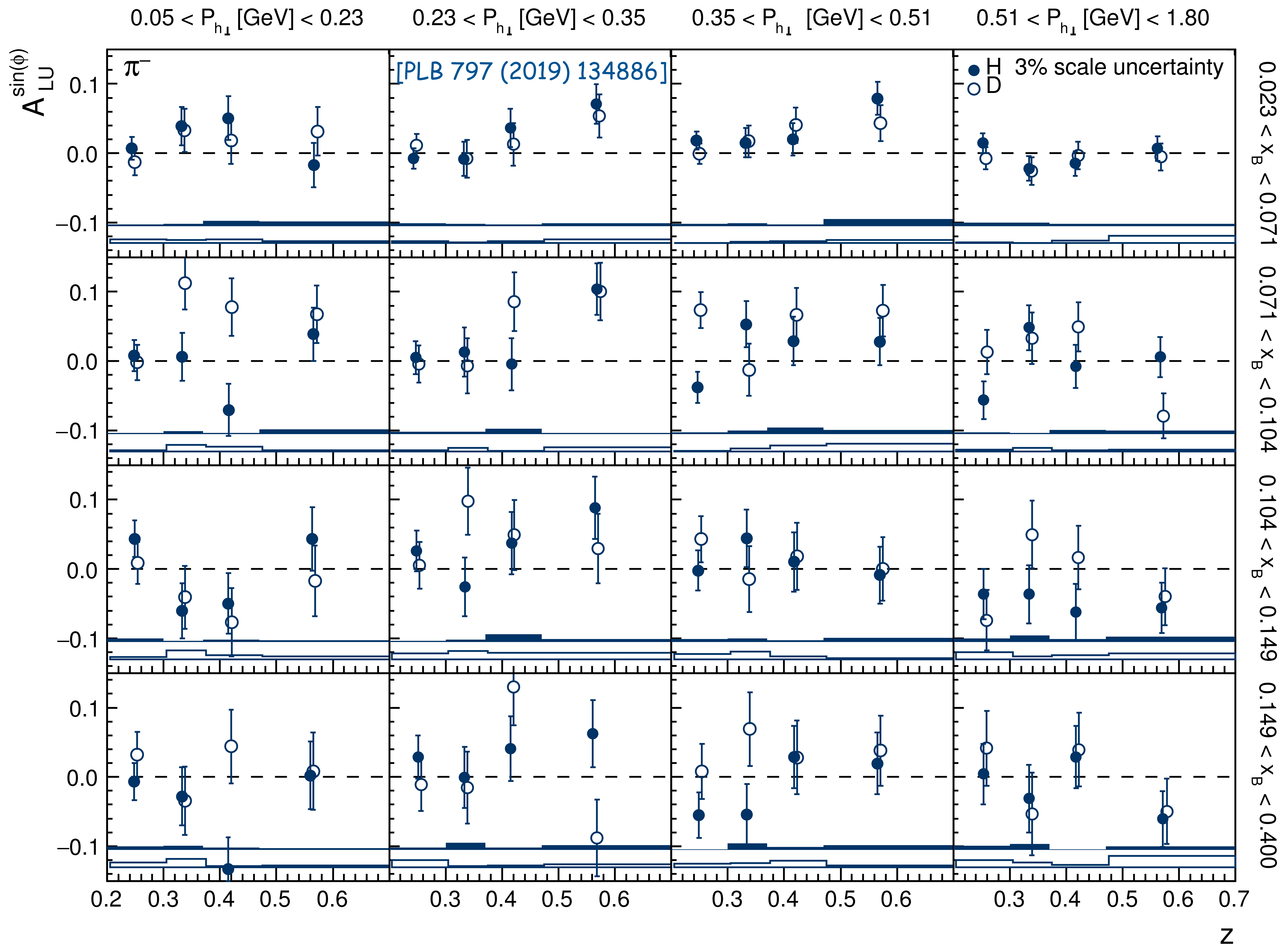
www.elsevier.com/locate/physletb

Beam-helicity asymmetries for single-hadron production in semi-inclusive deep-inelastic scattering from unpolarized hydrogen and deuterium targets

The HERMES Collaboration

A. Airapetian[m,p], N. Akopov[z], Z. Akopov[f], E.C. Aschenauer[g], W. Augustyniak[y], S. Belostotski[s], H.P. Blok[r,x], V. Bryzgalov[t], G.P. Capitani[k], E. Cisbani[u], G. Ciullo[j], M. Contalbrigo[j], W. Deconinck[f], E. De Sanctis[k], M. Diefenthaler[i], P. Di Nezza[k], M. Düren[m], G. Elbakian[z], F. Ellinghaus[e], A. Fantoni[k], L. Felawka[v], G. Gapienko[t], F. Garibaldi[u], G. Gavrilov[f,s,v], V. Gharibyan[z], A. Hillenbrand[g], Y. Holler[f], A. Ivanilov[t], H.E. Jackson[a,1], S. Joosten[l], R. Kaiser[n], G. Karyan[f,z], E. Kinney[e], A. Kisselev[s], V. Korotkov[t,1], V. Kozlov[q], P. Kravchenko[i,s], L. Lagamba[b], L. Lapikás[r], I. Lehmann[n], P. Lenisa[j], W. Lorenzon[p], S.I. Manaenkov[s], B. Marianski[y], H. Marukyan[z], A. Movsisyan[j,z], V. Muccifora[k], A. Nass[i], G. Nazaryan[z], W.-D. Nowak[g], L.L. Pappalardo[j], A.R. Reolon[k], C. Riedl[g,o], K. Rith[i], G. Rosner[n], A. Rostomyan[f], D. Ryckbosch[l], G. Schnell[c,d,l,*], B. Seitz[n], T.-A. Shibata[w], V. Shutov[h], M. Statera[j], A. Terkulov[q], A. Trzcinski[y,1], M. Tytgat[l], Y. Van Haarlem[l], C. Van Hulse[c,l], D. Veretennikov[c,s], I. Vilardi[b], C. Vogel[i], S. Yaschenko[i], V. Zagrebelnyy[f,m], D. Zeiler[i], B. Zihlmann[f], P. Zupranski[y]

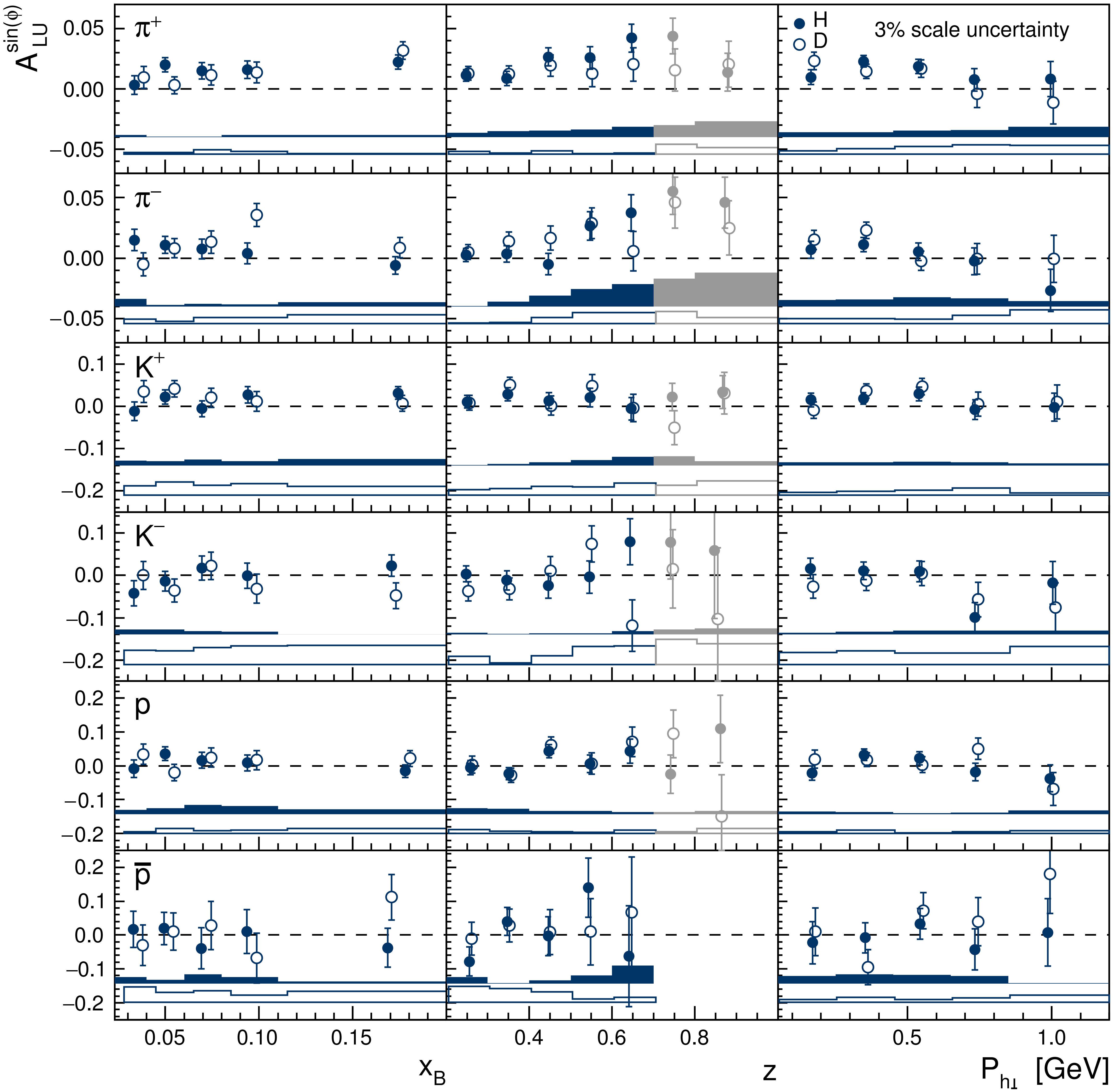
subleading twist II - $\langle\sin(\phi)\rangle_{LU}$ HERMES 3d analysis



most comprehensive presentation; use 1d binning for discussion

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

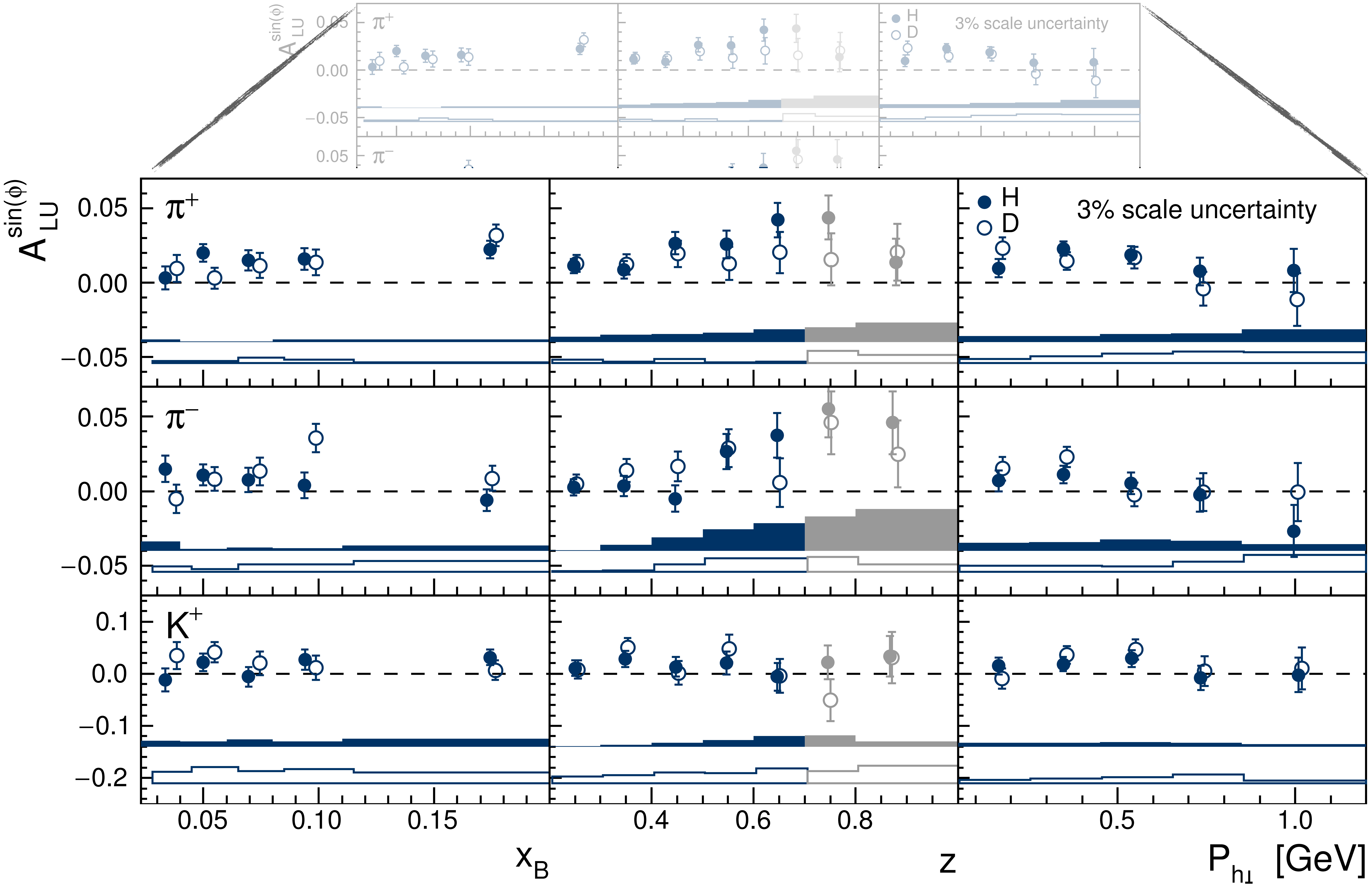
[HERMES, PLB 797 (2019) 134886]



- p & d targets
- π, K, p & $\bar{p}$ final-state h
- SIDIS and high-z transition regions

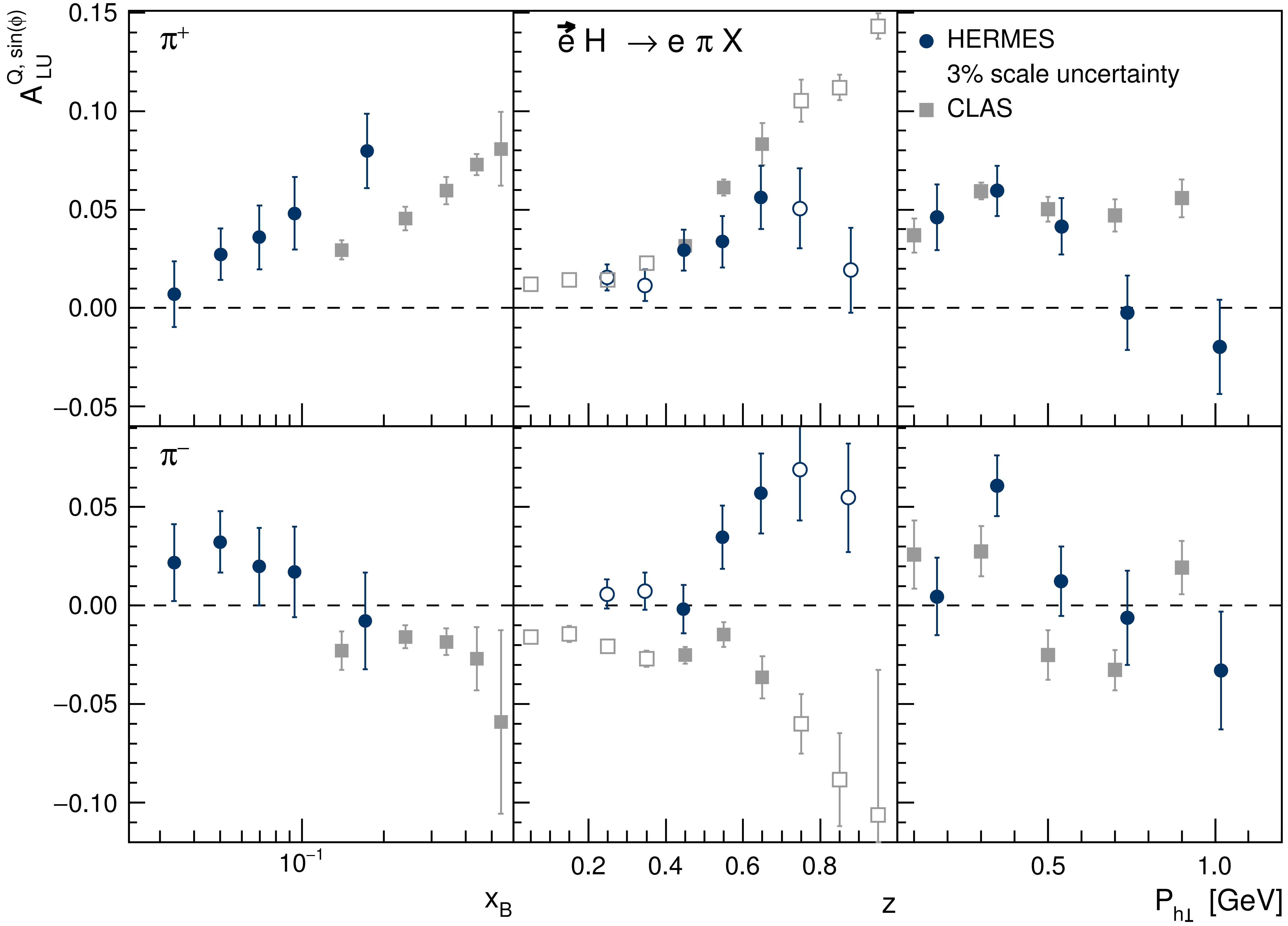
$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$

[HERMES, PLB 797 (2019) 134886]



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

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

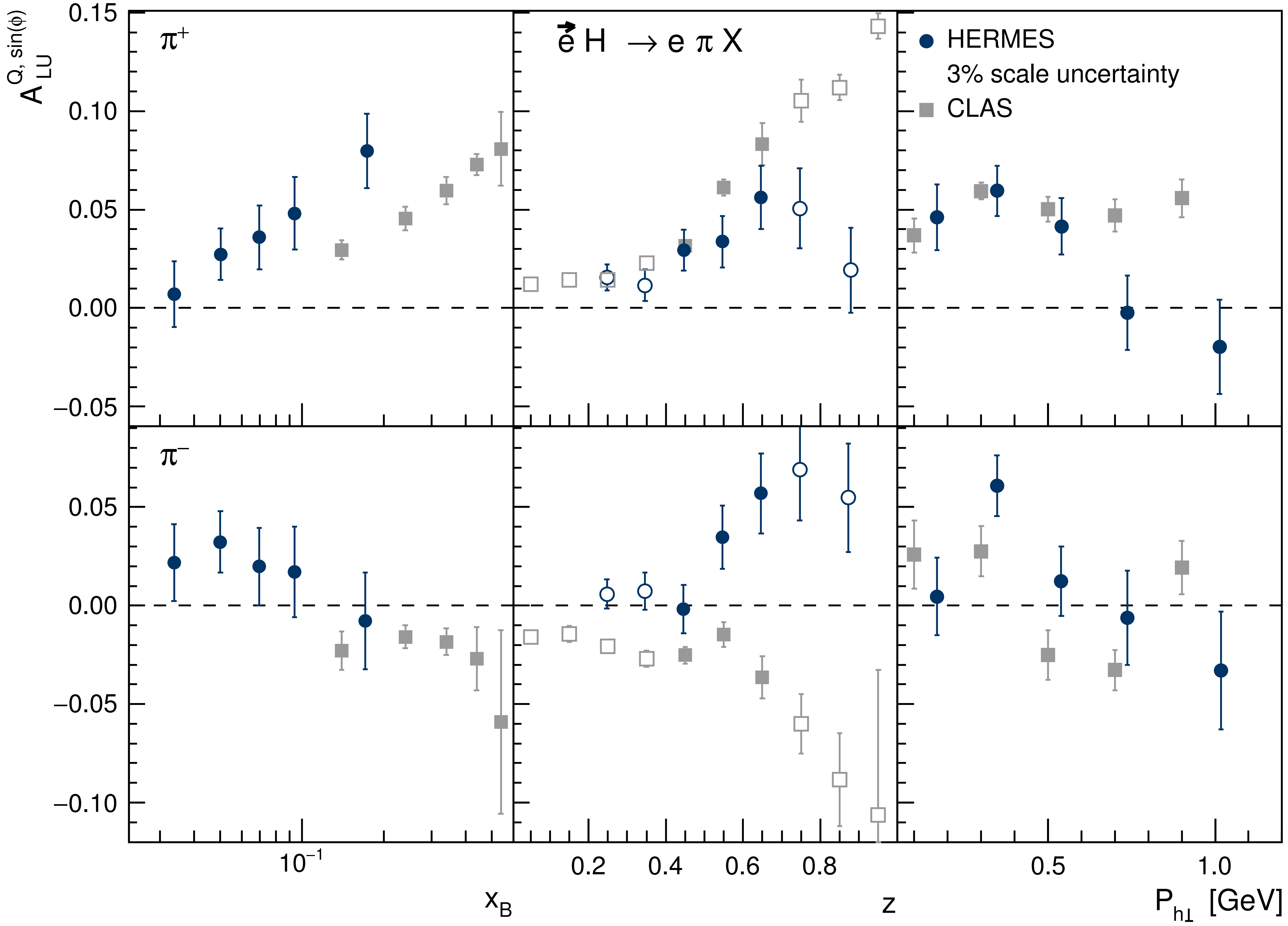


[HERMES, PLB 797 (2019) 134886]

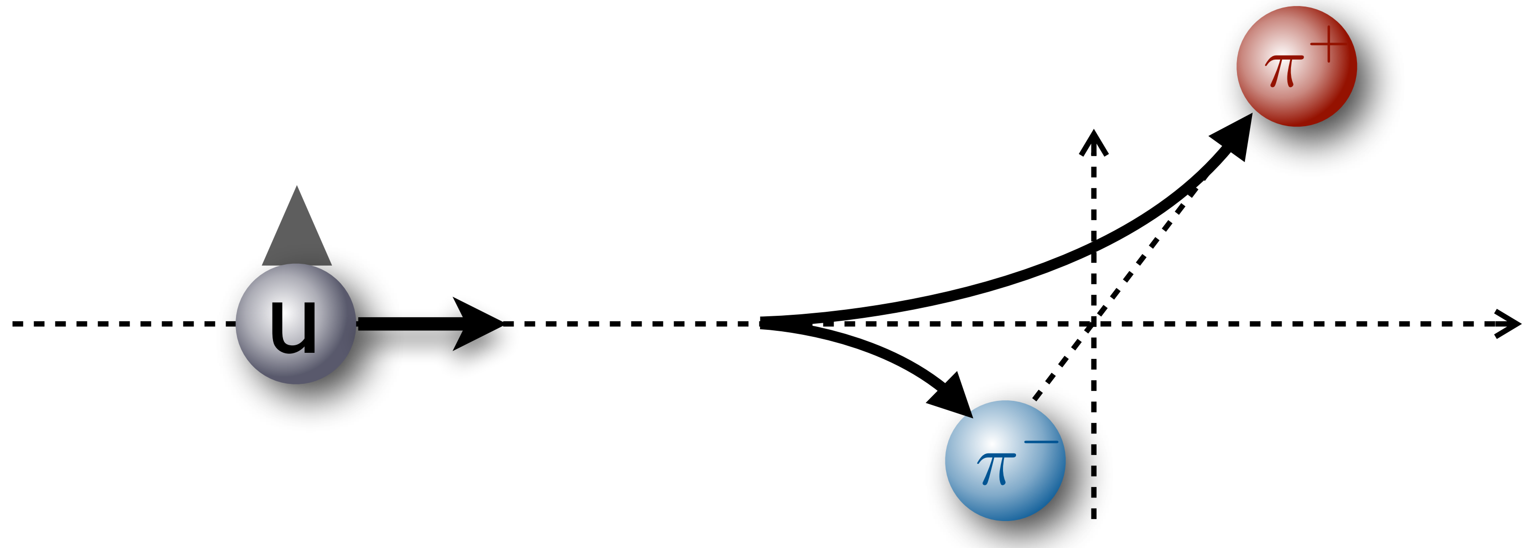
- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed

subleading twist II - $\langle\sin(\phi)\rangle_{LU}$ HERMES & CLAS

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



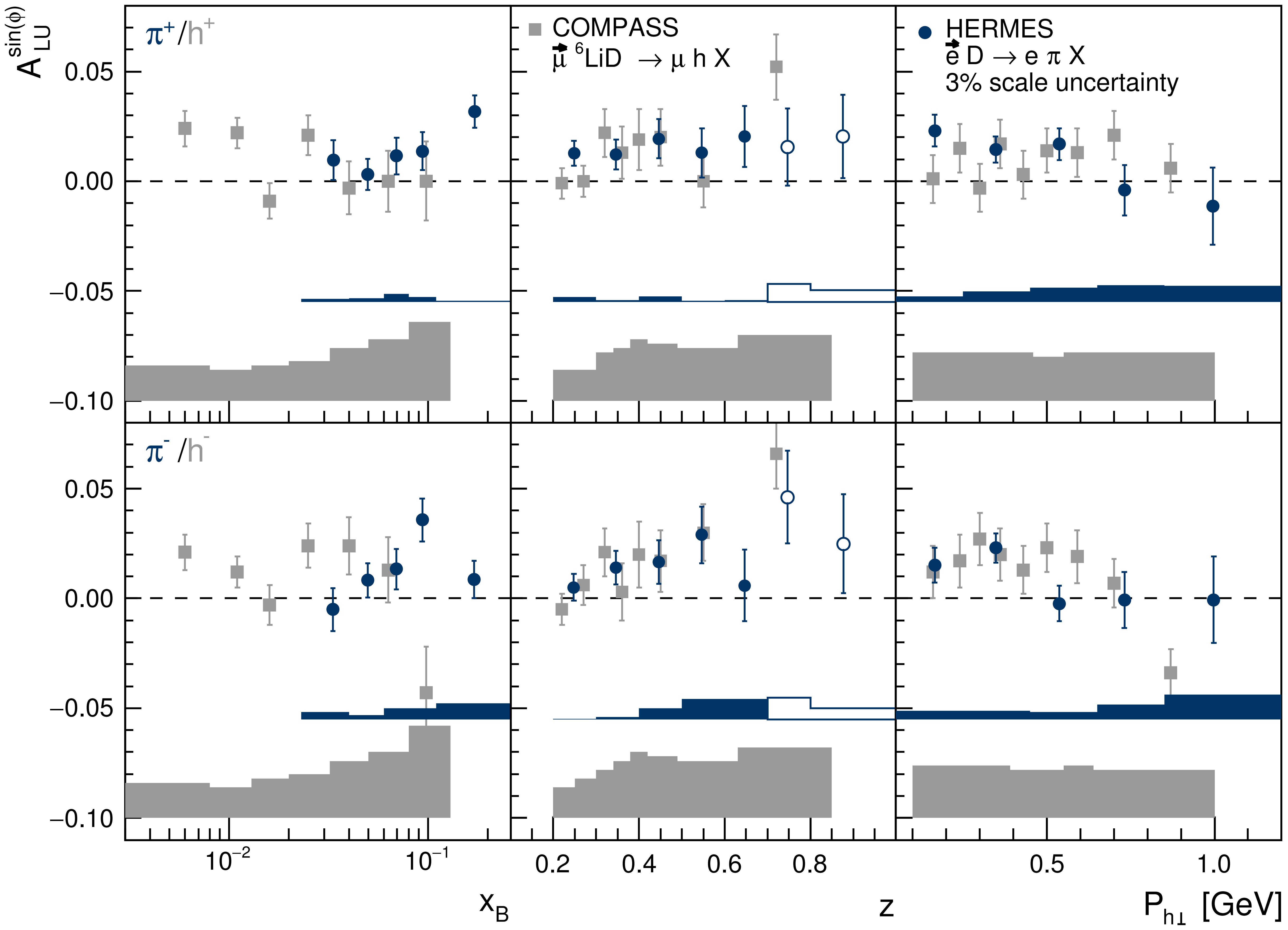
[HERMES, PLB 797 (2019) 134886]



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

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

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

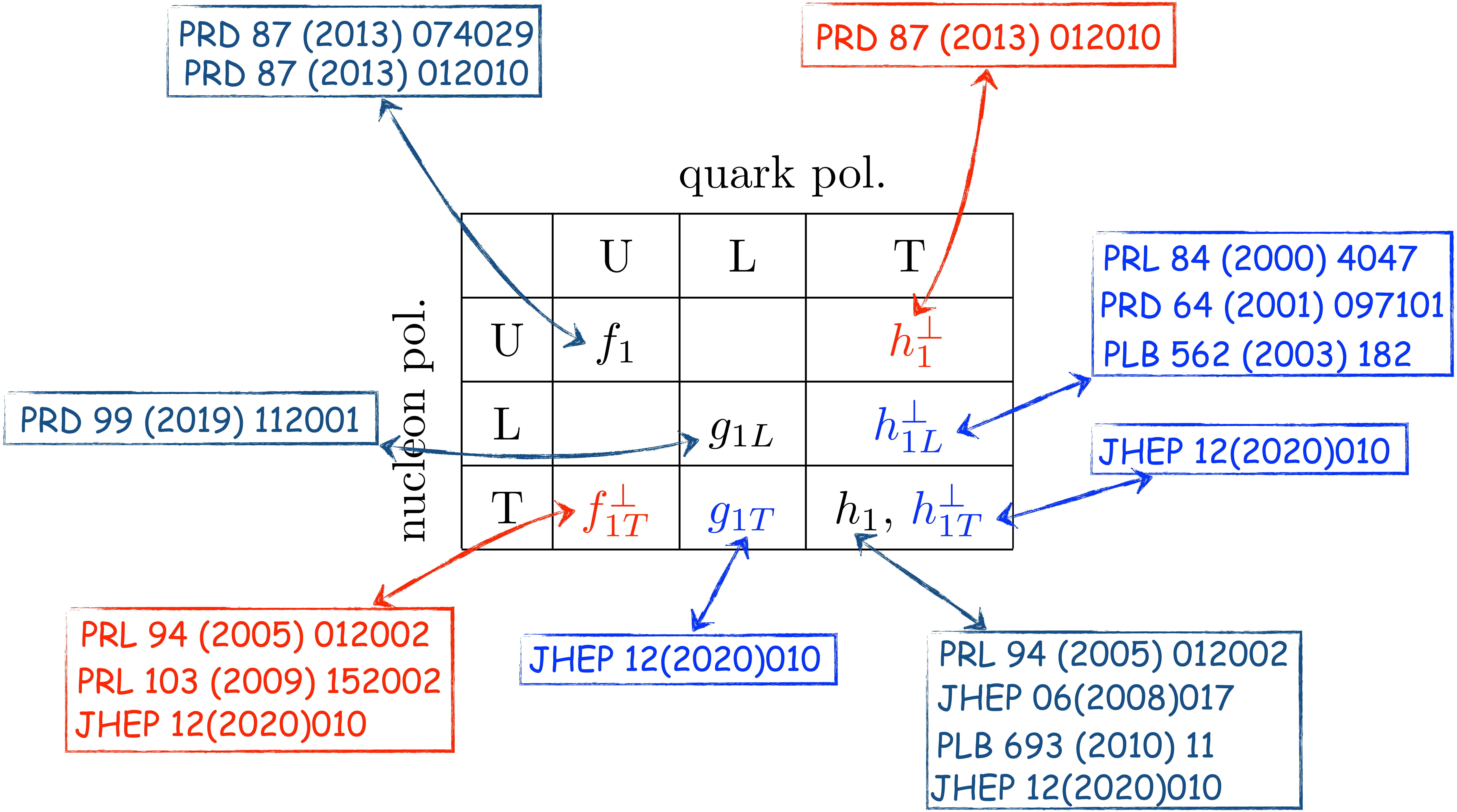


[HERMES, PLB 797 (2019) 134886]

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

conclusions

- HERMES continues producing results long after its shut-down
  - latest pub's providing 3d presentations of **longitudinal** & **transverse SSA & DSA**
  - **completes the TMD analyses** of single-hadron production
  - 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
- equally important are studies of generalized parton distributions (see DVCS summary in backup) and many other results not related to 3d structure (e.g., nuclear effects)



PRD 87 (2013) 074029
PRD 87 (2013) 012010

PRD 87 (2013) 012010

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, $h_{1T}^\perp$

PRL 84 (2000) 4047
PRD 64 (2001) 097101
PLB 562 (2003) 182

JHEP 12(2020)010

PRD 99 (2019) 112001

PRL 94 (2005) 012002
PRL 103 (2009) 152002
JHEP 12(2020)010

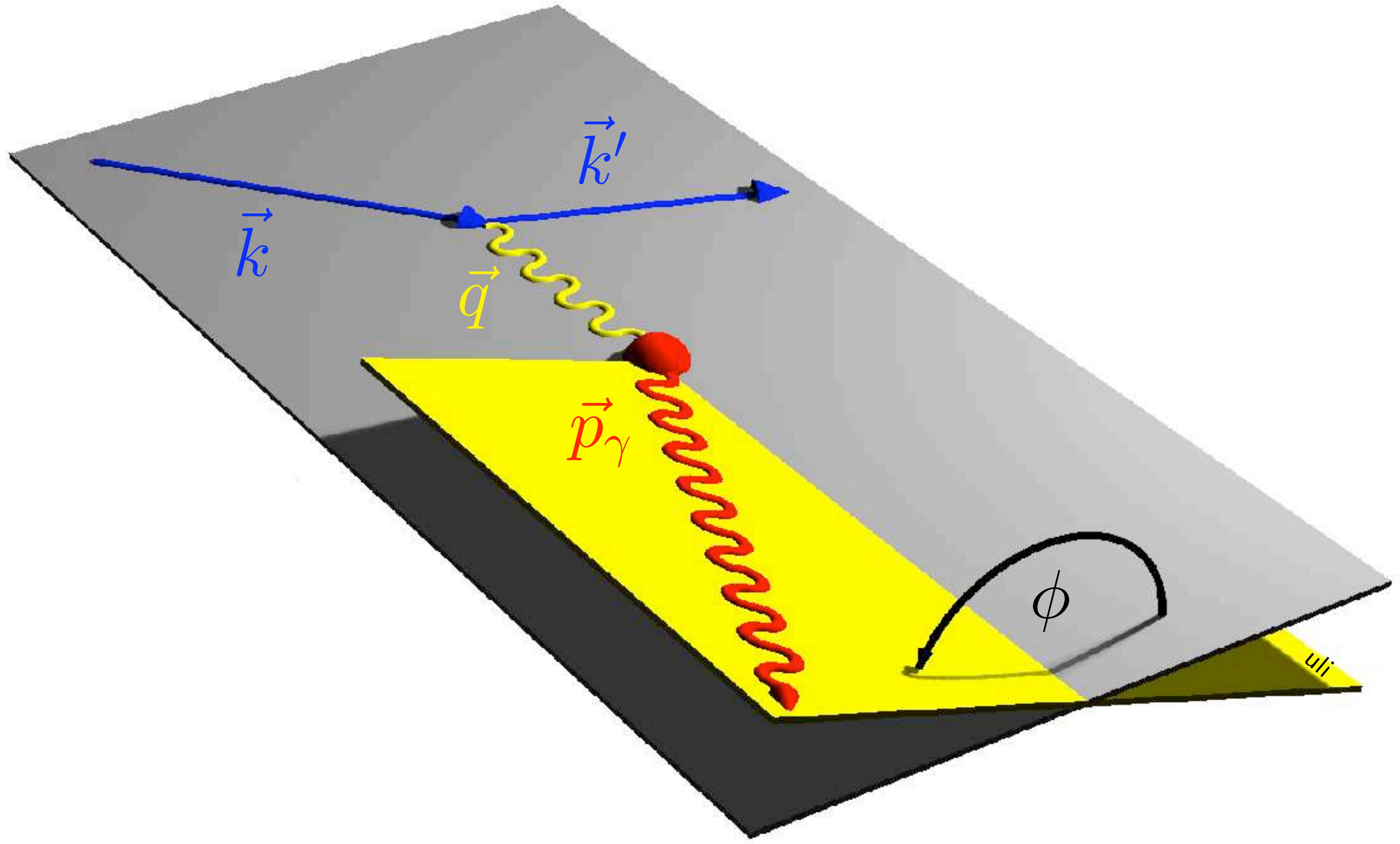
JHEP 12(2020)010

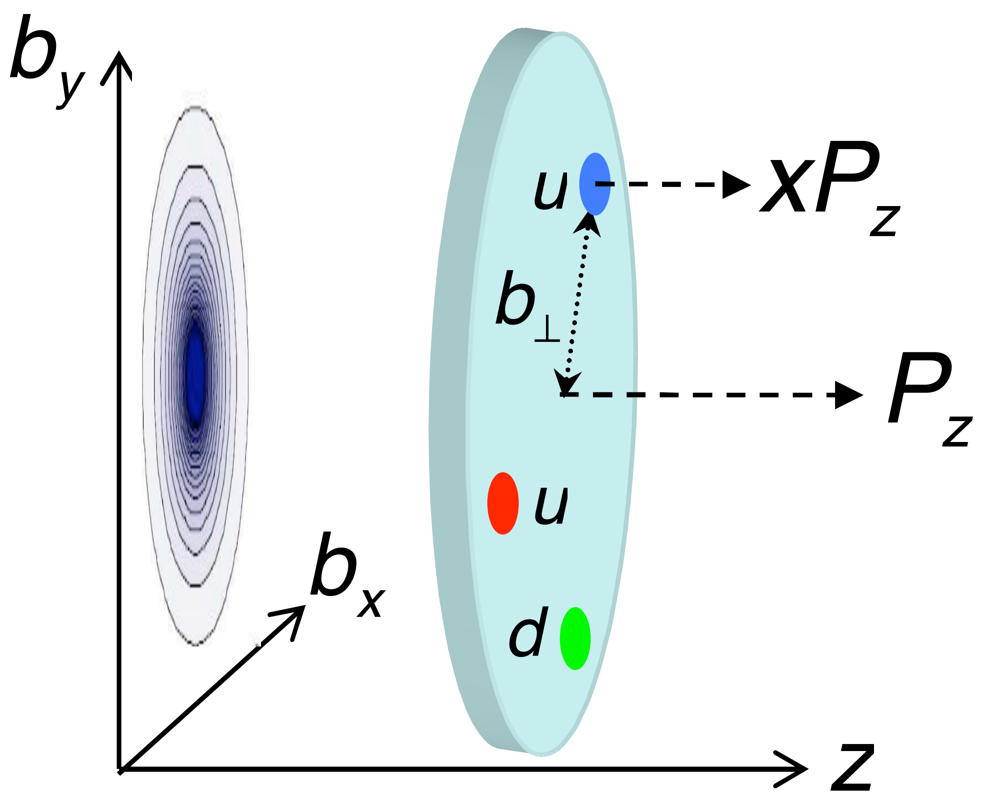
PRL 94 (2005) 012002
JHEP 06(2008)017
PLB 693 (2010) 11
JHEP 12(2020)010

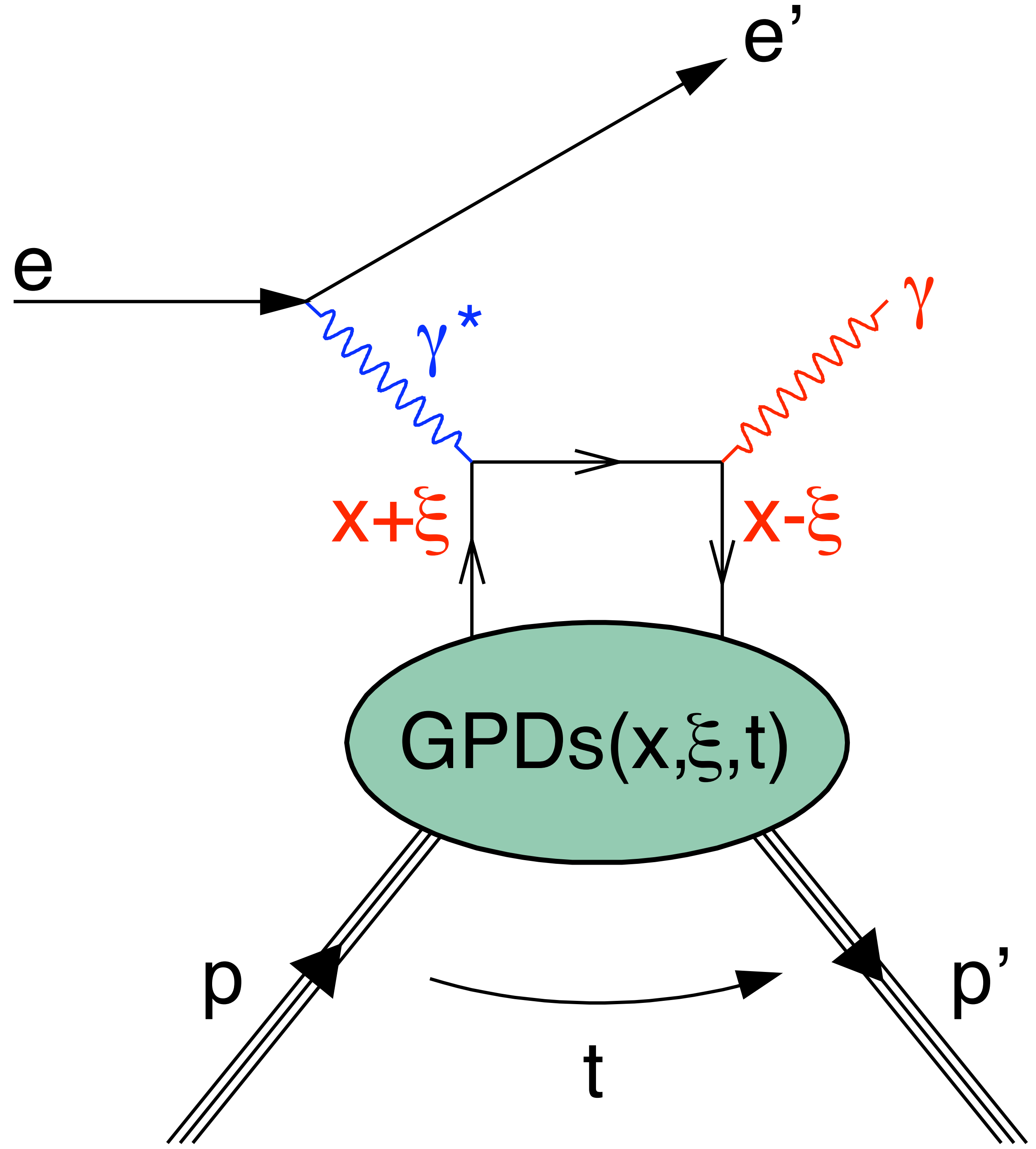
backup slides

deeply virtual Compton scattering (DVCS)

DVCS





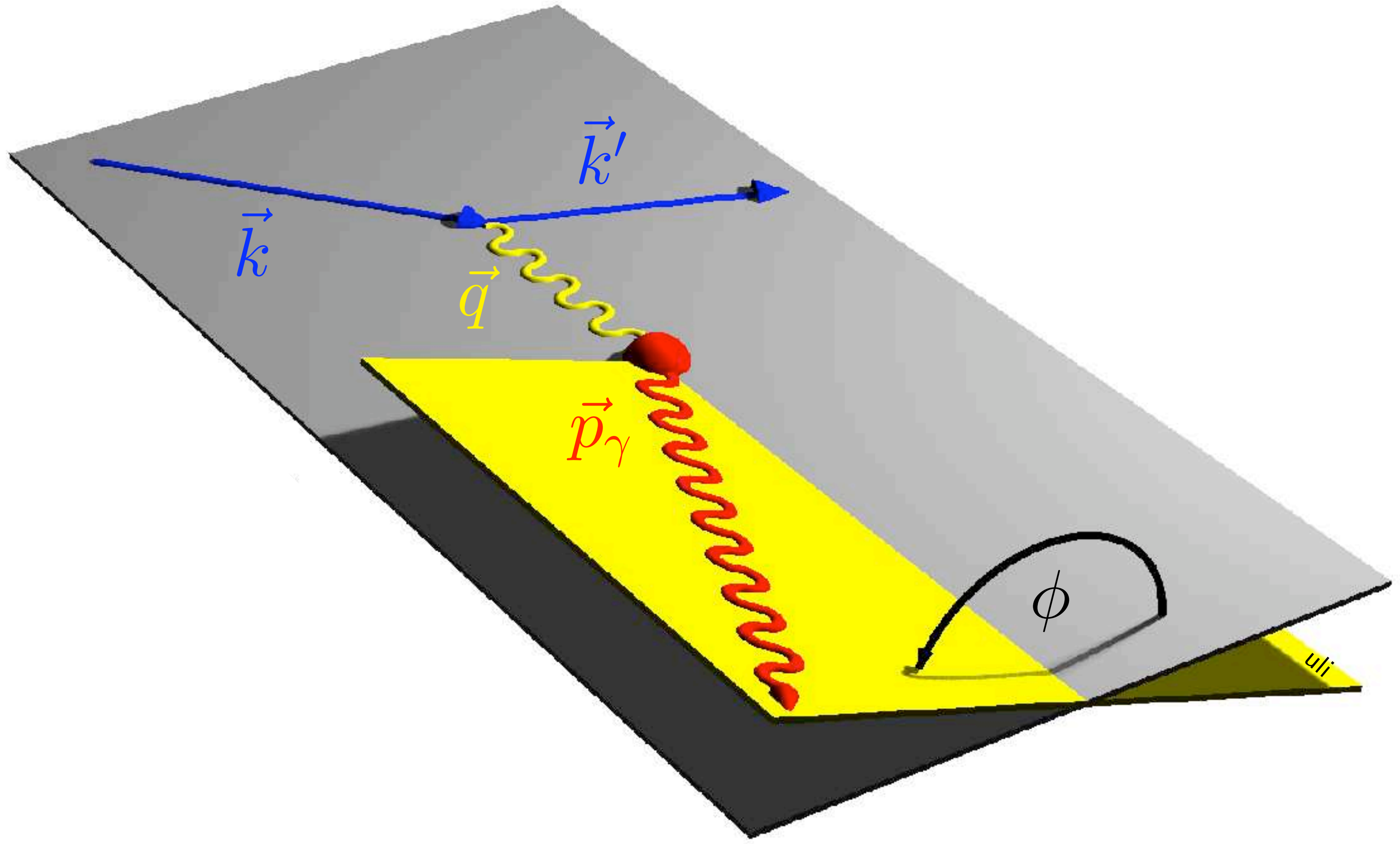


- beam polarization P_B
- beam charge C_B
- here: unpolarized target (many more modulations for polarized targets)

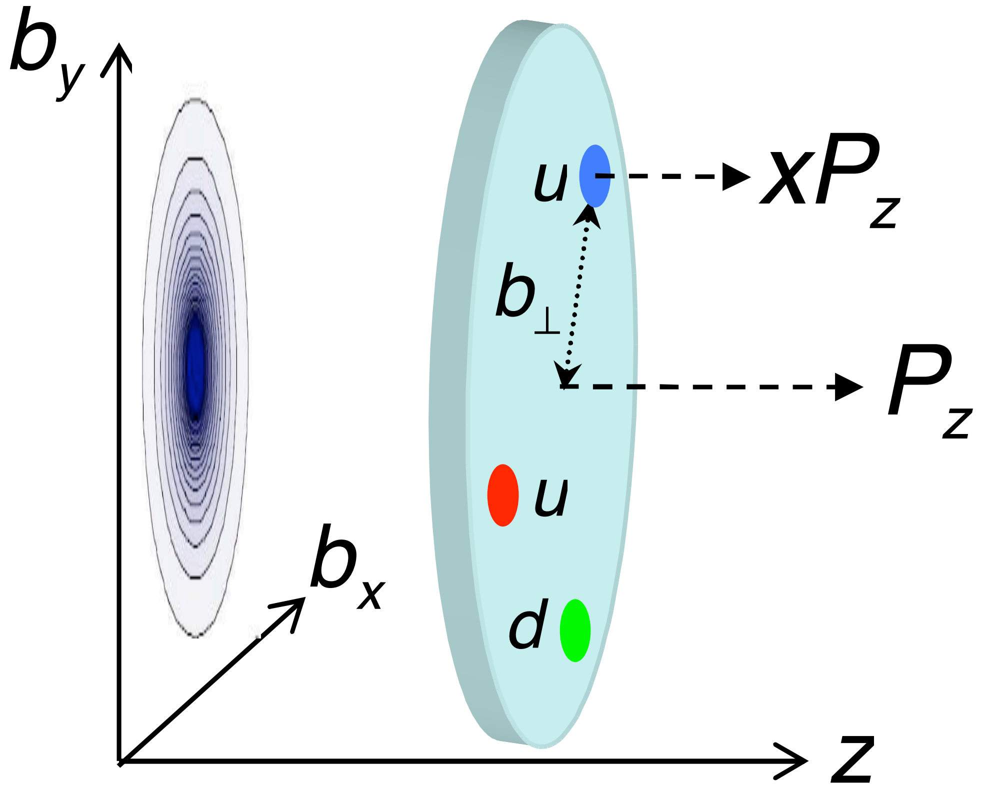
Fourier expansion for ϕ:

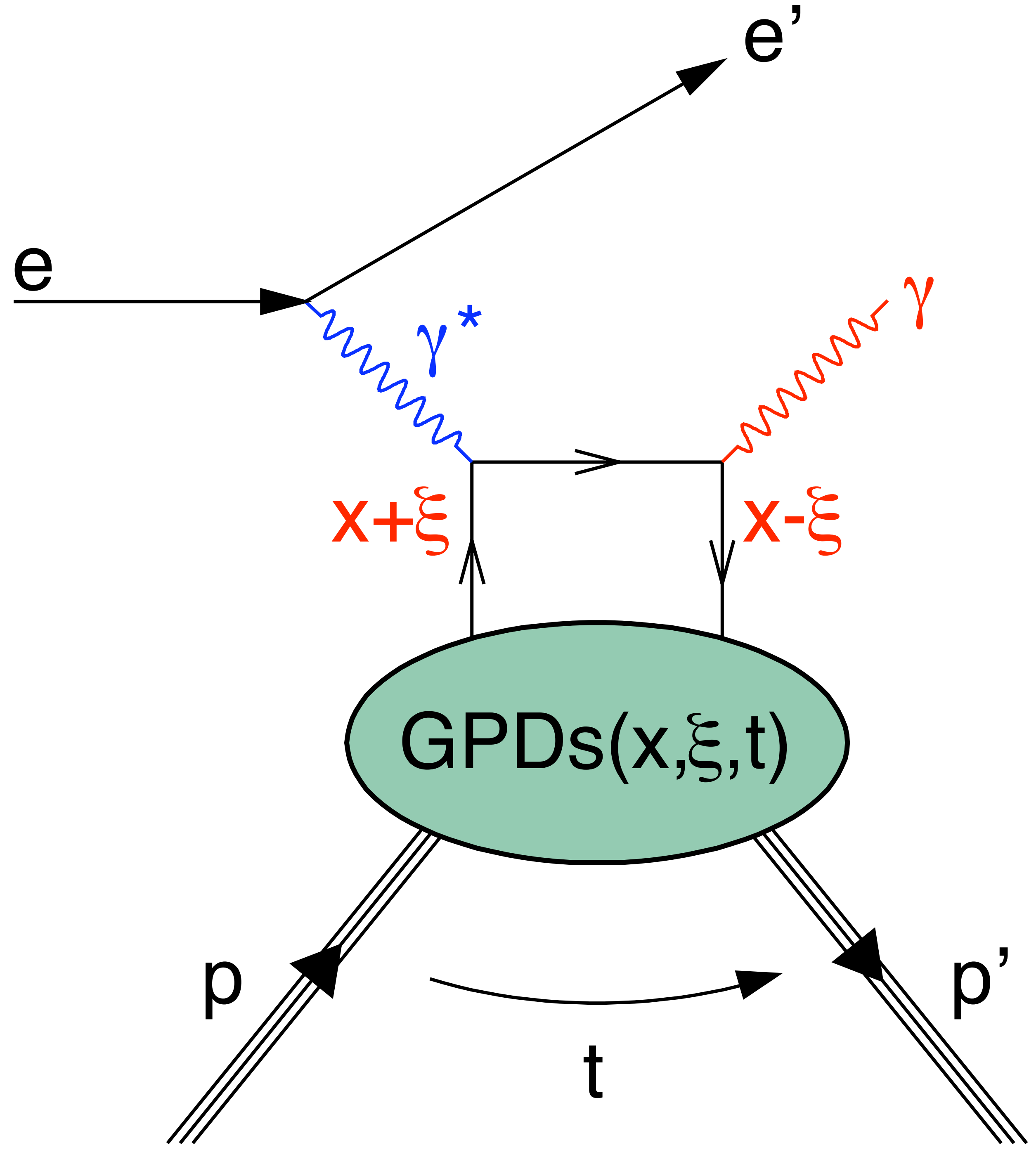
$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

calculable in QED
(using form-factor measurements)



DVCS





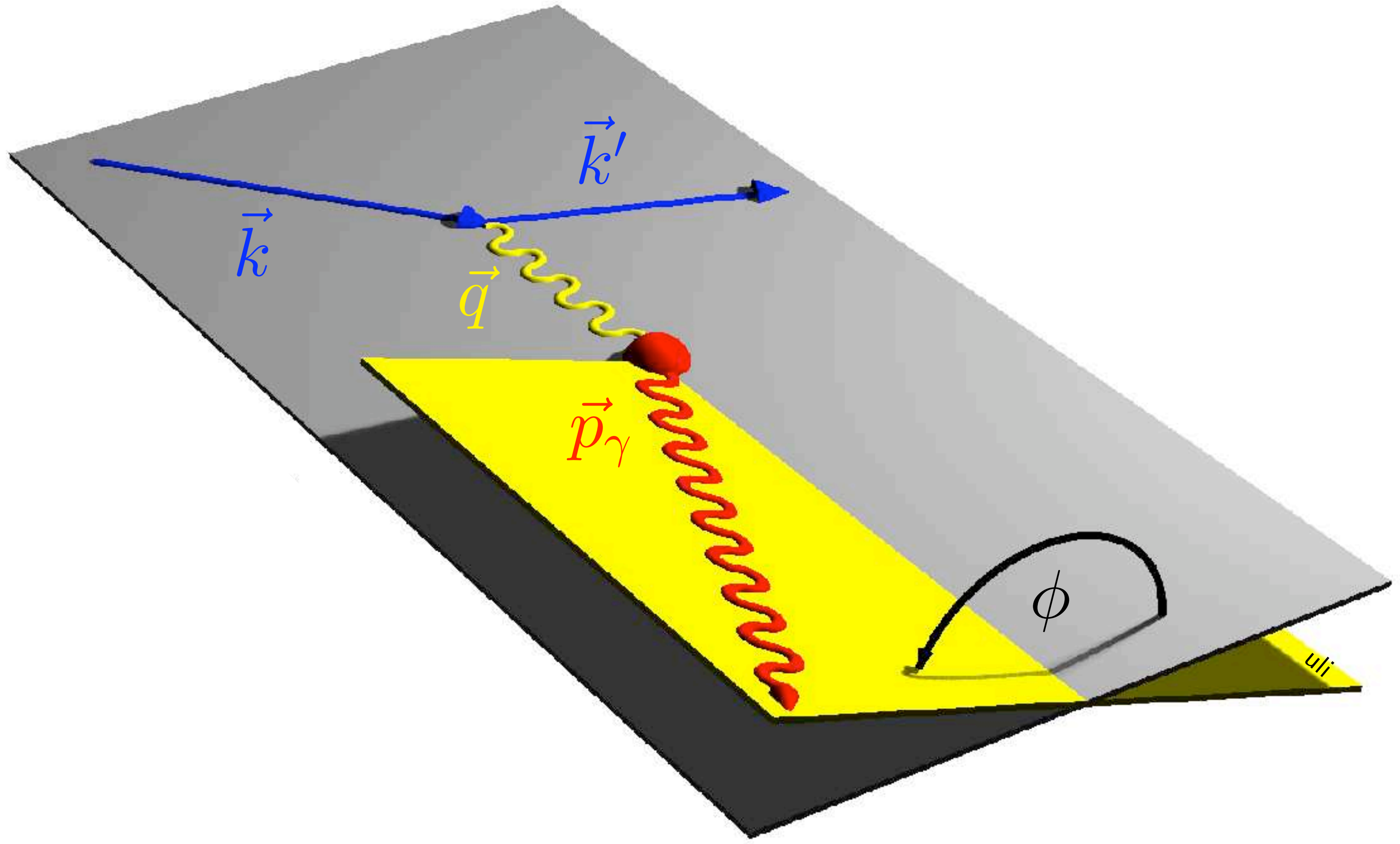
- beam polarization P_B
- beam charge C_B
- here: unpolarized target (many more modulations for polarized targets)

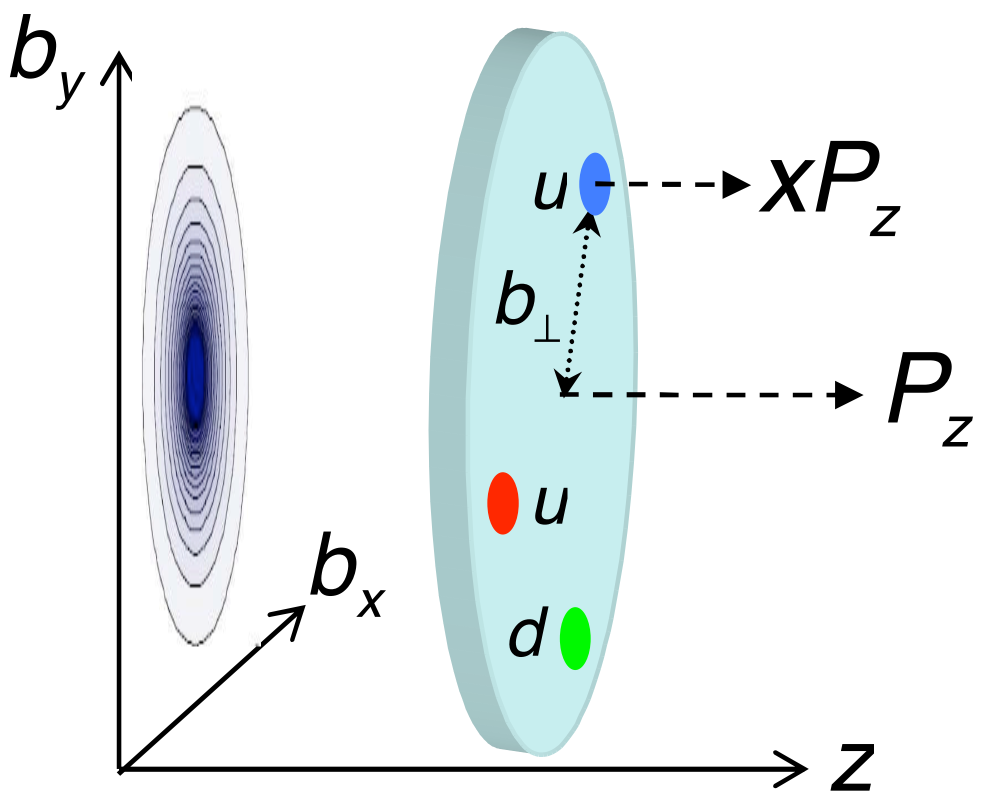
Fourier expansion for ϕ:

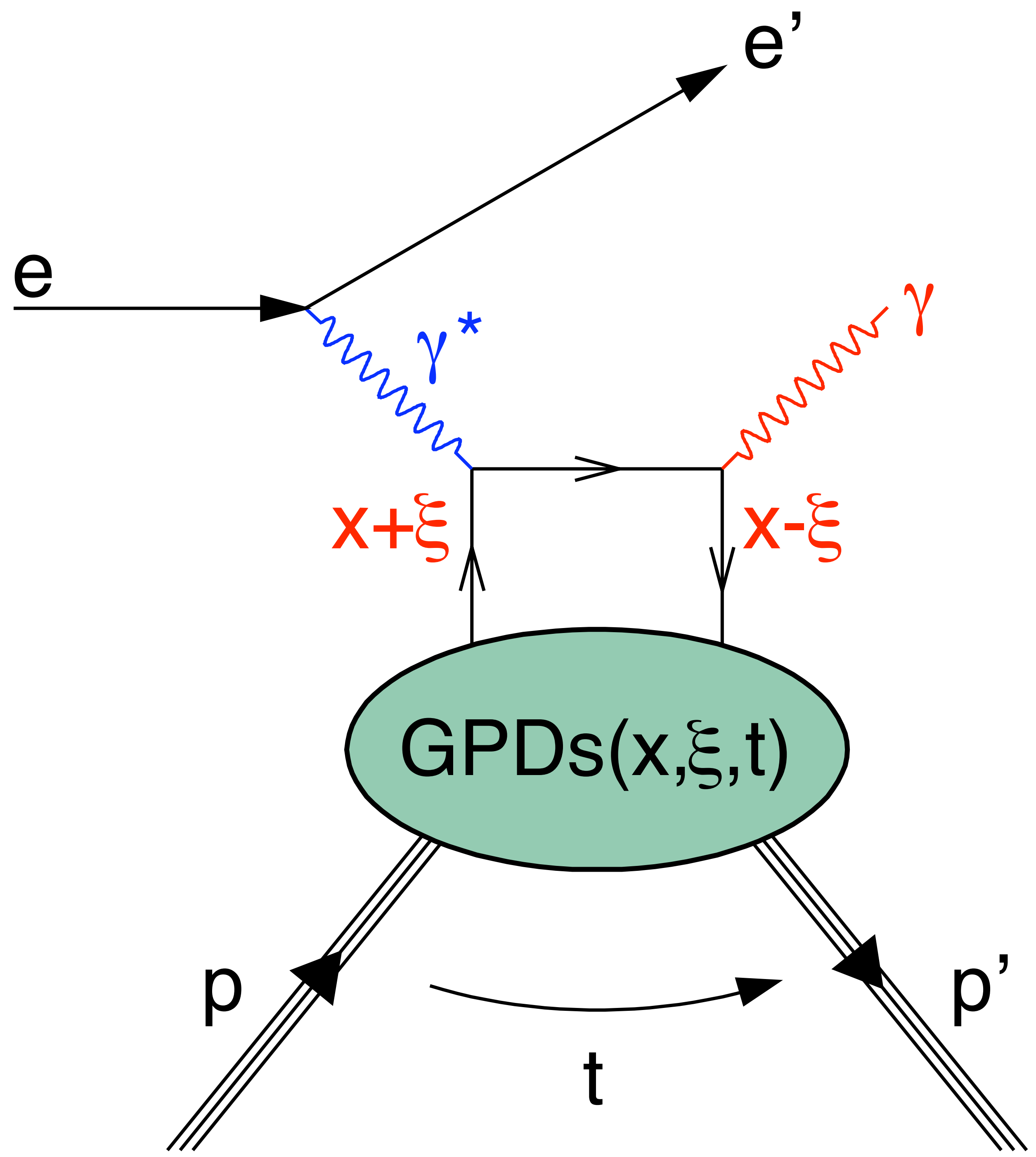
$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

DVCS







- beam polarization P_B
- beam charge C_B
- here: unpolarized target (many more modulations for polarized targets)

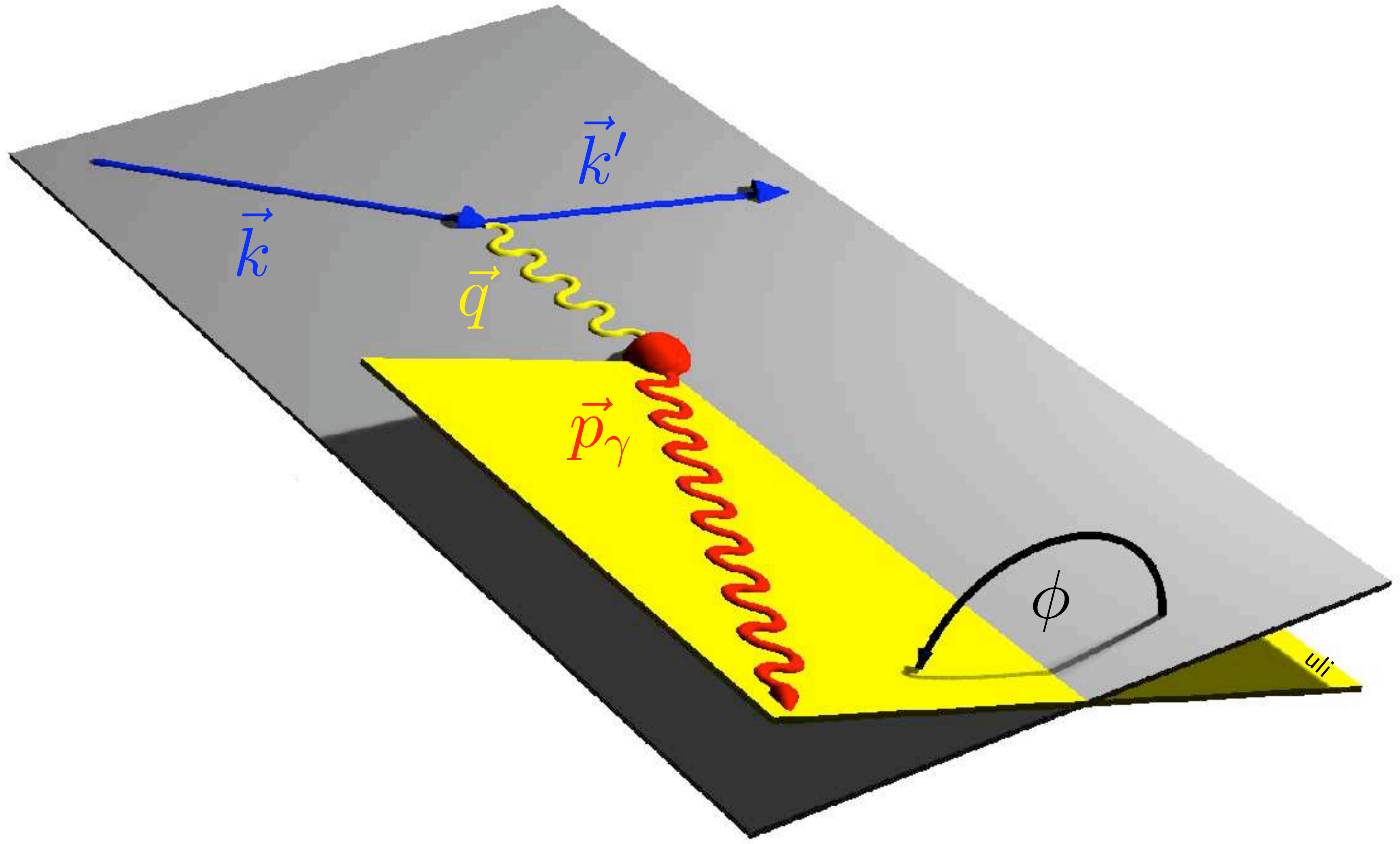
Fourier expansion for ϕ:

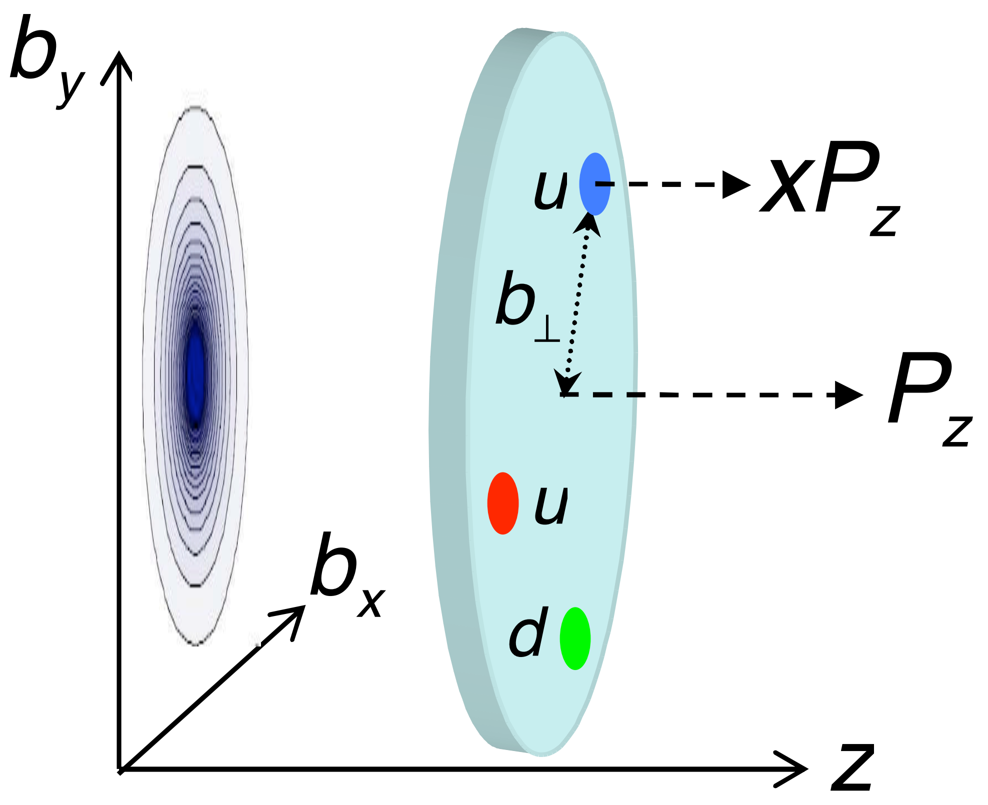
$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

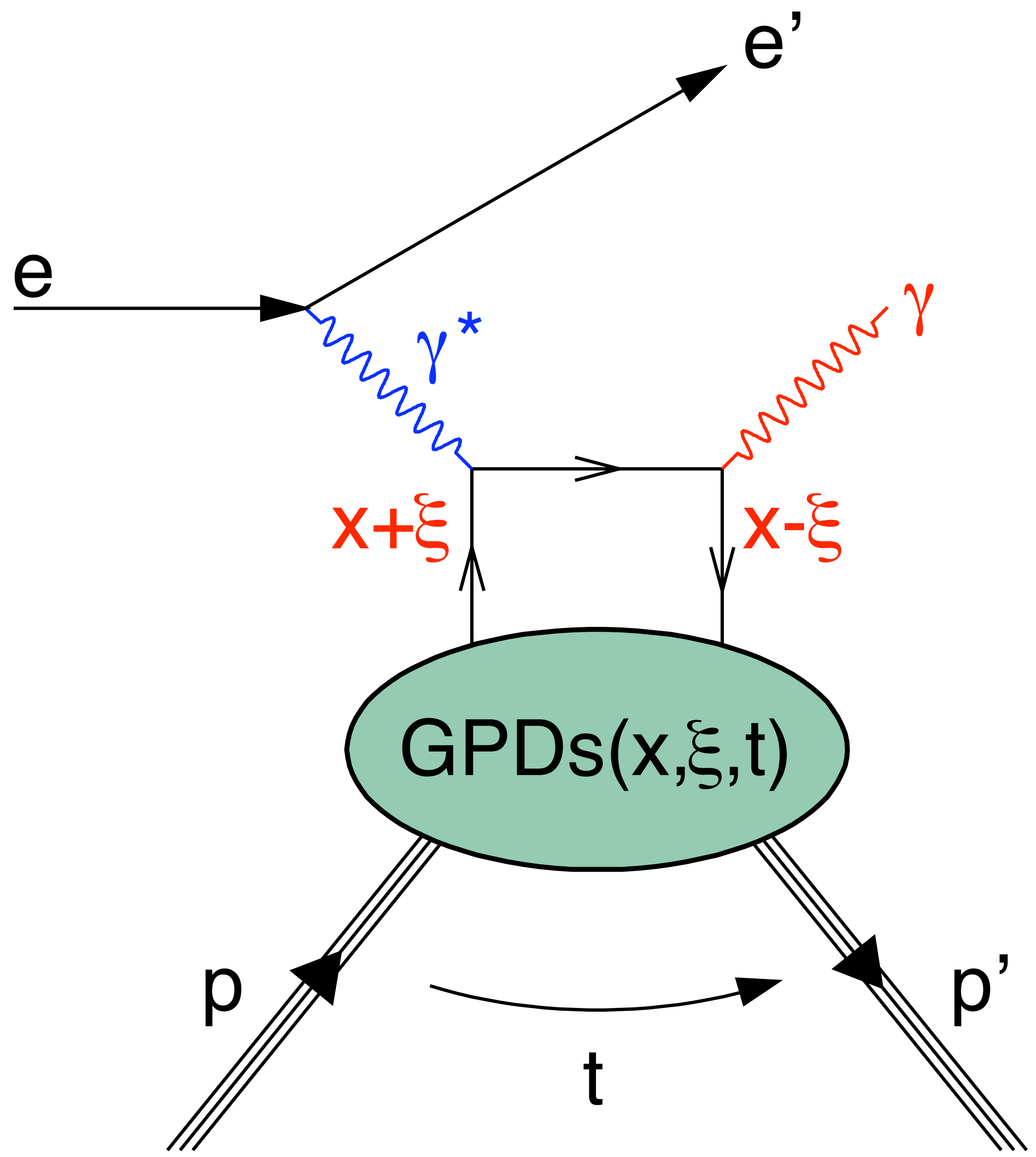
$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS} \left[\sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\rm DVCS} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

DVCS







- beam polarization P_B
- beam charge C_B
- here: unpolarized target (many more modulations for polarized targets)

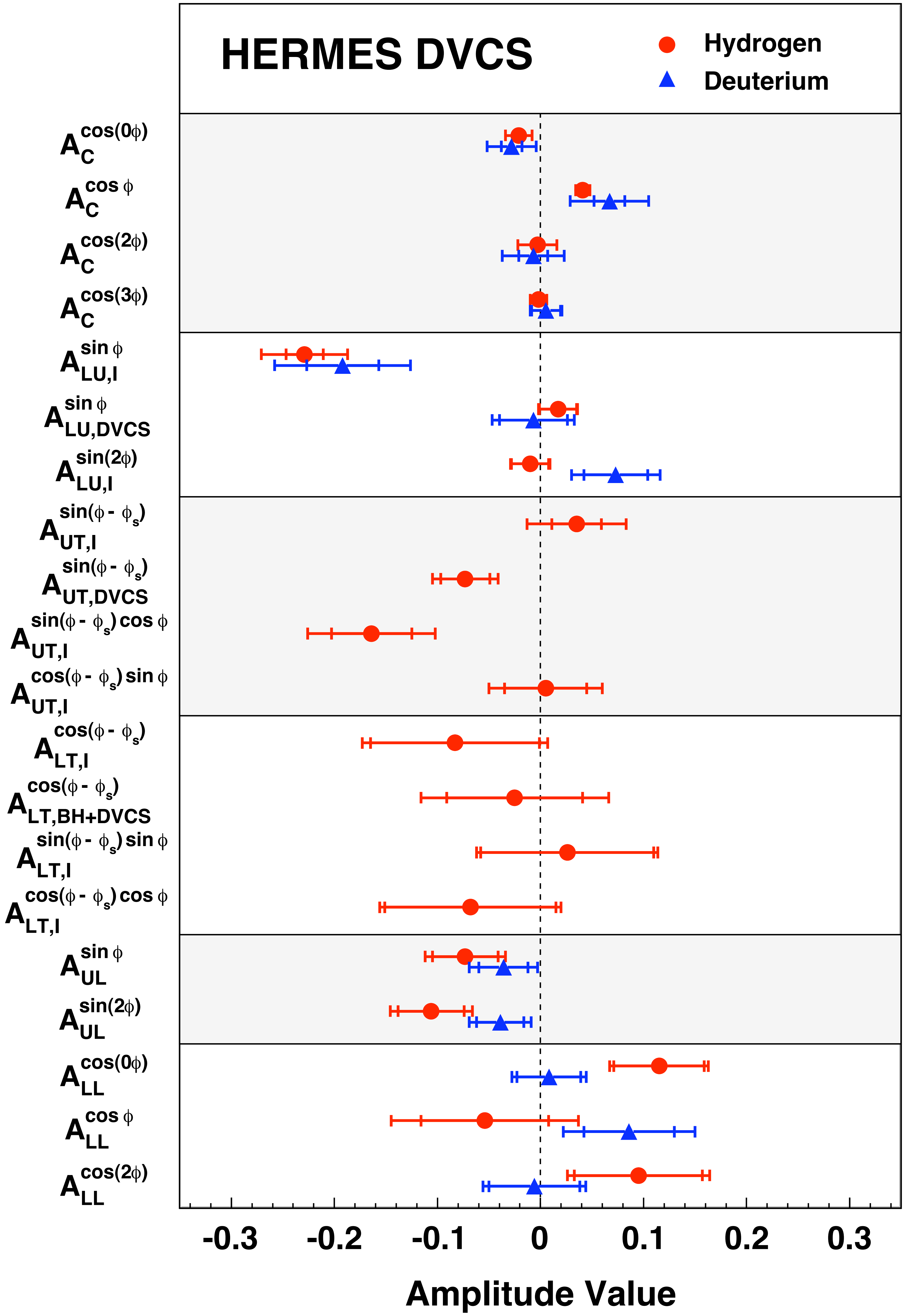
Fourier expansion for ϕ:

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

bilinear (“DVCS”) or linear in GPDs



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103

NPB 829 (2010) 1

JHEP 11 (2009) 083

Beam-helicity asymmetry:

GPD H

PRC 81 (2010) 035202

PRL 87 (2001) 182001

JHEP 07 (2012) 032

Transverse target spin asymmetries:

GPD E from proton target

JHEP 06 (2008) 066

PLB 704 (2011) 15

Longitudinal target spin asymmetry:

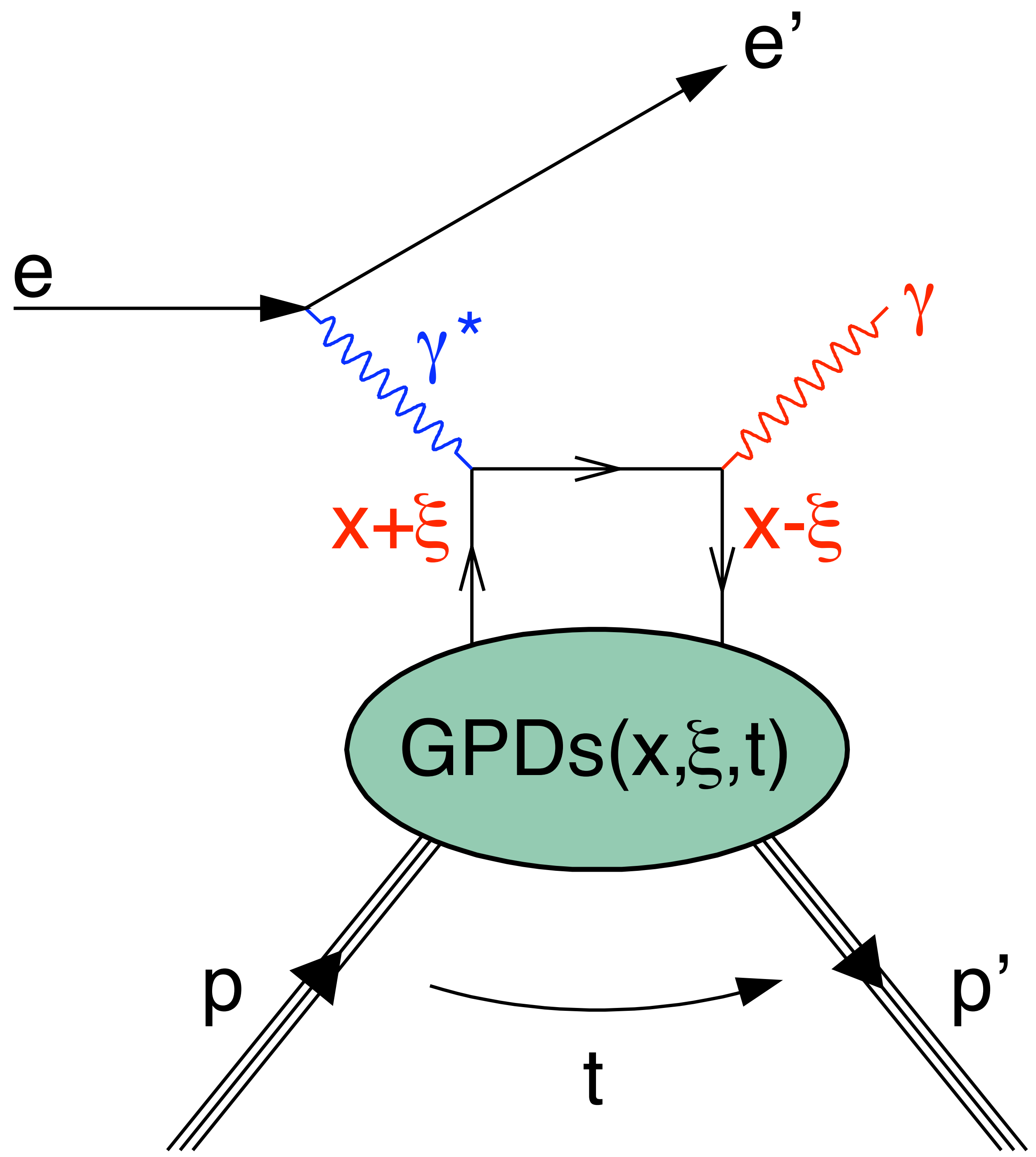
GPD $\tilde{H}$

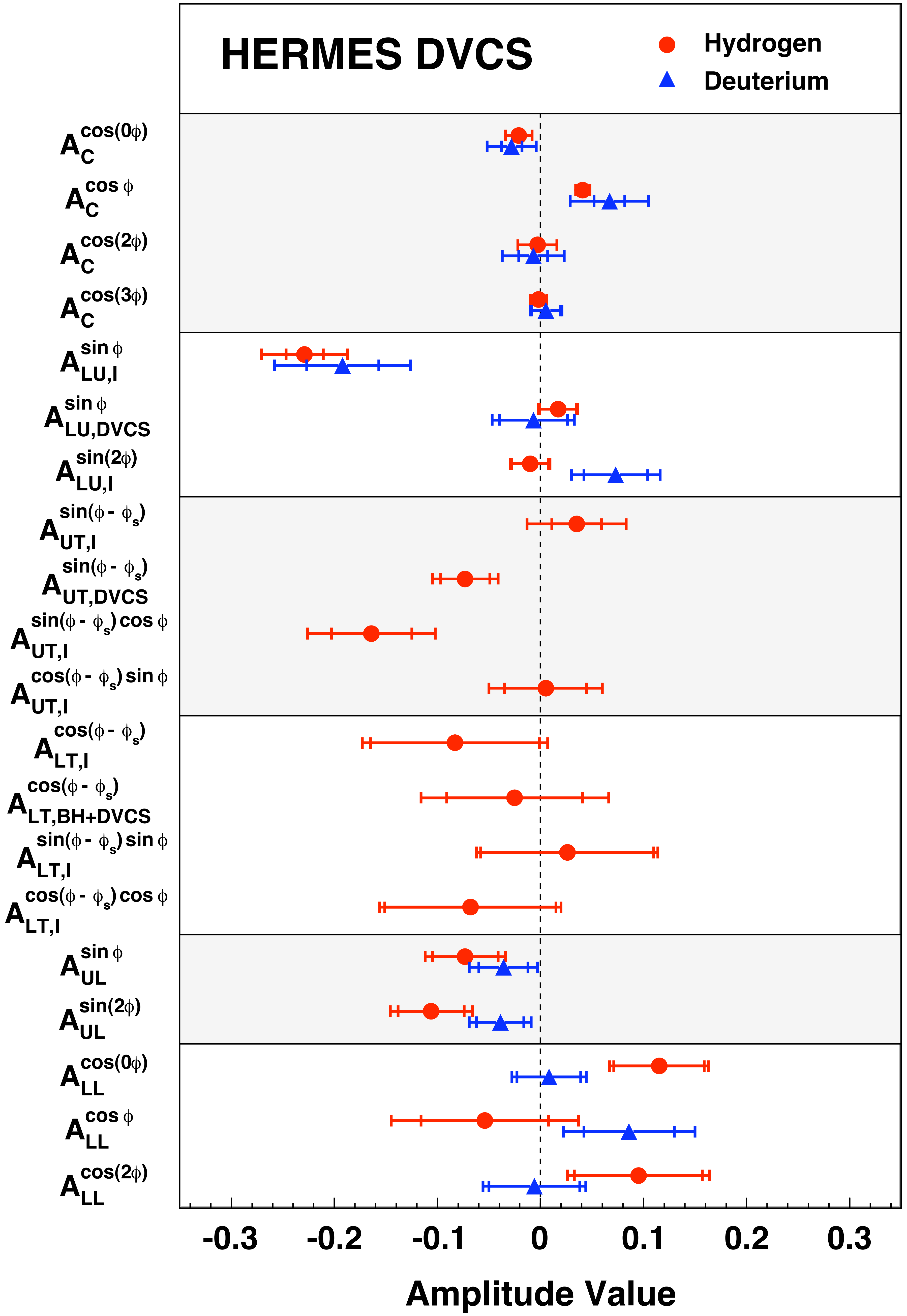
JHEP 06 (2010) 019

NPB 842 (2011) 265

Double-spin asymmetry:

GPD $\tilde{H}$





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PRD 75 (2007) 011103

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PRL 87 (2001) 182001

JHEP 07 (2012) 032

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JHEP 06 (2010) 019

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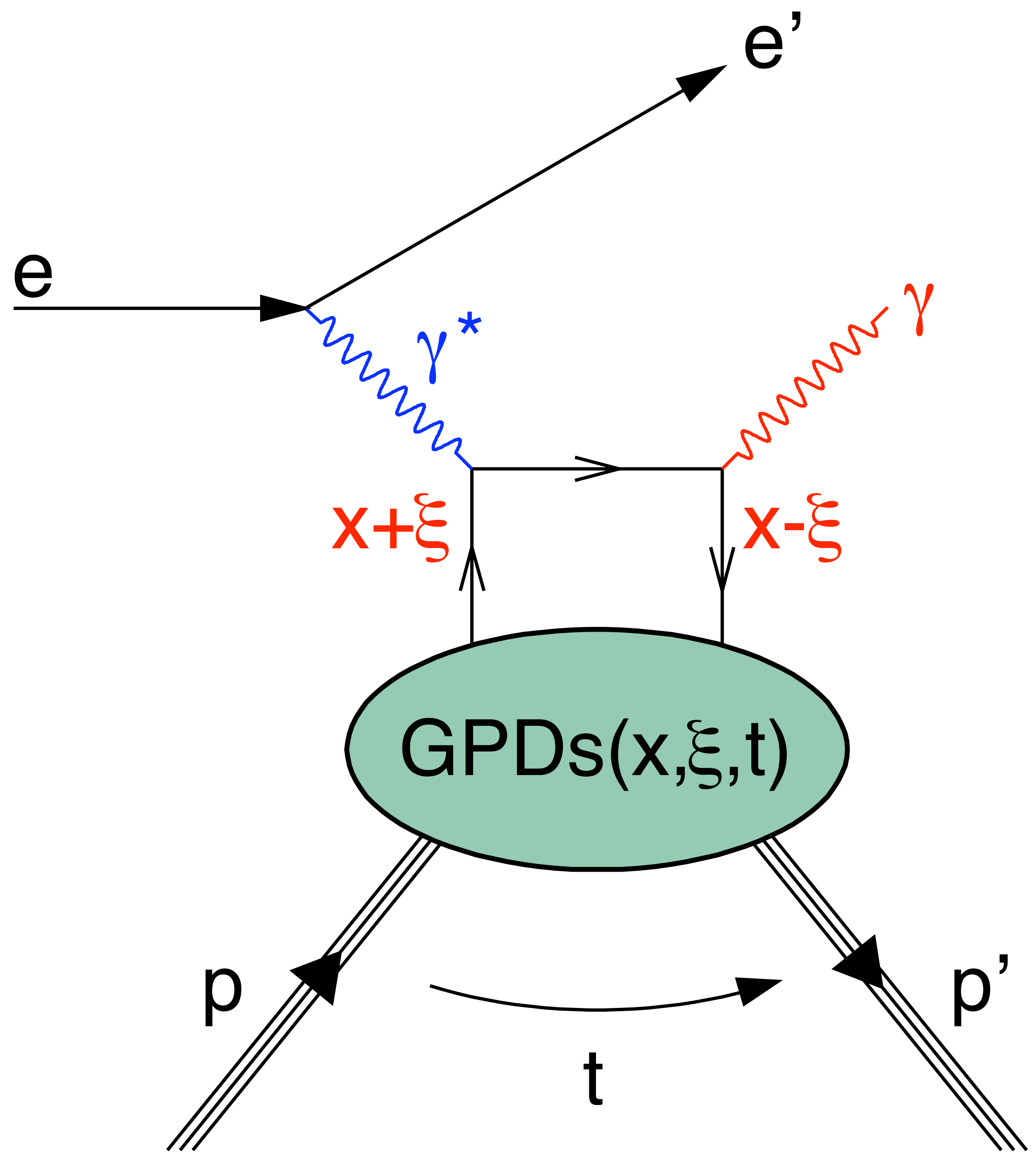
Double-spin asymmetry:

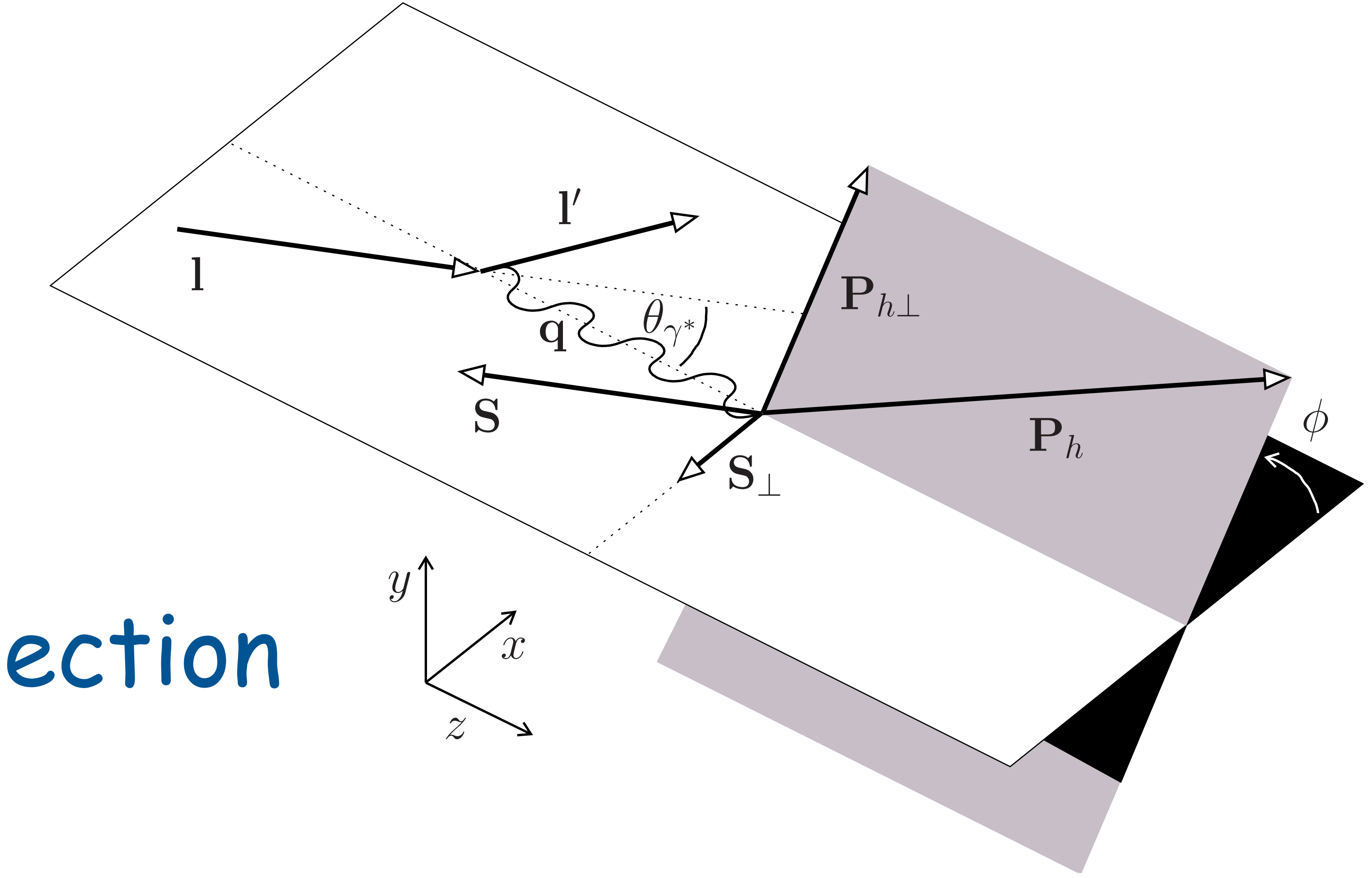
GPD $\tilde{H}$



however, no cross-section measurement so far at HERMES kinematics!

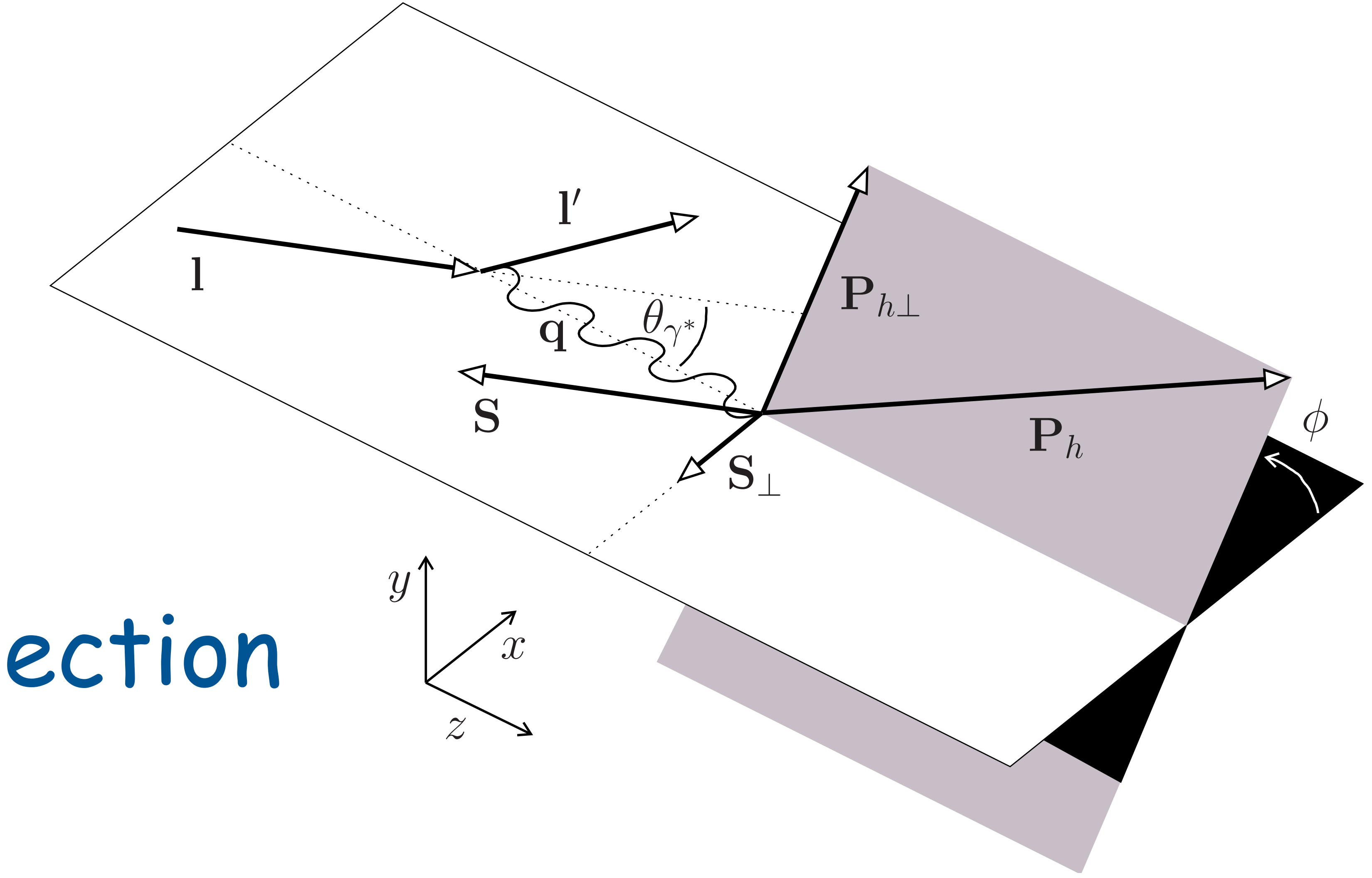
non-vanishing twist-3

subleading twist I - <sin(ϕ)>$_{UL}$



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

subleading twist I - <sin(ϕ)>$_{UL}$

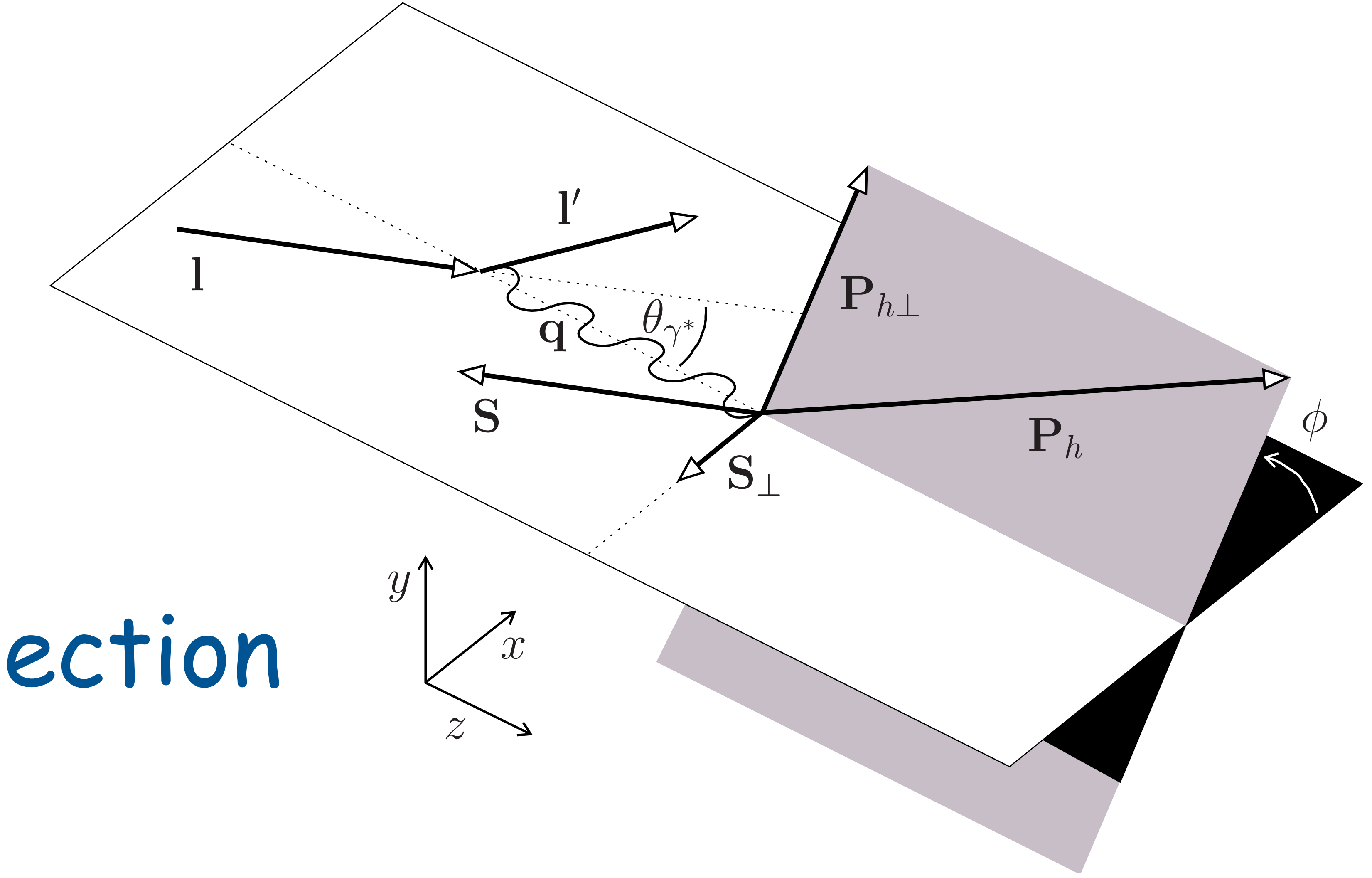


- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

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

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

subleading twist I - <sin(φ)>UL



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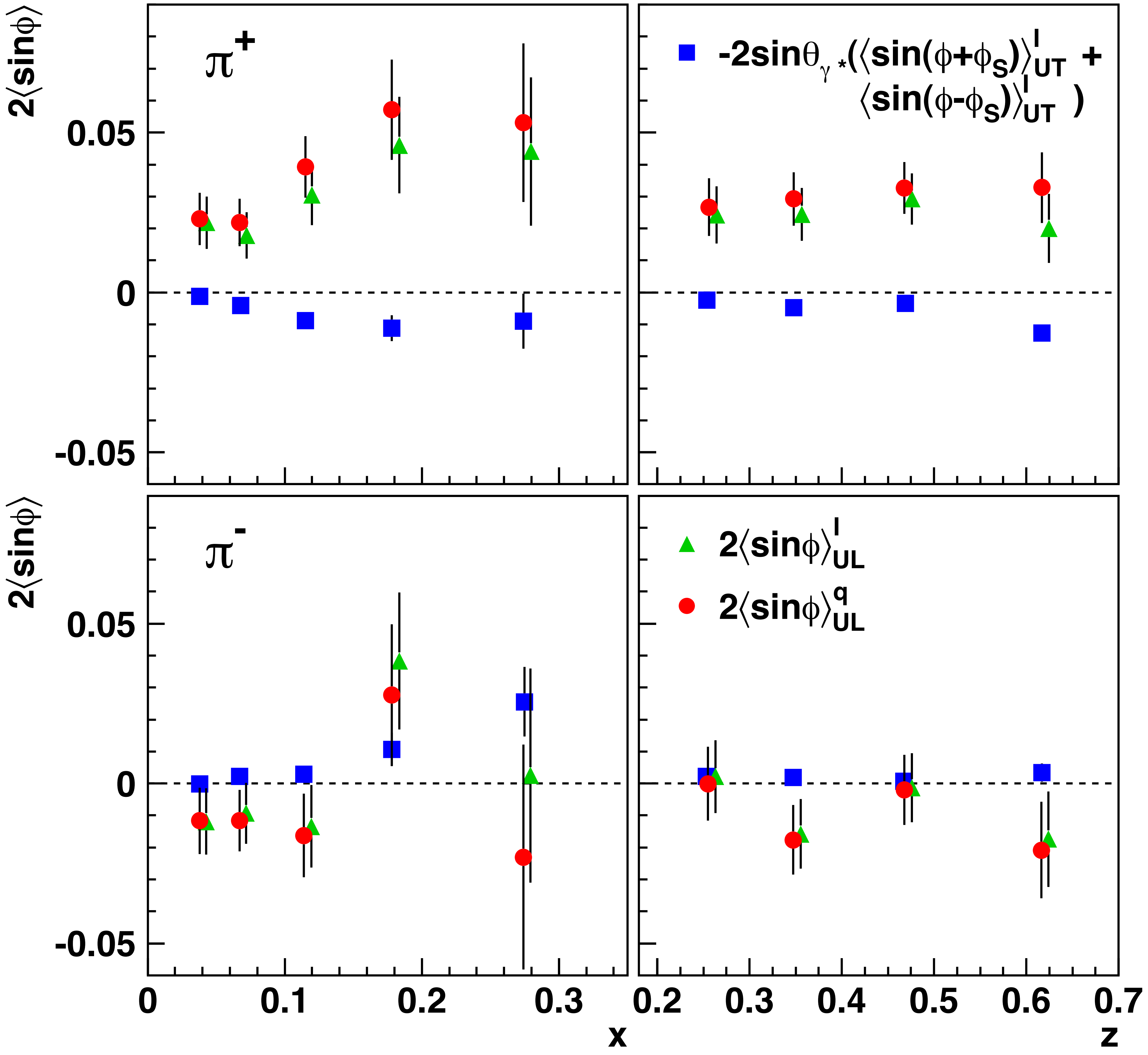
➡ need data on same target for both polarization orientations!

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

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

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

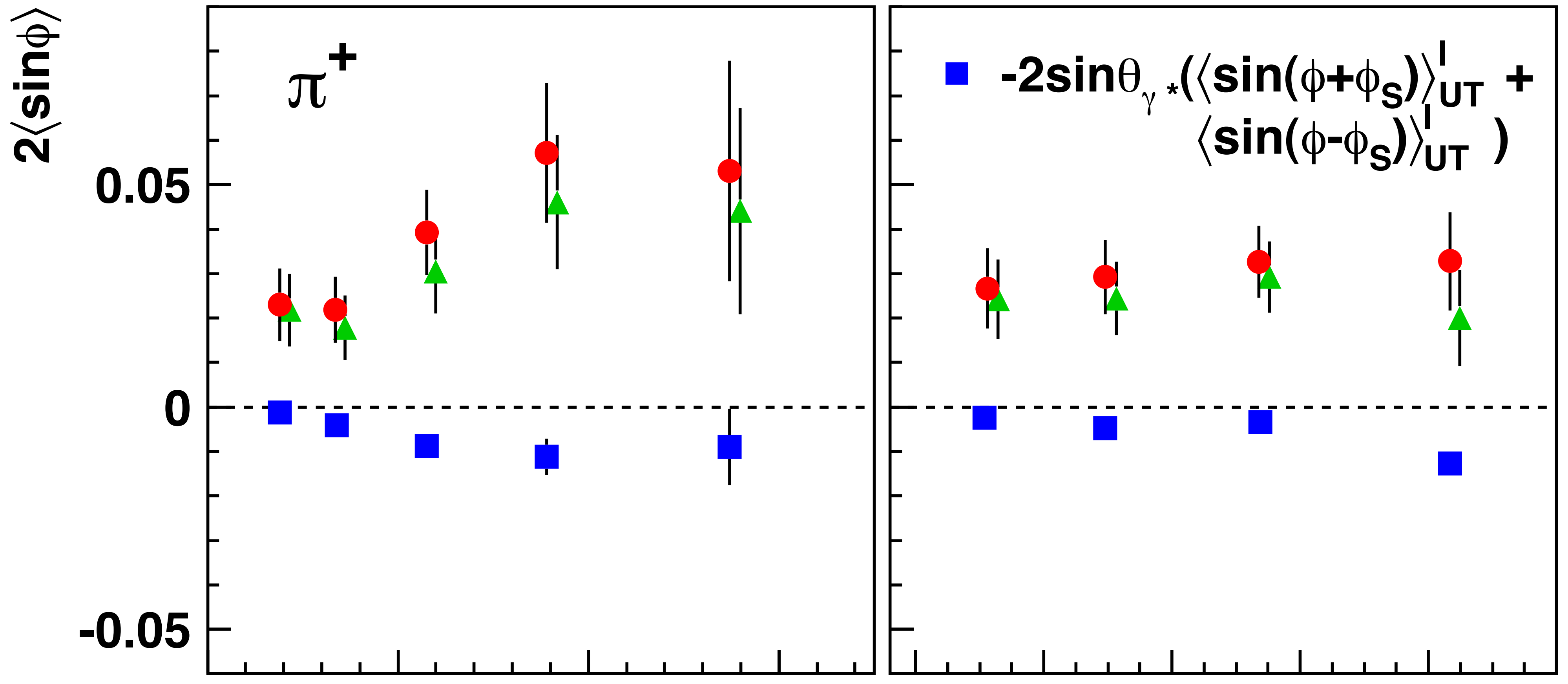


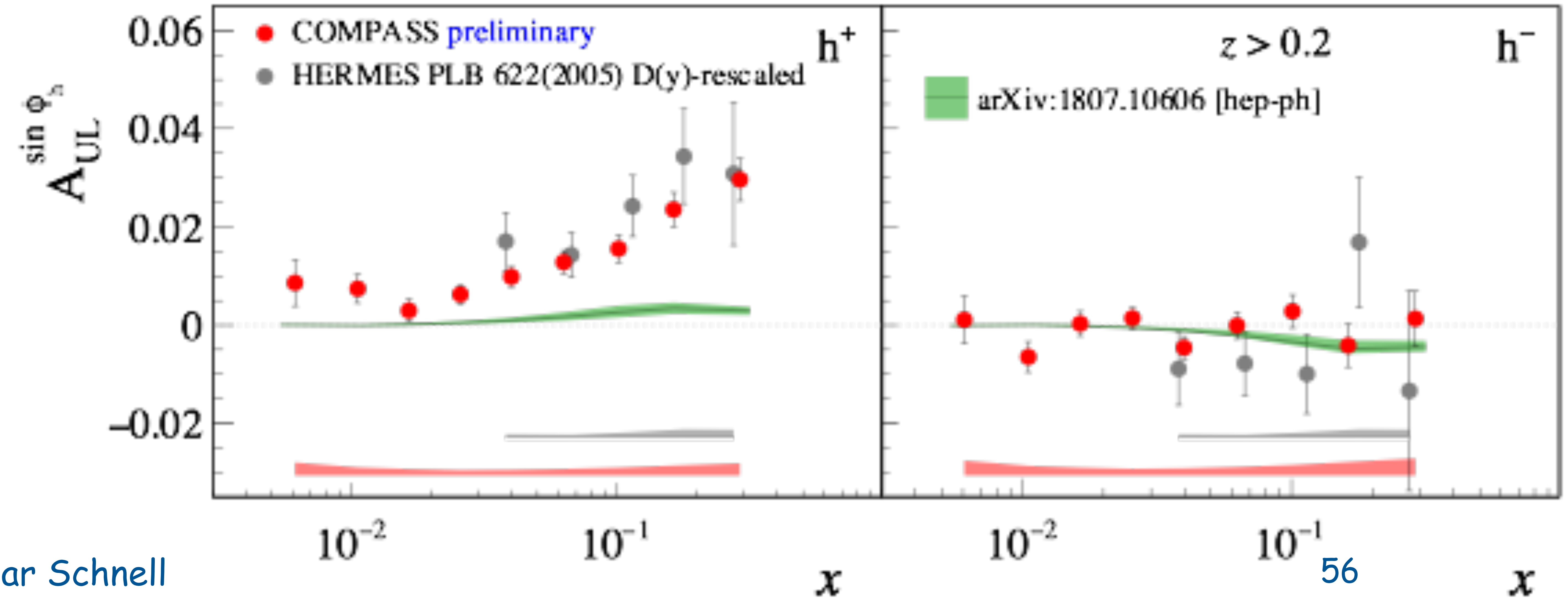
- experimental A_{UL} dominated by twist-3 contribution
- correction for A_{UT} contribution **increases** the longitudinal asymmetry for positive pions
- consistent with zero for π^-

subleading twist I - <sin(ϕ)>$_{UL}$

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

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



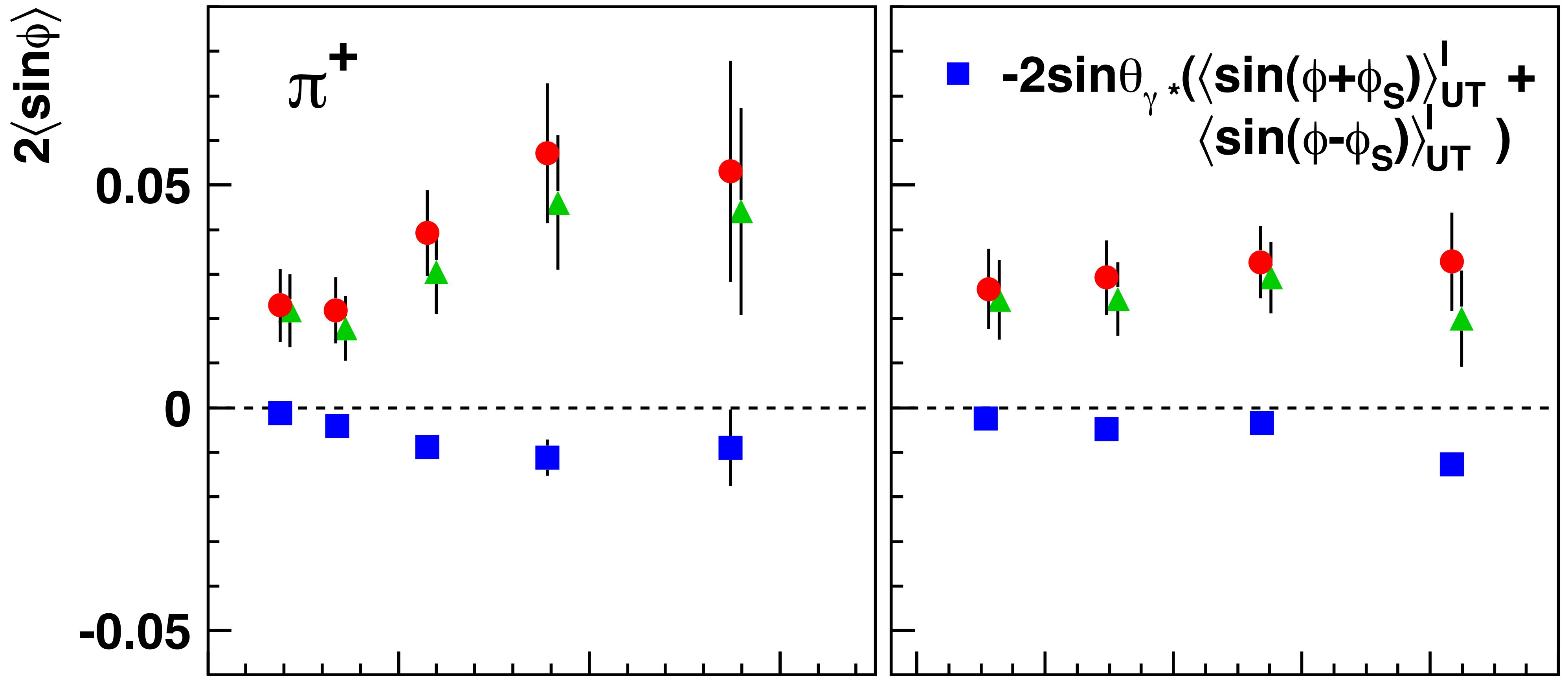


- experimental A_{UL} dominated by twist-3 contribution
- in contrast to WW-type approximation [1807.10606] (both COMPASS and HERMES data)

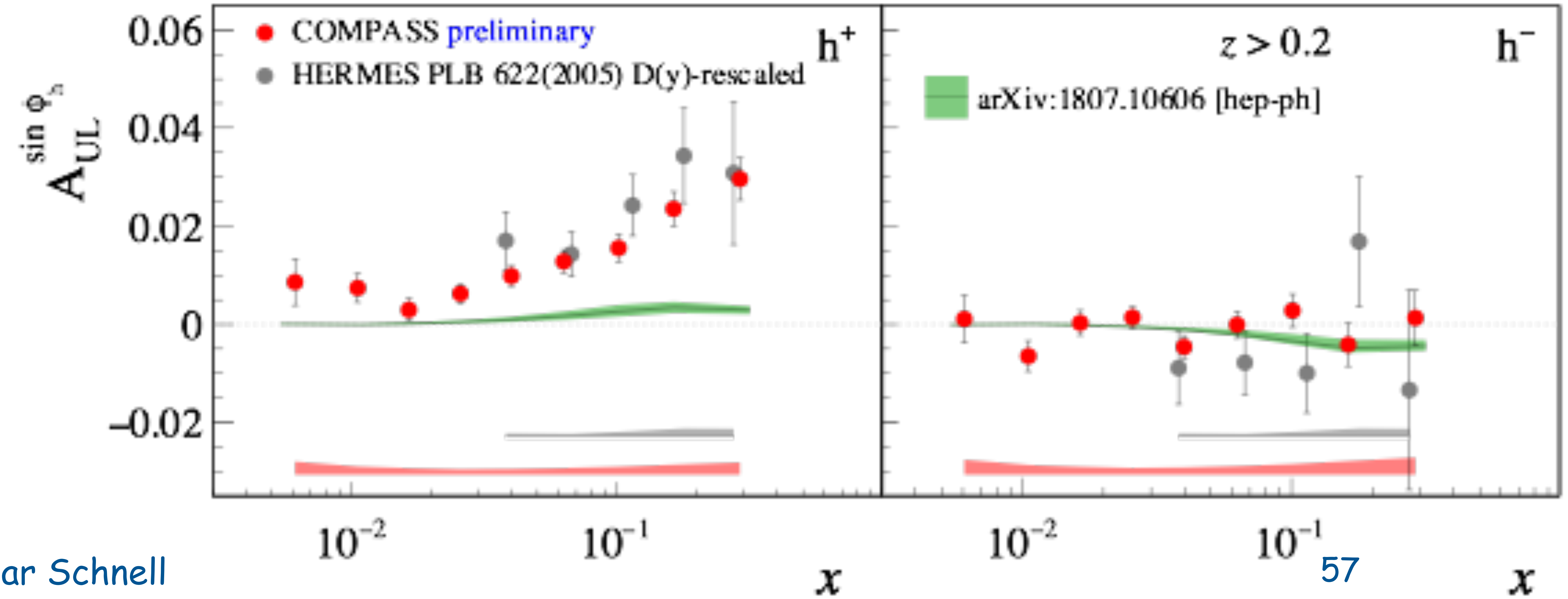
subleading twist I - <sin(φ)>$_{UL}$

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

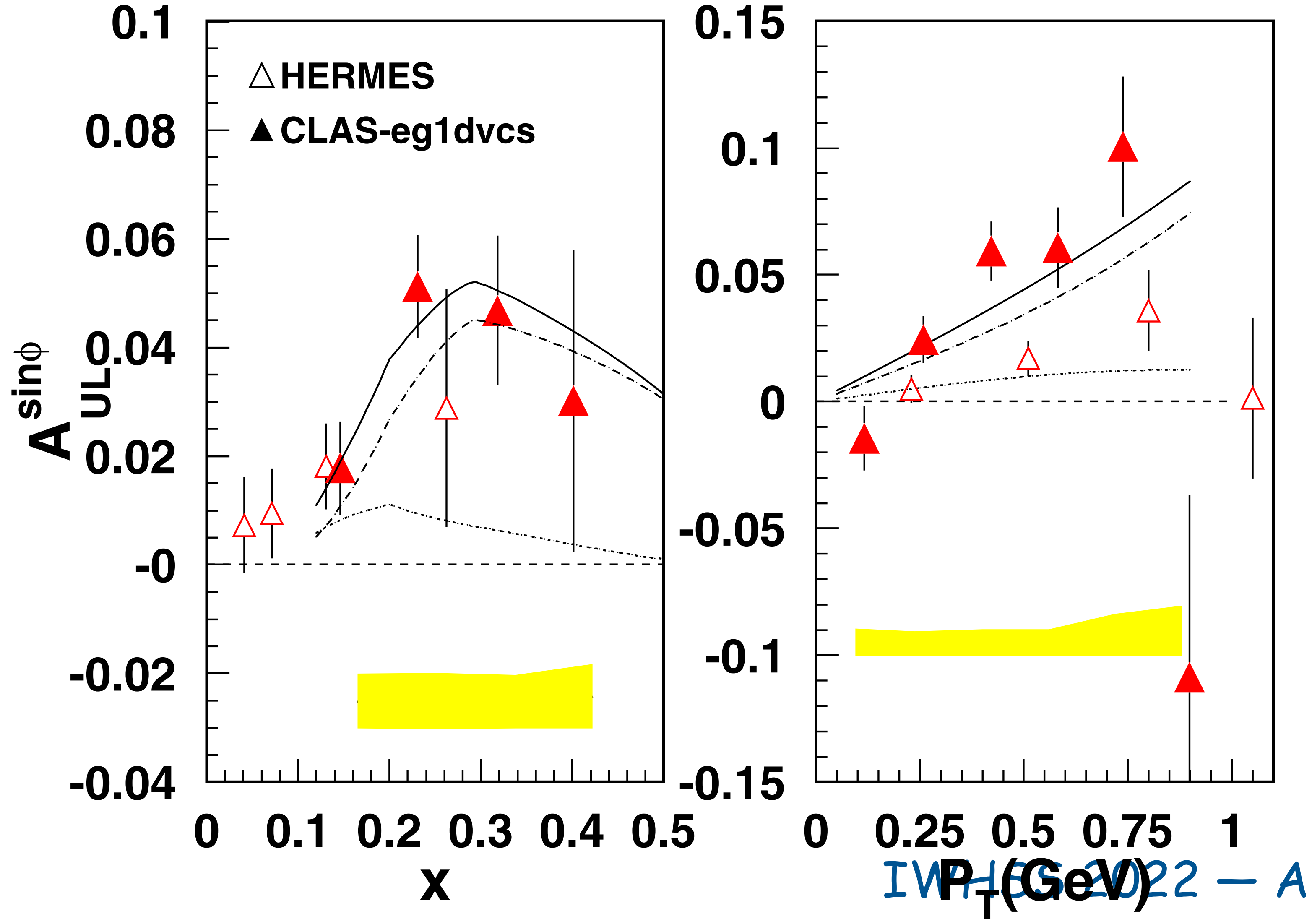
[Airapetian et al., PLB 622 (2005) 14]



- experimental A$_{UL}$ dominated by twist-3 contribution
- in contrast to WW-type approximation [1807.10606] (for both COMPASS and HERMES data)
- sizable also for new CLAS neutral-pion data



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



subleading twist II - <sin(ϕ)>$_{LU}$

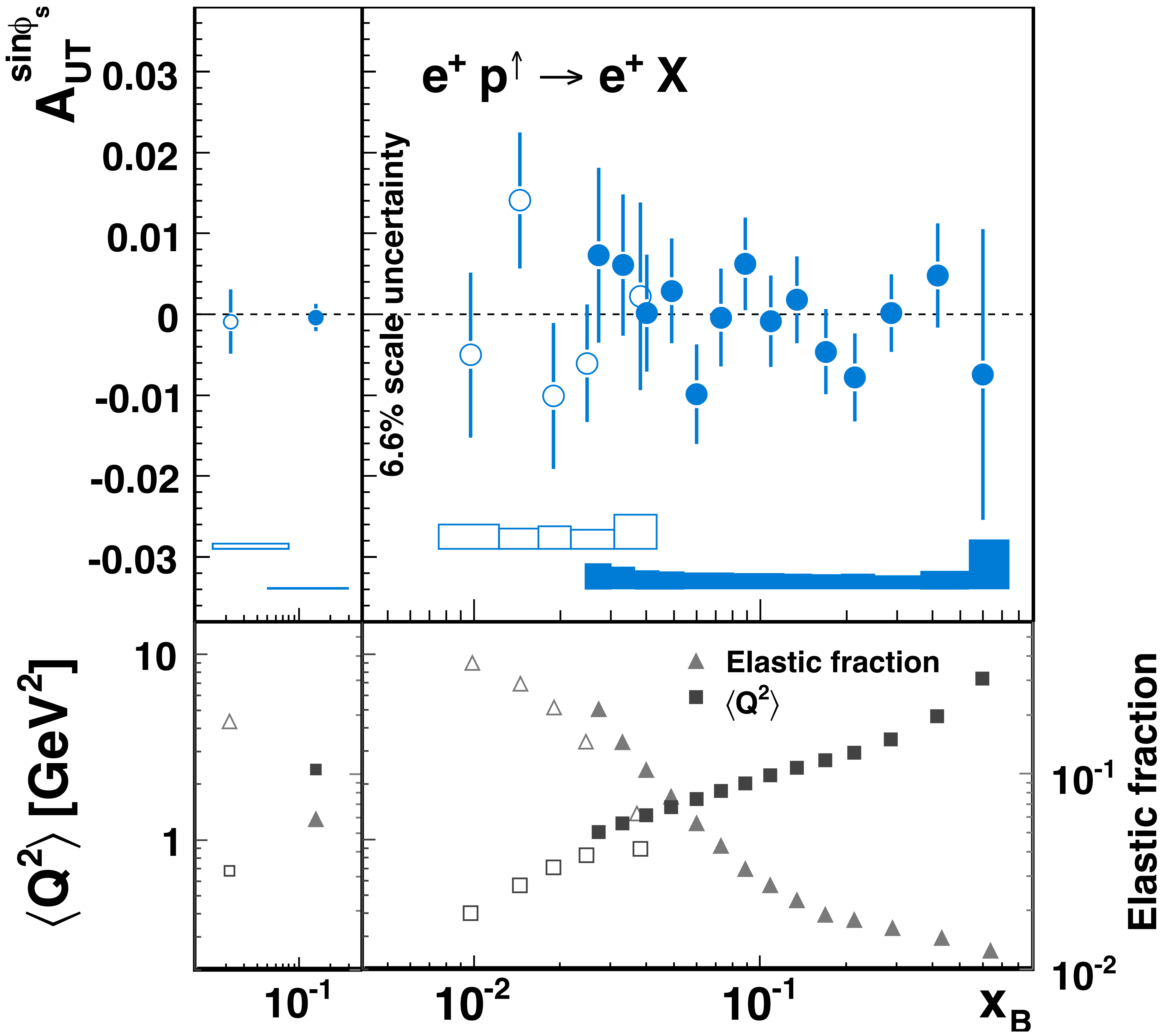
$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$

- 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
- **all terms vanish in WW-type approximation**

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
  - tested to permille level at HERMES:

[Phys. Lett. B682 (2010) 351]



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 contributing terms related to transversity, worm-gear, Sivers etc.:

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

- non-vanishing collinear limit:

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

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

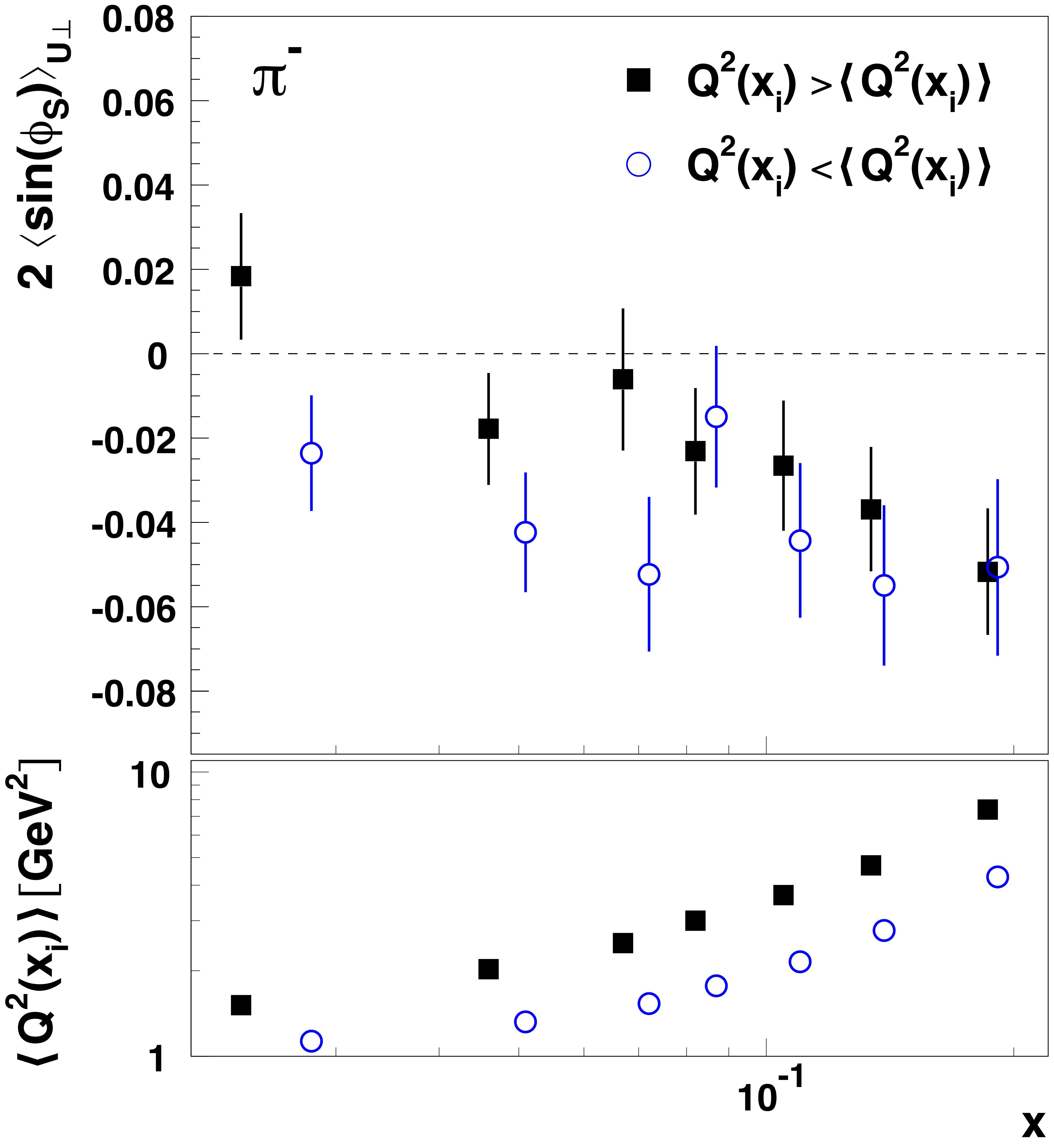
- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various contributing terms related to transversity, worm-gear, Sivers etc.:

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

- non-vanishing collinear limit:

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

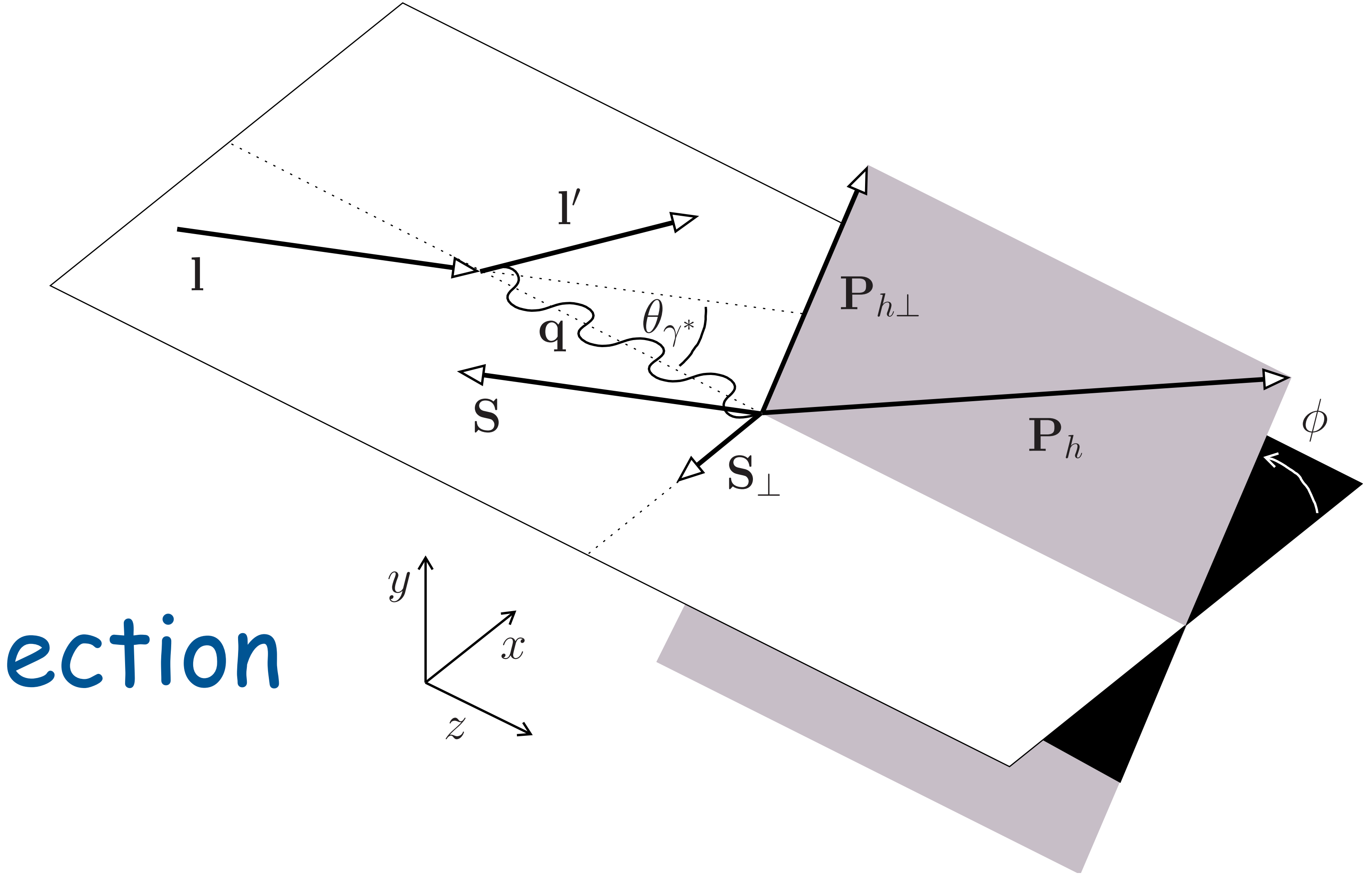
subleading twist III - $\langle \sin(\phi_S) \rangle_{UT}$



- hint of Q^2 dependence seen in signal for negative pions

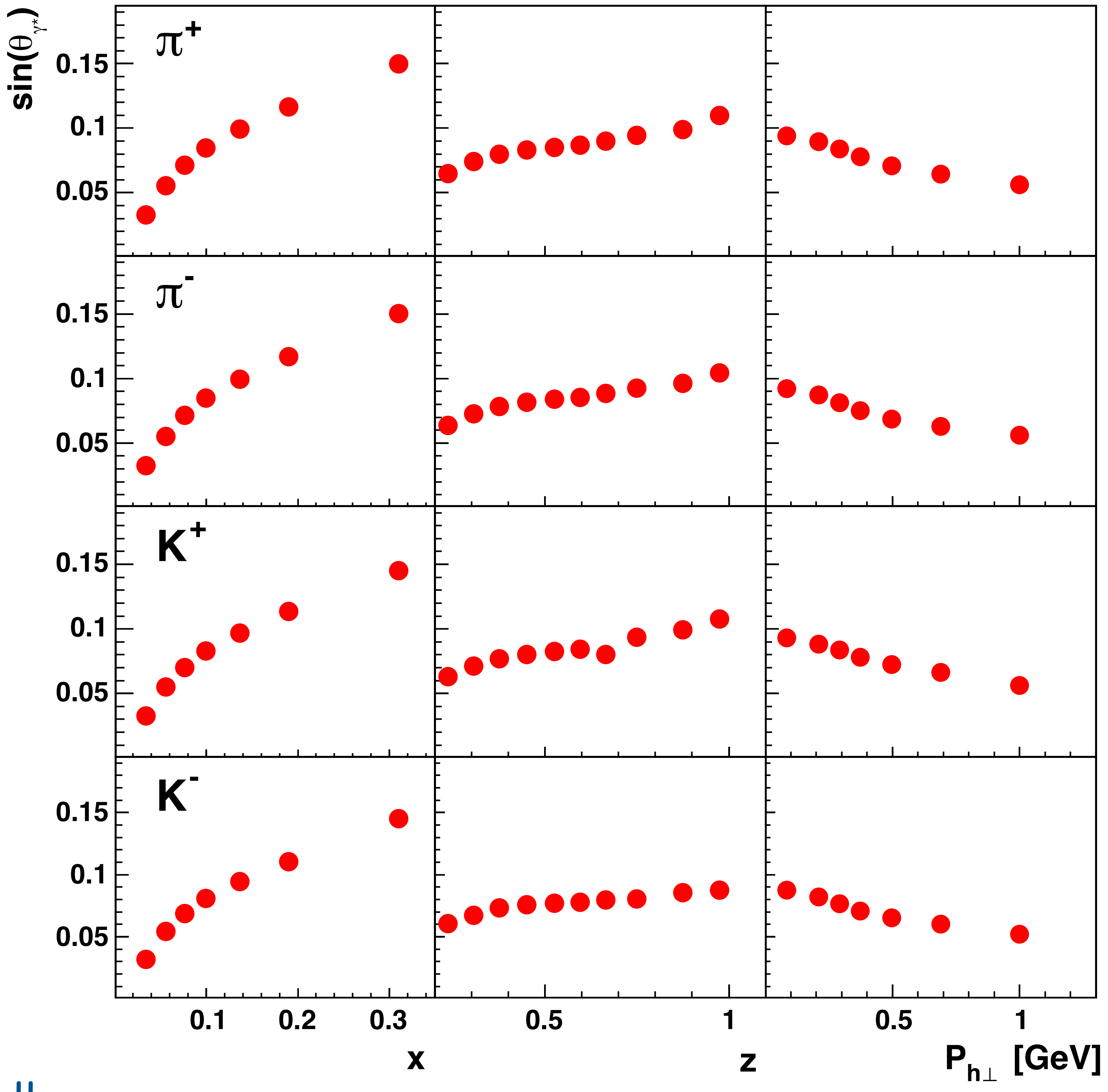
devil in the details & lessons learnt on the way

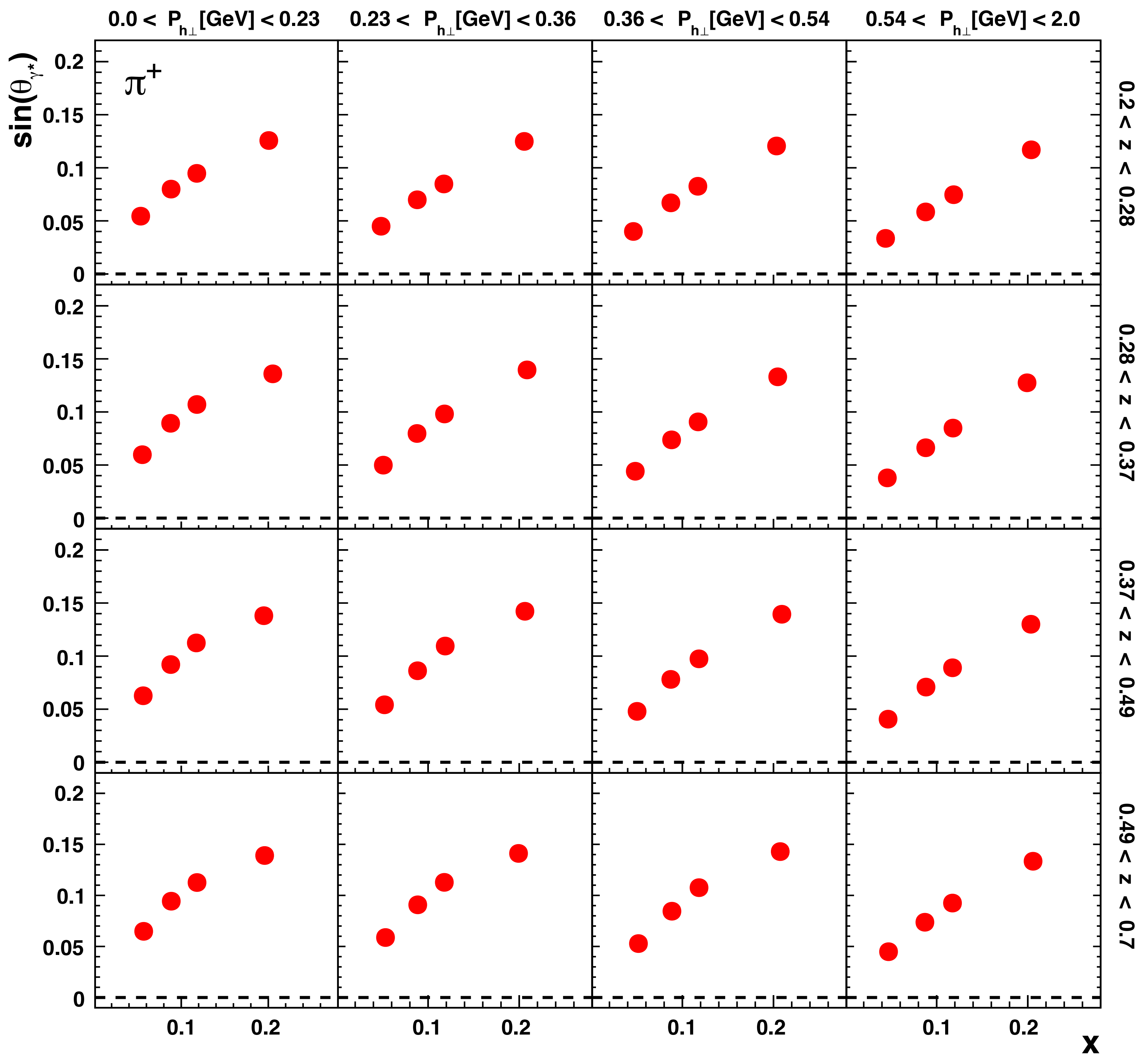
mixing of target polarizations



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

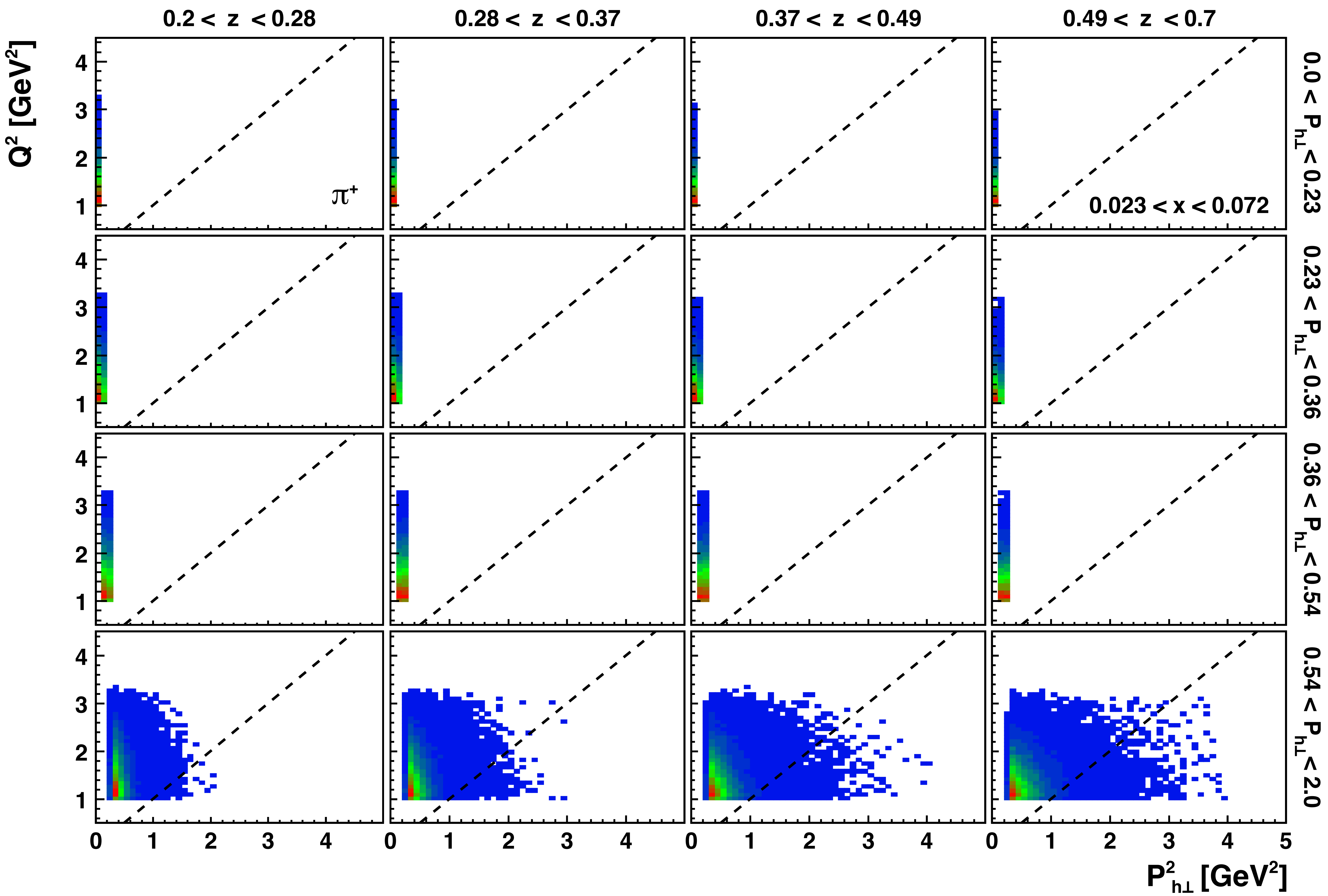
➡ mixing of longitudinal and transverse polarization effects





TMD factorization: a 2-scale problem

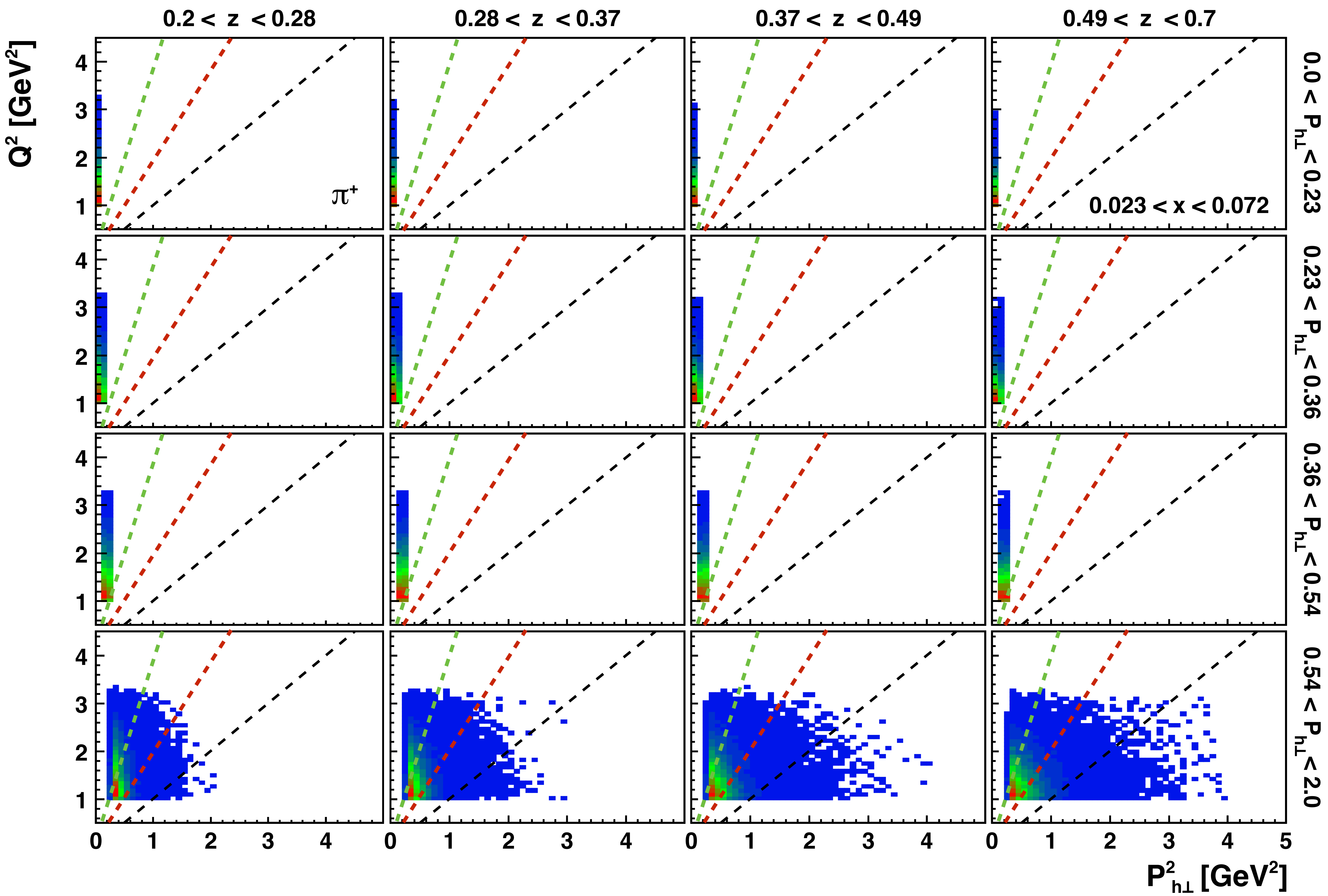
lowest x bin



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

TMD factorization: a 2-scale problem

lowest x bin



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

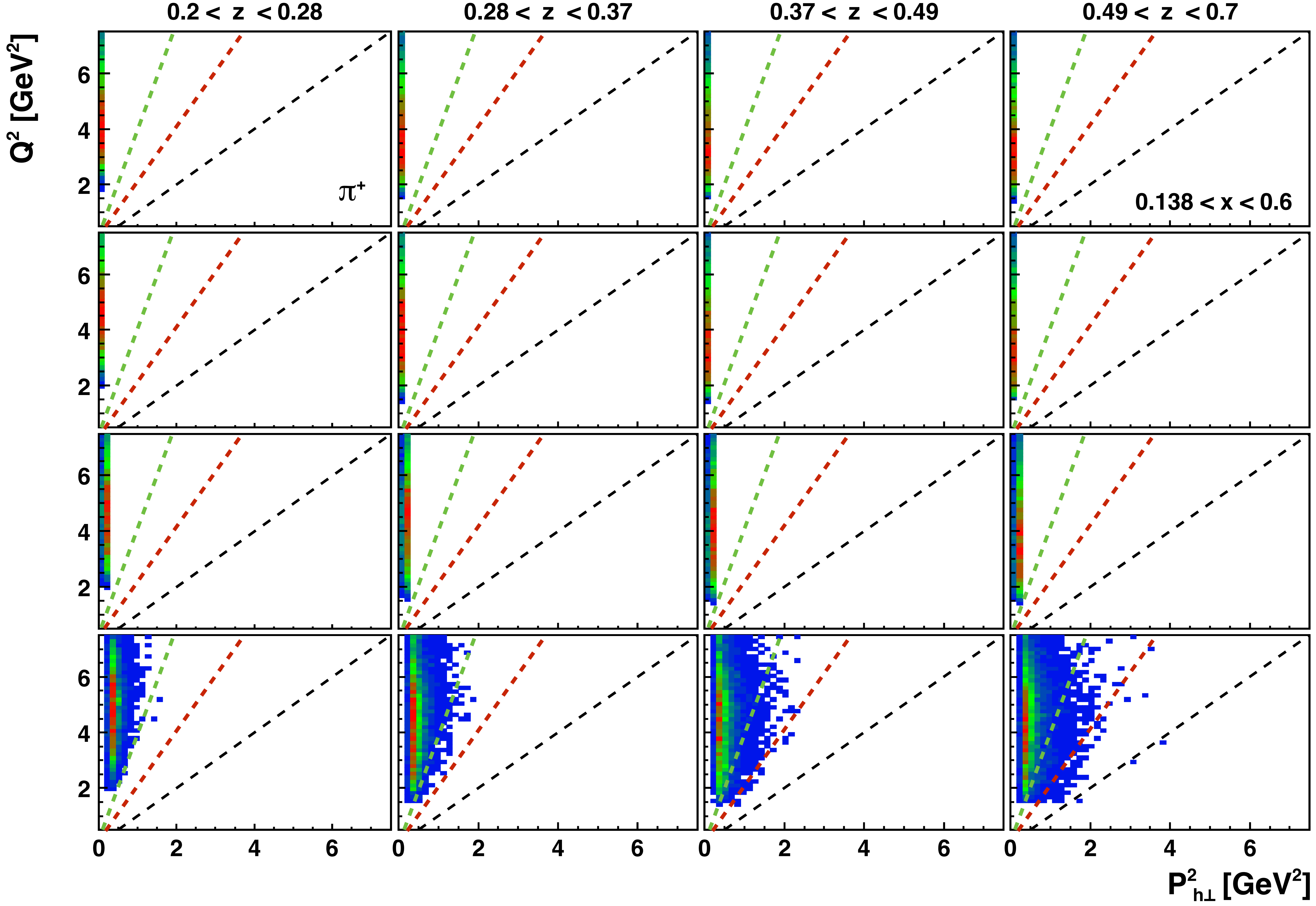
$Q^2 = 2\ P^2_{h\perp}$

$Q^2 = 4\ P^2_{h\perp}$

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

highest x bin



┅ $Q^2 = P^2_{h\perp}$

┅ $Q^2 = 2\ P^2_{h\perp}$

┅ $Q^2 = 4\ P^2_{h\perp}$

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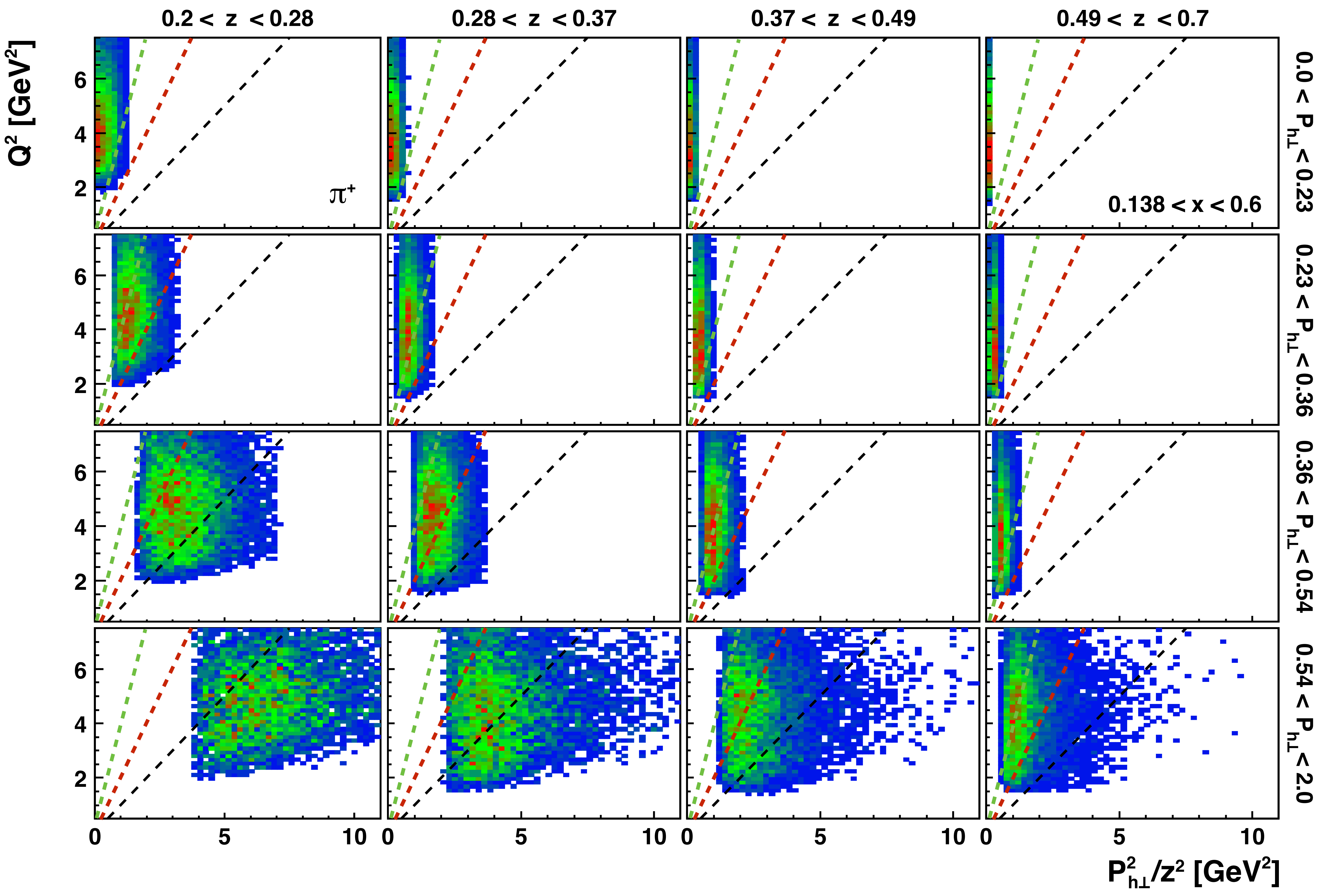
TMD factorization: a 2-scale problem

highest x bin



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

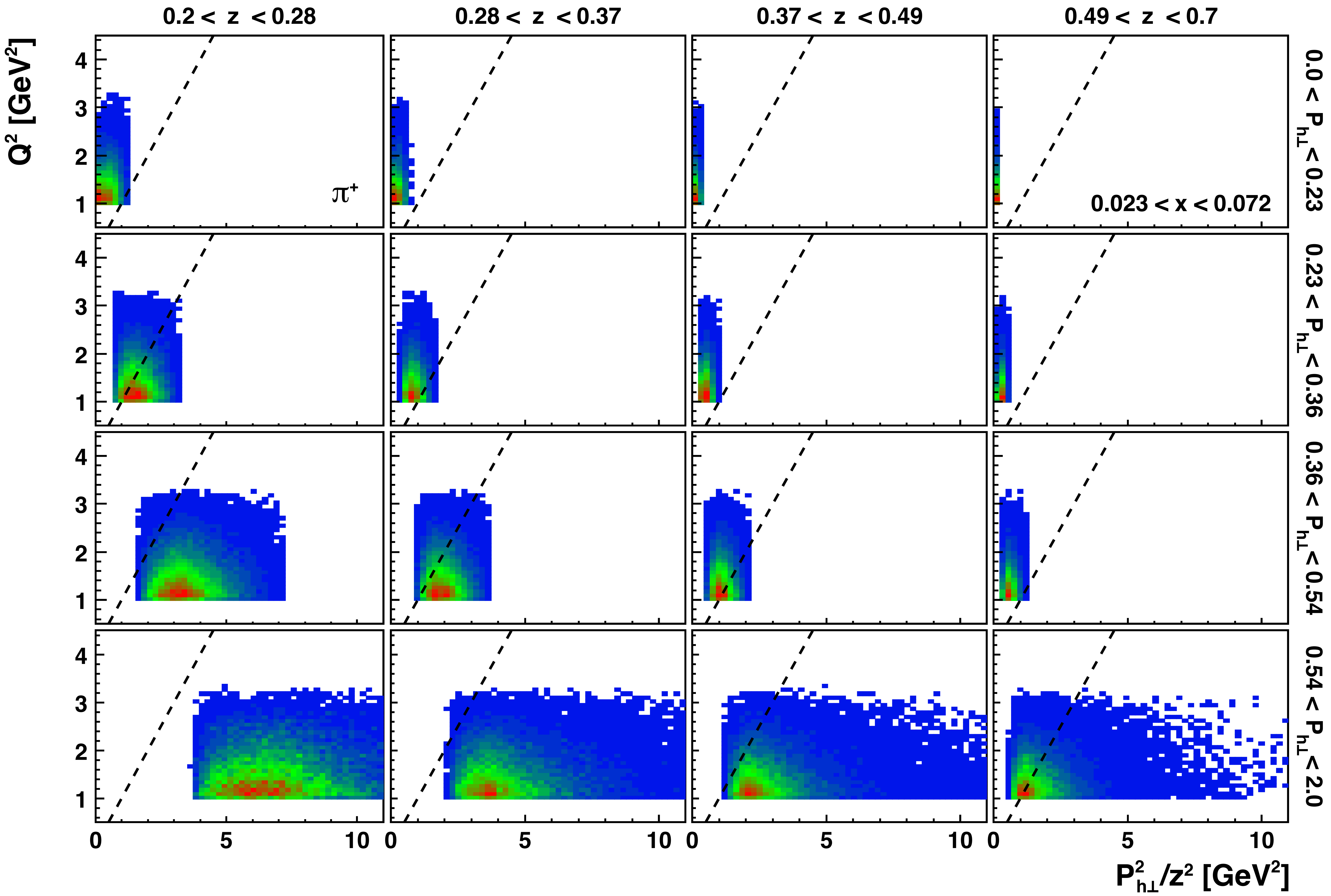
$Q^2 = 2\, P^2_{h\perp}/z^2$

$Q^2 = 4\, P^2_{h\perp}/z^2$

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

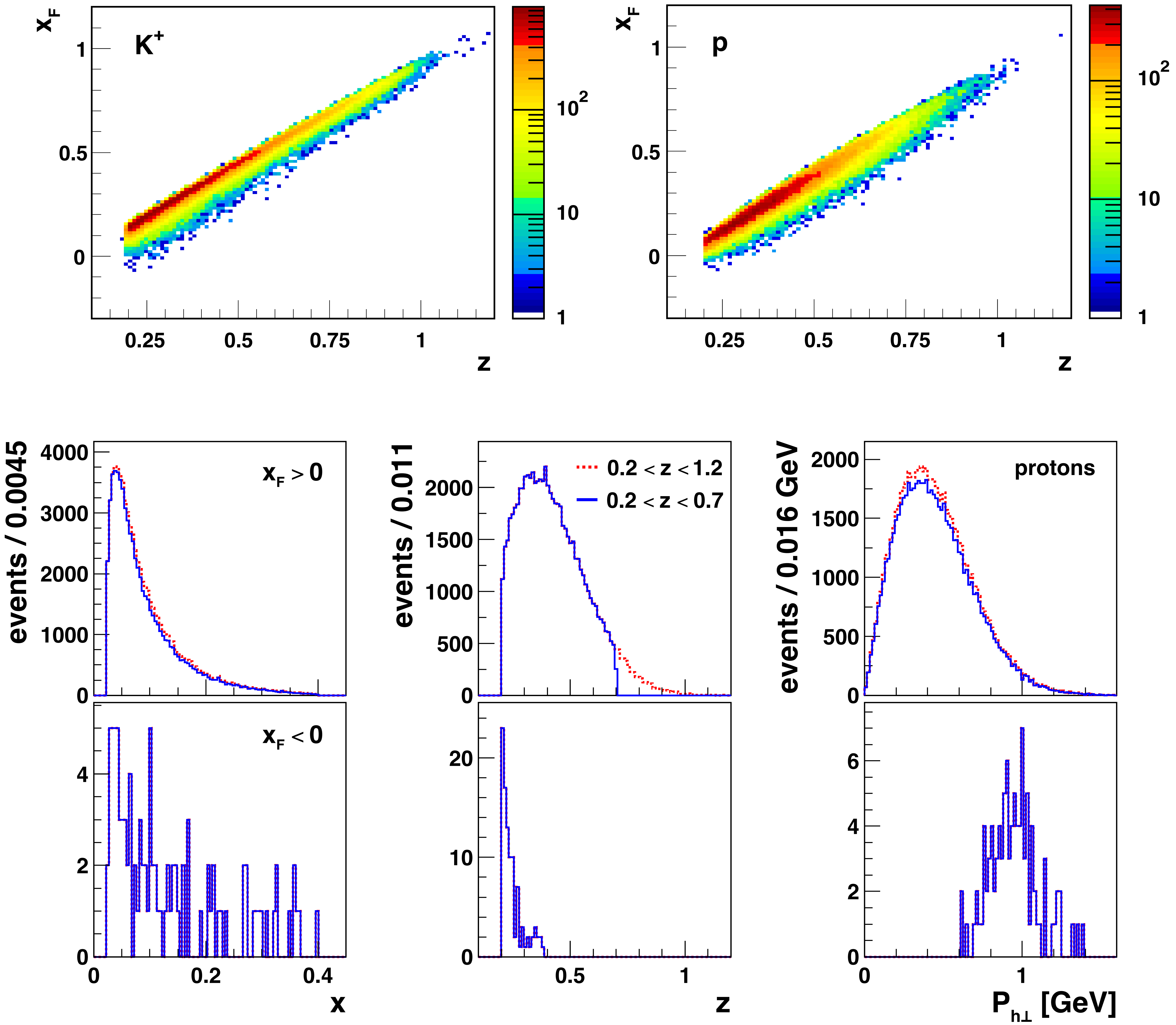
lowest x bin



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

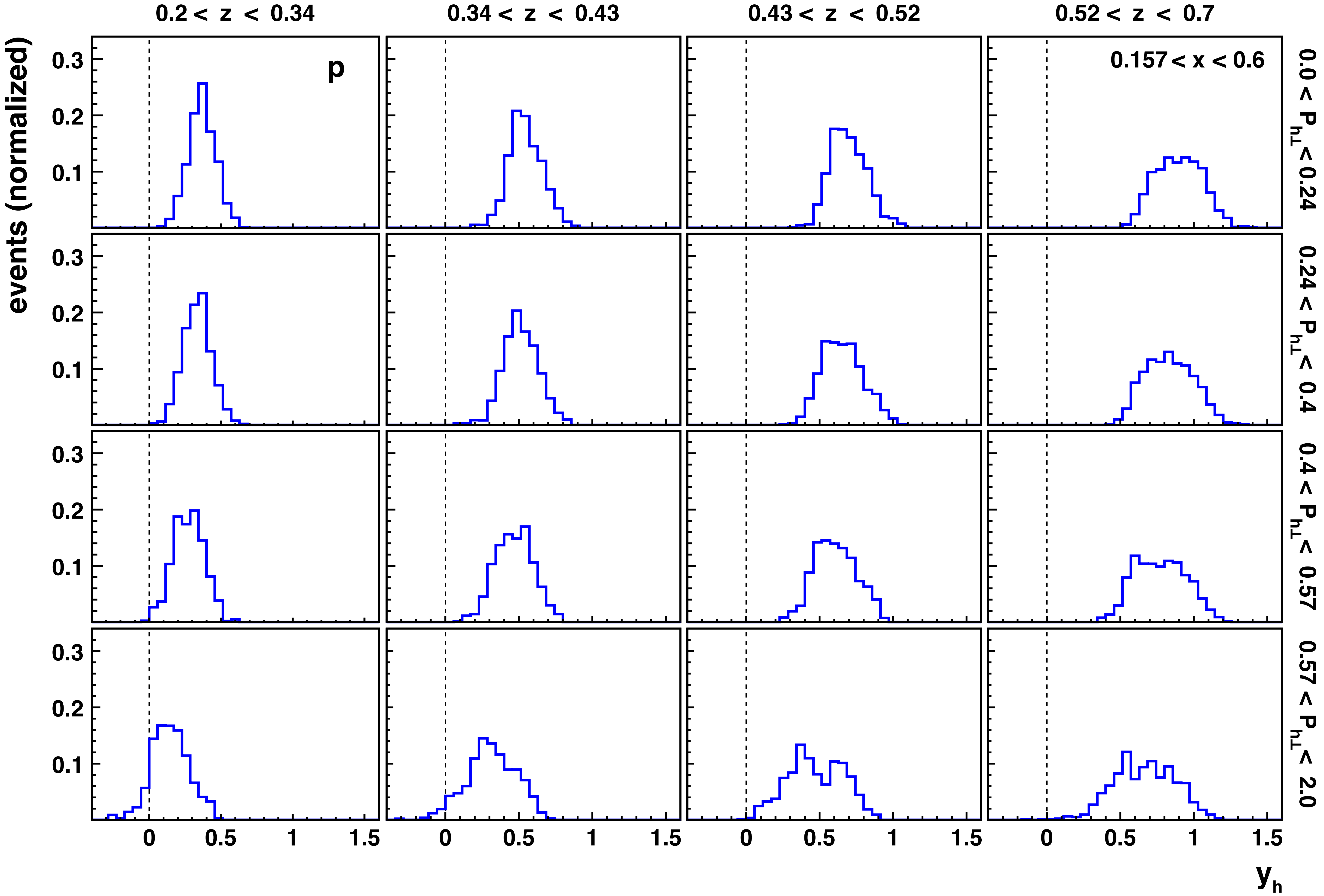
all other x-bins included in the Supplemental Material of JHEP12(2020)010

hadron production at HERMES



- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]

hadron production at HERMES

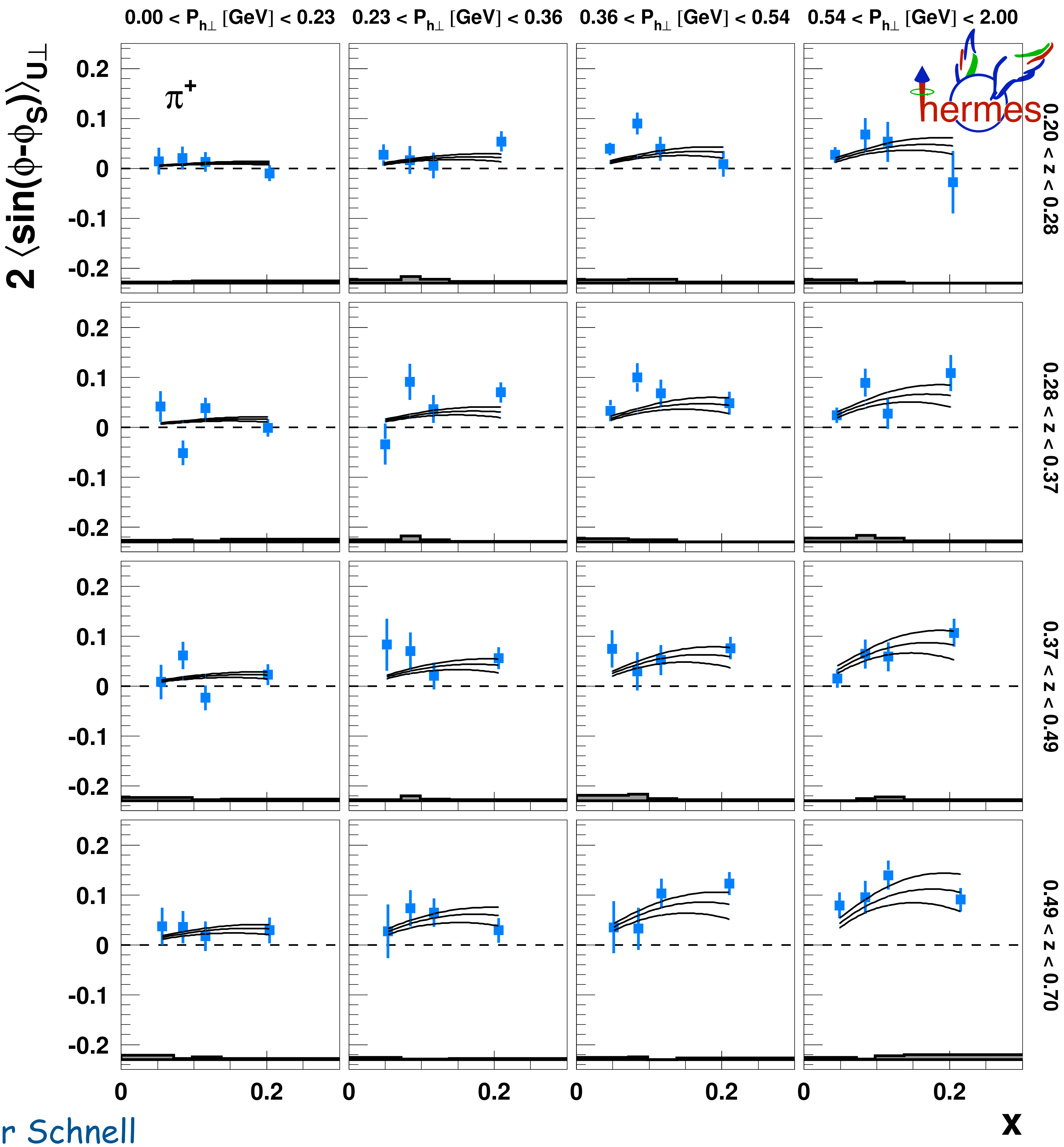


- forward-acceptance favors current fragmentation
- backward rapidity populates large-$P_{h\perp}$ region [as expected]
- rapidity distributions available for all kinematic bins (e.g., highest-x bin protons)

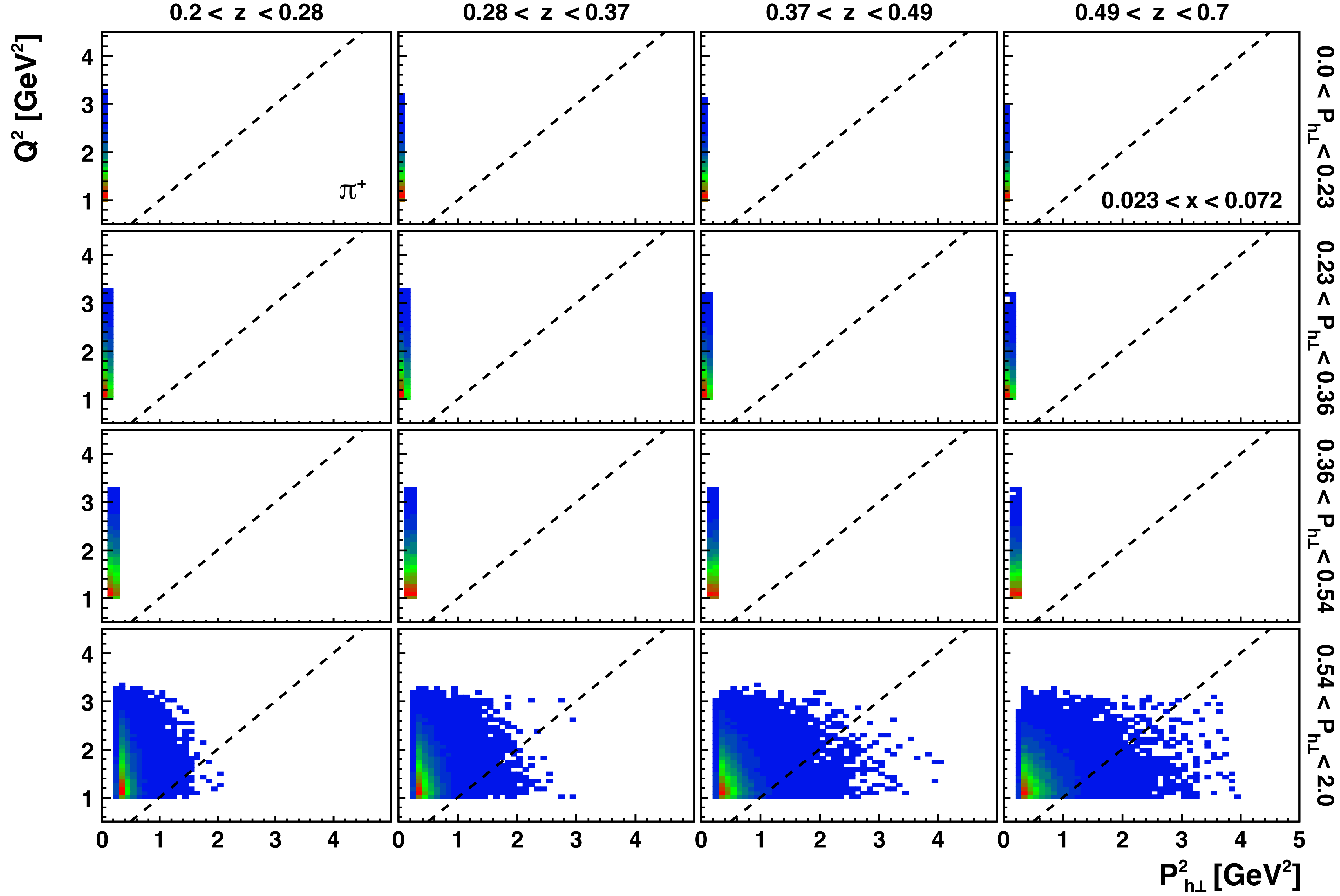
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

Sivers amplitudes multi-dimensional analysis

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



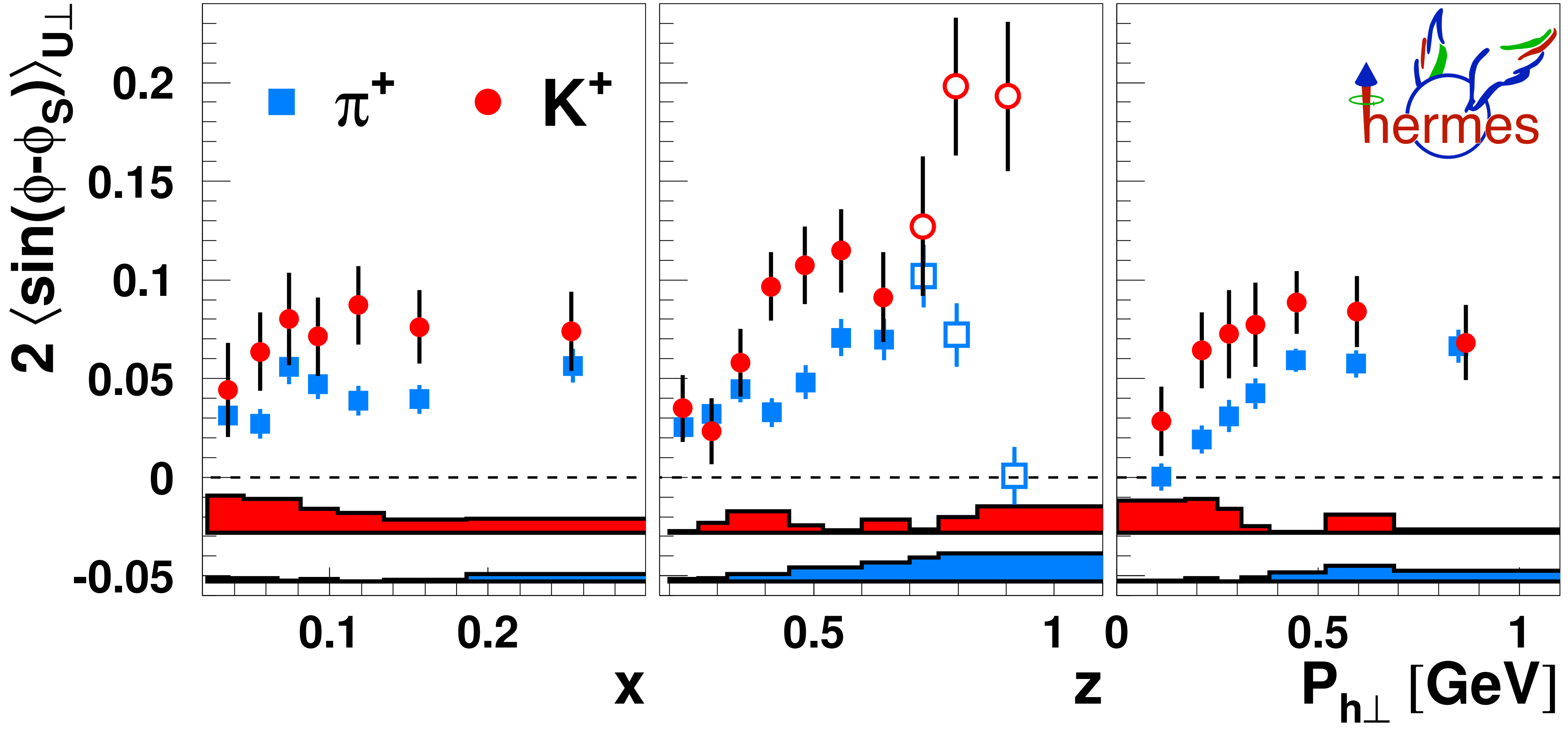
[A. Airapetian et al., arXiv:2007.07755]



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

	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:

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

	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

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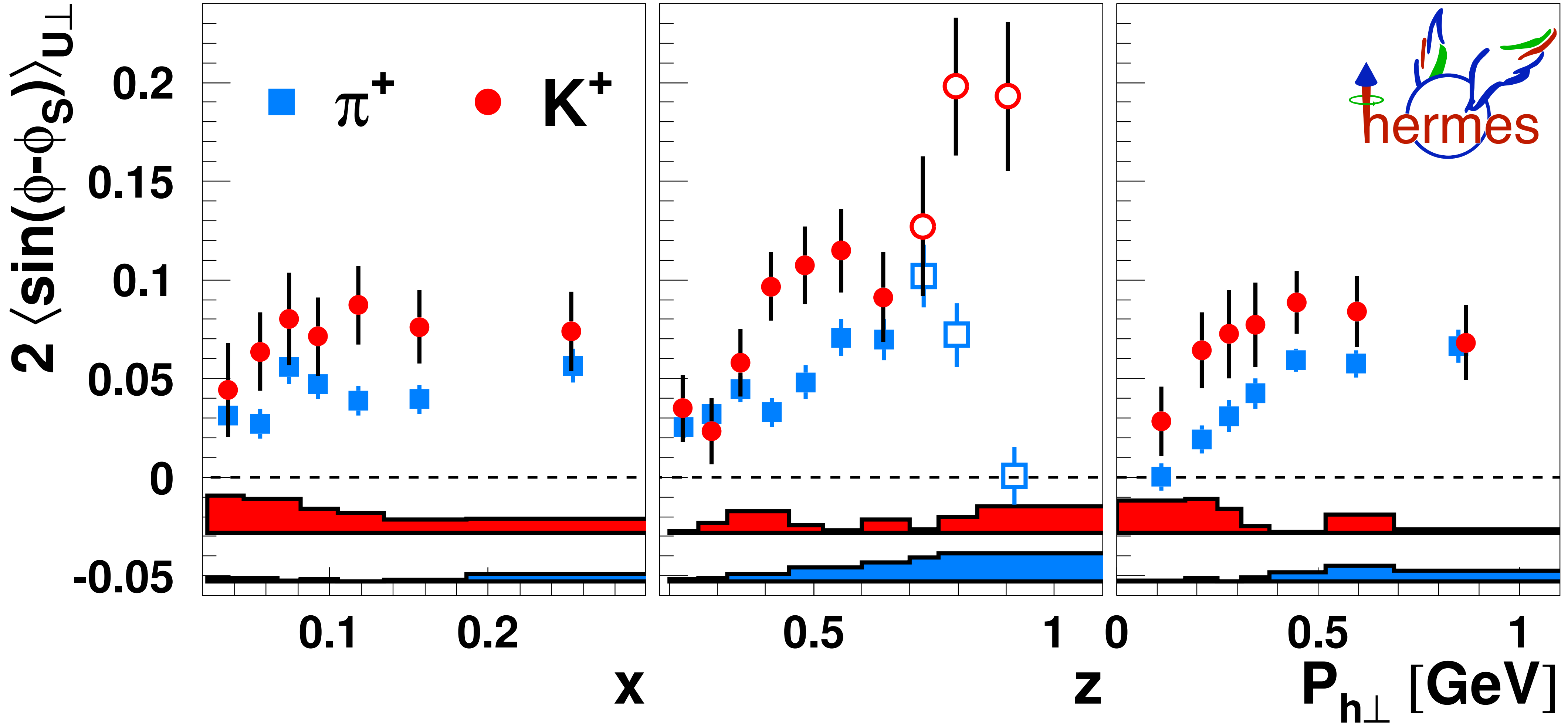
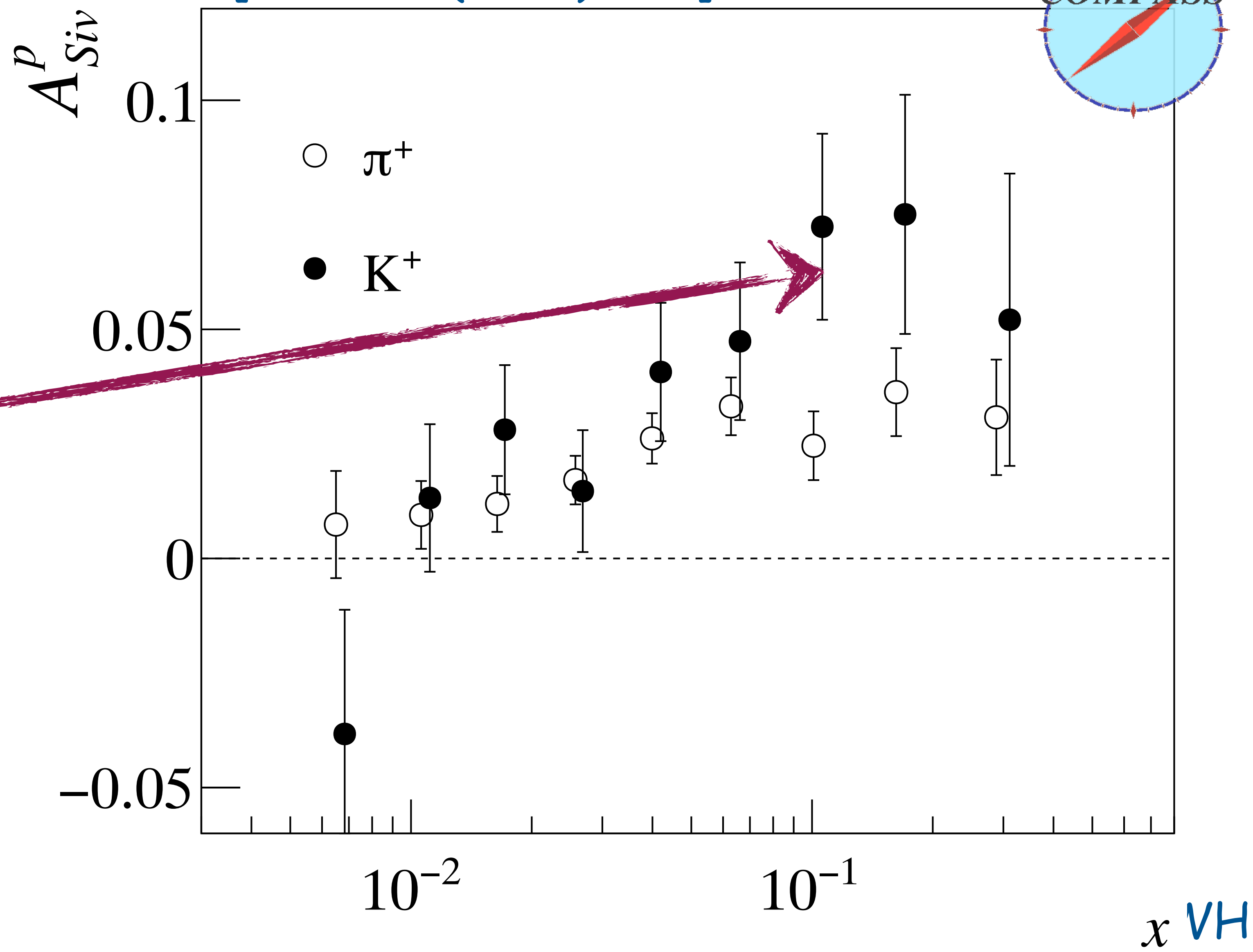


somewhat unexpected if dominated by scattering from u-quarks:

$$\simeq -\frac{\mathbf{f}_{1T}^{\perp,u}(\mathbf{x},\mathbf{p}_T^2)\otimes_{\mathcal{W}}\mathbf{D}_1^{u\to\pi^+/K^+}(\mathbf{z},\mathbf{k}_T^2)}{\mathbf{f}_1^{u}(\mathbf{x},\mathbf{p}_T^2)\ \otimes\mathbf{D}_1^{u\to\pi^+/K^+}(\mathbf{z},\mathbf{k}_T^2))}$$

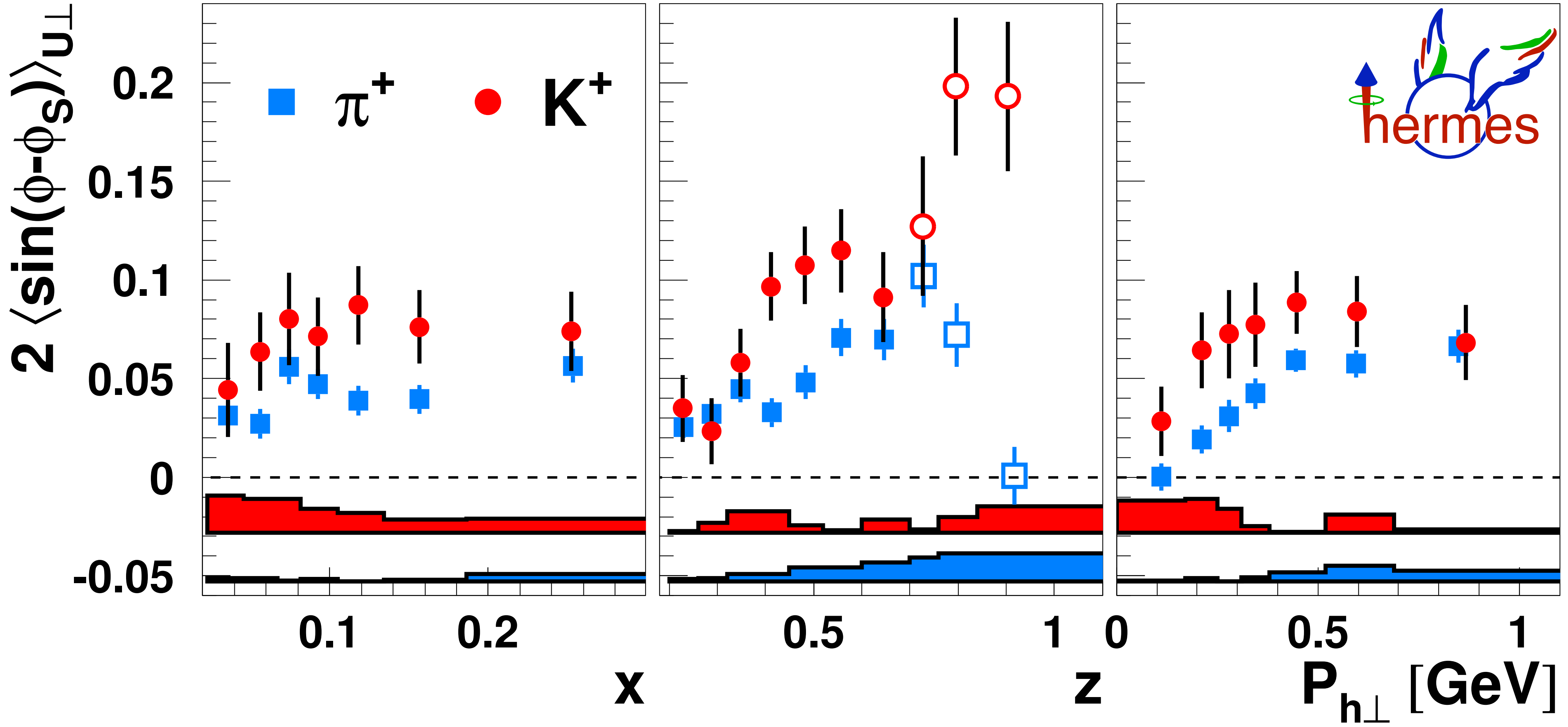
[PLB 744 (2015) 250]



larger amplitudes seen also by COMPASS

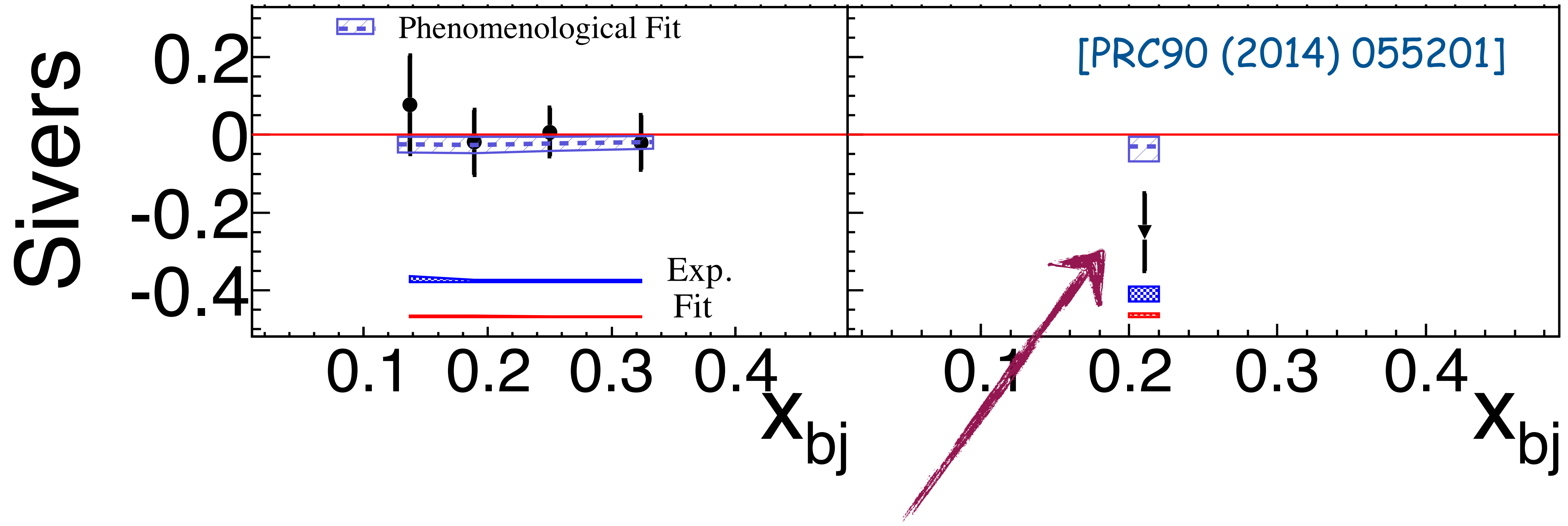
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes
pions vs. kaons

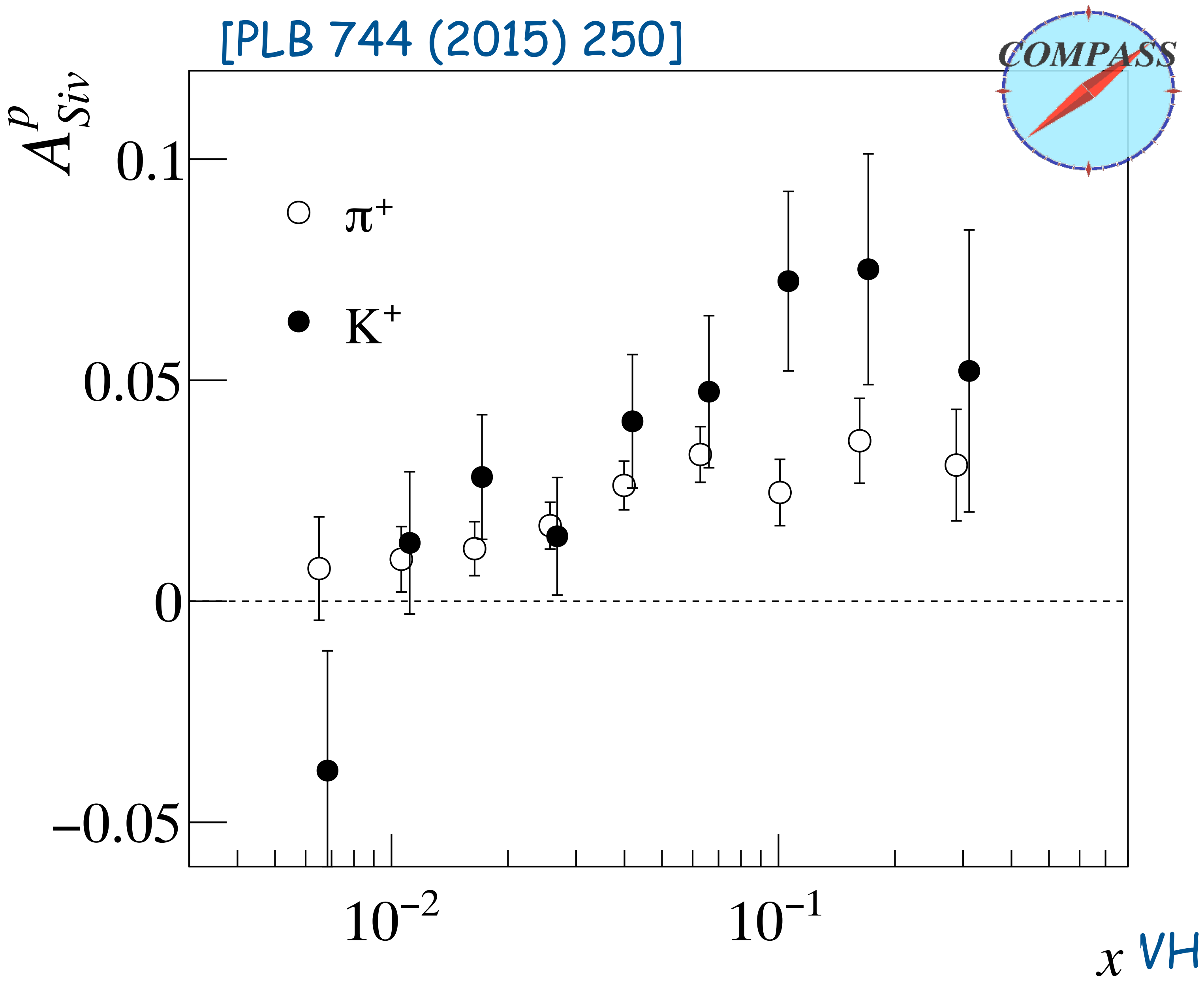

[A. Airapetian et al., arXiv:2007.07755]

somewhat unexpected if dominated by scattering from u-quarks:

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


[PRC90 (2014) 055201]

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


[PLB 744 (2015) 250]

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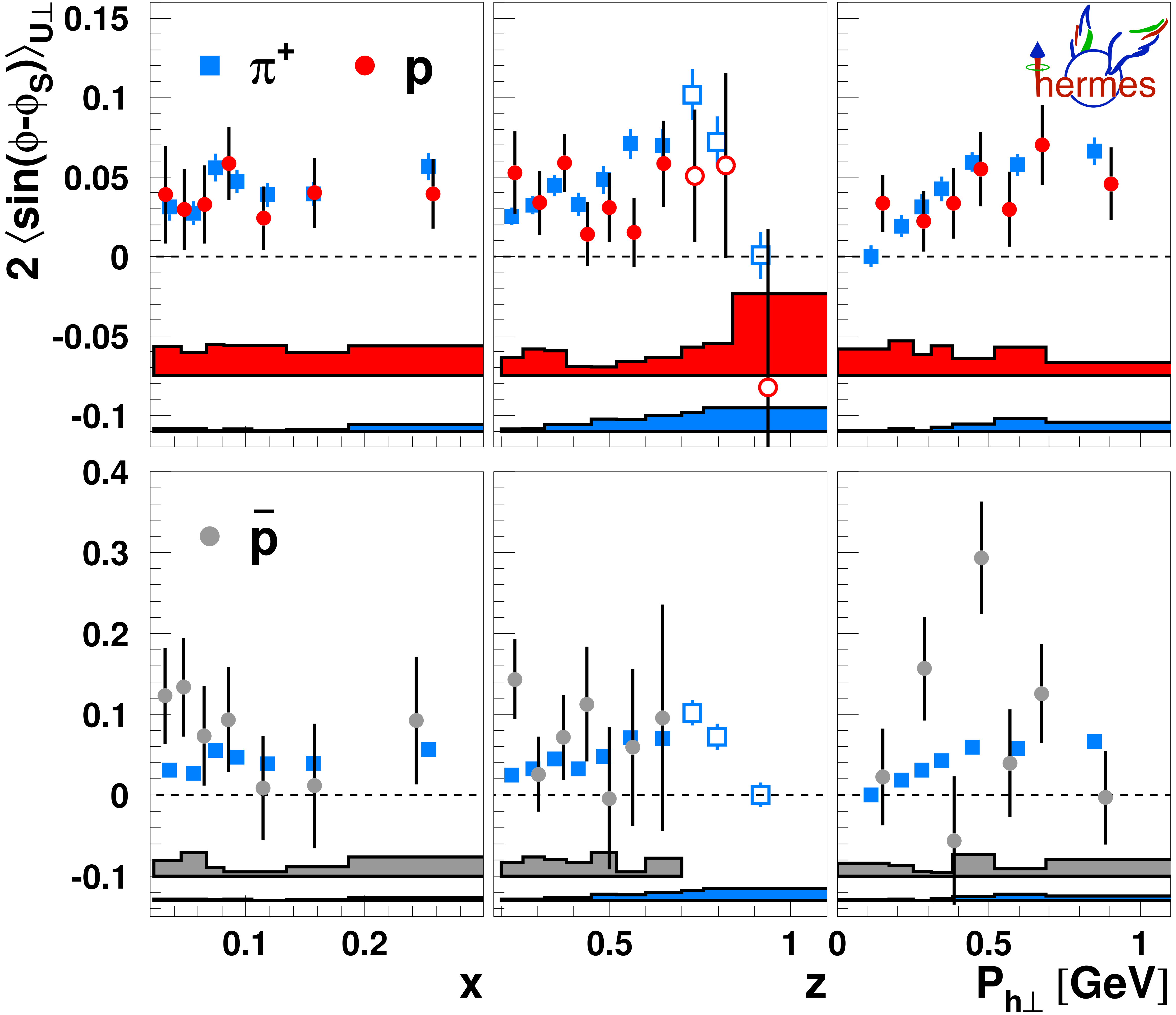
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes
pions vs. (anti)protons

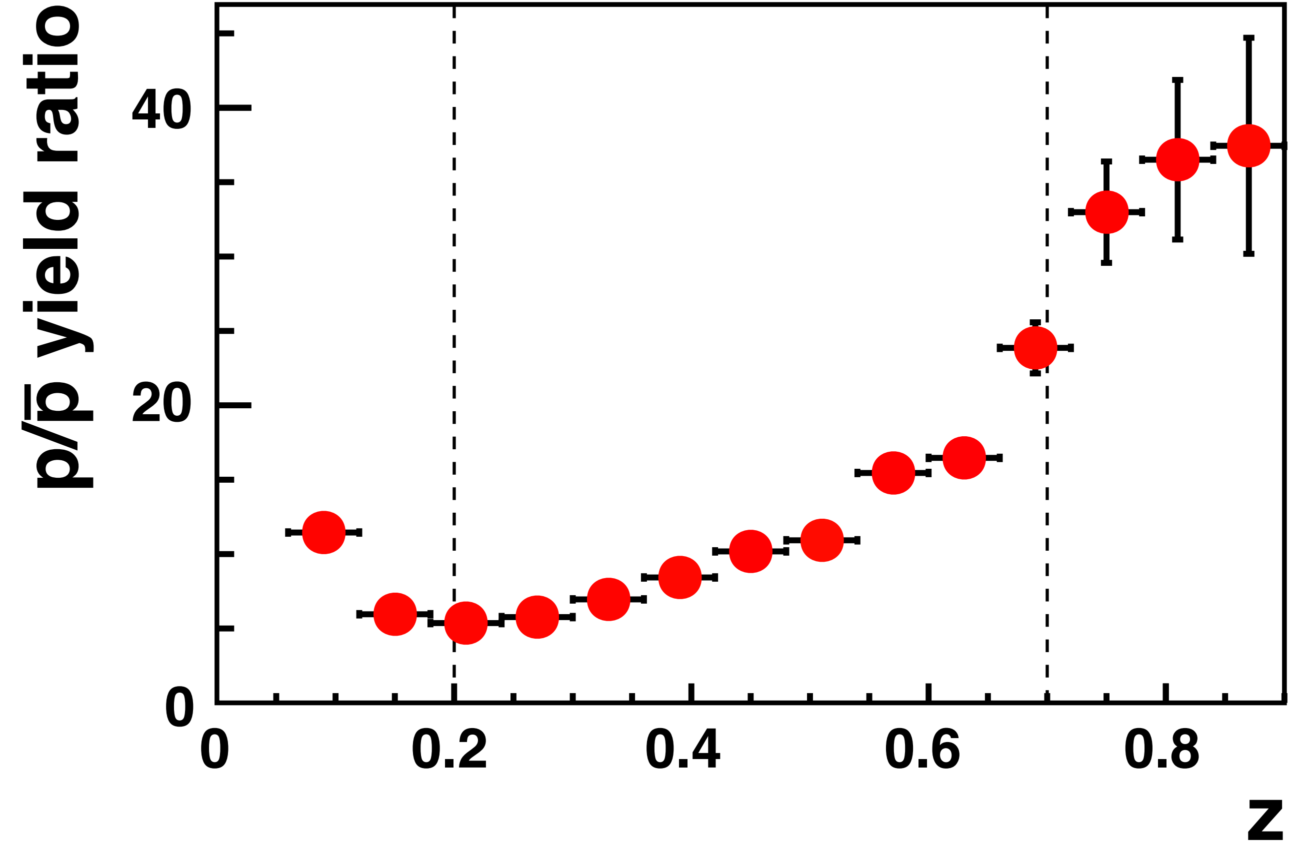
[A. Airapetian et al., arXiv:2007.07755]



similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

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

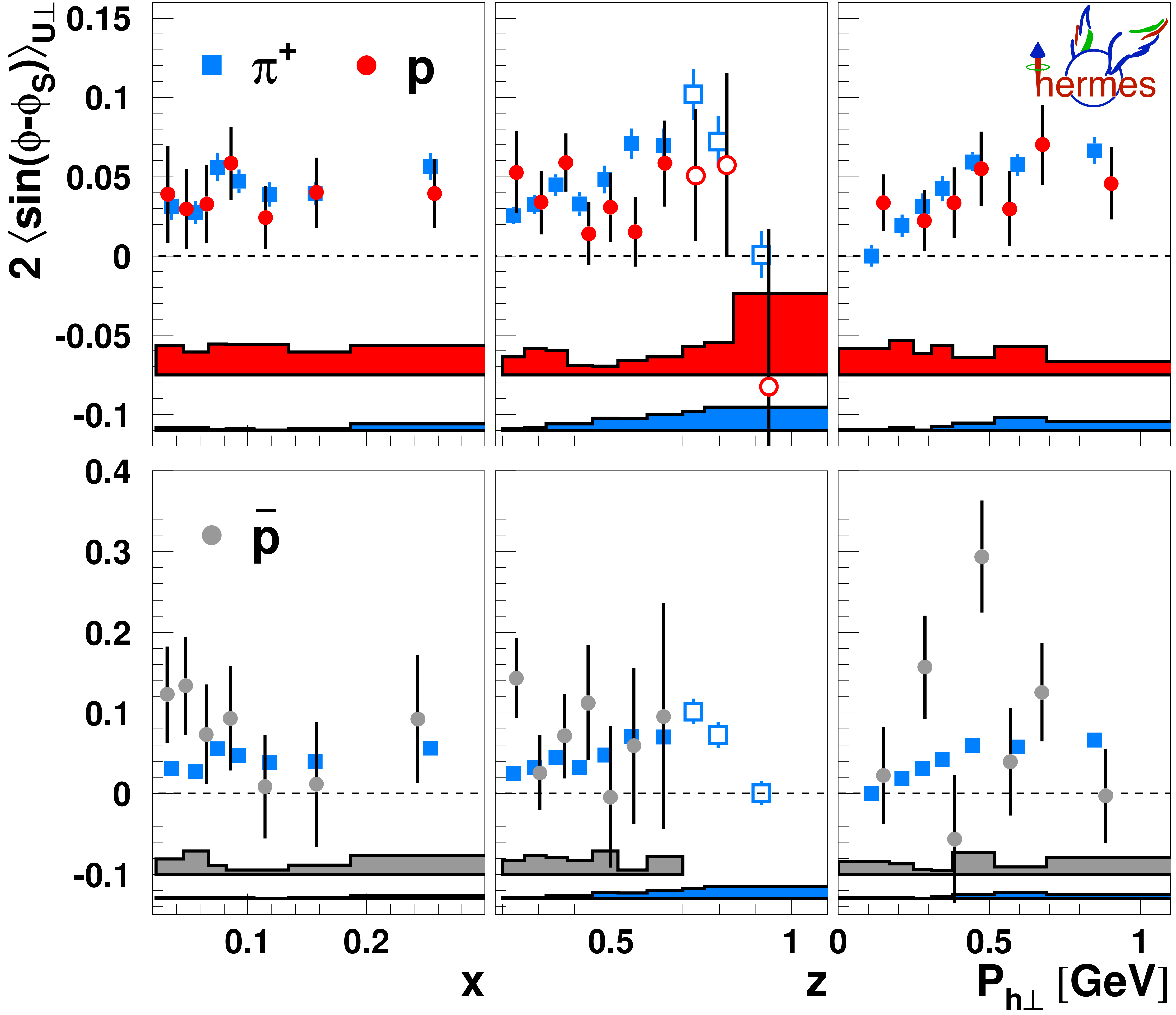


possibly, onset of target fragmentation only at lower z

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

Sivers amplitudes
pions vs. (anti)protons

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



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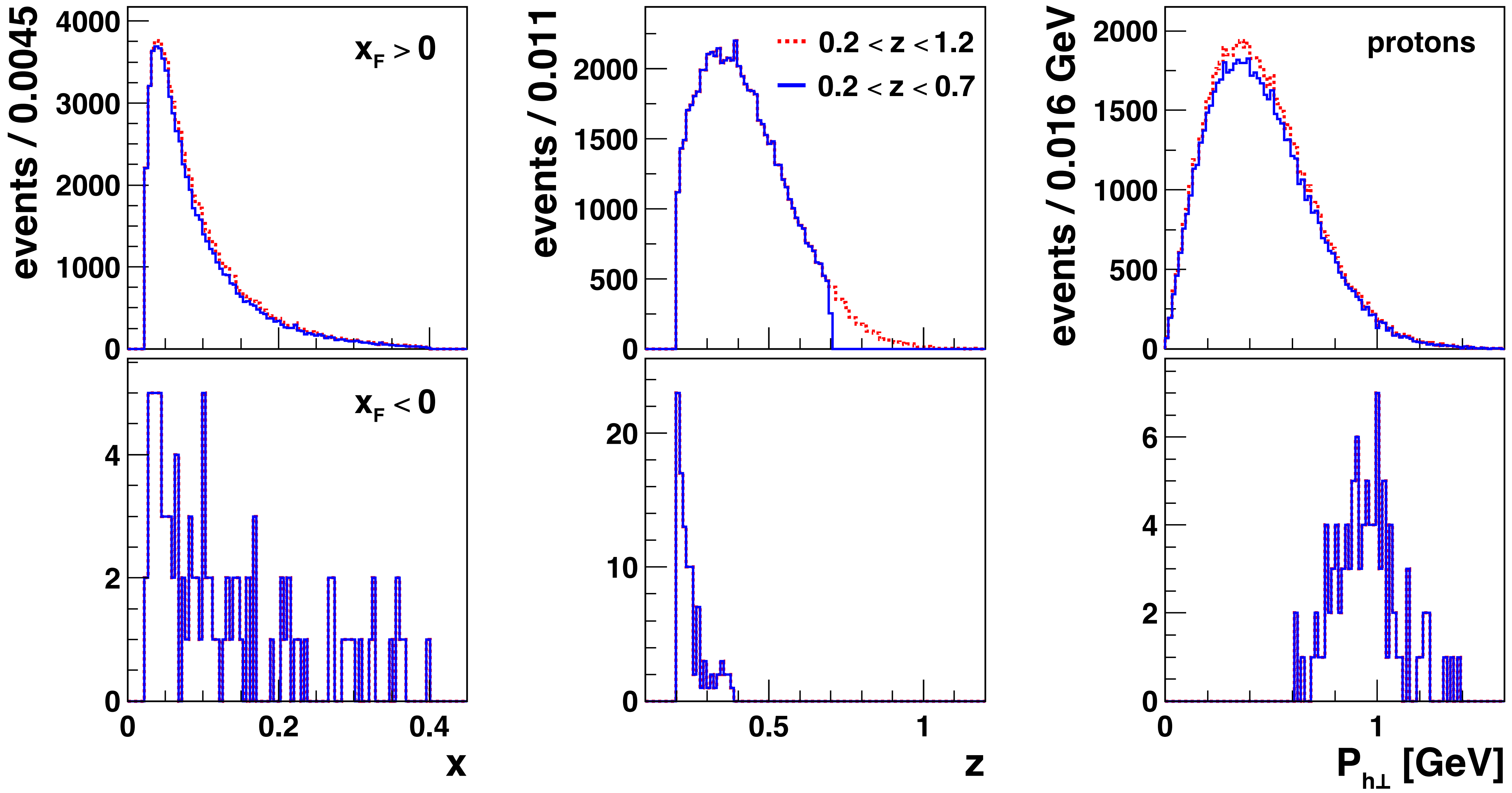

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