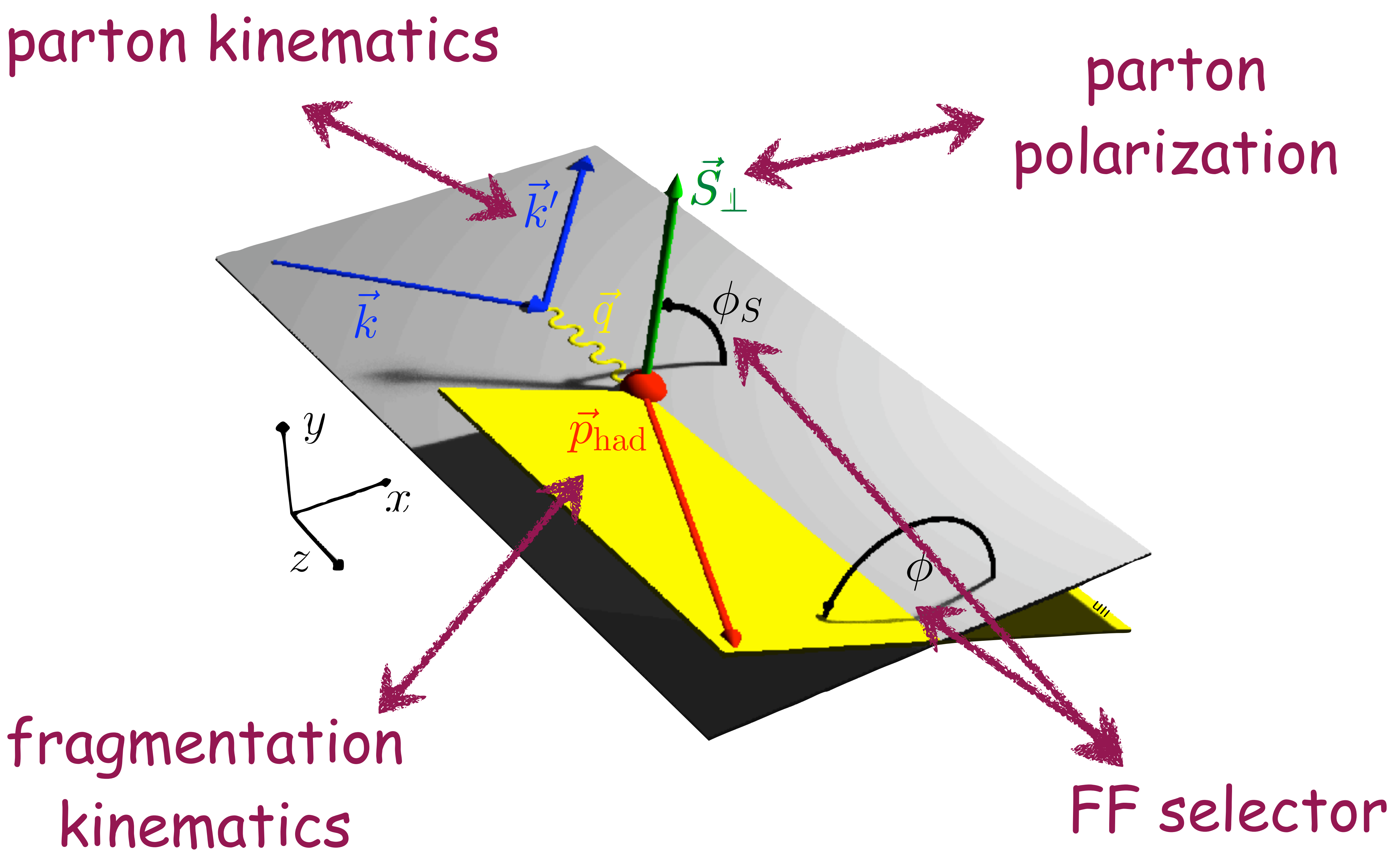
Transversity 2022

Pavia, 23-27 May 2022



Investigation of TMDs at hermes

Gunar.Schnell @ DESY.de

ikerbasque Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

ELSEVIER

Nuclear Physics B 461 (1996) 197–237

NUCLEAR PHYSICS B

The complete tree-level result up to order $1/Q$ for polarized deep-inelastic leptoproduction

P.J. Mulders [a,b], R.D. Tangerman [a]

[a] *National Institute for Nuclear Physics and High–Energy Physics (NIKHEF), P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands*

[b] *Department of Physics and Astronomy, Free University, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands*

Received 18 October 1995; accepted 1 December 1995

PHYSICAL REVIEW D VOLUME 57, NUMBER 9 1 MAY 1998

Time-reversal odd distribution functions in leptoproduction

D. Boer

National Institute for Nuclear Physics and High-Energy Physics, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands

P. J. Mulders

National Institute for Nuclear Physics and High-Energy Physics, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands and Department of Physics and Astronomy, Free University of Amsterdam, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands

(Received 1 December 1997; published 18 March 1998)

We consider the various asymmetries, notably single spin asymmetries, that appear in leptoproduction as a consequence of the presence of time-reversal odd distribution functions. This could facilitate experimental searches for time-reversal odd phenomena. [S0556-2821(98)02709-X]

PACS number(s): 13.85.Ni, 13.87.Fh, 13.88.+e

186+31 equations

ELSEVIER
Nuclear Physics B 461 (1996) 197–237
NUCLEAR PHYSICS B

The complete tree-level result up to order $1/Q$ for polarized deep-inelastic leptoproduction

P.J. Mulders [a,b], R.D. Tangerman [a]
[a] National Institute for Nuclear Physics and High–Energy Physics (NIKHEF), P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands
[b] Department of Physics and Astronomy, Free University, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands

Received 18 October 1995; accepted 1 December 1995

PHYSICAL REVIEW D VOLUME 57, NUMBER 9 1 MAY 1998

Time-reversal odd distribution functions in leptoproduction

D. Boer
National Institute for Nuclear Physics and High-Energy Physics, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands

P. J. Mulders
National Institute for Nuclear Physics and High-Energy Physics, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands and Department of Physics and Astronomy, Free University of Amsterdam, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands
(Received 1 December 1997; published 18 March 1998)

We consider the various asymmetries, notably single spin asymmetries, that appear in leptoproduction as a consequence of the presence of time-reversal odd distribution functions. This could facilitate experimental searches for time-reversal odd phenomena. [S0556-2821(98)02709-X]

PACS number(s): 13.85.Ni, 13.87.Fh, 13.88.+e

JHEP
Published for SISSA by Springer
Received: July 31, 2020
Accepted: October 4, 2020
Published: December 2, 2020

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

JHEP12(2020)010

The HERMES Collaboration
A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E.C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26,a] A. Bacchetta,[21] S. Belostotski,[19,a] V. Bryzgalov,[20] G.P. Capitani,[11] E. Cisbani,[22] G. Ciullo,[10] M. Contalbrigo,[10] W. Deconinck,[6] R. De Leo,[2] 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,[23] G. Gavrilov,[6,19,23] V. Gharibyan,[26] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H.E. Jackson,[1,a] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[6,26] E. Kinney,[5] A. Kisselev,[19] V. Kozlov,[17] P. Kravchenko,[9,19] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] P. Lenisa,[10] W. Lorenzon,[16] S.I. Manaenkov,[19] B. Marianski,[25,a] H. Marukyan,[26] Y. Miyachi,[24] A. Movsisyan,[10,26] V. Muccifora,[11] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L.L. Pappalardo,[10] 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] A. Schäfer,[21] G. Schnell,[3,4,12] B. Seitz,[14] T.-A. Shibata,[24] V. Shutov,[8] M. Statera,[10] A. Terkulov,[17] M. Tytgat,[12] Y. Van Haarlem,[12] C. Van Hulse,[12] D. Veretennikov,[3,19] I. Vilardi,[2] S. Yaschenko,[9] D. Zeiler,[9] B. Zihlmann[6] and P. Zupranski[25]

[1] Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, U.S.A.
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy
[3] Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain
[4] IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain
[5] Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, U.S.A.
[6] DESY, 22603 Hamburg, Germany
[7] DESY, 15738 Zeuthen, Germany
[8] Joint Institute for Nuclear Research, 141980 Dubna, Russia

[a] Deceased.

https://doi.org/10.1007/JHEP12(2020)010

🍾 to you, Piet! 🍾

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

The HERMES Collaboration

Abstract: The data tables of azimuthal single-spin and double-spin asymmetries in semi-inclusive leptoproduction of pions, charged kaons, protons, and antiprotons from transversely polarized protons are presented. The sine of the polar angle between the lepton-beam and the virtual-photon directions is tabulated to facilitate corrections for the contribution from the longitudinal target-polarization component. The data tables are complemented with additional figures of rapidity, transverse momentum versus Q^2, as well as of numerous two-dimensional distributions in typical kinematics of the deep-inelastic scattering process.

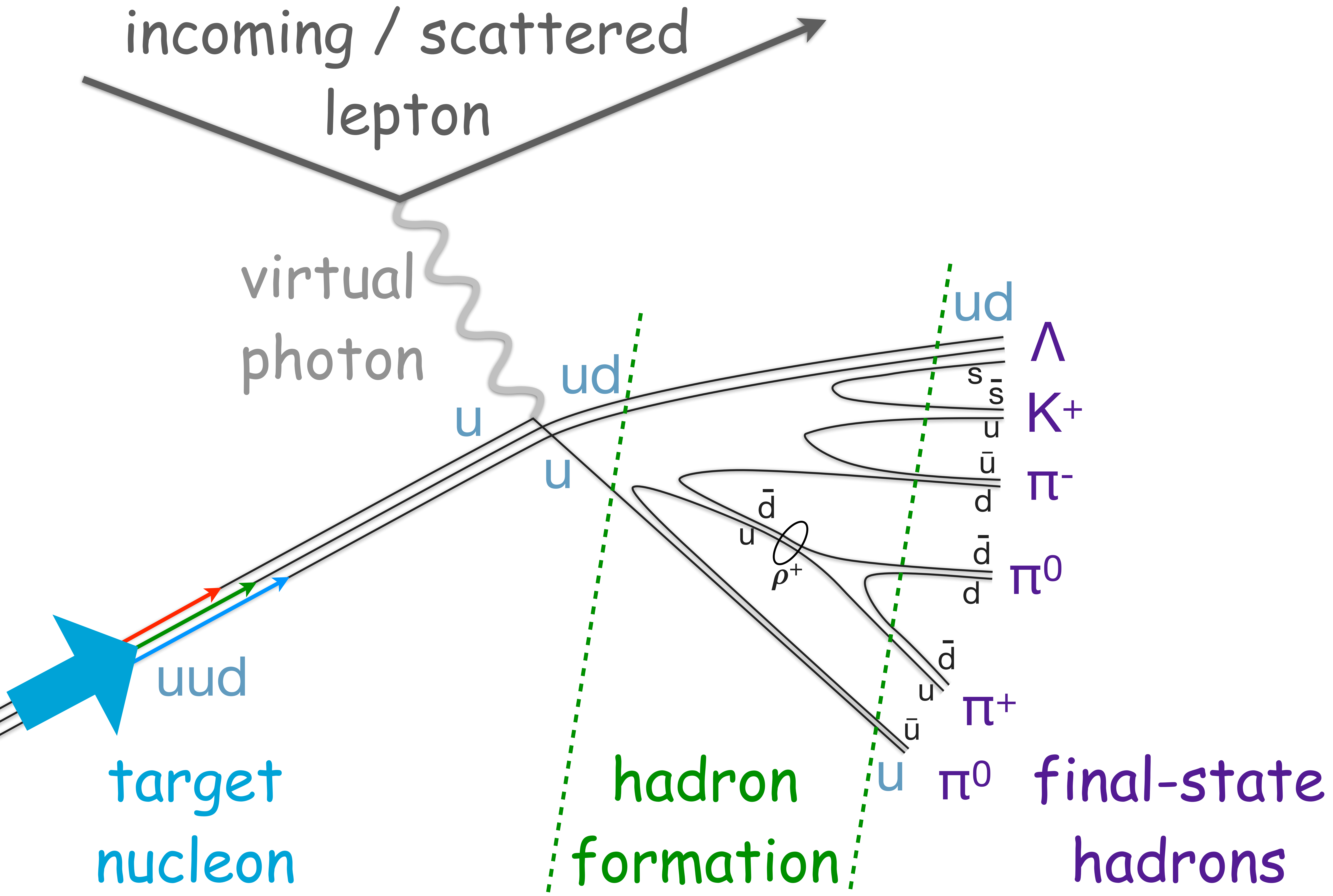
Keywords: Lepton-nucleon scattering, fixed-target experiments, QCD, polarization

ArXiv ePrint: 2007.07755

186+31 equations

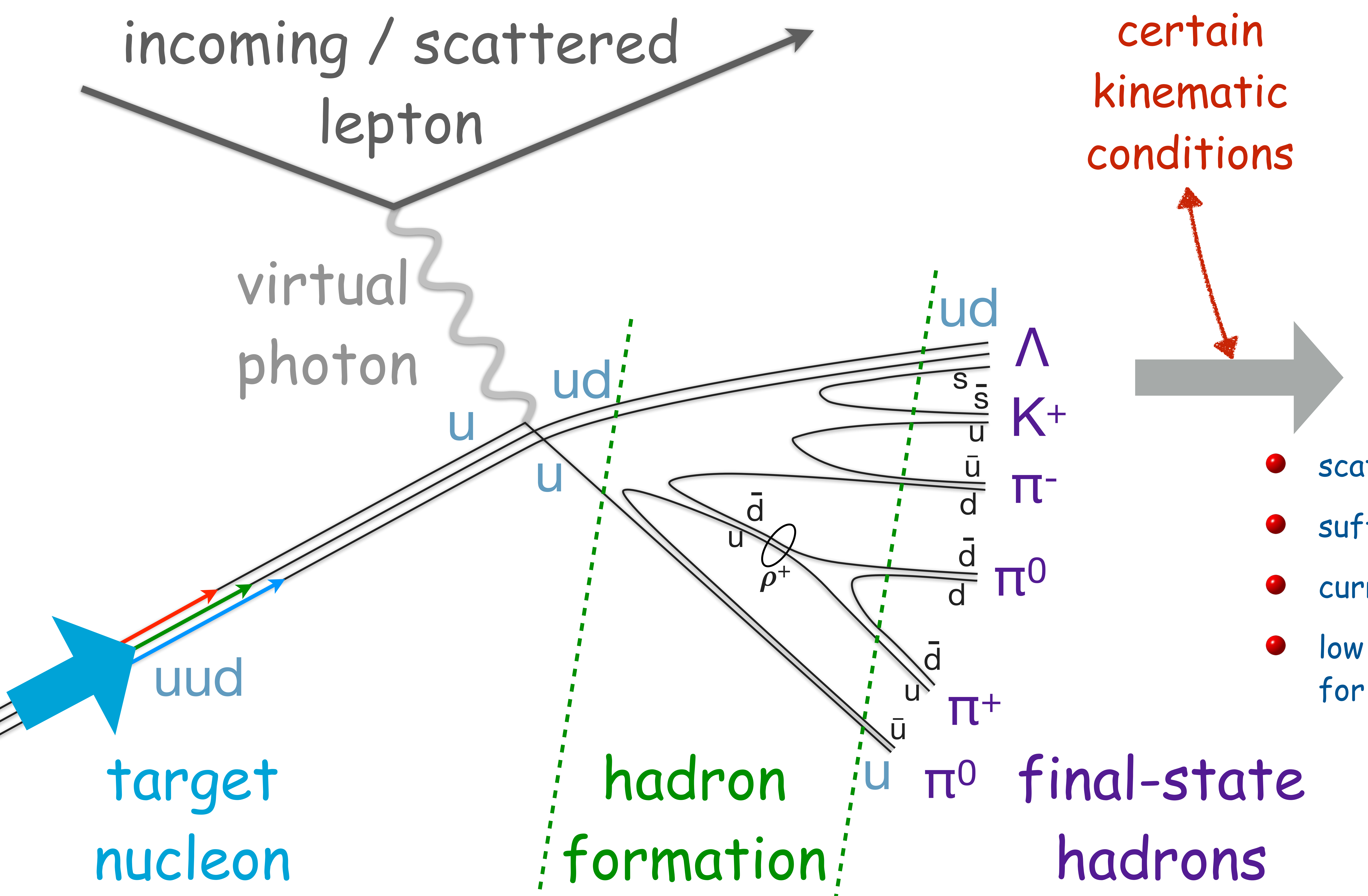
83+115 pages

SIDIS: probing TMD PDFs through fragmentation



SIDIS: probing TMD PDFs through fragmentation

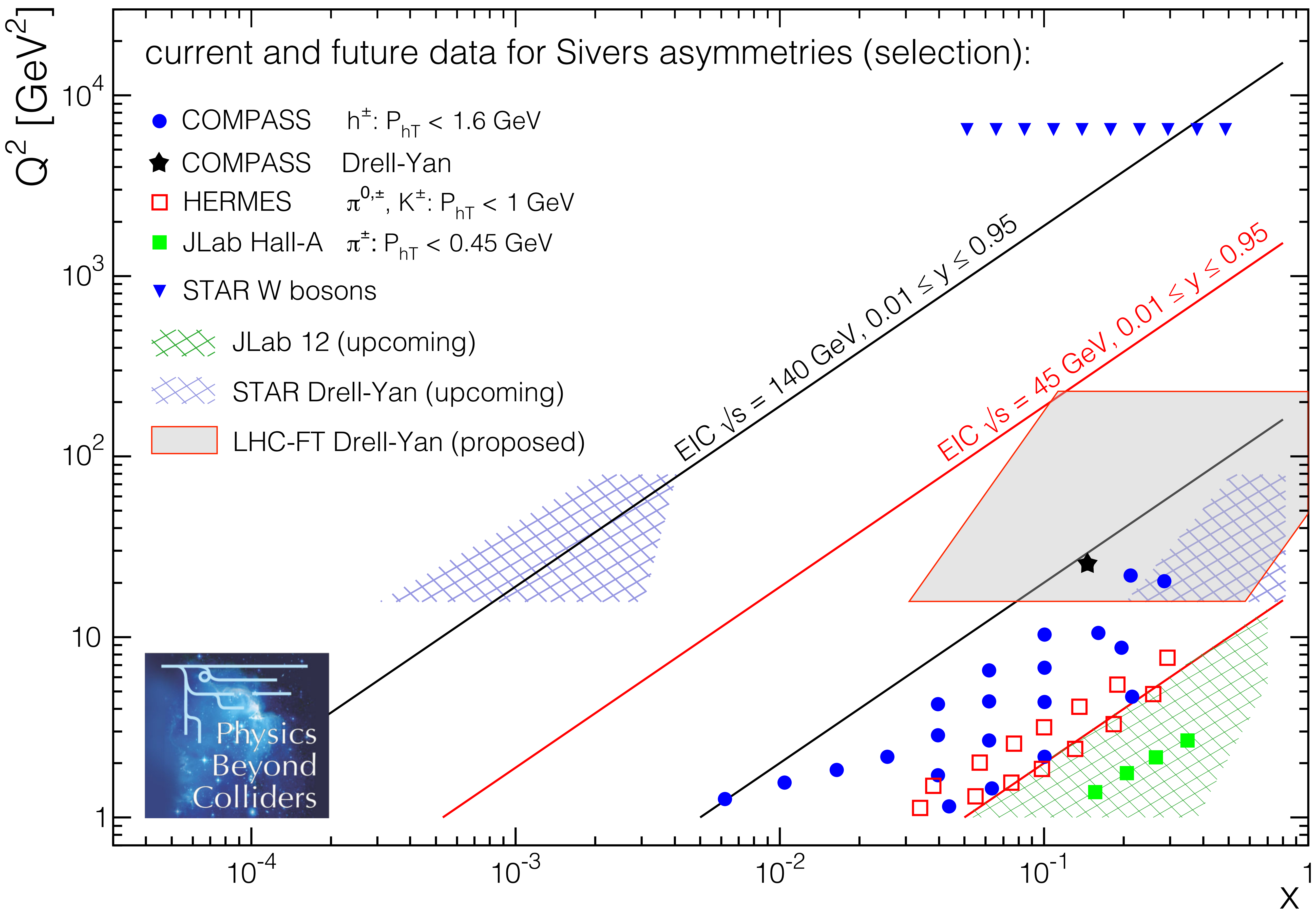
SIDIS: probing TMD PDFs through fragmentation



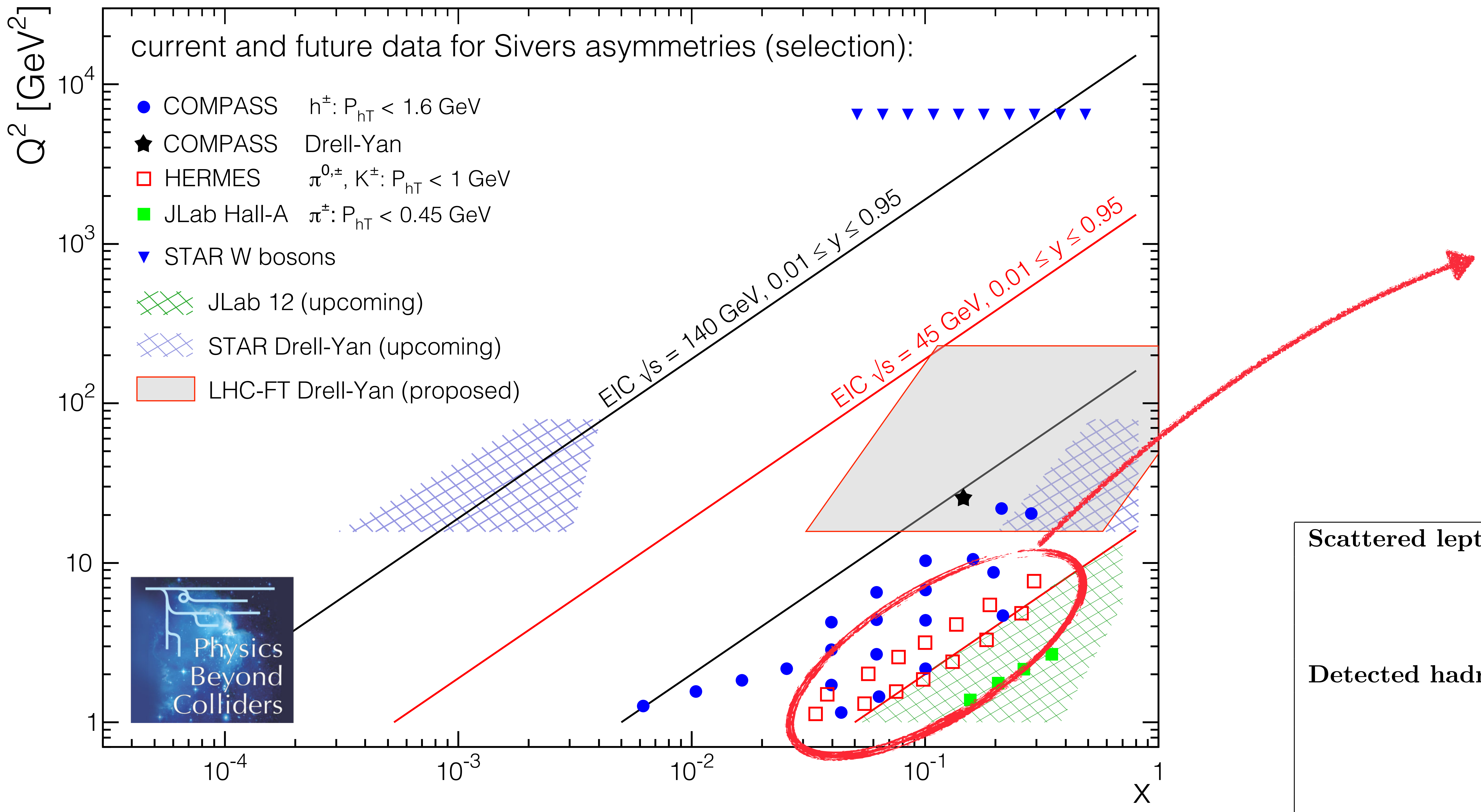
TMD PDF ⊗ TMD FF

- scattering by partons
- sufficient energy for hadronization
- current vs. target fragmentation
- low enough transverse momentum for TMD factorization

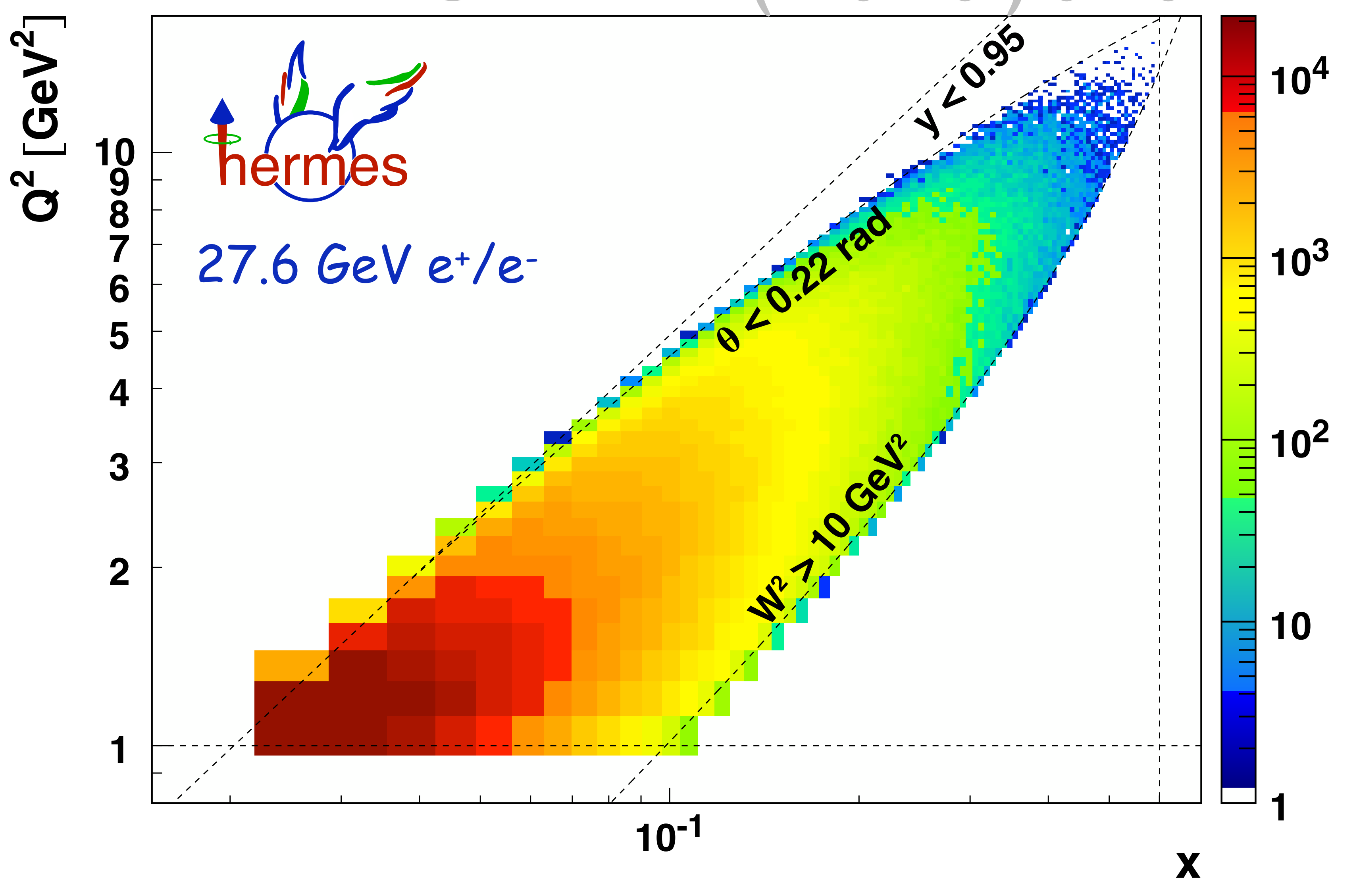
2d kinematic phase space



2d kinematic phase space



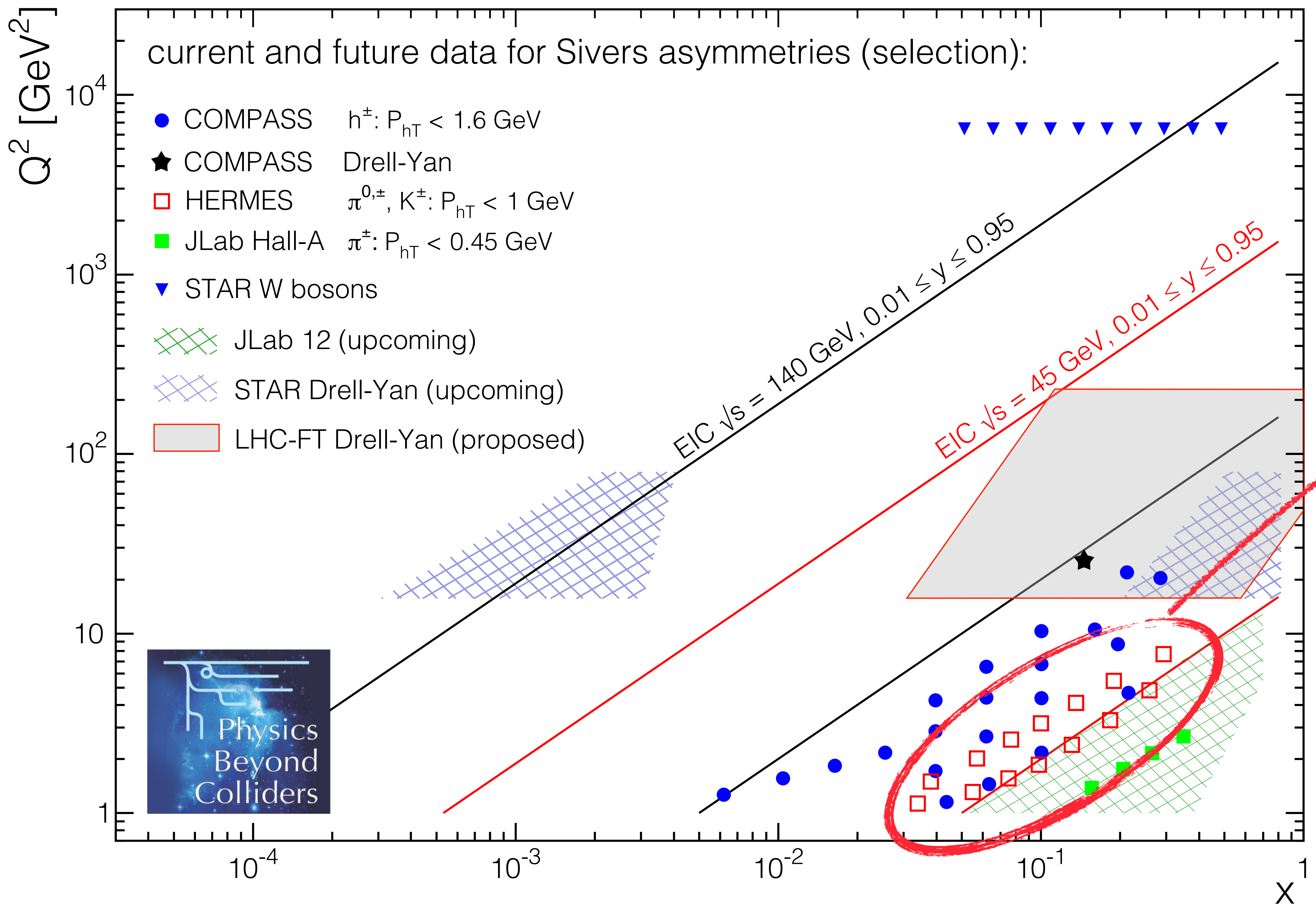
JHEP12(2020)010



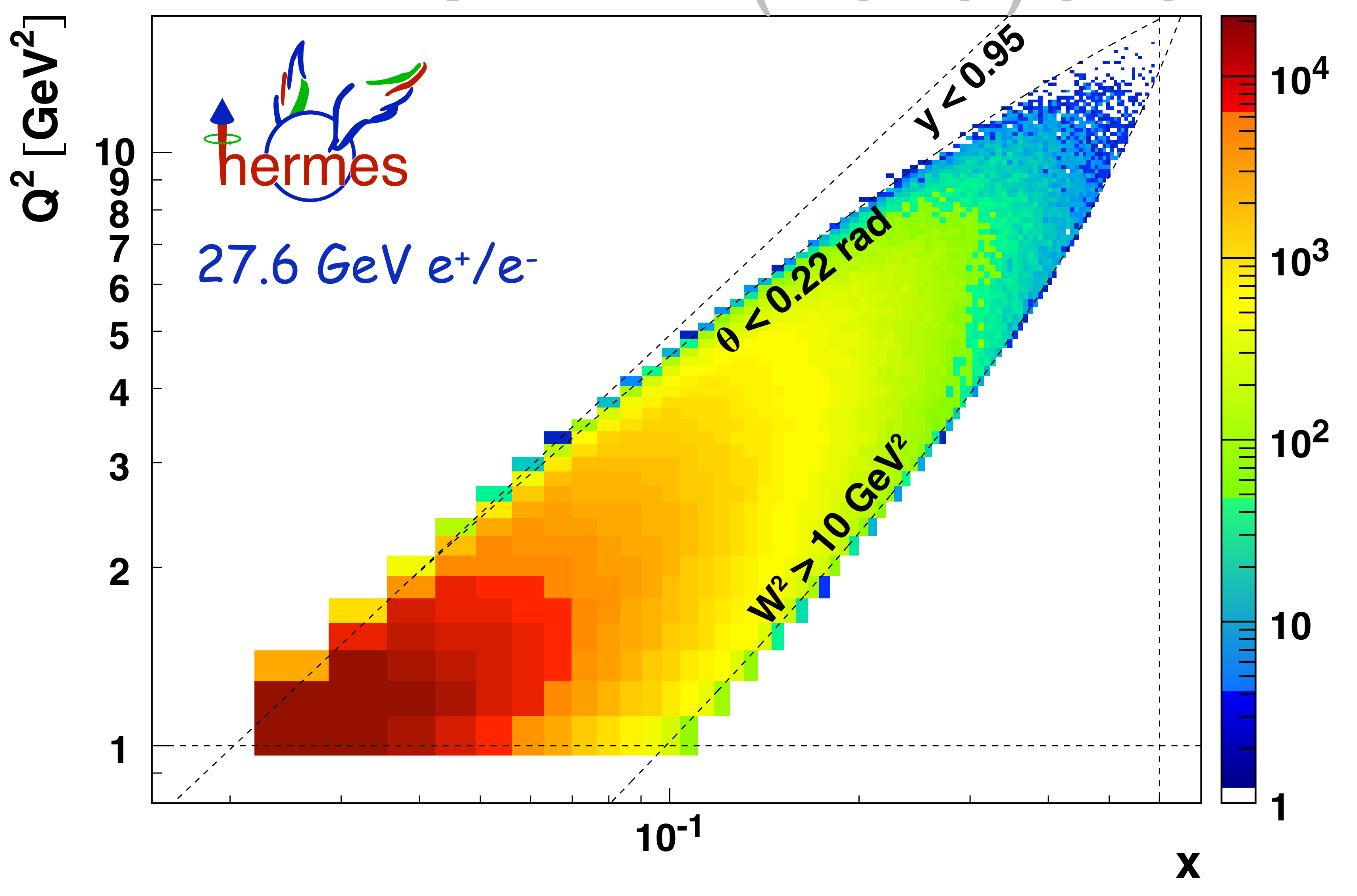
Scattered lepton:		Q^2	$> 1\,\text{GeV}^2$	
		W^2	$> 10\,\text{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\text{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\text{GeV}$	charged mesons
	$4\,\text{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\text{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\text{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\text{GeV}$	
	$0.2 <$	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

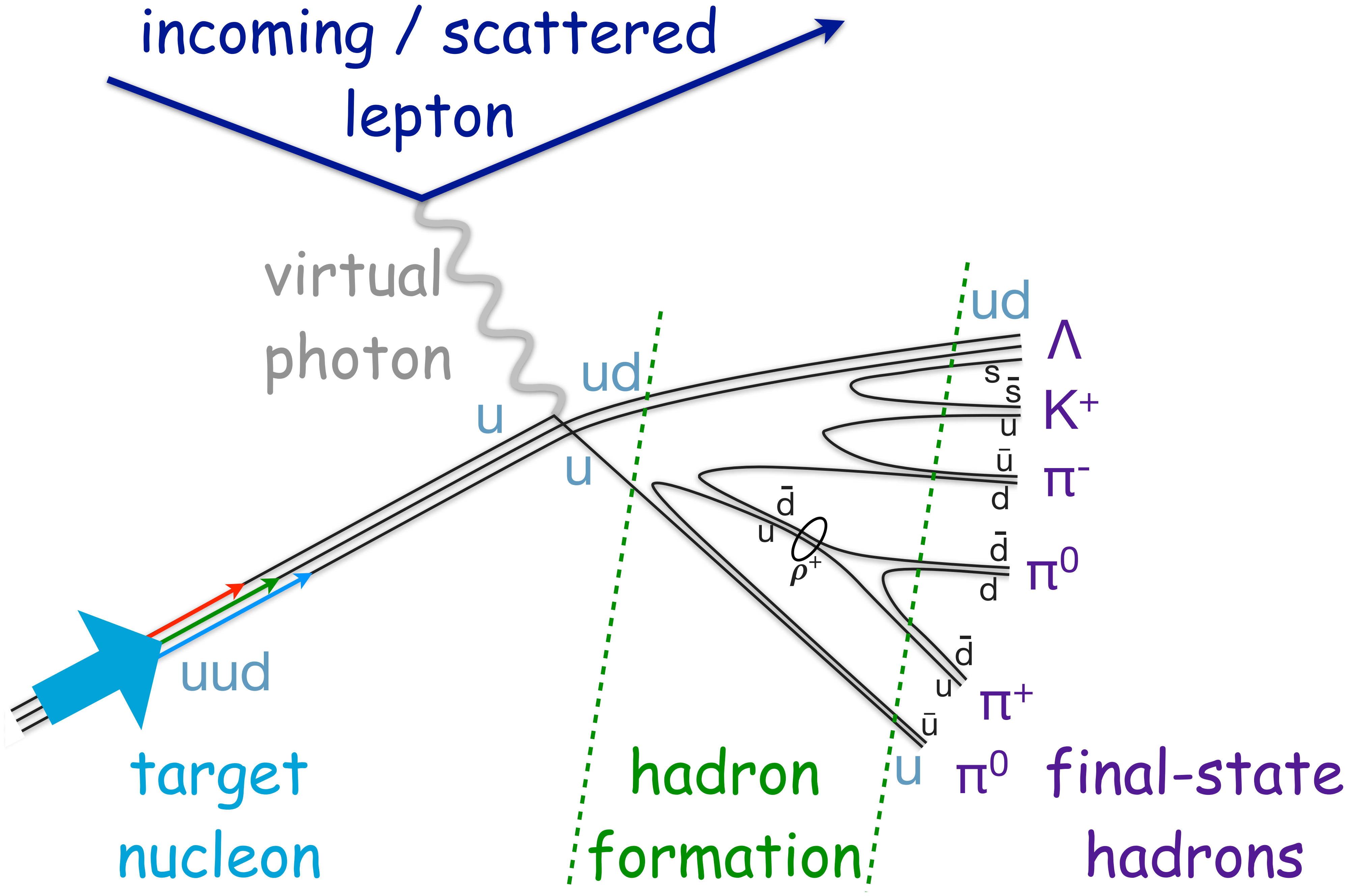


JHEP12(2020)010

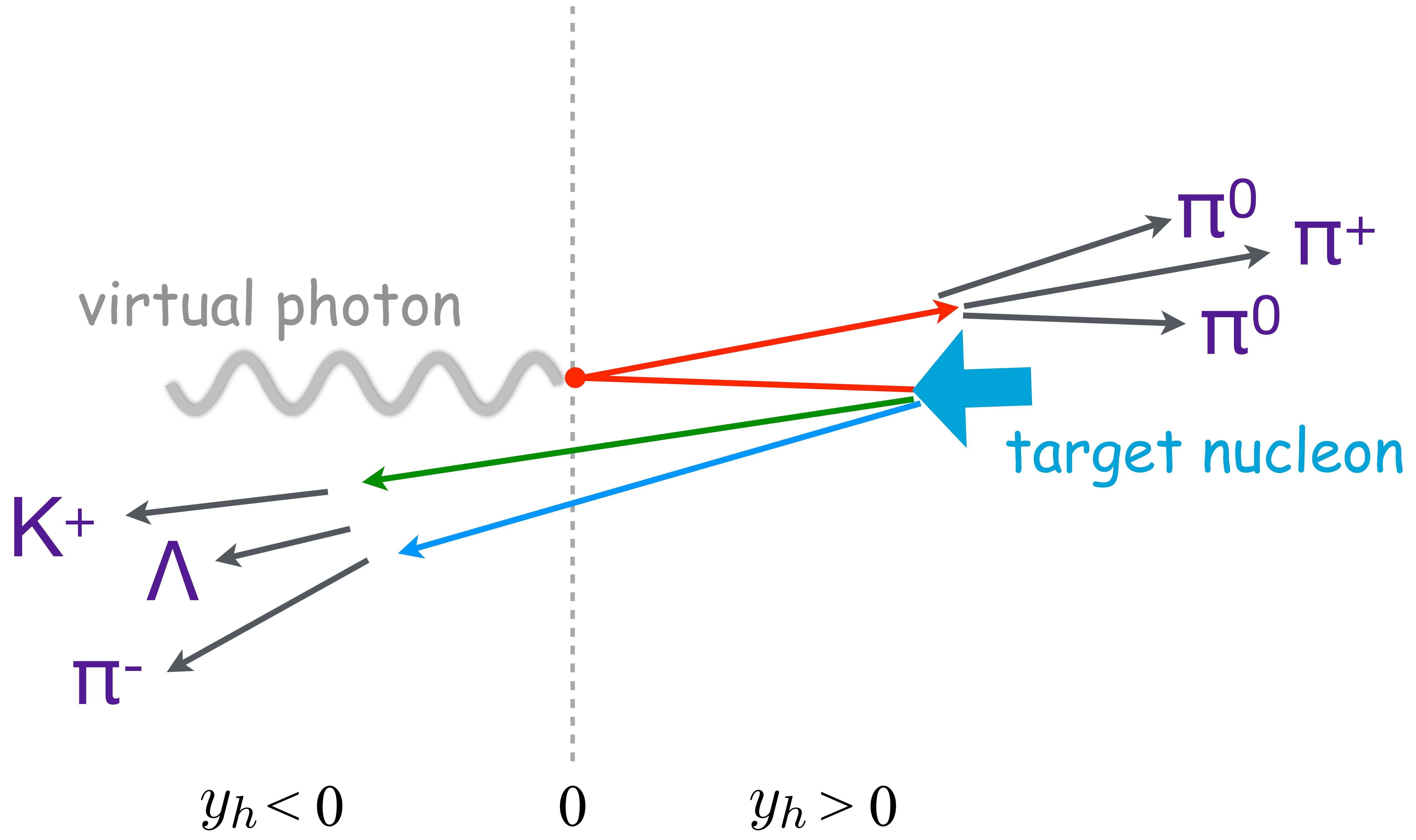


2d (x-Q^2) kinematic space not the only one relevant for SIDIS interpretation

current vs. target fragmentation



virtual-photon—nucleon c.m.s

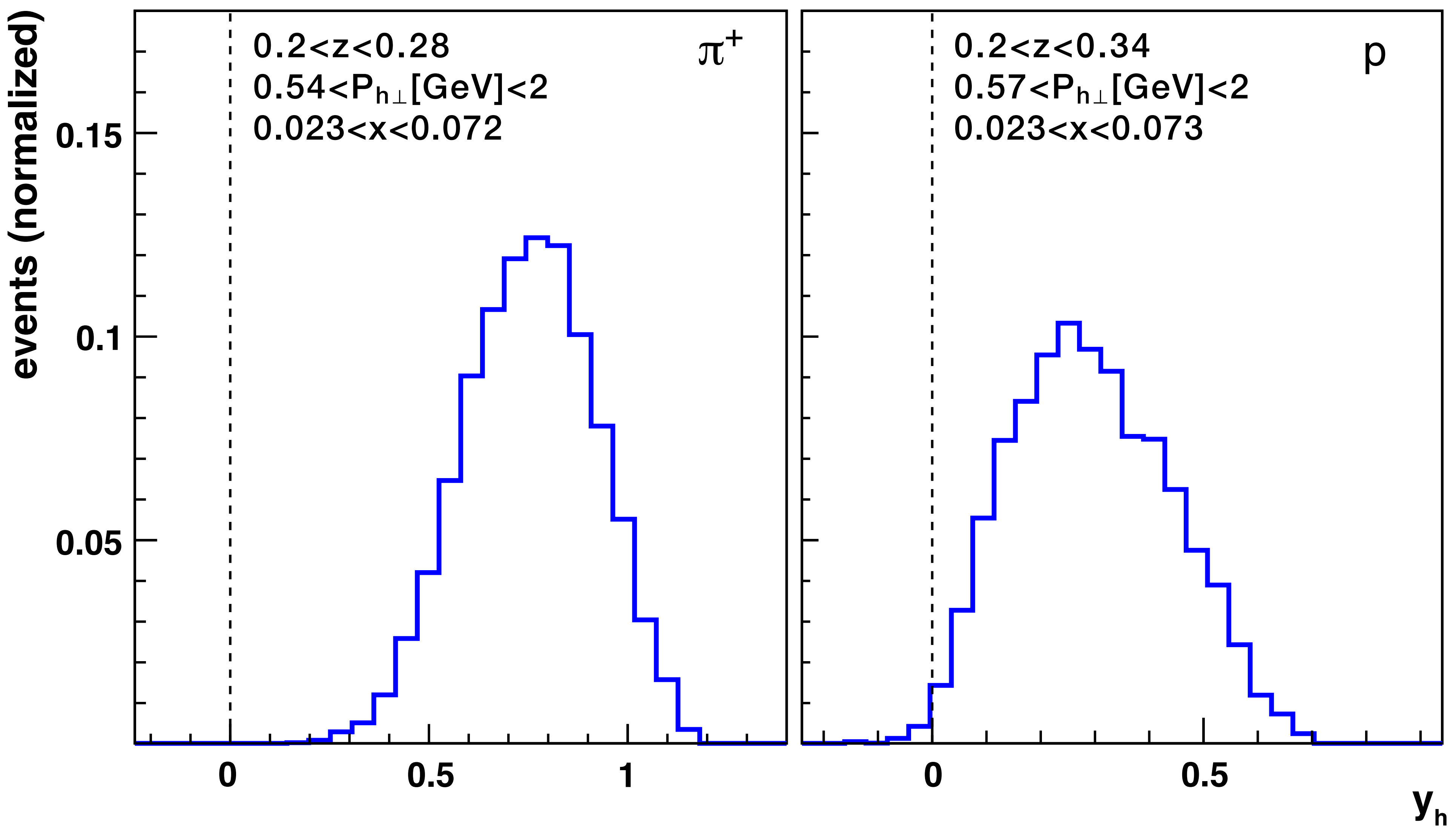


$$y_h \equiv \frac{1}{2} \ln \frac{P_h^+}{P_h^-}$$

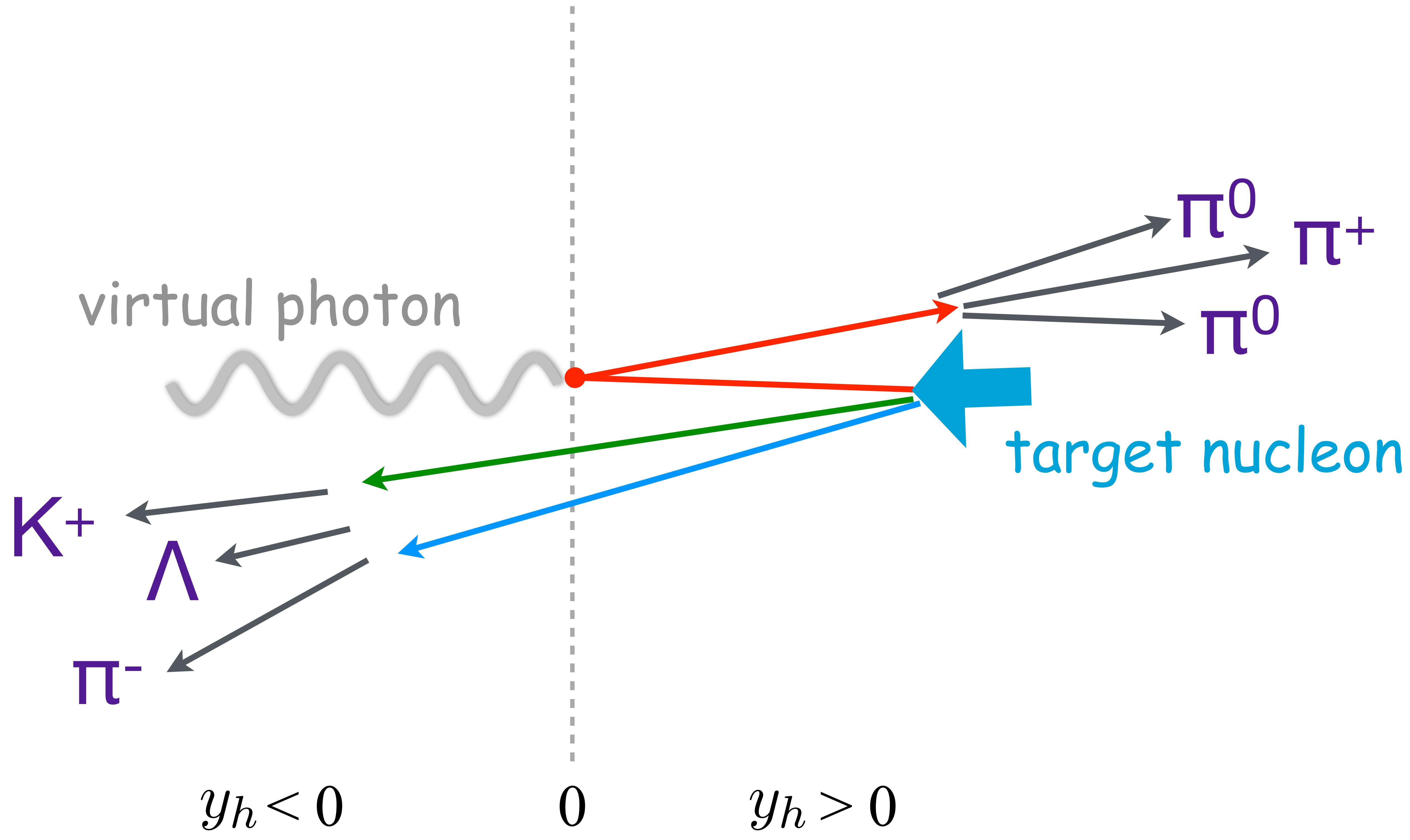
$P_h^\pm$ ... light-cone momenta

current vs. target fragmentation

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



virtual-photon—nucleon c.m.s

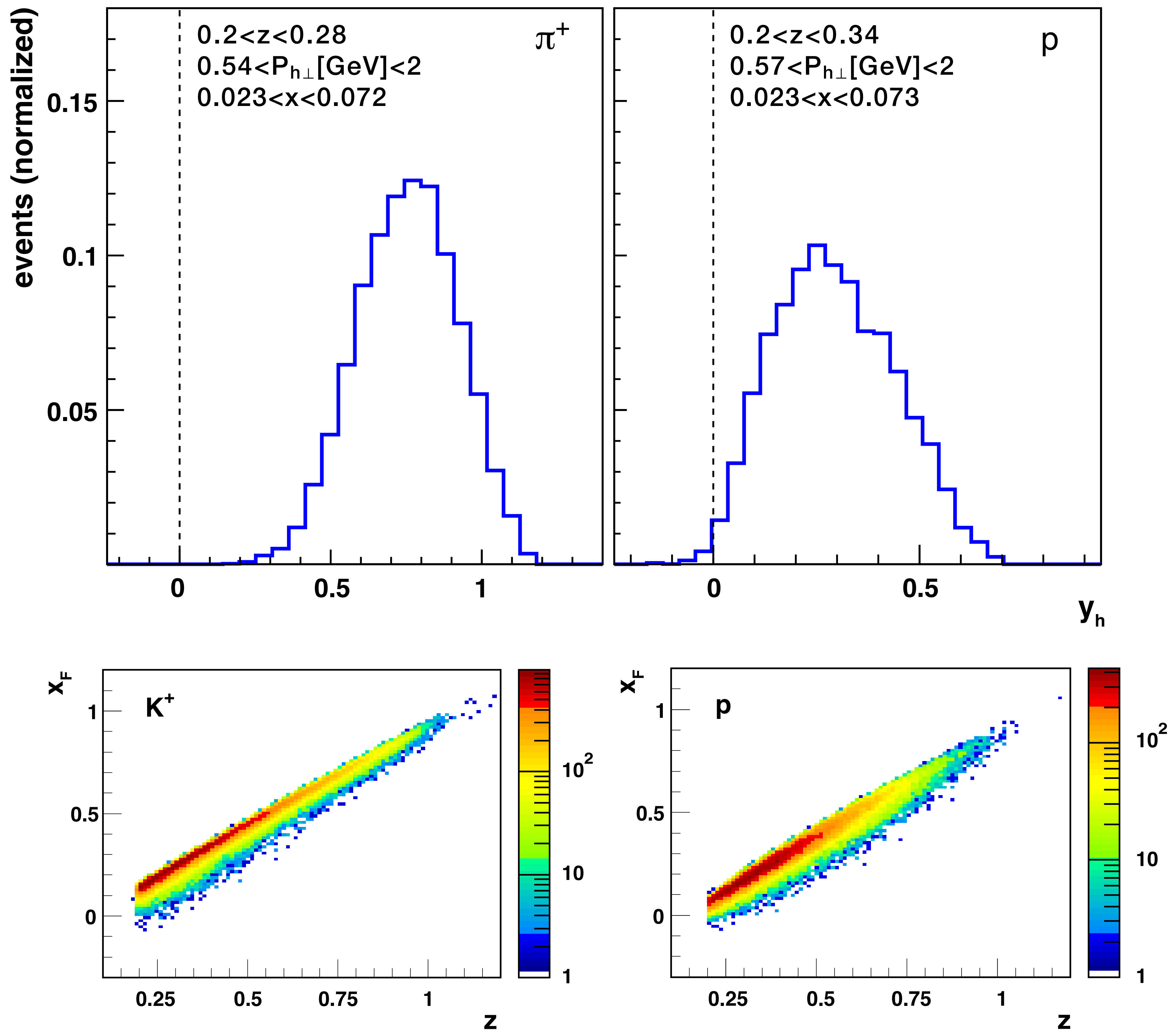


$$y_h \equiv \frac{1}{2} \ln \frac{P_h^+}{P_h^-}$$

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

current vs. target fragmentation

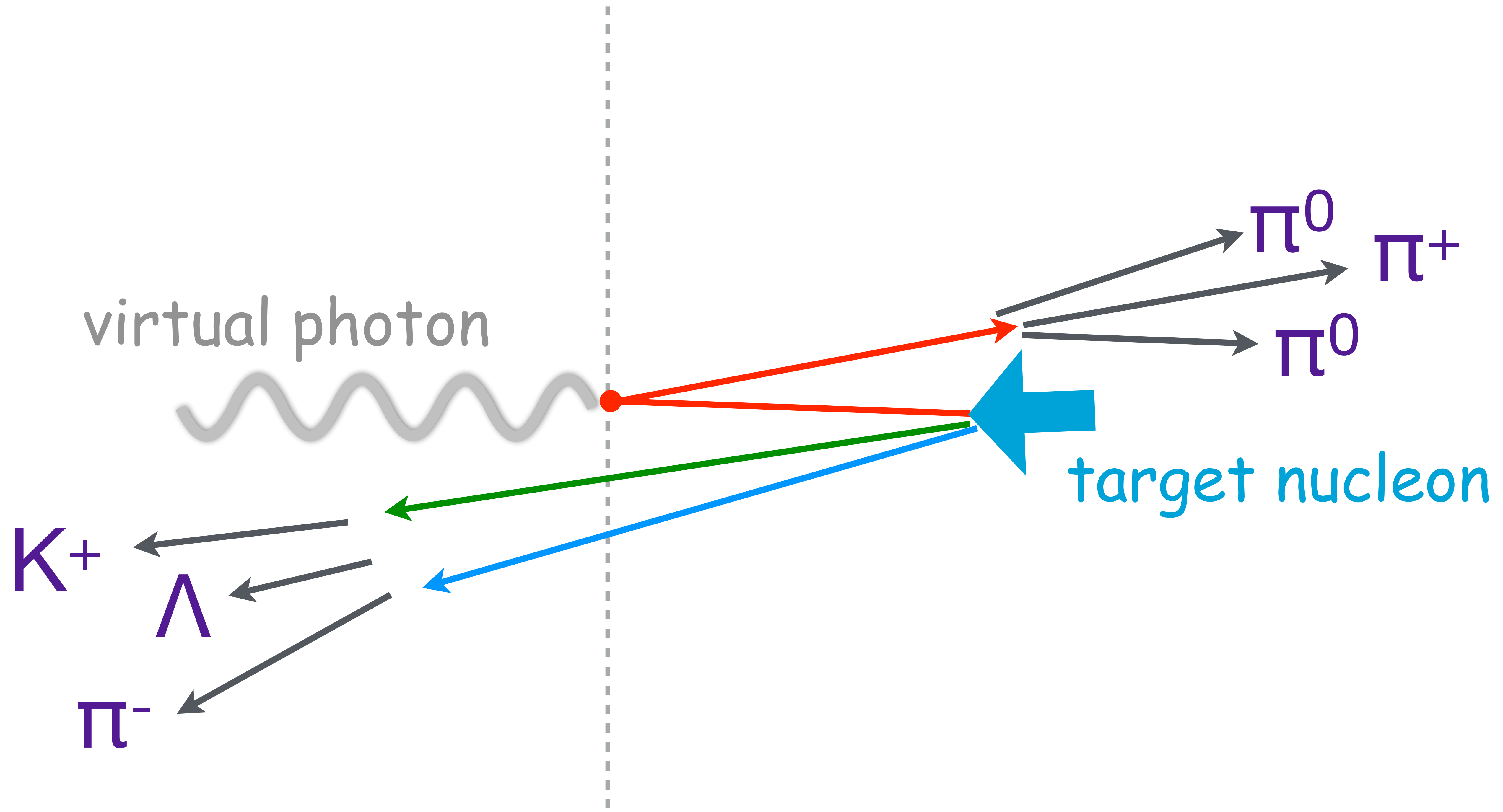
[A. Airapetian et al., JHEP12(2020)010]



x_F ... Feynman x

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

virtual-photon—nucleon c.m.s



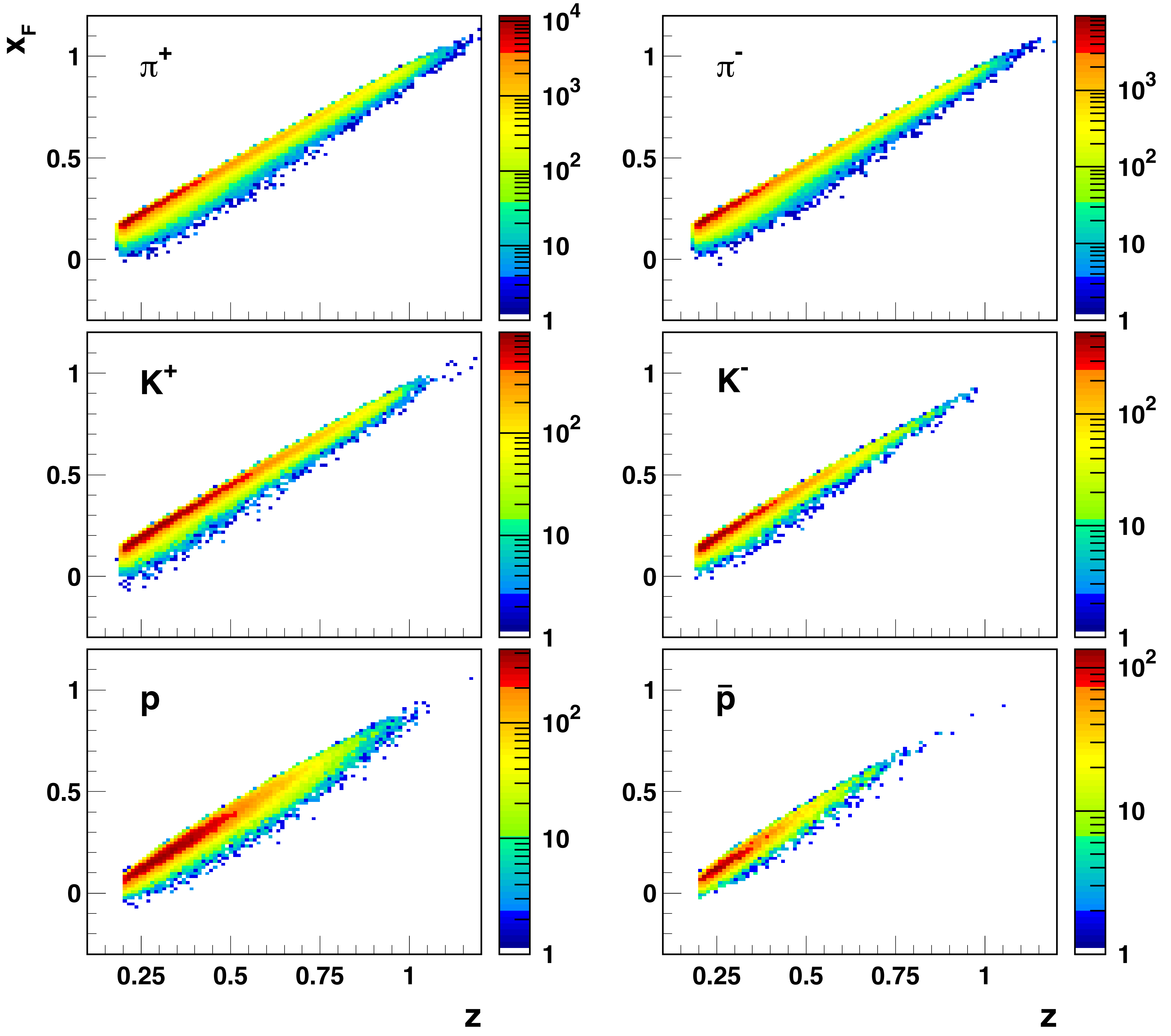
$y_h < 0$ 0 $y_h > 0$

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

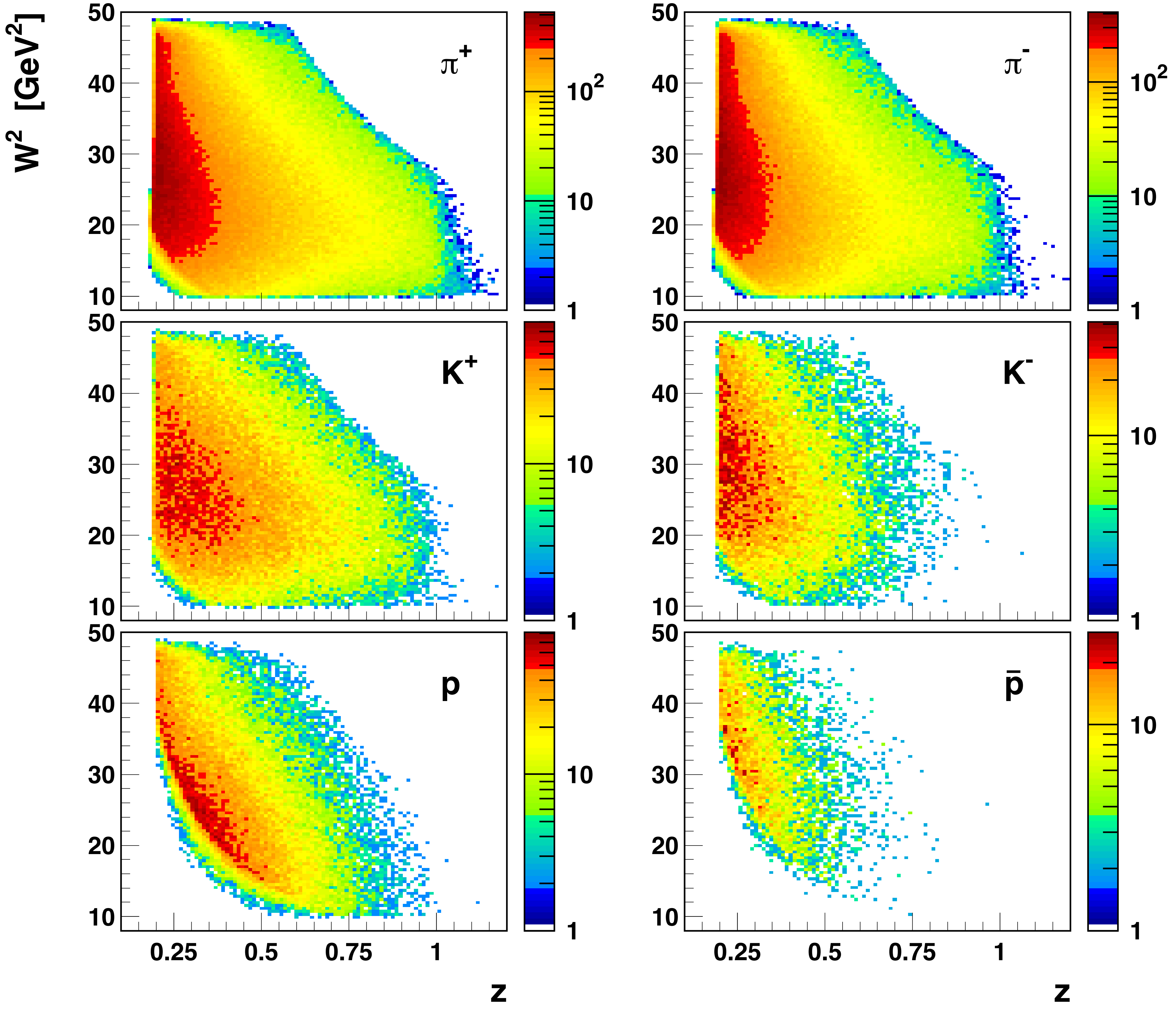
$P_h^\pm$ ... light-cone momenta

current vs. target fragmentation

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

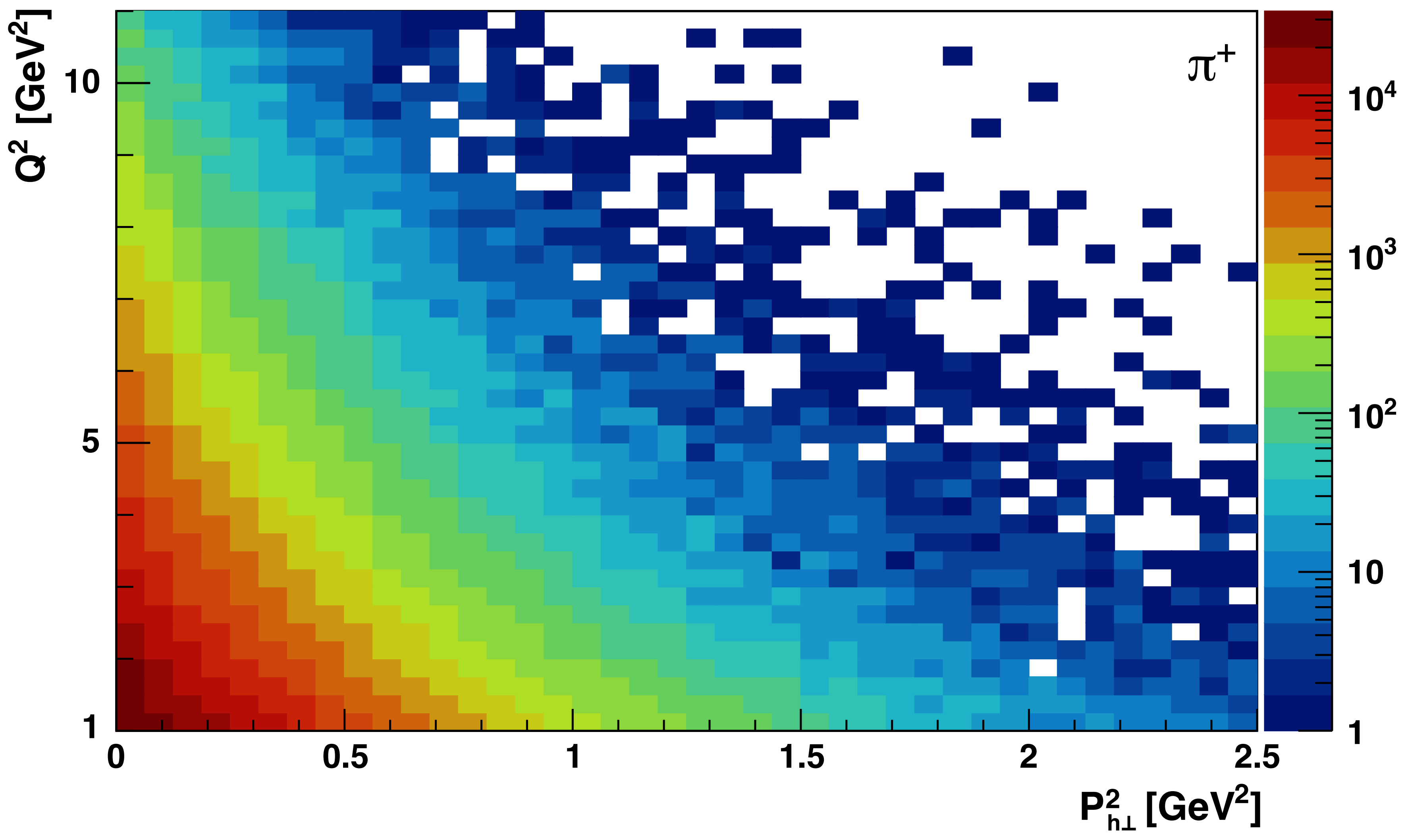


[A. Airapetian et al., JHEP12(2020)010]



TMD factorization: a 2-scale problem

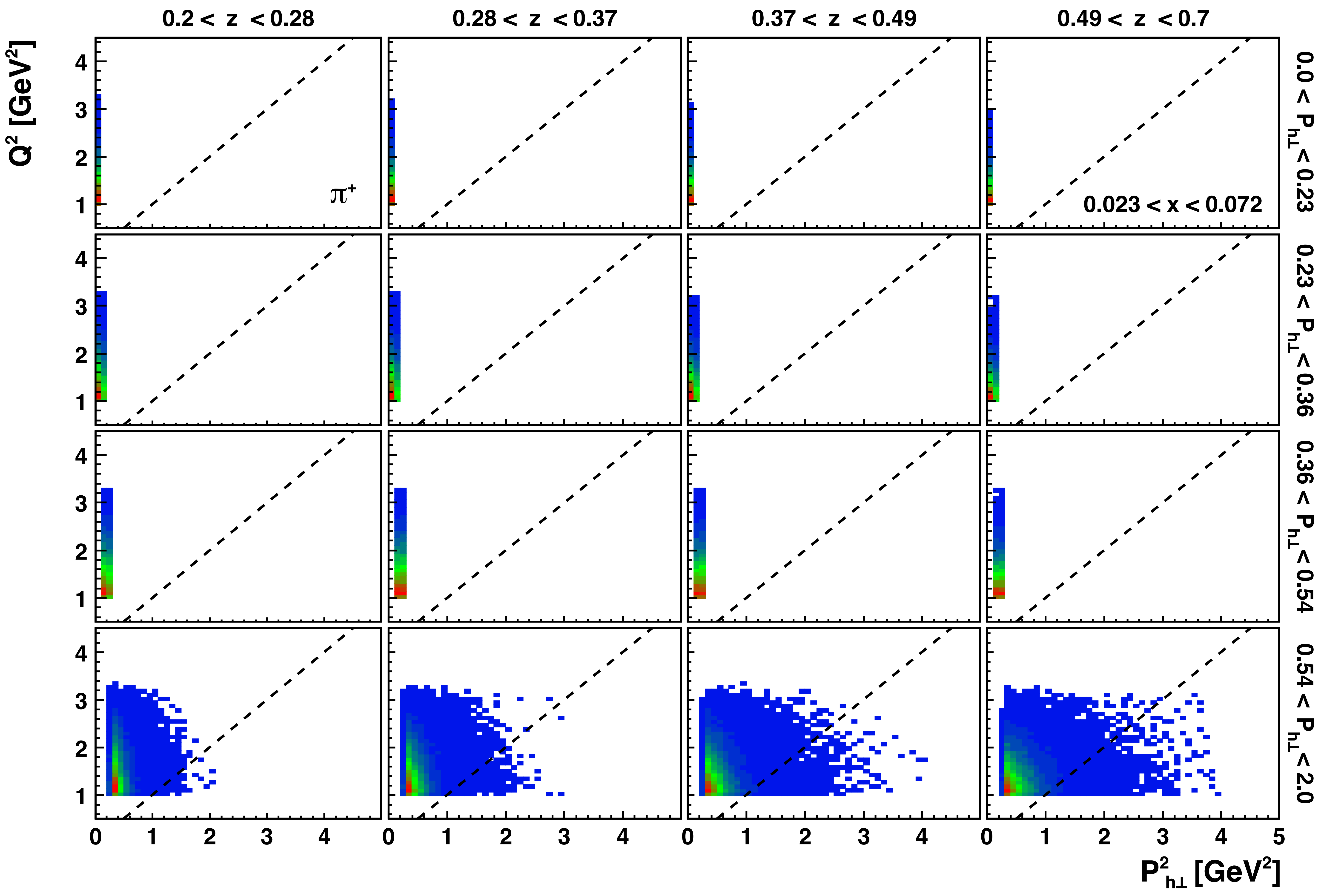
all events



- TMD factorization requires a large scale (Q^2) and small transverse momentum
- overall, Q mainly larger than $P_{h\perp}$
- not fulfilled in all kinematic bins
- more challenging, especially at low x (=low Q^2), for more stringent constraint of $zQ \gg P_{h\perp}$

TMD factorization: a 2-scale problem

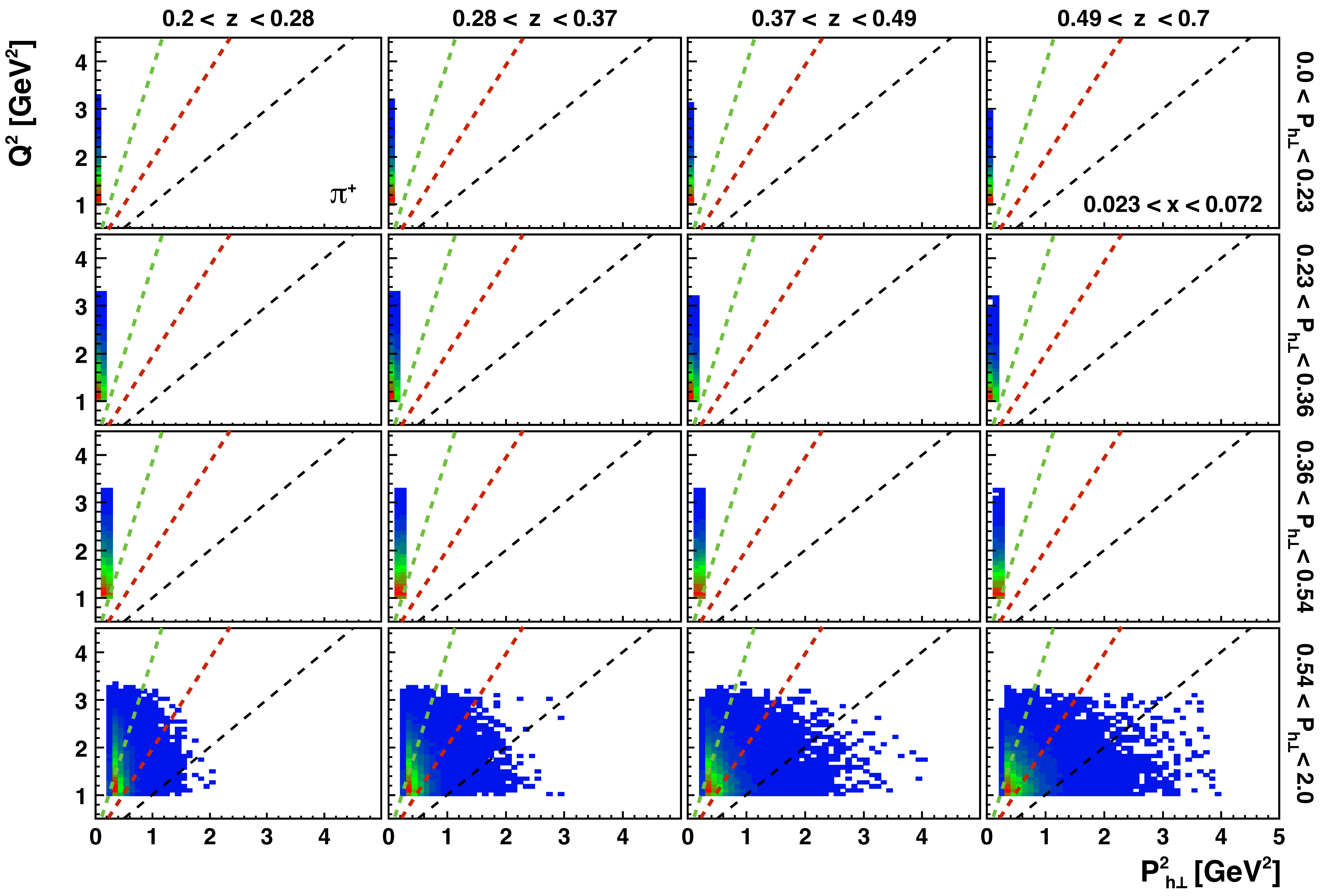
lowest x bin



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

TMD factorization: a 2-scale problem

lowest x bin



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

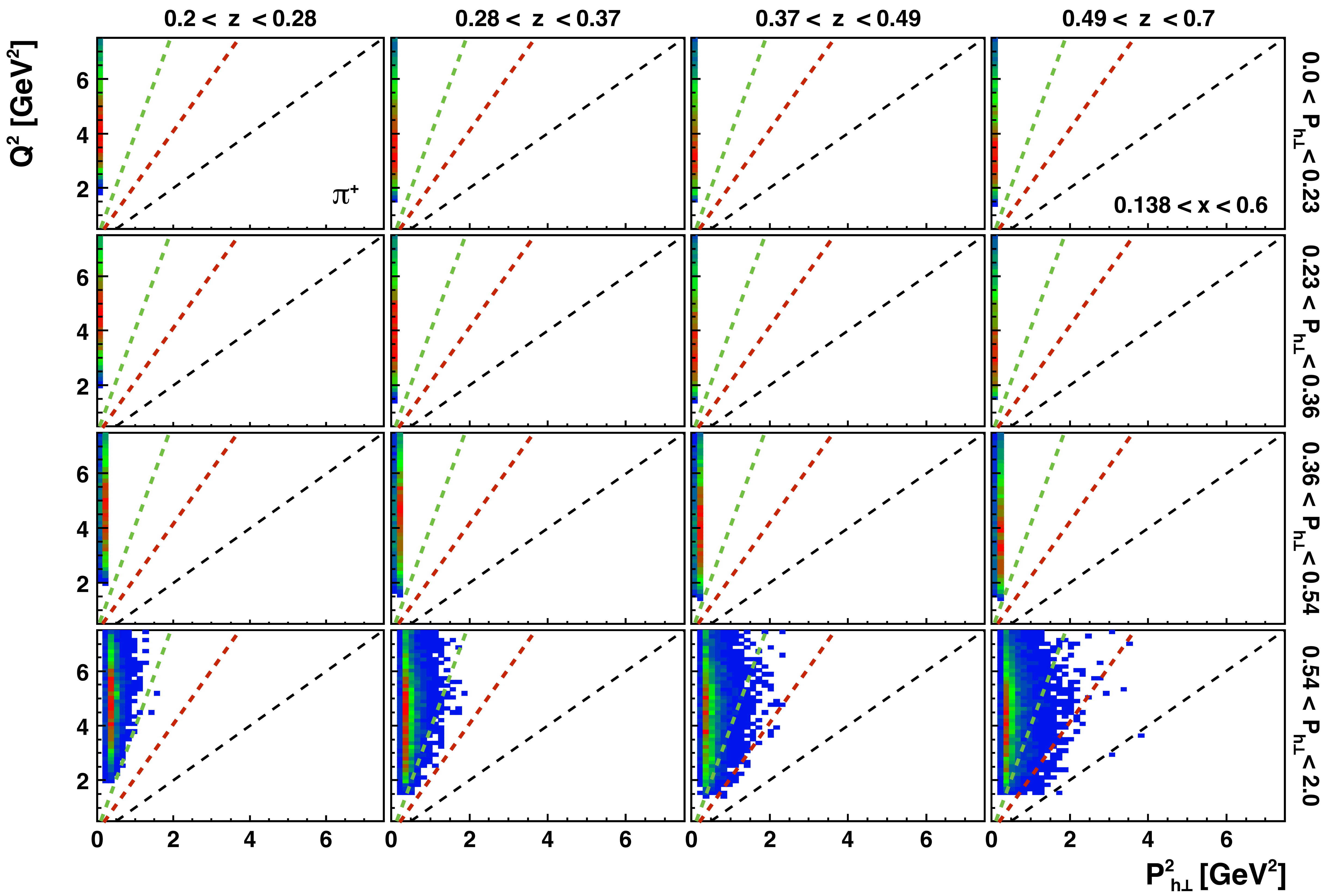
$Q^2 = 2\,P^2_{h\perp}$

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

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

highest x bin



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

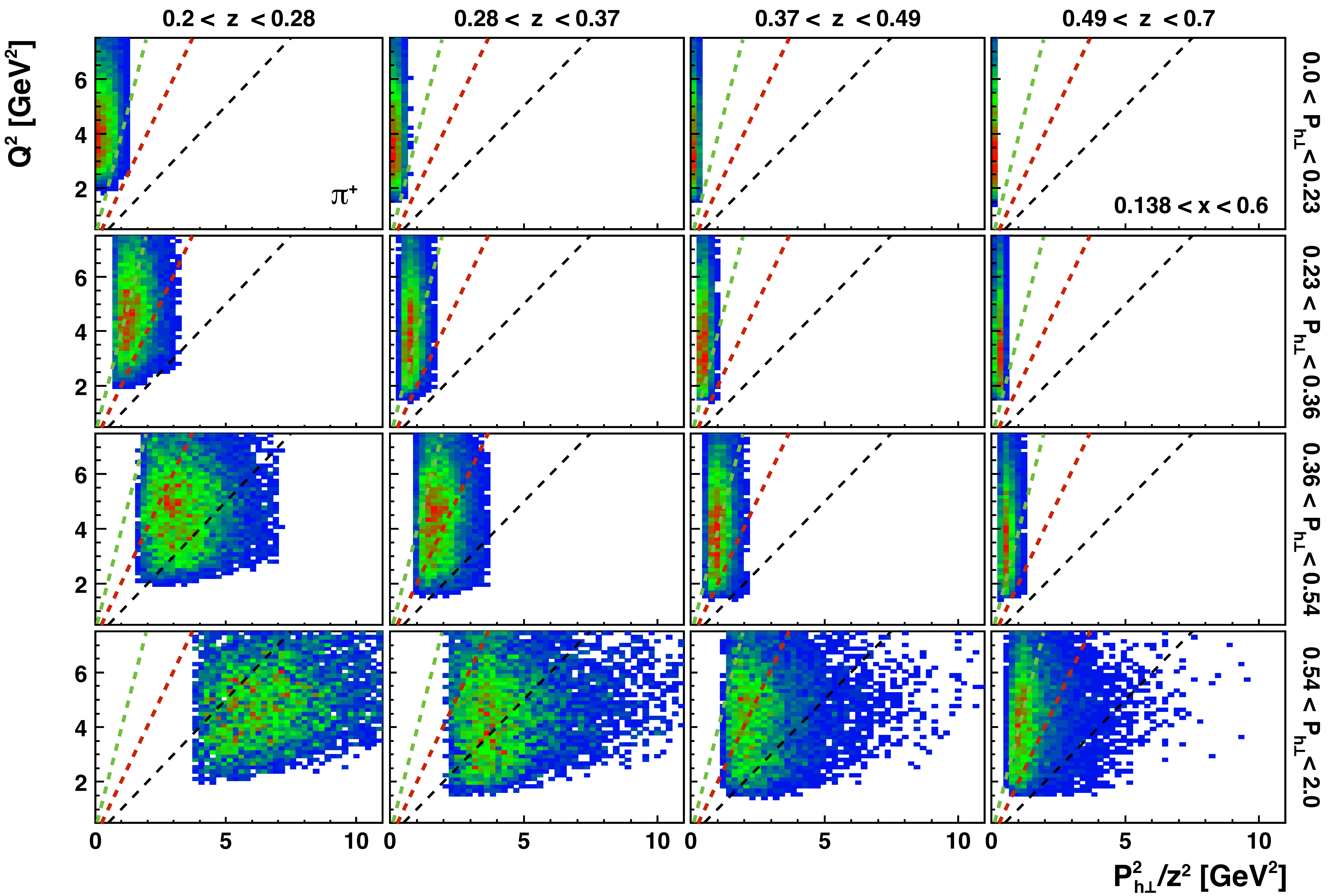
$Q^2 = 2\ P^2_{h\perp}$

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

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

highest x bin



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

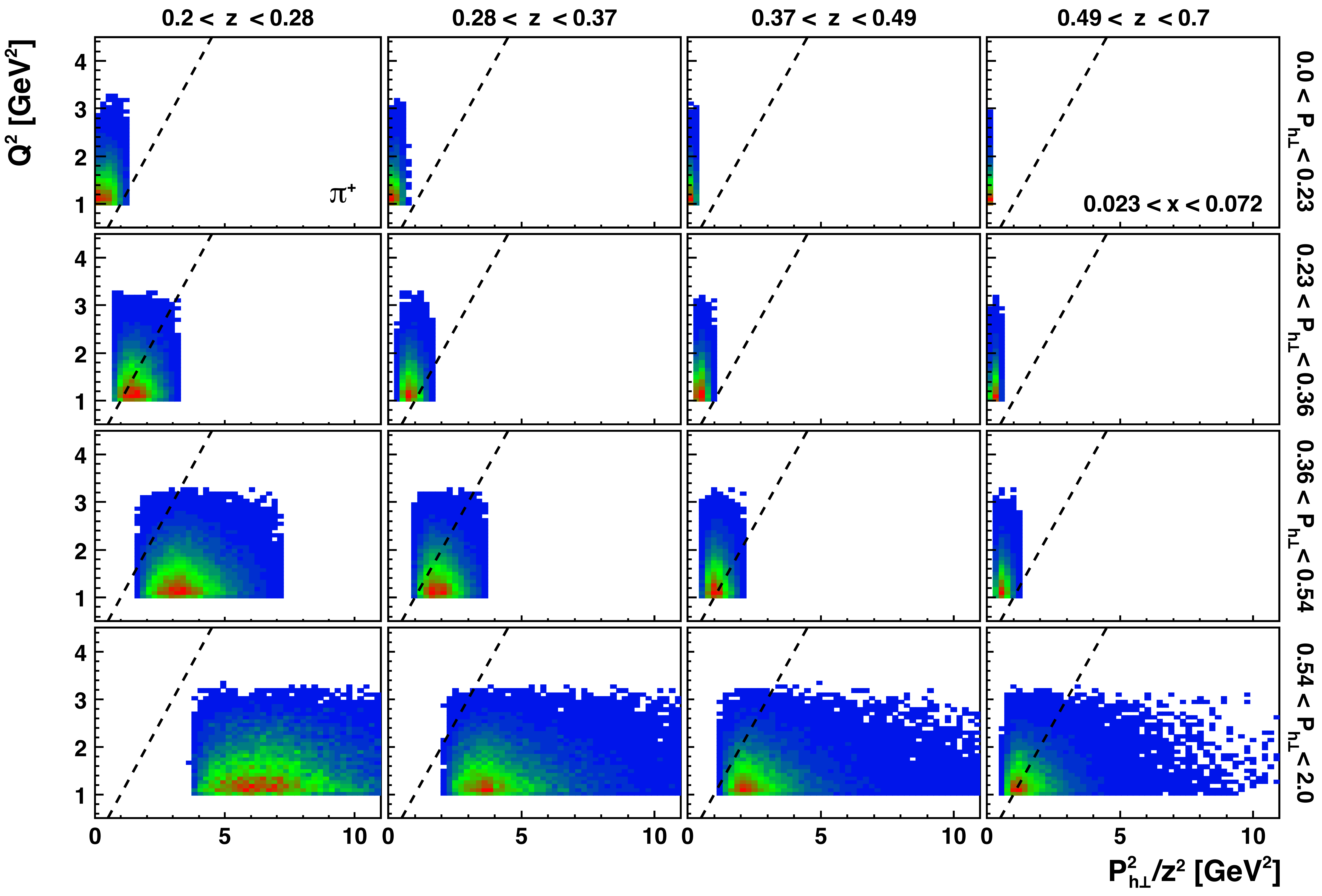
$Q^2 = 2\, P^2_{h\perp}/z^2$

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

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

semi-inclusive DIS

- excluding transverse polarization:

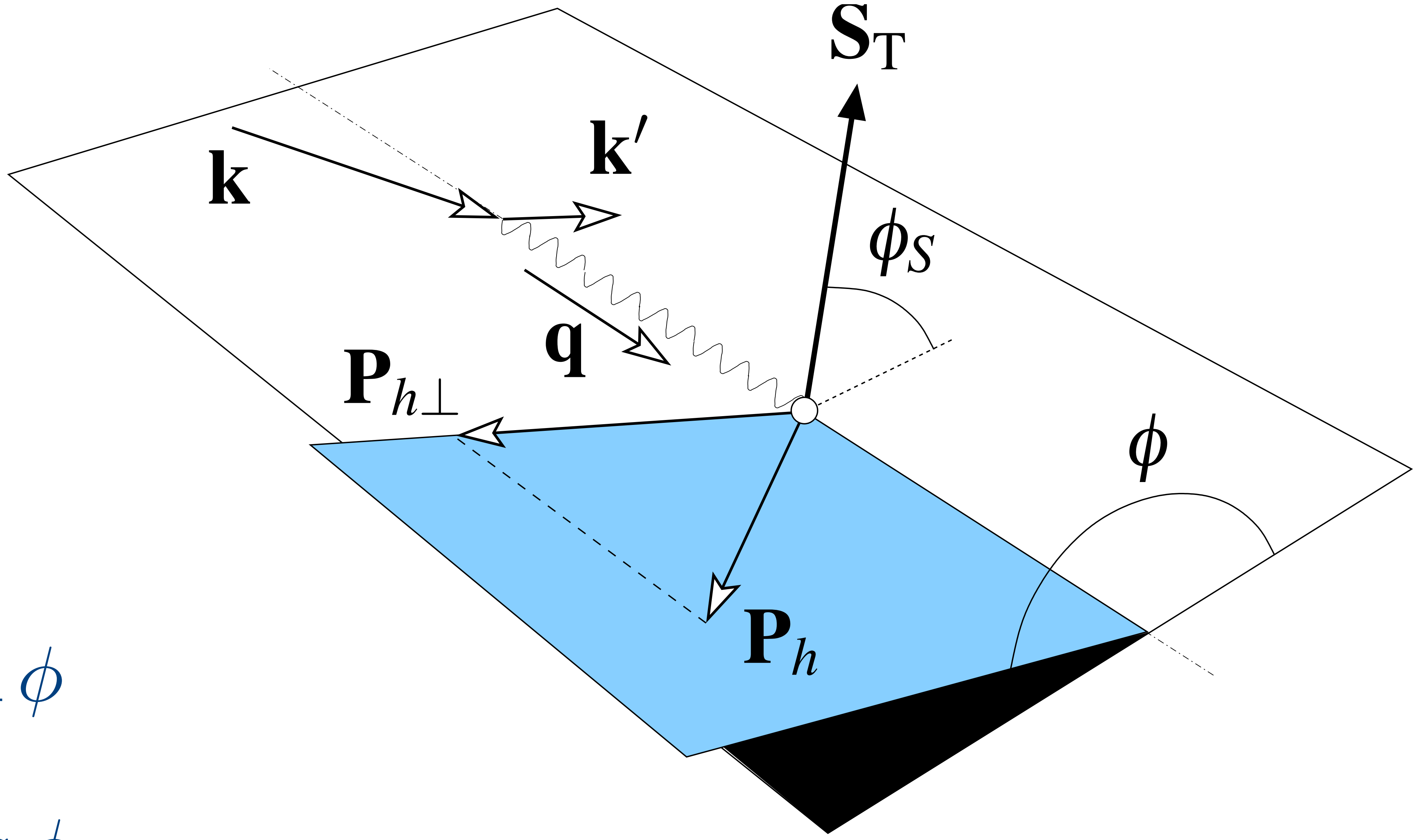
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



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

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

- excluding transverse polarization:

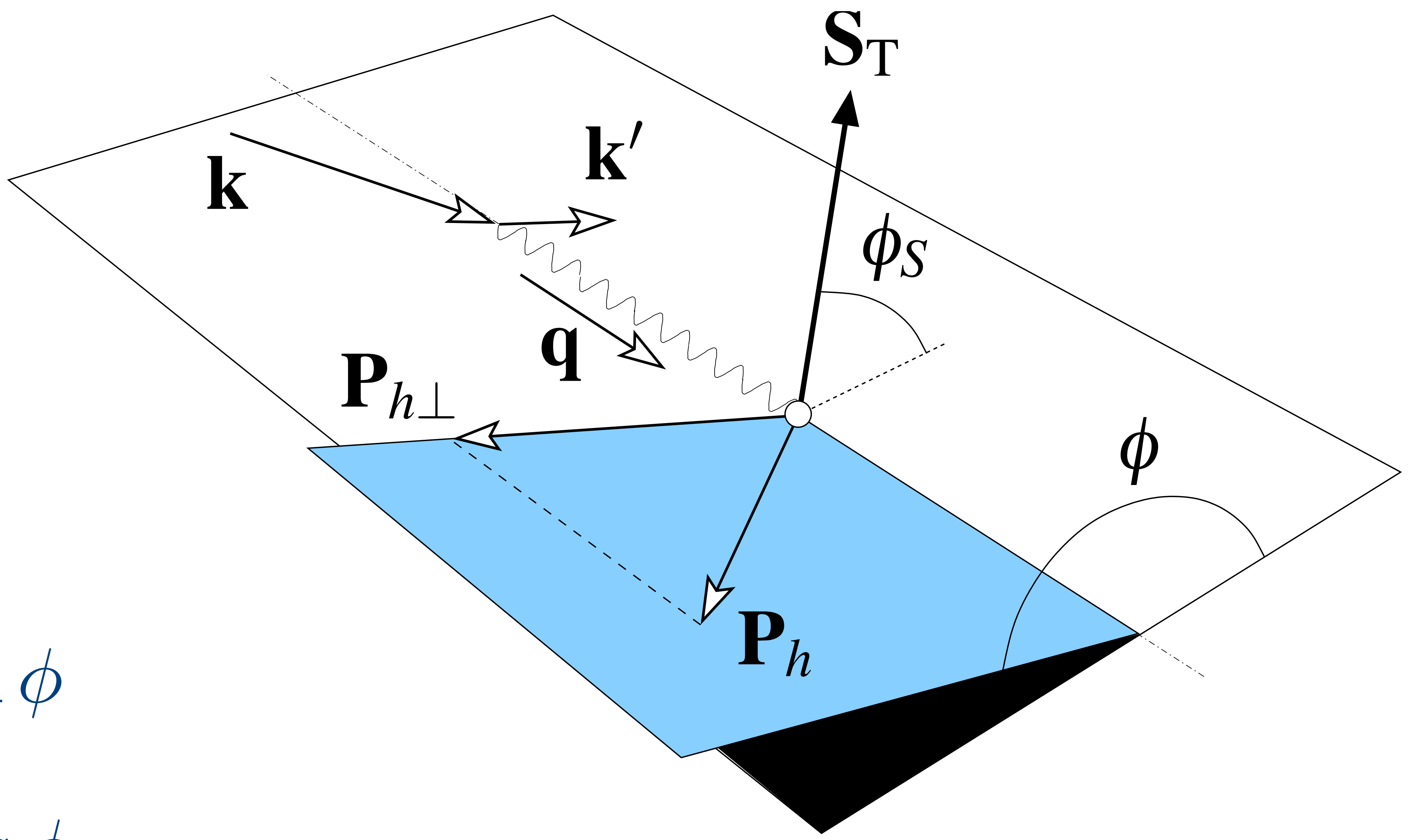
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- 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:

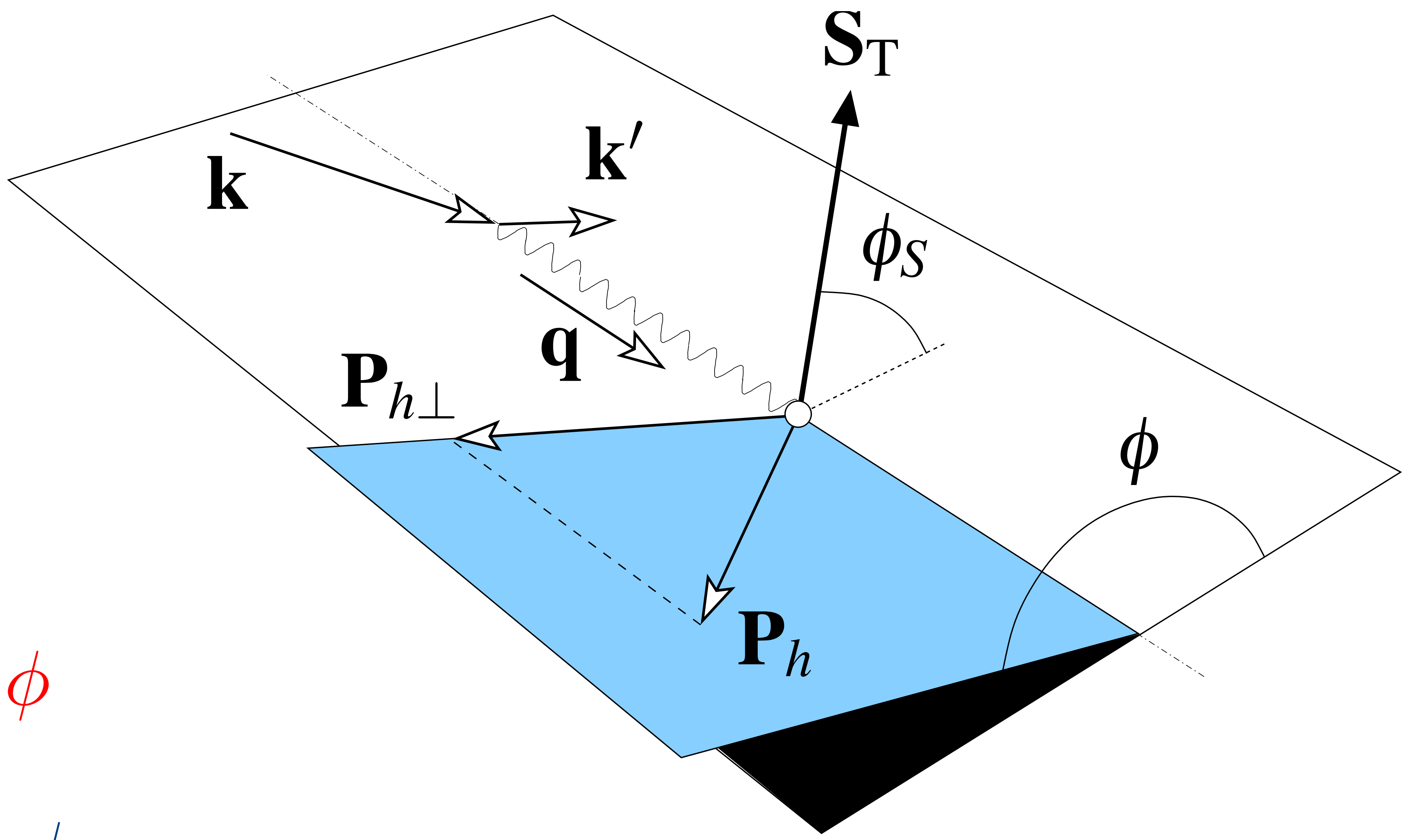
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- single-spin asymmetry:

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

  - explicit angular dependence to be fitted

semi-inclusive DIS

- with **transverse** target polarization:

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

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

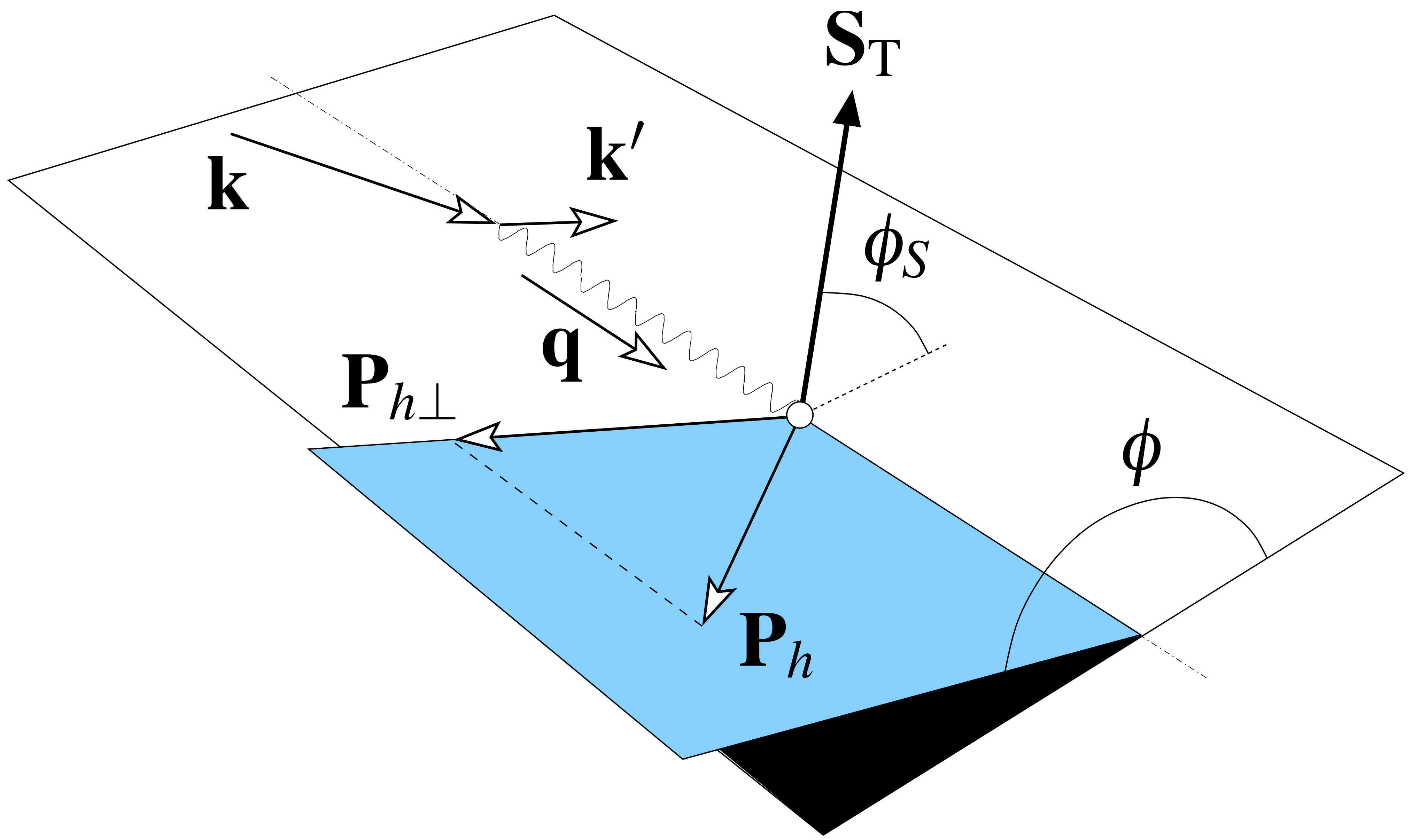
$$+ S_T \Bigg[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi-\phi_s)$$

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

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

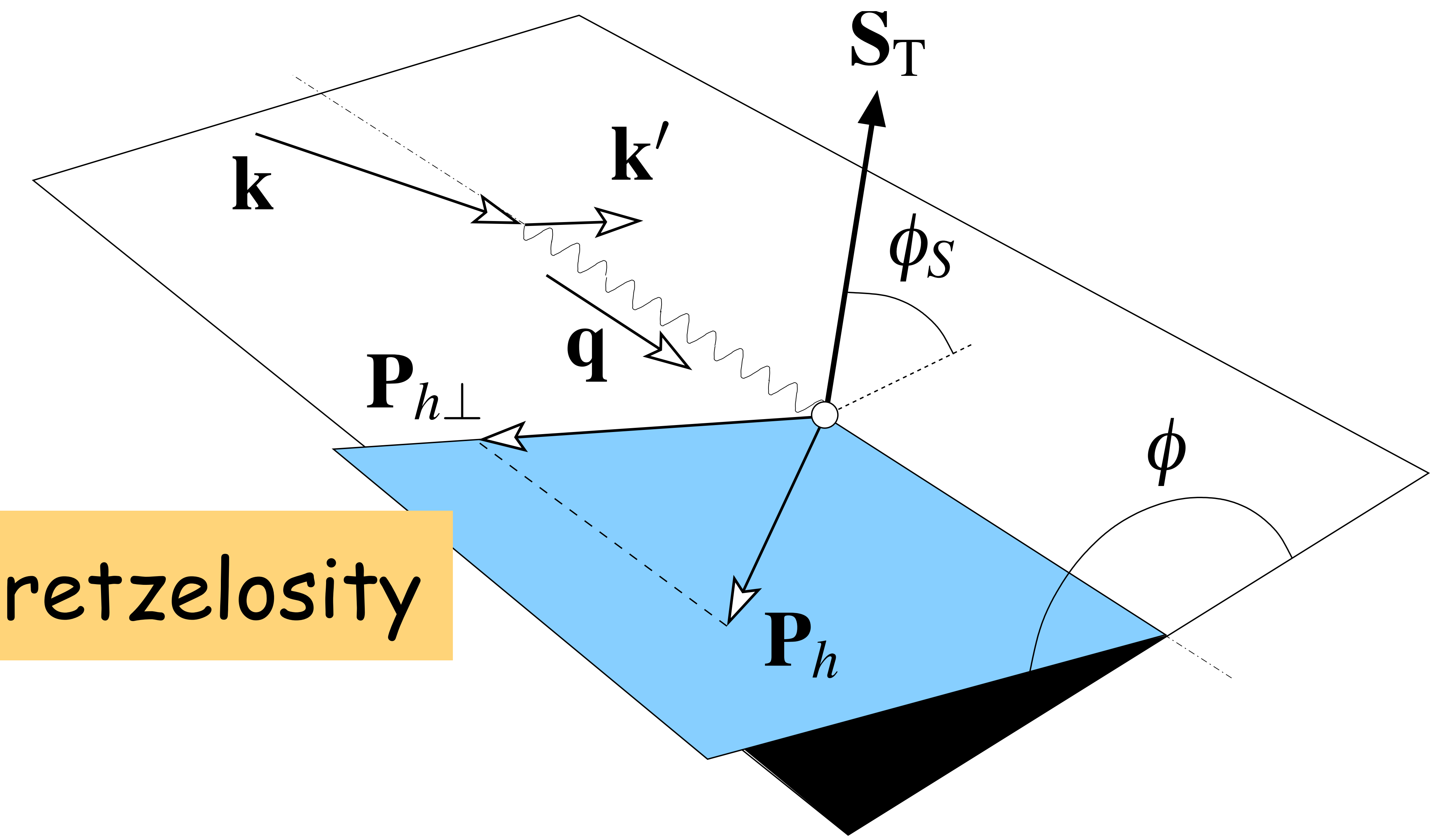
$$+ S_T\lambda \Bigg[\sqrt{1-\epsilon^2}\, F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi-\phi_s)$$

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



semi-inclusive DIS

- with **transverse** target polarization:



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

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

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

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

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

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

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

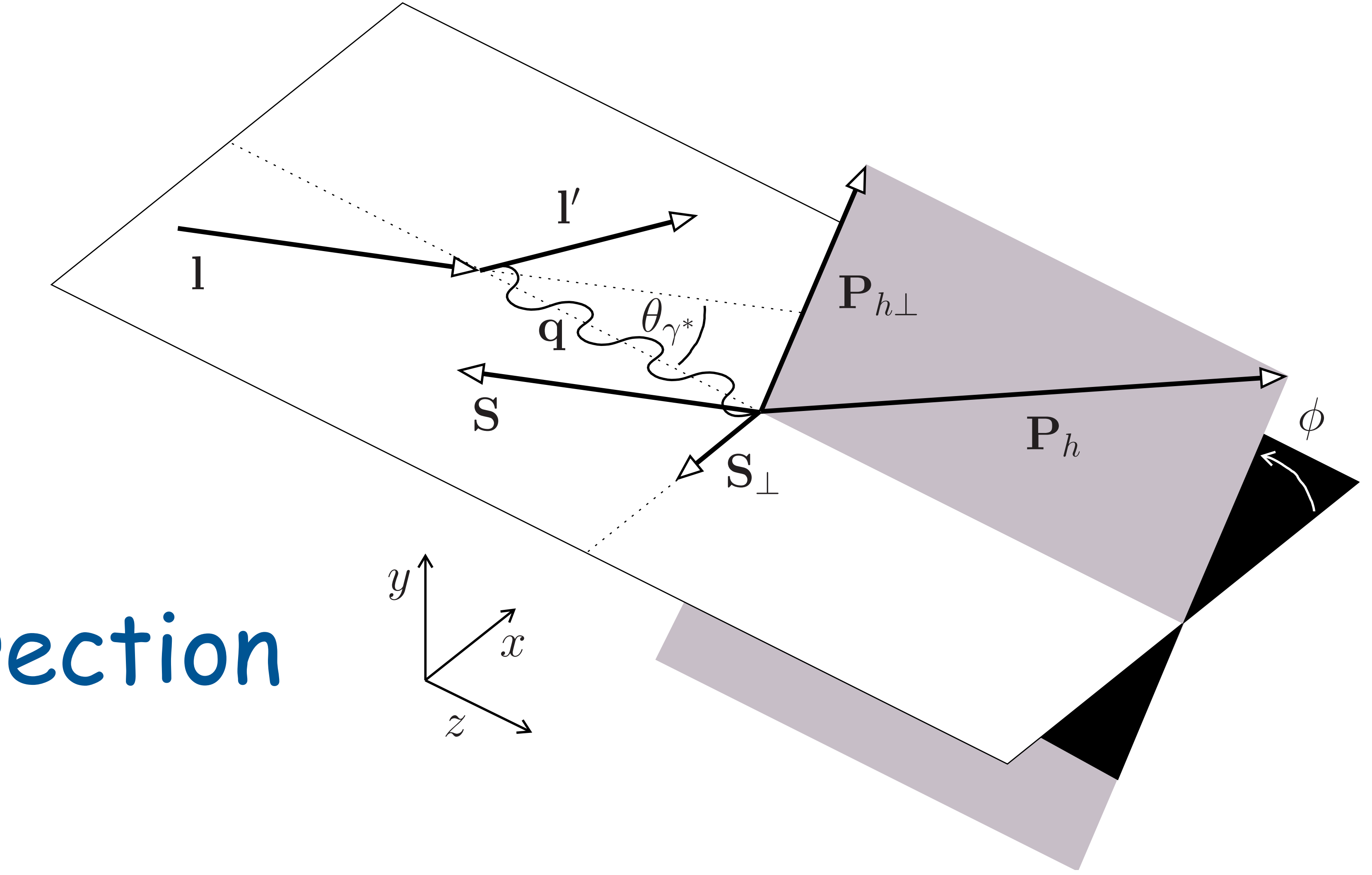
Sivers

pretzelosity

transversity

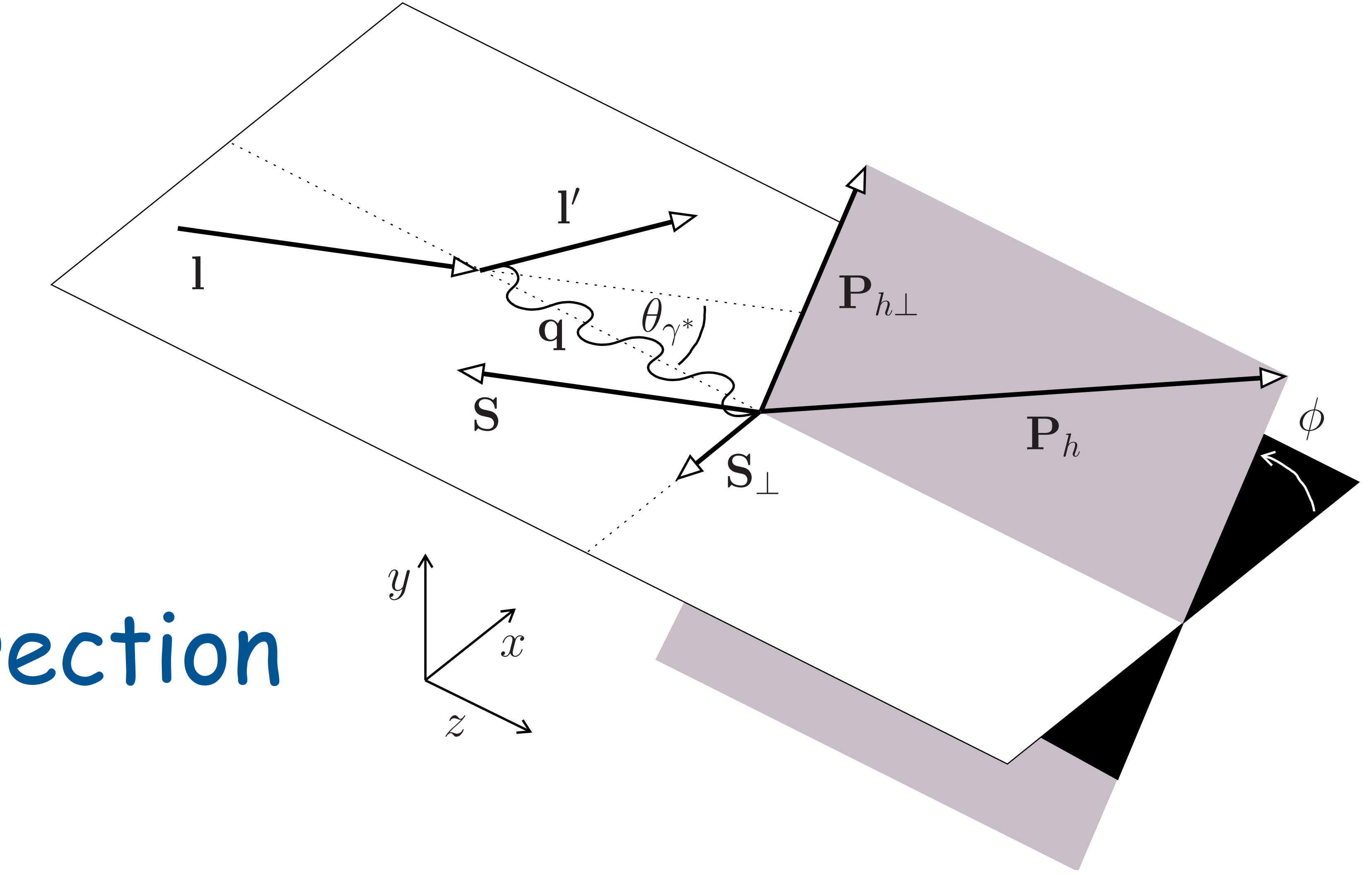
worm-gear

mixing of target polarizations



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

mixing of target polarizations

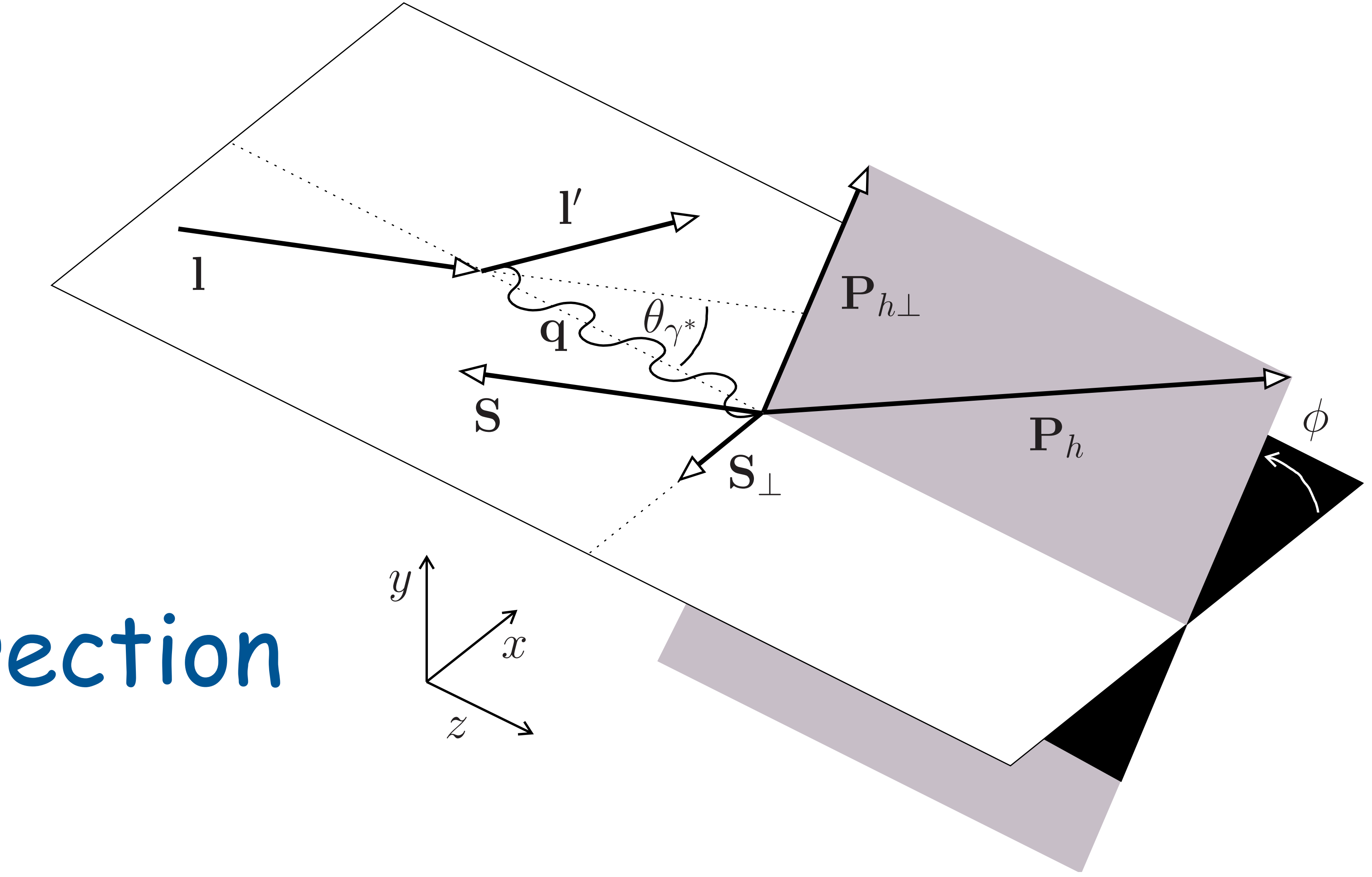


- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

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

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

mixing of target polarizations



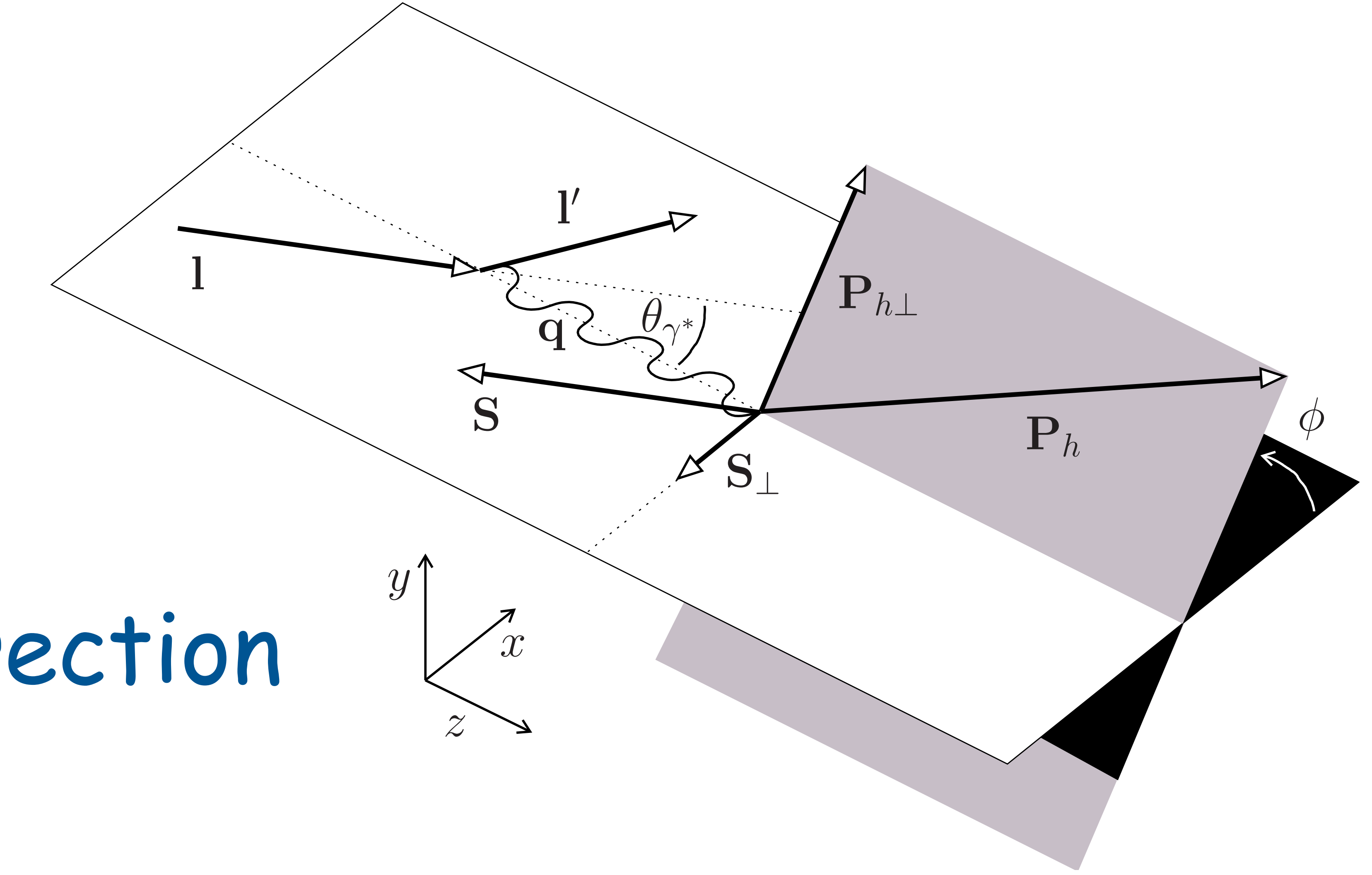
- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

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

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

➡ need data on same target for both polarization orientations!

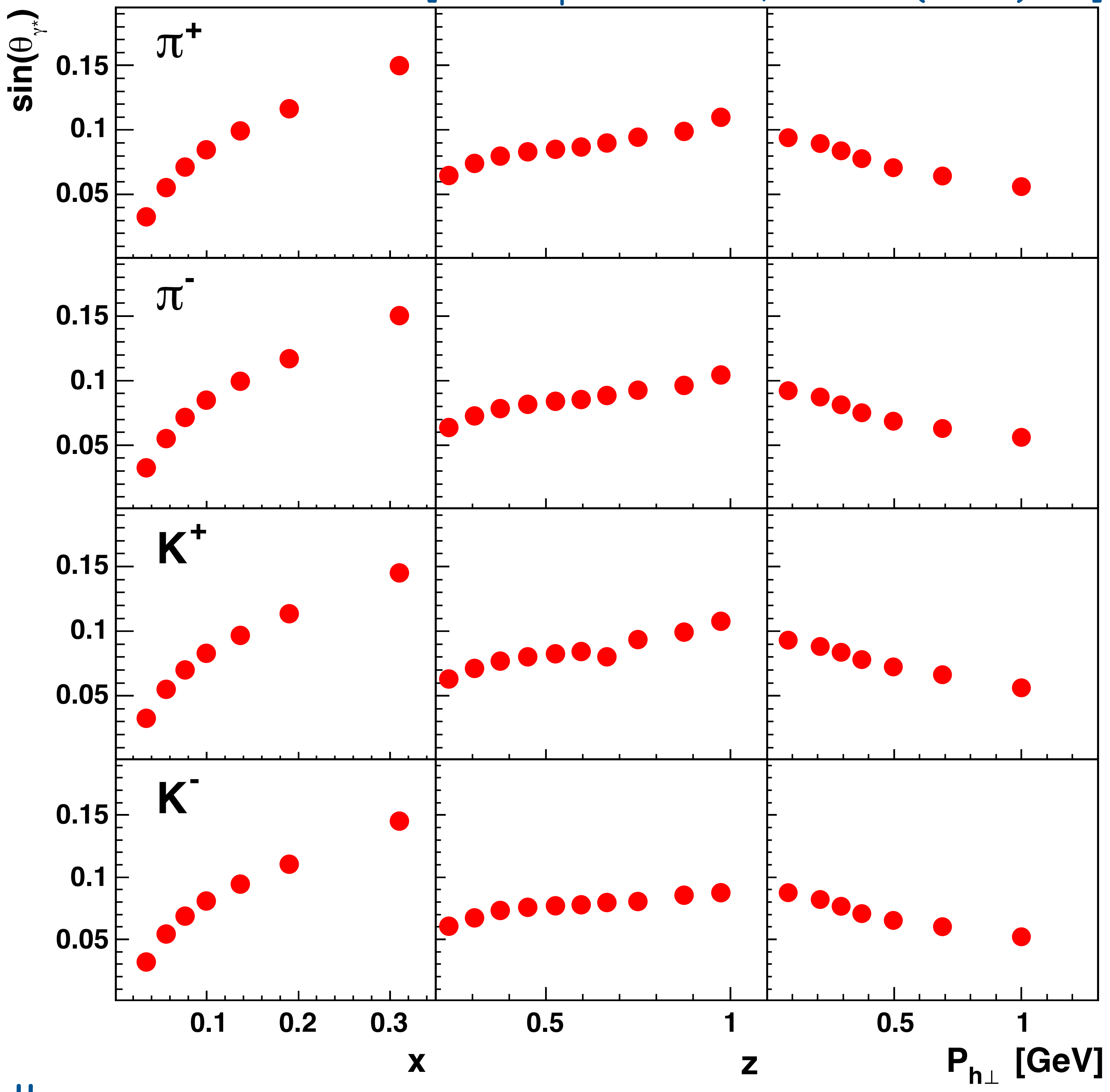
mixing of target polarizations

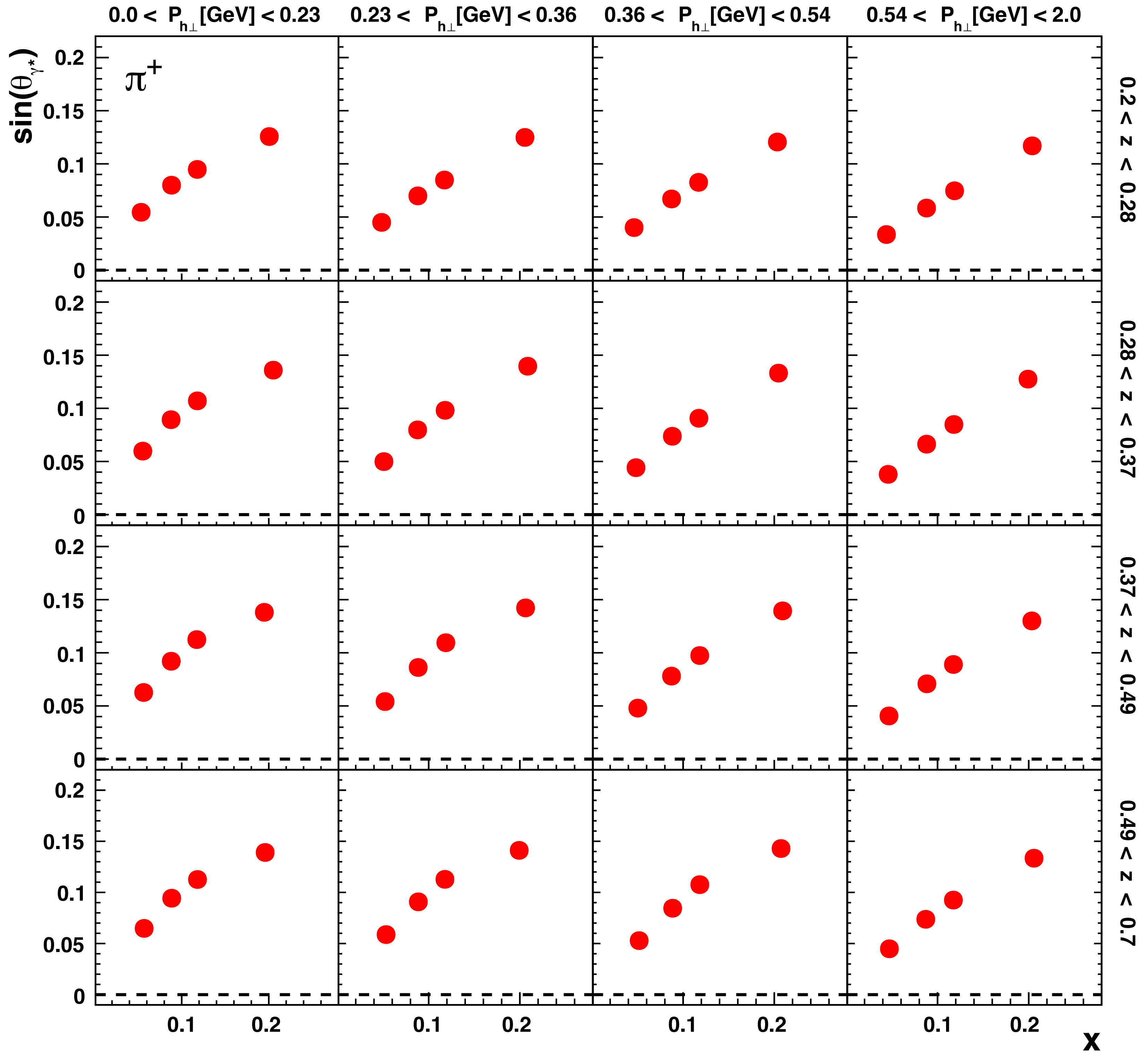


- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

➡ mixing of longitudinal and transverse polarization effects

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





some highlights

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**

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

  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**

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**

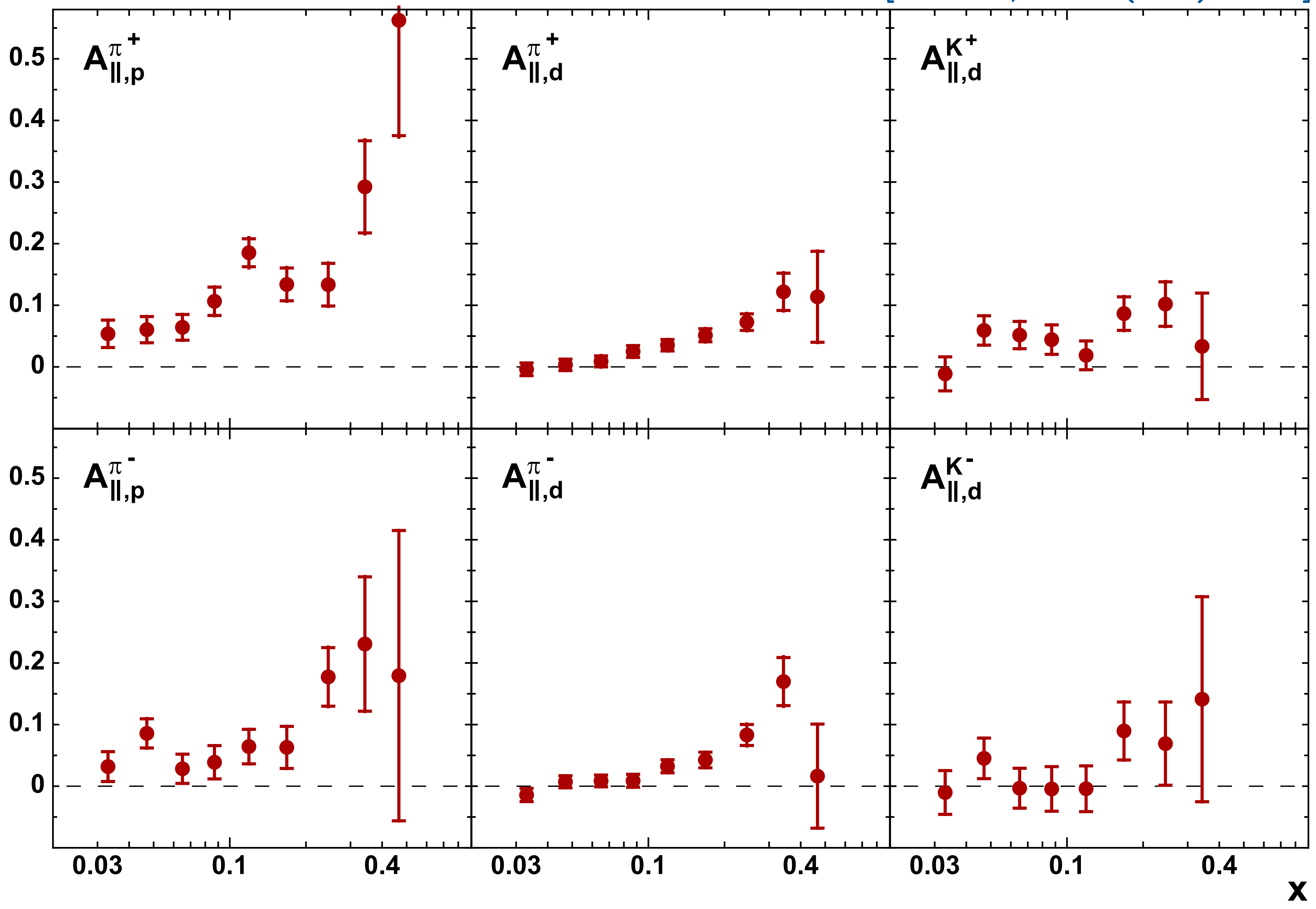
$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_\parallel^h \qquad D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

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 … consistent with zero***

x dependence of $A_{||}$

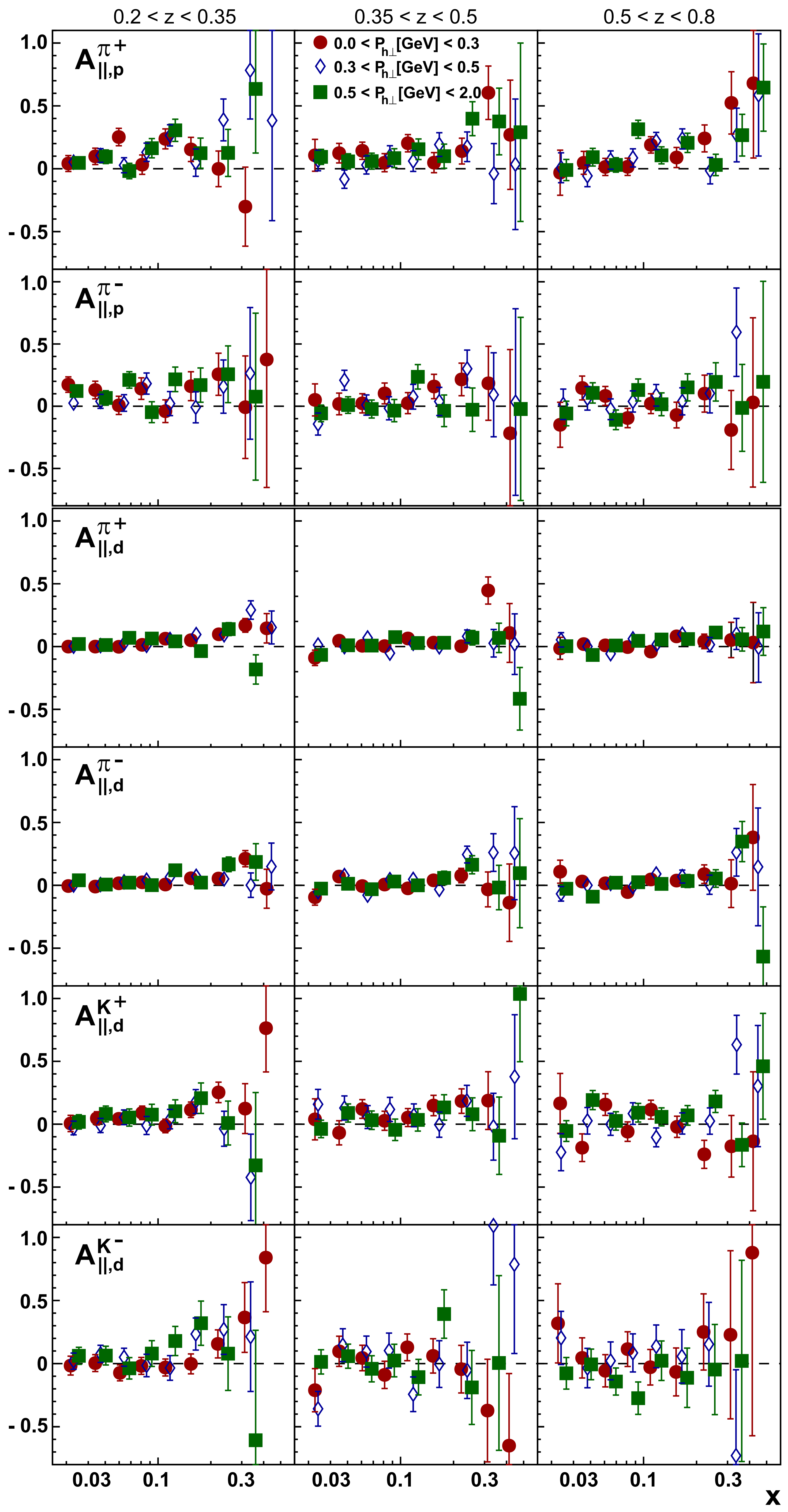
[HERMES, PRD 99 (2019) 112001]



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

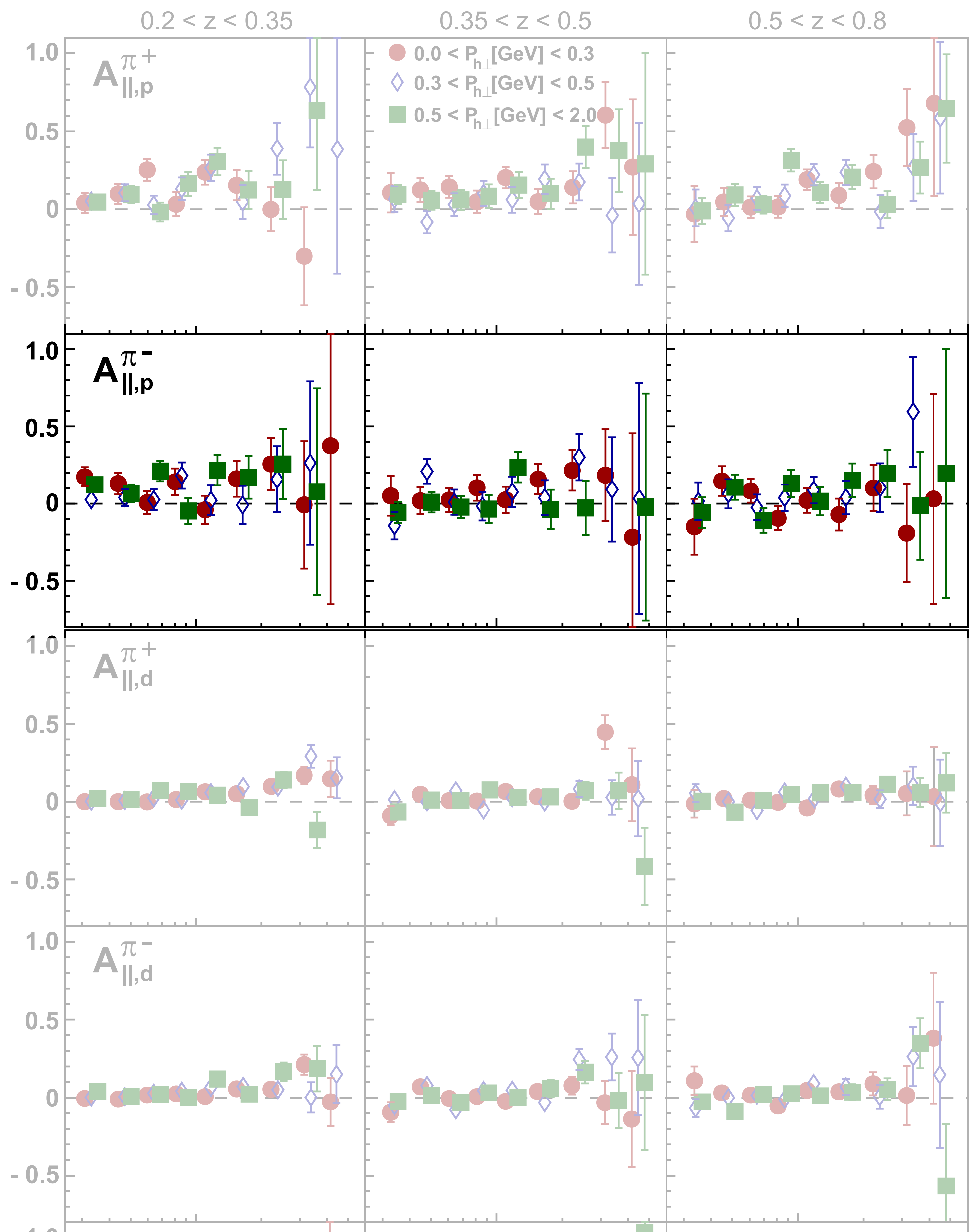
3-dimensional binning

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

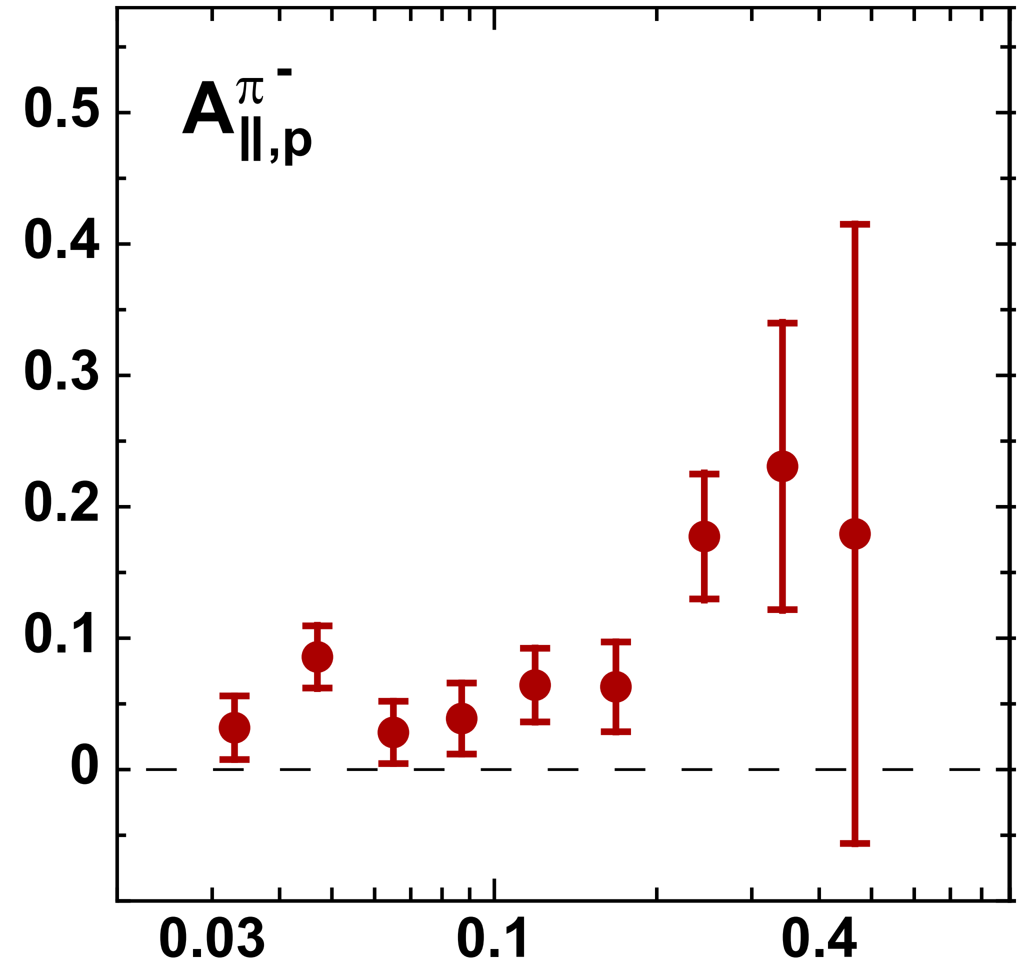


3-dimensional binning

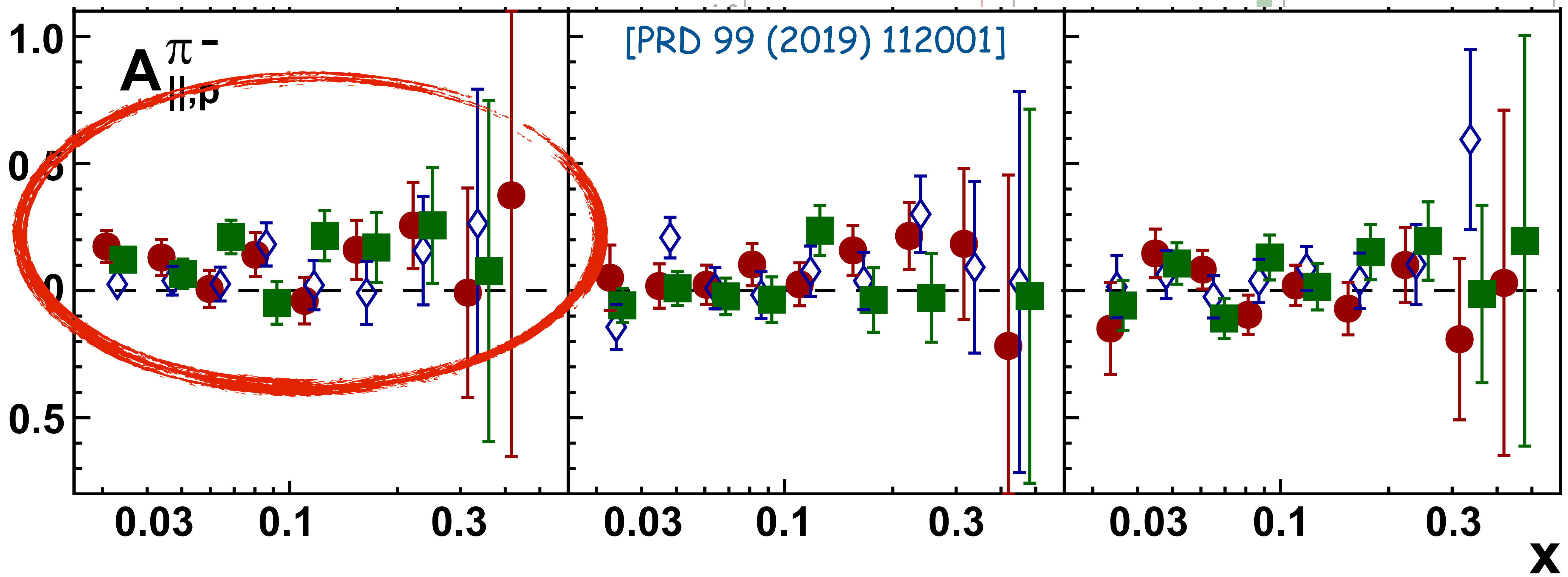
- **first-ever 3d binning** provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - π^- asymmetries mainly coming from **low-z** region where **disfavored fragmentation** large and thus **sensitivity** to the large **positive up-quark polarization**



1d



3d



JHEP

Published for SISSA by Springer

Received: *July 31, 2020*
Accepted: *October 4, 2020*
Published: *December 2, 2020*

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

hermes

The HERMES Collaboration

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E.C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26,a] A. Bacchetta,[21] S. Belostotski,[19,a] V. Bryzgalov,[20] G.P. Capitani,[11] E. Cisbani,[22] G. Ciullo,[10] M. Contalbrigo,[10] W. Deconinck,[6] R. De Leo,[2] 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,[23] G. Gavrilov,[6,19,23] V. Gharibyan,[26] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H.E. Jackson,[1,a] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[6,26] E. Kinney,[5] A. Kisselev,[19] V. Kozlov,[17] P. Kravchenko,[9,19] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] P. Lenisa,[10] W. Lorenzon,[16] S.I. Manaenkov,[19] B. Marianski,[25,a] H. Marukyan,[26] Y. Miyachi,[24] A. Movsisyan,[10,26] V. Muccifora,[11] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L.L. Pappalardo,[10] 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] A. Schäfer,[21] G. Schnell,[3,4,12] B. Seitz,[14] T.-A. Shibata,[24] V. Shutov,[8] M. Statera,[10] A. Terkulov,[17] M. Tytgat,[12] Y. Van Haarlem,[12] C. Van Hulse,[12] D. Veretennikov,[3,19] I. Vilardi,[2] S. Yaschenko,[9] D. Zeiler,[9] B. Zihlmann[6] and P. Zupranski[25]

[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, U.S.A.*
[2] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy*
[3] *Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain*
[5] *Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, U.S.A.*
[6] *DESY, 22603 Hamburg, Germany*
[7] *DESY, 15738 Zeuthen, Germany*
[8] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[a] Deceased.

https://doi.org/10.1007/JHEP12(2020)010

JHEP12(2020)010

Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi + \phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi - \phi_S)$	[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]	✓	(✓)	(✓)				
$\cos(\phi + \phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi - \phi_S)$								

JHEP

Published for SISSA by Springer

Received: July 31, 2020
Accepted: October 4, 2020
Published: December 2, 2020

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

JHEP12(2020)010

hermes

The HERMES Collaboration

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E.C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26,a] A. Bacchetta,[21] S. Belostotski,[19,a] V. Bryzgalov,[20] G.P. Capitani,[11] E. Cisbani,[22] G. Ciullo,[10] M. Contalbrigo,[10] W. Deconinck,[6] R. De Leo,[2] 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,[23] G. Gavrilov,[6,19,23] V. Gharibyan,[26] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H.E. Jackson,[1,a] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[6,26] E. Kinney,[5] A. Kisselev,[19] V. Kozlov,[17] P. Kravchenko,[9,19] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] P. Lenisa,[10] W. Lorenzon,[16] S.I. Manaenkov,[19] B. Marianski,[25,a] H. Marukyan,[26] Y. Miyachi,[24] A. Movsisyan,[10,26] V. Muccifora,[11] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L.L. Pappalardo,[10] 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] A. Schäfer,[21] G. Schnell,[3,4,12] B. Seitz,[14] T.-A. Shibata,[24] V. Shutov,[8] M. Statera,[10] A. Terkulov,[17] M. Tytgat,[12] Y. Van Haarlem,[12] C. Van Hulse,[12] D. Veretennikov,[3,19] I. Vilardi,[2] S. Yaschenko,[9] D. Zeiler,[9] B. Zihlmann[6] and P. Zupranski[25]

[1] Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, U.S.A.
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy
[3] Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain
[4] IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain
[5] Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, U.S.A.
[6] DESY, 22603 Hamburg, Germany
[7] DESY, 15738 Zeuthen, Germany
[8] Joint Institute for Nuclear Research, 141980 Dubna, Russia

[a] Deceased.

https://doi.org/10.1007/JHEP12(2020)010

Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

95%

JHEP
Published for SISSA by Springer
Received: July 31, 2020
Accepted: October 4, 2020
Published: December 2, 2020

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

JHEP12(2020)010

hermes

The HERMES Collaboration

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E.C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26,a] A. Bacchetta,[21] S. Belostotski,[19,a] V. Bryzgalov,[20] G.P. Capitani,[11] E. Cisbani,[22] G. Ciullo,[10] M. Contalbrigo,[10] W. Deconinck,[6] R. De Leo,[2] 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,[23] G. Gavrilov,[6,19,23] V. Gharibyan,[26] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H.E. Jackson,[1,a] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[6,26] E. Kinney,[5] A. Kisselev,[19] V. Kozlov,[17] P. Kravchenko,[9,19] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] P. Lenisa,[10] W. Lorenzon,[16] S.I. Manaenkov,[19] B. Marianski,[25,a] H. Marukyan,[26] Y. Miyachi,[24] A. Movsisyan,[10,26] V. Muccifora,[11] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L.L. Pappalardo,[10] 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] A. Schäfer,[21] G. Schnell,[3,4,12] B. Seitz,[14] T.-A. Shibata,[24] V. Shutov,[8] M. Statera,[10] A. Terkulov,[17] M. Tytgat,[12] Y. Van Haarlem,[12] C. Van Hulse,[12] D. Veretennikov,[3,19] I. Vilardi,[2] S. Yaschenko,[9] D. Zeiler,[9] B. Zihlmann[6] and P. Zupranski[25]

[1] Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843, U.S.A.
[2] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70124 Bari, Italy
[3] Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain
[4] IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain
[5] Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0390, U.S.A.
[6] DESY, 22603 Hamburg, Germany
[7] DESY, 15738 Zeuthen, Germany
[8] Joint Institute for Nuclear Research, 141980 Dubna, Russia

[a] Deceased.

https://doi.org/10.1007/JHEP12(2020)010

3d

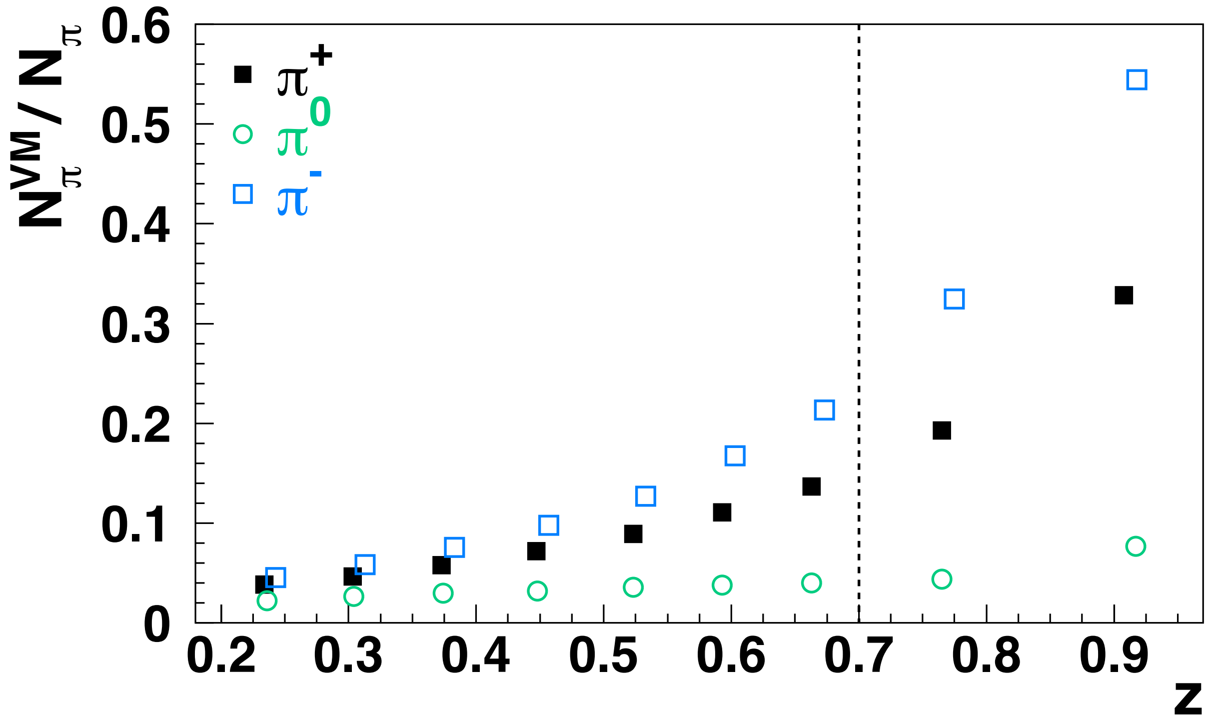
1d

Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

95%

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

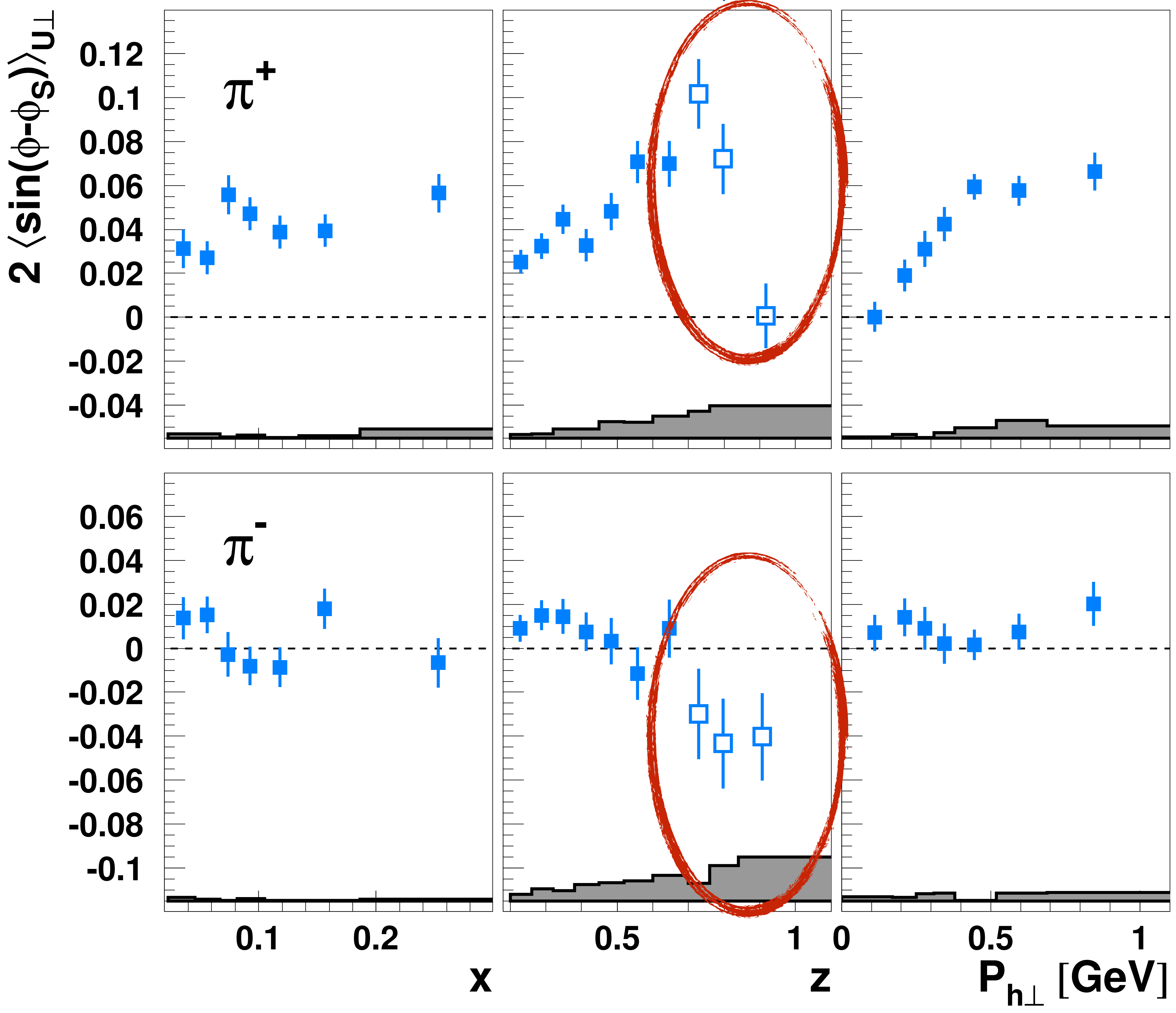


Sivers amplitudes for pions

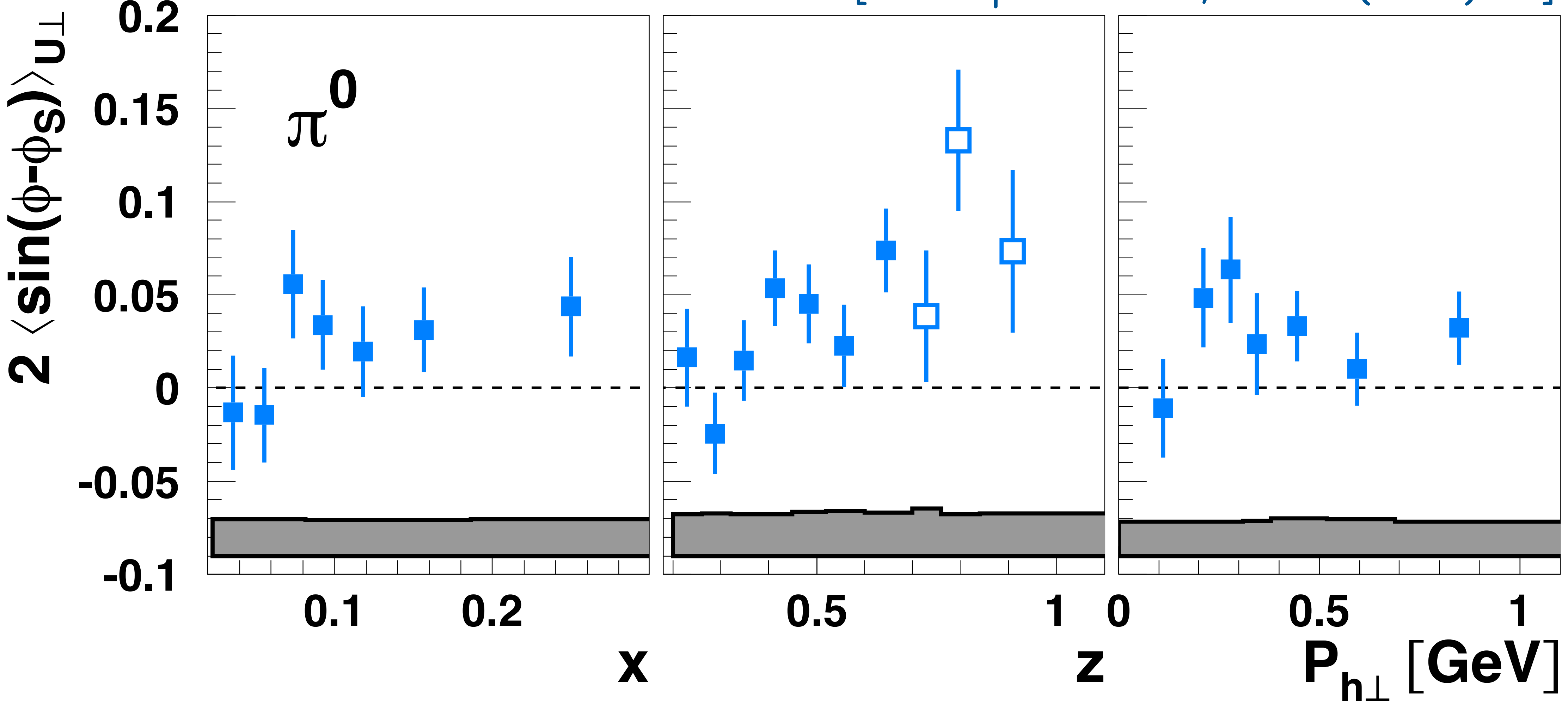
- **high-z data** probes region of **increased flavor sensitivity** to struck quark (but also where contributions from exclusive vector-meson production becomes significant)

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

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



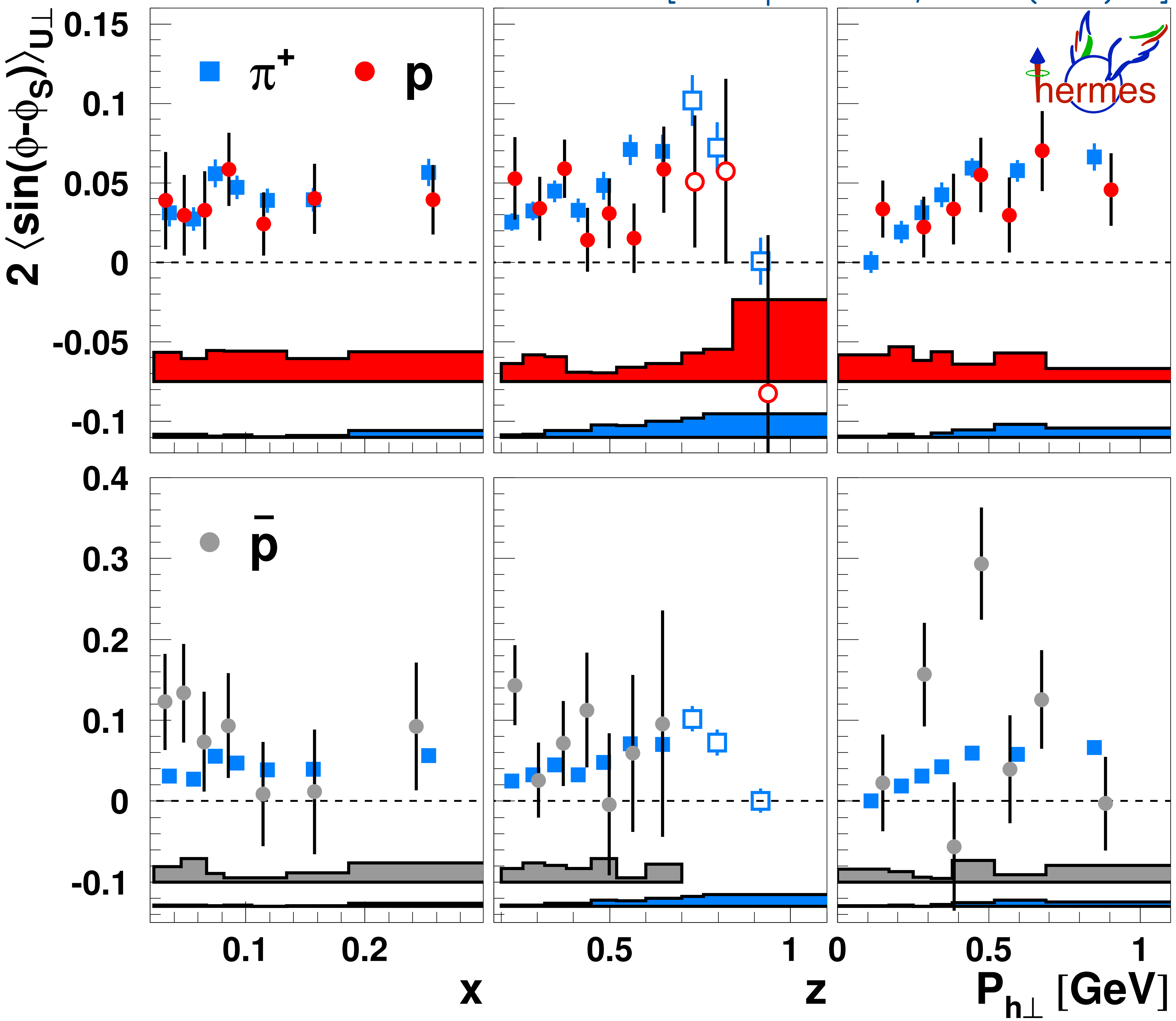
[A. Airapetian et al., JHEP12(2020)010]



	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]



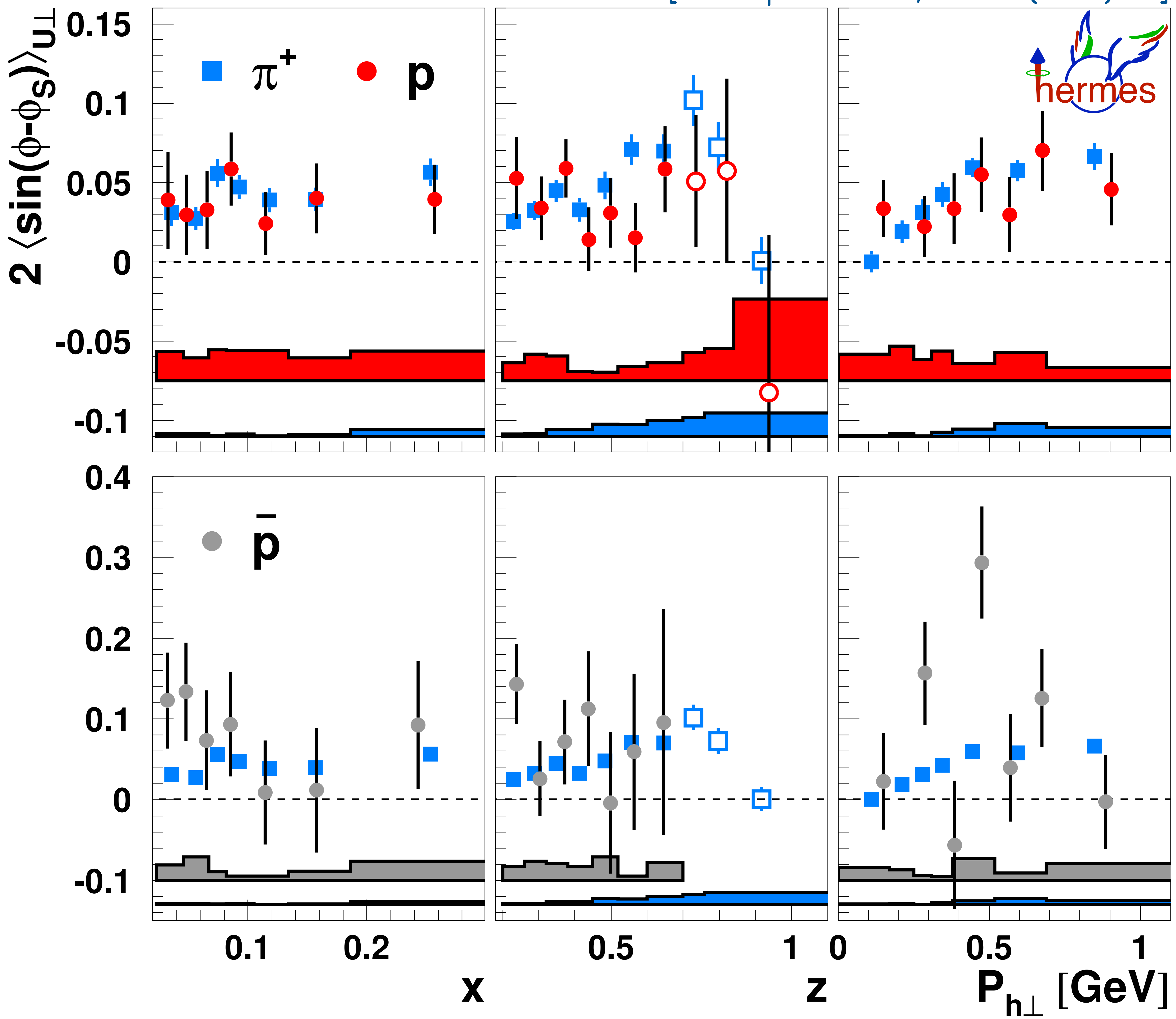
similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

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

Sivers amplitudes
pions vs. (anti)protons

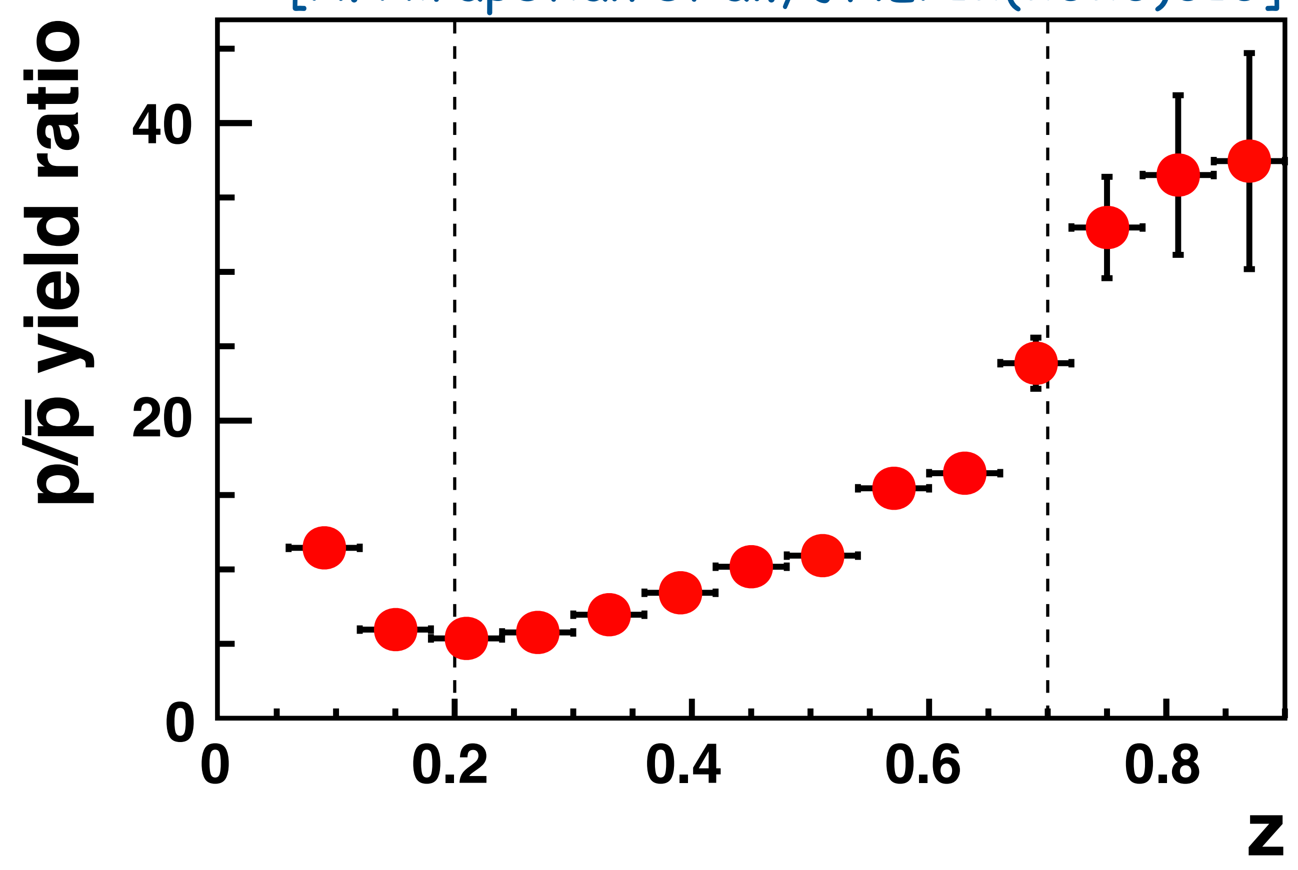
[A. Airapetian et al., JHEP12(2020)010]



similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

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

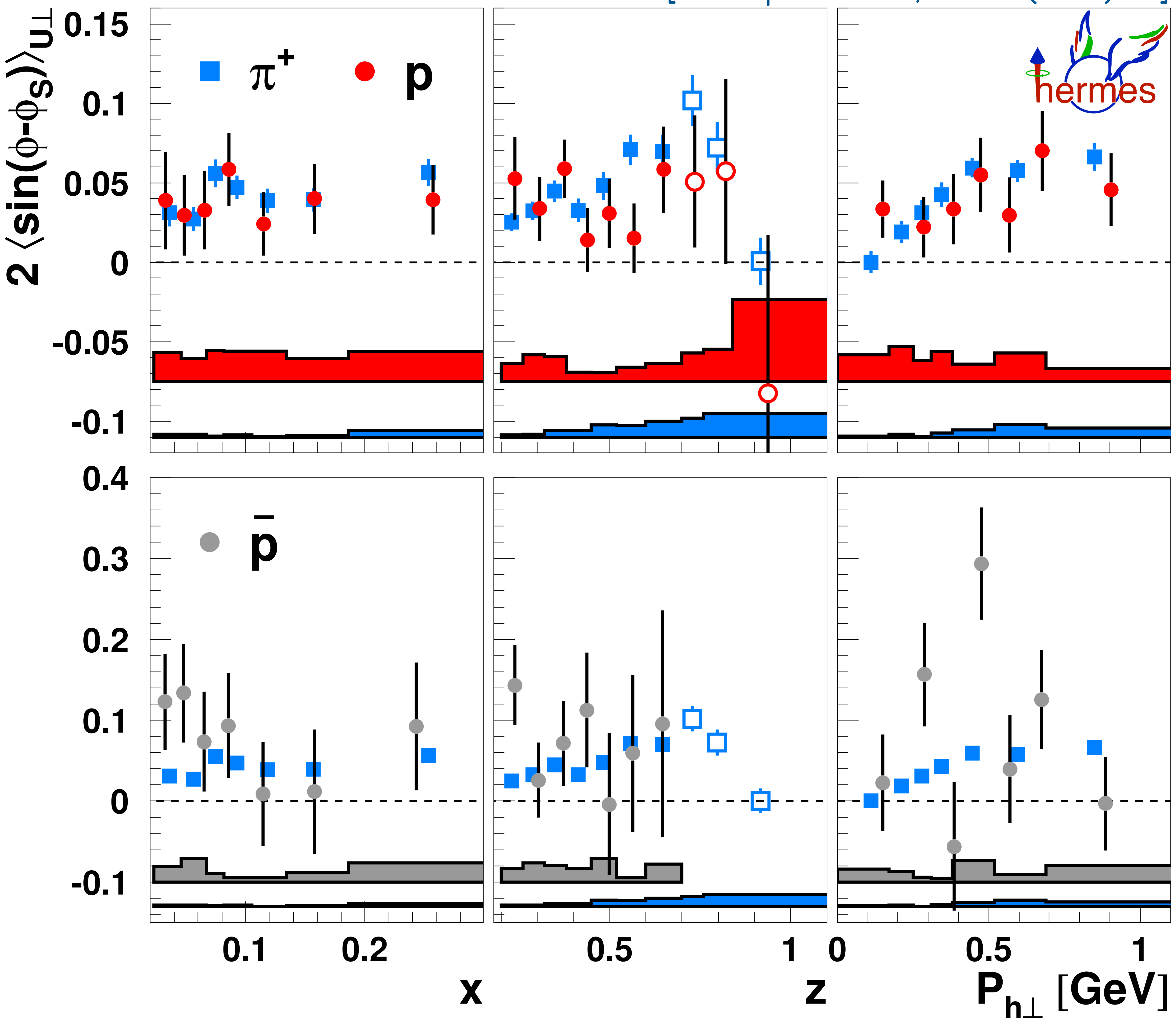


possibly, onset of target fragmentation only at lower z

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

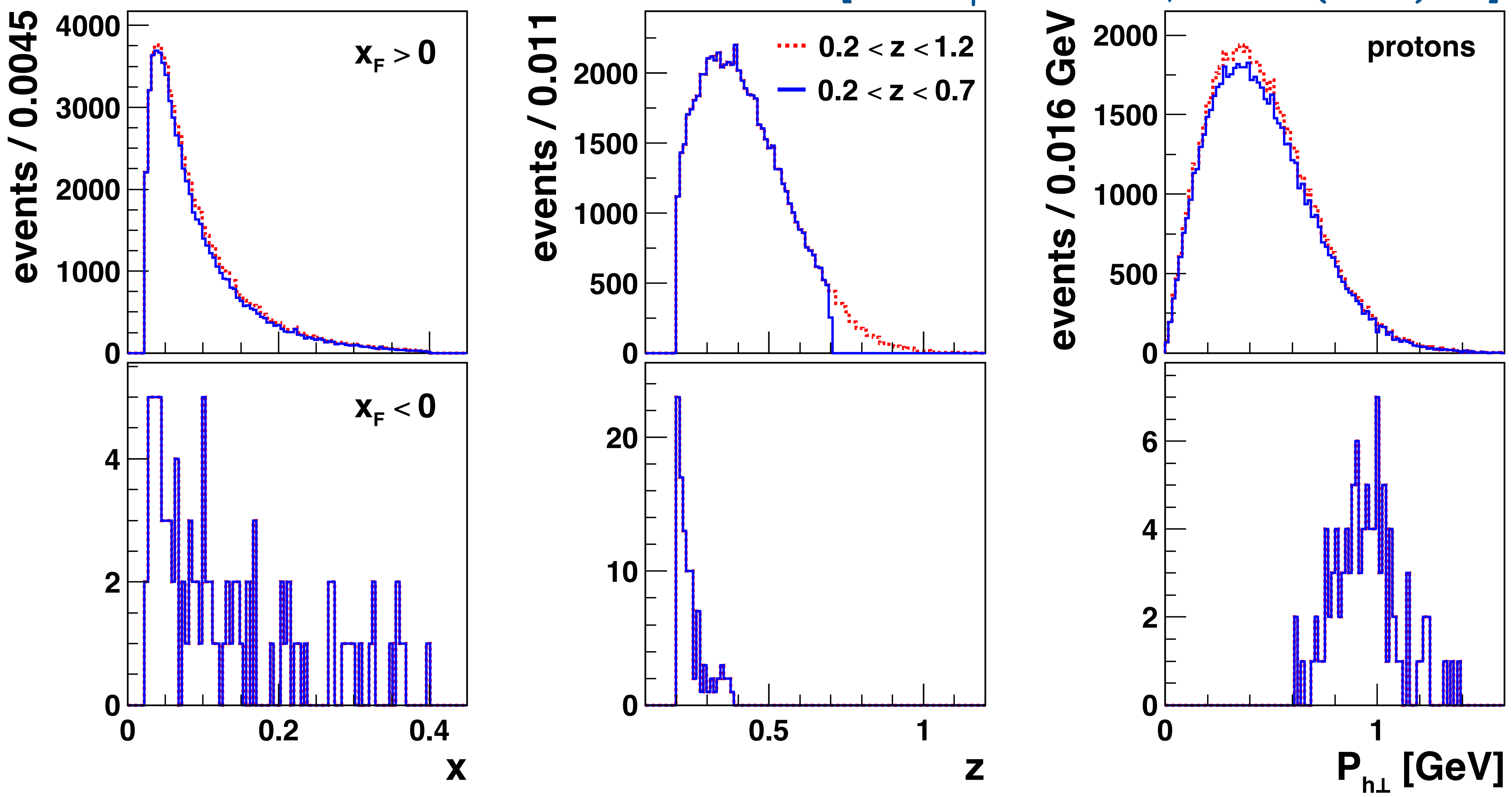
Sivers amplitudes
pions vs. (anti)protons

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



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

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

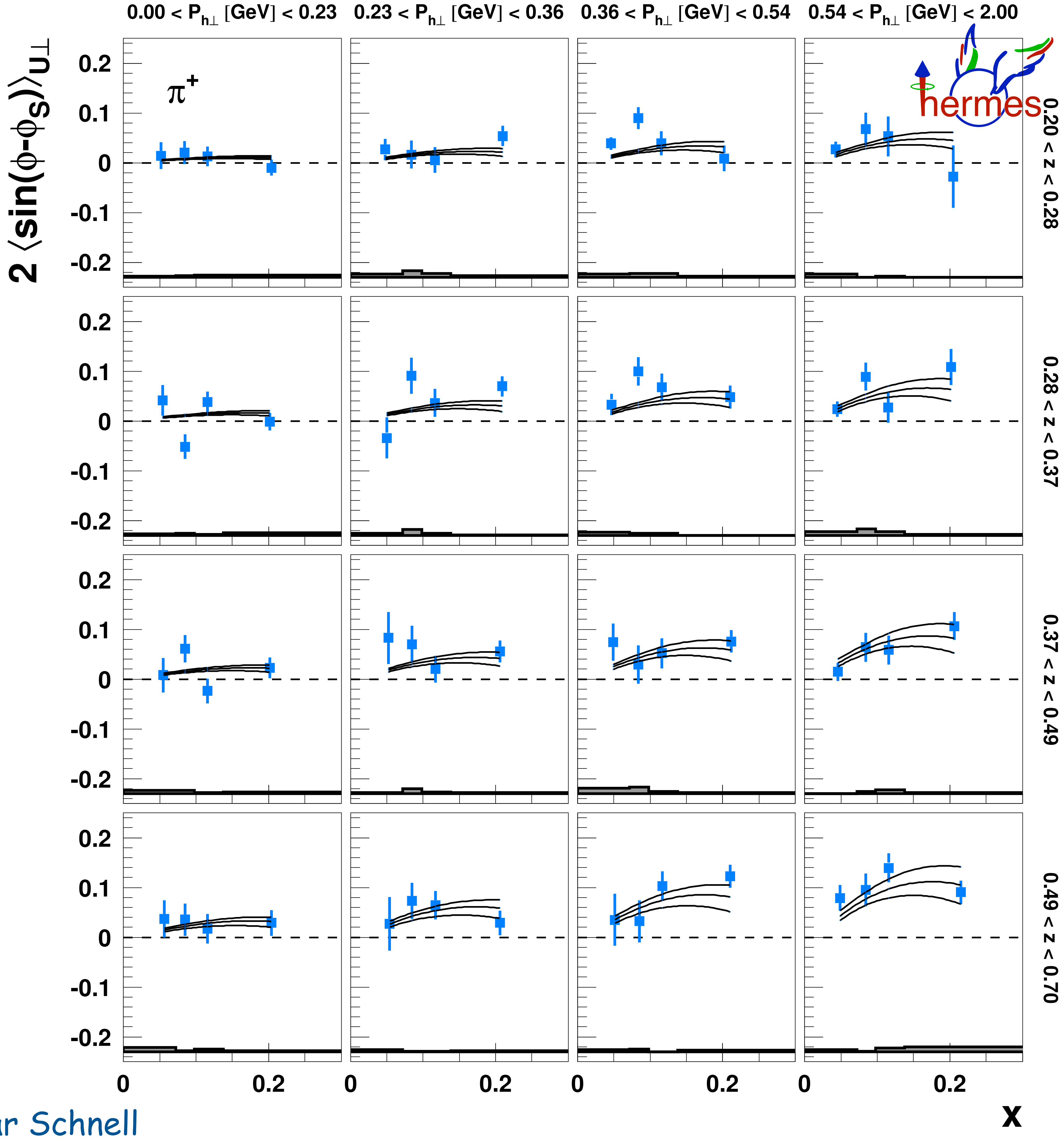


possibly, onset of target fragmentation only at lower z

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

Sivers amplitudes multi-dimensional analysis

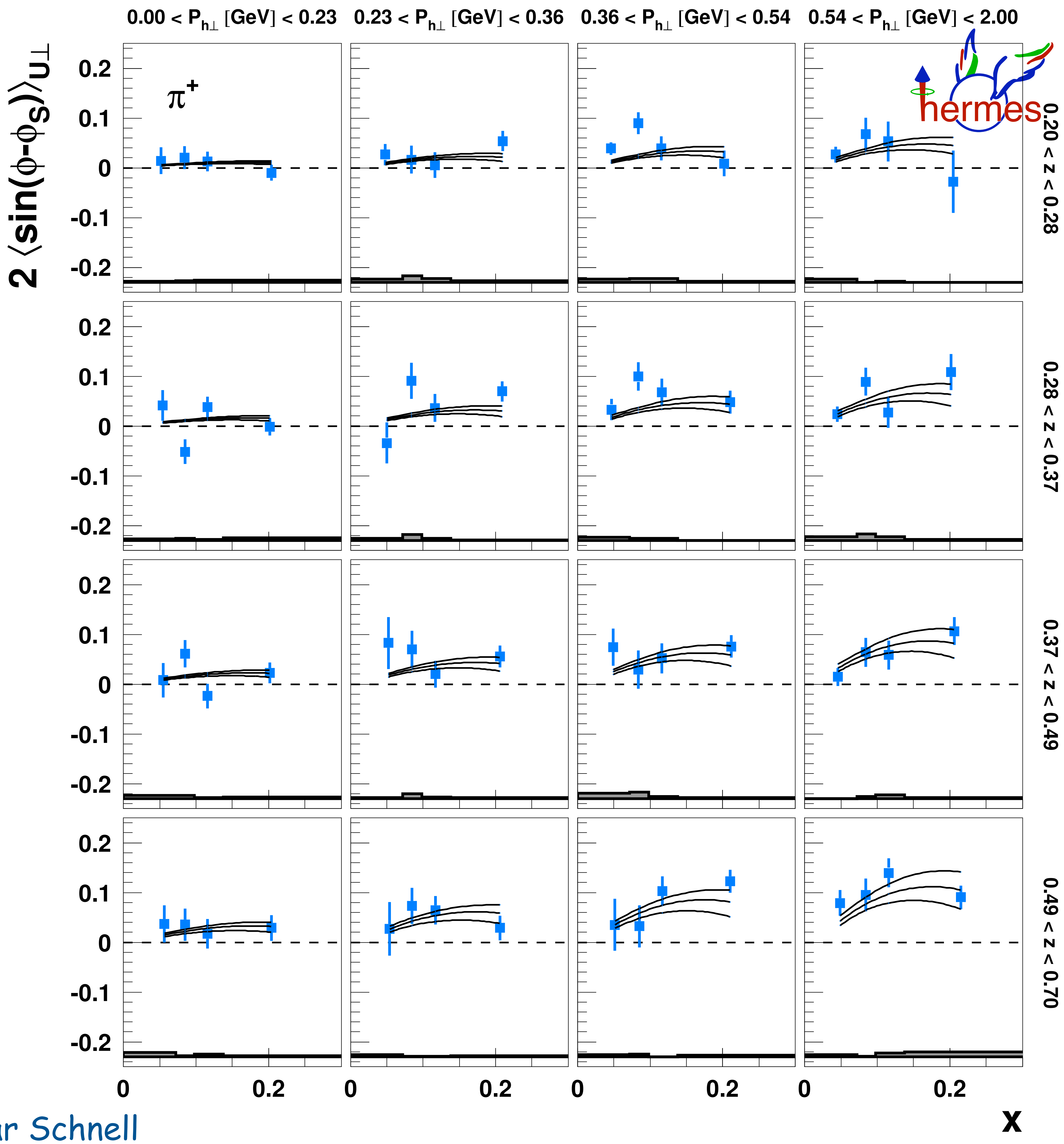
[A. Airapetian et al., JHEP12(2020)010]



	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 multi-dimensional analysis

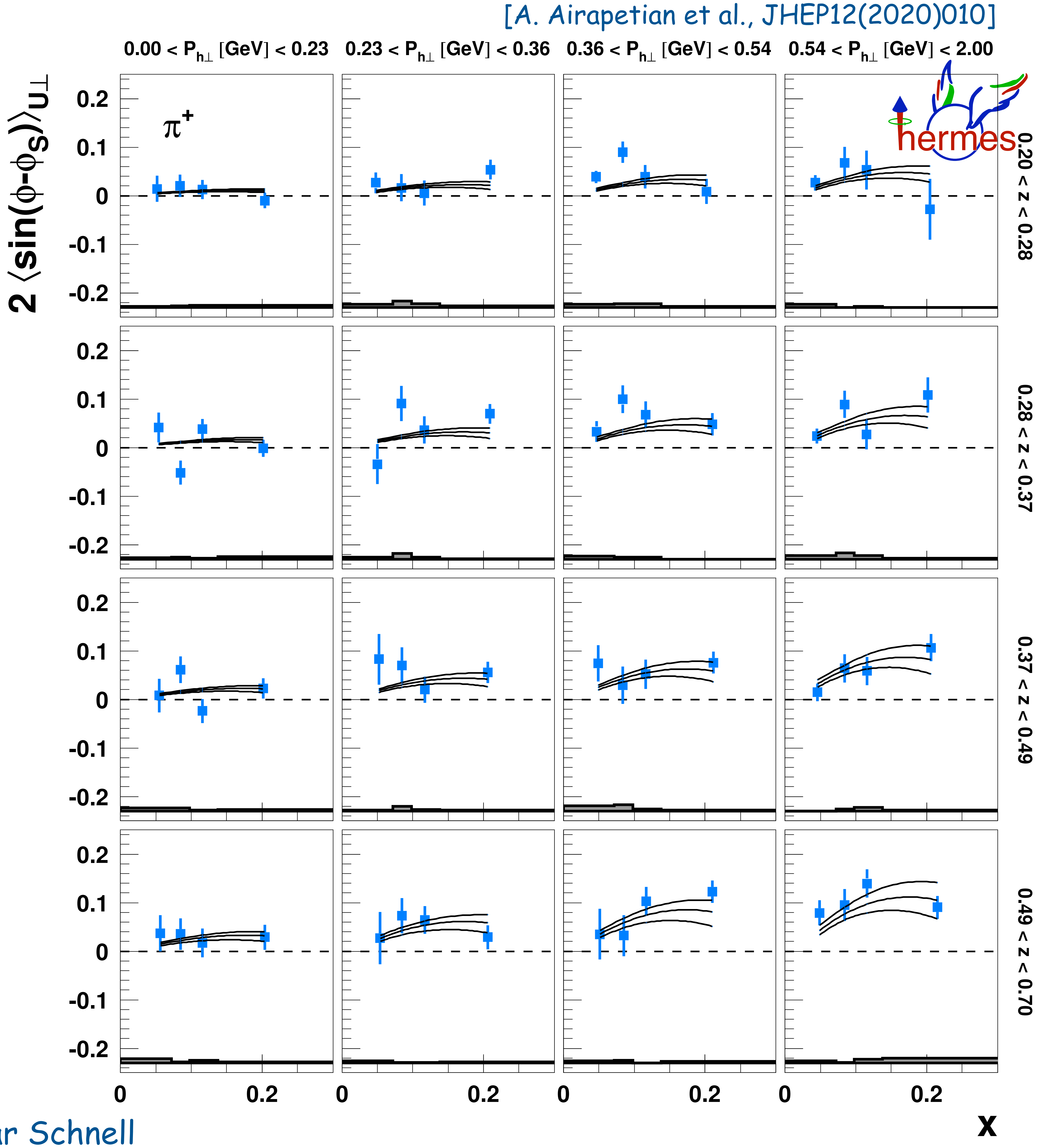
[A. Airapetian et al., JHEP12(2020)010]



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

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

Sivers amplitudes multi-dimensional analysis

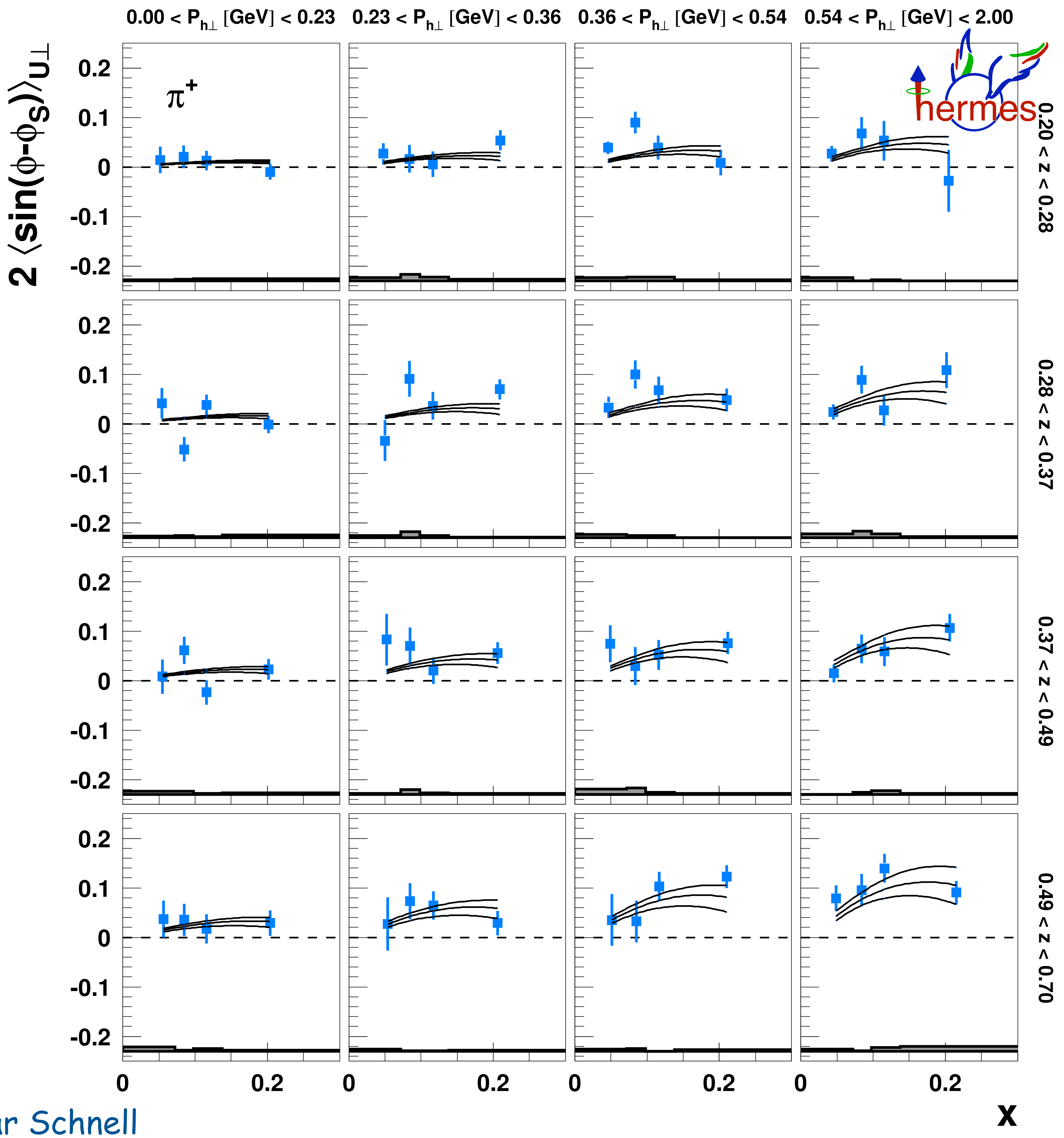


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

	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]

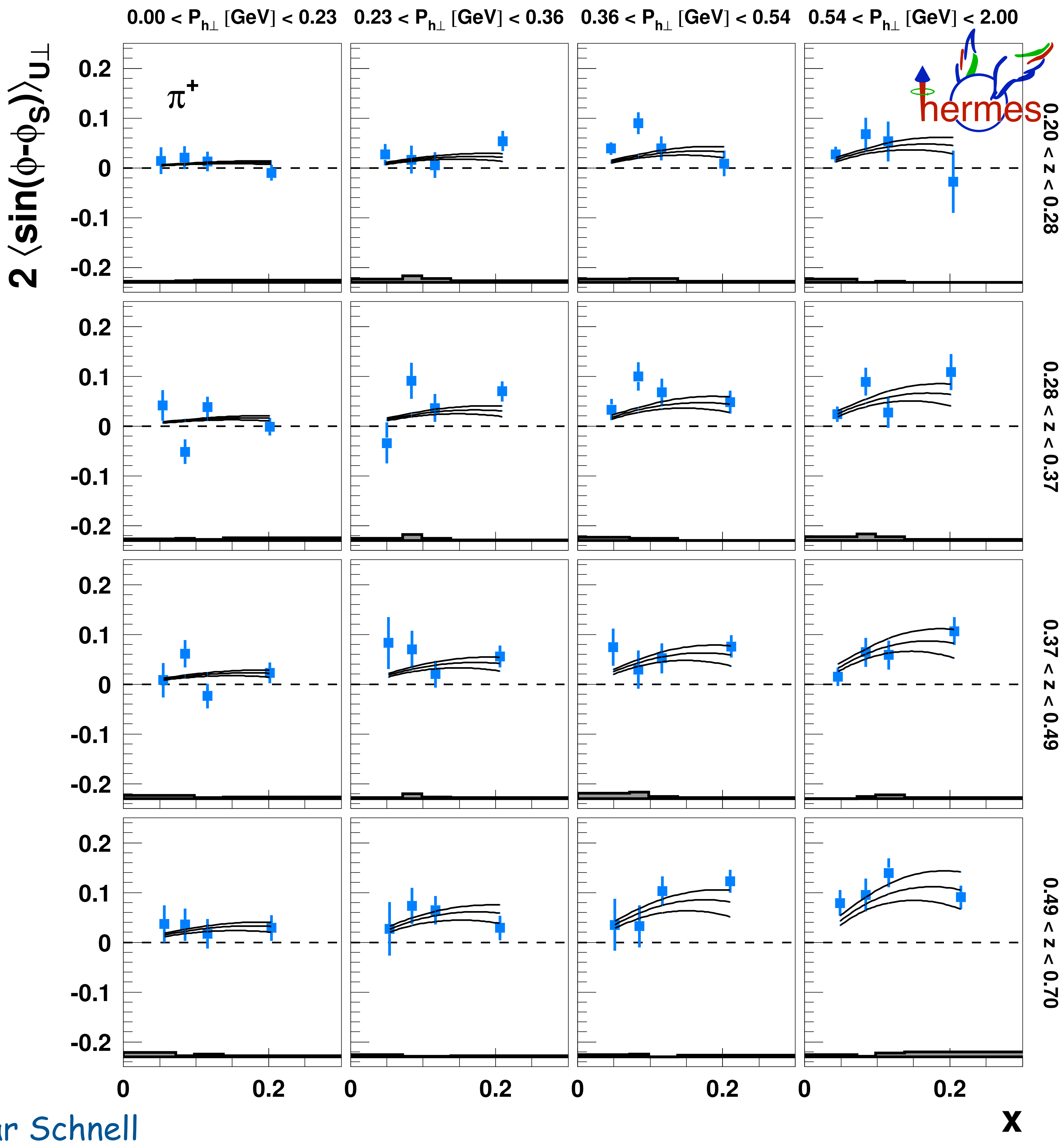


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations

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

Sivers amplitudes
multi-dimensional analysis

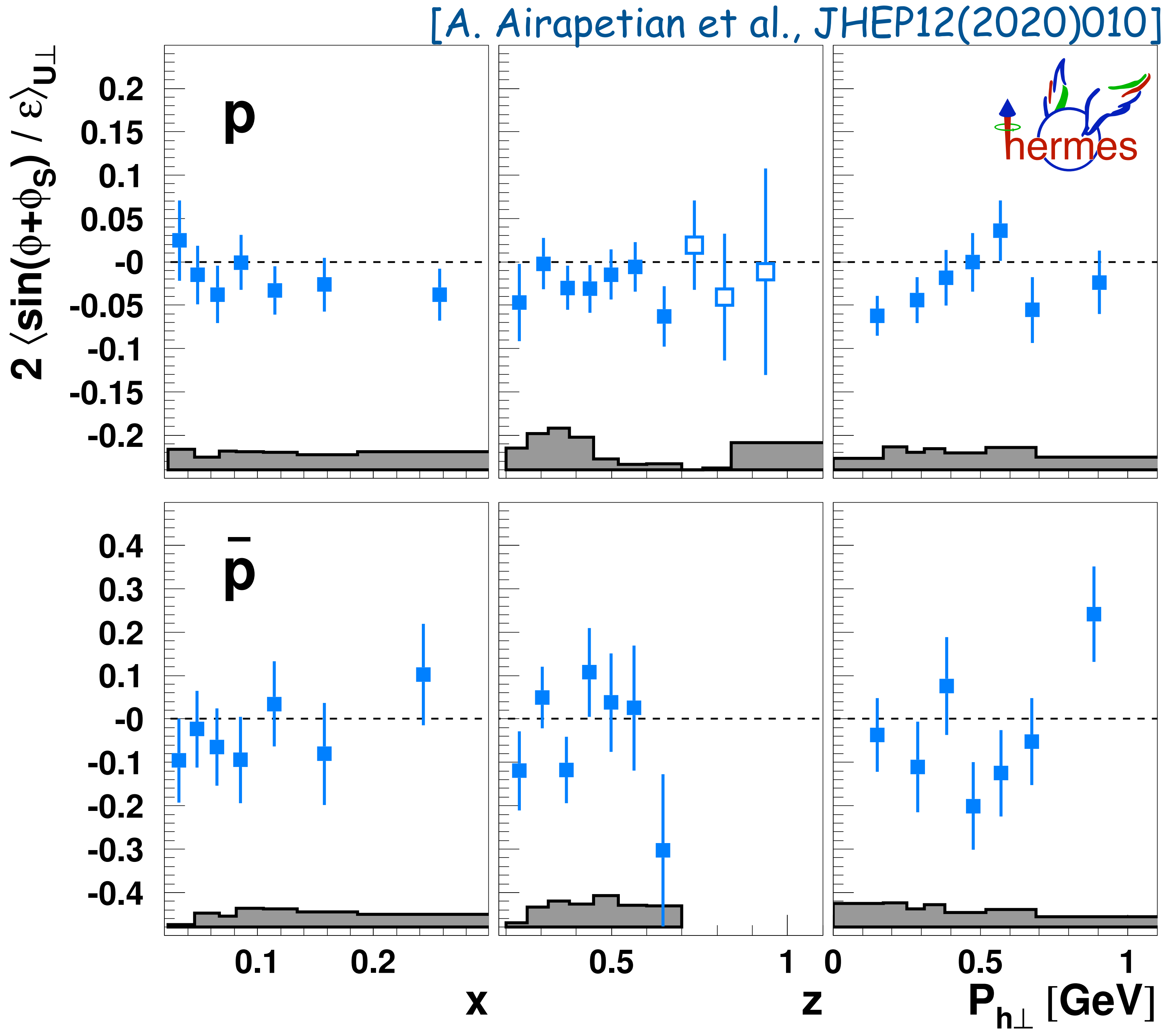
[A. Airapetian et al., JHEP12(2020)010]



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

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

new HERMES results on Collins amplitudes

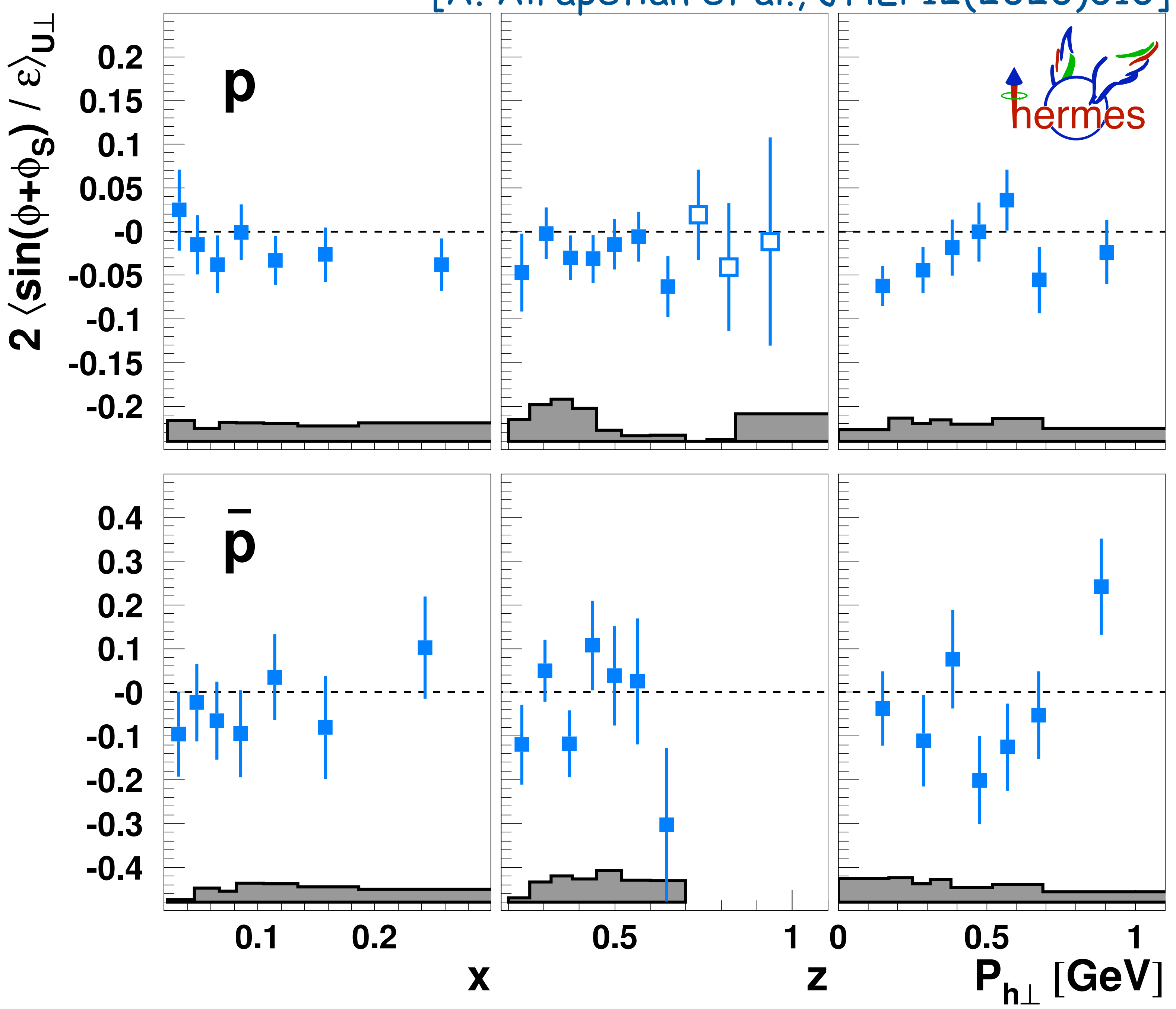


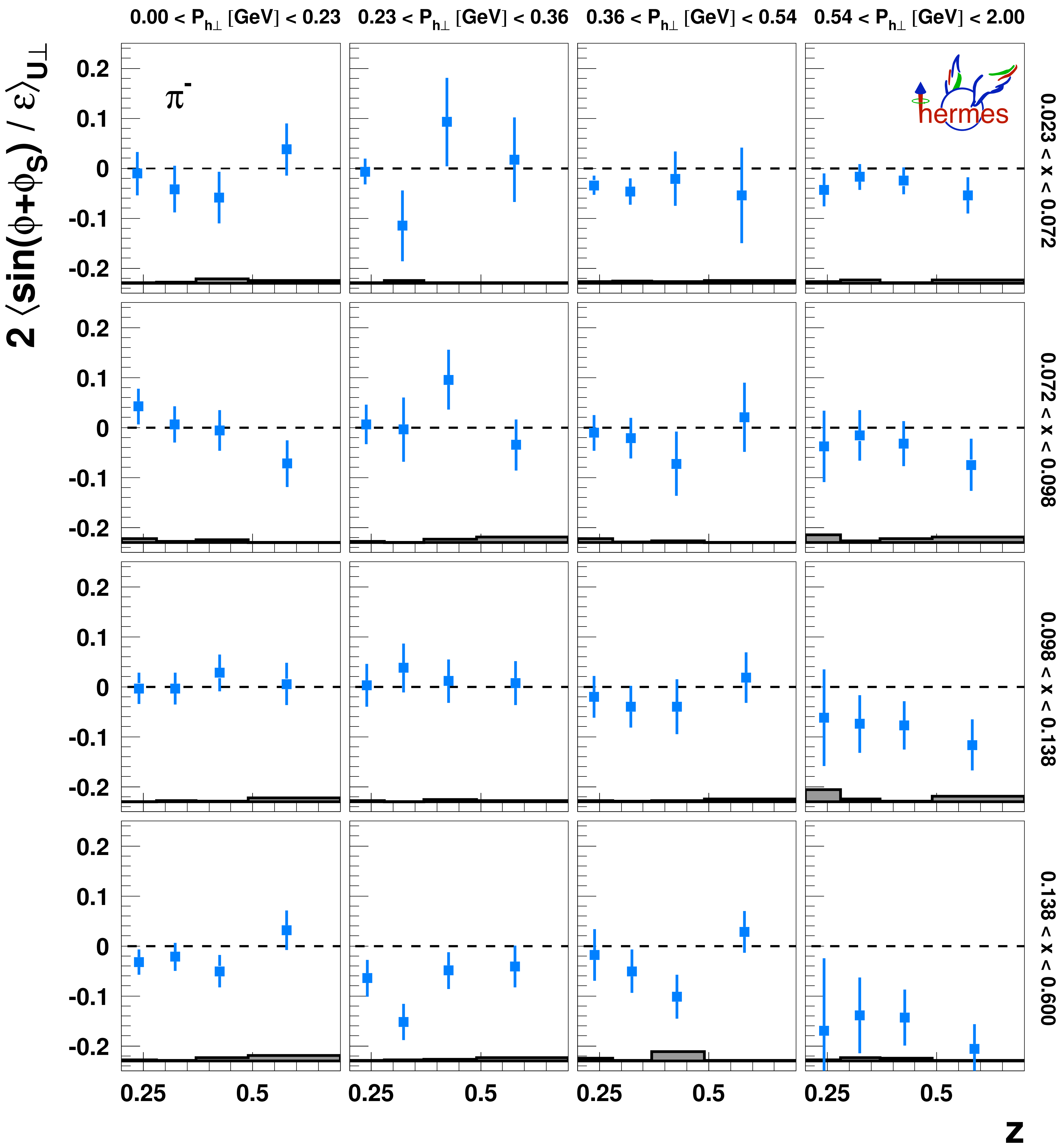
- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?

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

new HERMES results on Collins amplitudes

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

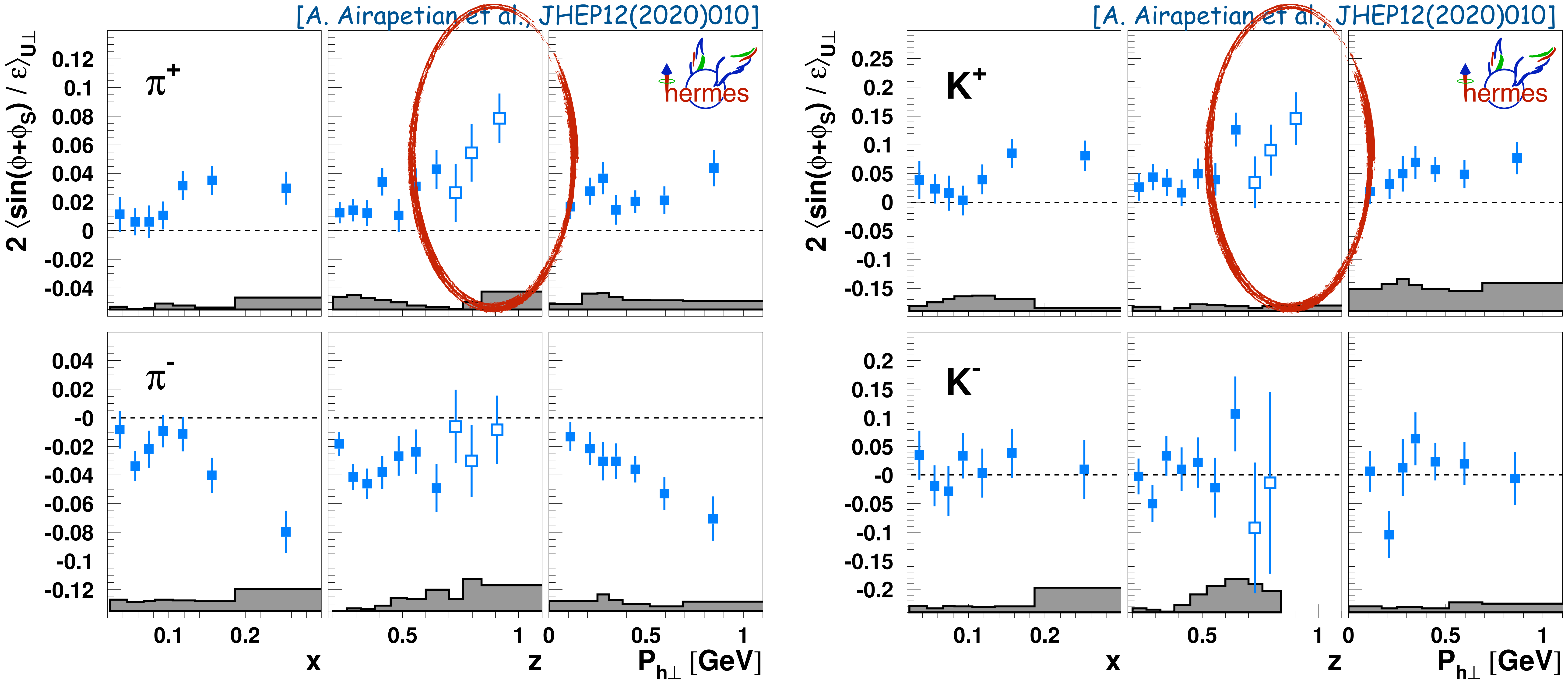




- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic "depolarization" prefactor

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

new HERMES results on Collins amplitudes

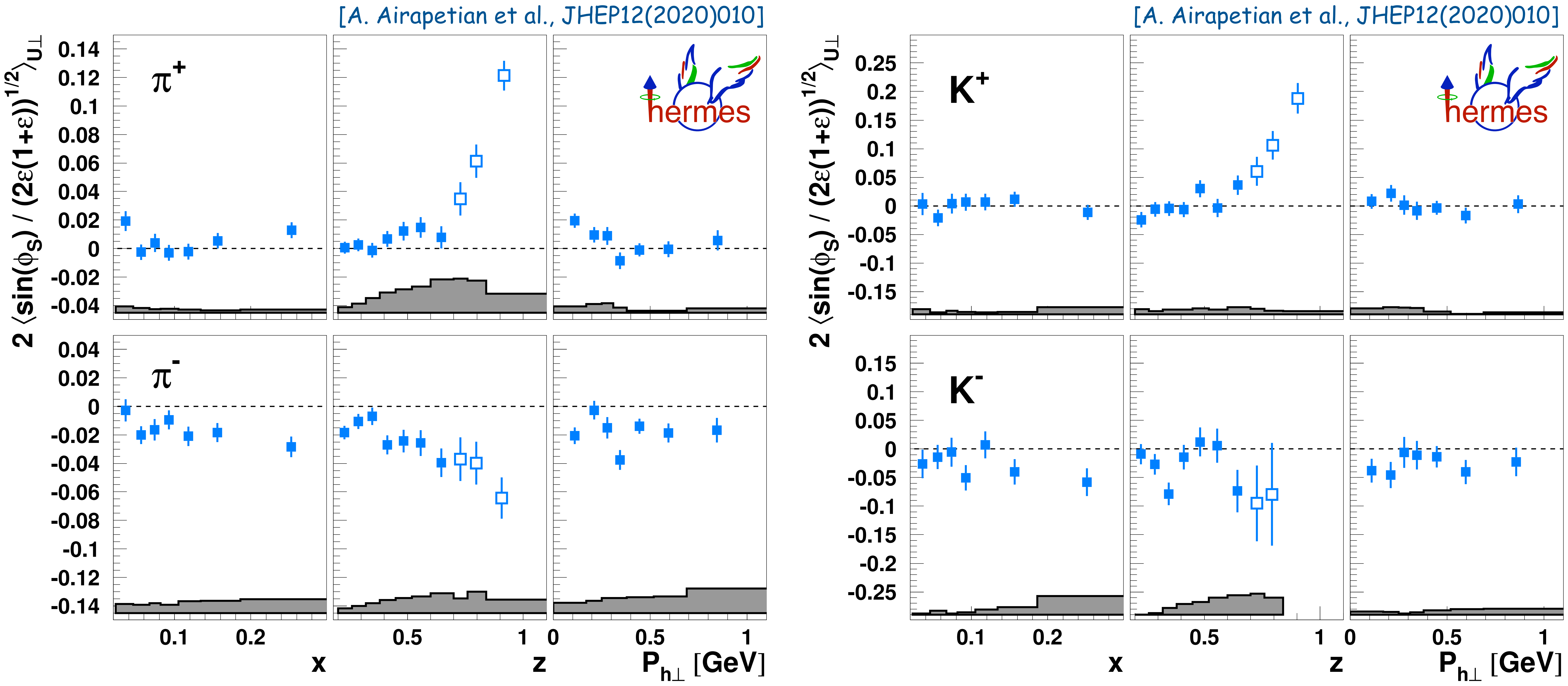


- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?

- 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

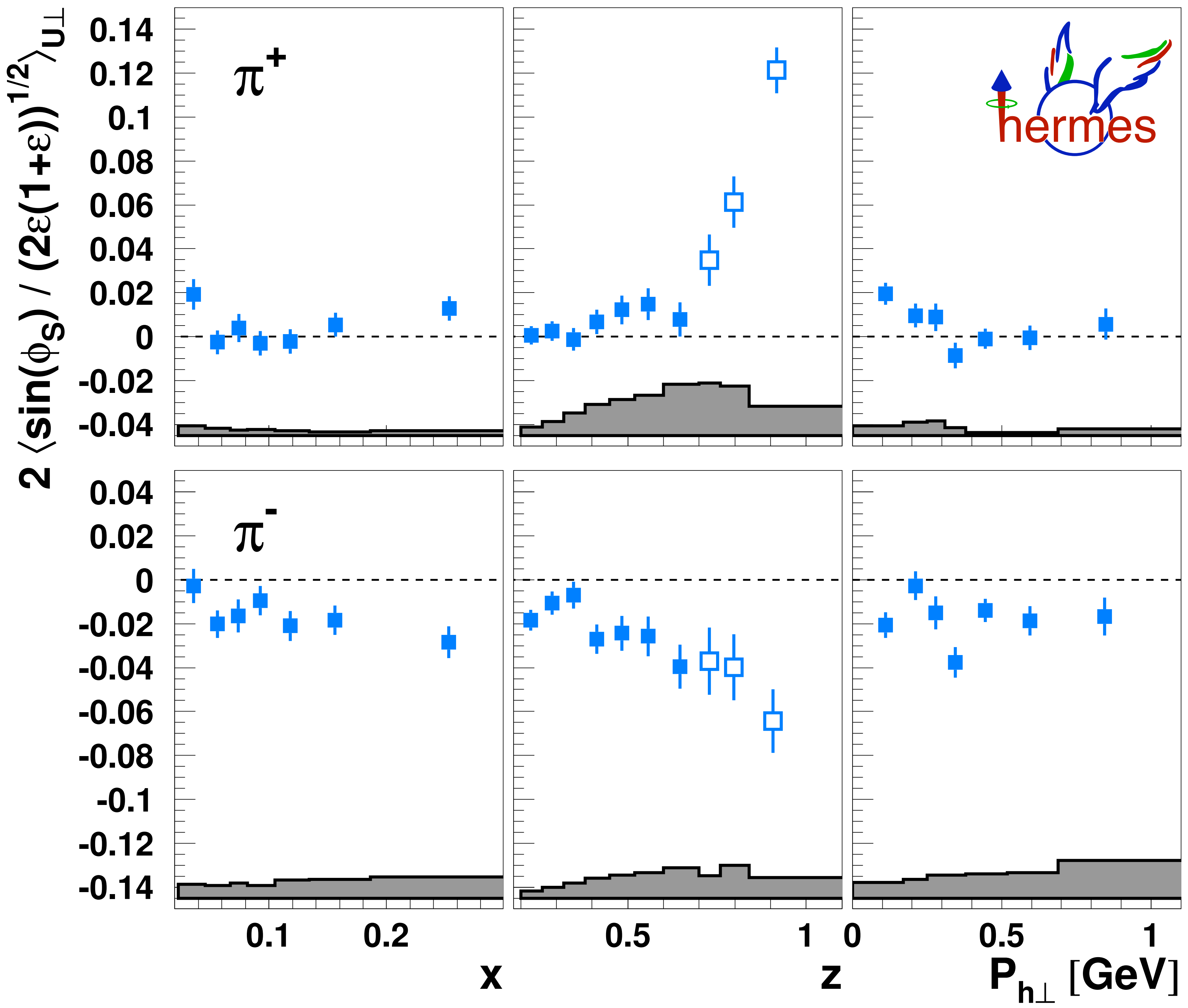
subleading twist I — $\langle \sin(\phi_S) \rangle_{UT}$



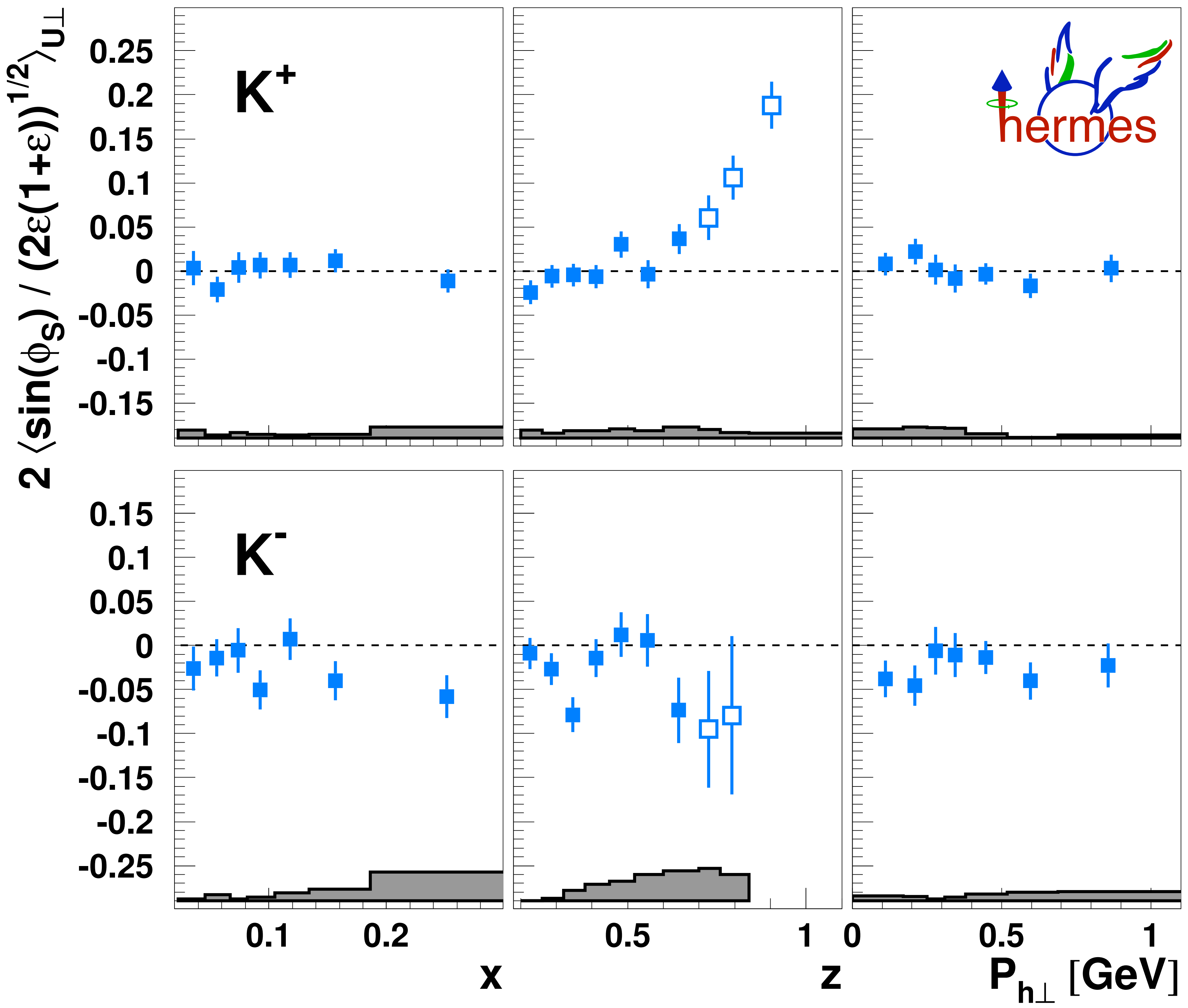
- clearly **non-zero** asymmetries
- **opposite sign** for charged pions (Collins-like behavior)
- **striking z dependence** and magnitude

subleading twist I — <sin(ϕs)>UT

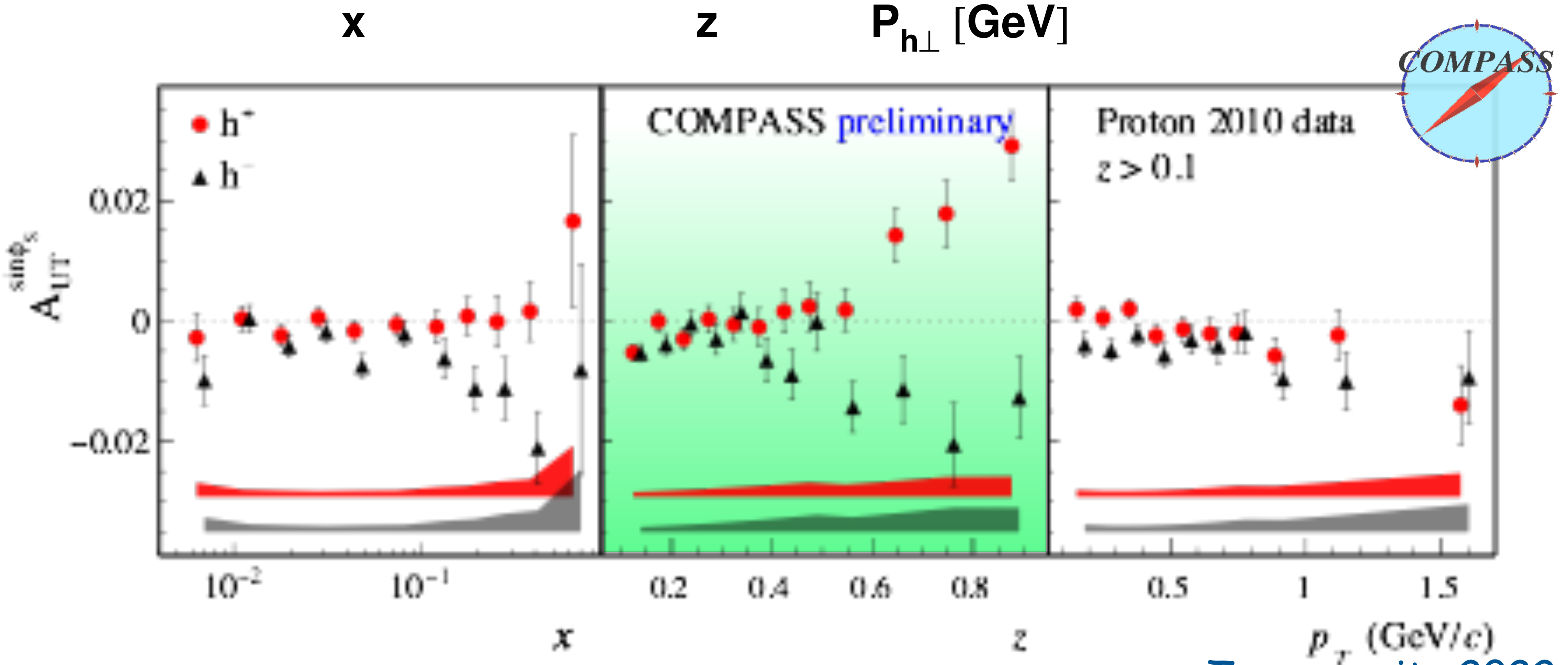
[A. Airapetian et al., JHEP12(2020)010]



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



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



Physics Letters B 797 (2019) 134886

Contents lists available at ScienceDirect

Physics Letters B

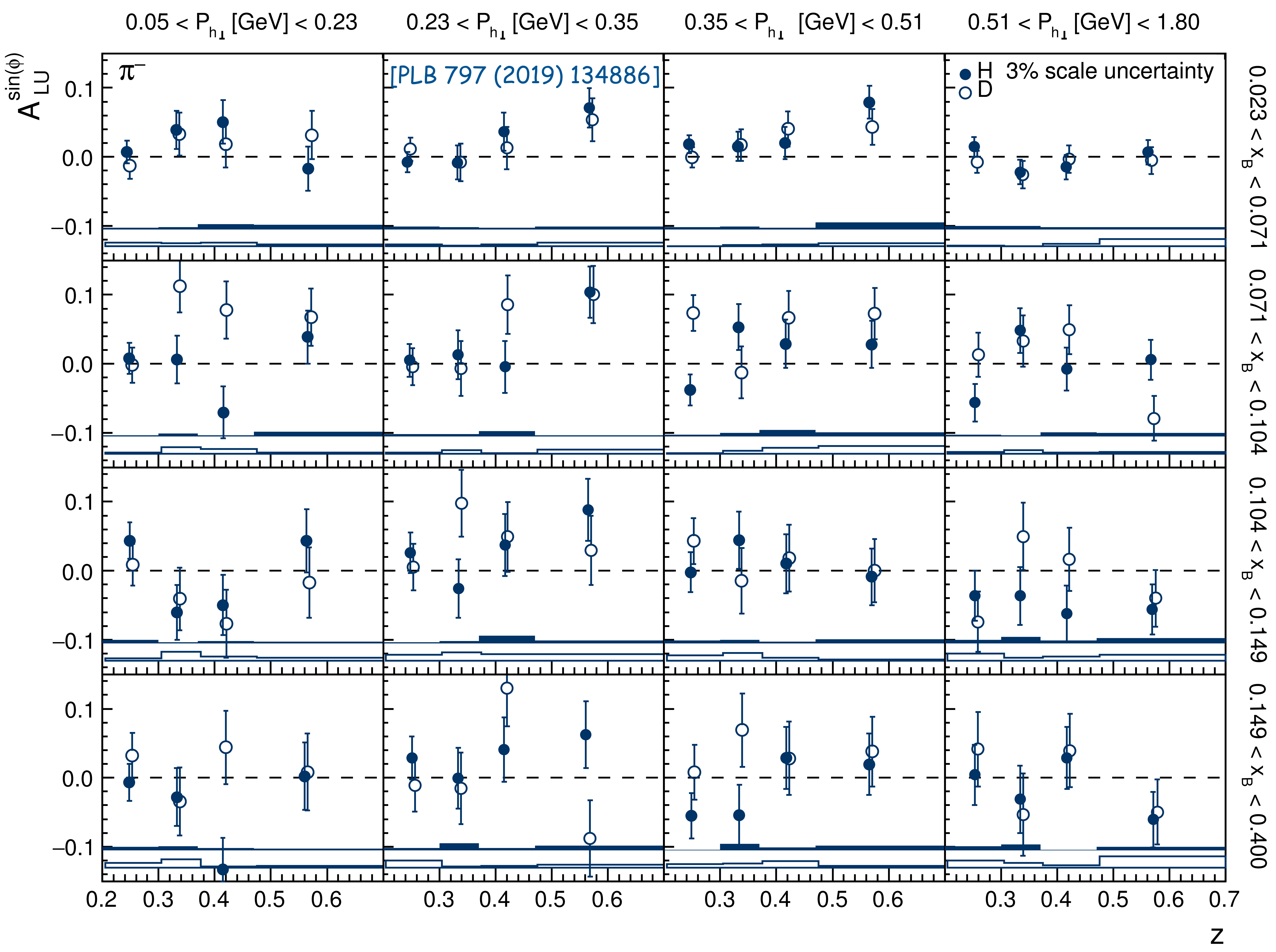
www.elsevier.com/locate/physletb

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]

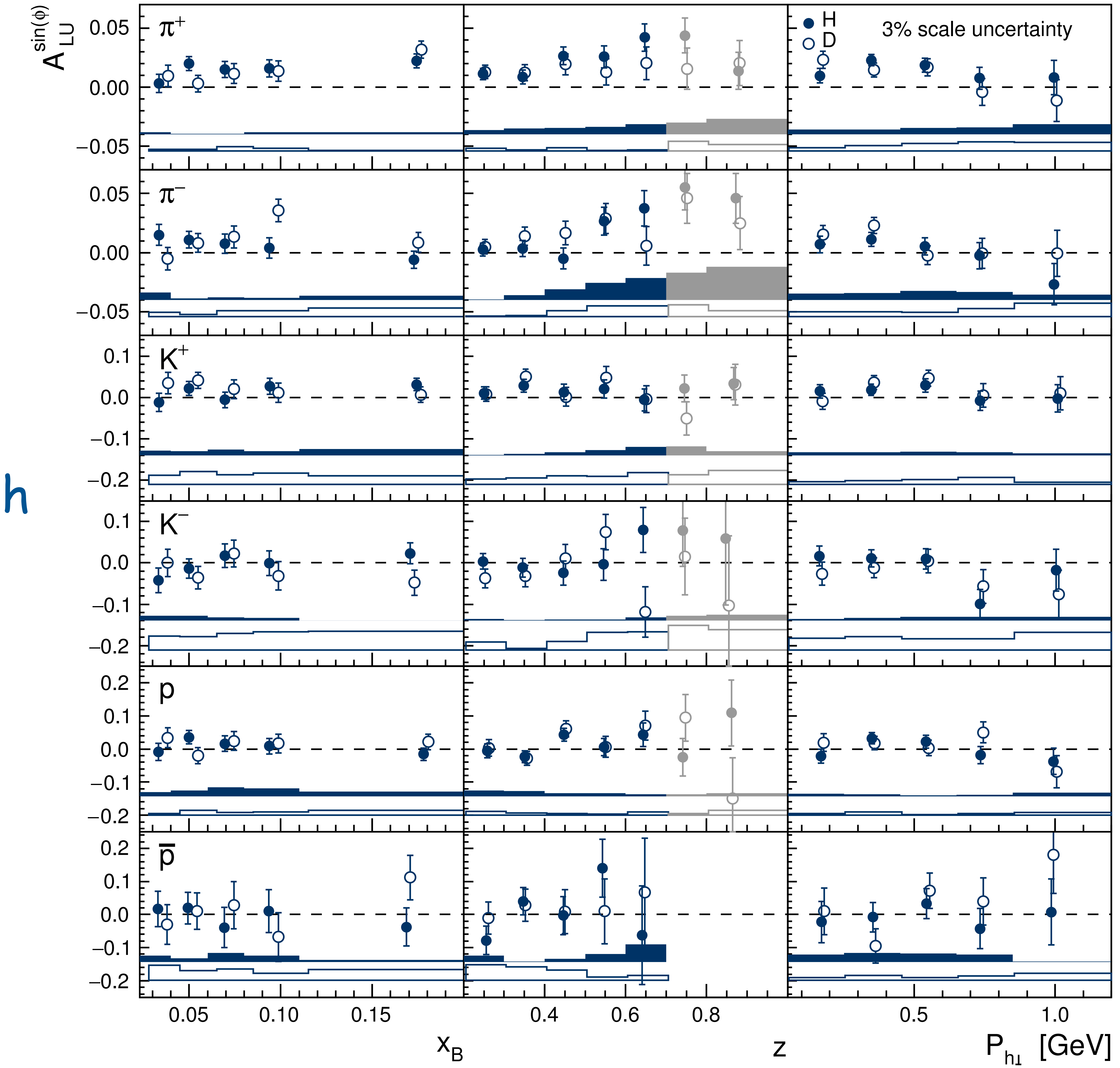
subleading twist II - $\langle\sin(\phi)\rangle_{LU}$ HERMES 3d analysis



most comprehensive presentation, for discussion use 1d binning

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

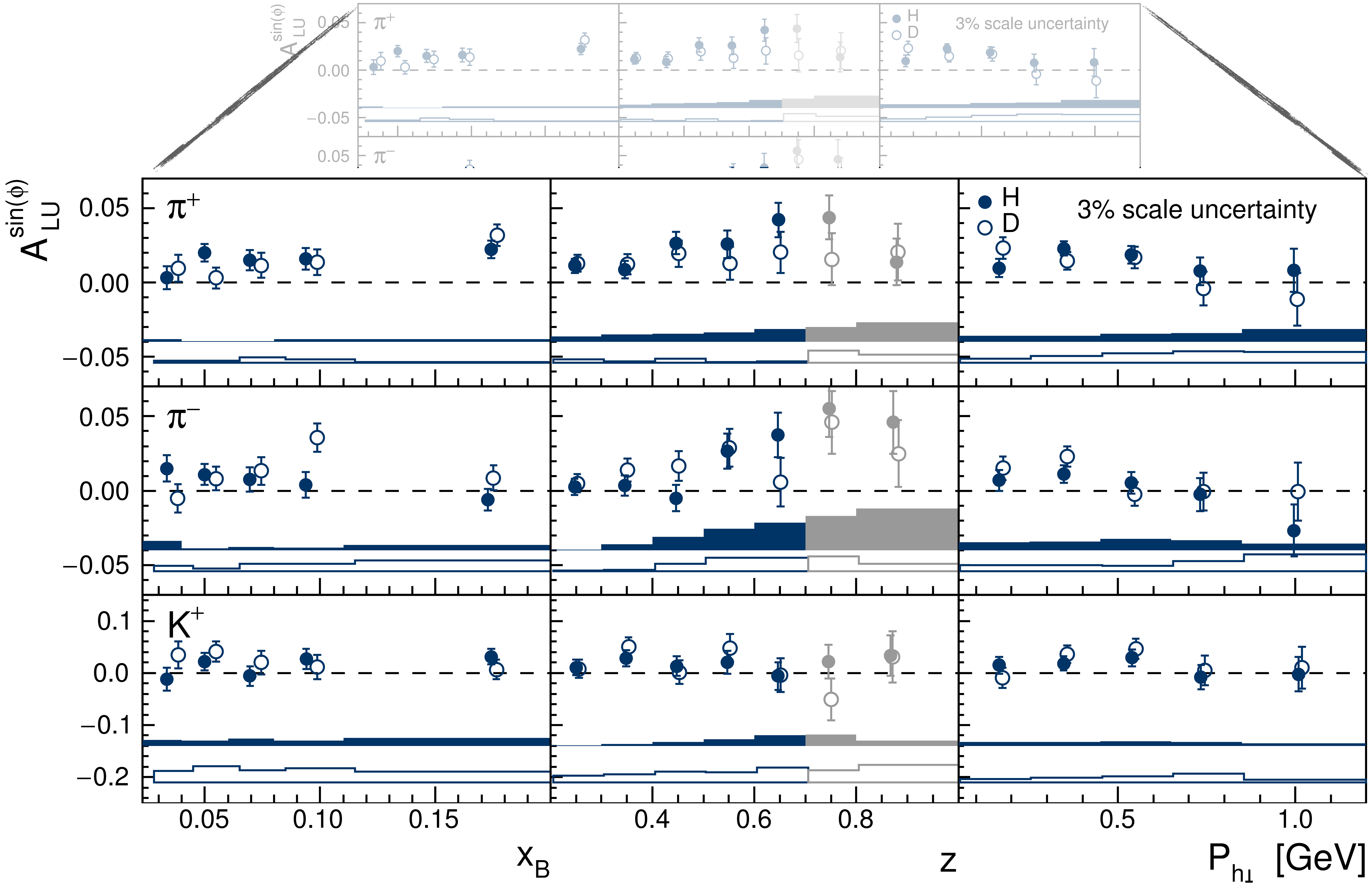
[HERMES, PLB 797 (2019) 134886]



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

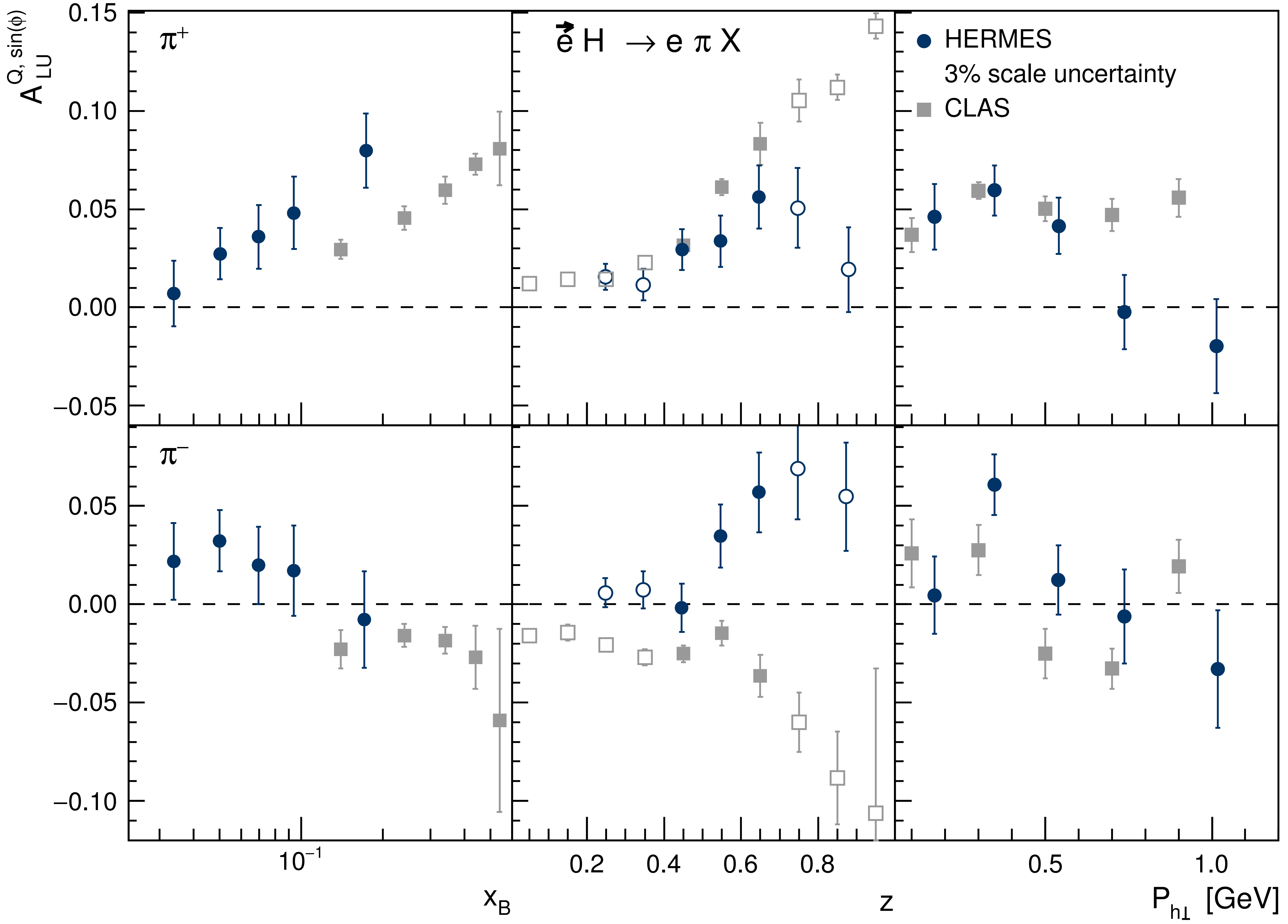
$$\frac{M_h}{Mz} h_1^{\perp} \tilde{E} \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^{\perp} \oplus x e H_1^{\perp}$$

[HERMES, PLB 797 (2019) 134886]



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

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

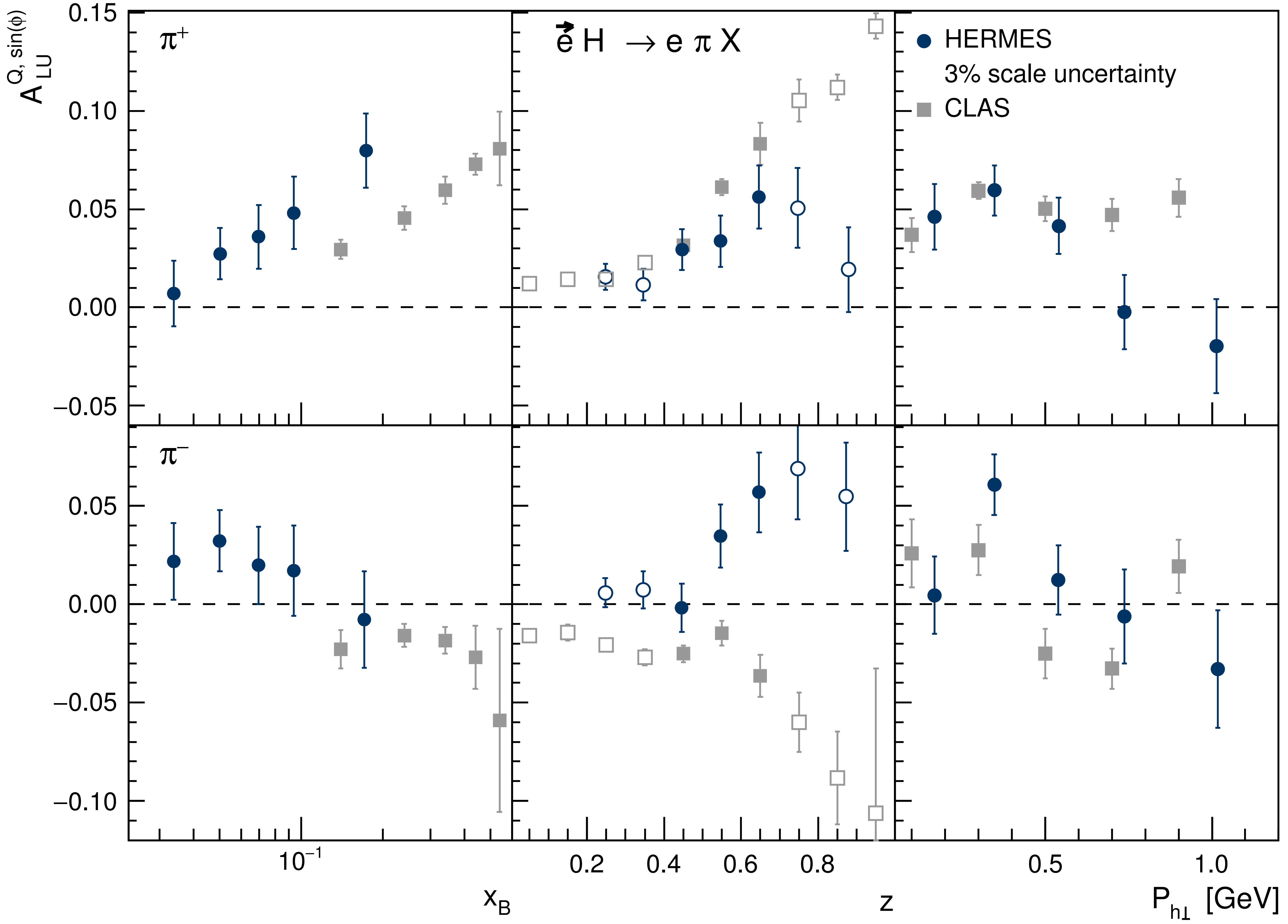


[HERMES, PLB 797 (2019) 134886]

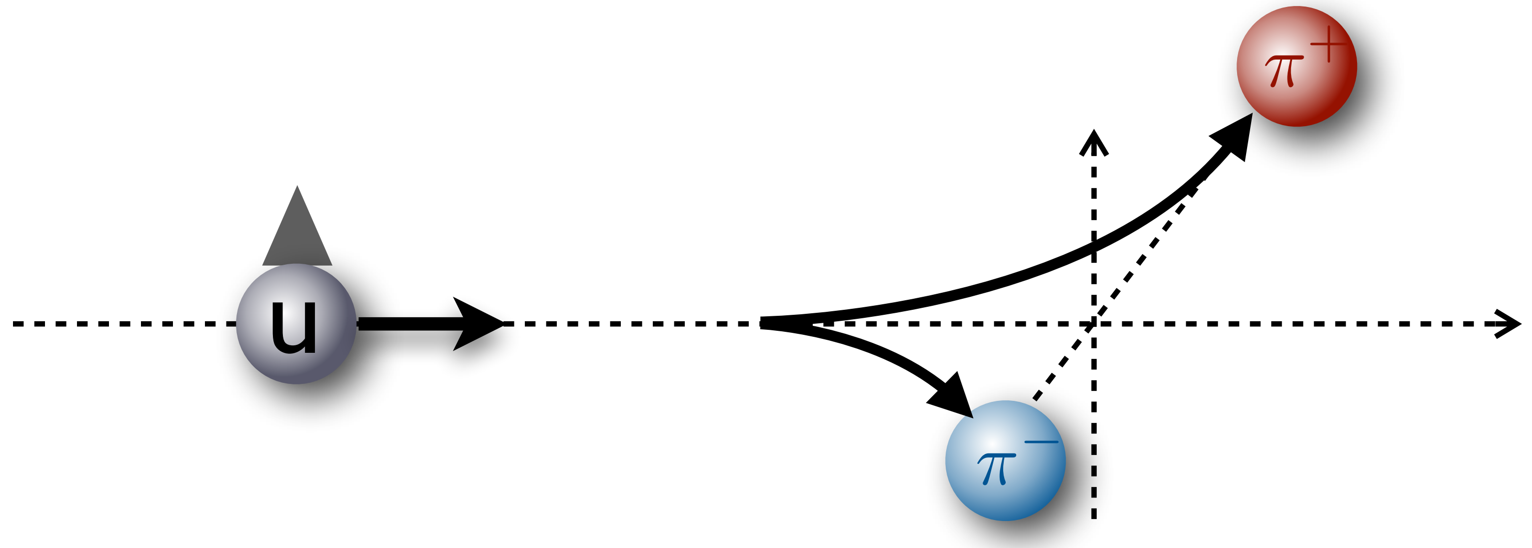
- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed

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

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



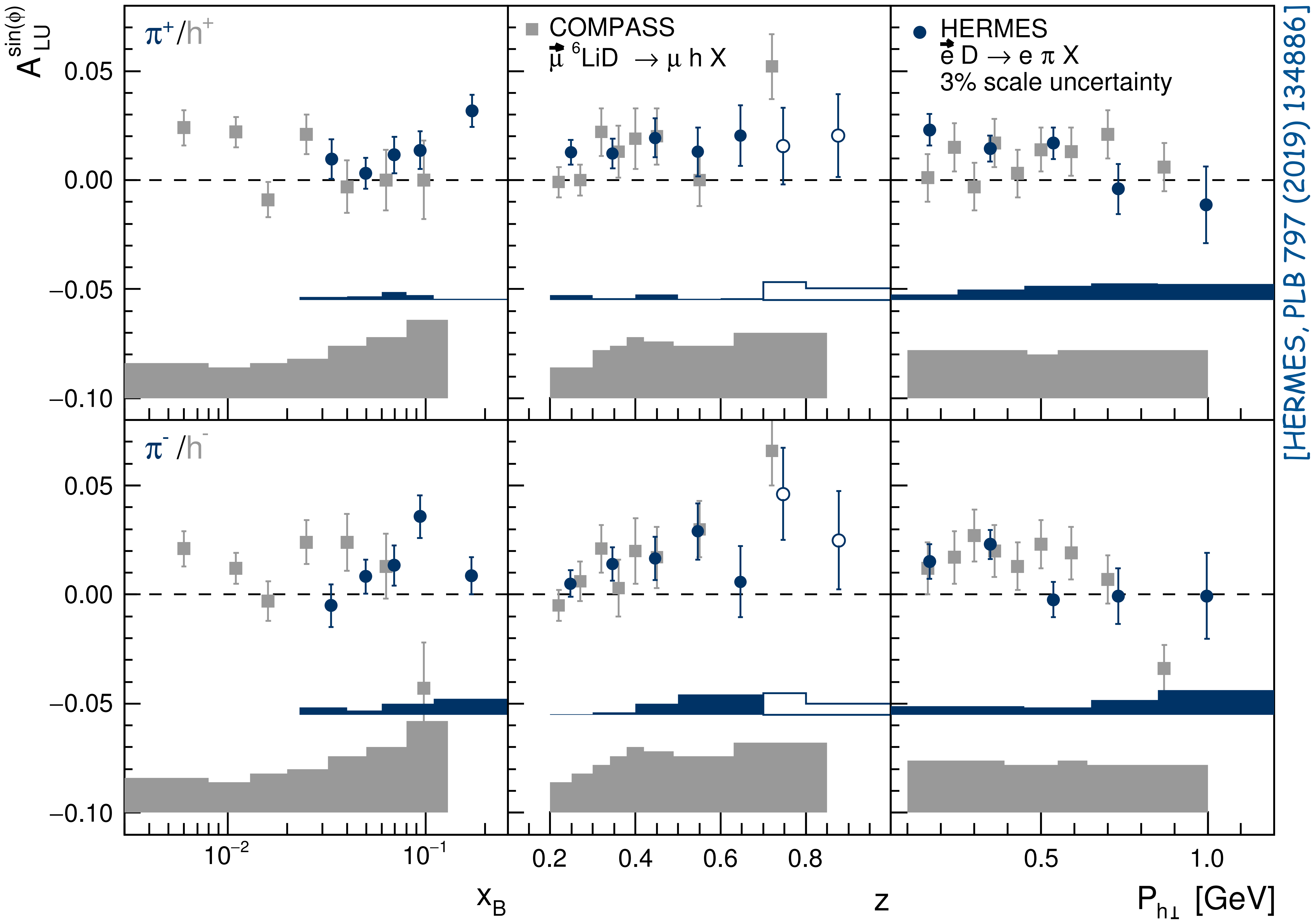
[HERMES, PLB 797 (2019) 134886]



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

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

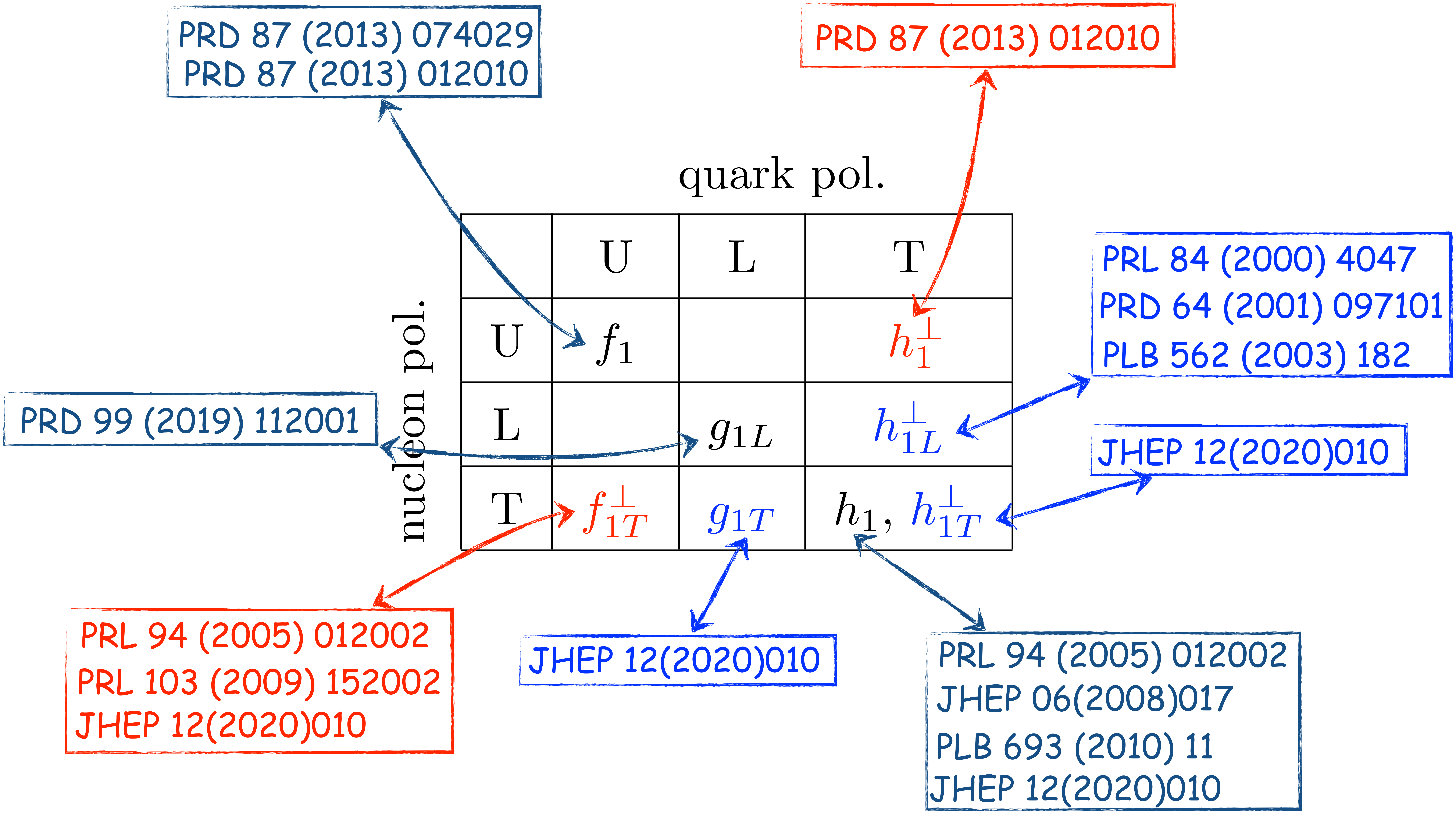
$$\frac{M_h}{Mz} h_1^\perp \tilde{E} \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^\perp \oplus x e H_1^\perp$$



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


PRD 87 (2013) 074029
PRD 87 (2013) 012010
PRD 87 (2013) 012010
quark pol.
nucleon pol.
U
L
T
U
L
T
f_1
$h_1^\perp$
g_{1L}
$h_{1L}^\perp$
$f_{1T}^\perp$
g_{1T}
h_1, $h_{1T}^\perp$
PRL 84 (2000) 4047
PRD 64 (2001) 097101
PLB 562 (2003) 182
PRD 99 (2019) 112001
JHEP 12(2020)010
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