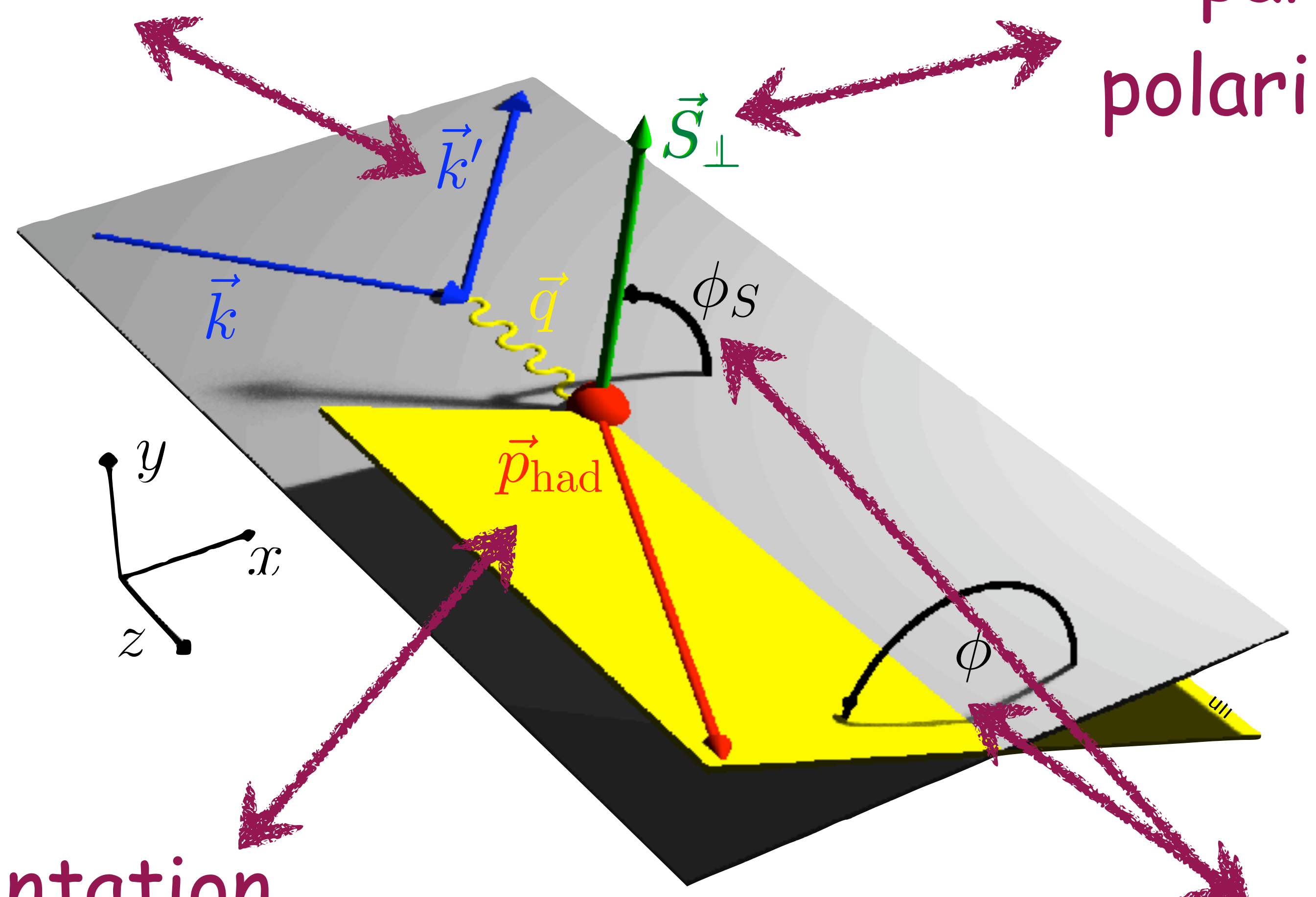
From Quarks and Gluons to the Internal Dynamics of Hadrons
CFNS@Stony Brook — May 15-17, 2024



Multi-d SIDIS Analyses

a personal HERMES-biased perspective on challenges and achievements

Proyecto PCI2022-132984 financiado por
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Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
Universidad del País Vasco Euskal Herriko Unibertsitatea
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ikerbasque Basque Foundation for Science

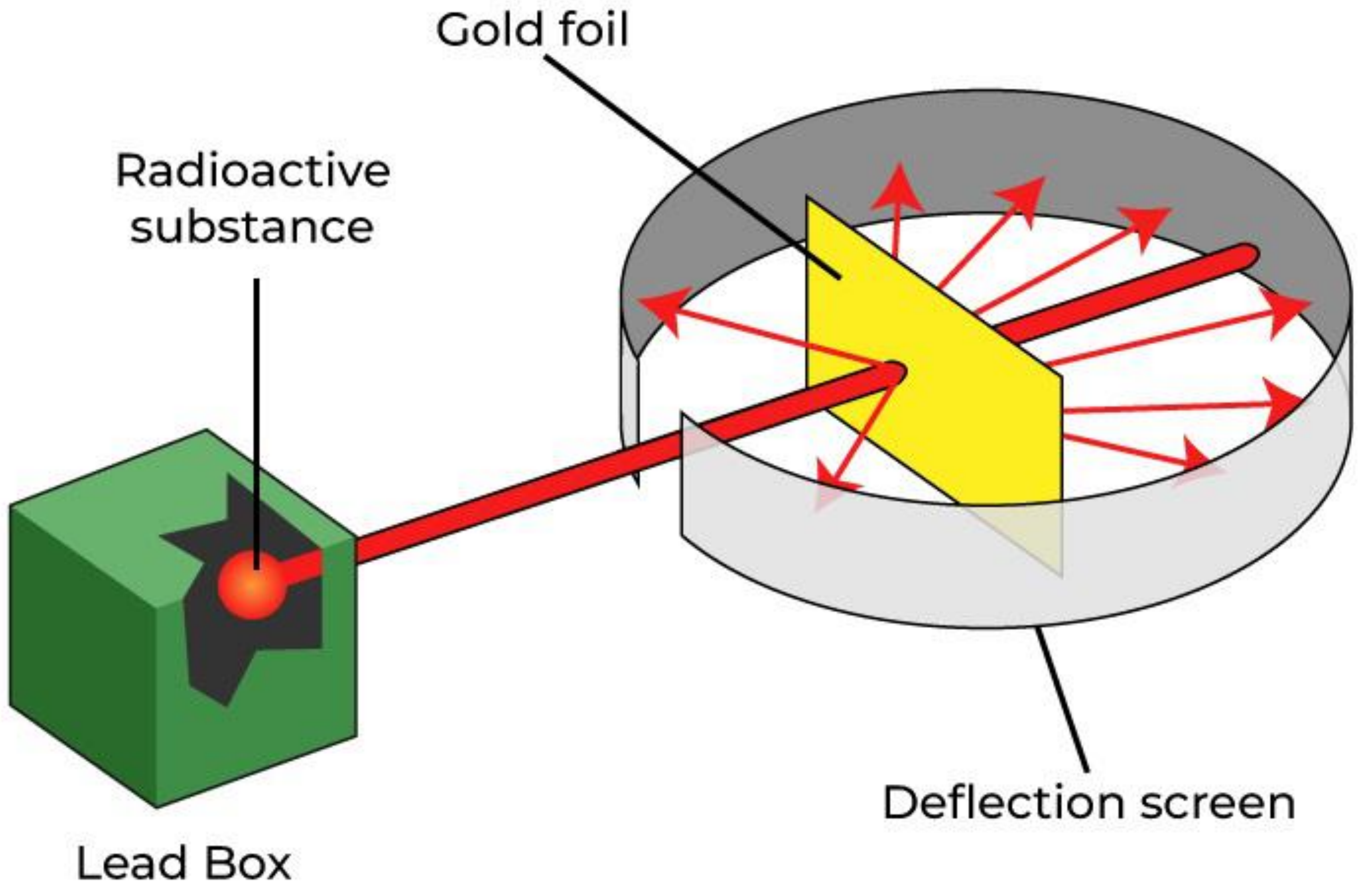
Gunar.Schnell @ DESY.de

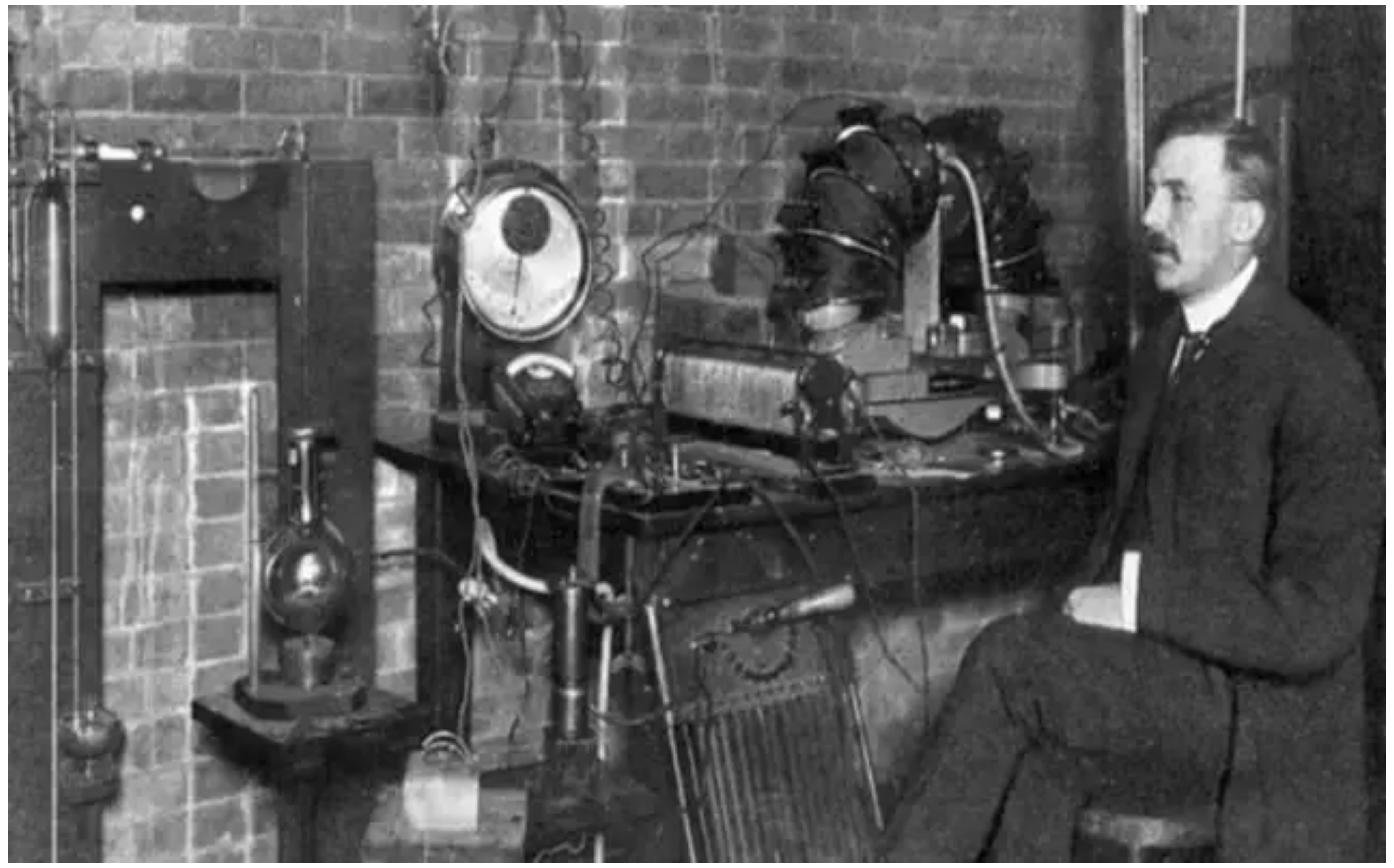
disclaimer: after two and a half days of intense discussion, refrain from introducing basics of SIDIS and PDFs, TMDs, and FFs

➟ cf. Ralf's talk yesterday

from 1d to 9d

- a century ago, things were "simple":





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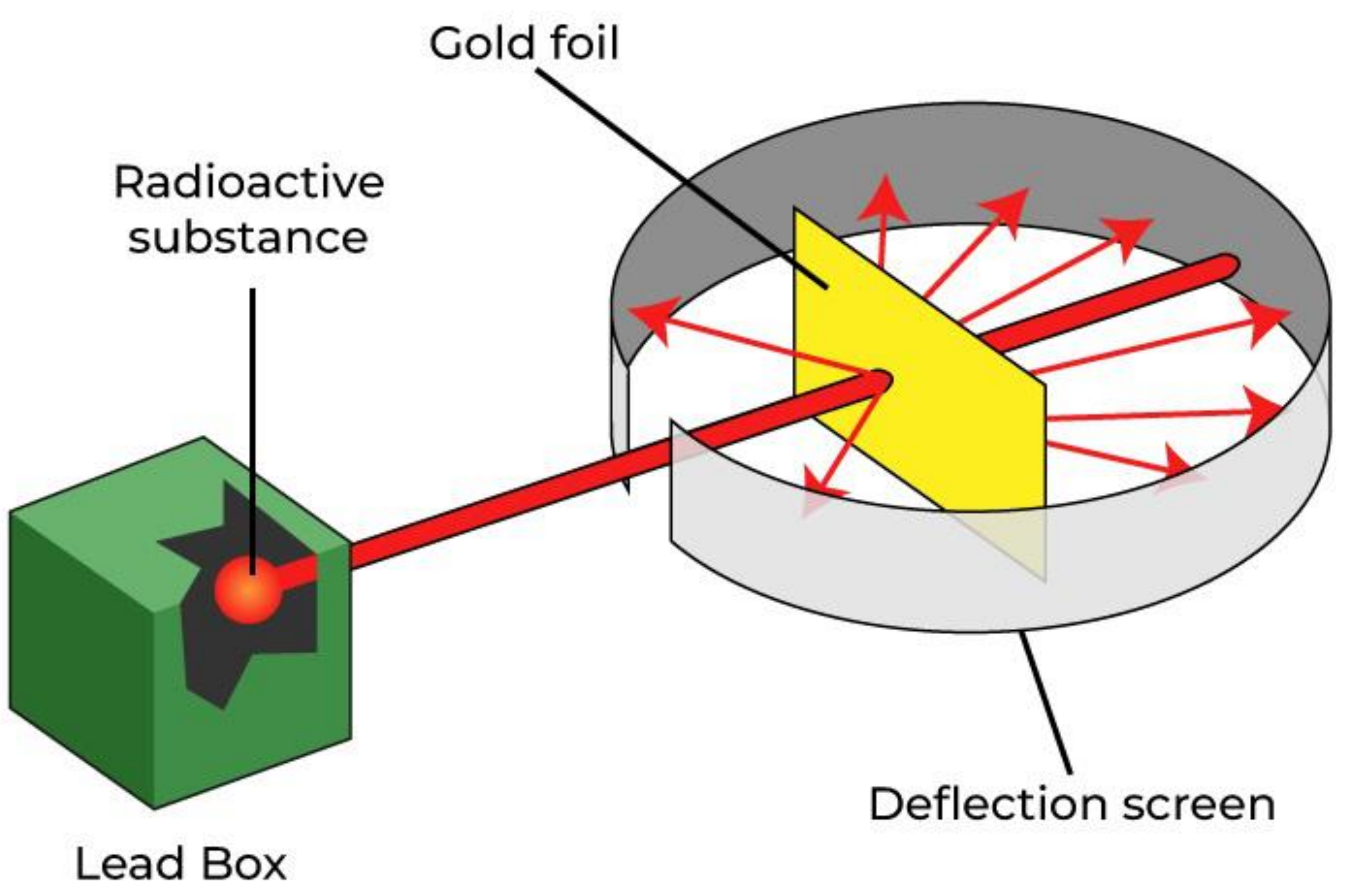
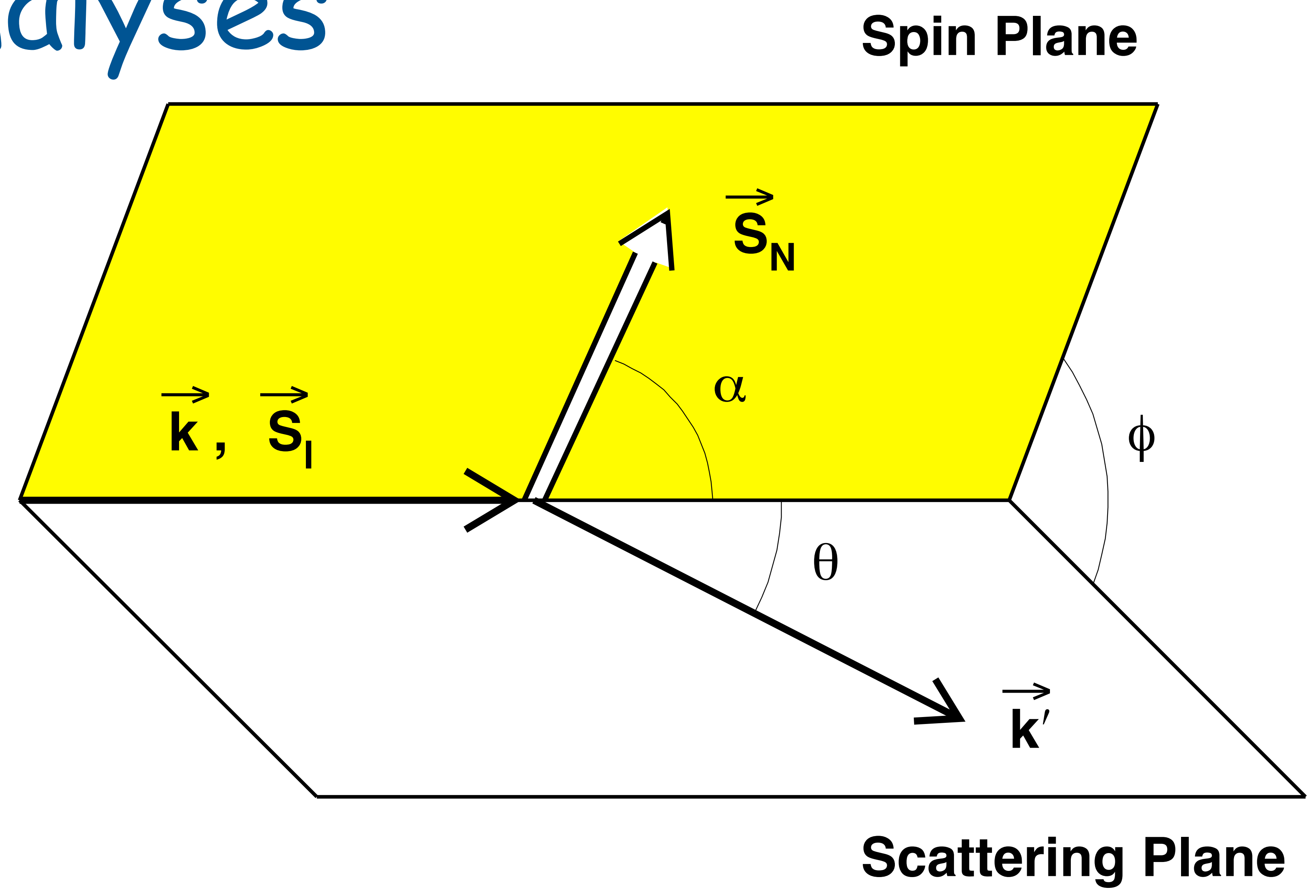


- inclusive DIS already requires 2d or 3d analyses



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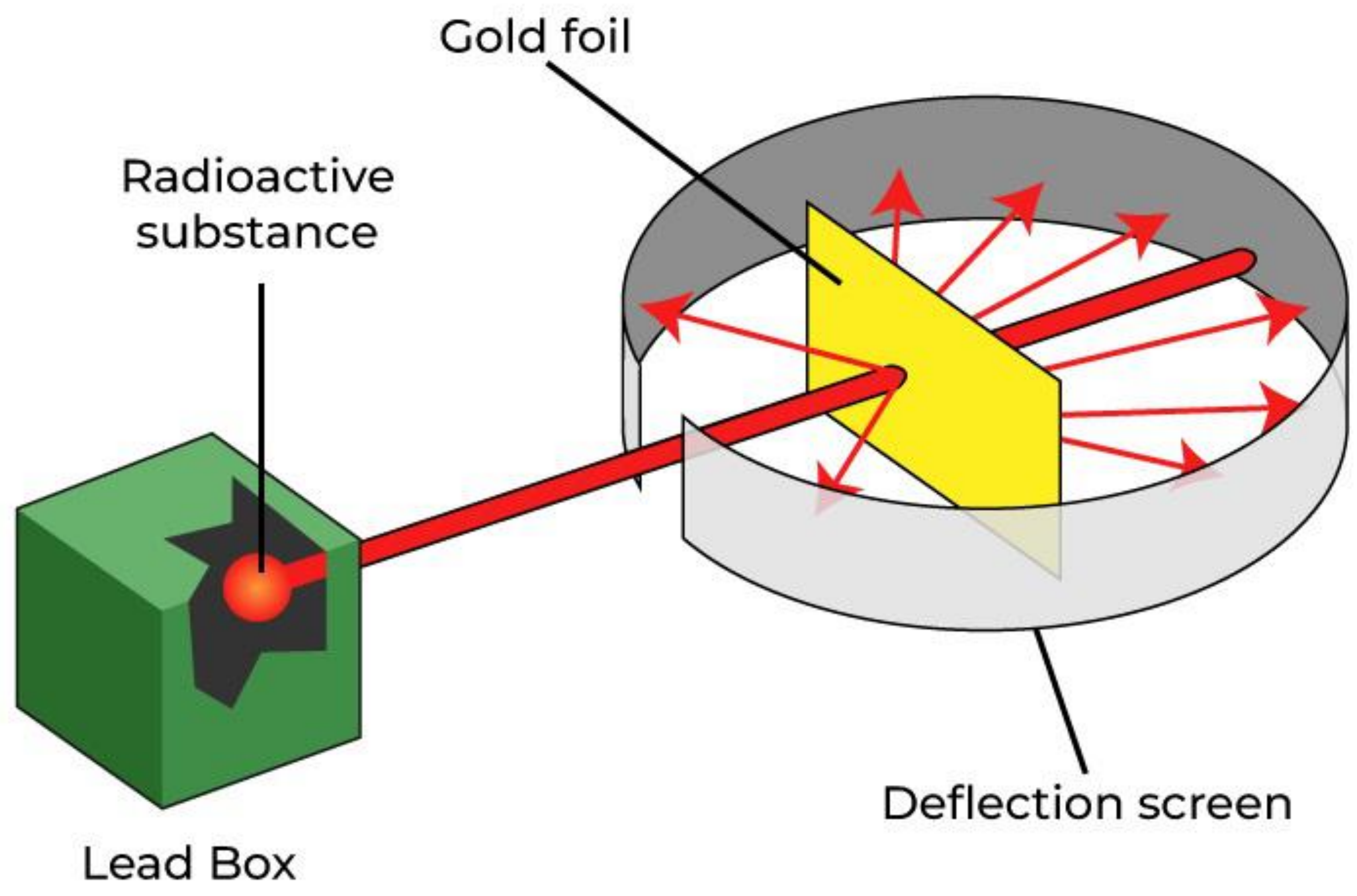

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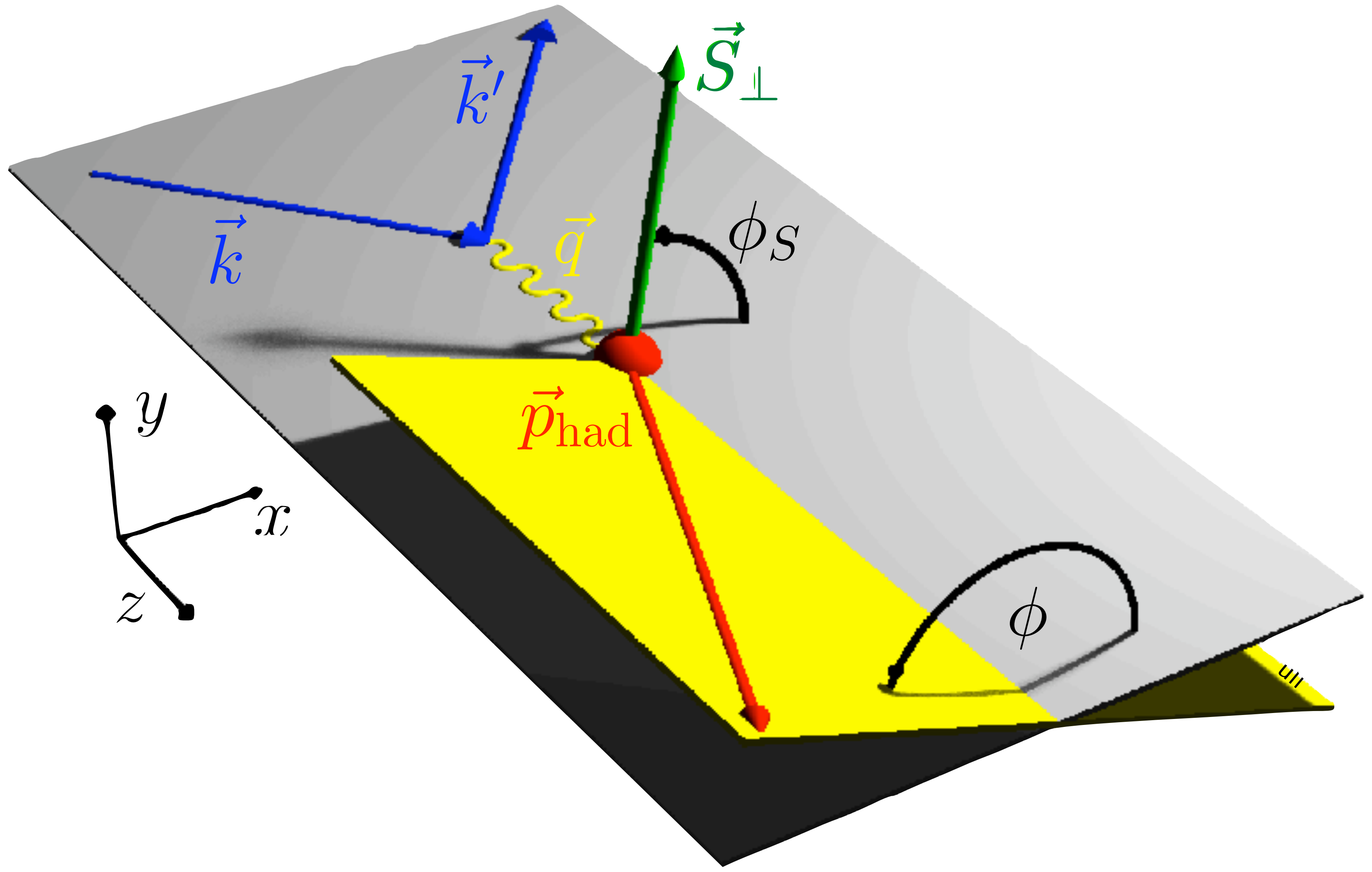

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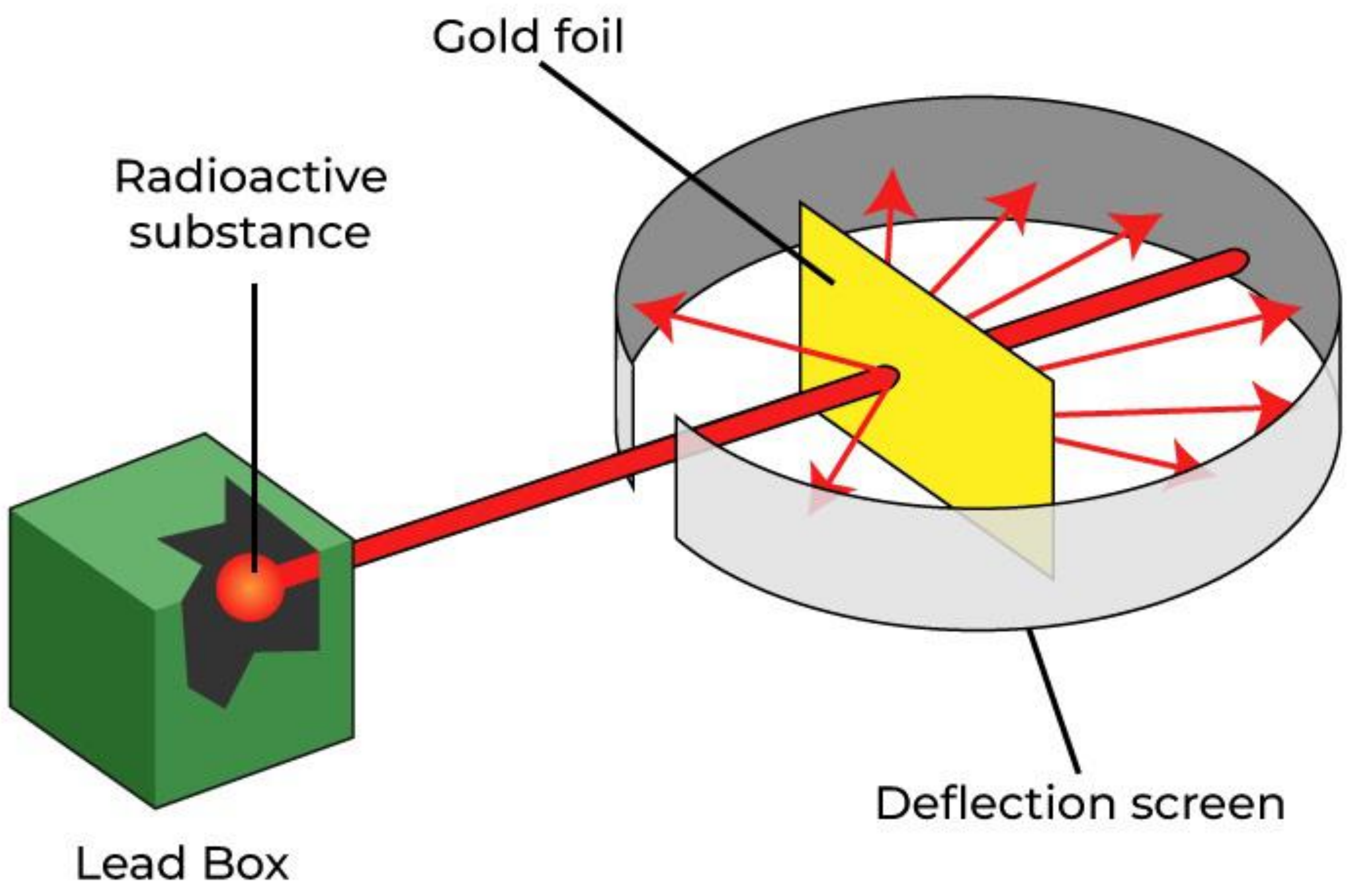

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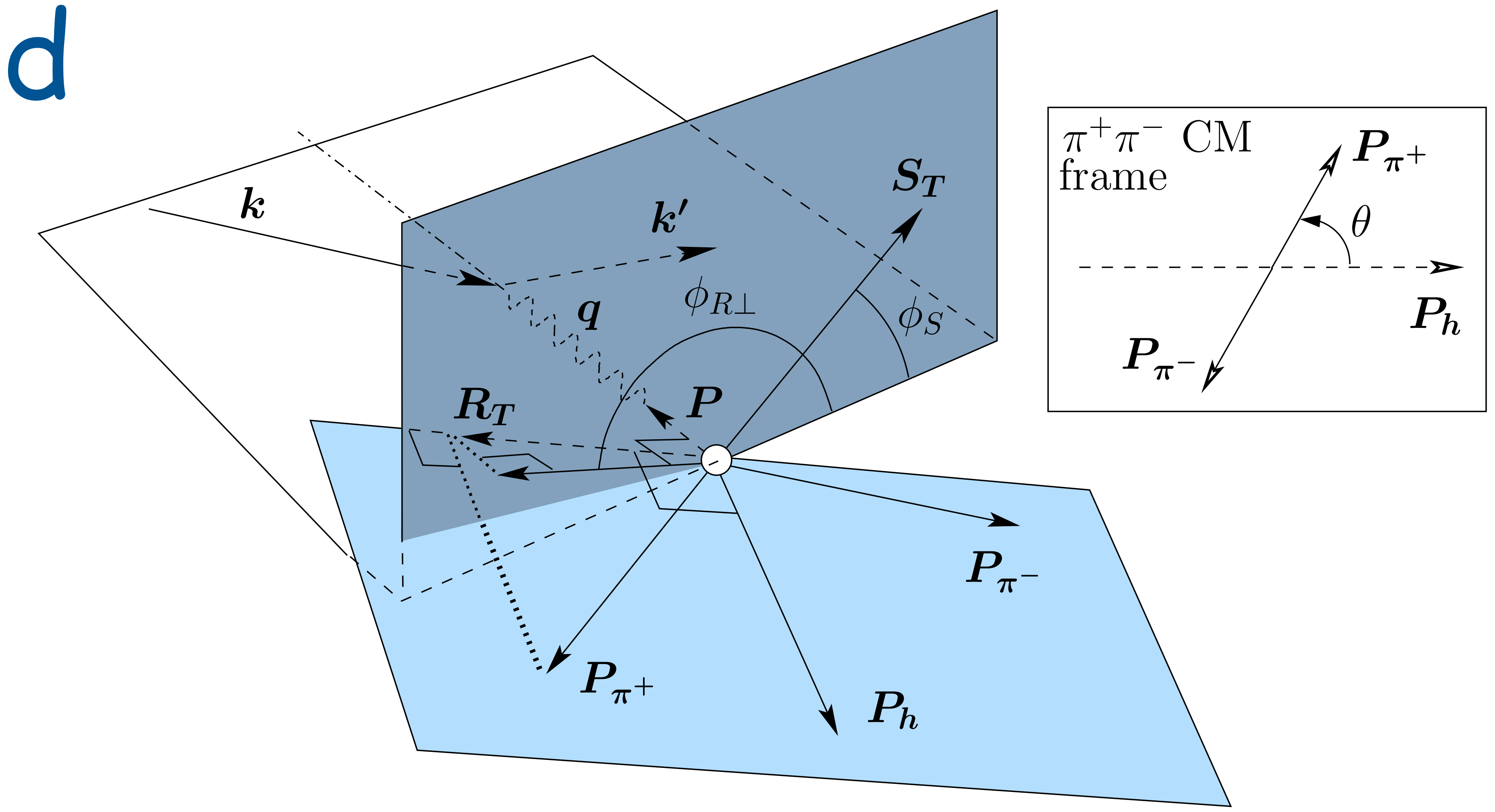

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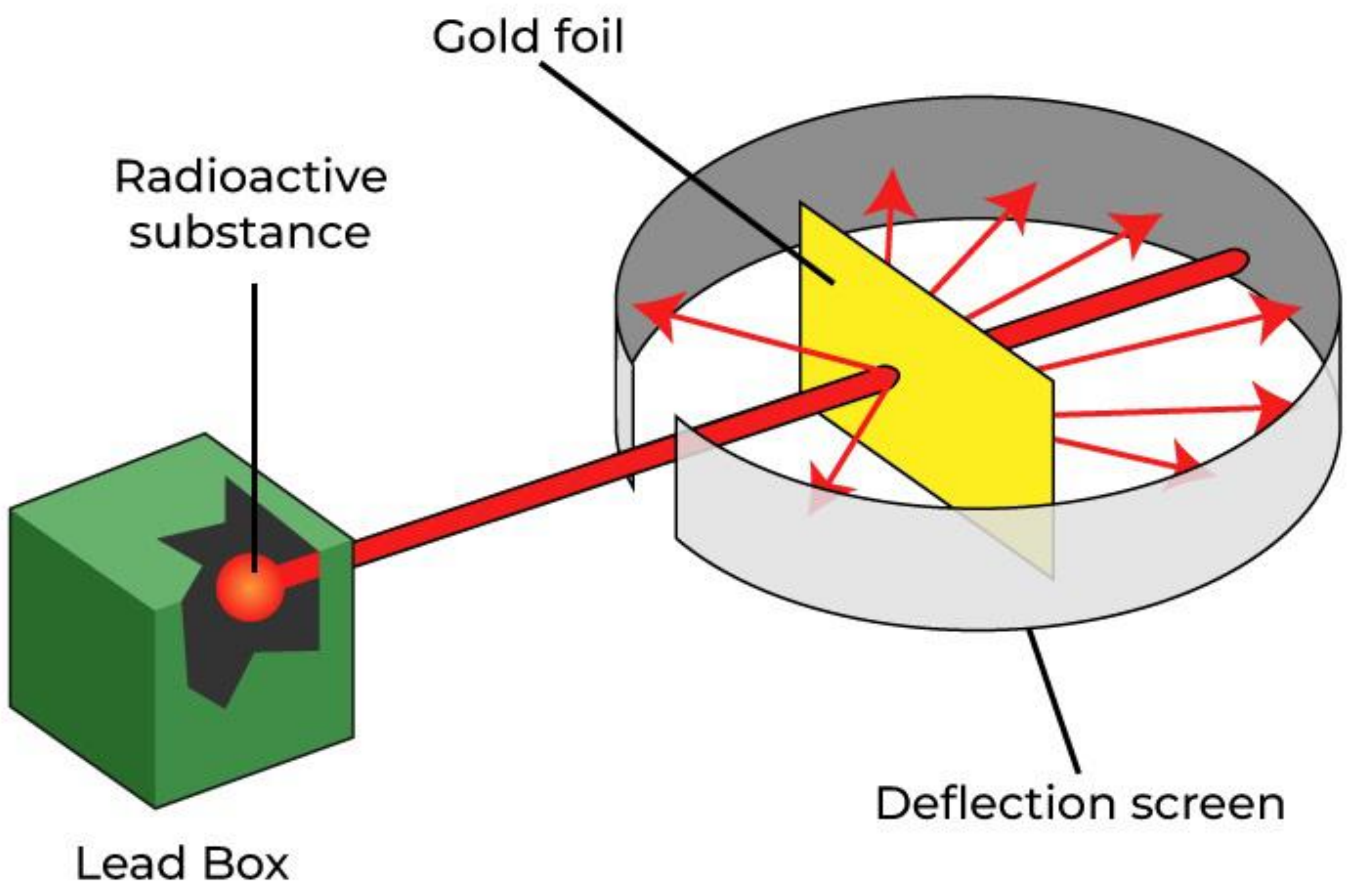

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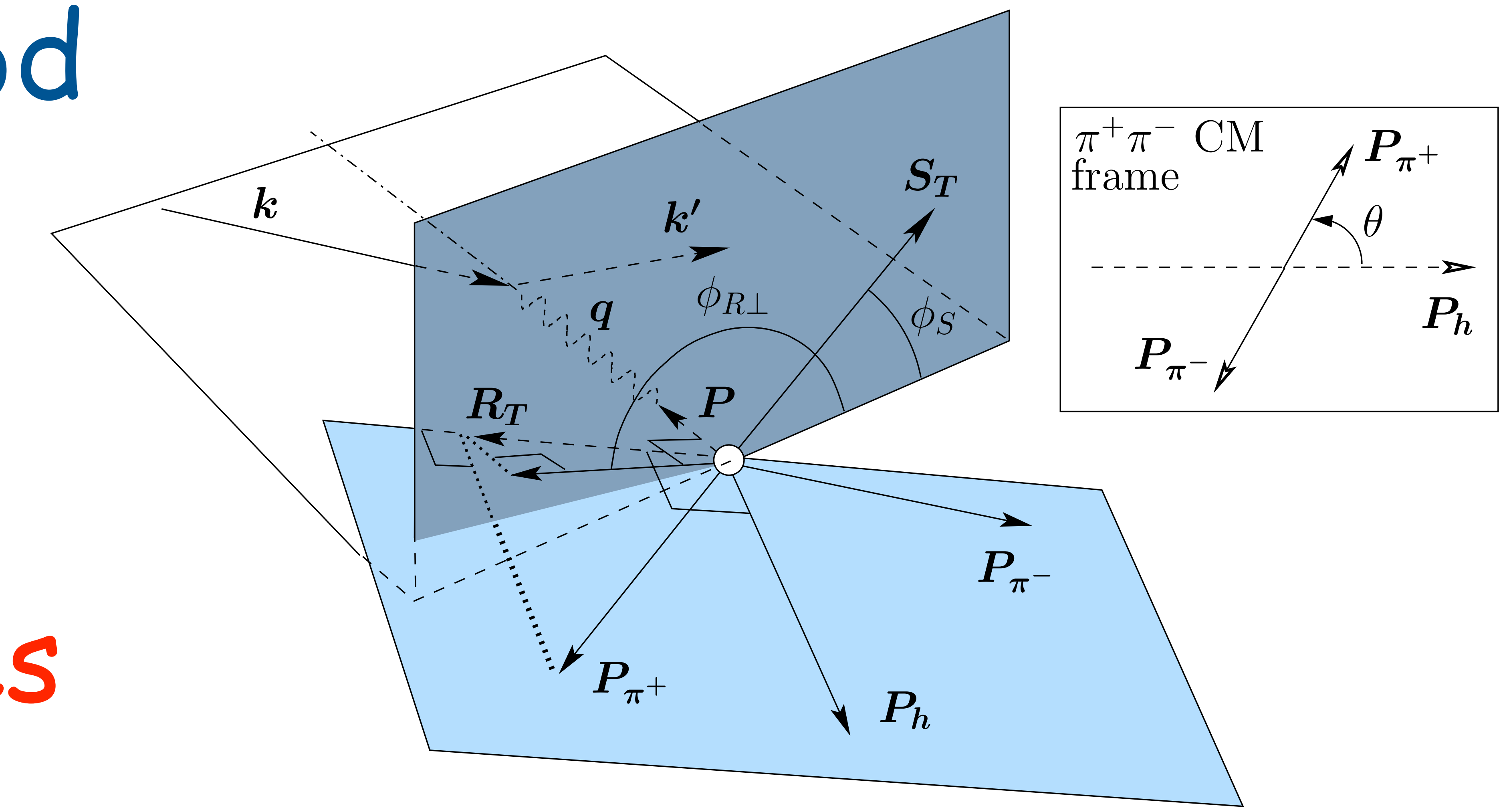
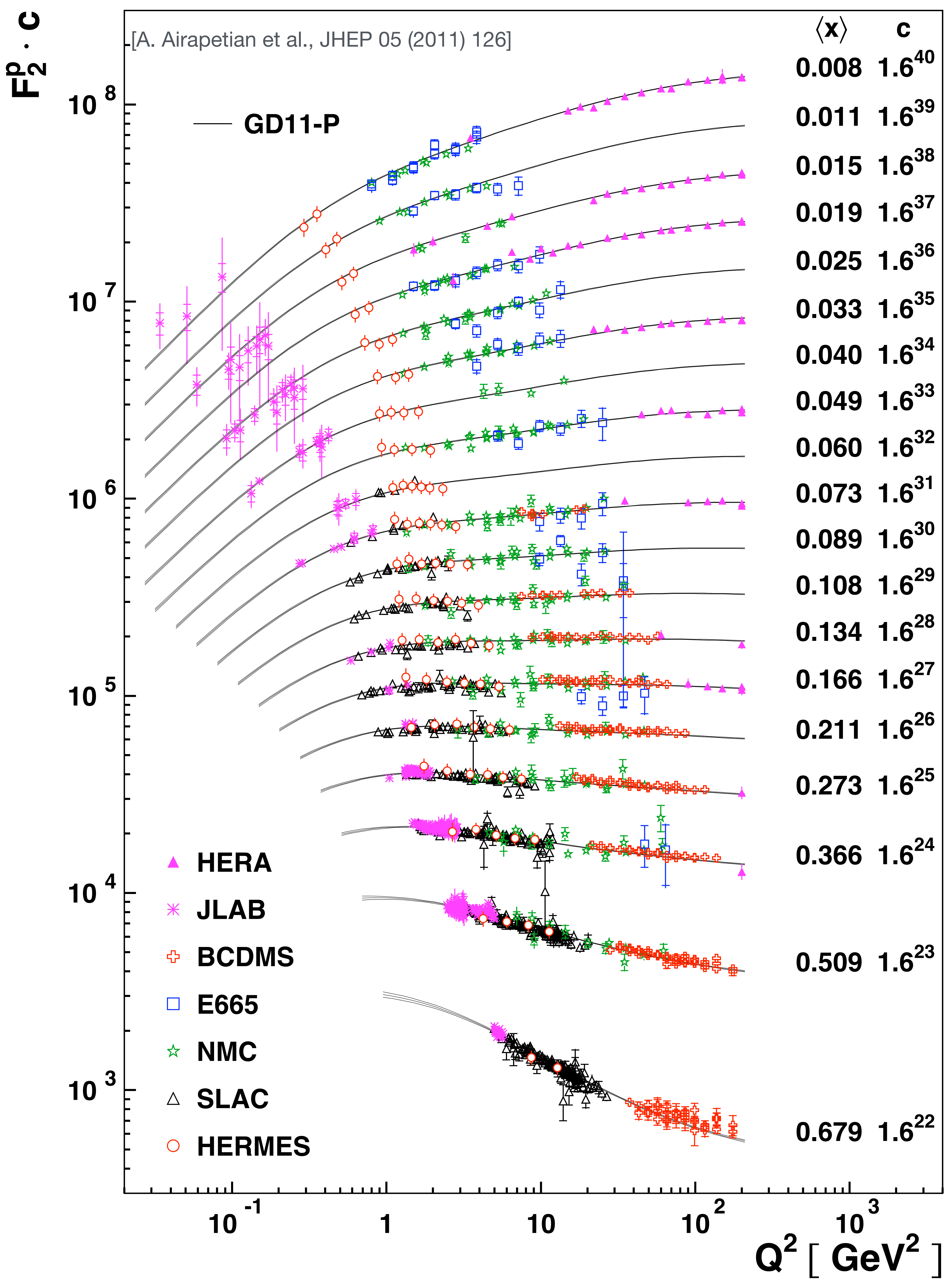
➡ both theoretical & experimental challenges



from 1d to 9d

- unpolarised DIS: obviously bin and unfold in 2d



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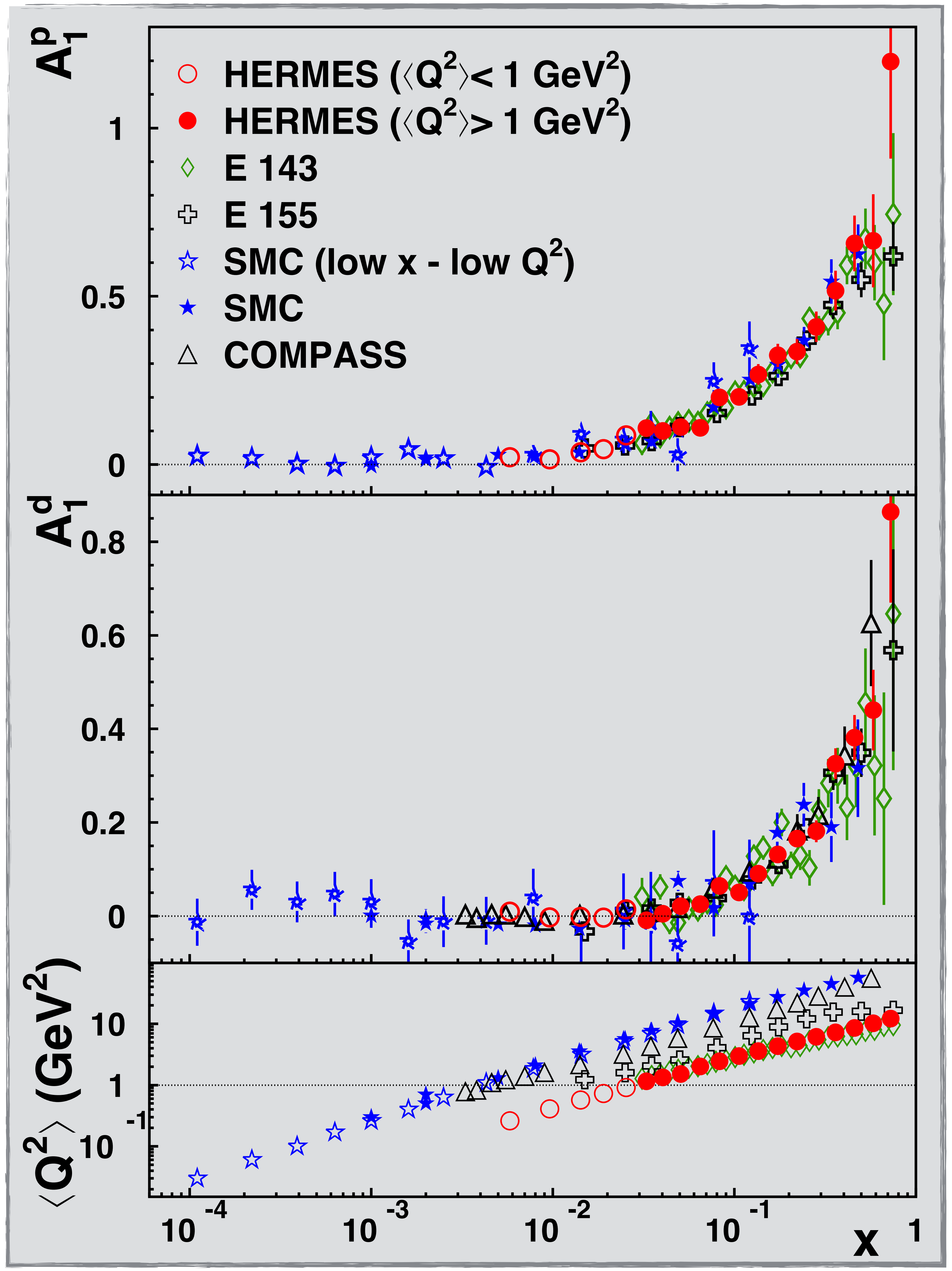

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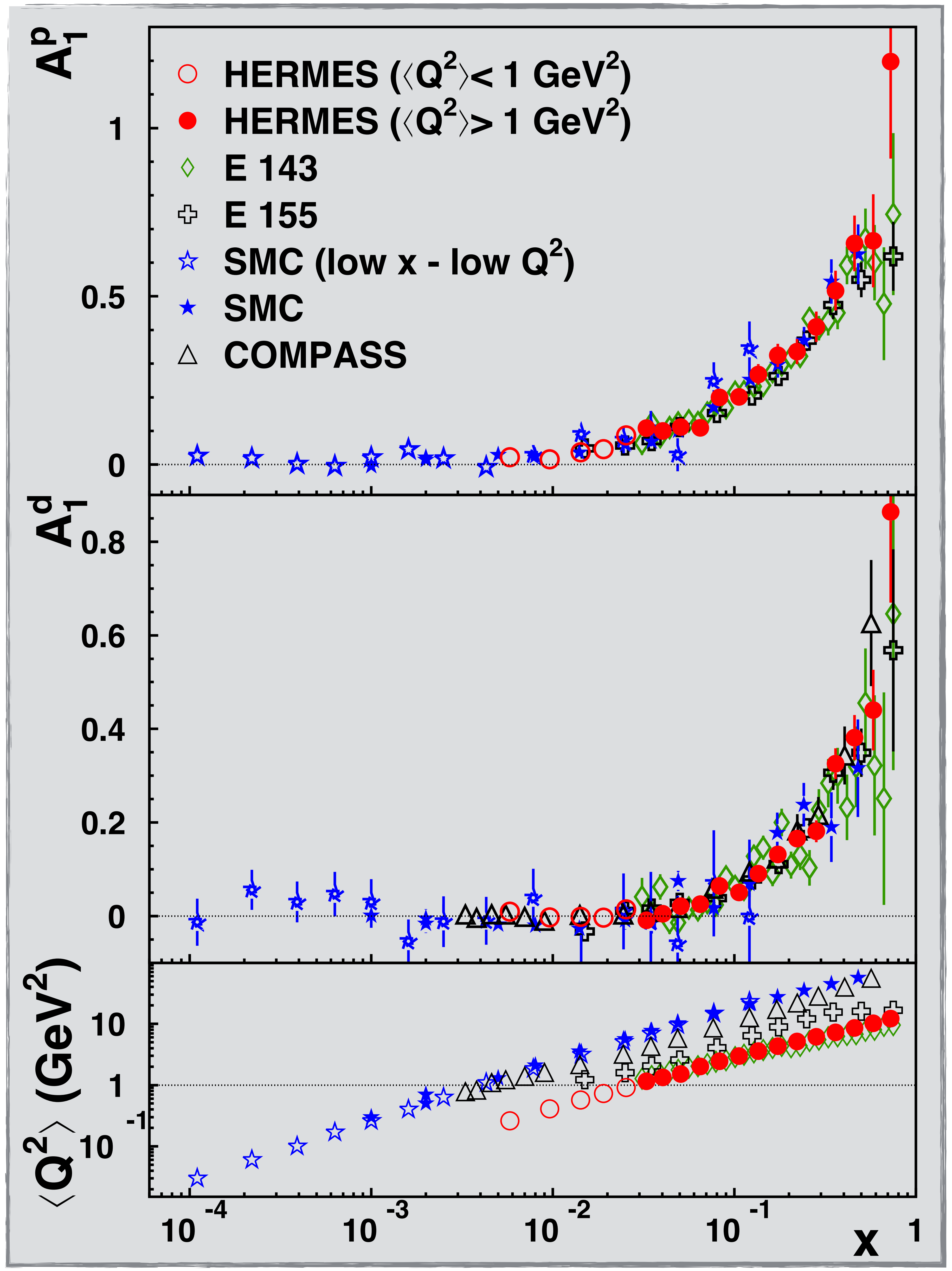

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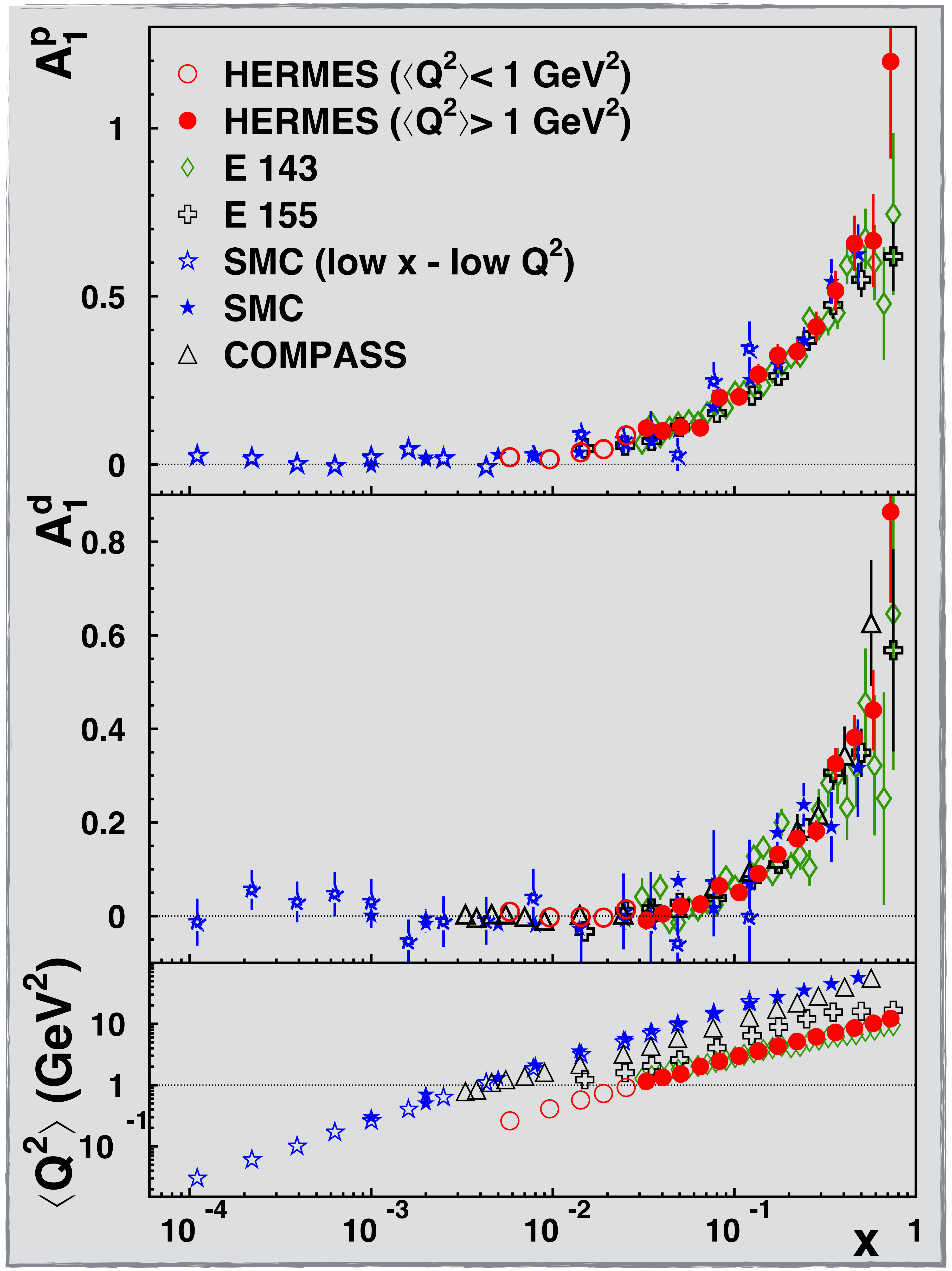
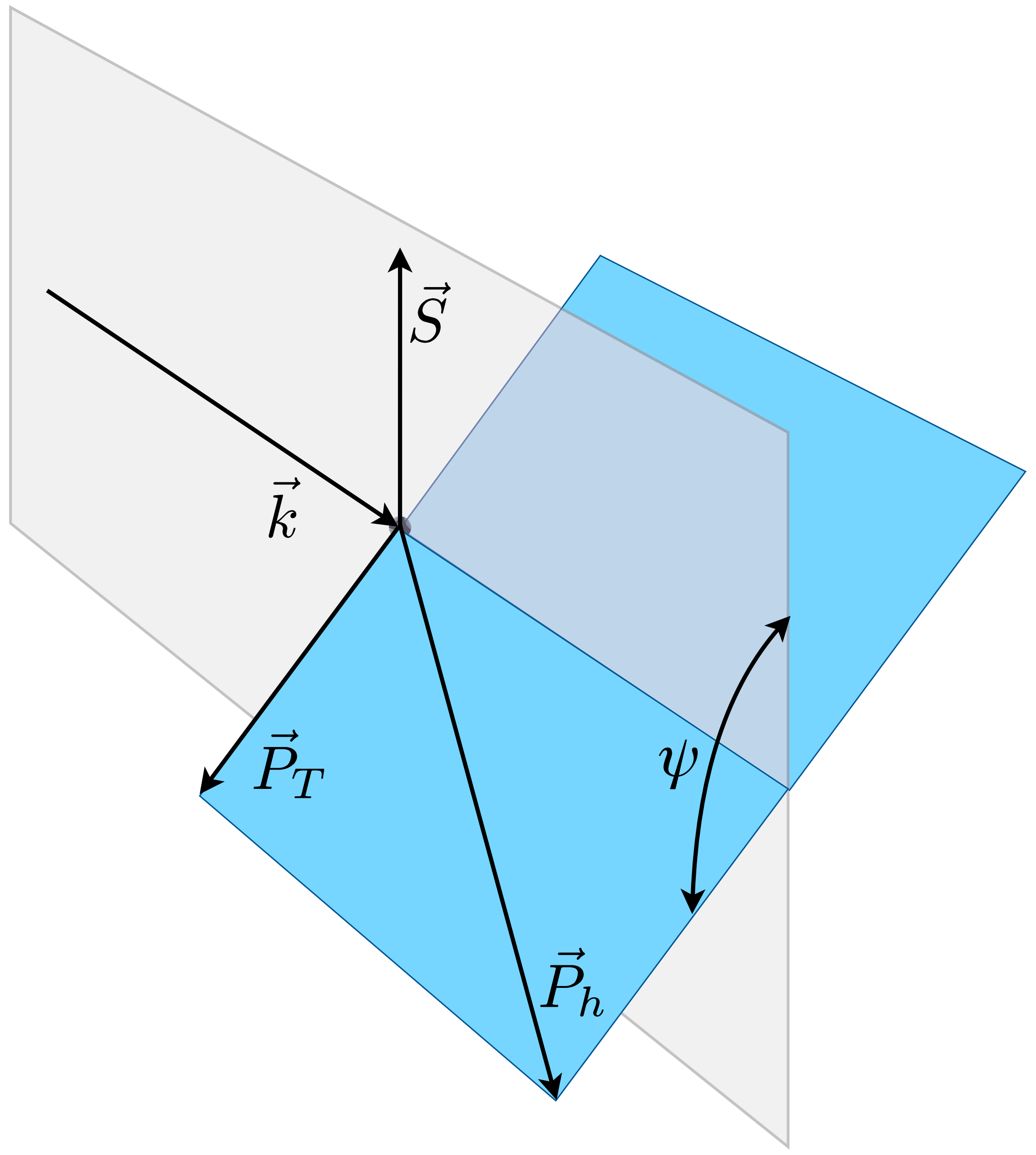
➡ binning in only one variable might hide dependence on other variable(s)



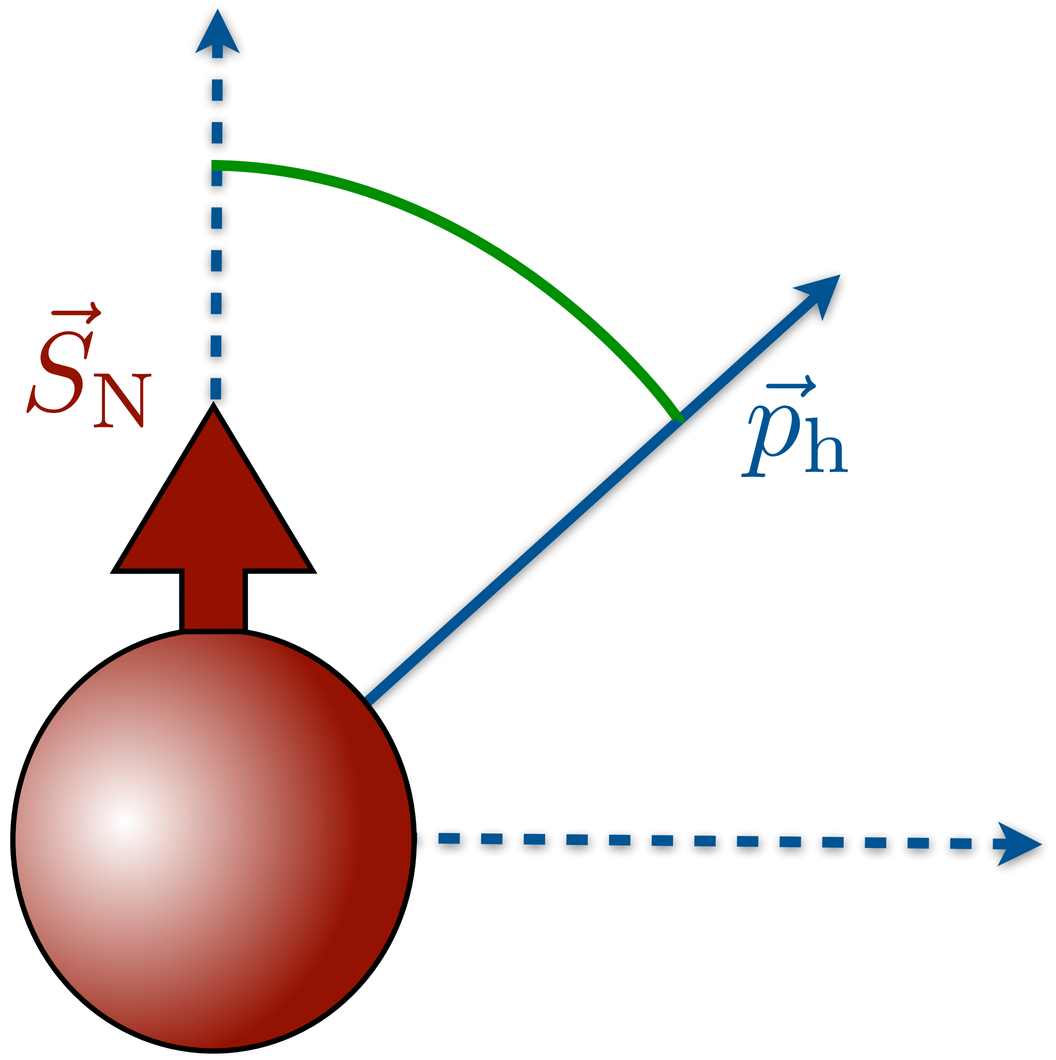
inclusive hadrons: A_{UT} sinψ amplitude

[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]

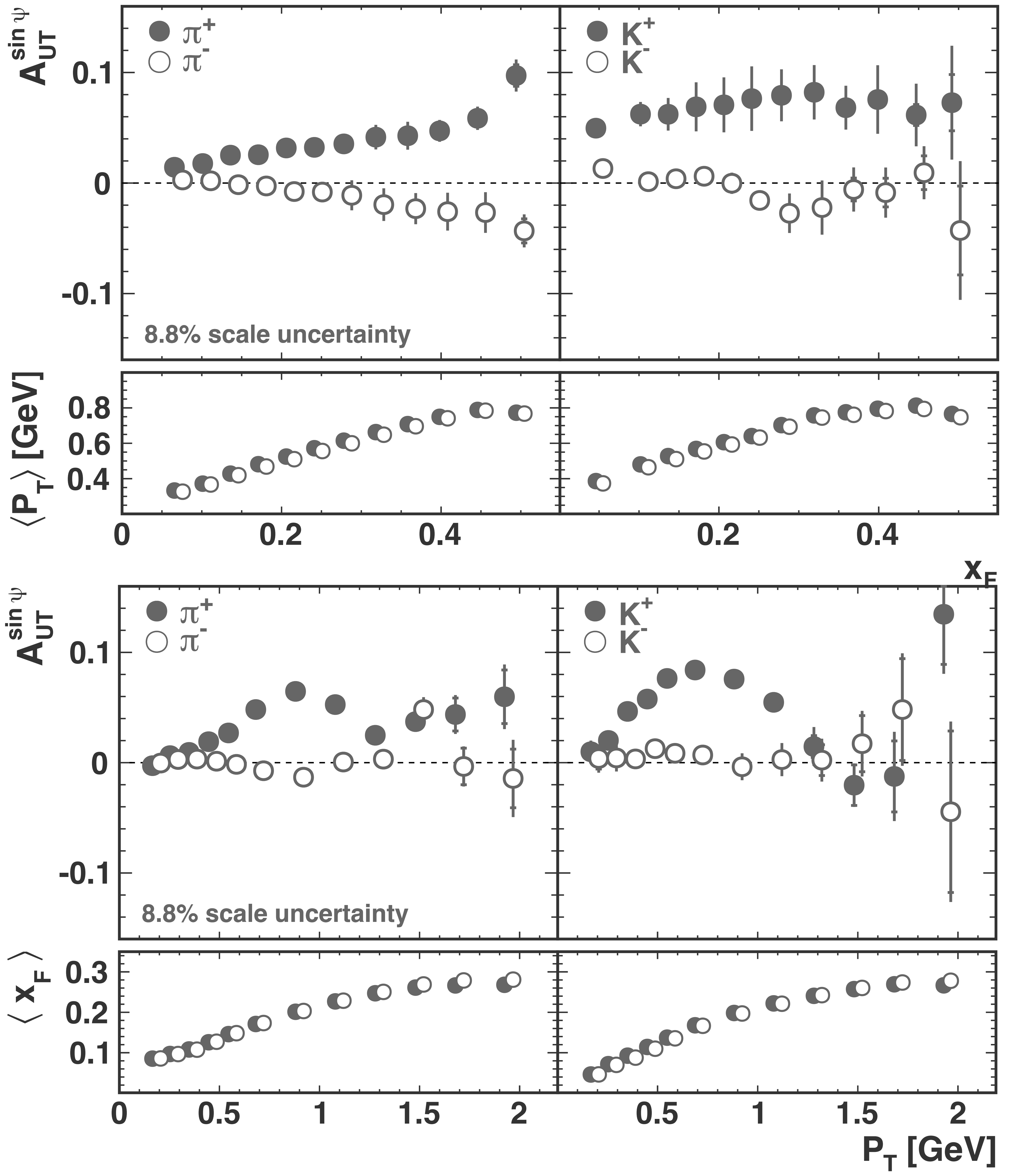
- clear left-right asymmetries for pions and positive kaons



$$ep^{\uparrow} \rightarrow hX$$



lepton going into the plane



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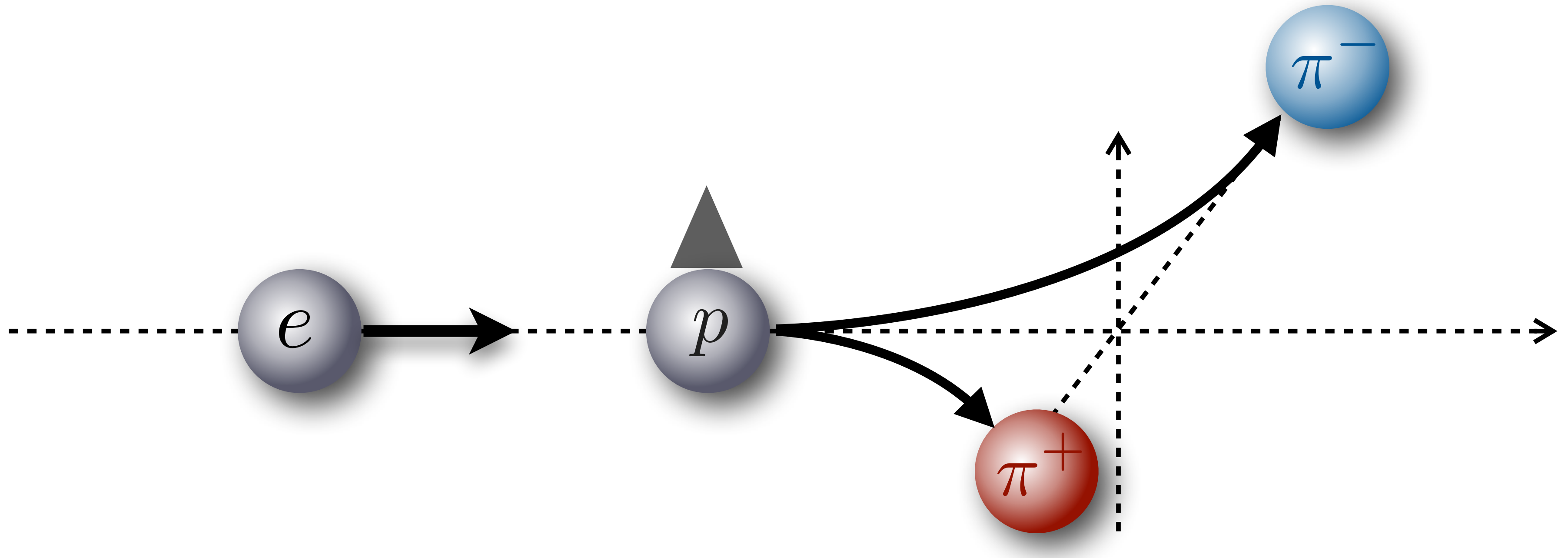

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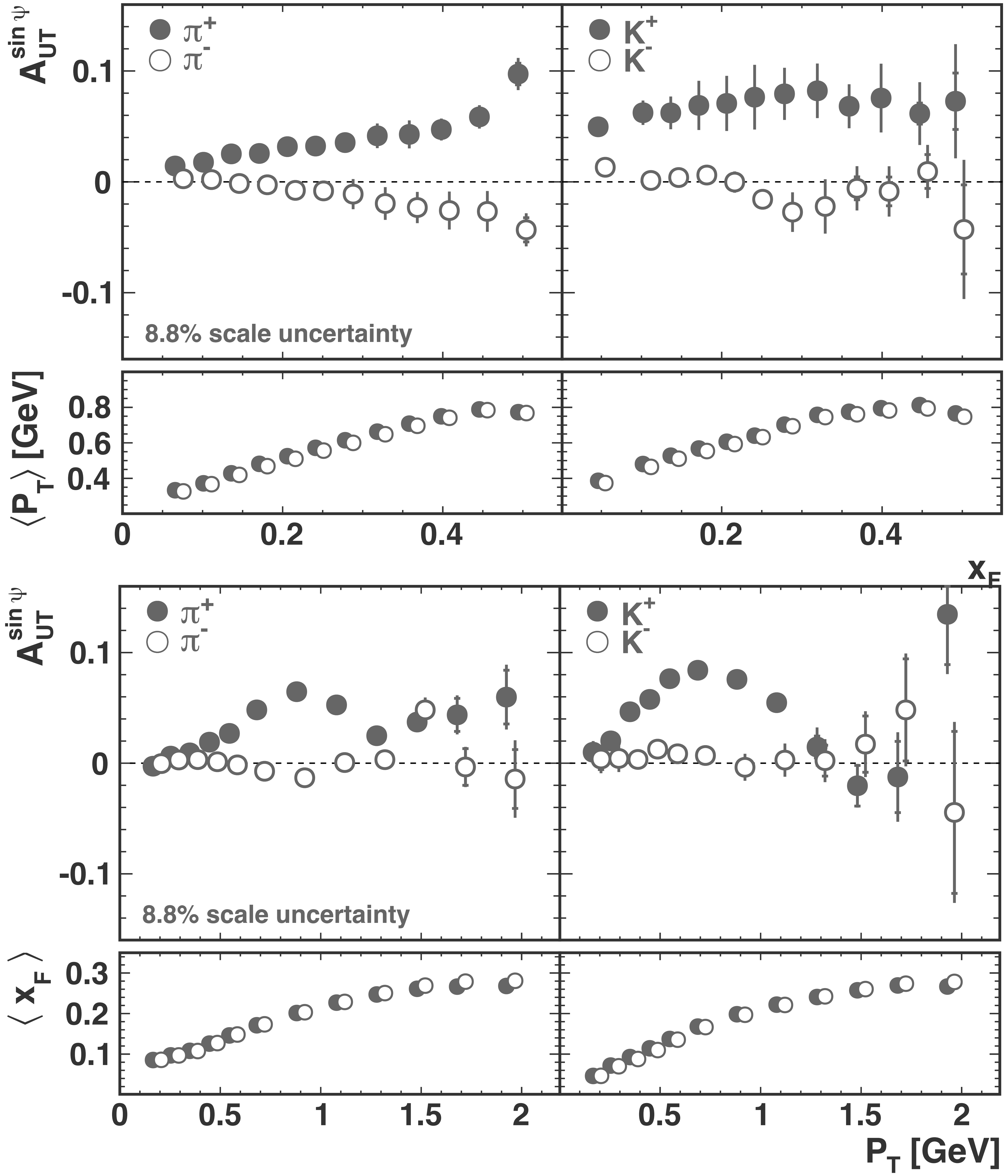

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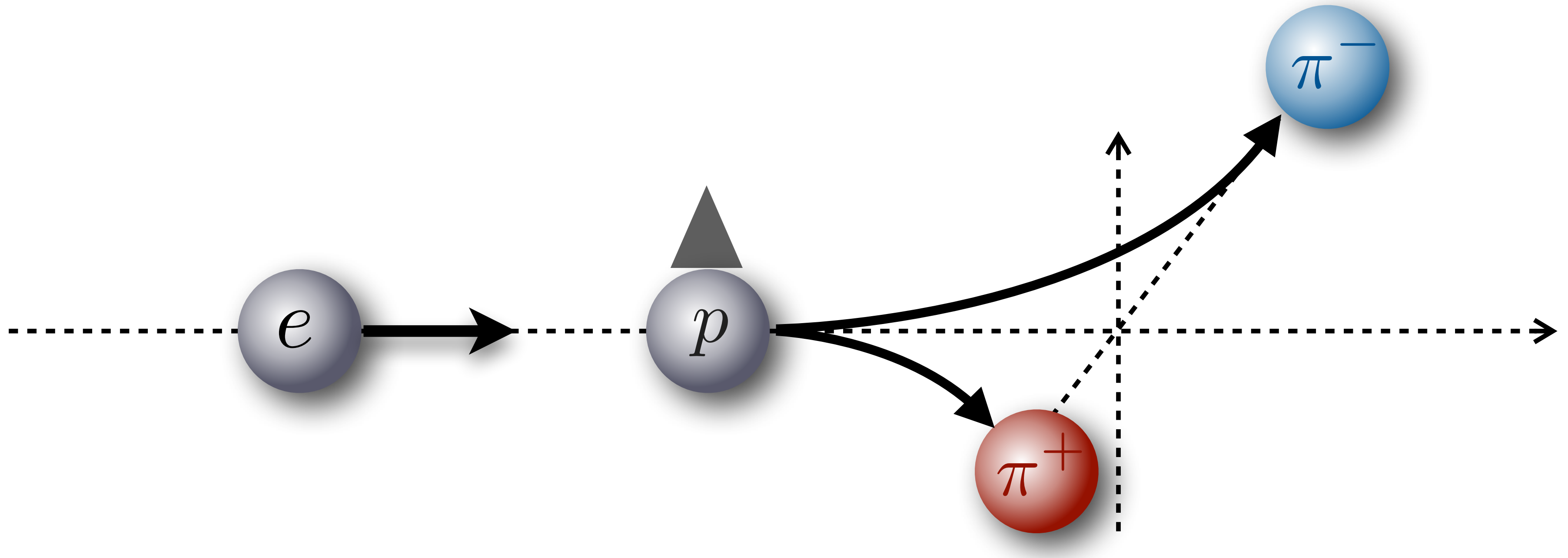

- initially increasing with P_T with a fall-off at larger P_T

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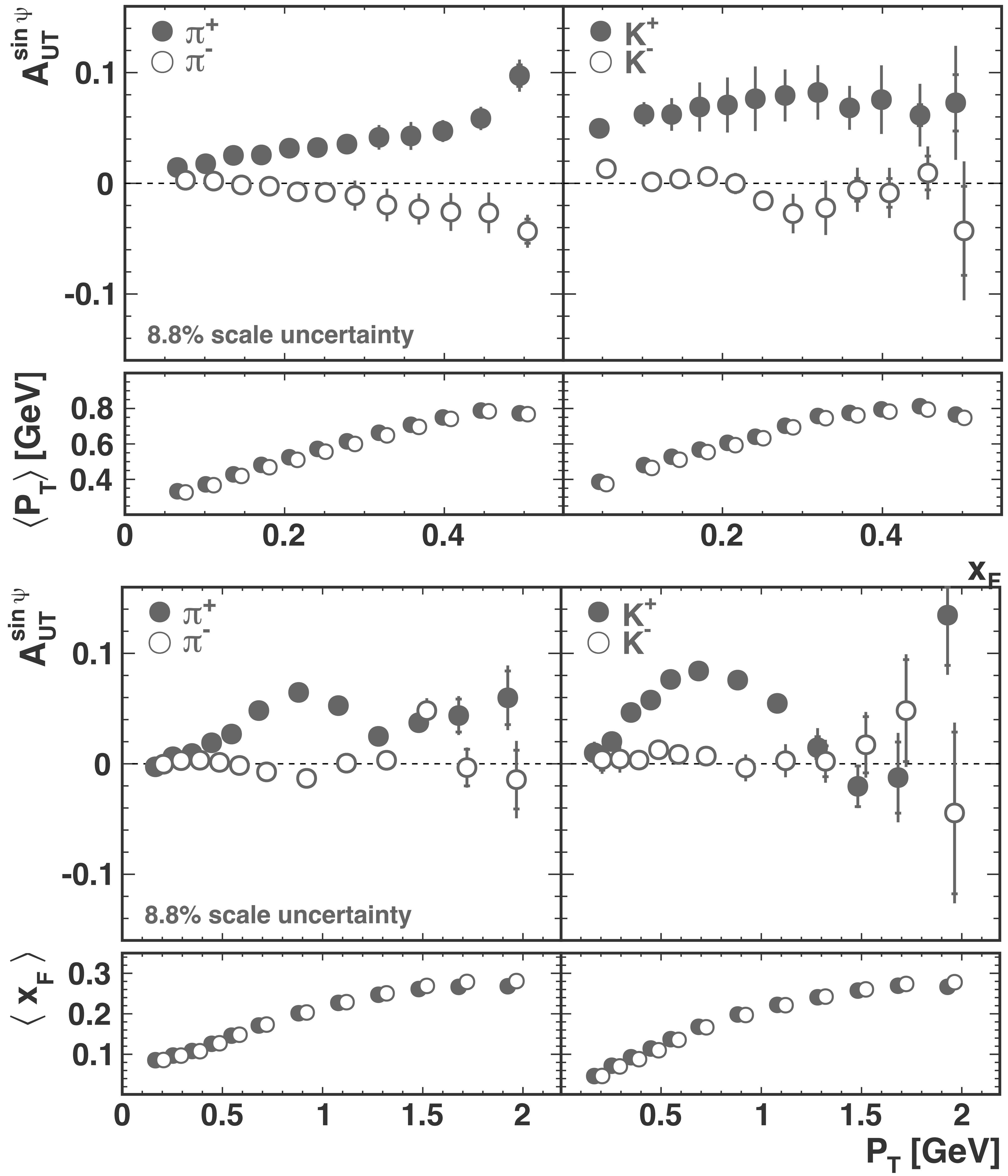

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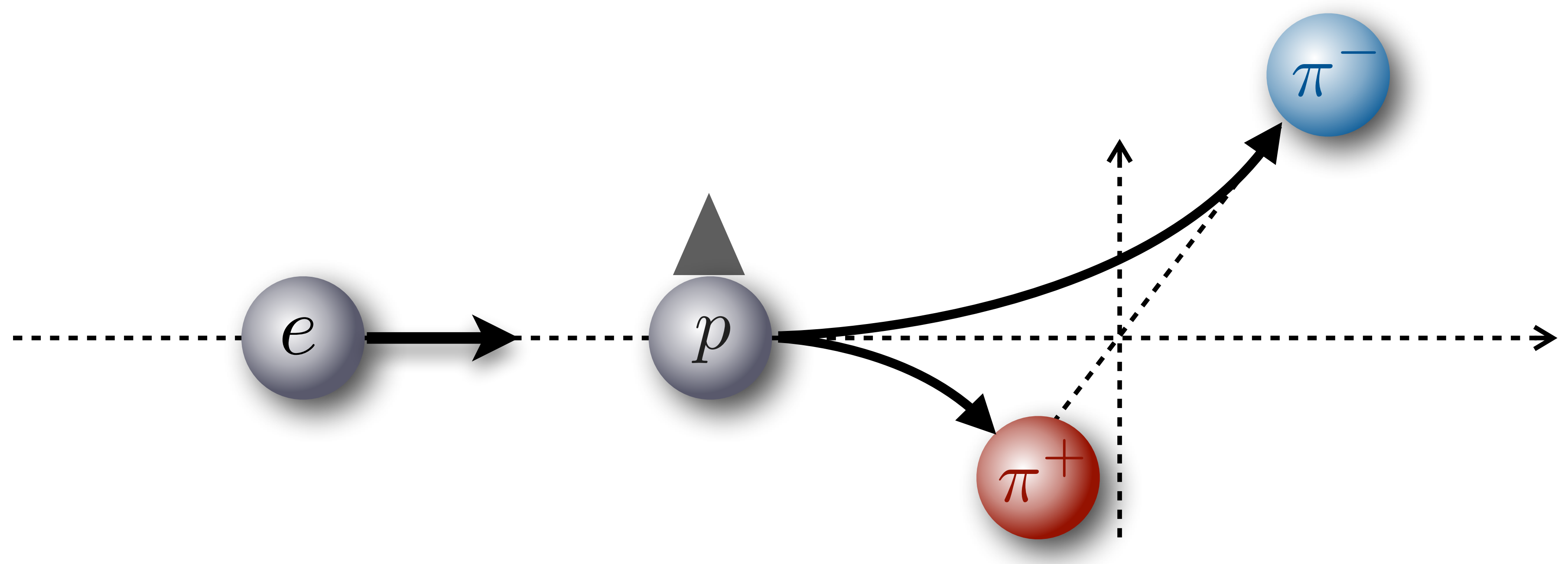

- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated

➥ look at 2D dependences

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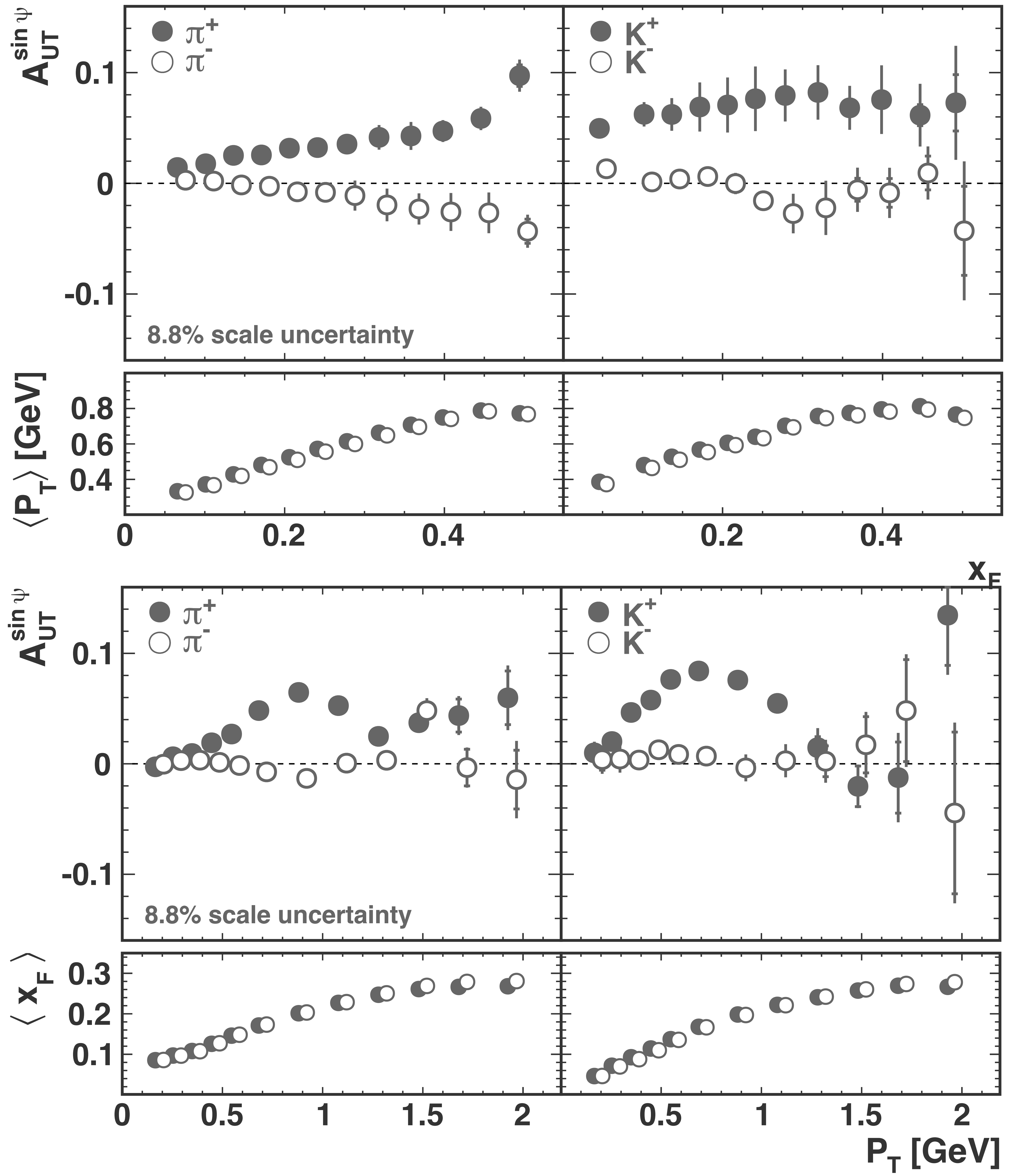

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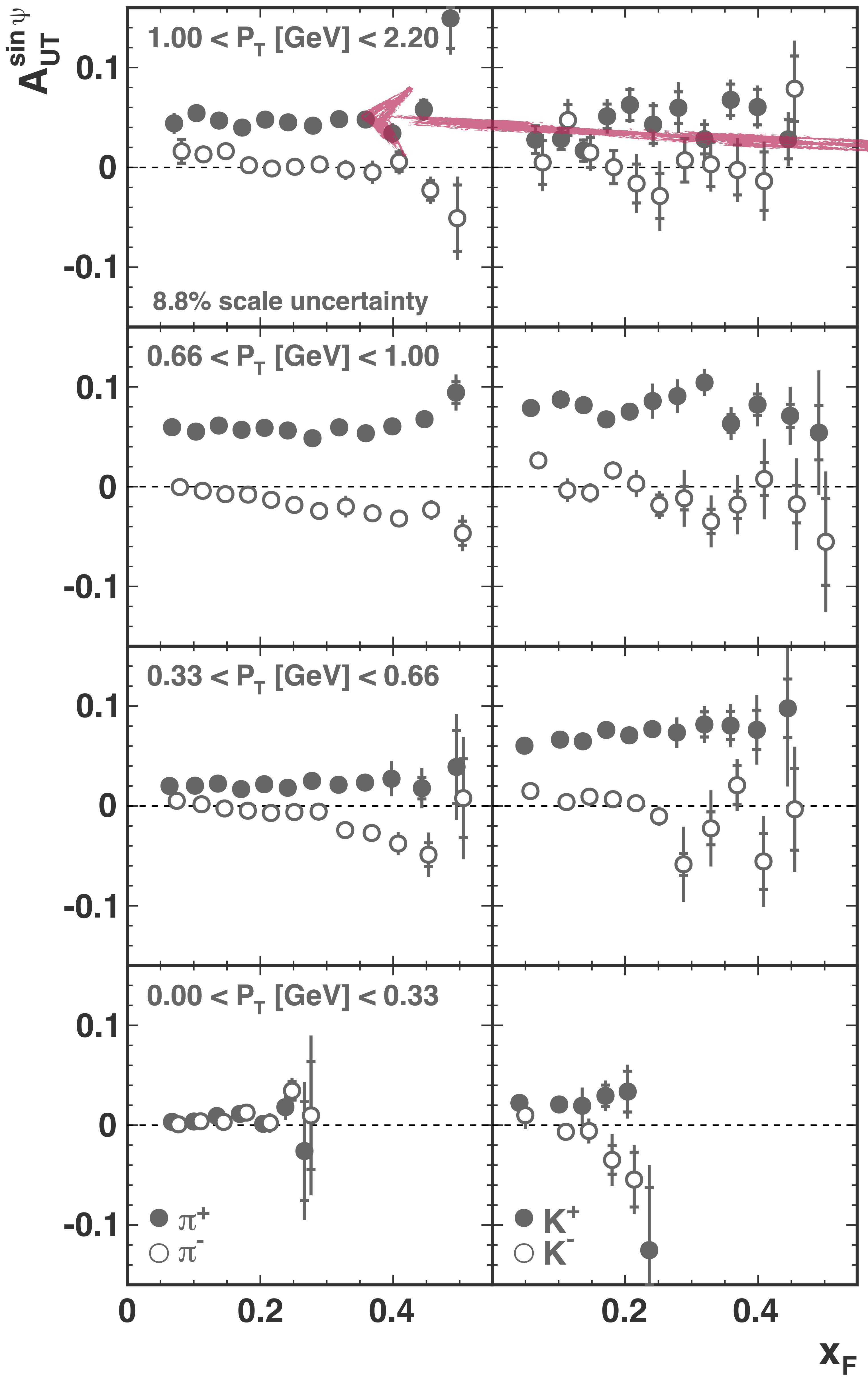

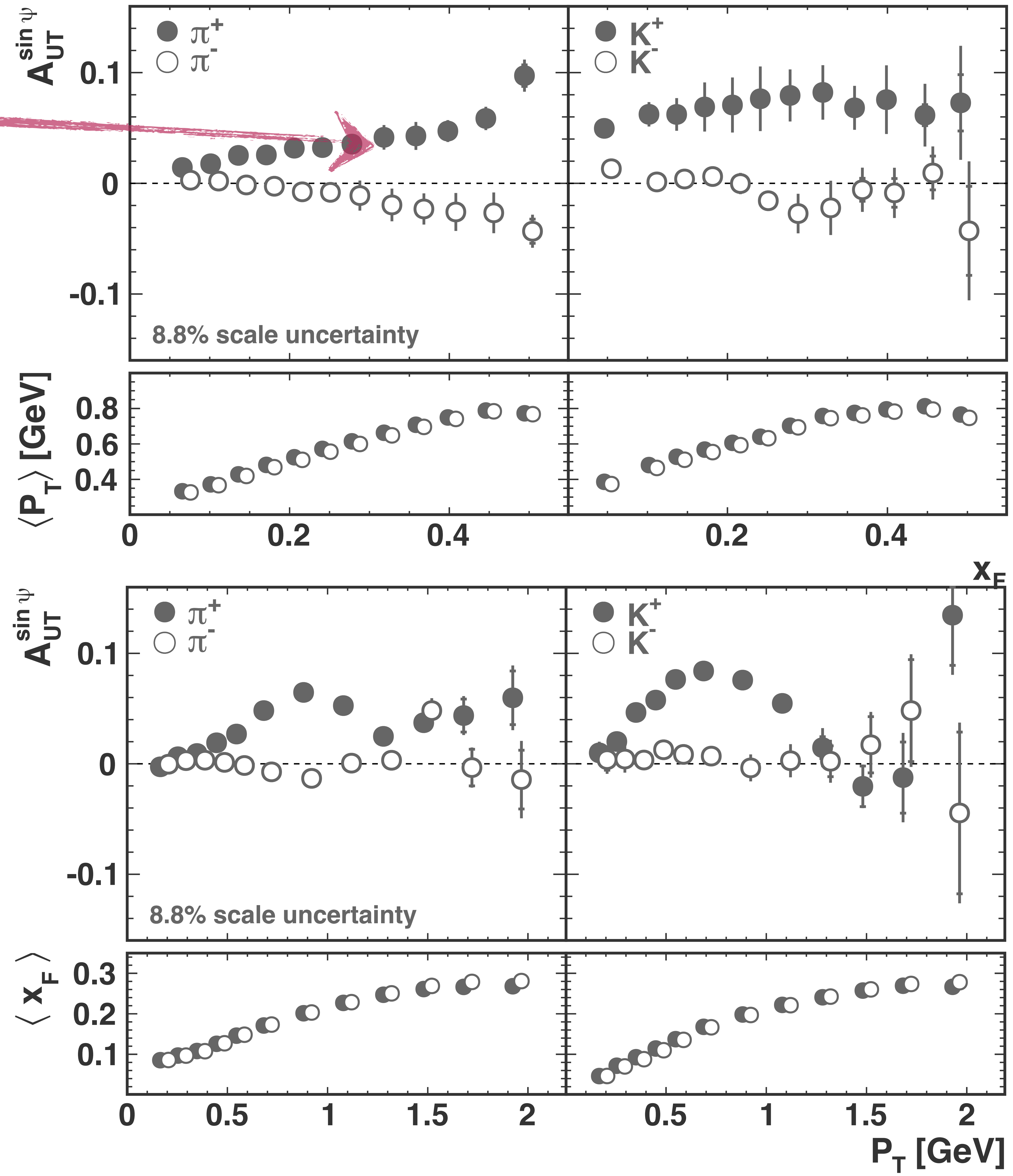

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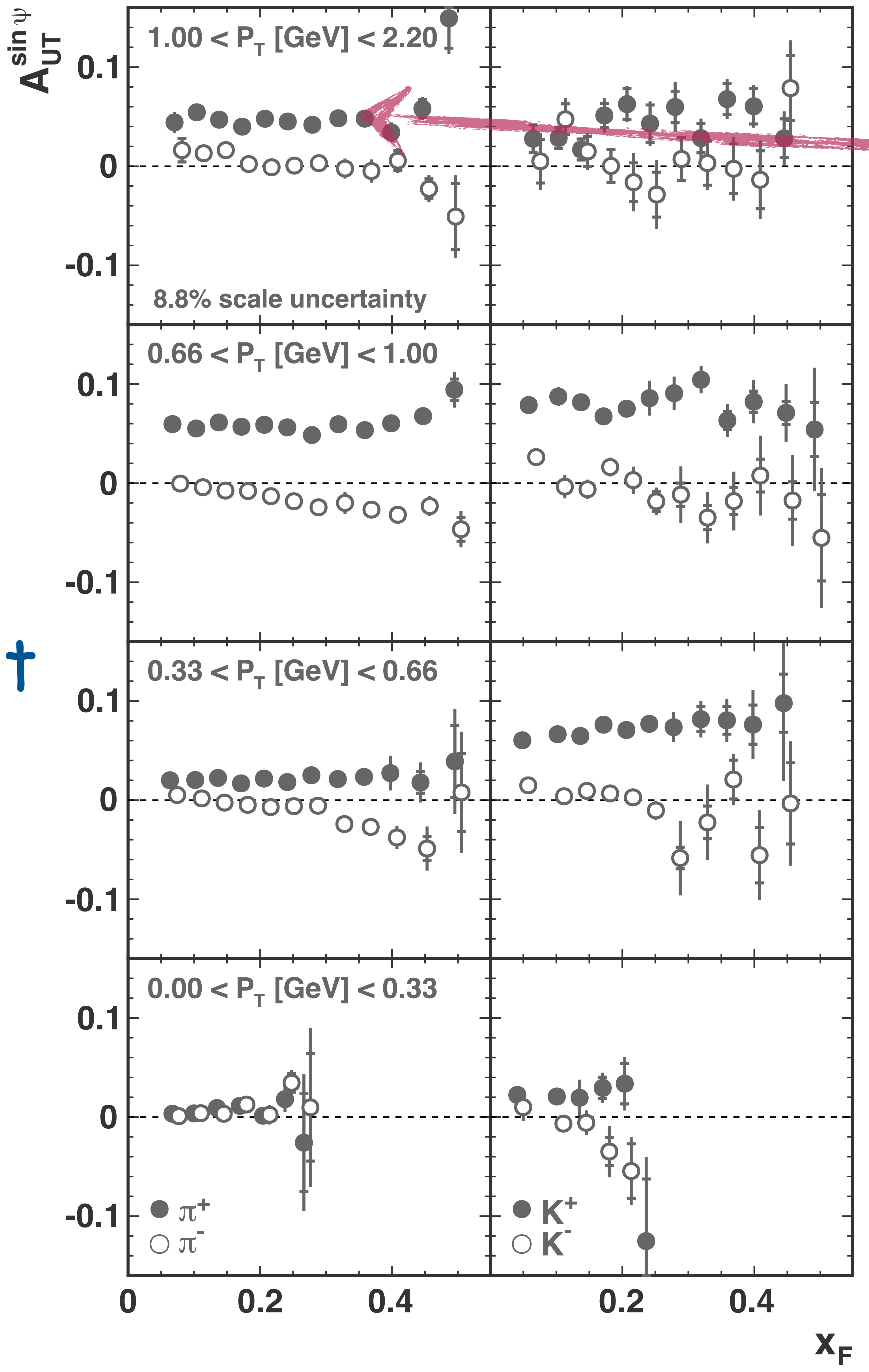
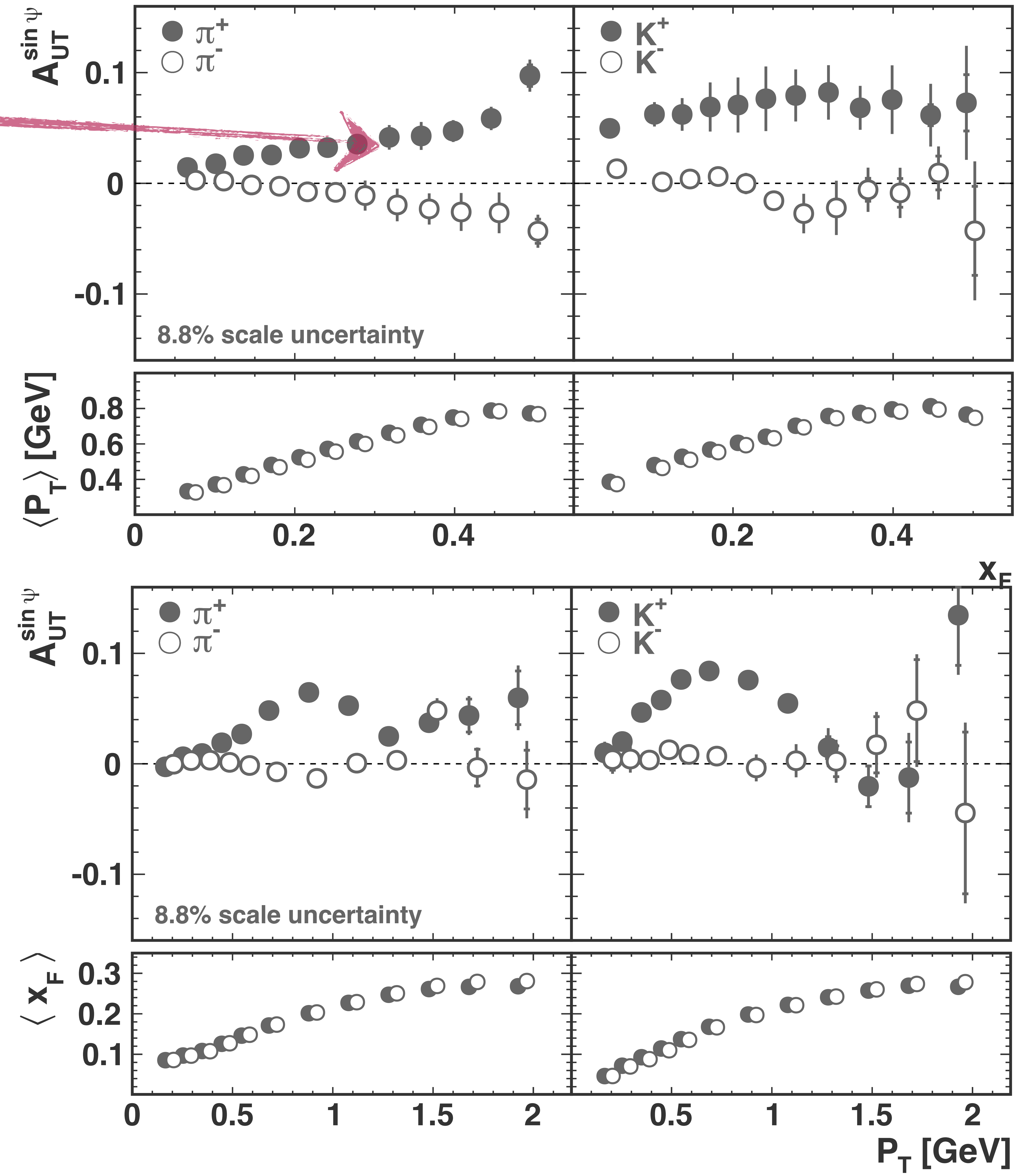
- increase with x_F disappears in 2d binning
- increase in 1d presentation result of underlying P_T dependence





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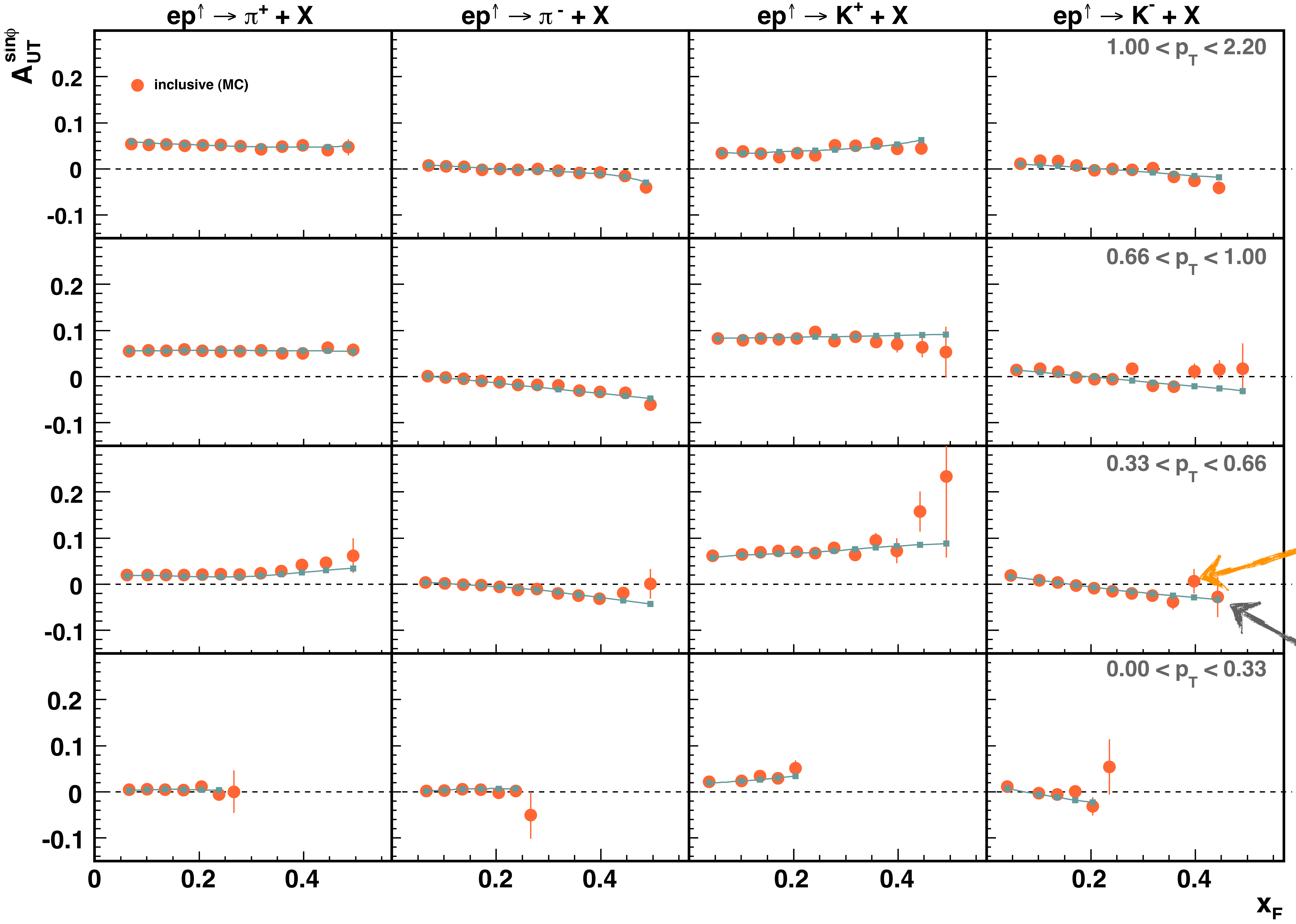

reconstructed MC

input model (fit to data)

small detector effects in fully differential analysis

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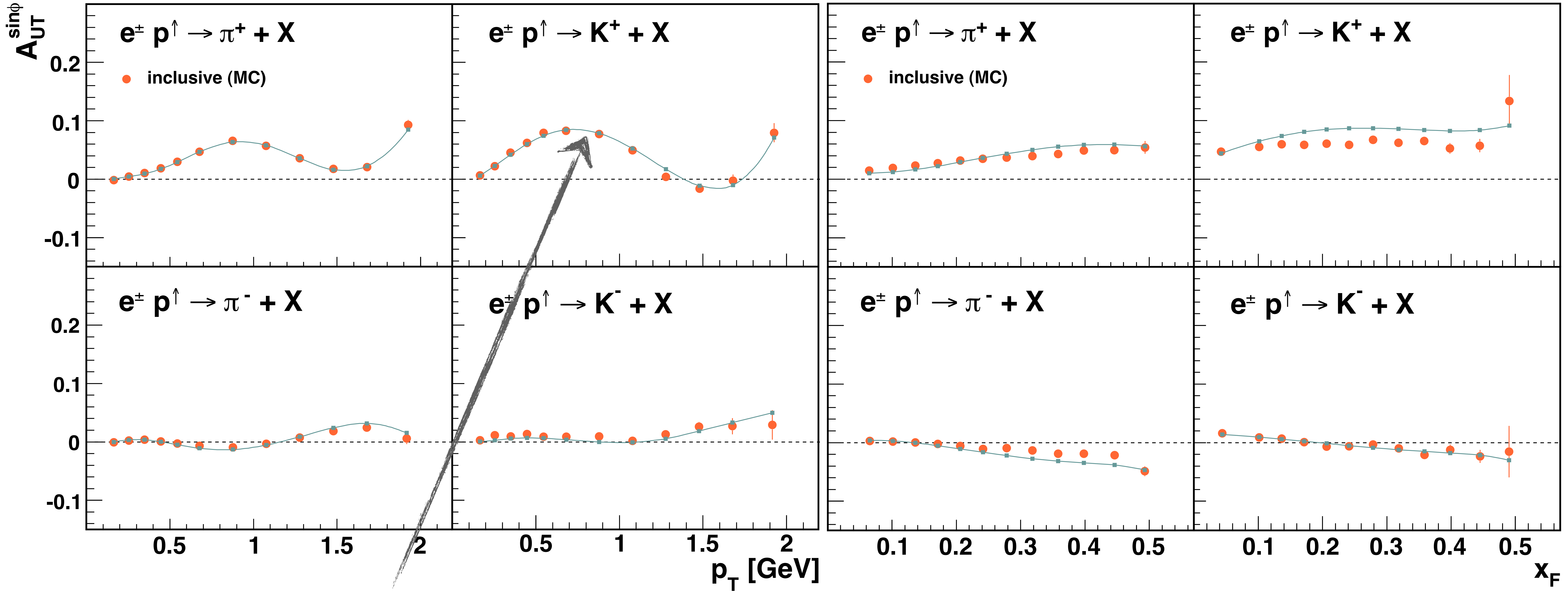

strong kinematic dependence can lead to large systematic effects if integrated over

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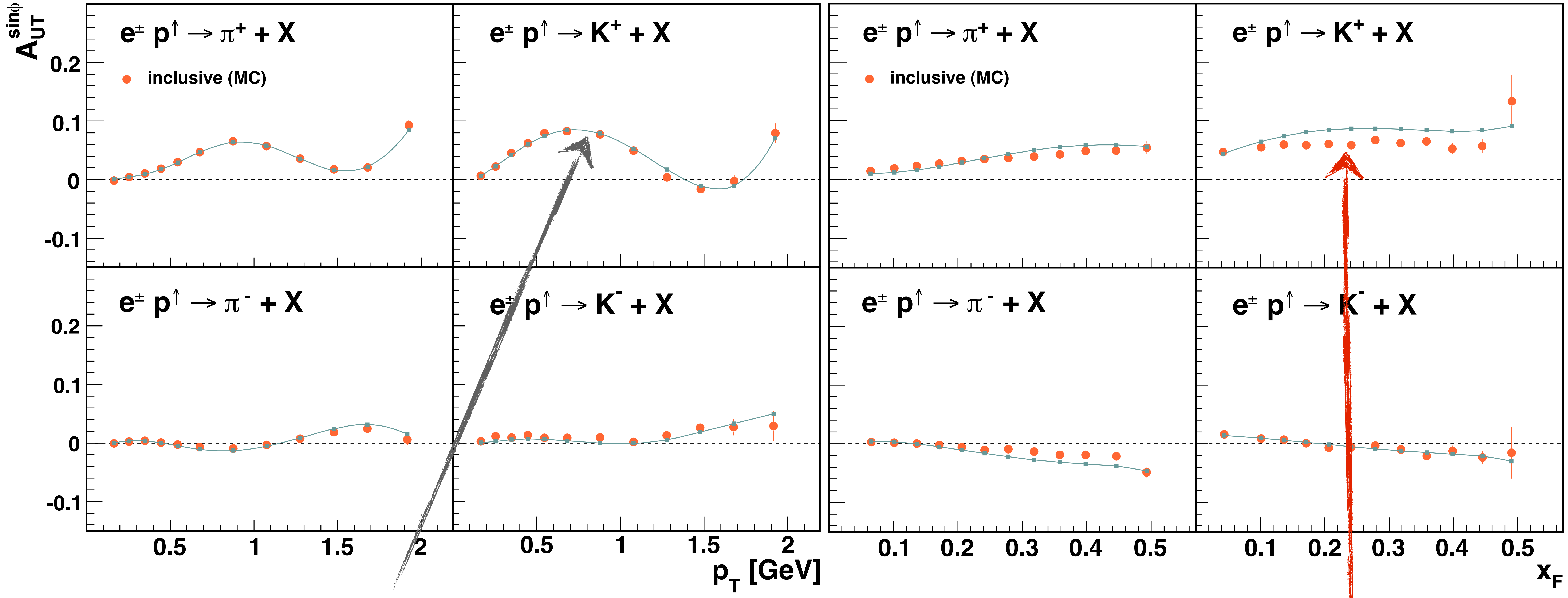

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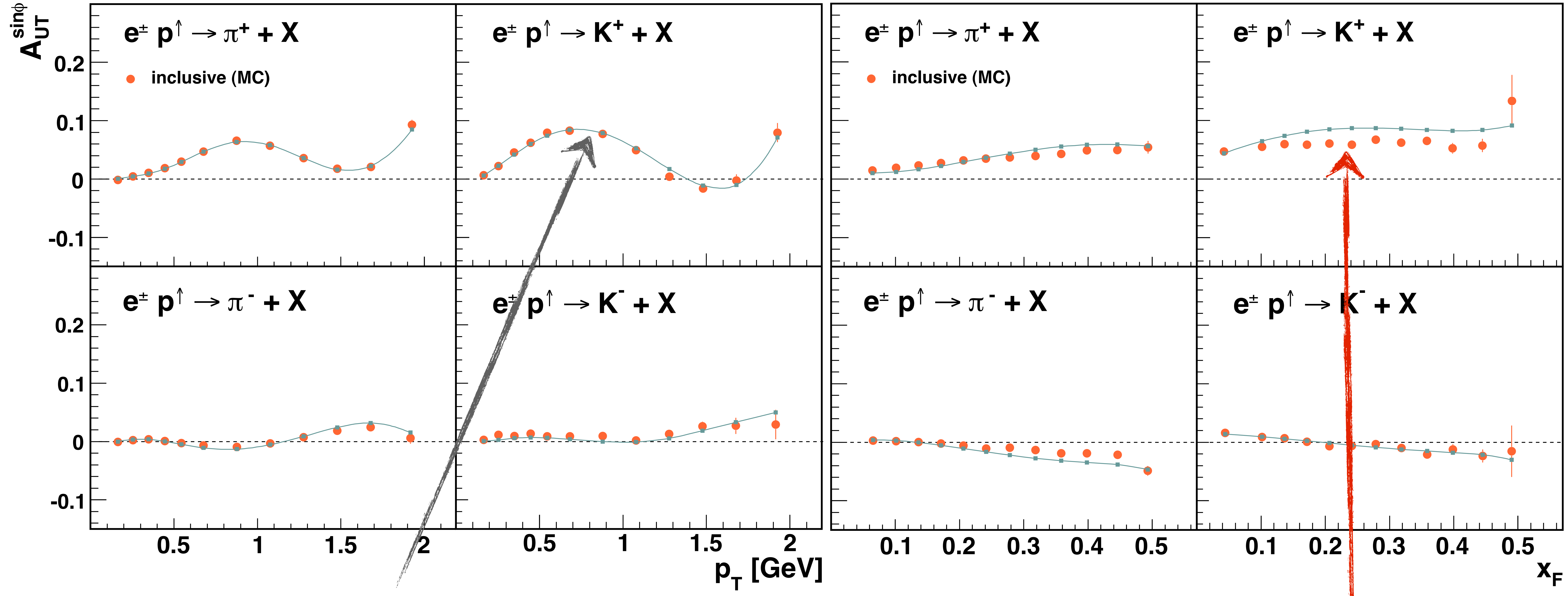

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➡ need a good MC model for realistic uncertainty estimate

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- somewhat more objective reasoning: e.g.,
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- somewhat more objective reasoning: e.g.,
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- some pragmatic reasoning: e.g.,
  - less precision
  - less phase space and thus less variation of cross sections, …
- some plainly wrong reasoning: e.g.,
  - stick to the approach that seemed to work before
  - multi-d dependences difficult to visualise
  - "we are doing collinear physics, no need for TMD d.o.f.

… example measurements

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

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normalize to inclusive DIS cross section

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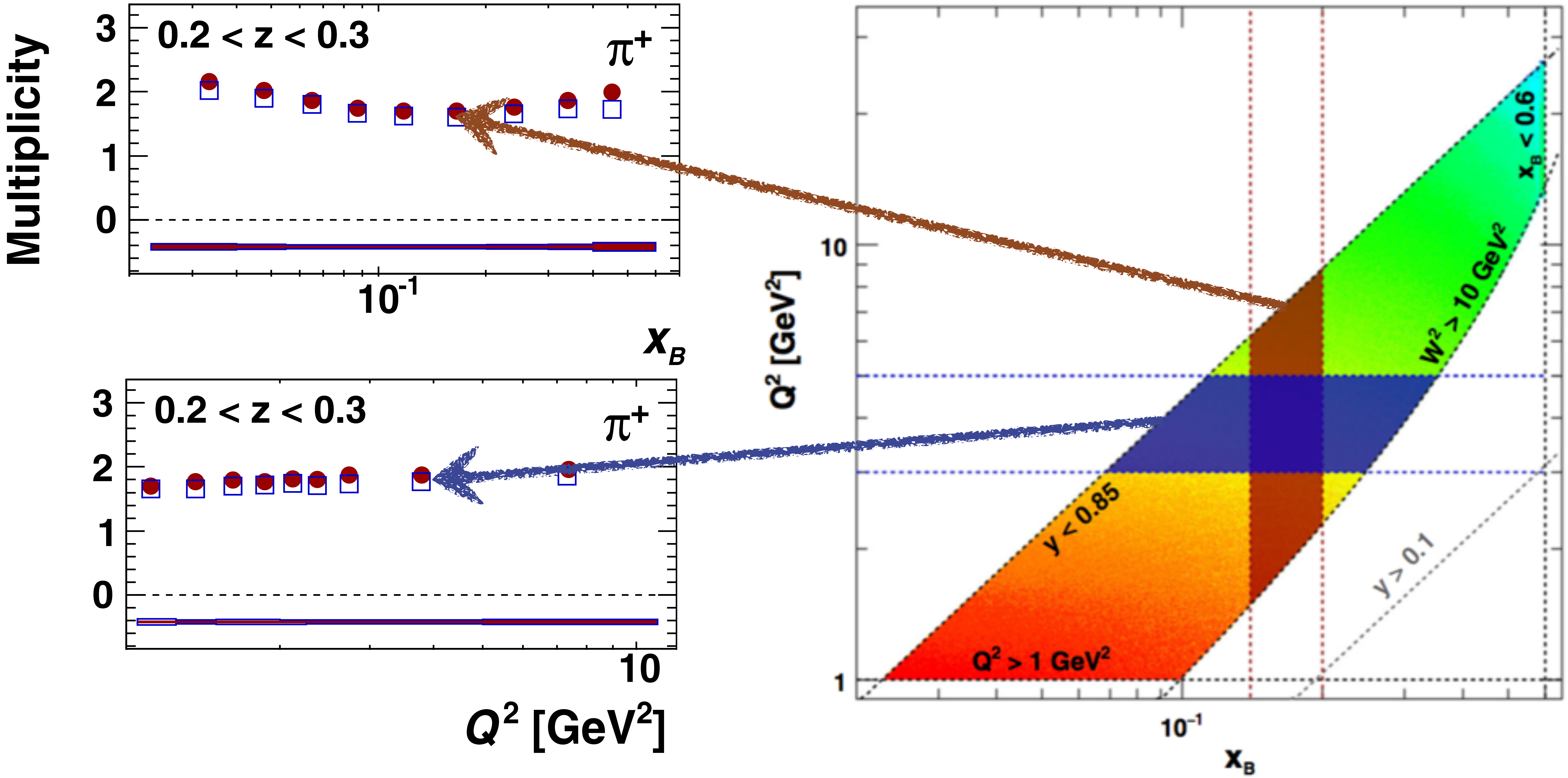

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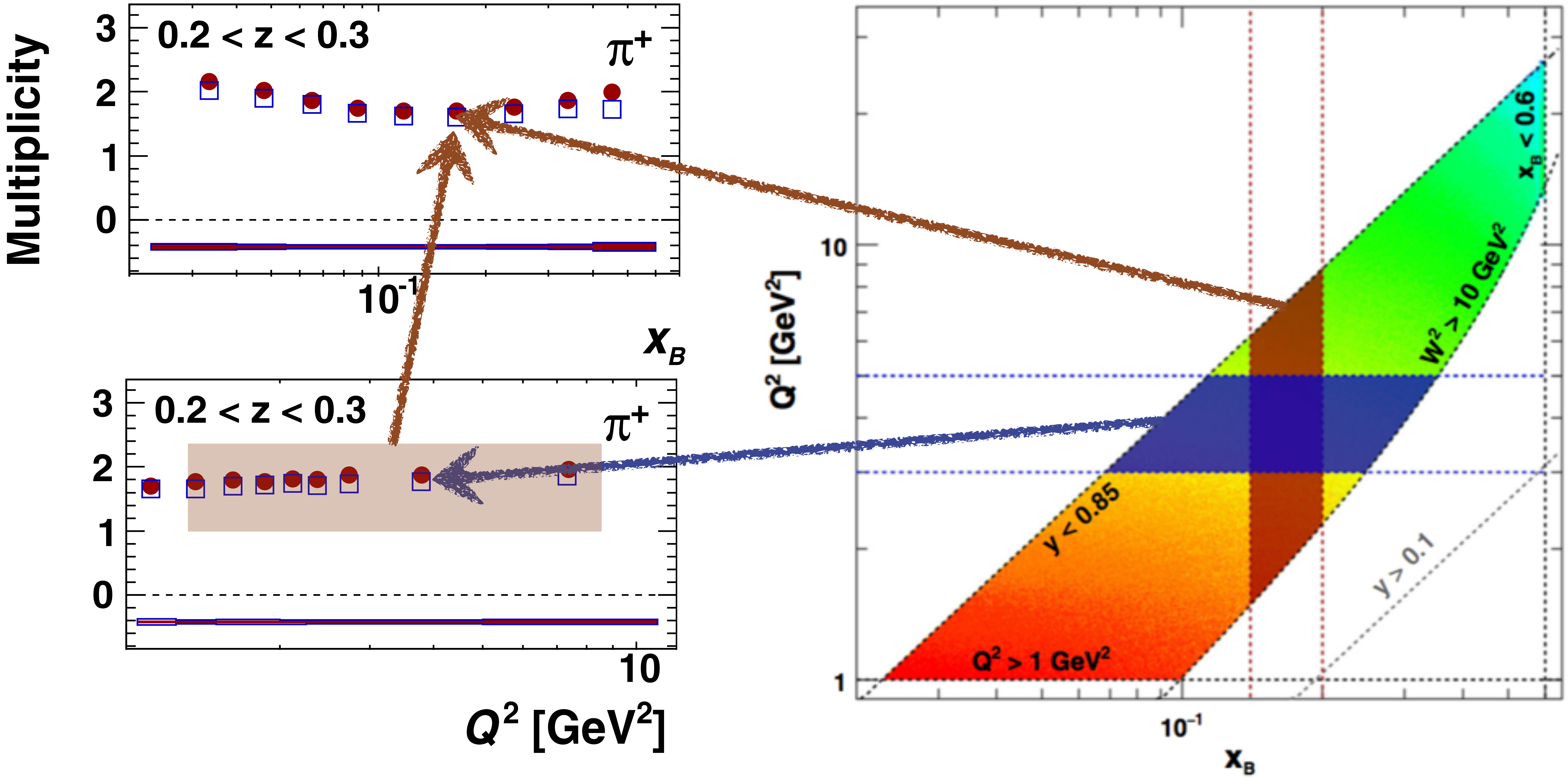

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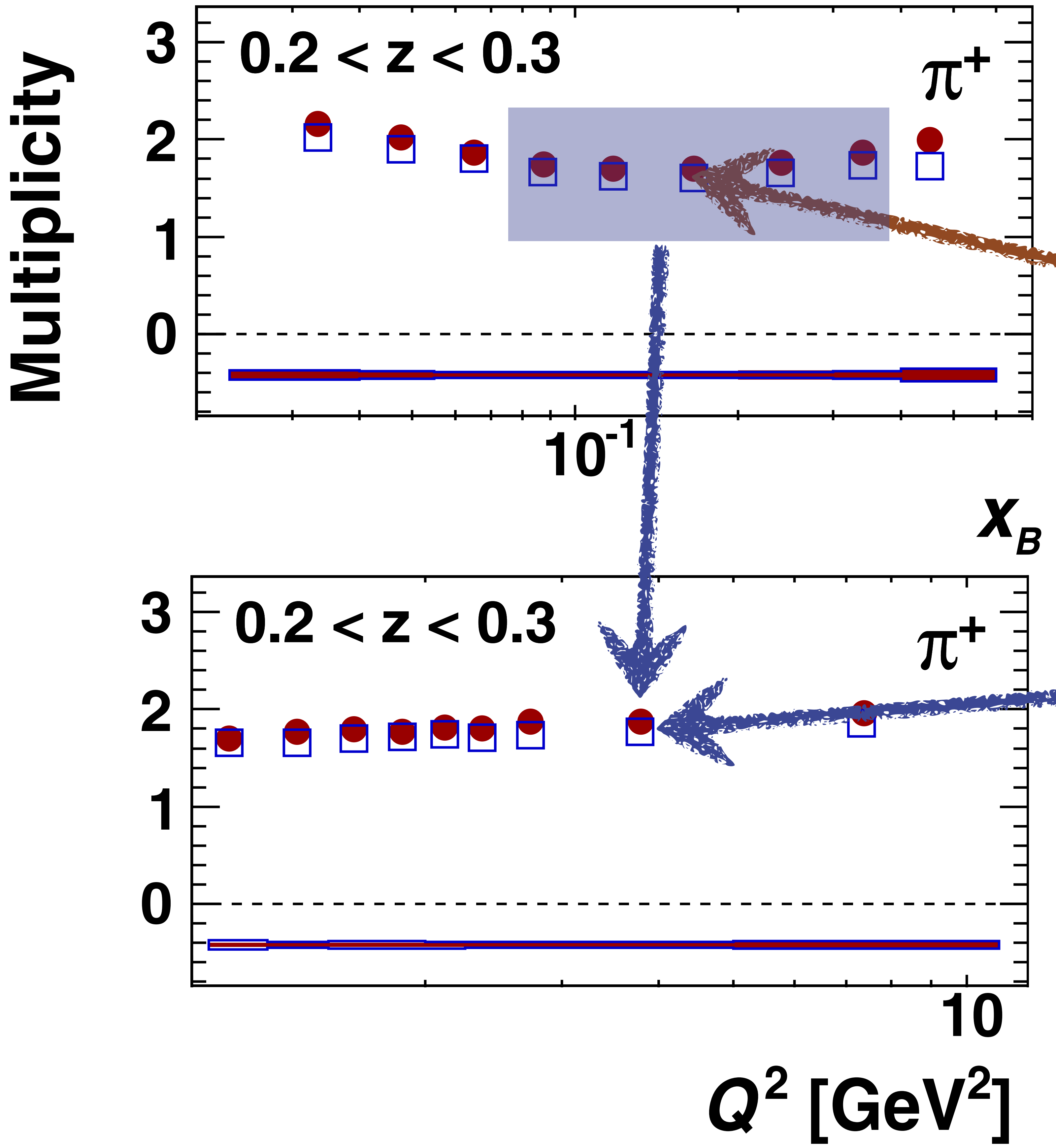

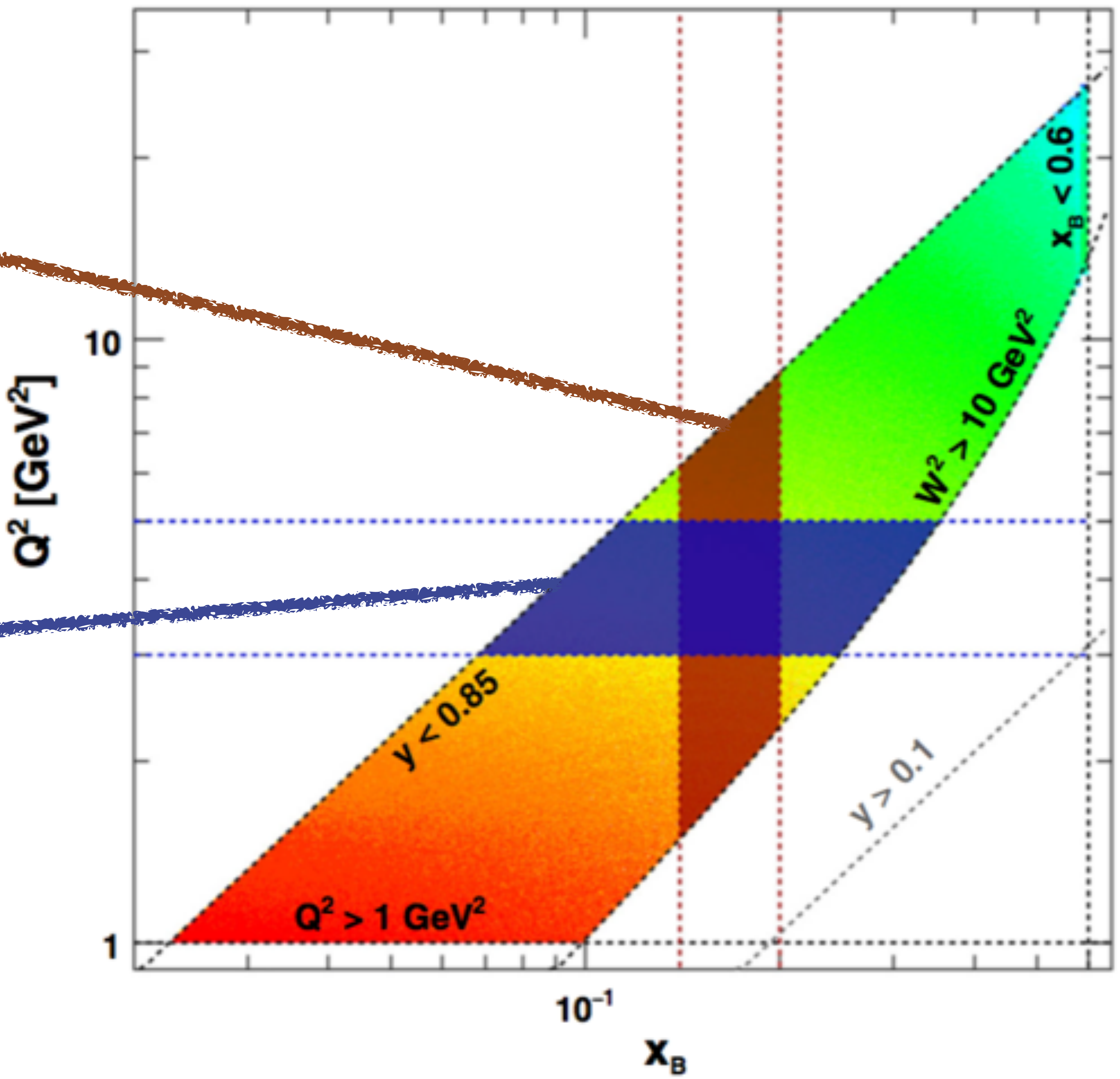

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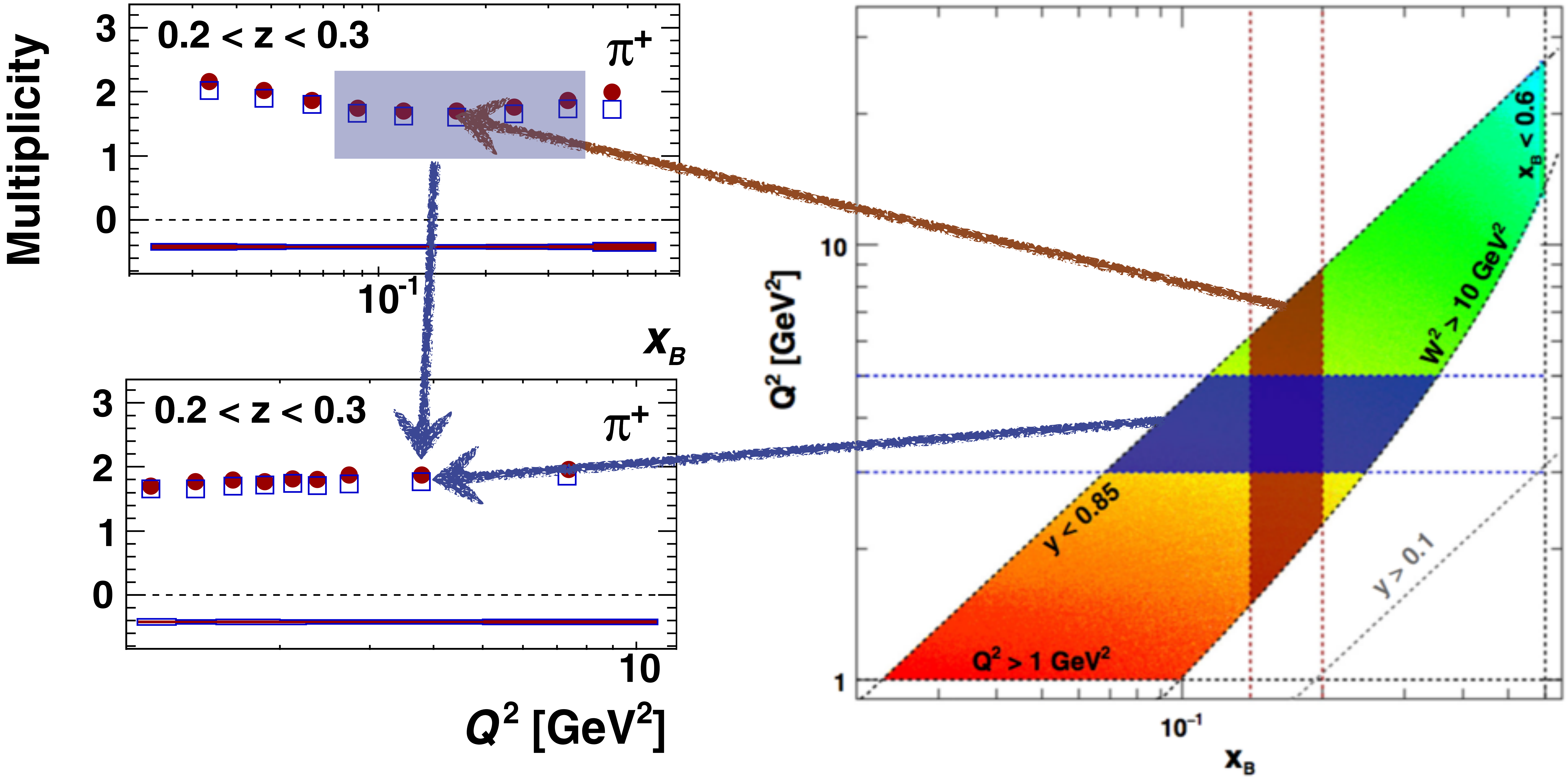
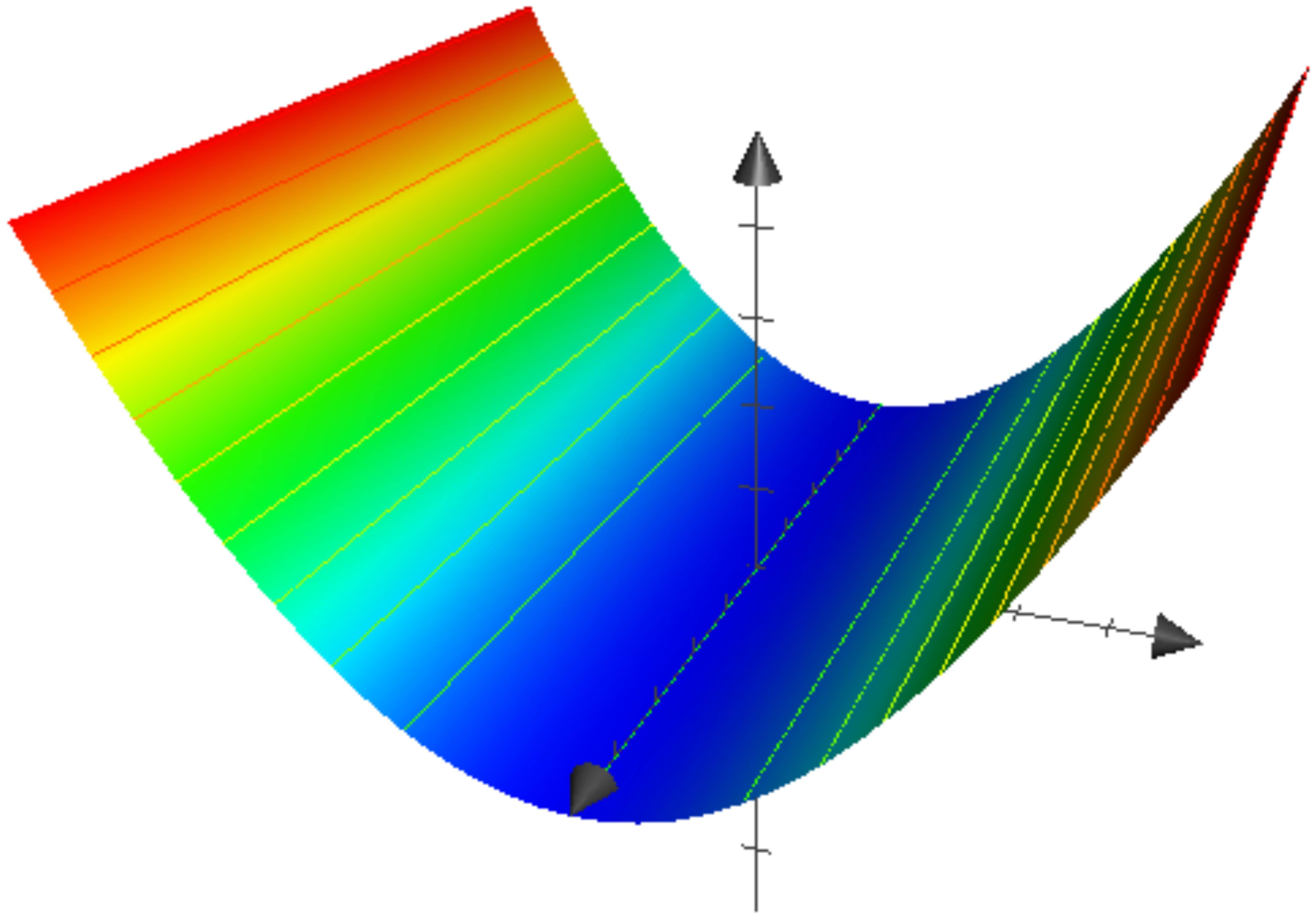


➟ even though two data points might have similar average kinematics, multiplicities in the two projections can be different

$\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$

- the average along the valley will be smaller than the average along the gradient



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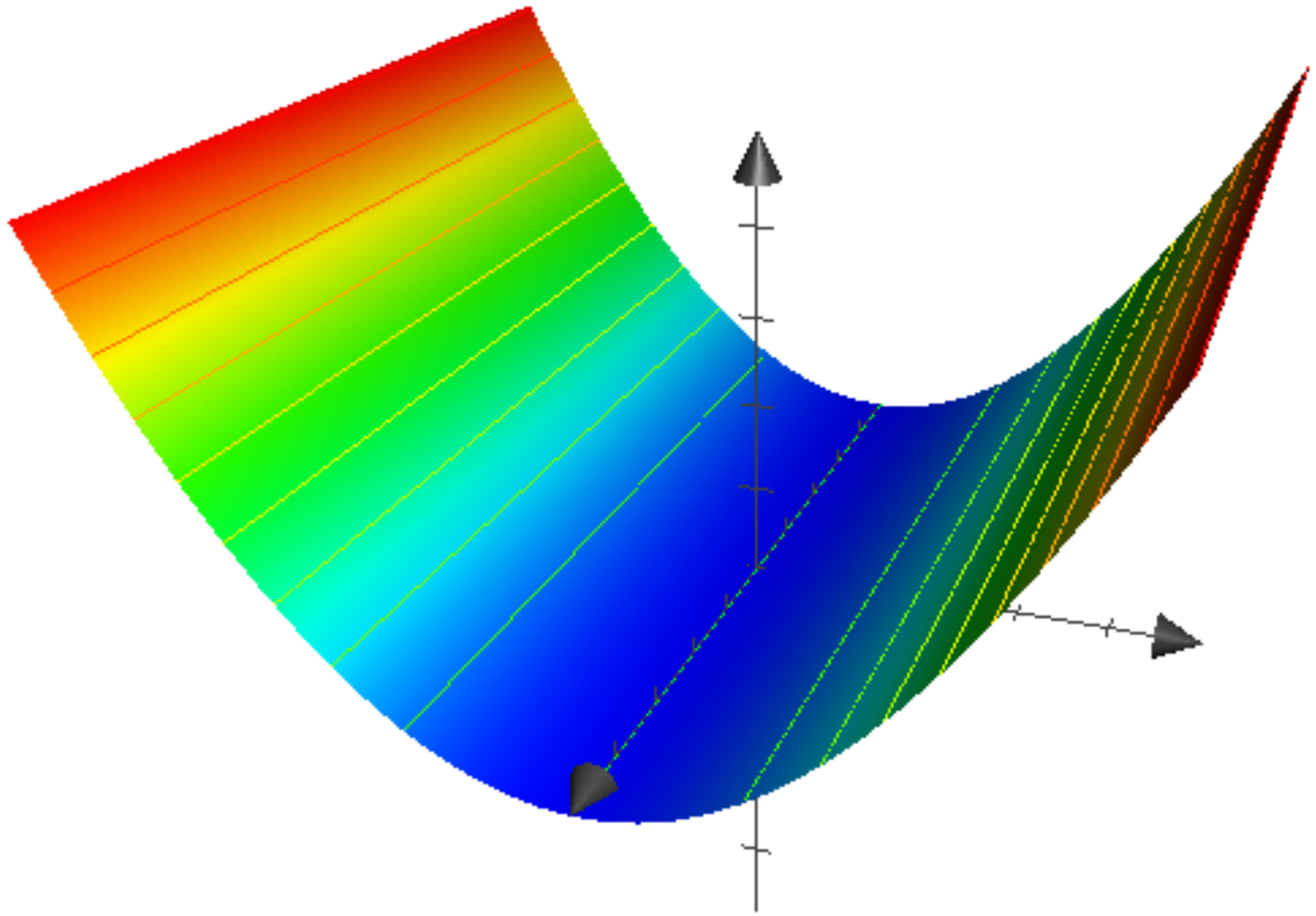

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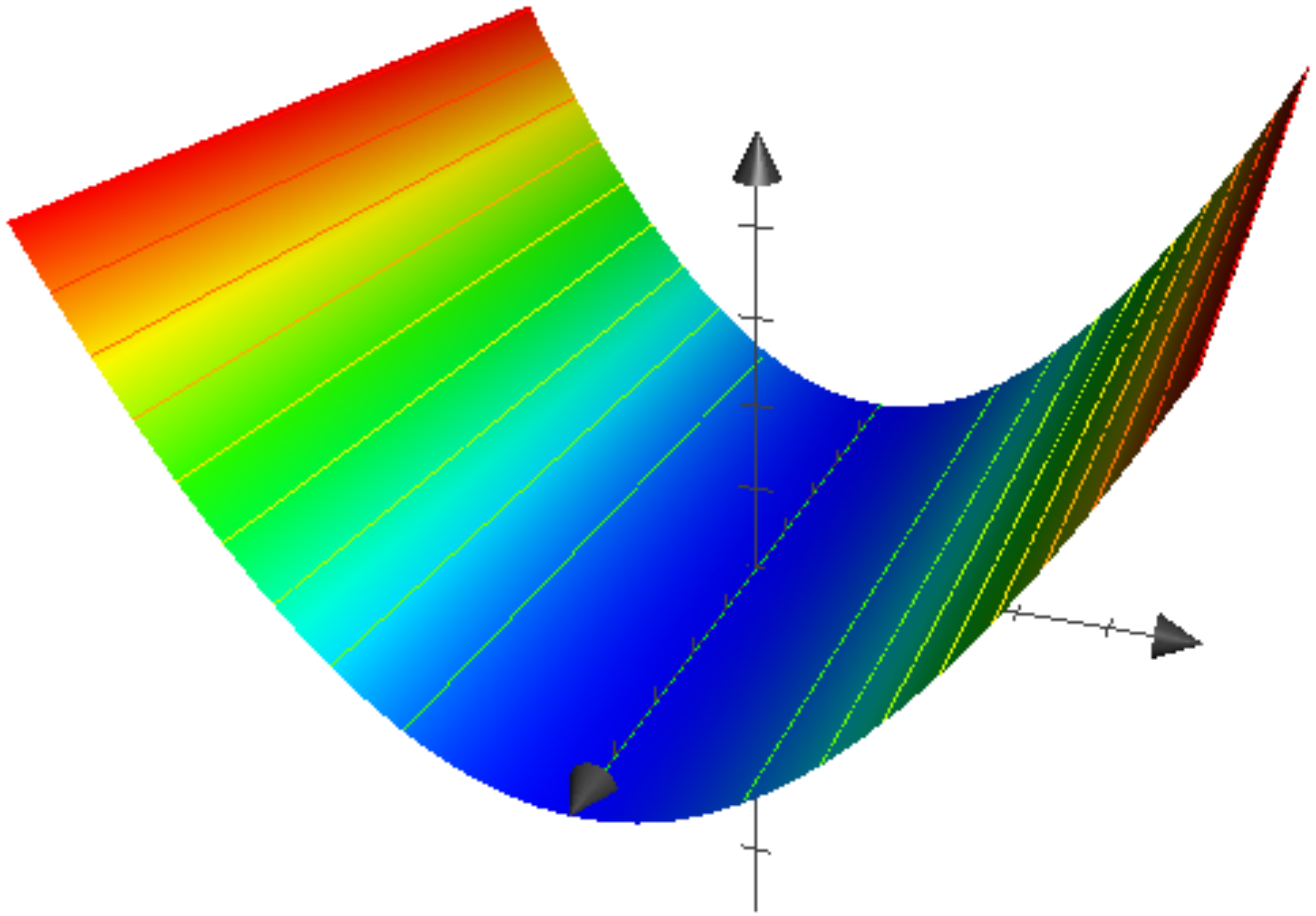
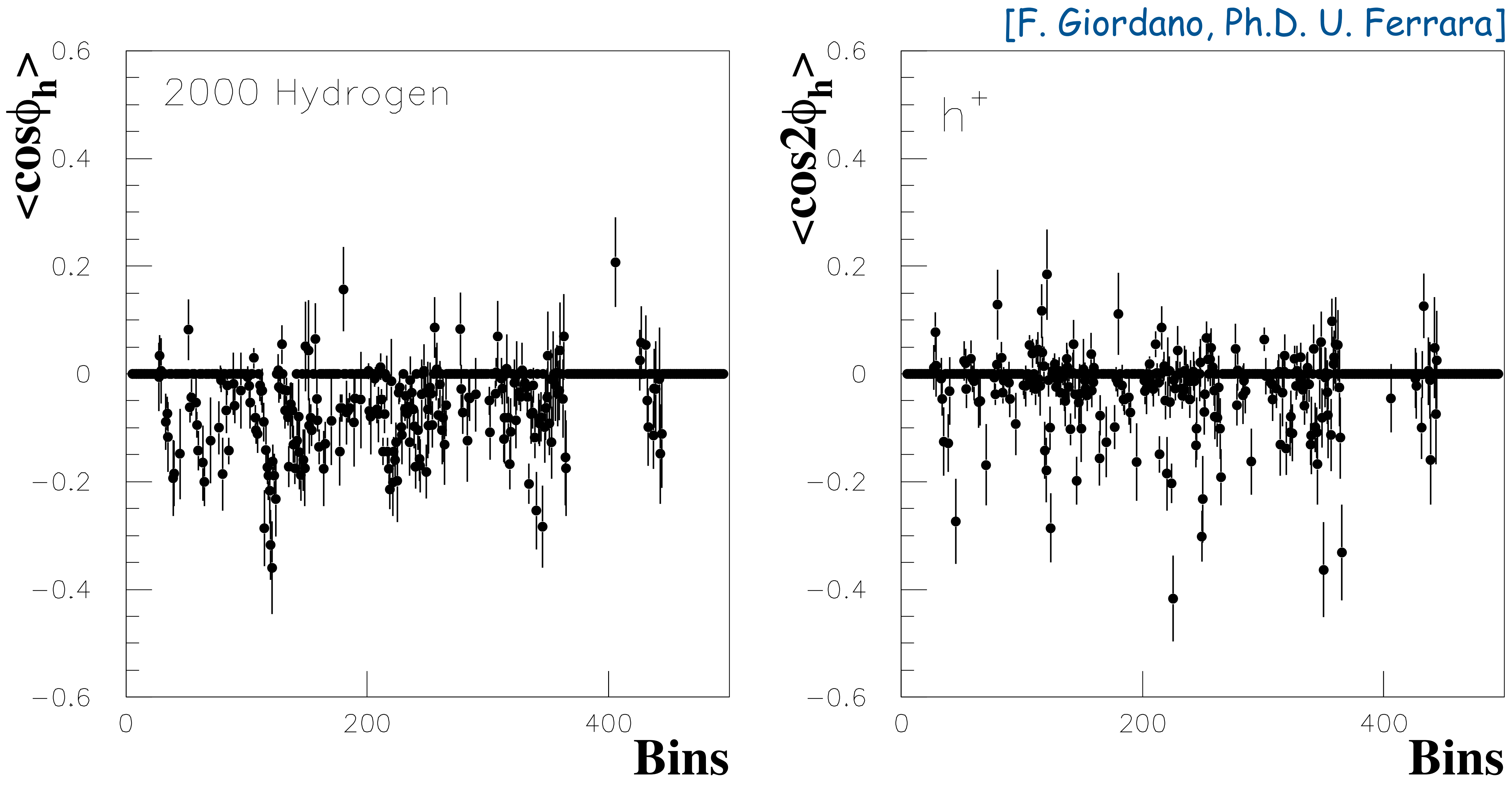
- still the **average kinematics** can be the same



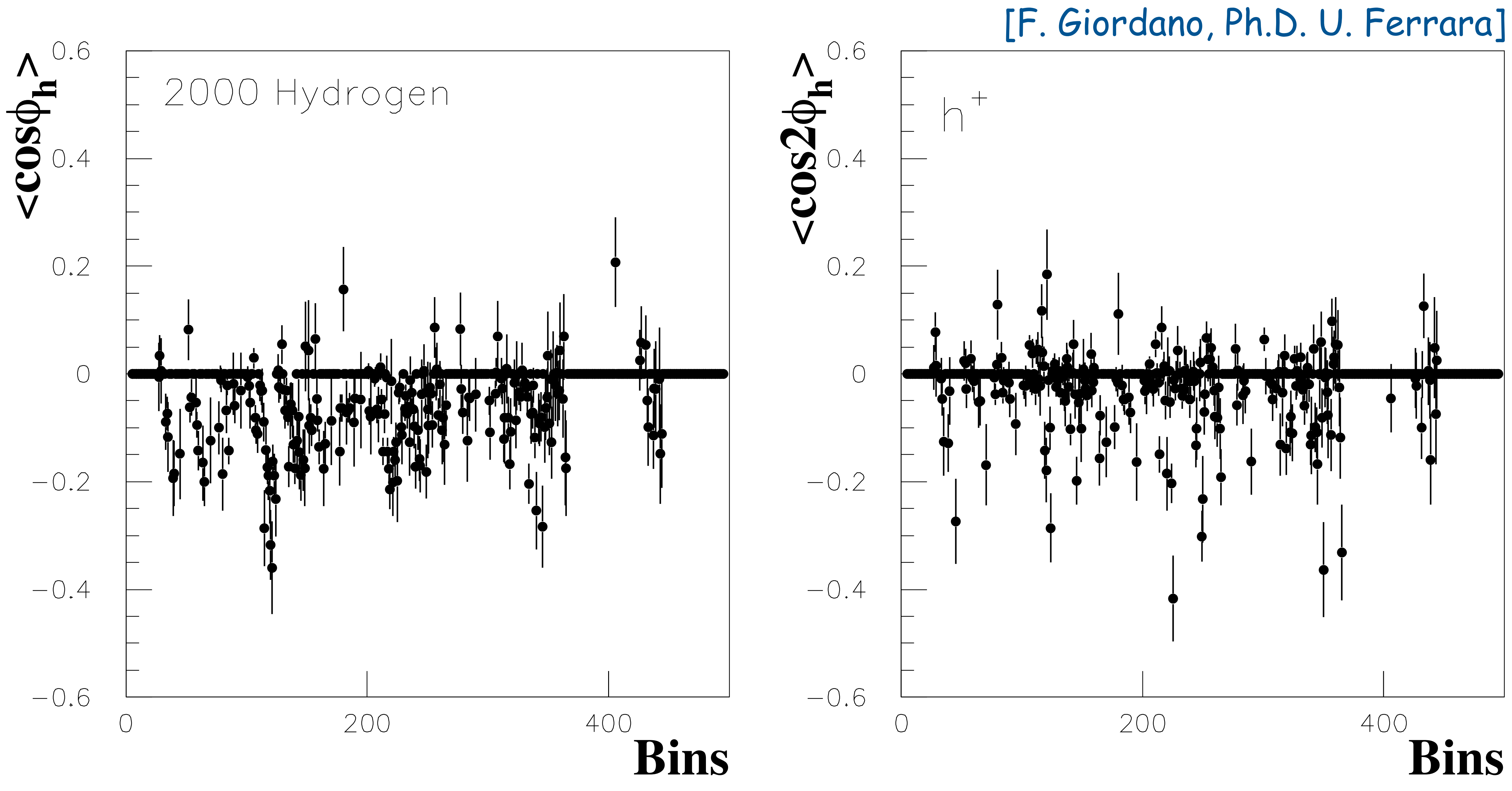
take-away message: (when told so) integrate your cross section over the kinematic ranges dictated by the experiment (e.g., do not simply evaluate it at the average kinematics)

to experiments: fully differential analyses!

back from 5d to 1d



- how to use fully differential results, e.g., cosine moments of unpolarised cross section?

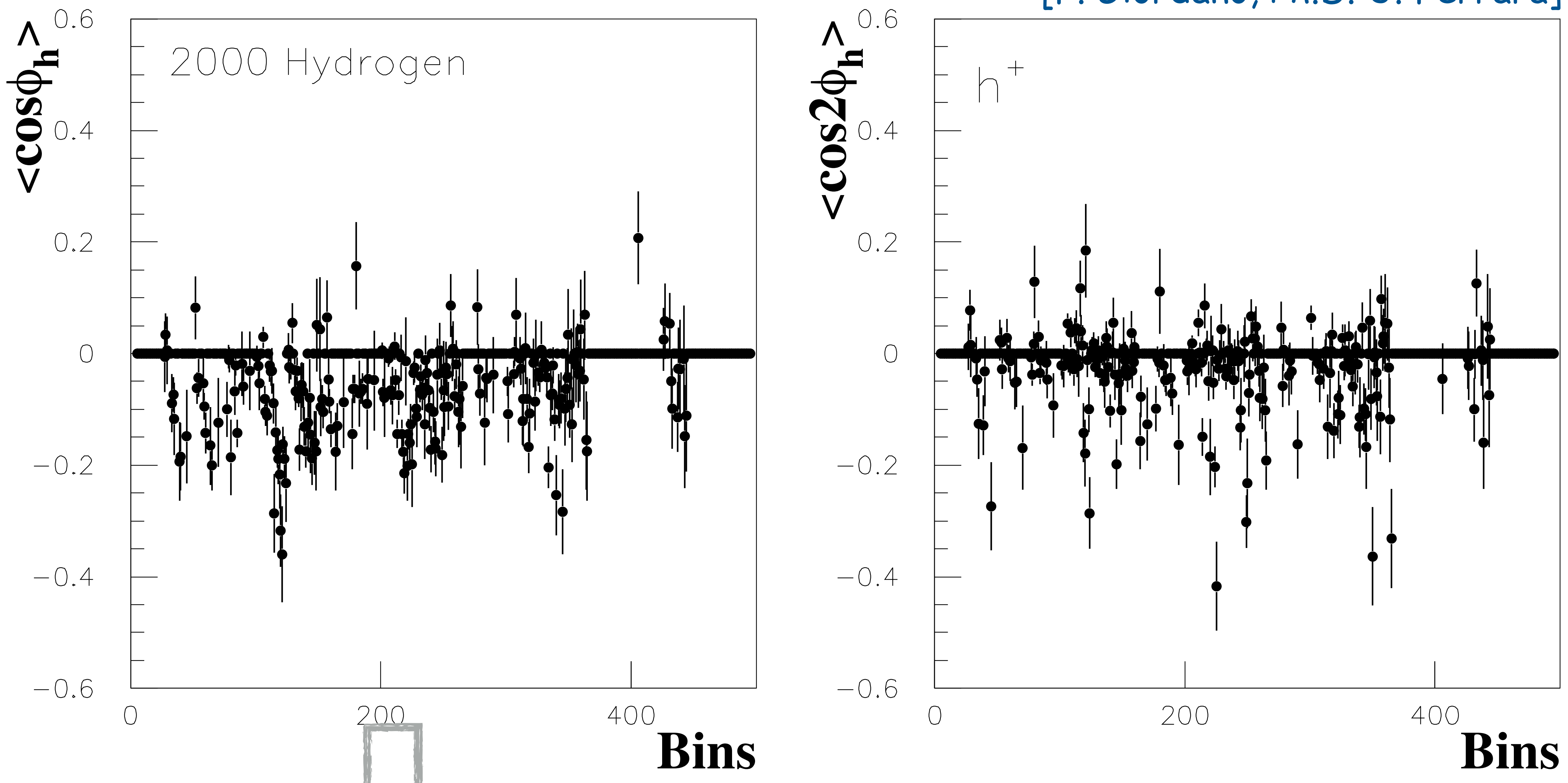


back from 5d to 1d

- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
  - either directly in fully differential fits

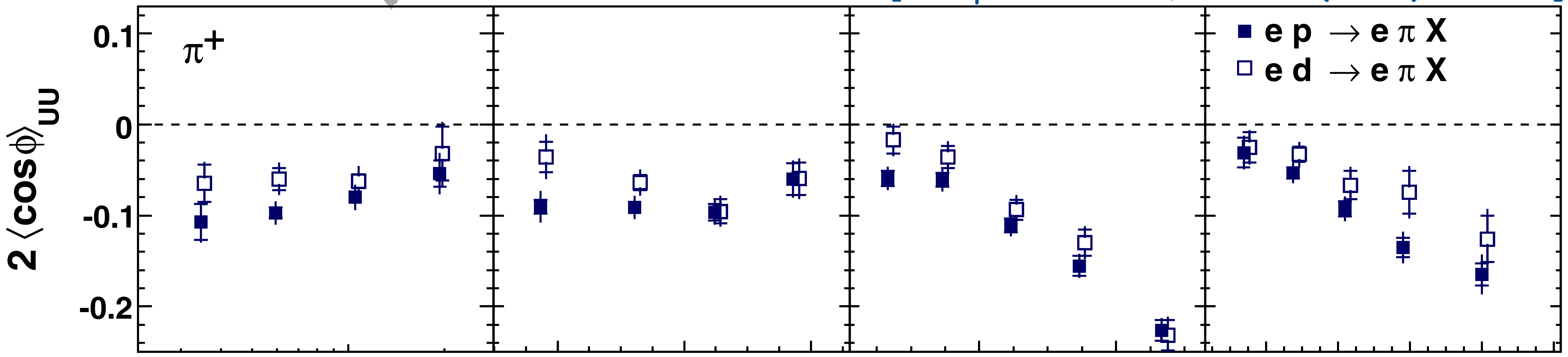
back from 5d to 1d

[F. Giordano, Ph.D. U. Ferrara]



$$\langle \cos n\phi \rangle(x) \simeq \frac{\sum_i \sigma_i^{4\pi} \langle \cos n\phi \rangle_i}{\sum_i \sigma_i^{4\pi}}$$

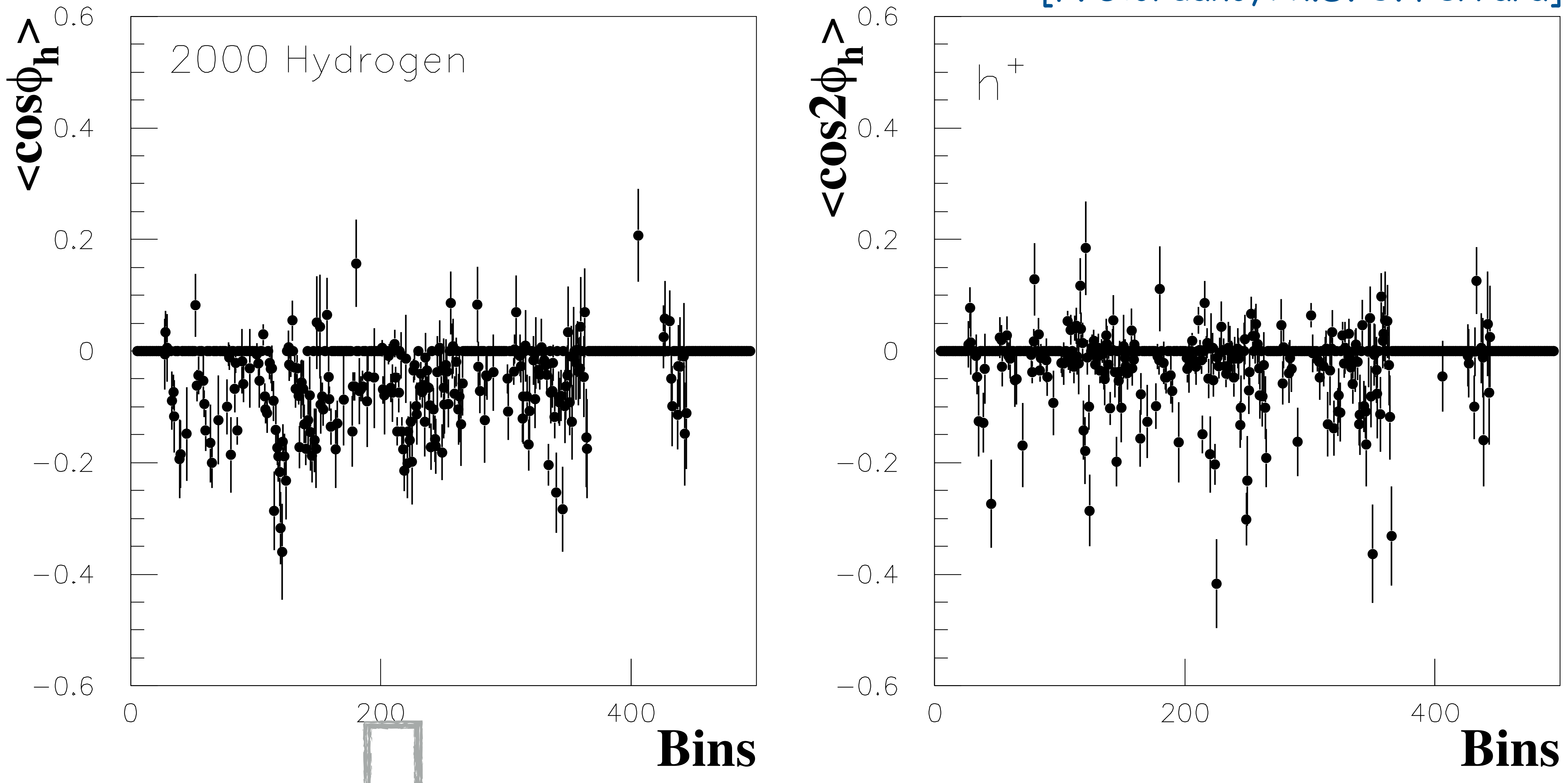
[Airapetian et al., PRD 87 (2013) 012010]



- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
  - either directly in fully differential fits
  - project back to 1d for vizualization

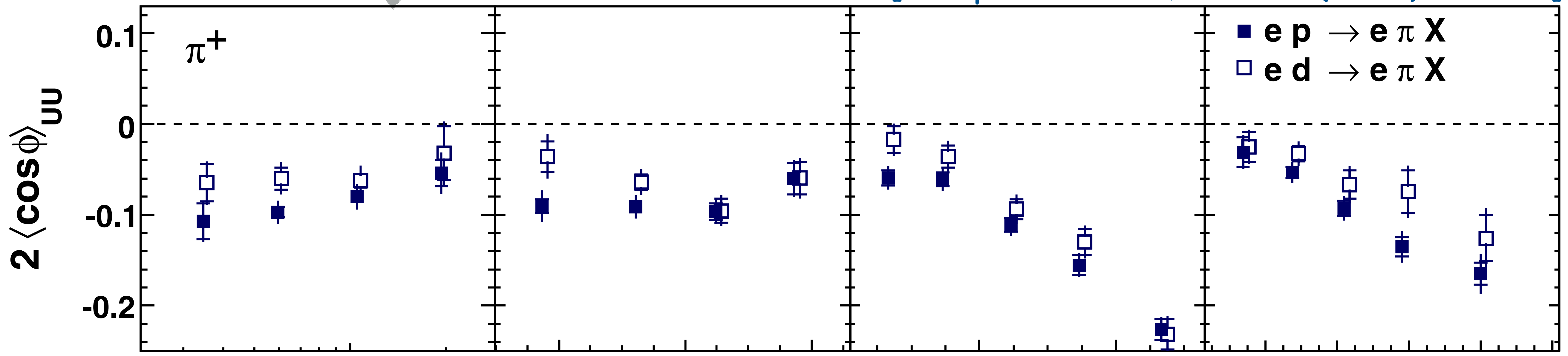
back from 5d to 1d

[F. Giordano, Ph.D. U. Ferrara]



$$\langle \cos n\phi \rangle(x) \simeq \frac{\sum_i \sigma_i^{4\pi} \langle \cos n\phi \rangle_i}{\sum_i \sigma_i^{4\pi}}$$

[Airapetian et al., PRD 87 (2013) 012010]



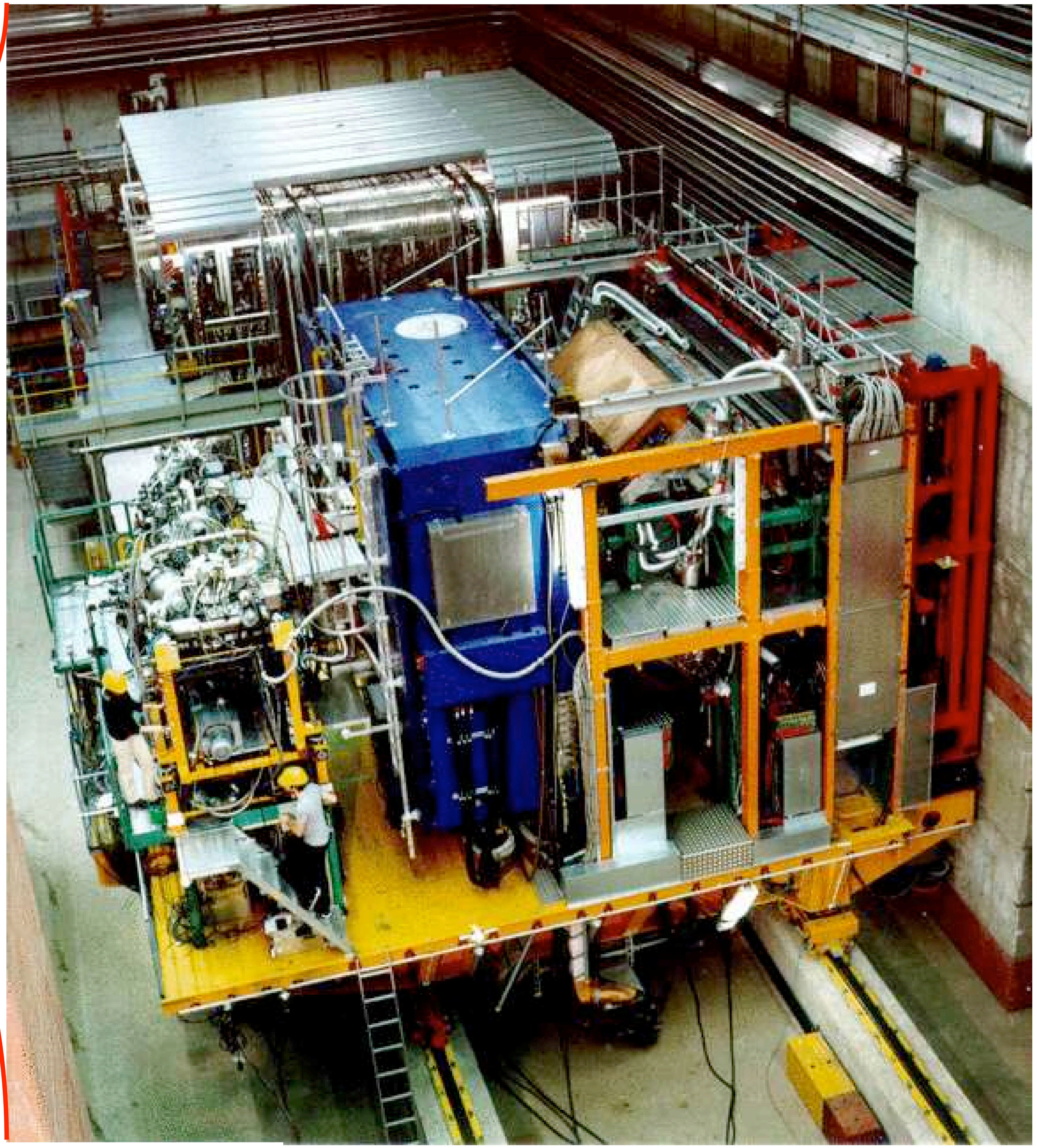
- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
  - either directly in fully differential fits
  - project back to 1d for vizualization

➠ requires good knowledge of unpolarized cross section

➠ when using 1d projections, ask yourself and your experiment's friends why 1d is sufficient and why not go multi-d?

HERMES (1995-2007) @ HERA

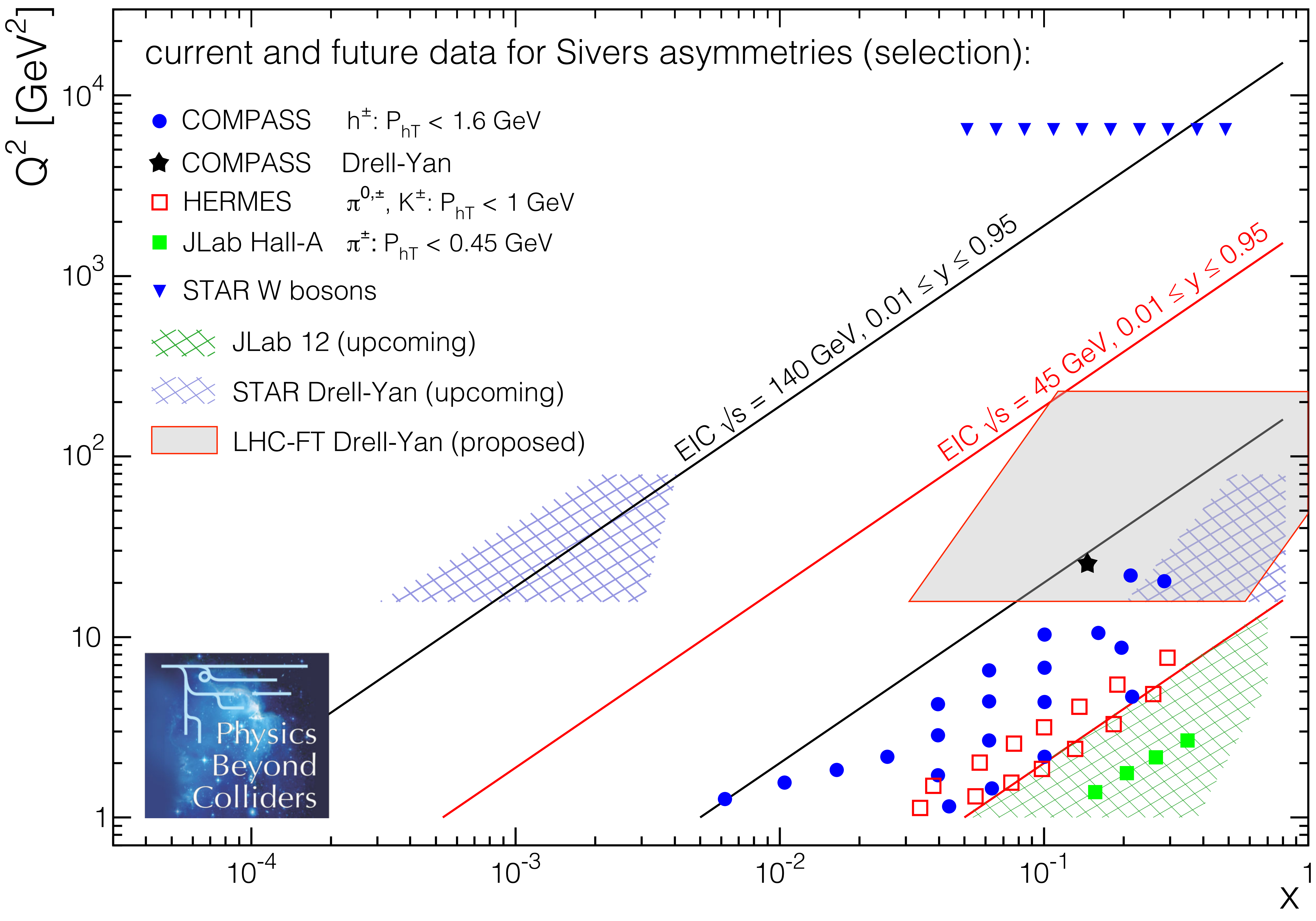
27.6 GeV polarized e^+/e^- beam scattered off ...



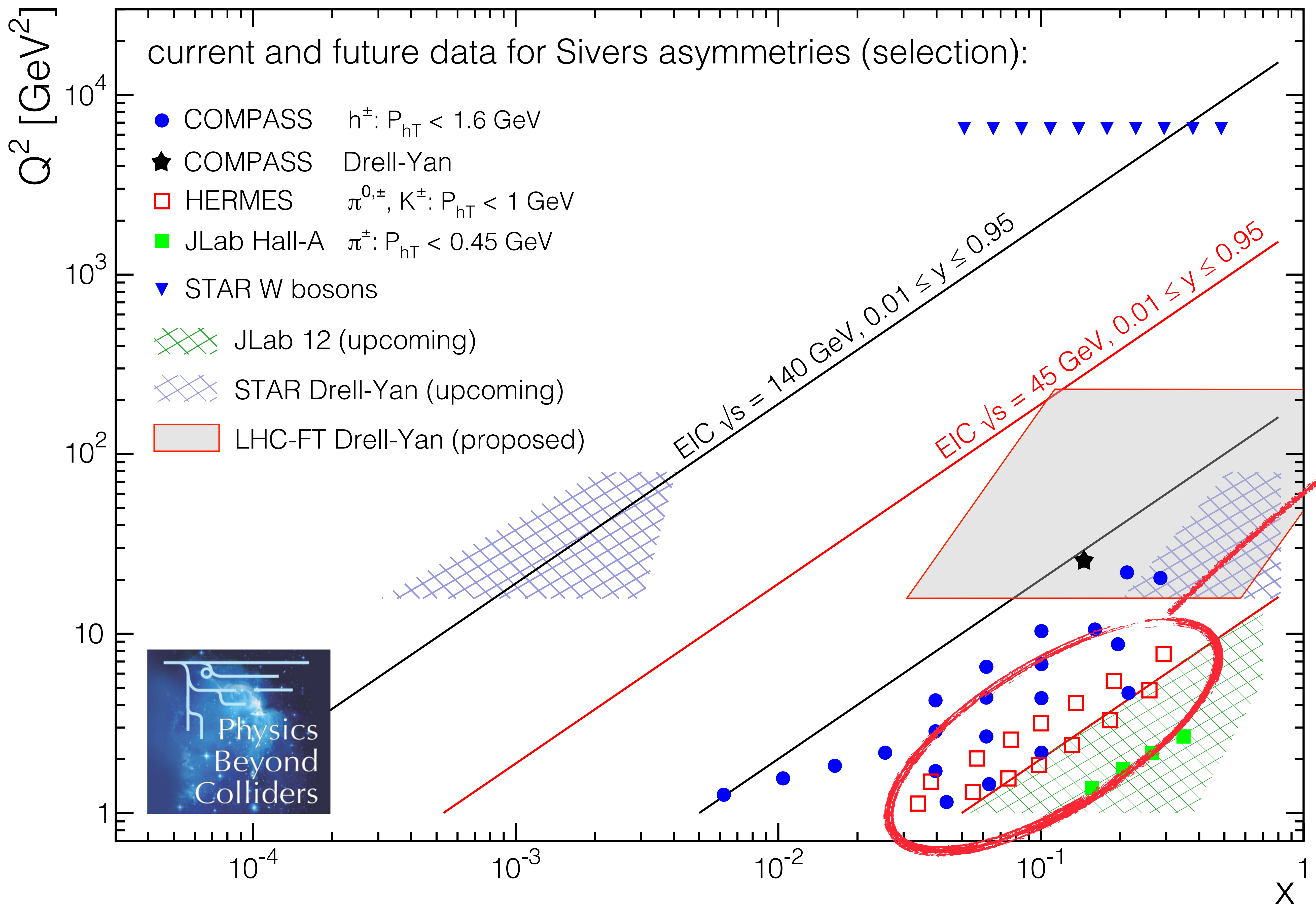
- unpolarized (H, D, He,..., Xe) as well as
- **transversely** (H) or
- **longitudinally** (H, D, He) polarized

pure gas targets

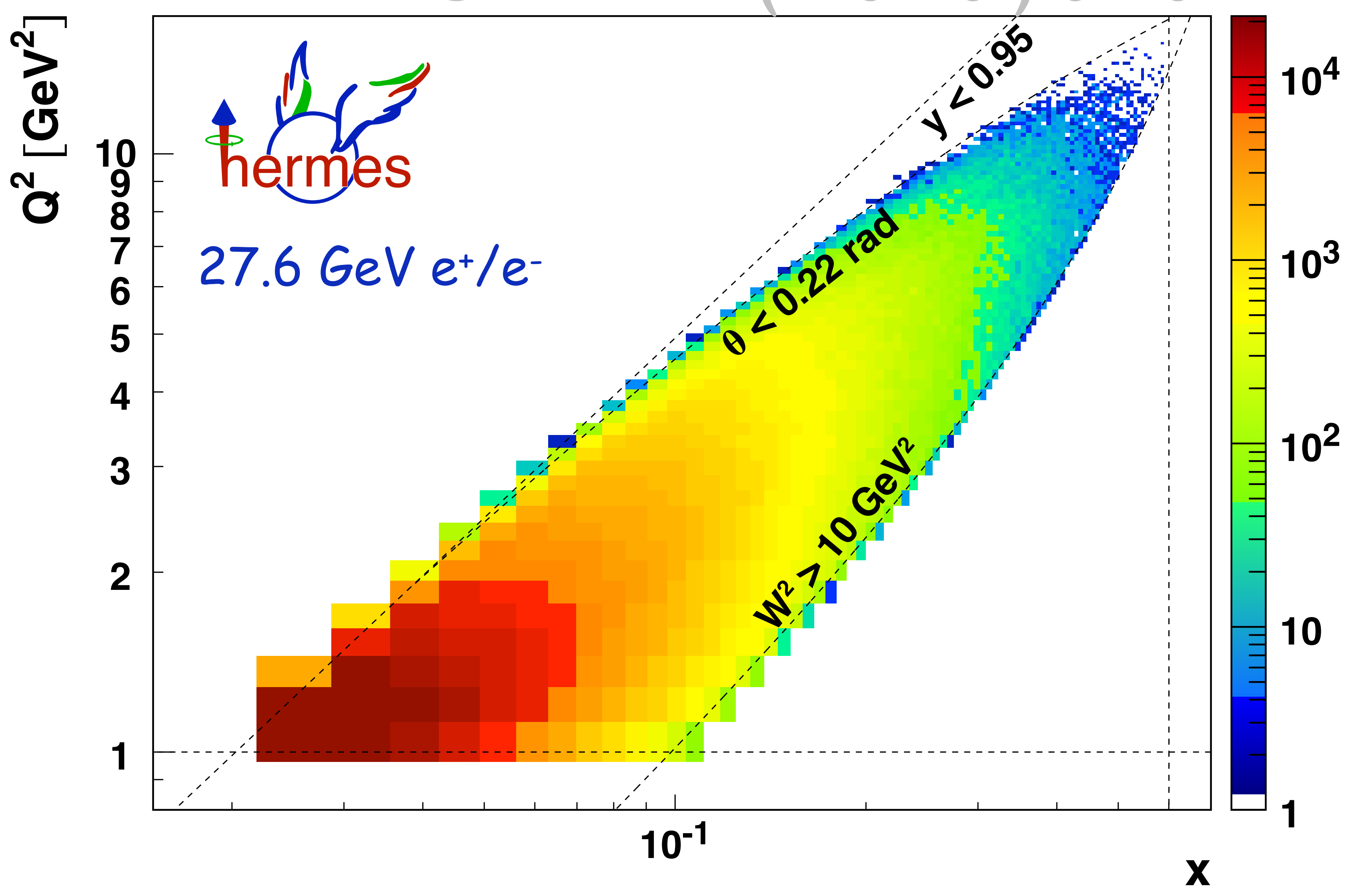
2d kinematic phase space



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.

semi-inclusive DIS

- excluding transverse polarization:

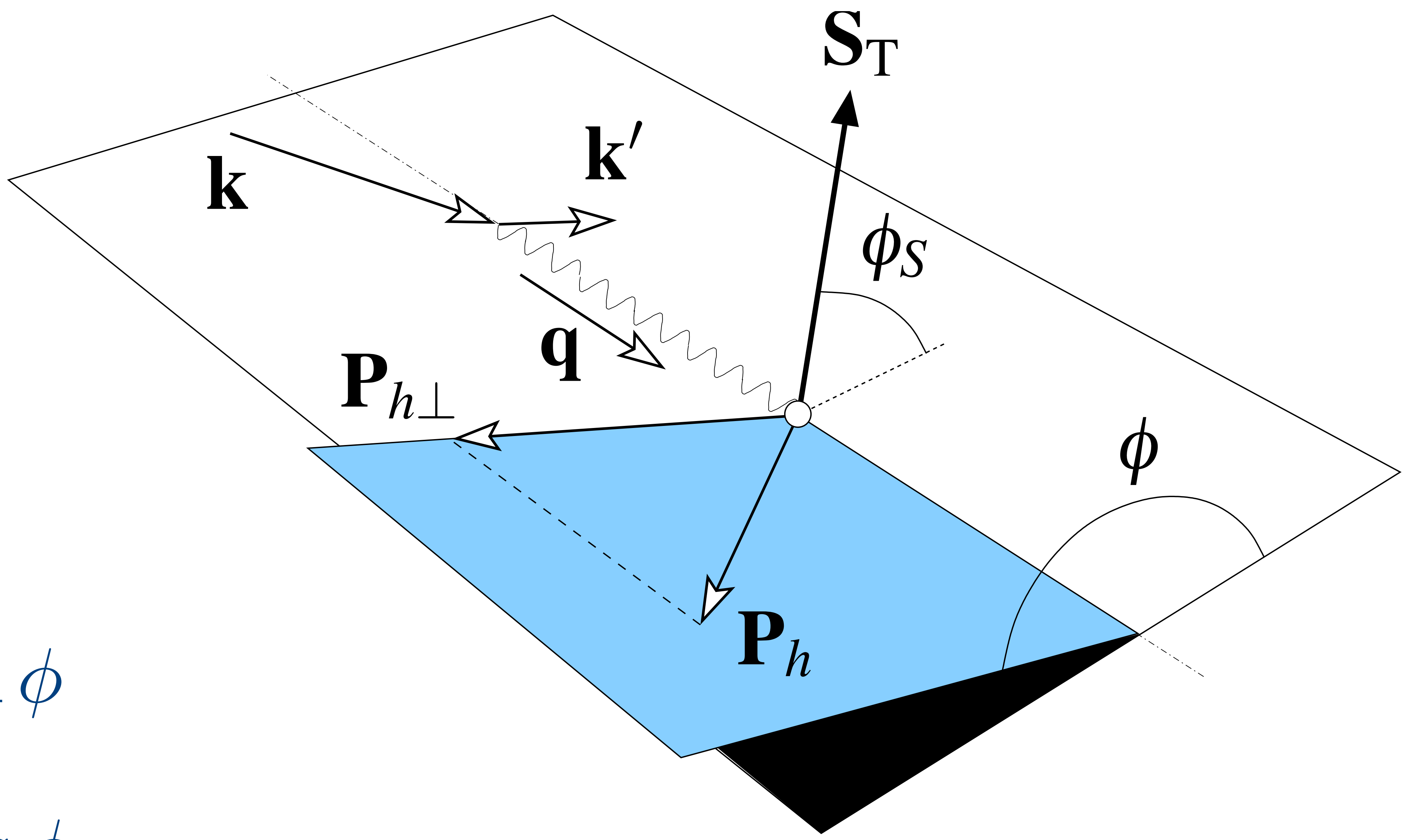
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



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

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

- excluding transverse polarization:

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

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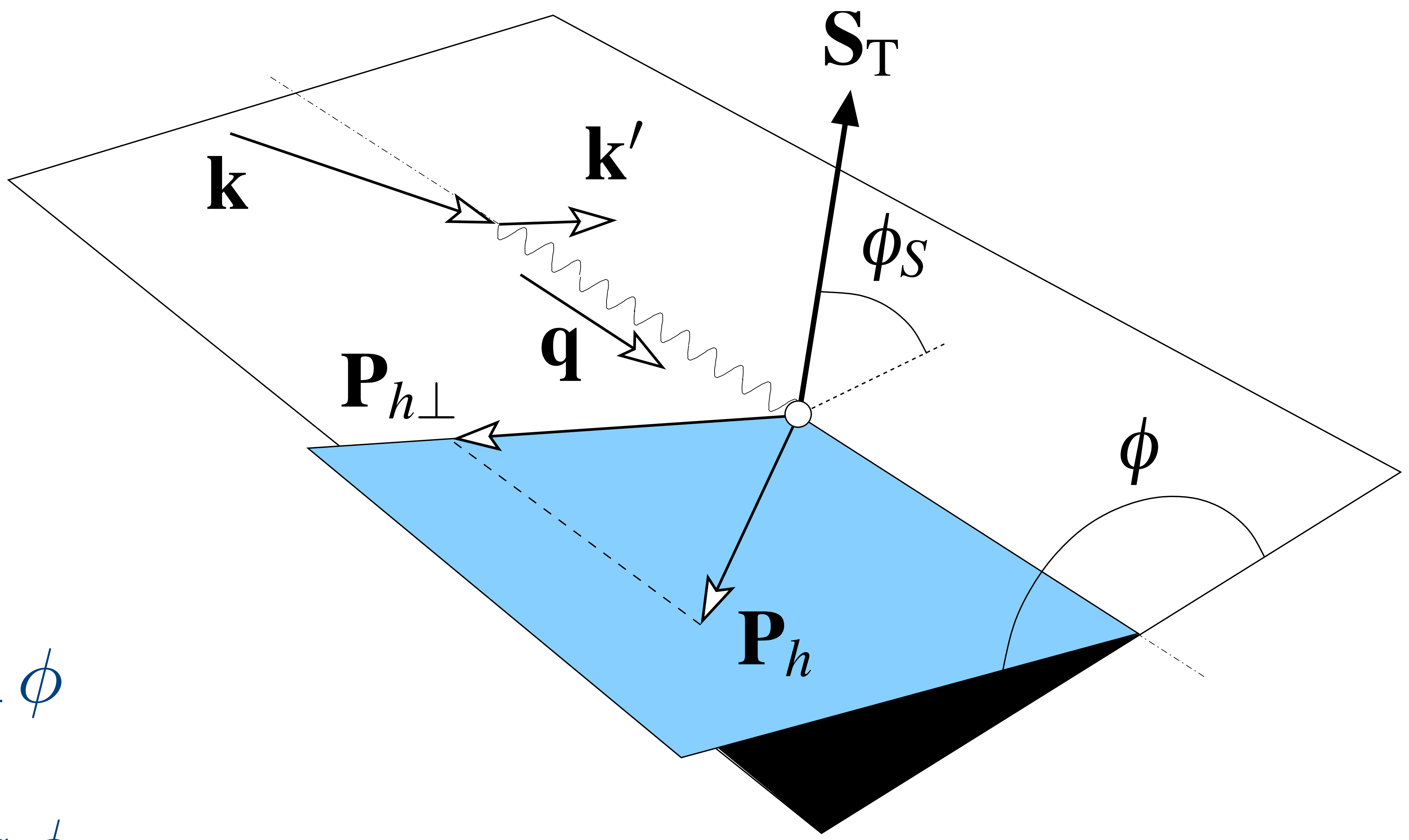
$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

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

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



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

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

- excluding transverse polarization:

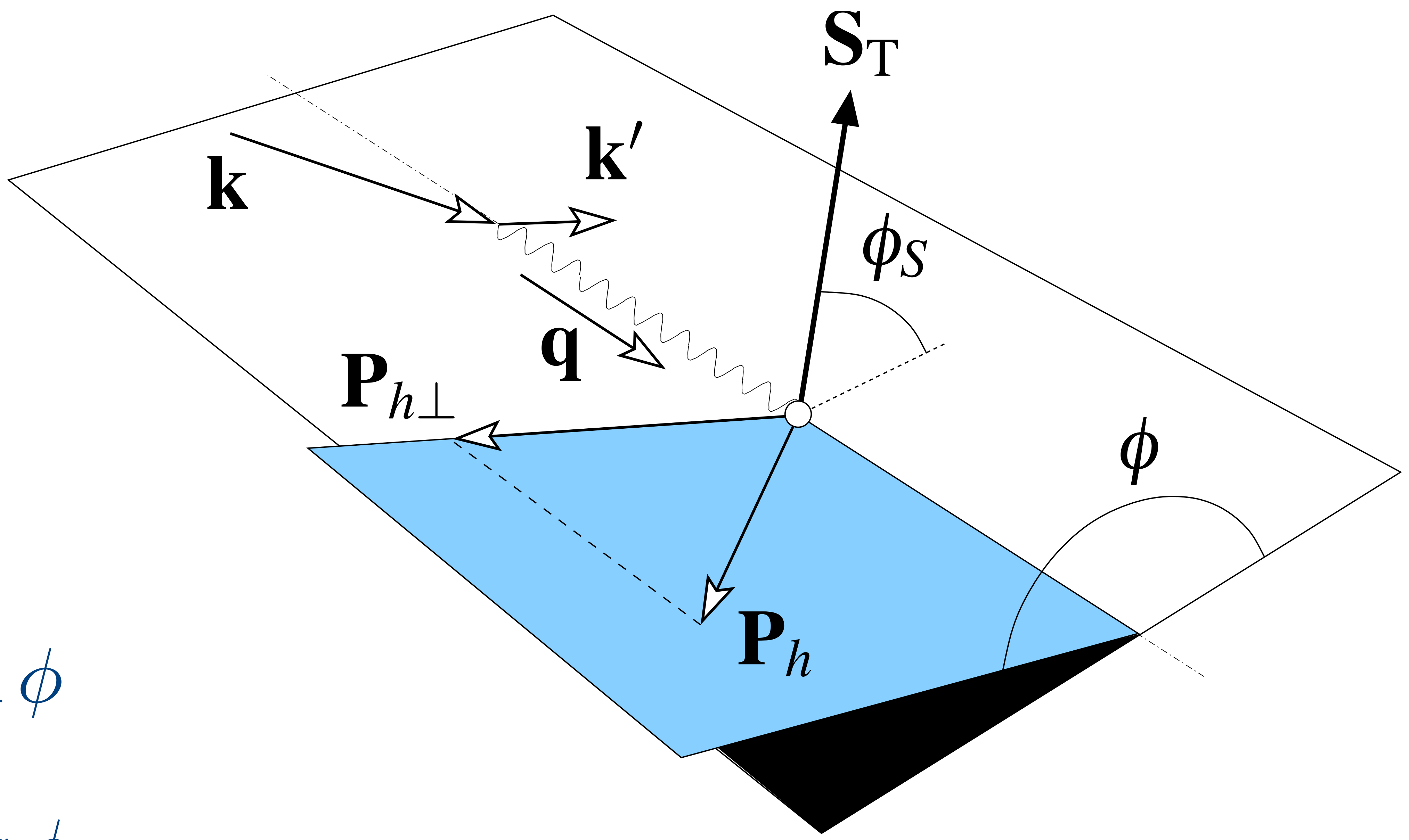
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- 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:

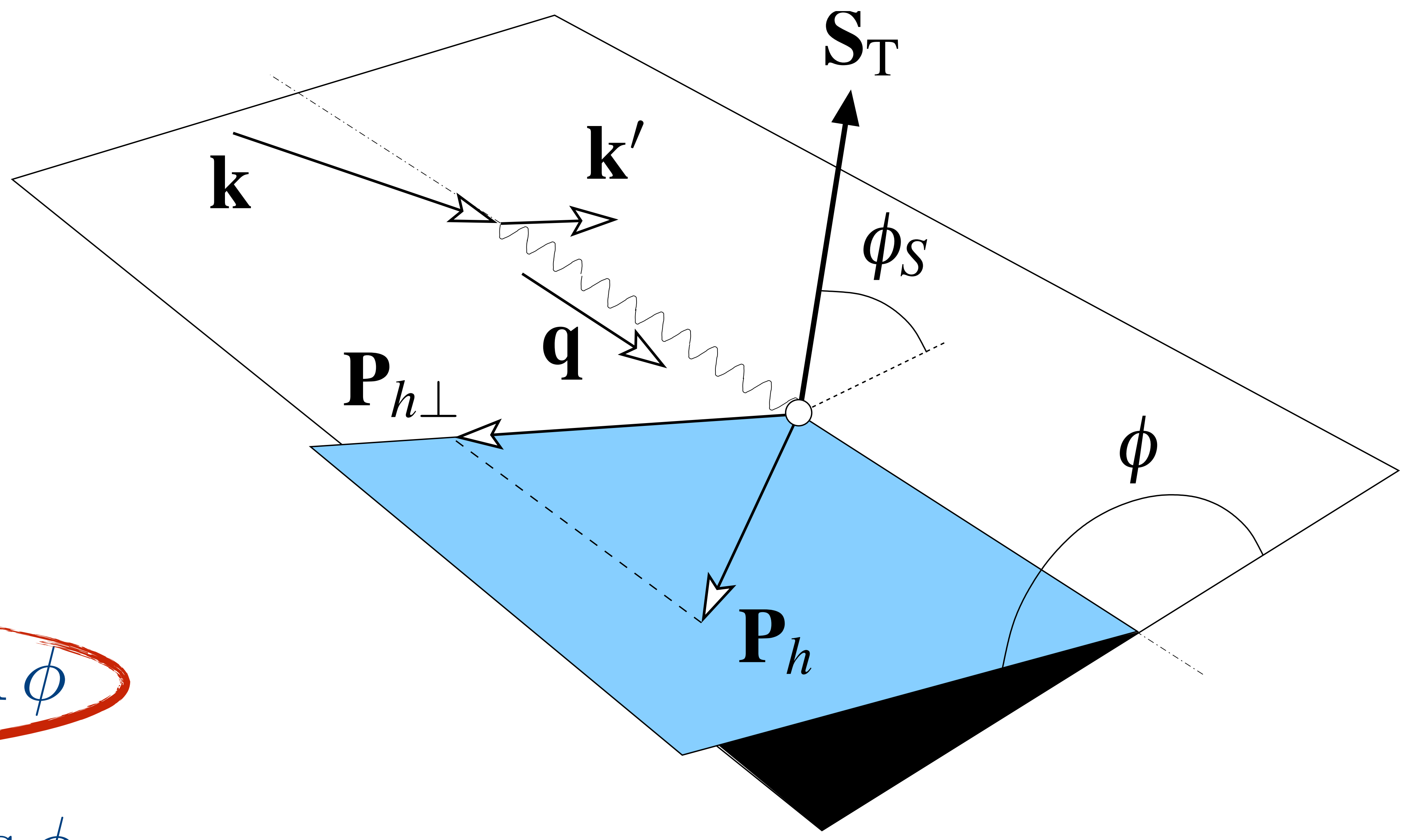
$$
\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)
$$

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

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

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

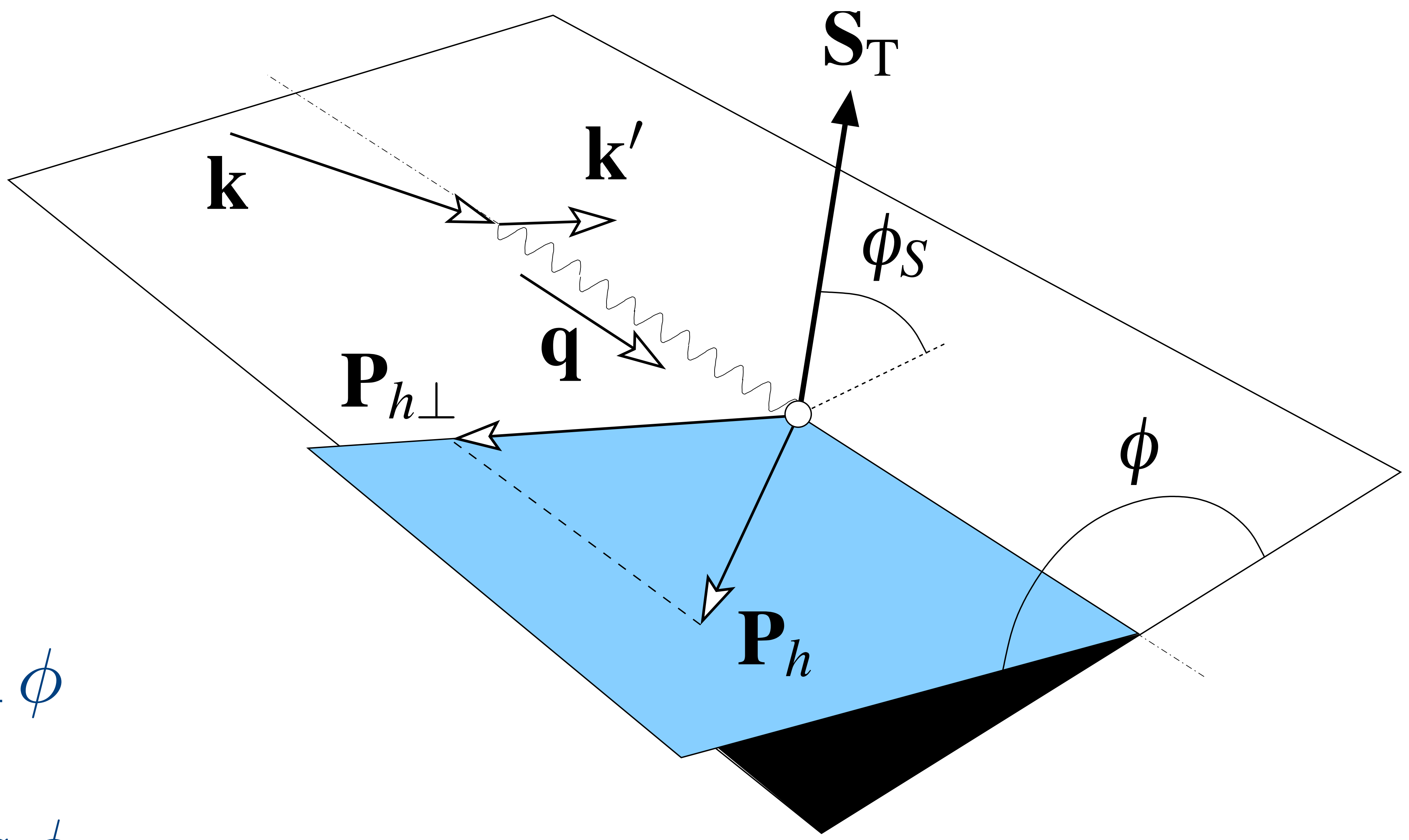
$$
+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \Big\}
$$



- double-spin asymmetry:

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

- excluding transverse polarization:



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

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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:

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

- excluding transverse polarization:

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\Big\{F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h$$
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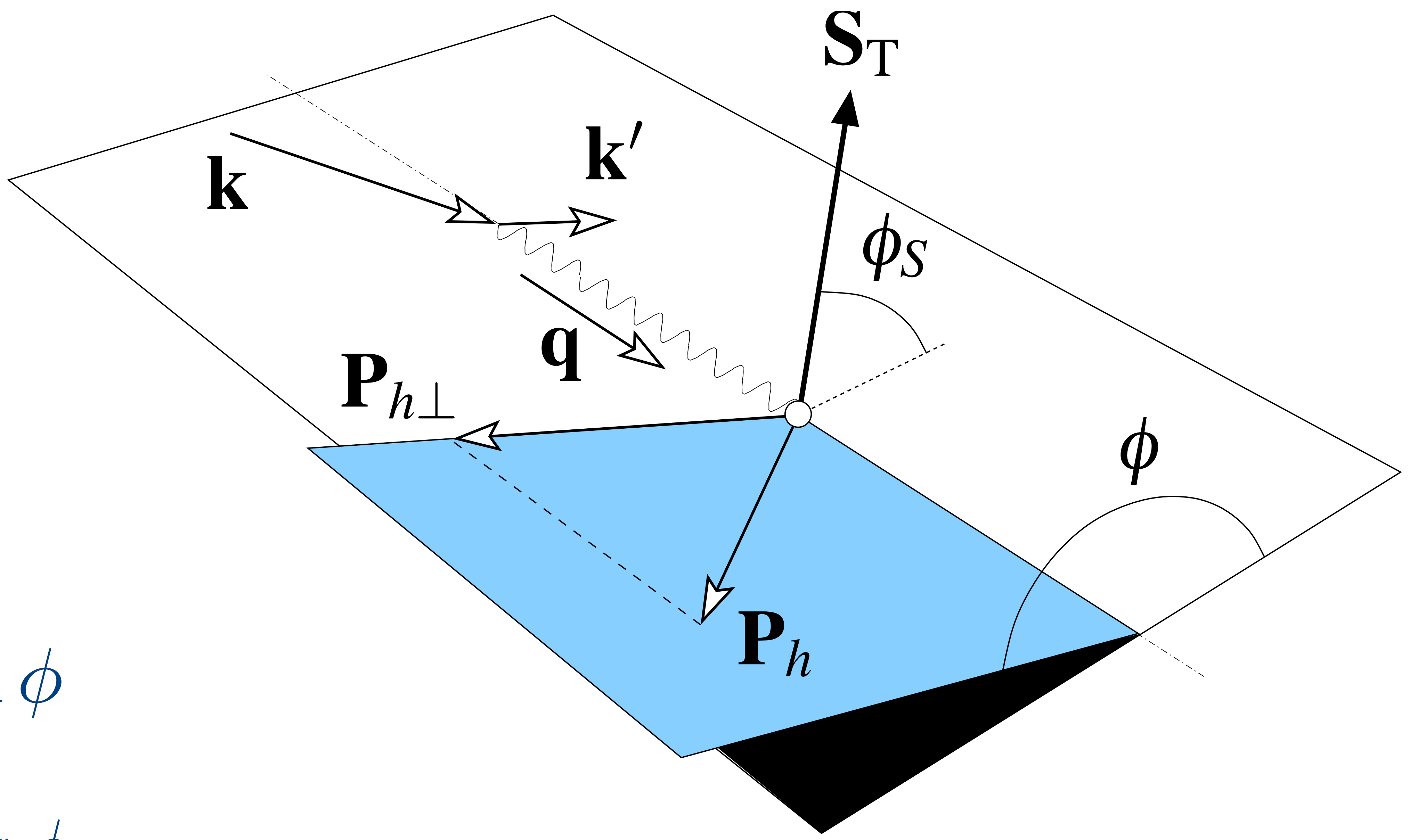
$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi\Big\}$$



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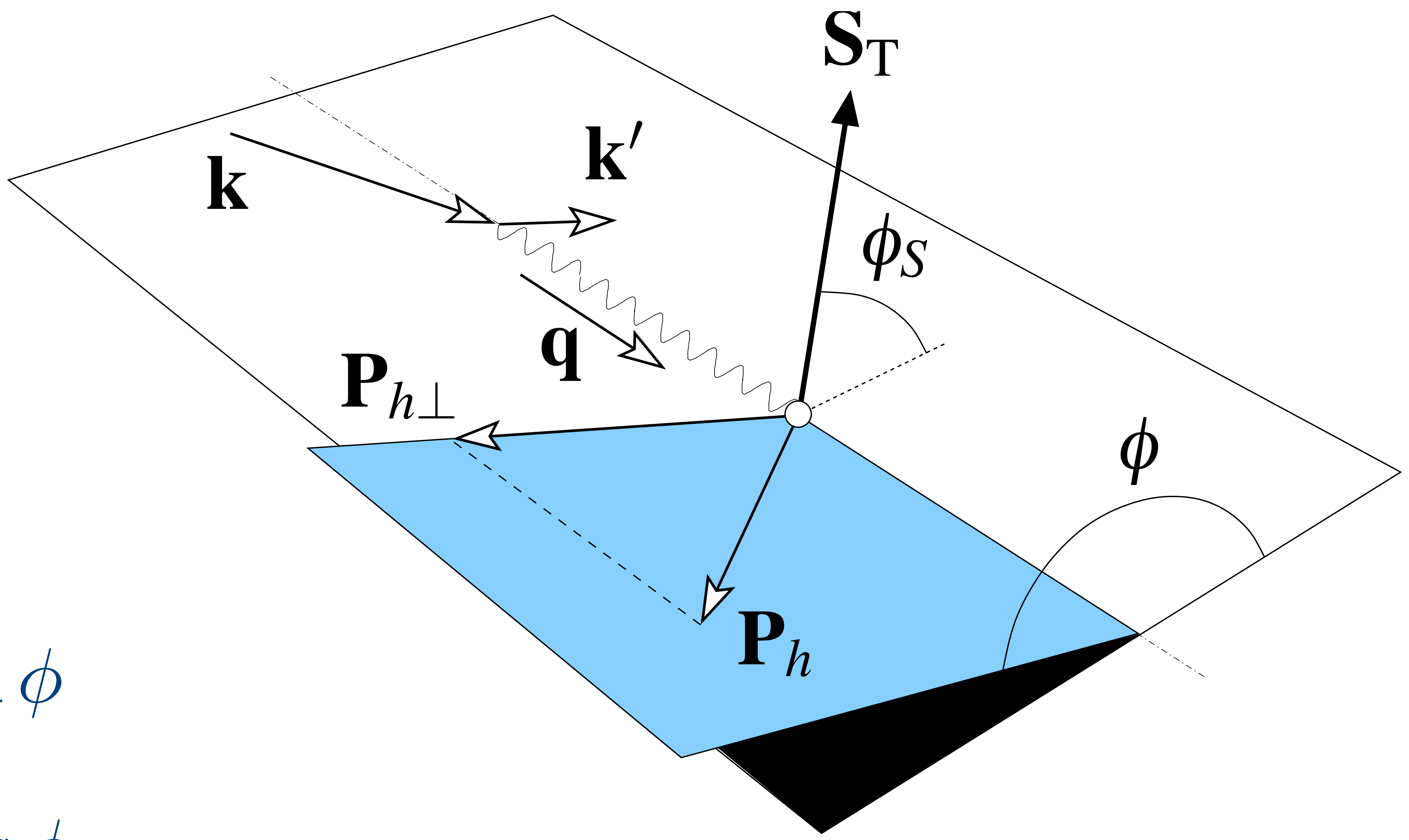

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semi-inclusive DIS

- excluding transverse polarization:

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

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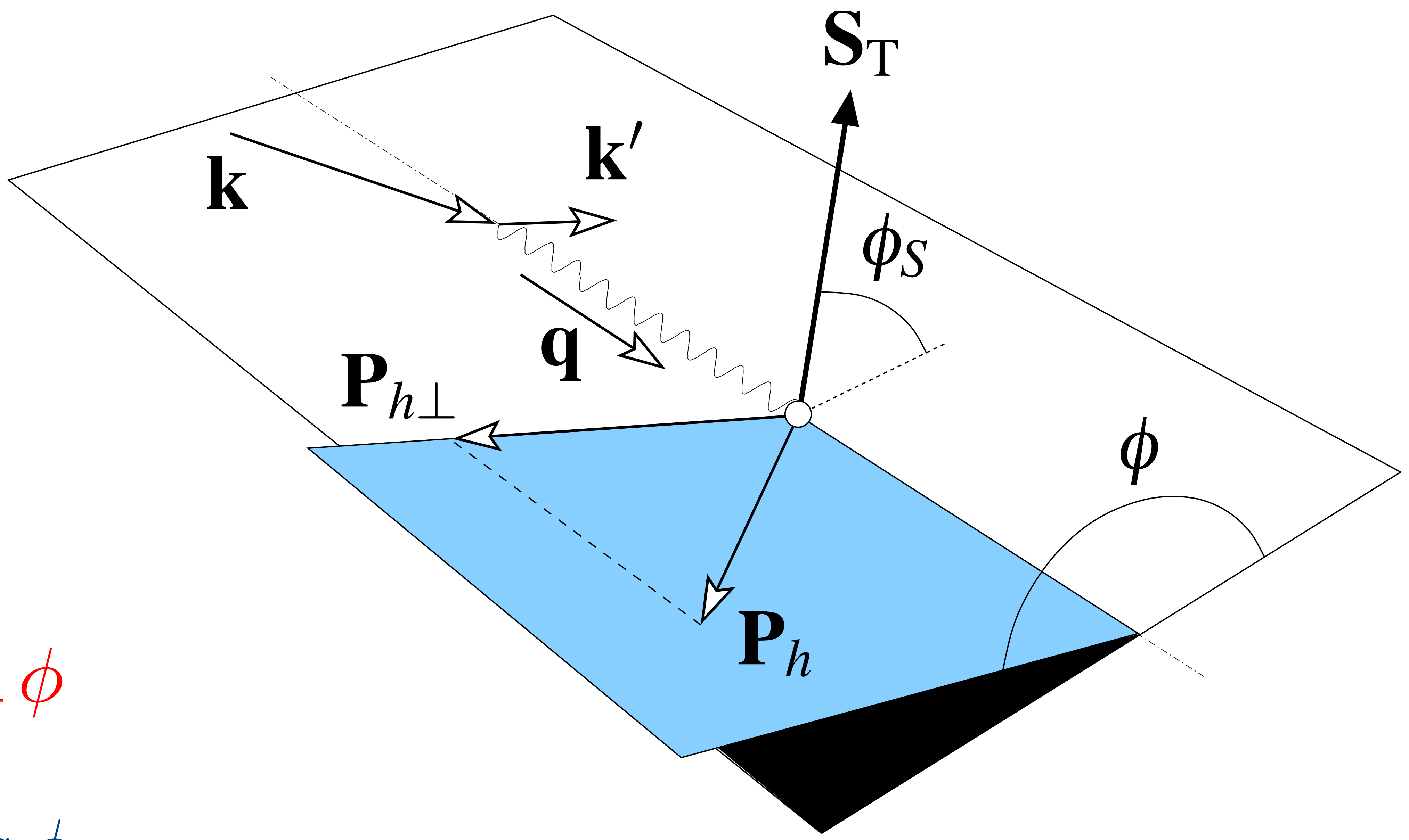
$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

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

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

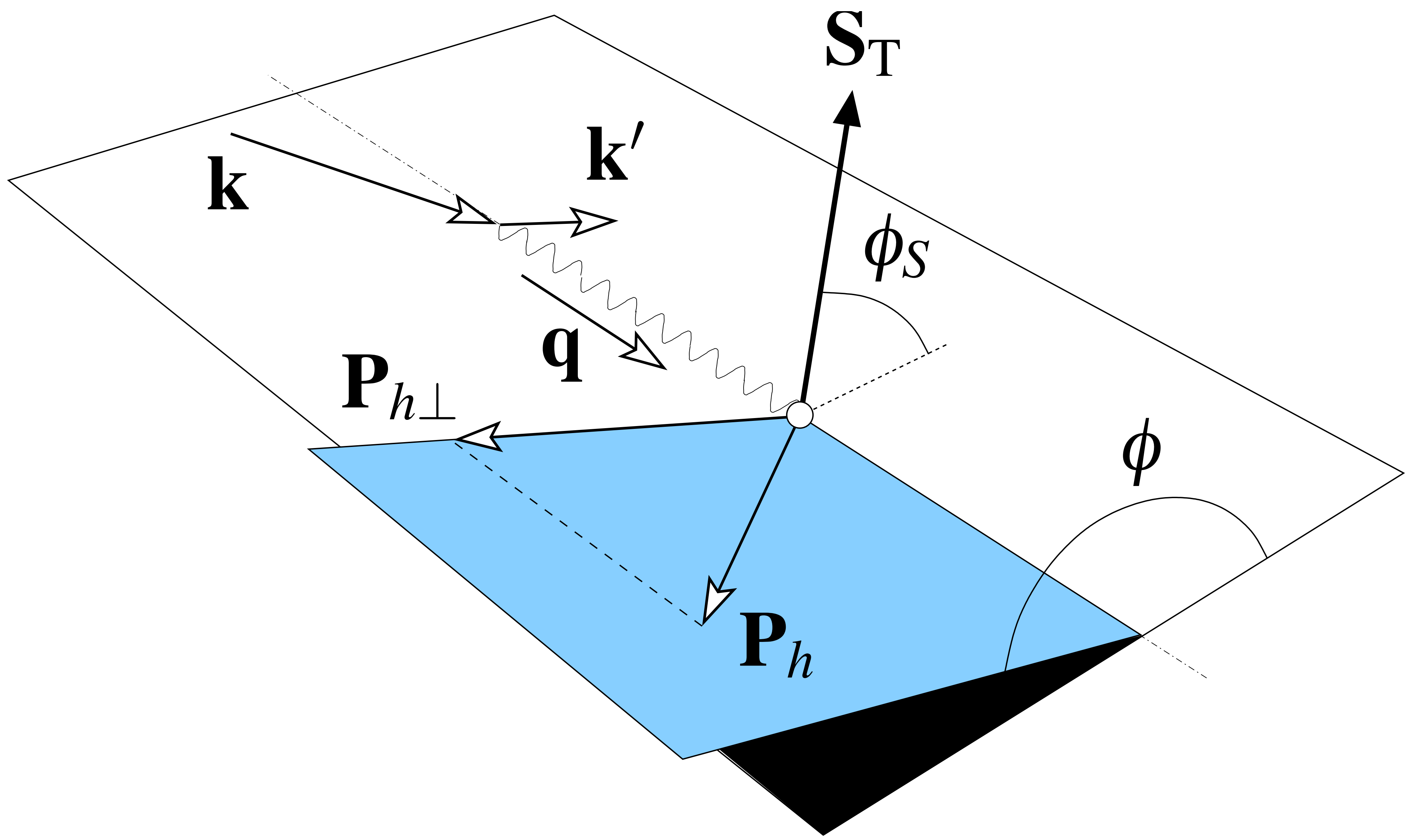


- single-spin asymmetry:

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

semi-inclusive DIS

- with **transverse** target polarization:



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

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

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

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

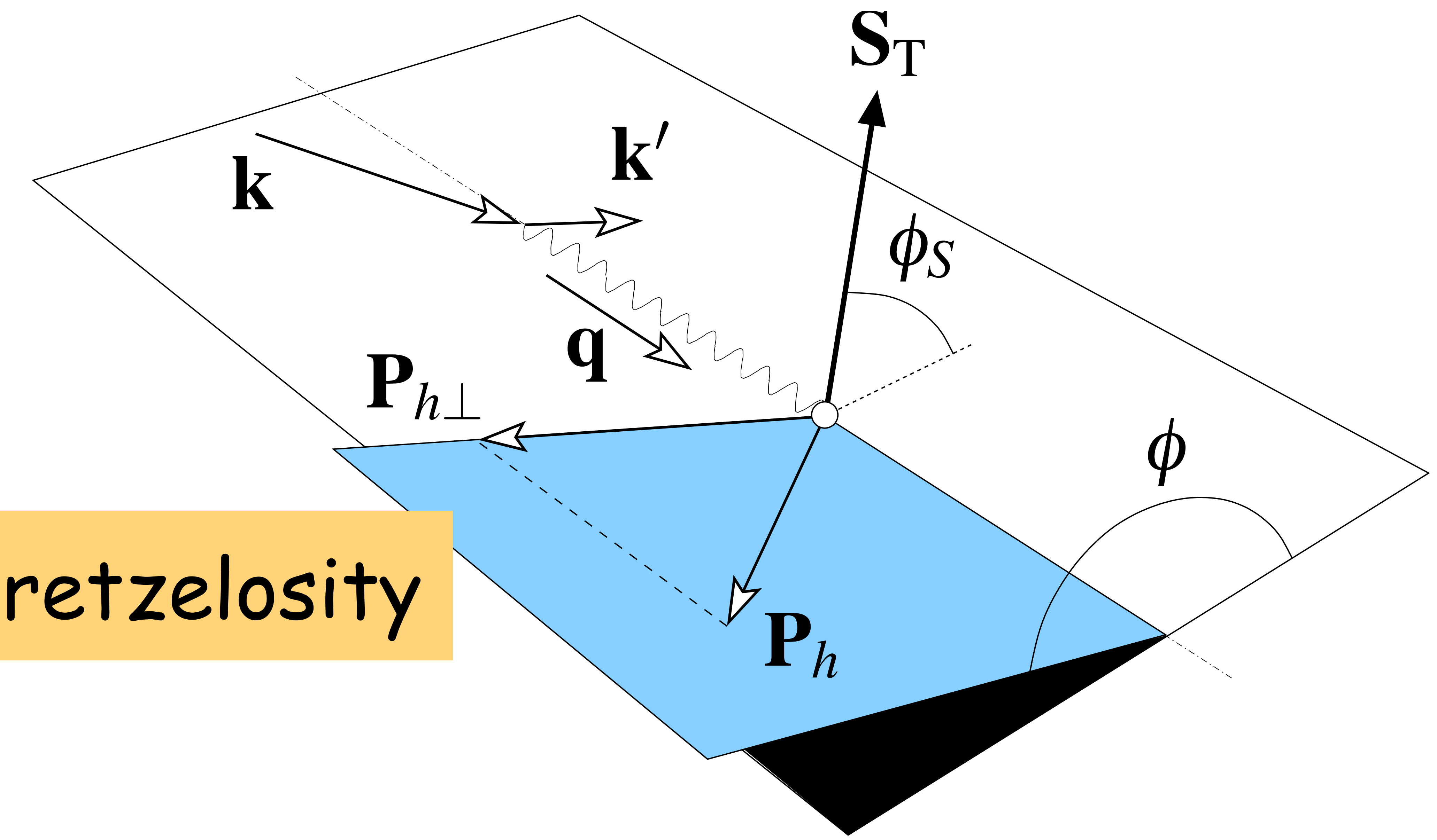
$$+ \sqrt{2\,\epsilon(1+\epsilon)}\,F_{UT}^{h,\sin\phi_s}\sin\phi_s + \sqrt{2\,\epsilon(1+\epsilon)}\,F_{UT}^{h,\sin(2\phi-\phi_s)}\sin(2\phi-\phi_s)\Big]$$

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

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

semi-inclusive DIS

- with **transverse** target polarization:



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

Sivers

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

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

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

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

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

worm-gear

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

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 $A_{\|}$ in addition to A_1**

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

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 $A_{\|}$ in addition to A_1**

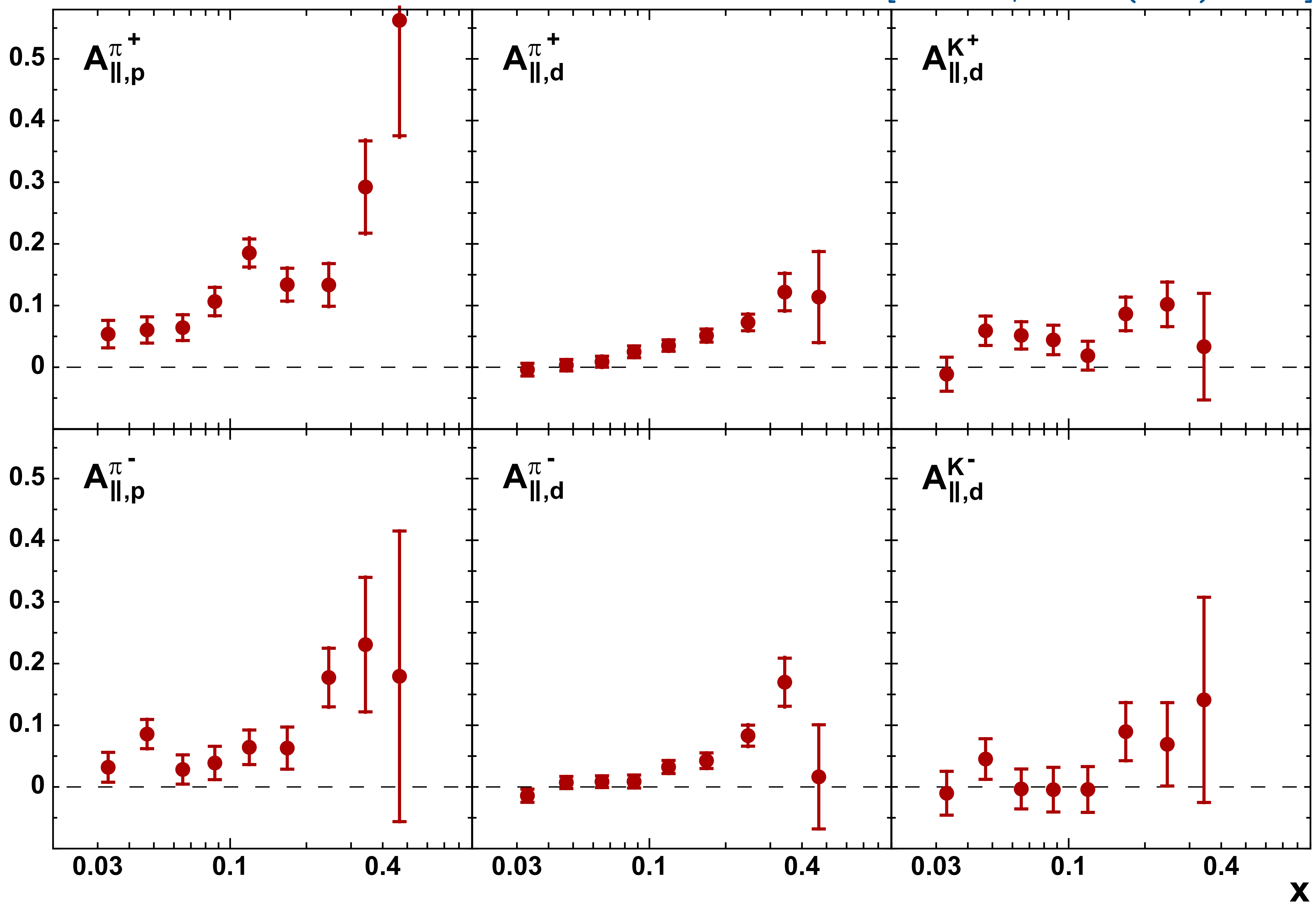
$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_{\|}^h \qquad D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

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 $A_{||}$

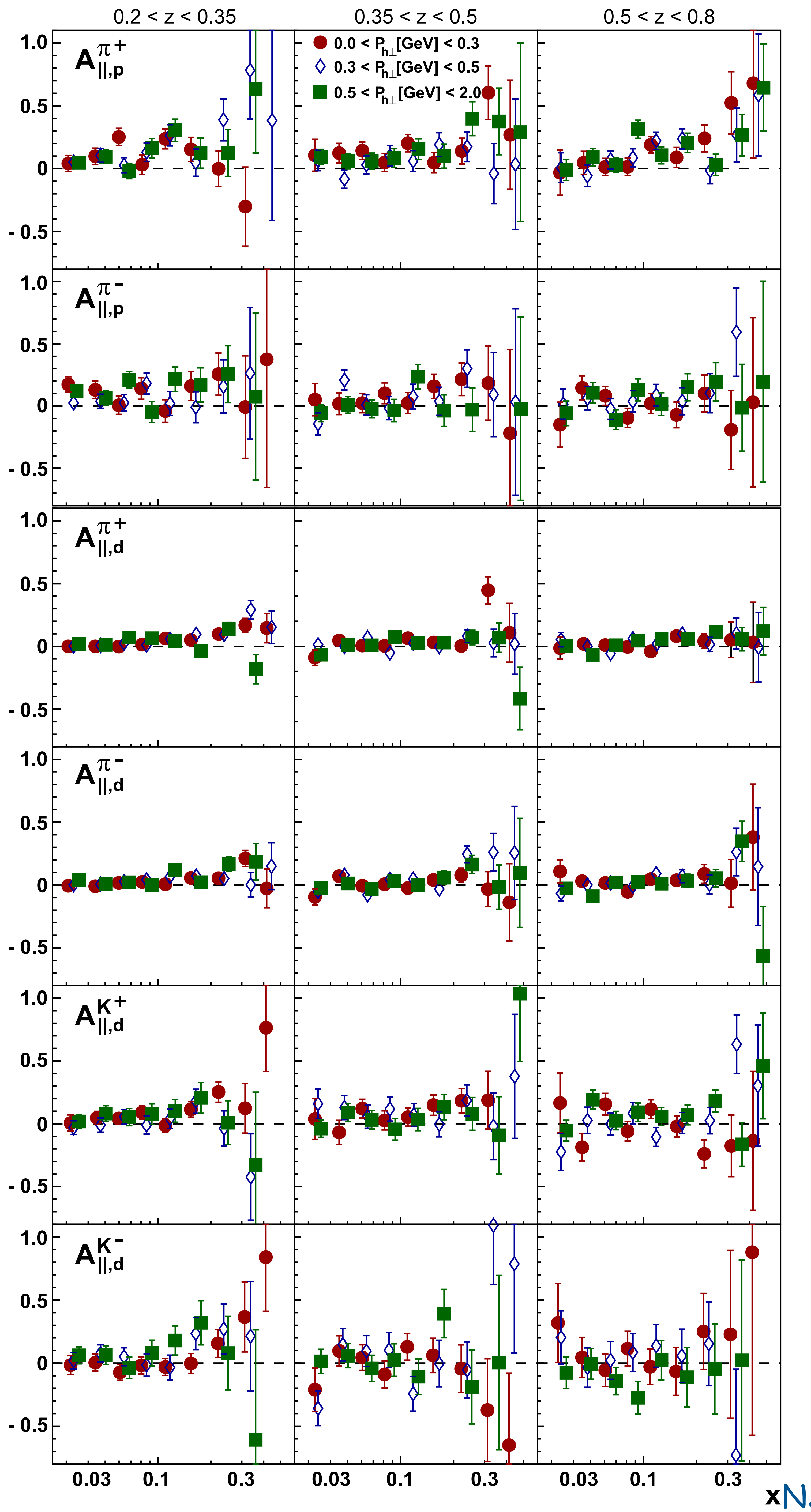
[HERMES, PRD 99 (2019) 112001]



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

3-dimensional binning

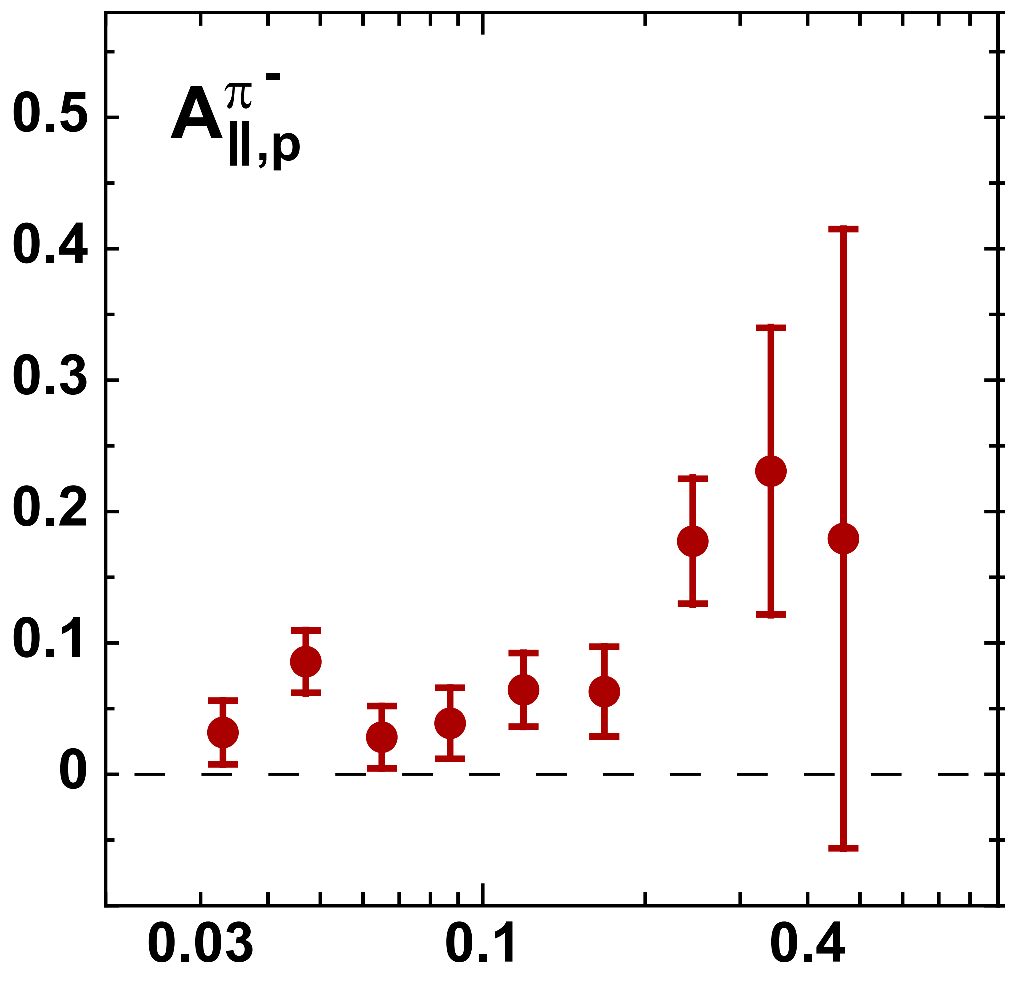
- **first-ever 3d binning** provides transverse-momentum dependence

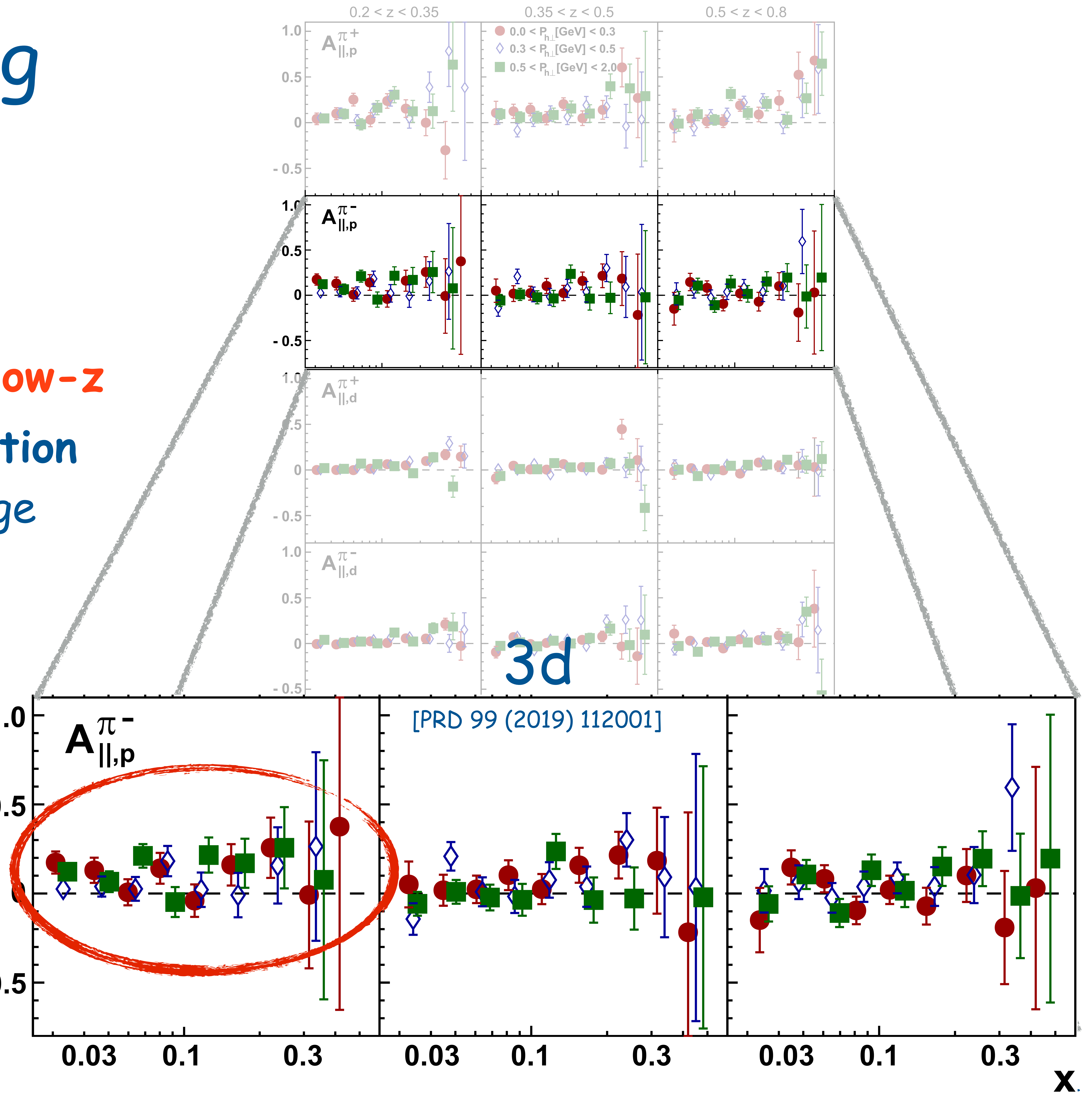


3-dimensional binning

- **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





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hermes

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

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$\sin(\phi+\phi_S)$	[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%

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Azimuthal modulation		3d: π^+	3d: π^-	3d: K^+	3d: K^-	3d: p	1d: π^0	1d: $\bar{p}$
		Significant non-vanishing Fourier amplitude						
$\sin(\phi+\phi_S)$	[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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

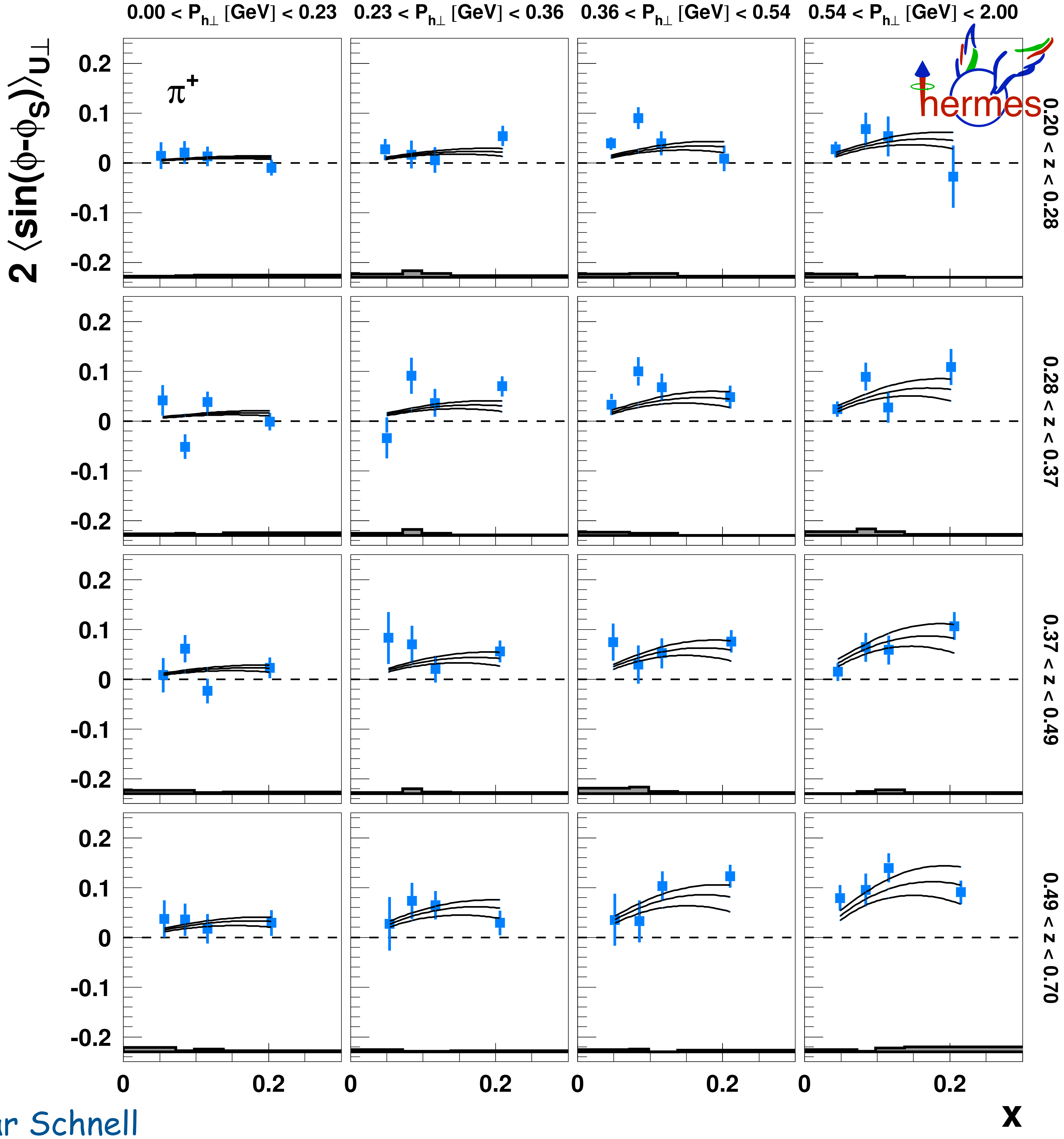
90%

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 multi-dimensional analysis

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



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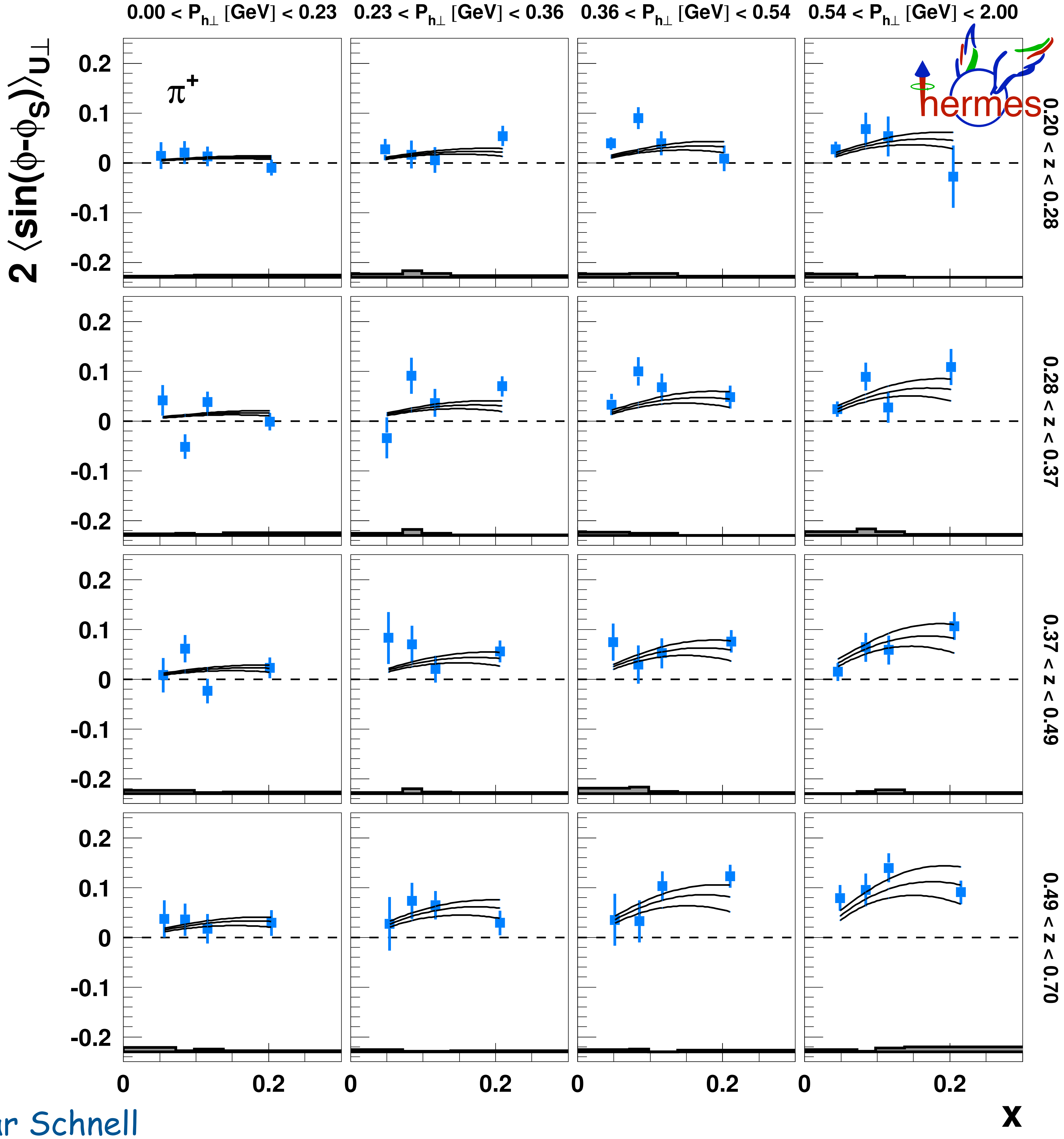

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$

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

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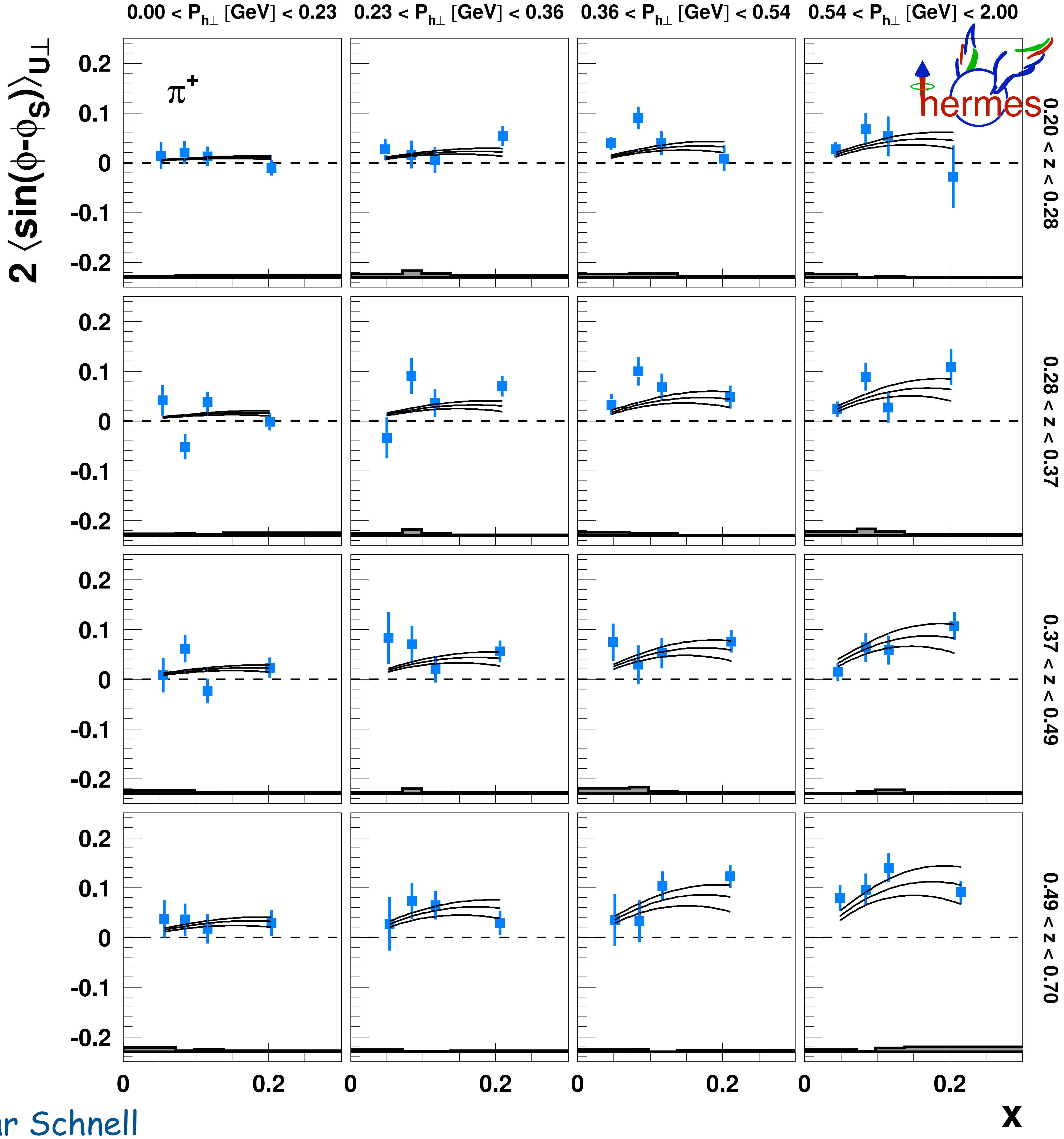

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

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

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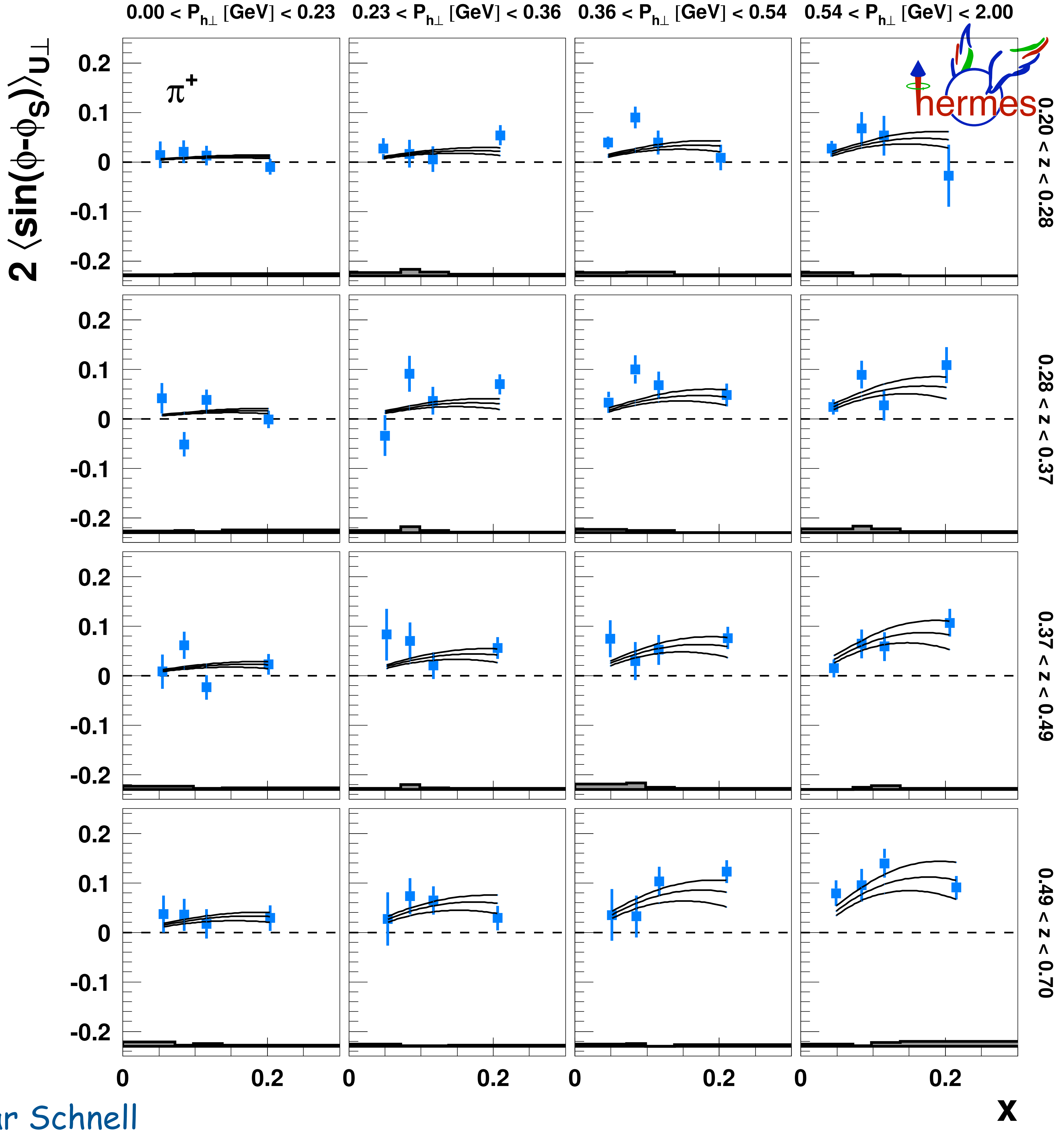

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations

	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

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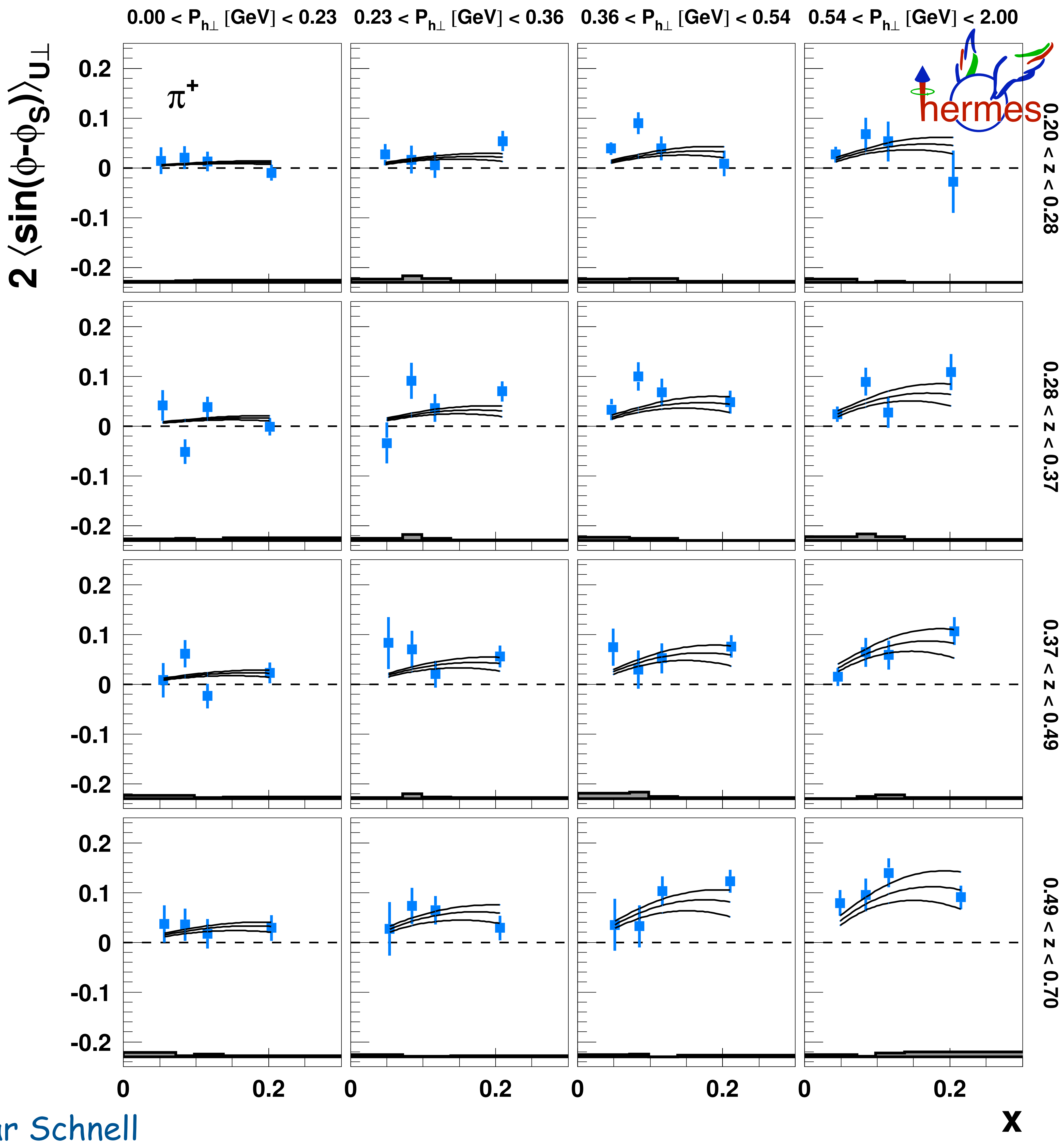
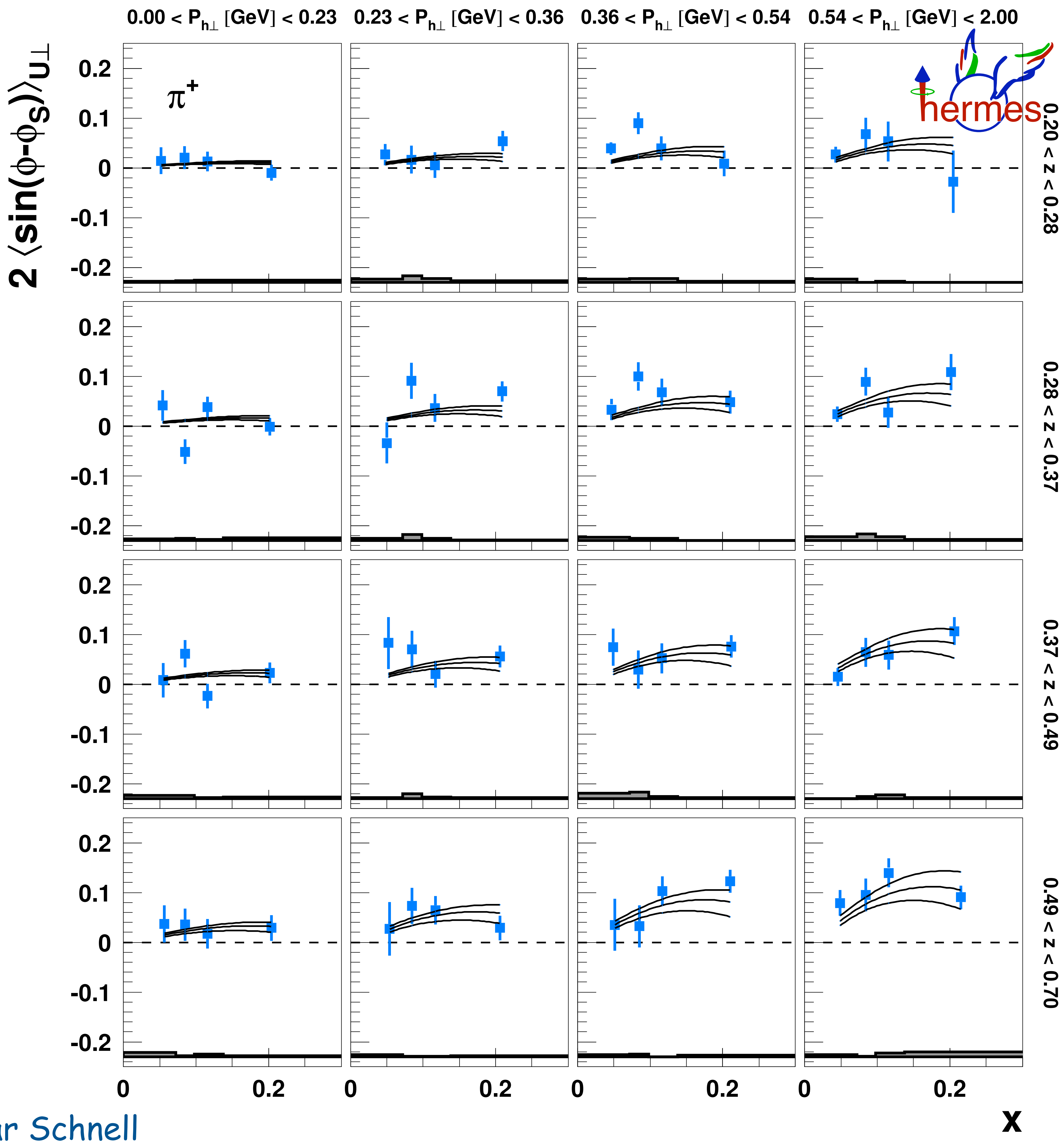


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

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

Sivers amplitudes
multi-dimensional analysis

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



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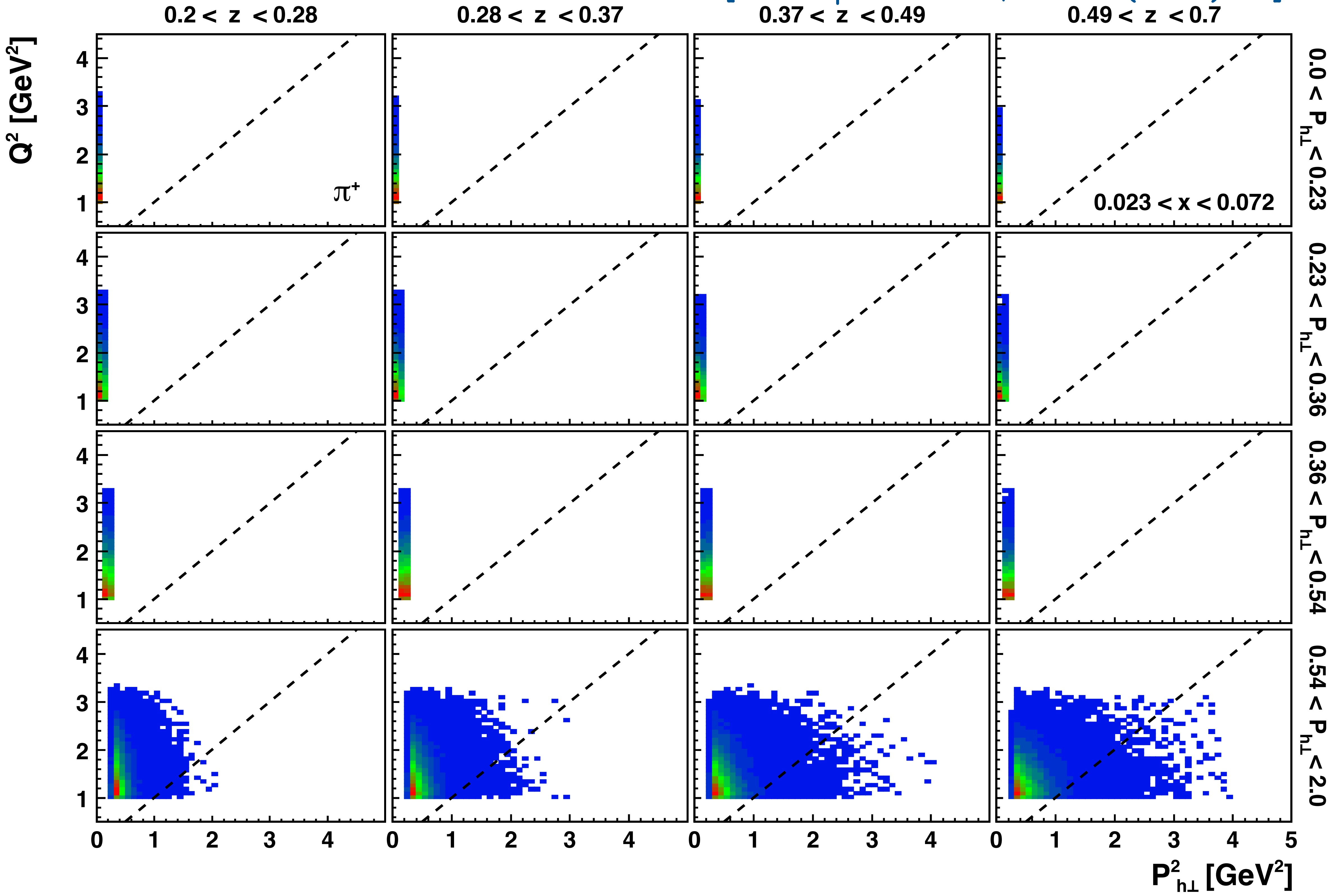
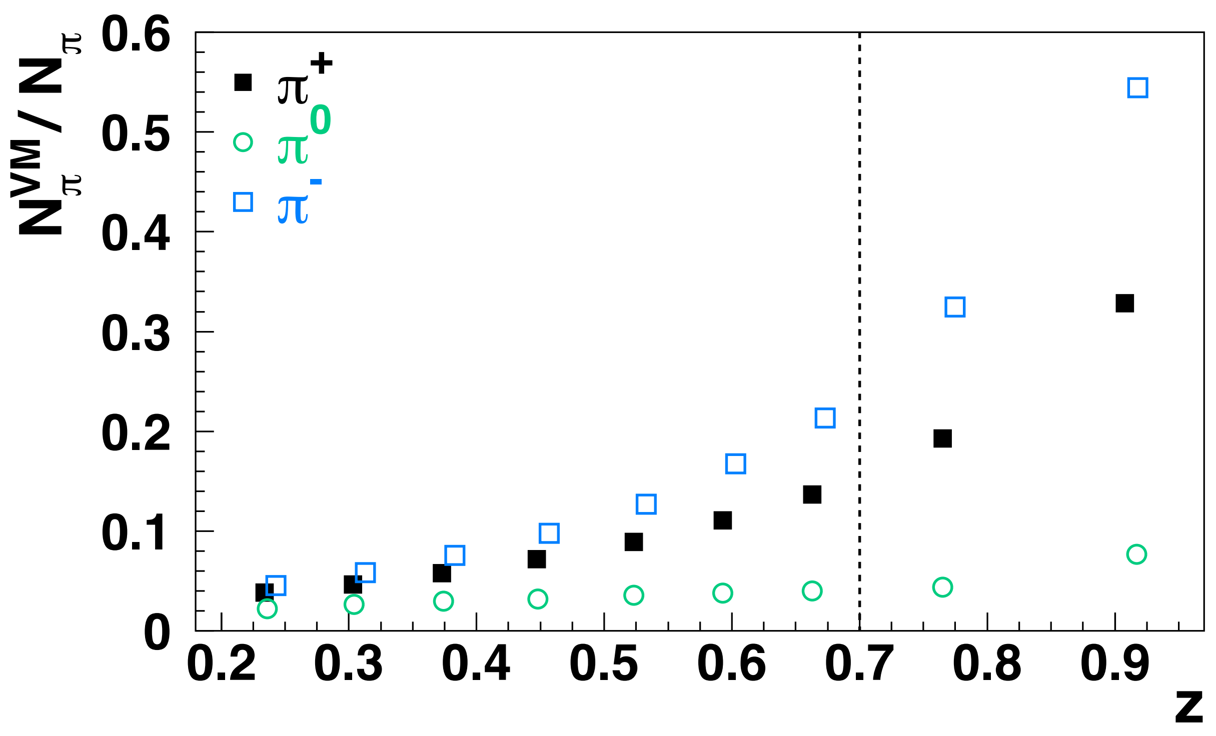


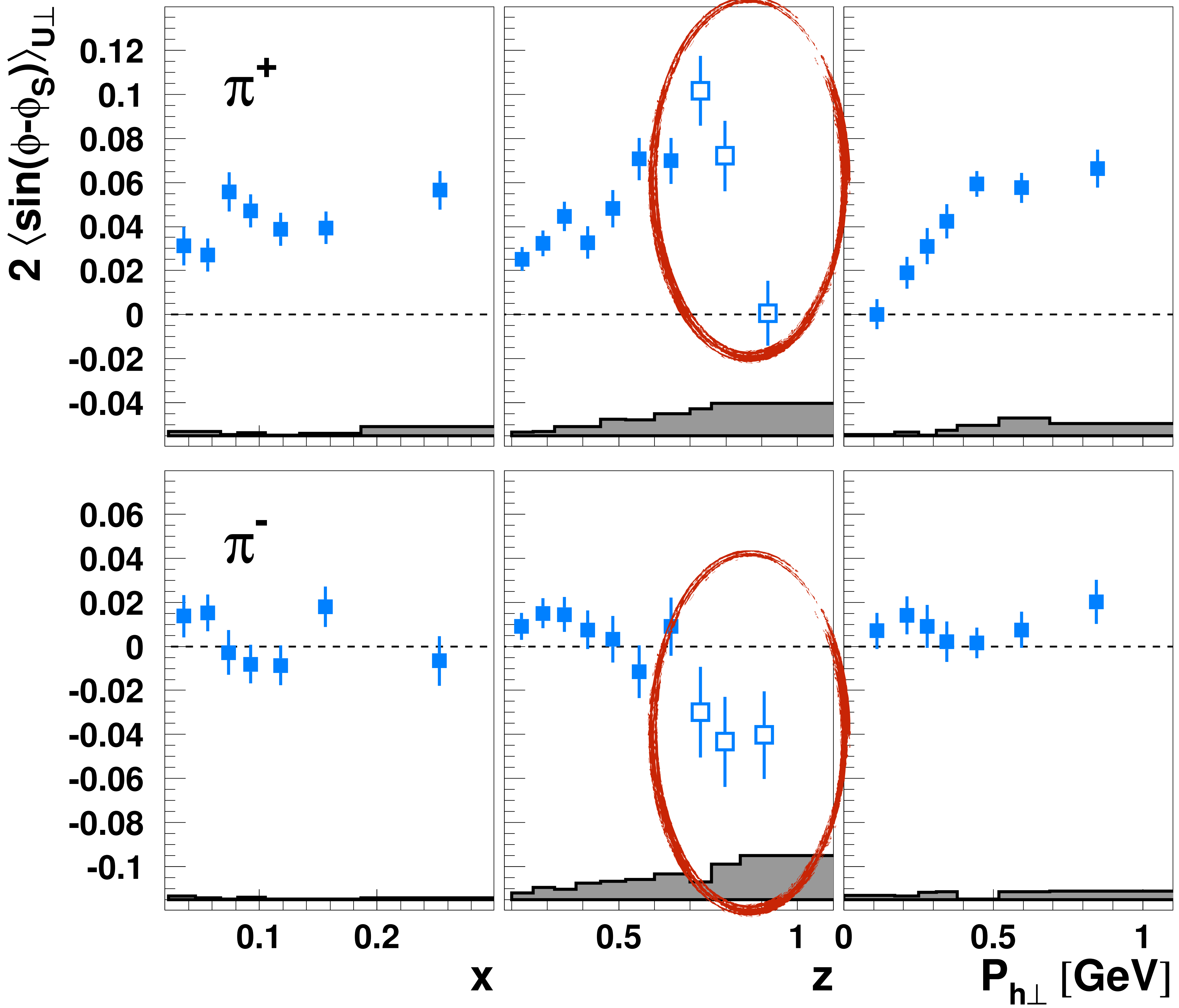
multi-d dependence and kinematical distribution should facilitate analyses within TMD formalism

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

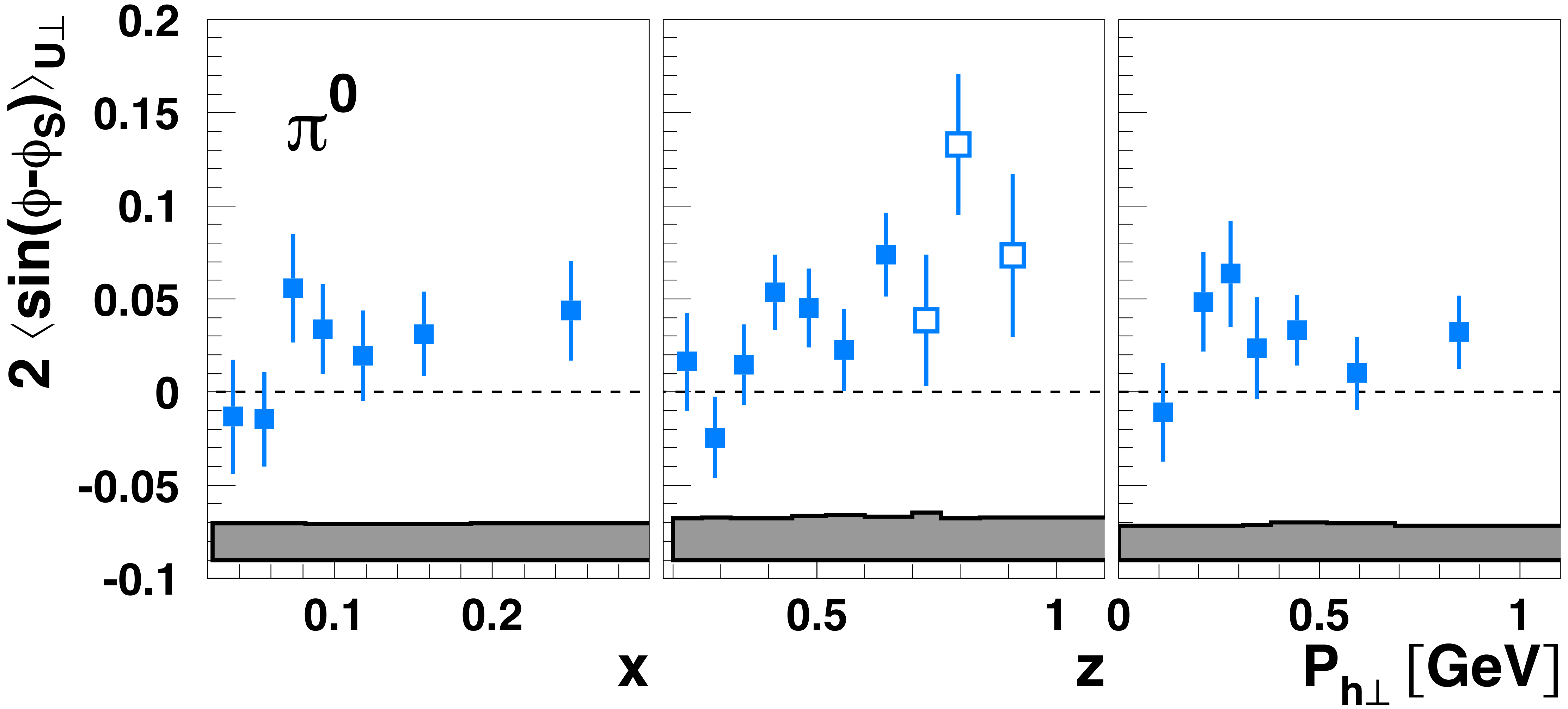


Sivers amplitudes for pions

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



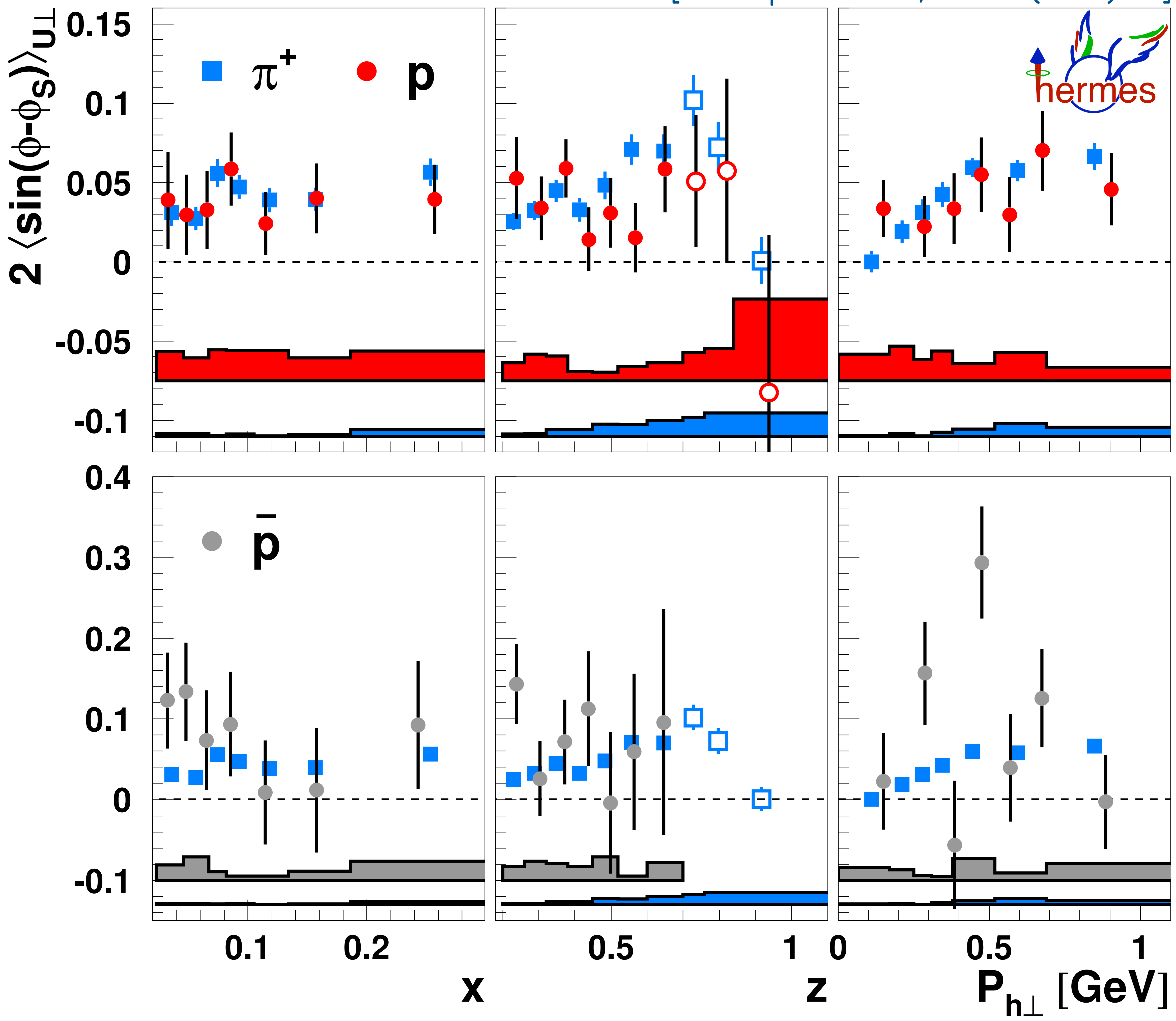
- **high-z data** probes region of **increased flavor sensitivity** to struck quark (but also where contributions from exclusive vector-meson production becomes significant)
  - only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)



	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?

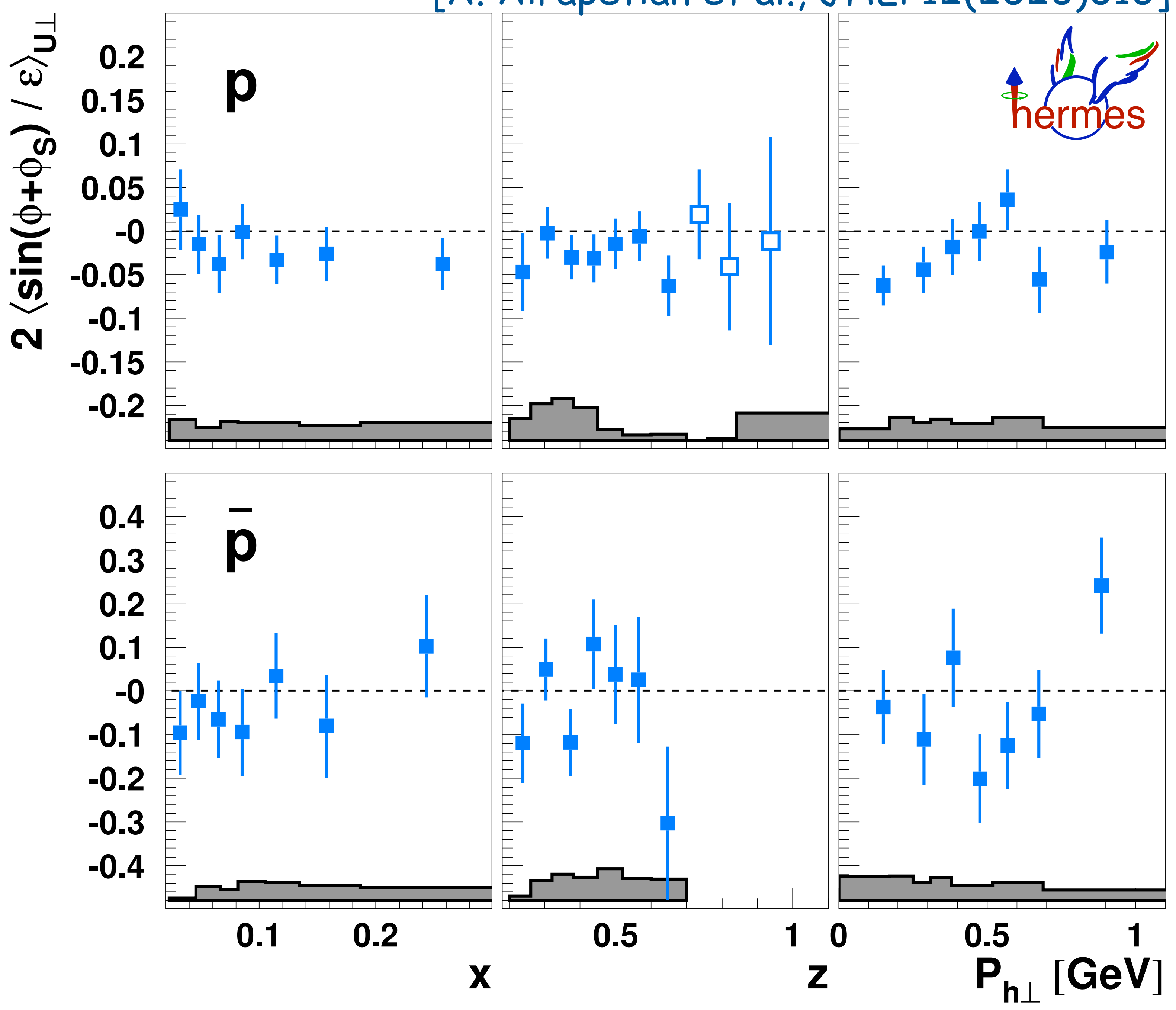
$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

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

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

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?

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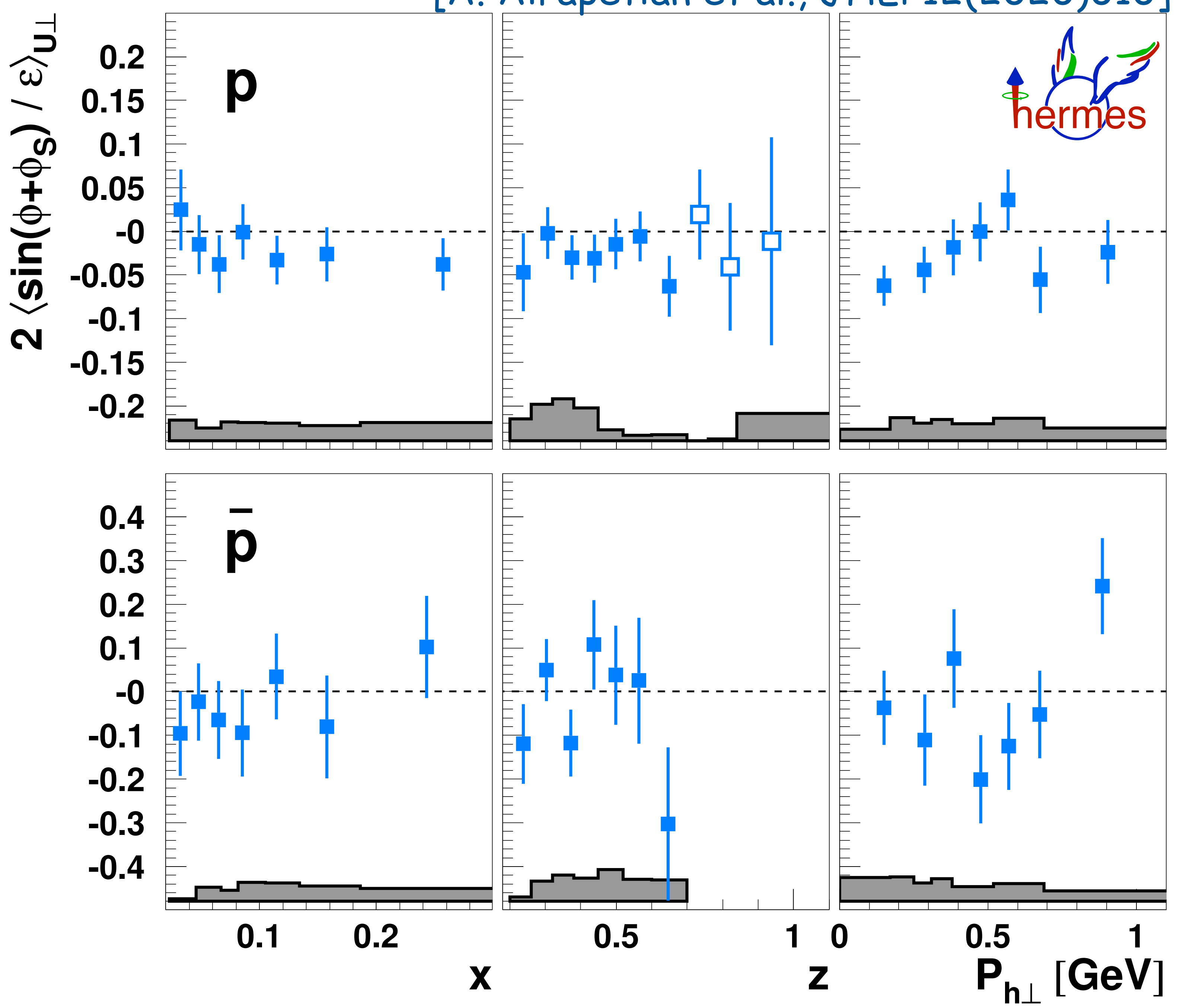
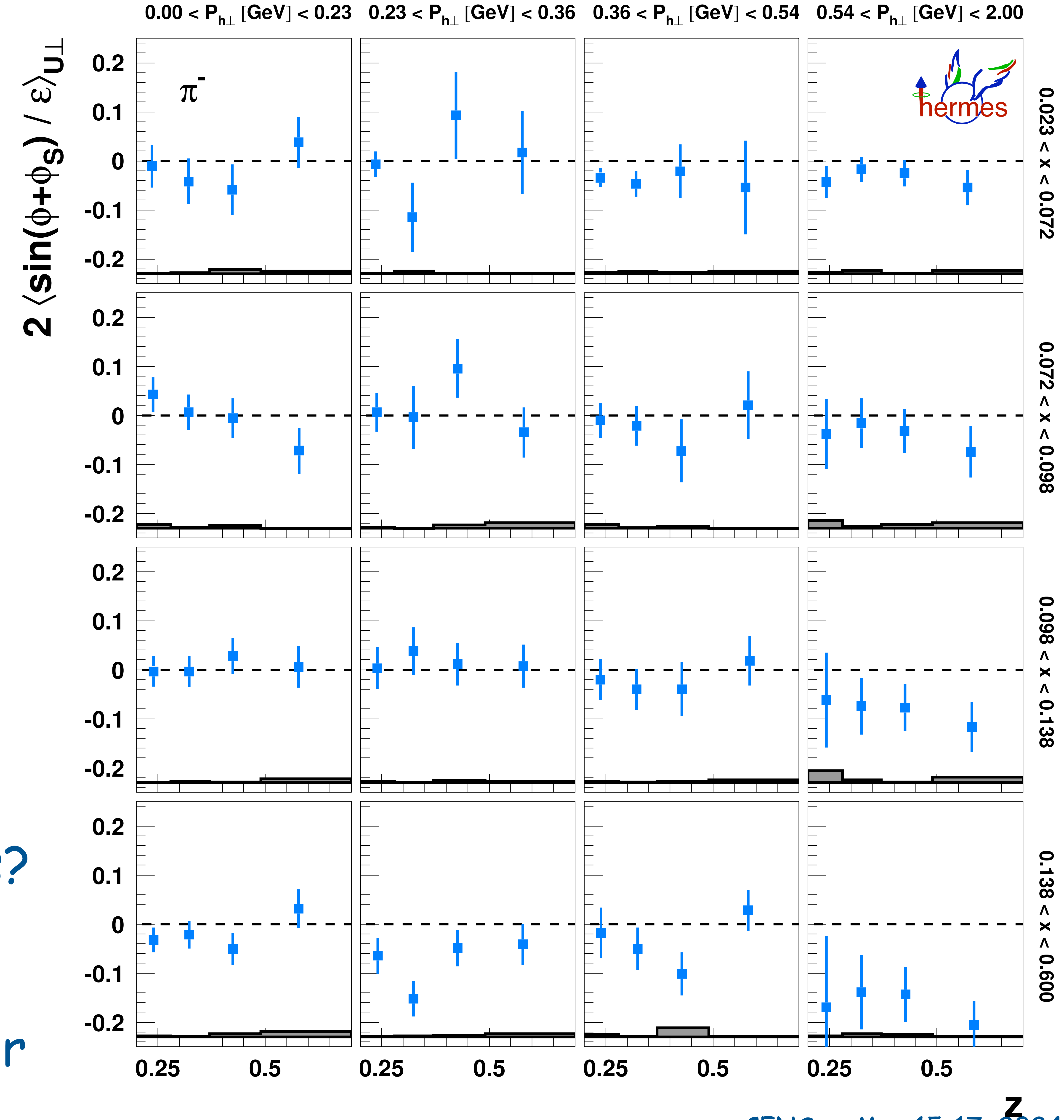


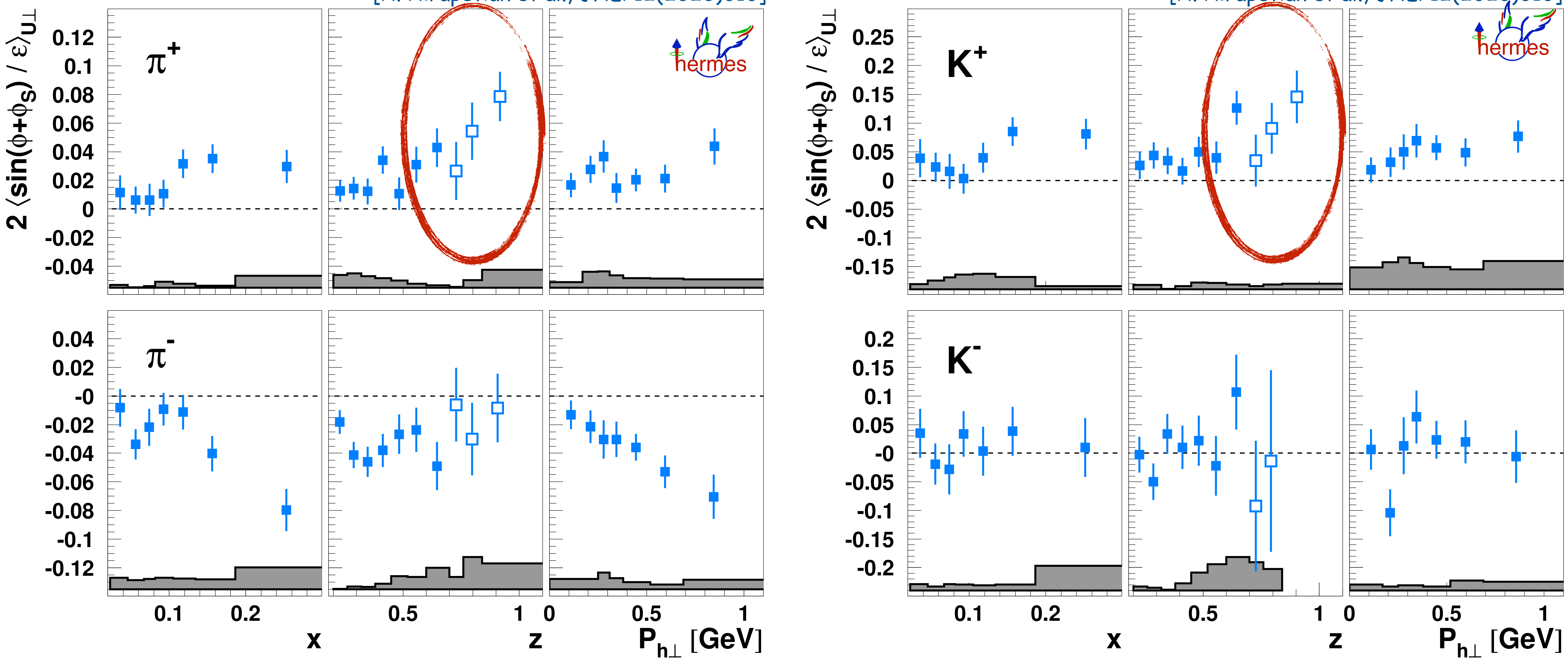


- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic "depolarization" prefactor

	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

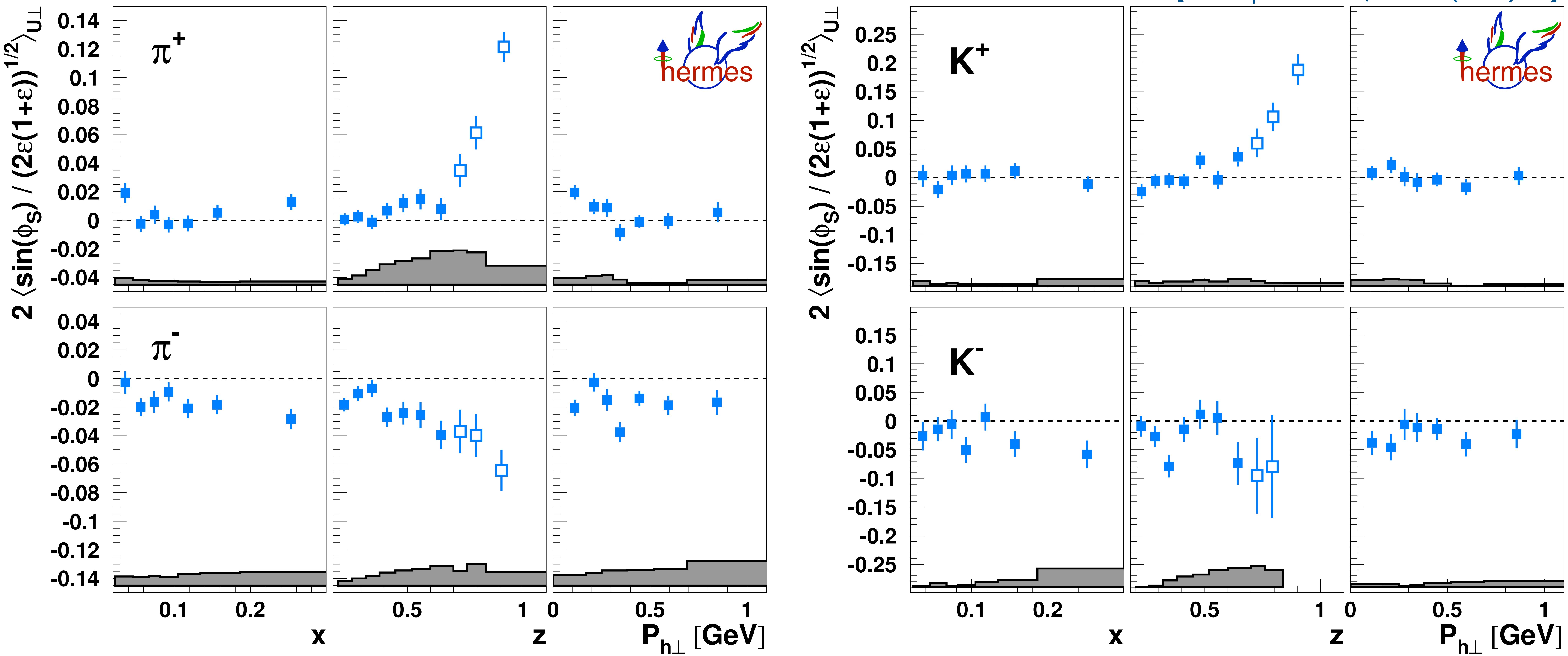
[A. Airapetian et al., JHEP12(2020)010]



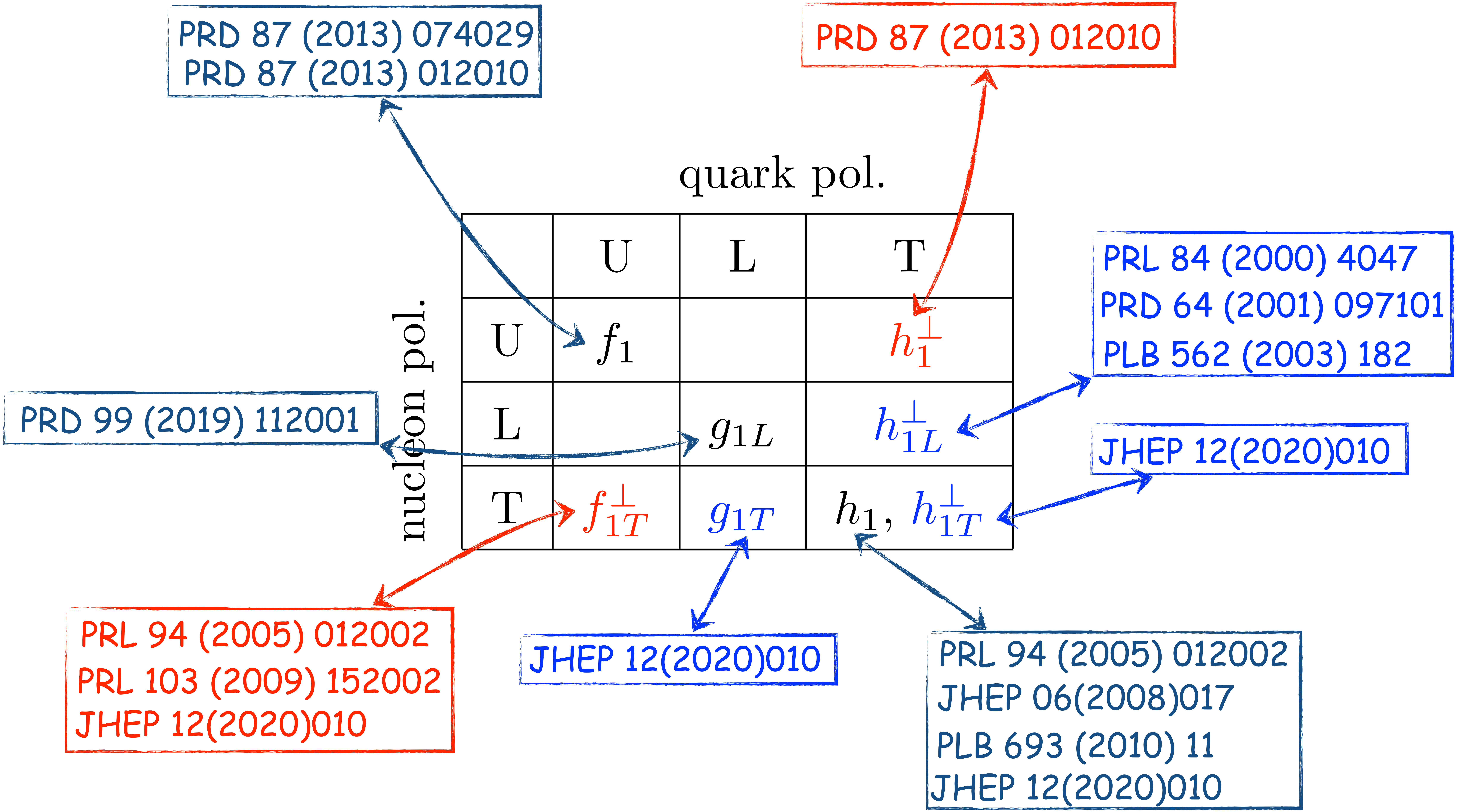
- **high-z region** with larger quark-flavour sensitivity, with **increasing amplitudes** for positive pions and kaons

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



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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

backup slides

non-vanishing twist-3

Physics Letters B 797 (2019) 134886

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

The HERMES Collaboration

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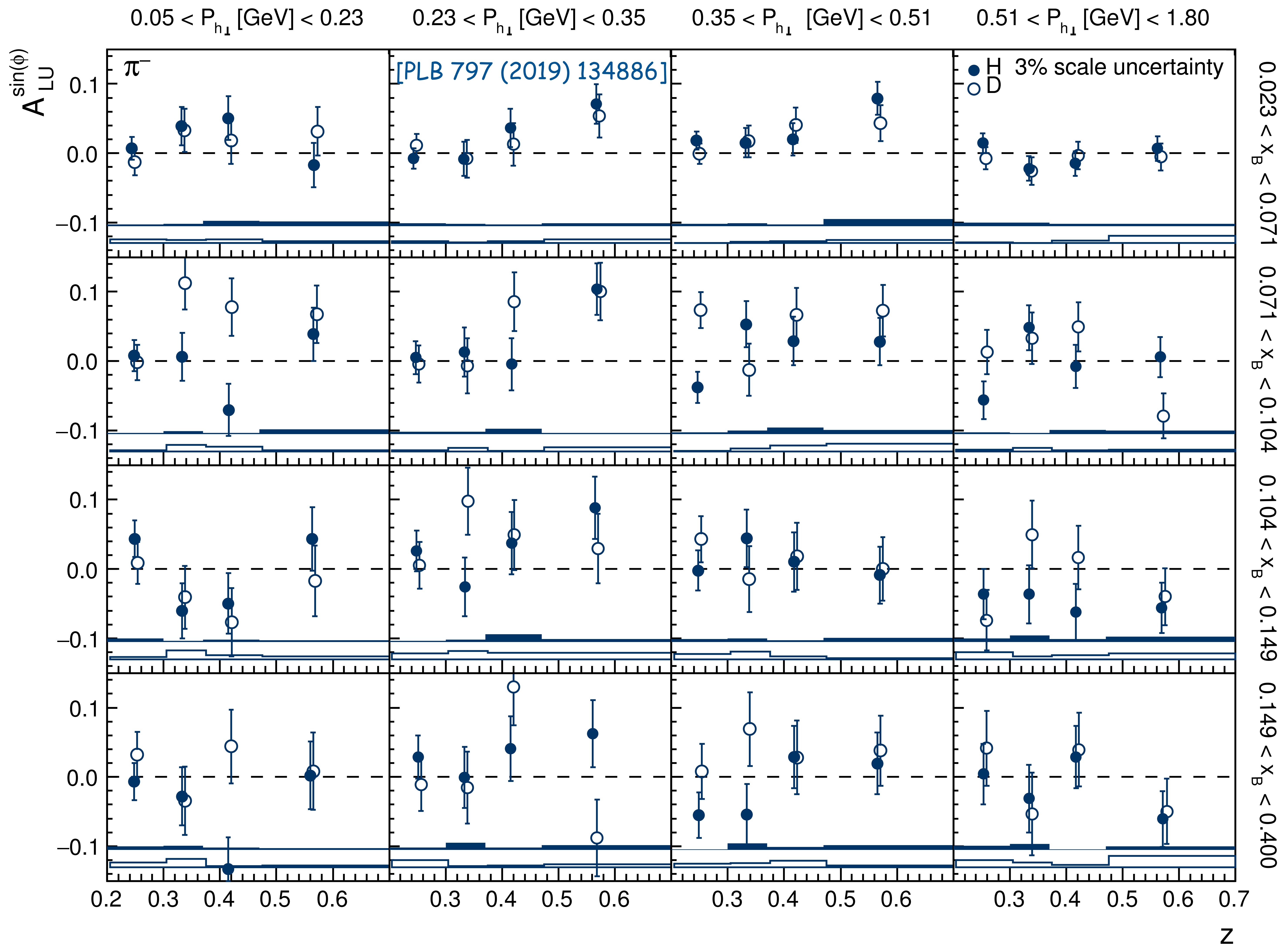
subleading twist I - <sin(ϕ)>$_{LU}$

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

- 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**

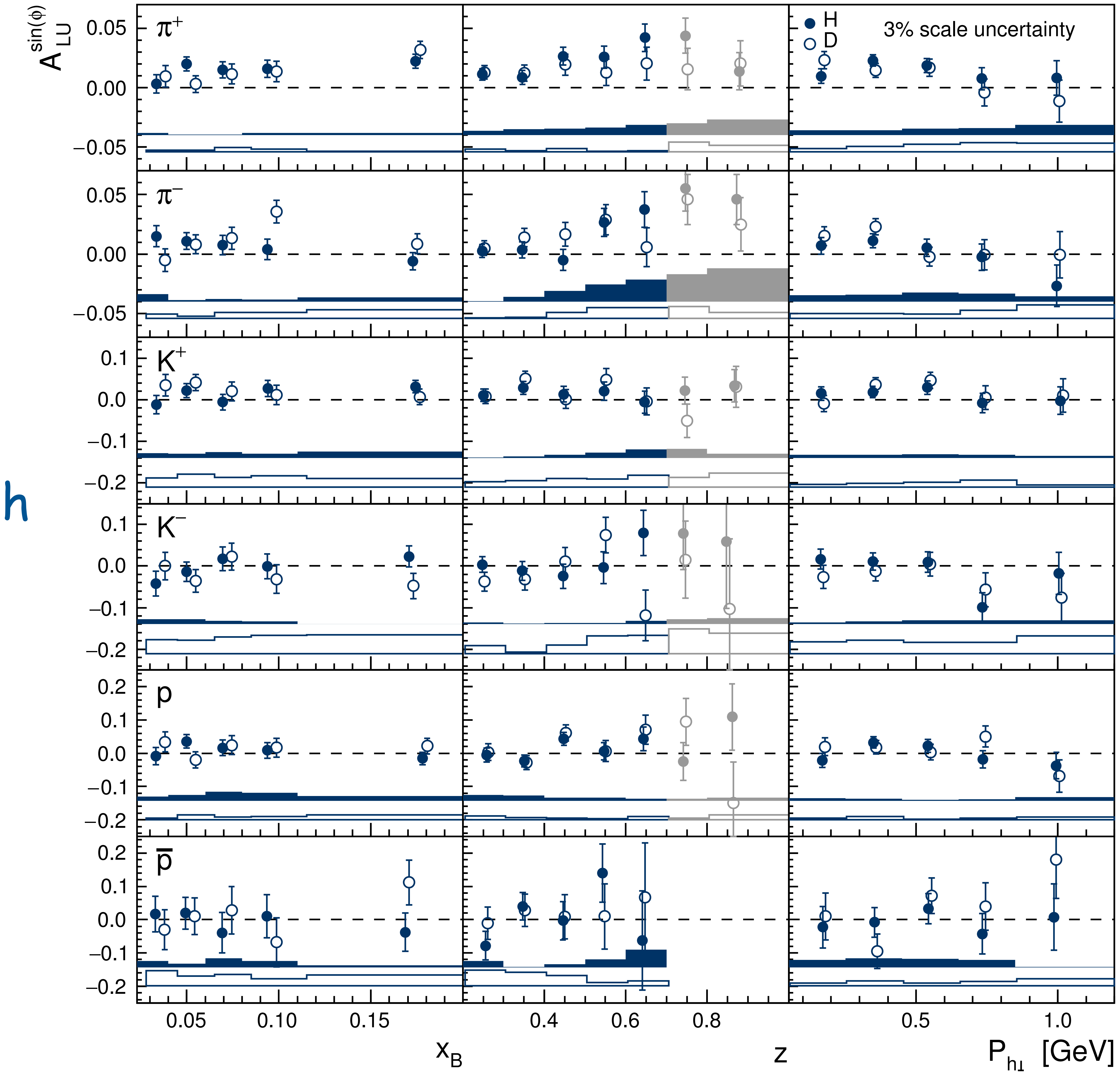
subleading twist I - <sin(φ)>$_{LU}$ HERMES 3d analysis



most comprehensive presentation; use 1d binning for discussion

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

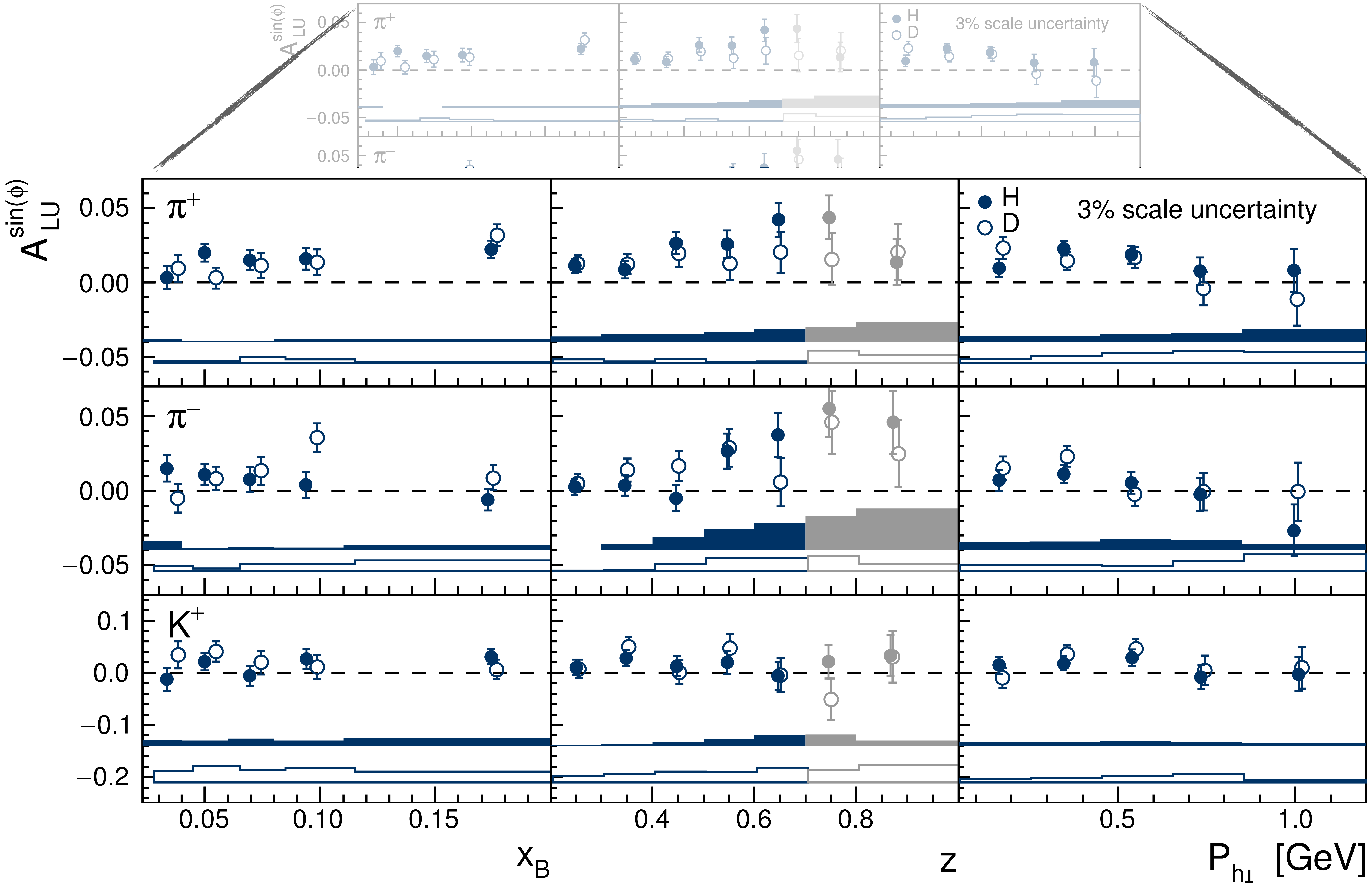
[HERMES, PLB 797 (2019) 134886]



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

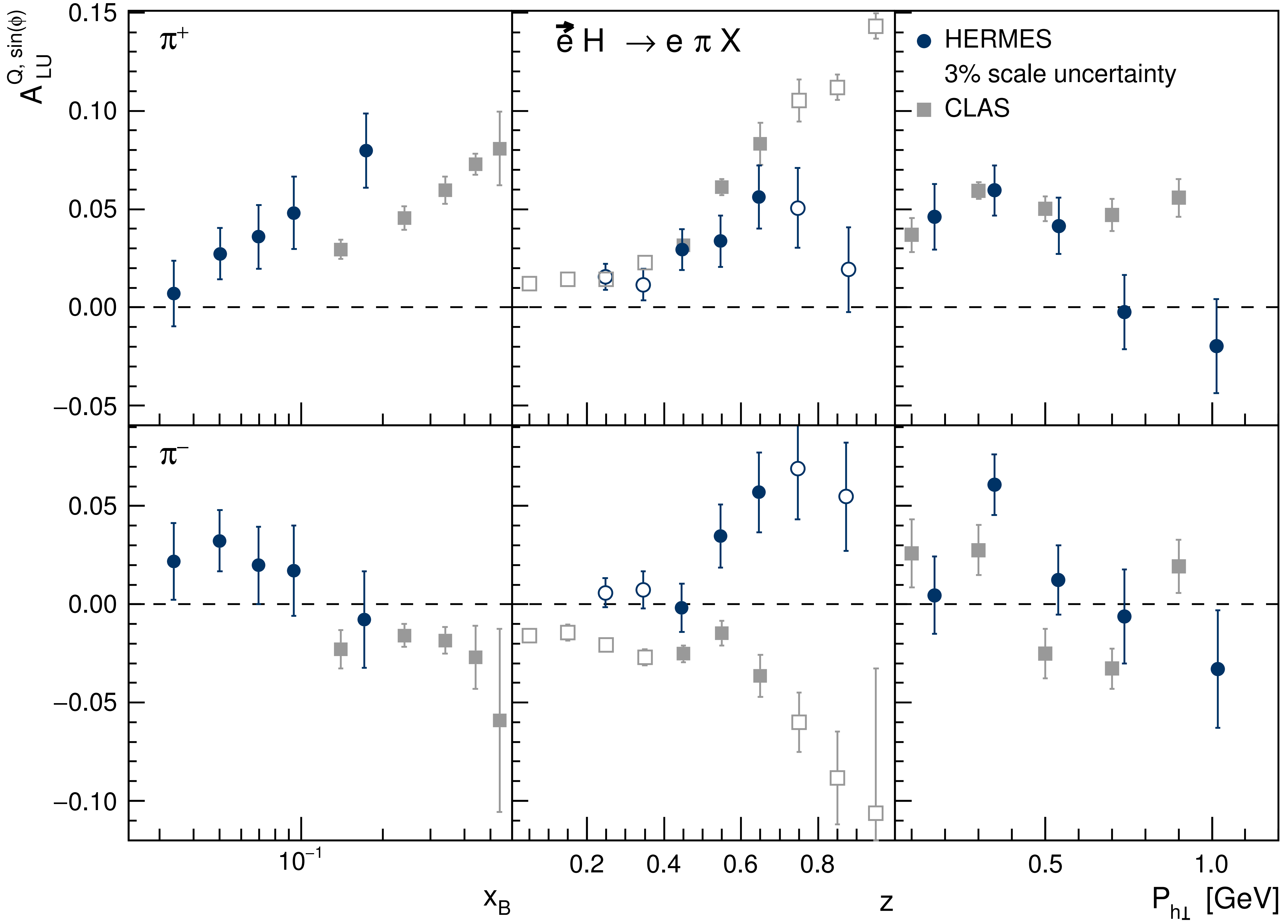
$$\frac{M_h}{Mz} h_1^{\perp} \tilde{E} \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 \tilde{G}^{\perp} \oplus x e H_1^{\perp}$$

[HERMES, PLB 797 (2019) 134886]



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

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

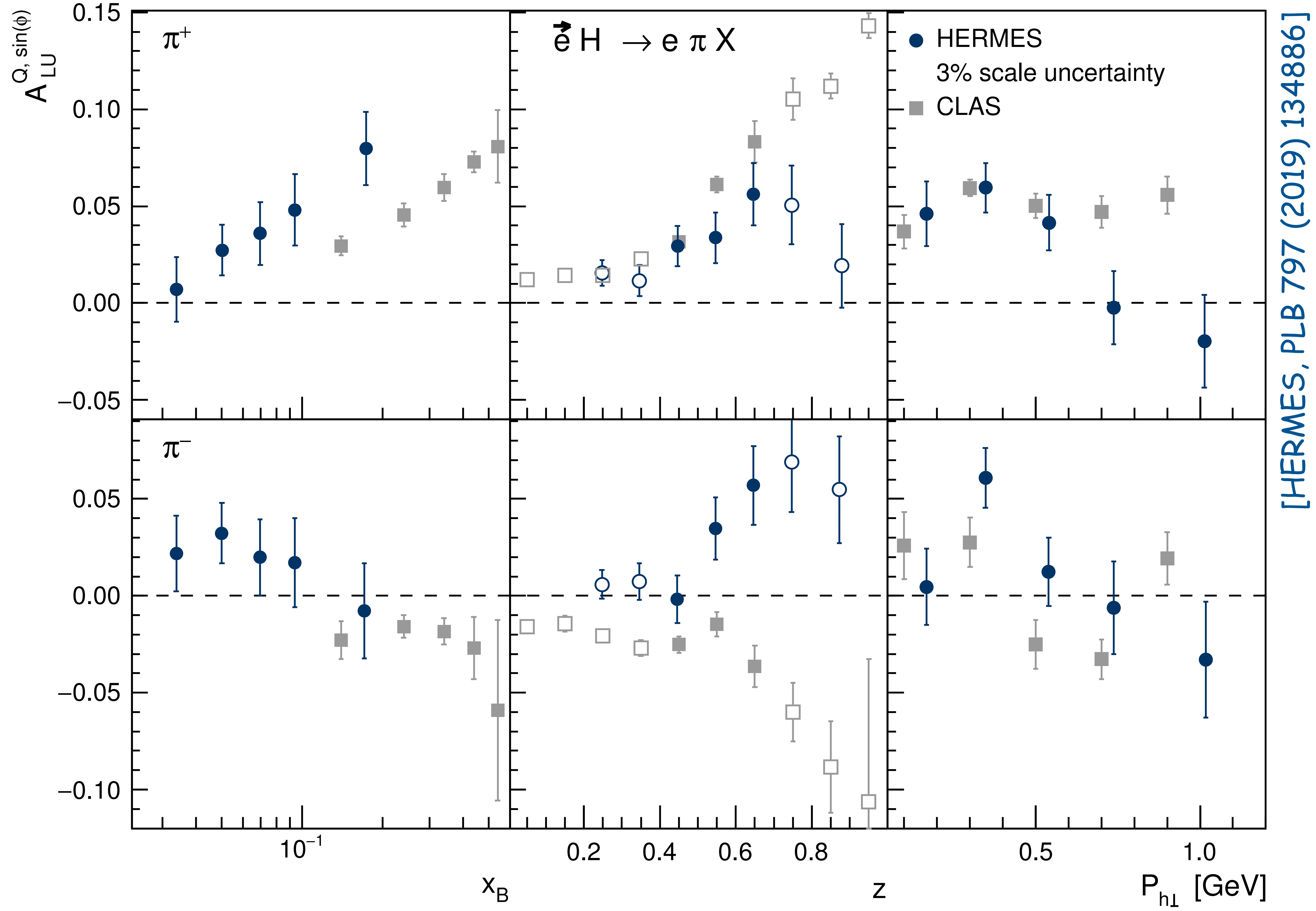


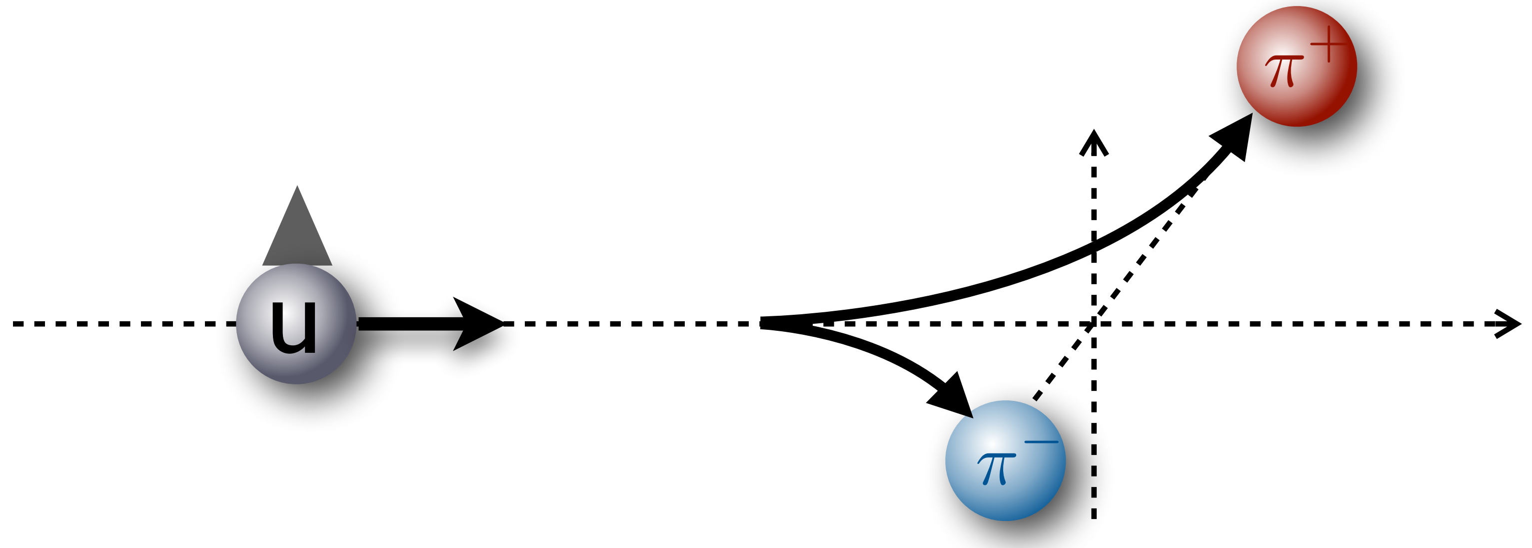
[HERMES, PLB 797 (2019) 134886]

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

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

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



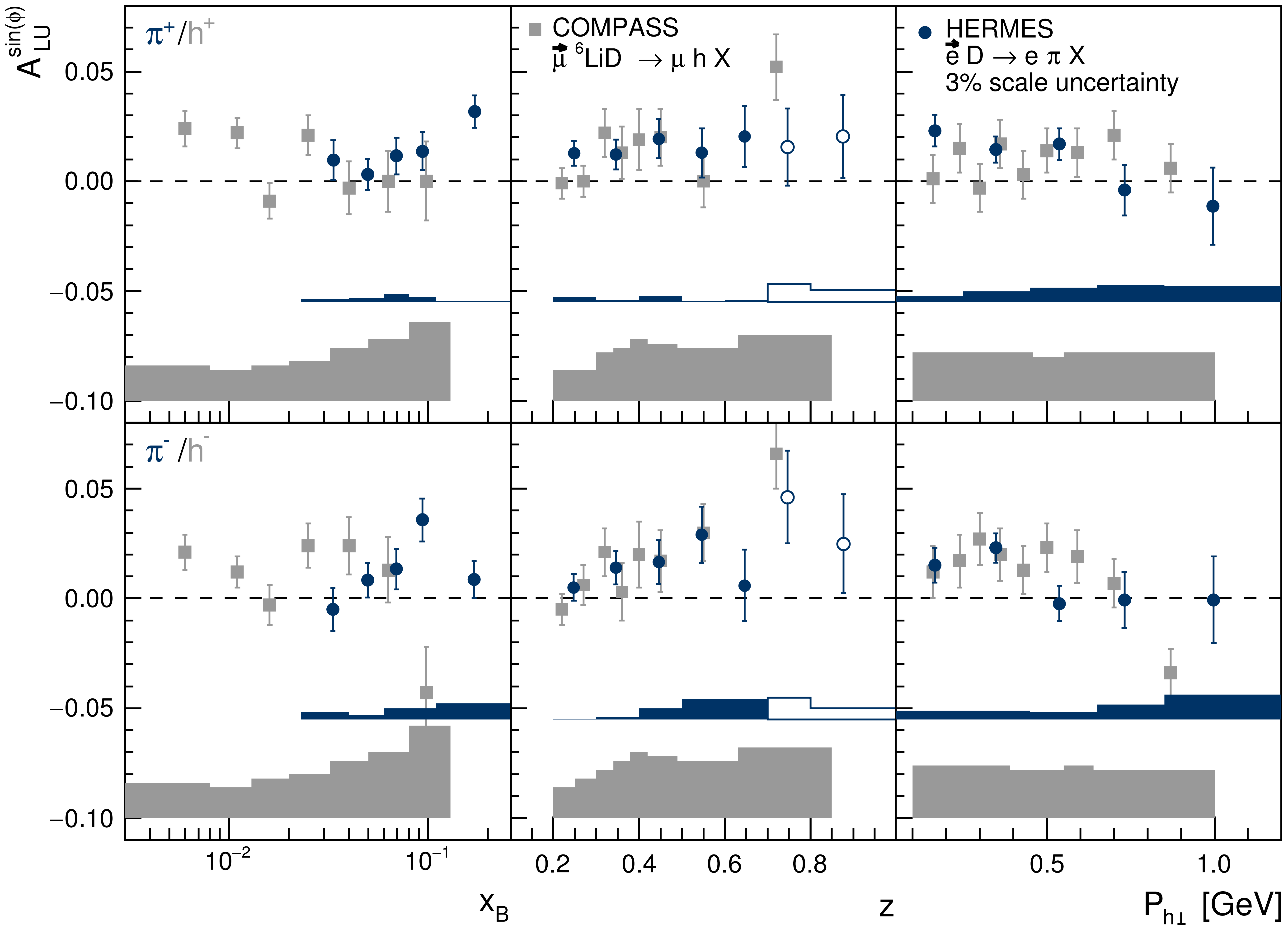


- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x)Collins term due to higher x probed?

subleading twist I - <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

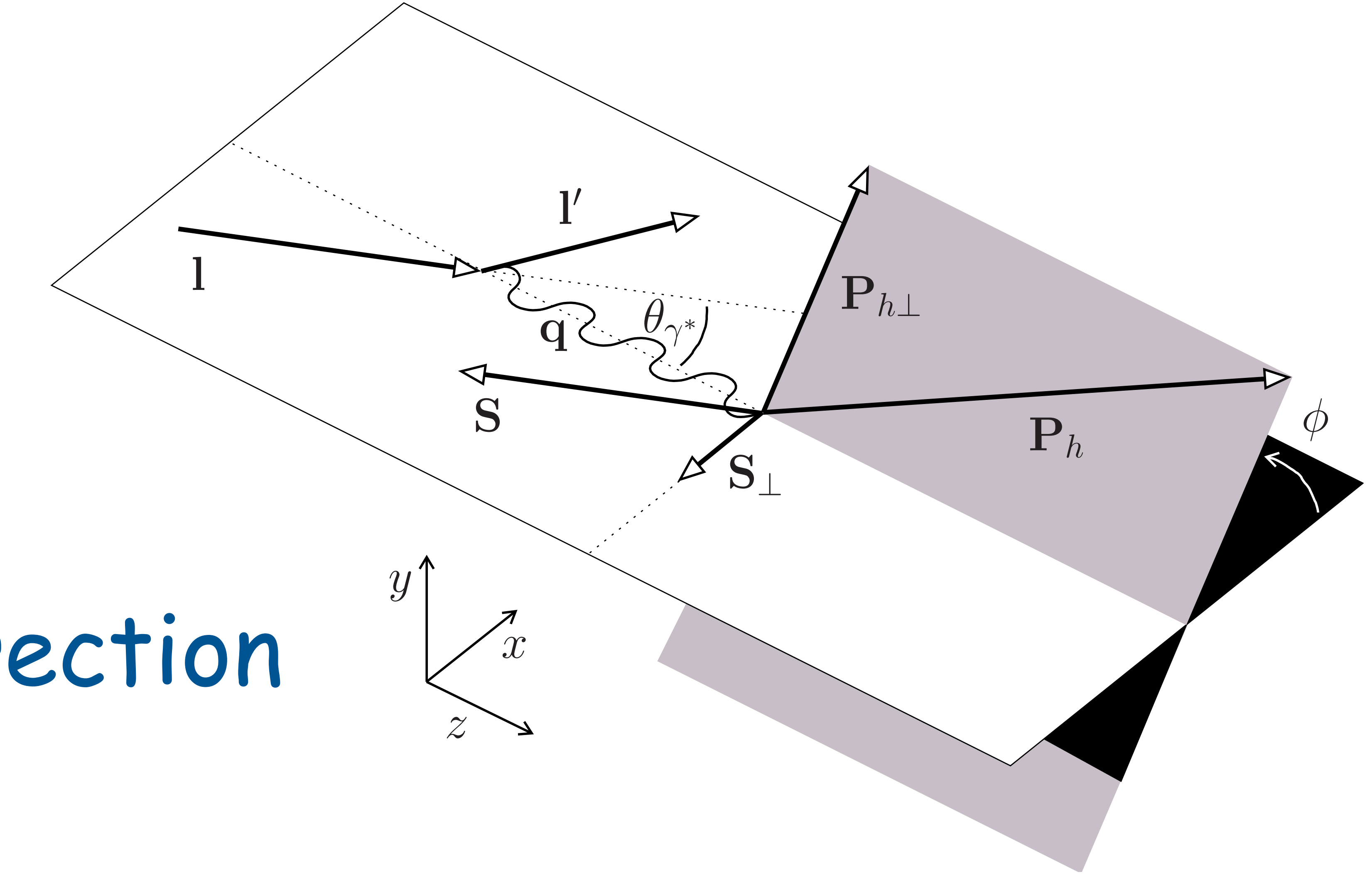


[HERMES, PLB 797 (2019) 134886]

conclusions

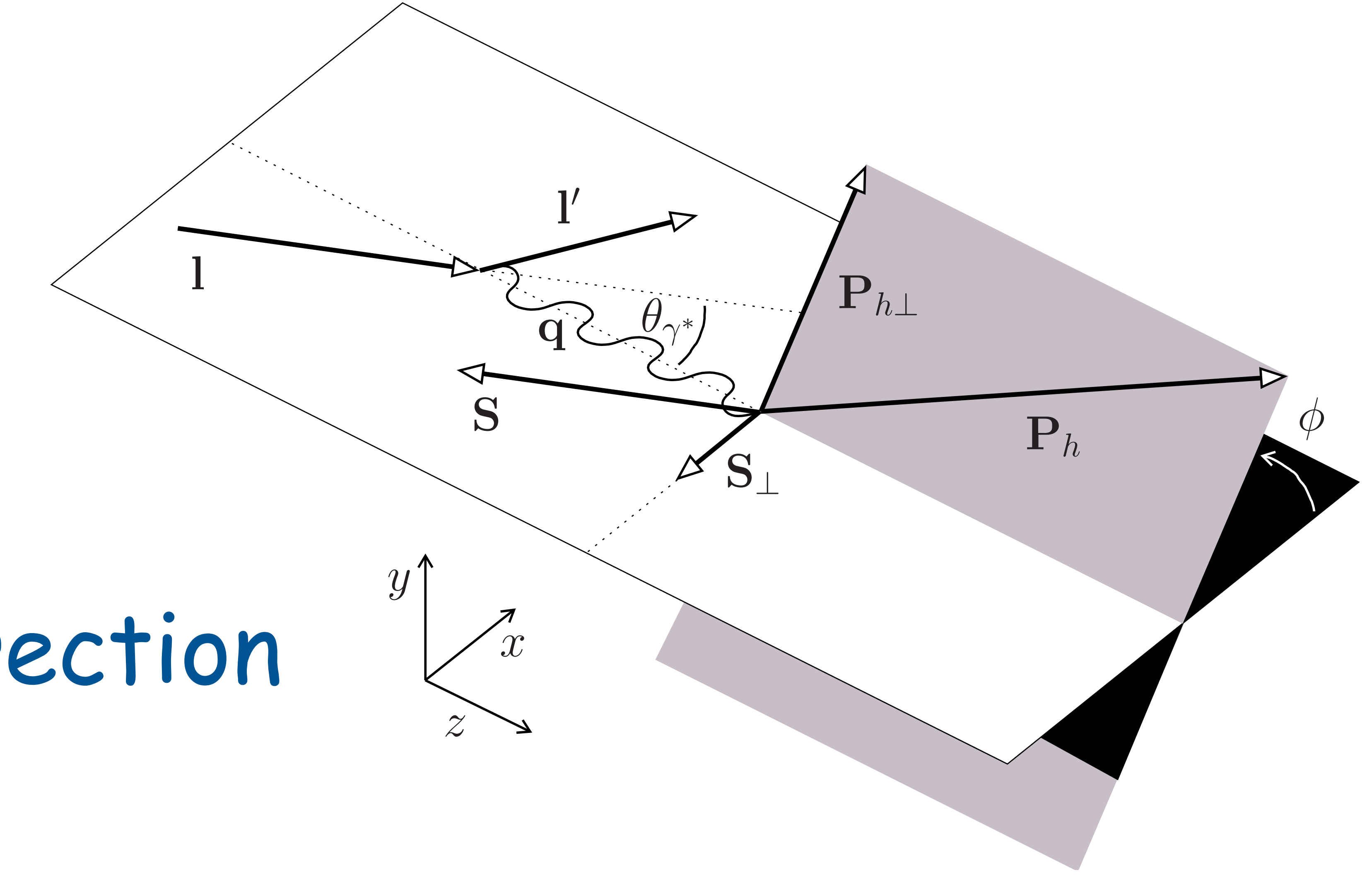
- HERMES continues producing results long after its shut-down
  - latest pub's providing 3d presentations of **longitudinal** & **transverse SSA & DSA**
  - **completes the TMD analyses** of single-hadron production
  - several significant leading-twist spin-momentum correlations (Sivers, Collins, worm-gear) 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)

subleading twist II - <sin(φ)>$_{UL}$



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

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

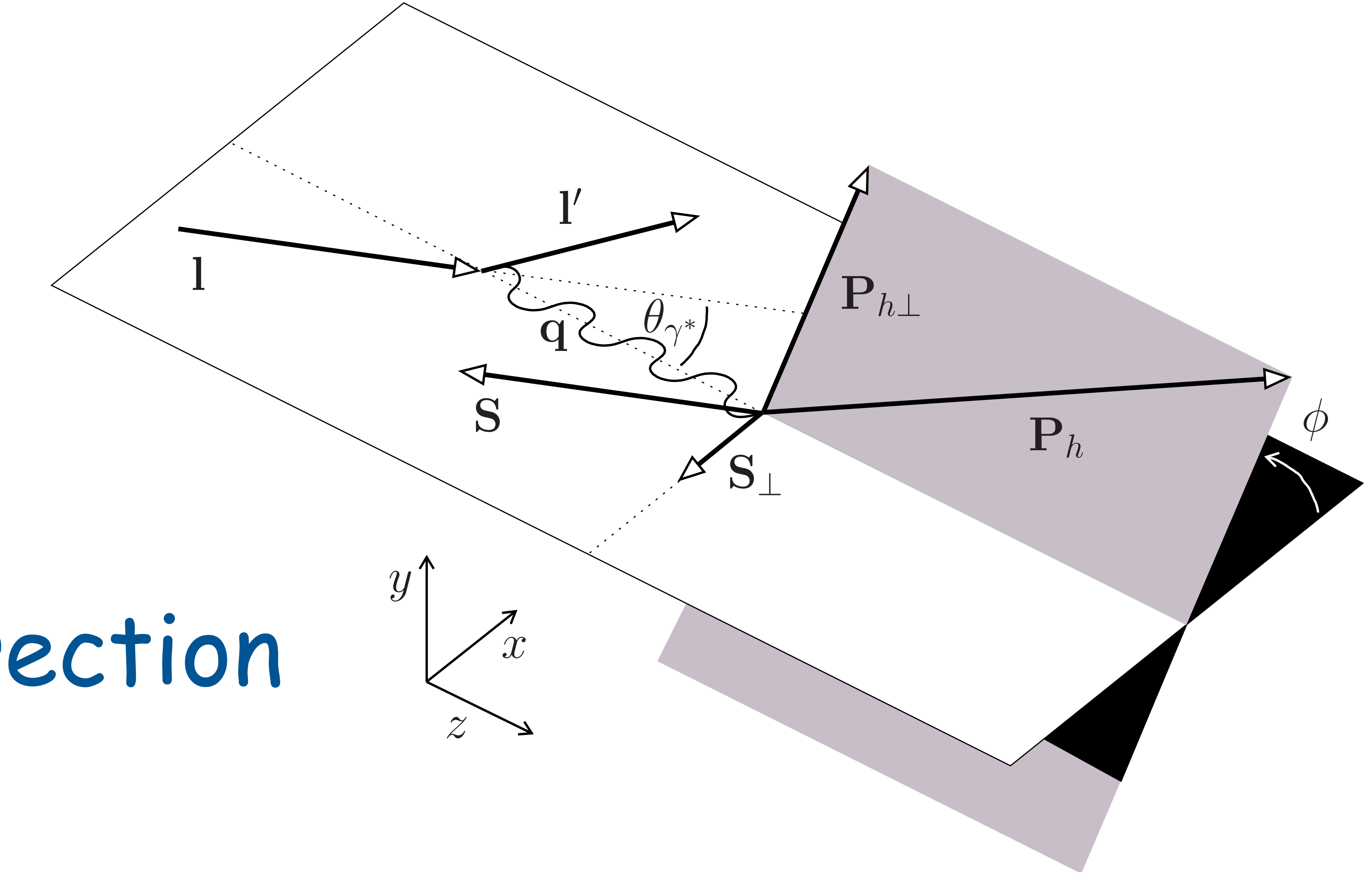


- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

➡ 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 II - <sin(ϕ)>$_{UL}$



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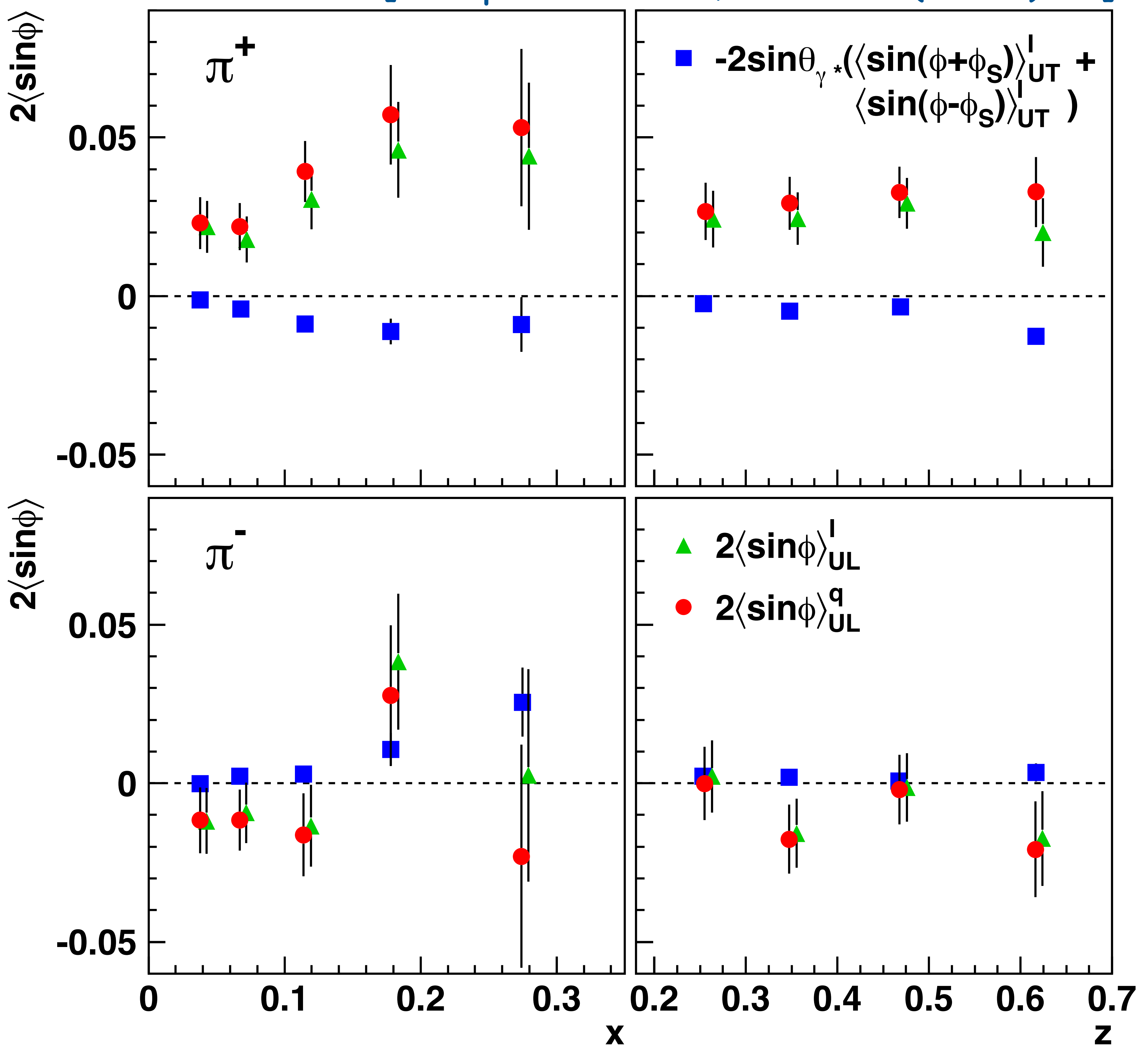
➡ need data on same target for both polarization orientations!

subleading twist II - <sin(ϕ)>UL

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

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

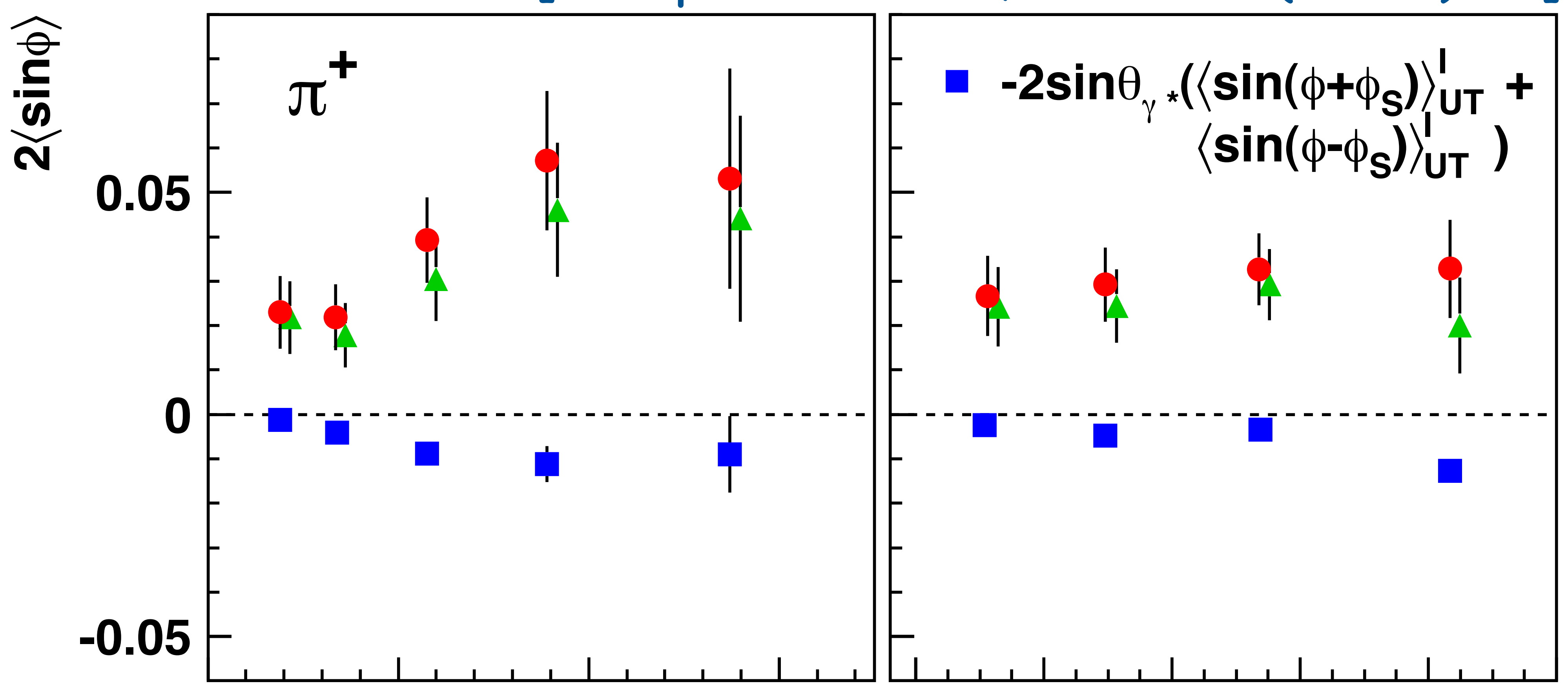


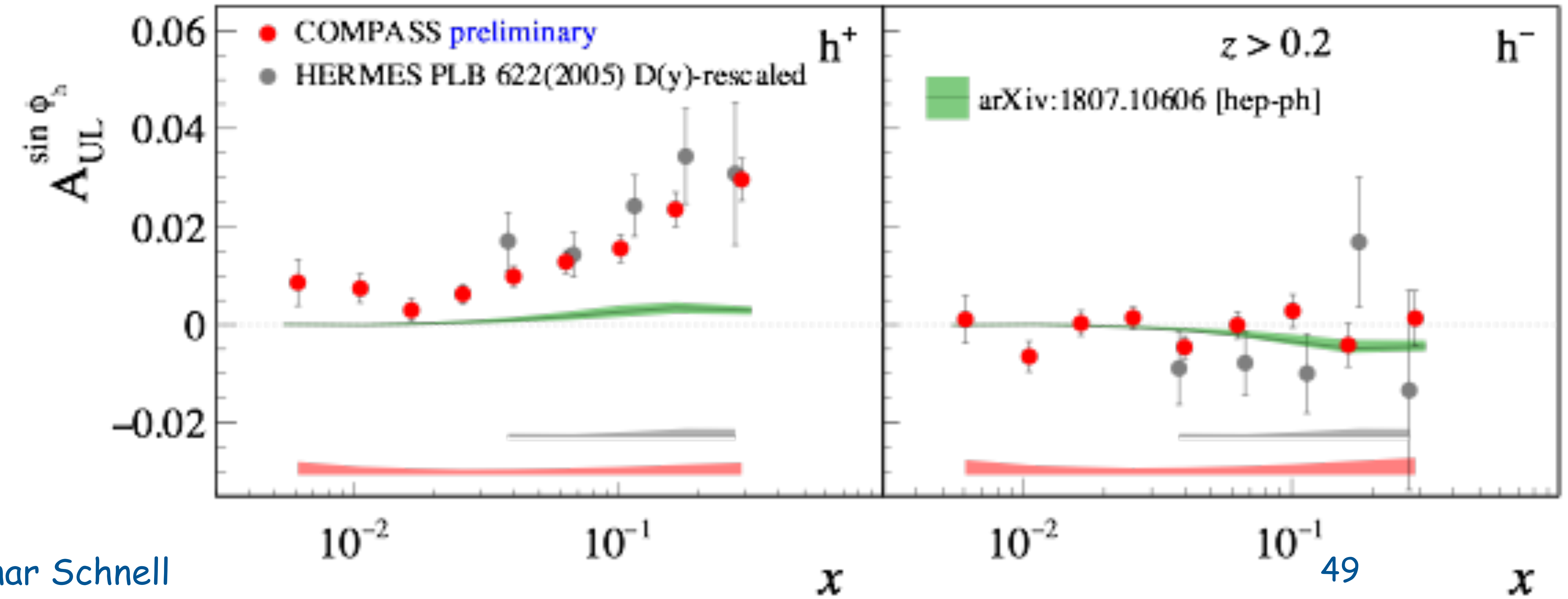
- experimental A_{UL} dominated by twist-3 contribution
- correction for A_{UT} contribution **increases** the longitudinal asymmetry for positive pions
- consistent with zero for π^-

subleading twist II - ‹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]





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

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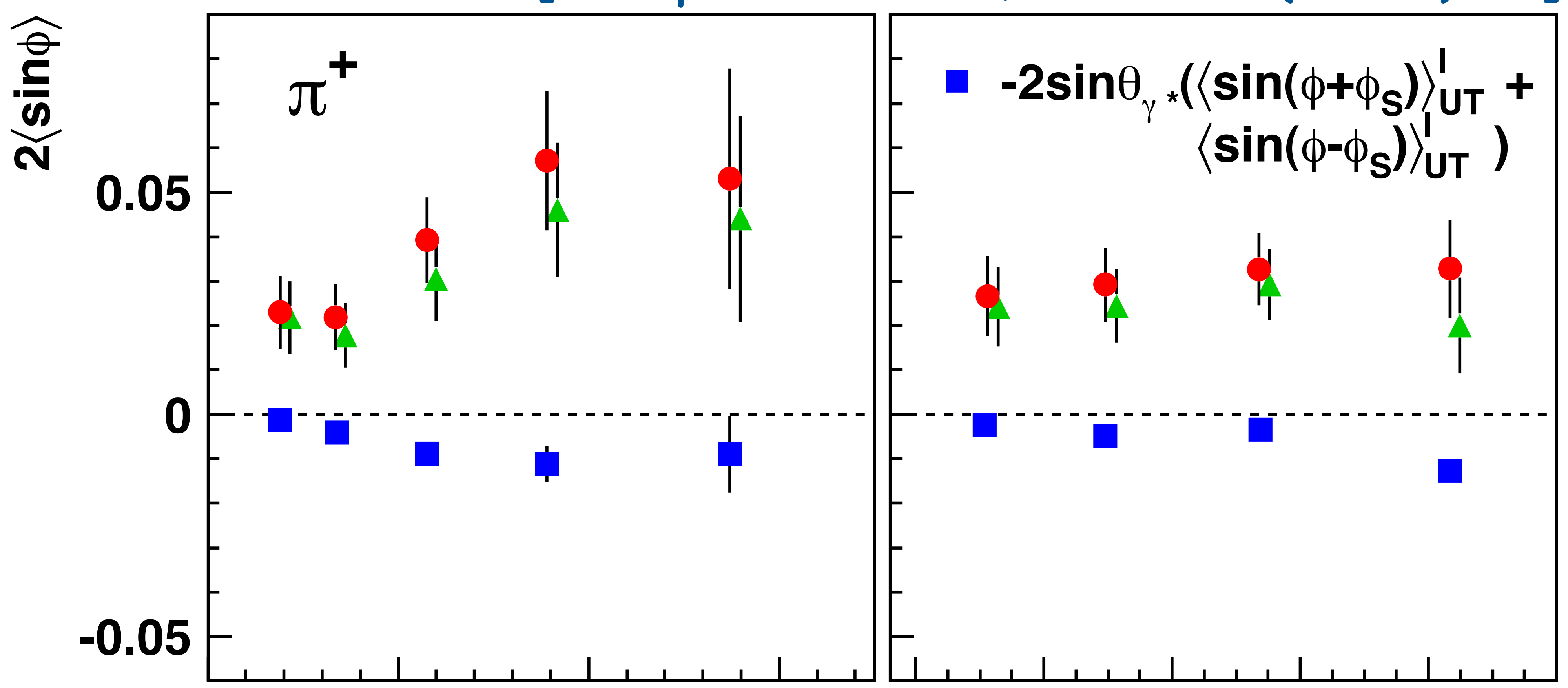
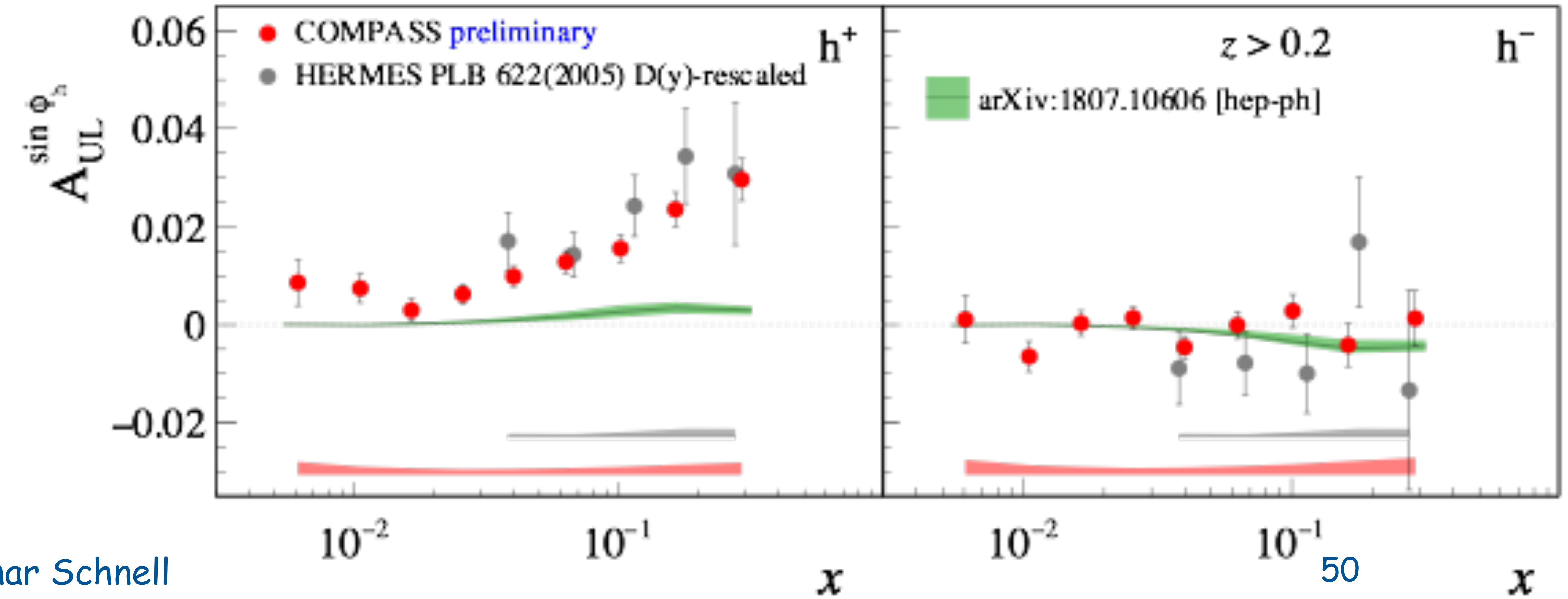
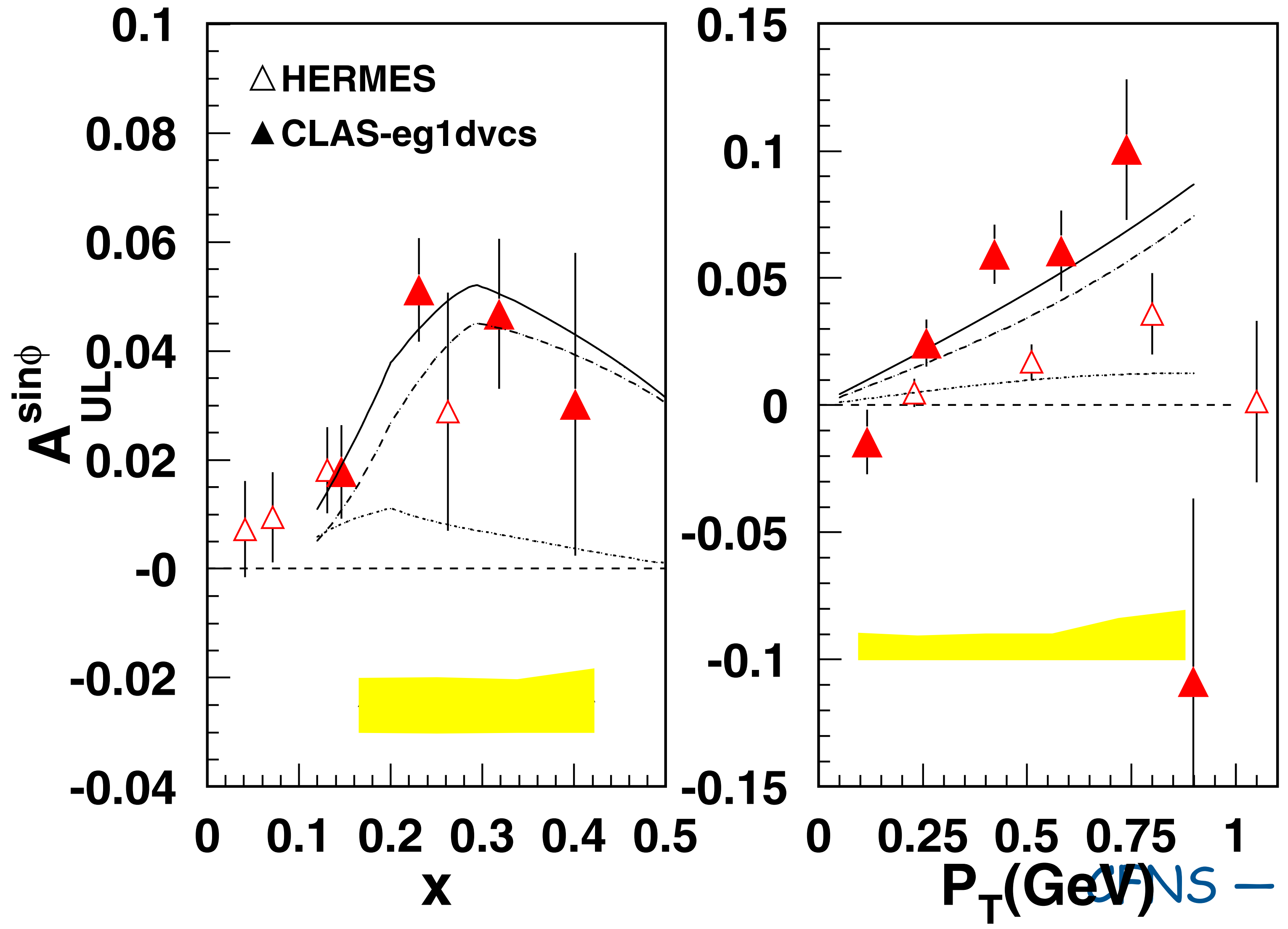
[Airapetian et al., PLB 622 (2005) 14]



- 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



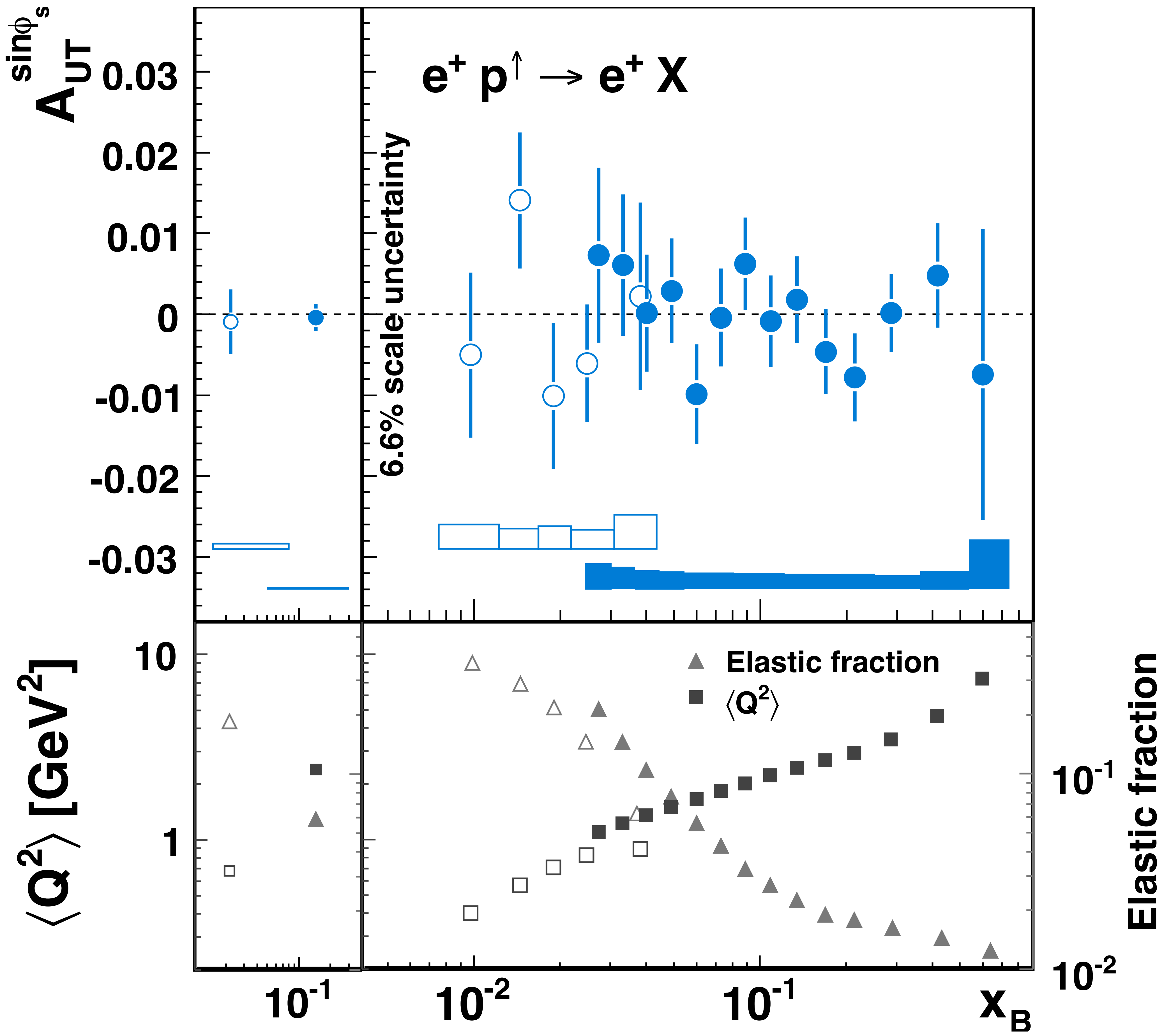
[CLAS, PLB 782 (2018) 662-667]



subleading twist 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 - <$\sin(\phi_S)$>$_{UT}$

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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.:

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

- 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)>$_{UT}$

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

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

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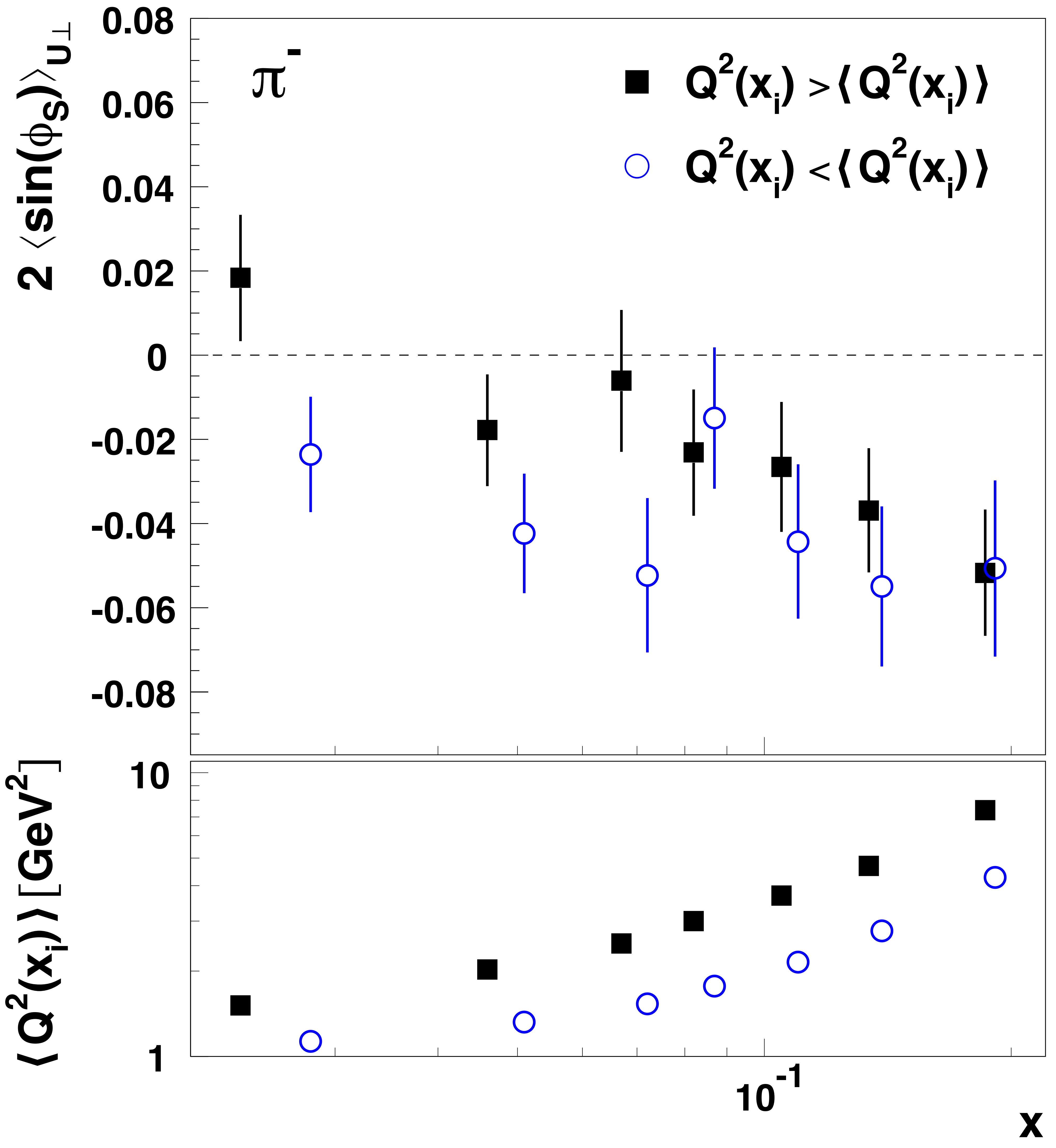
subleading twist III - $\langle \sin(\phi_S) \rangle_{UT}$



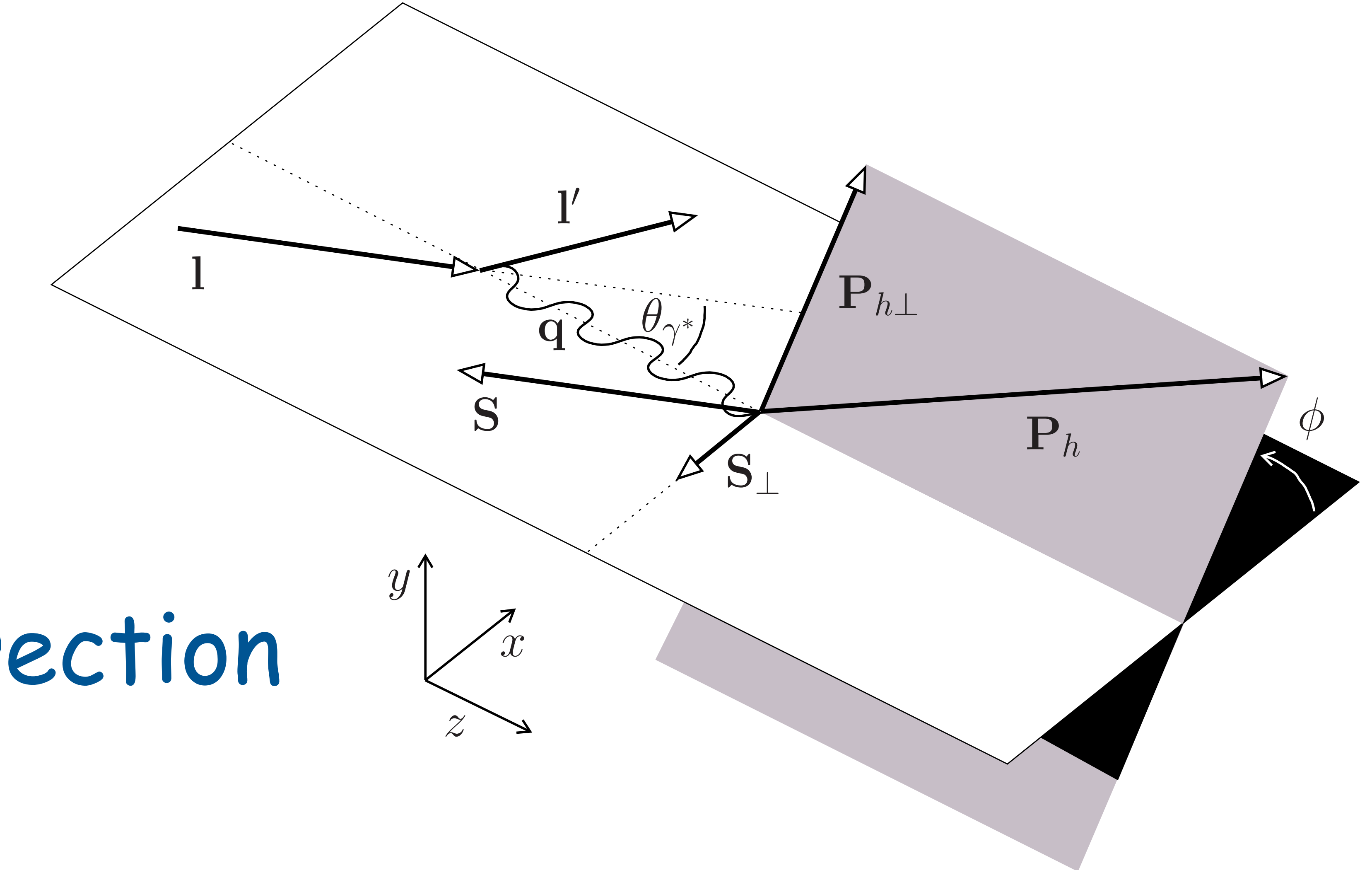
- hint of Q^2 dependence seen in signal for negative pions

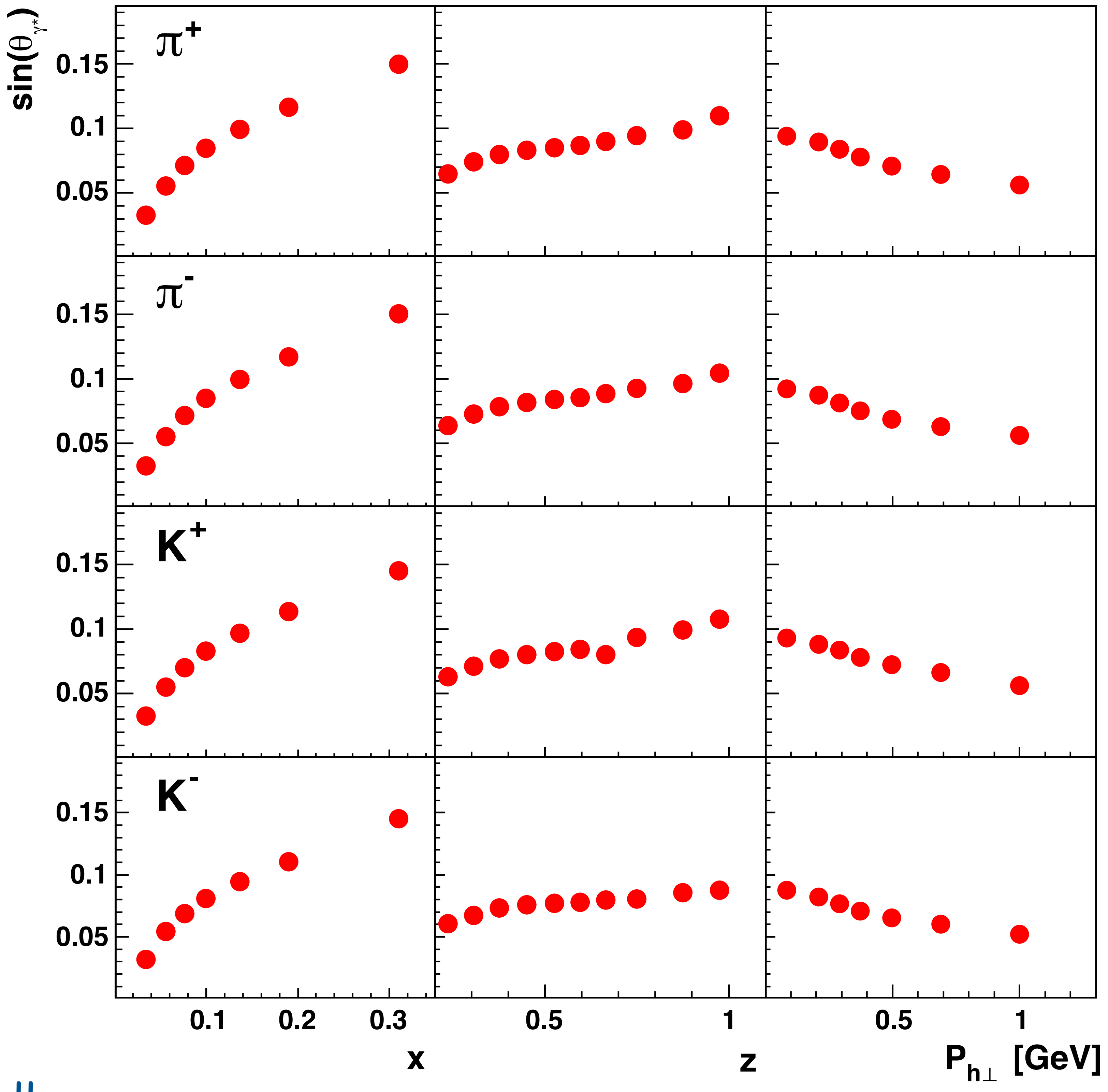
devil in the details &
lessons learnt on the way

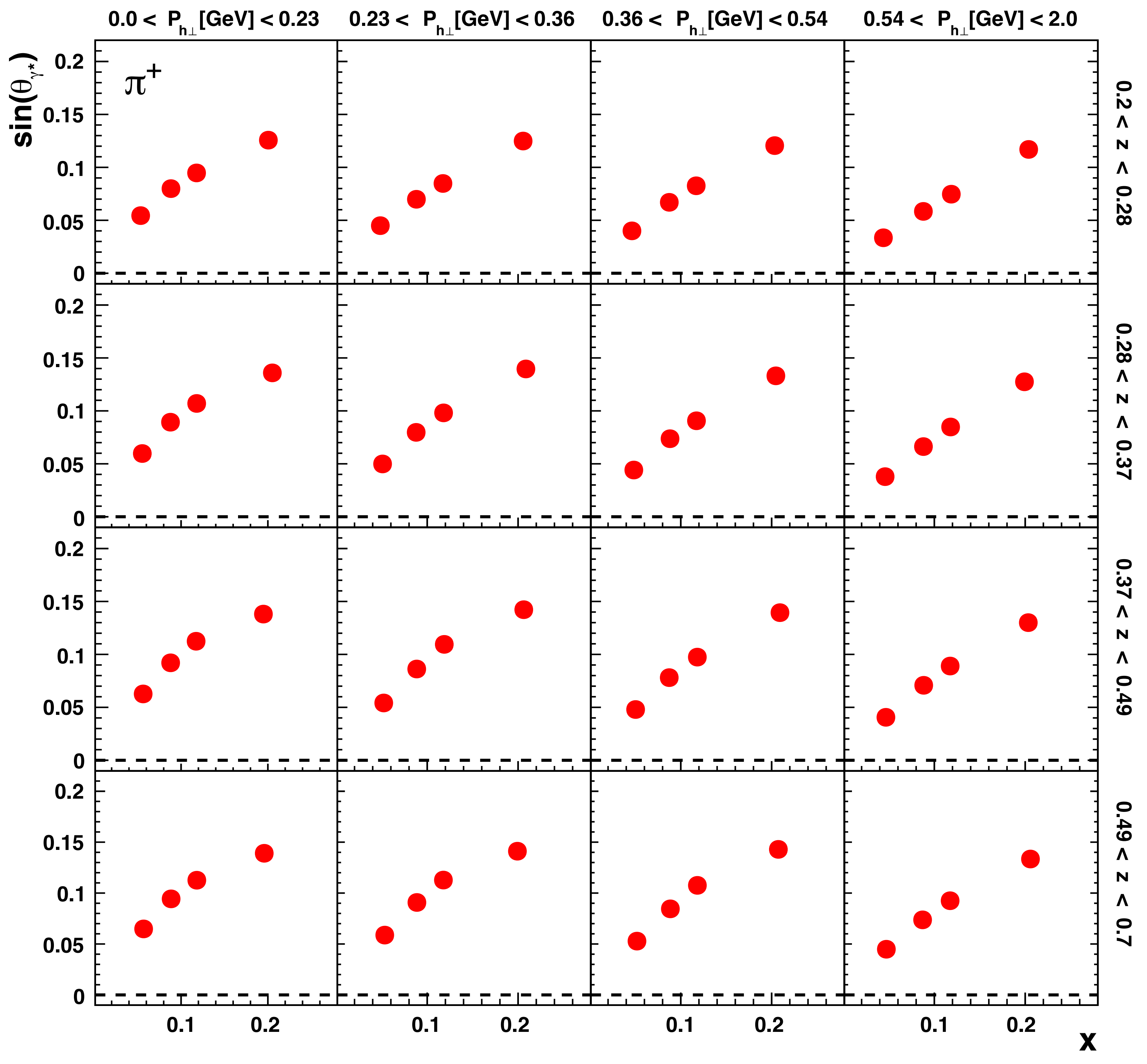
mixing of target polarizations

- 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

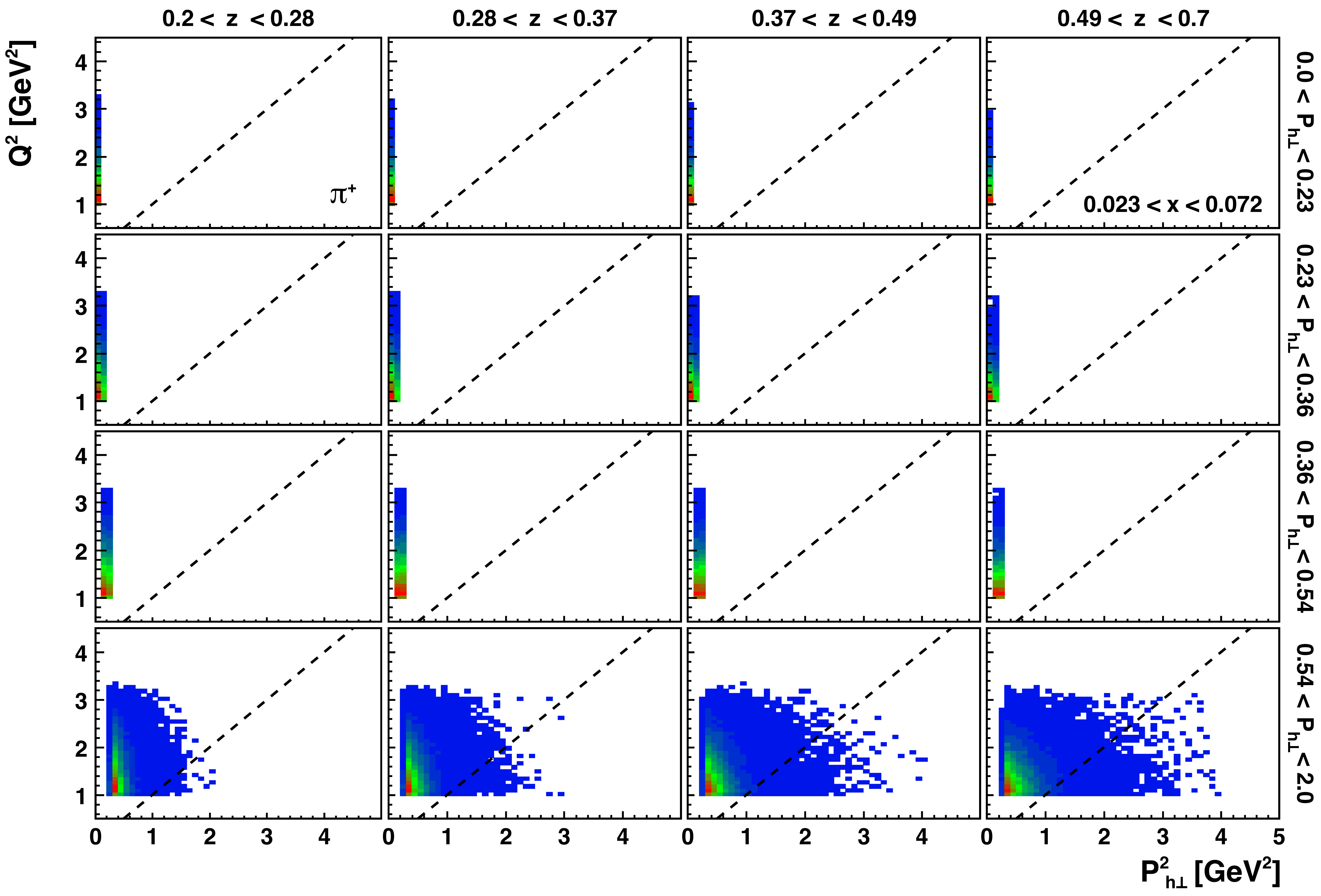






TMD factorization: a 2-scale problem

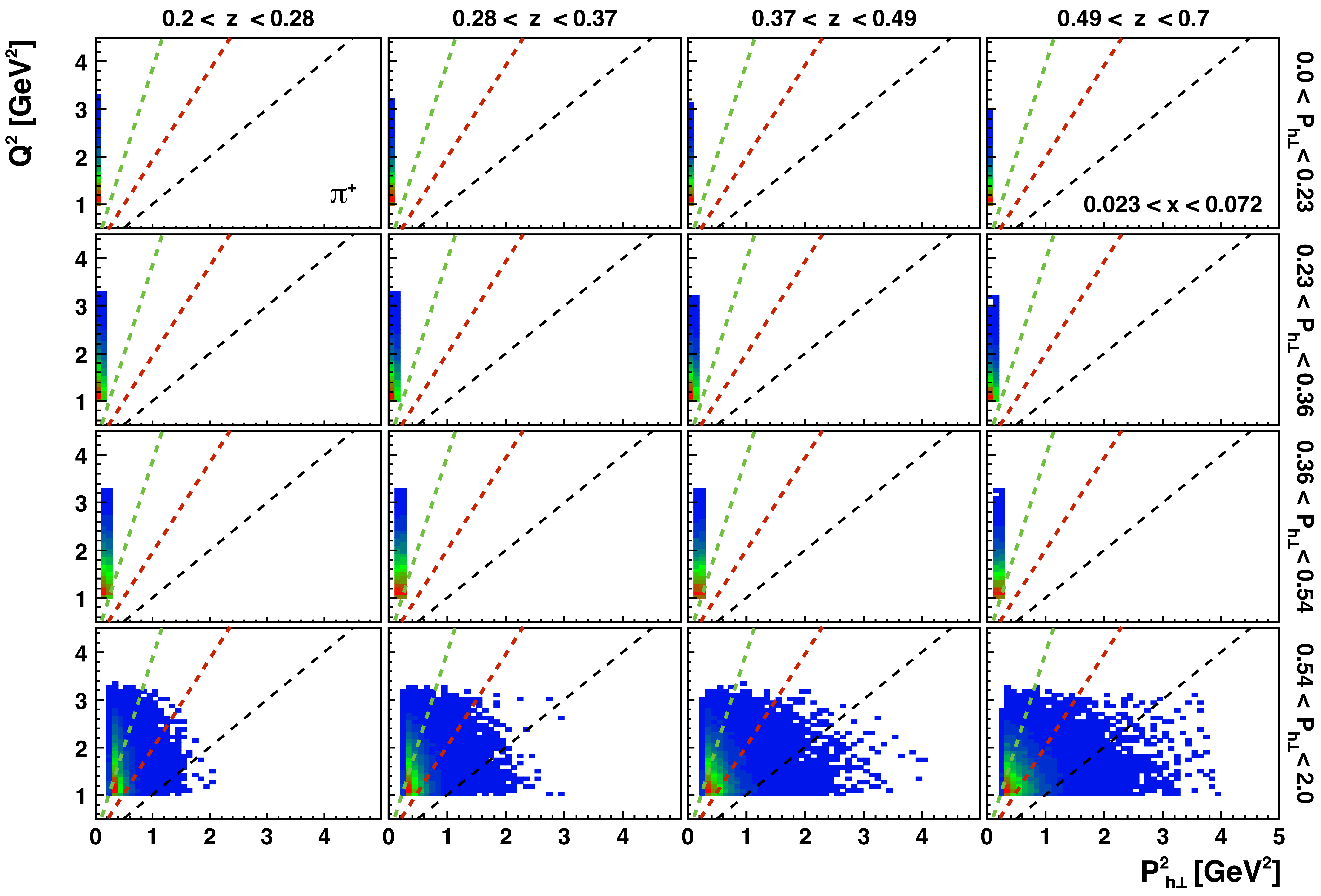
lowest x bin



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

TMD factorization: a 2-scale problem

lowest x bin



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

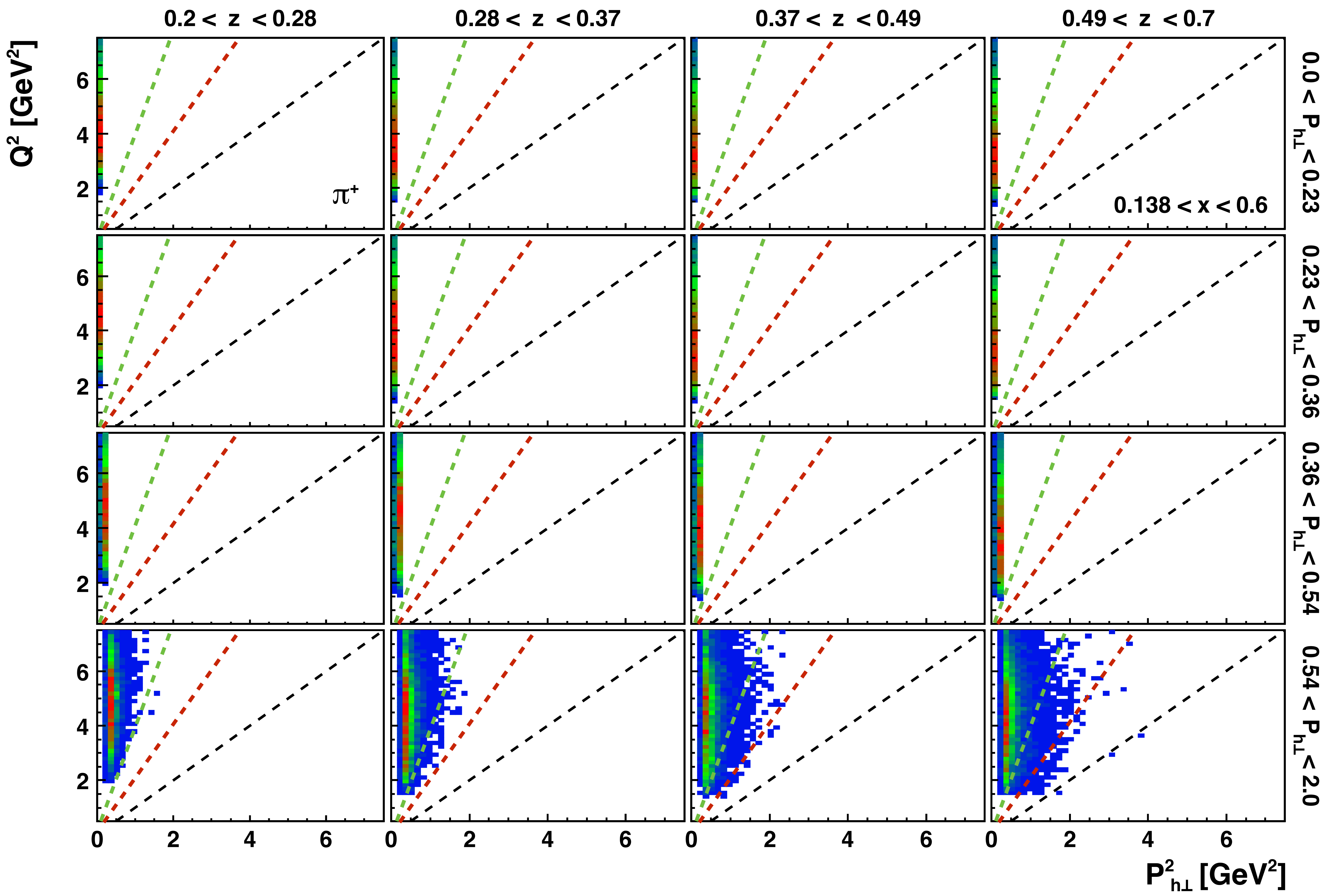
$Q^2 = 2\, P^2_{h\perp}$

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

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

highest x bin



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TMD factorization: a 2-scale problem

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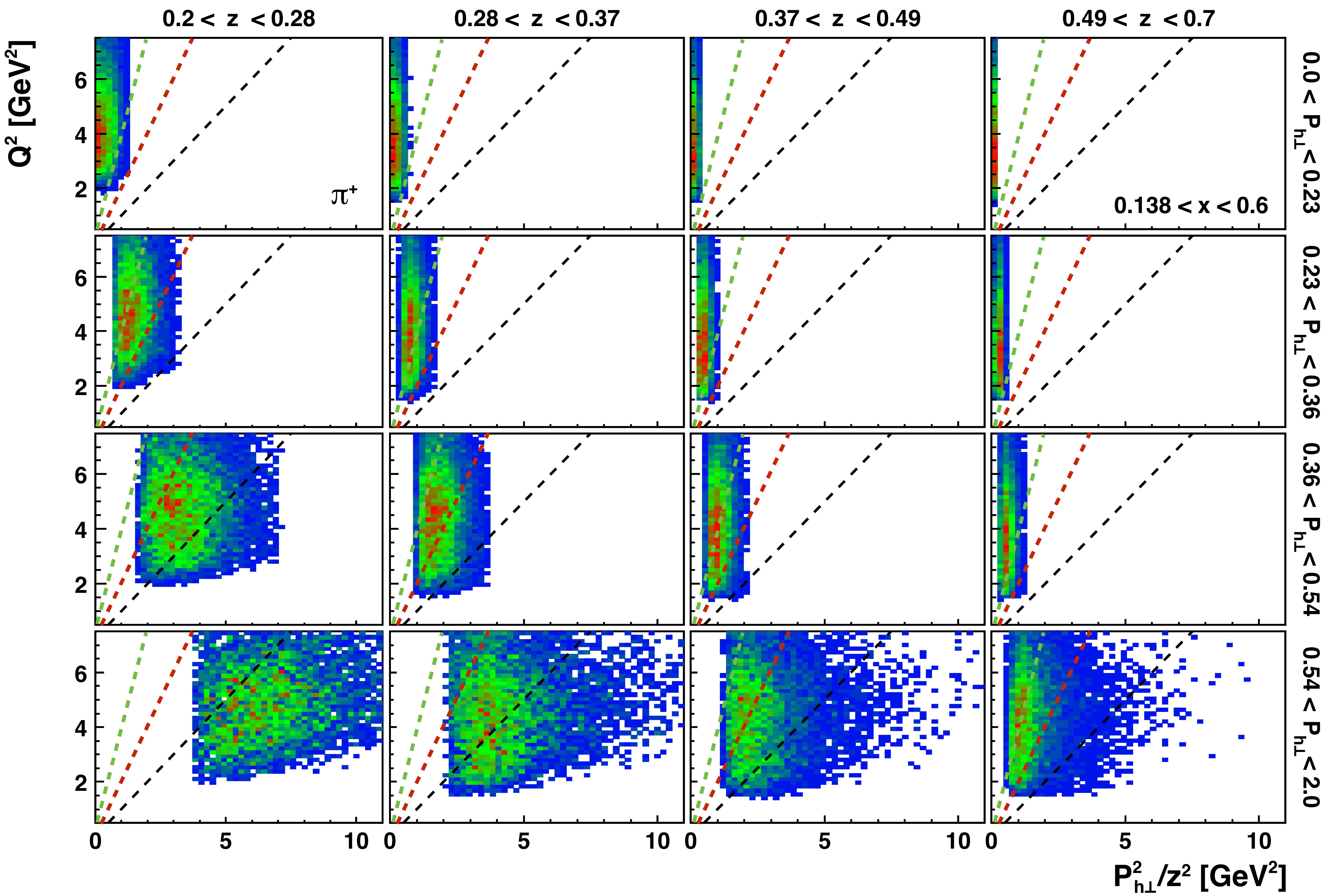


$Q^2 = P^2_{h\perp}/z^2$

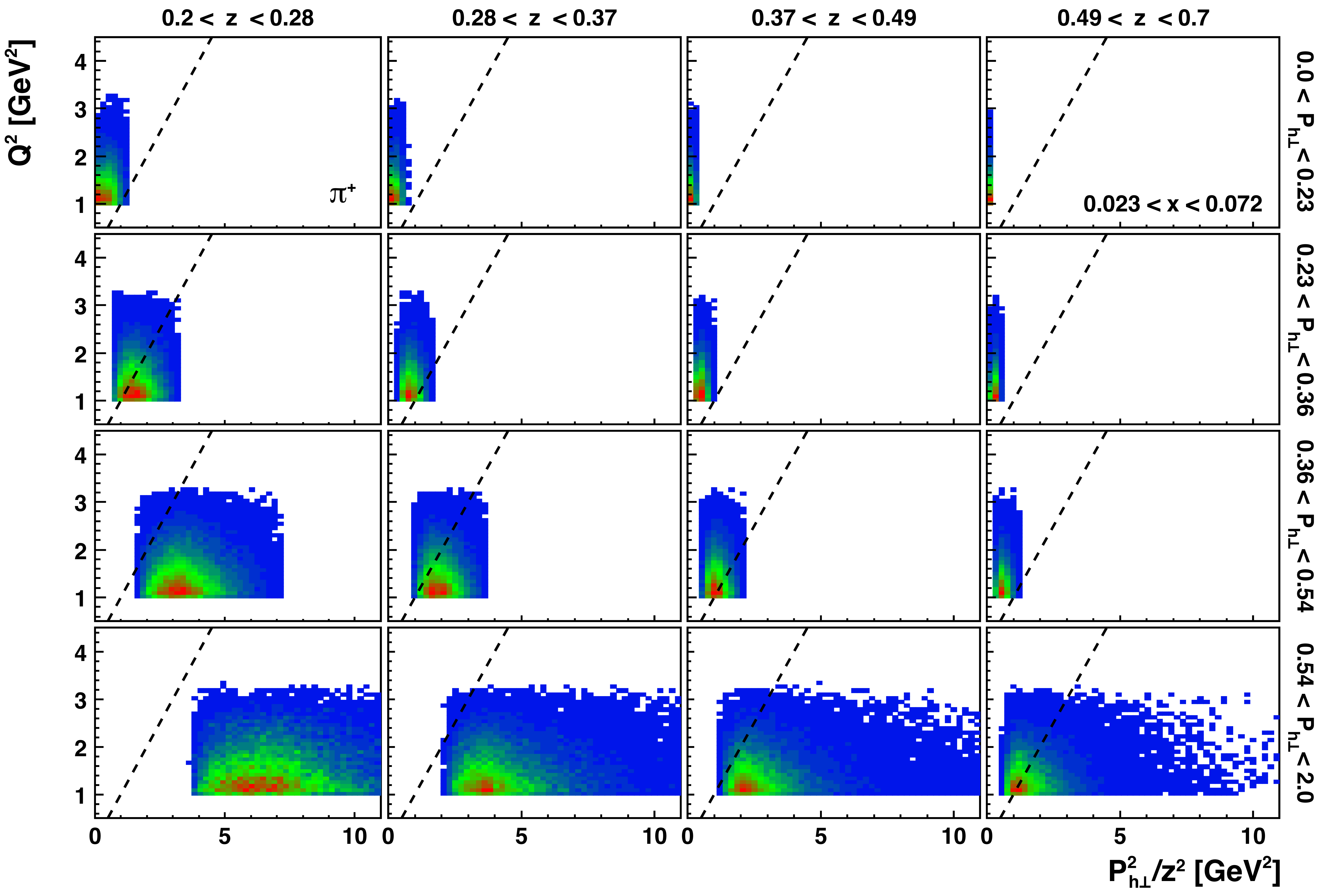
$Q^2 = 2\,P^2_{h\perp}/z^2$

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

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

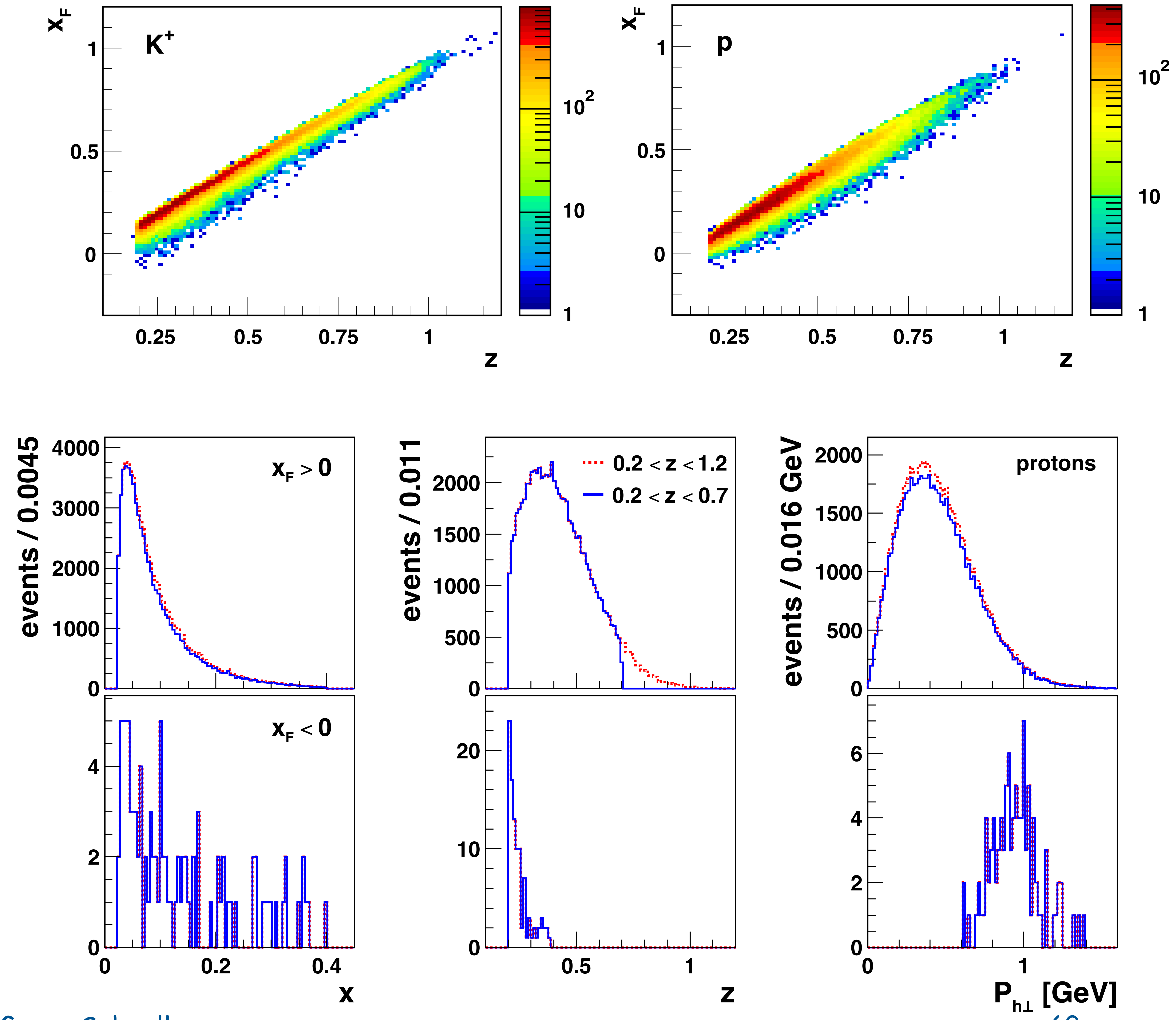
lowest x bin



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

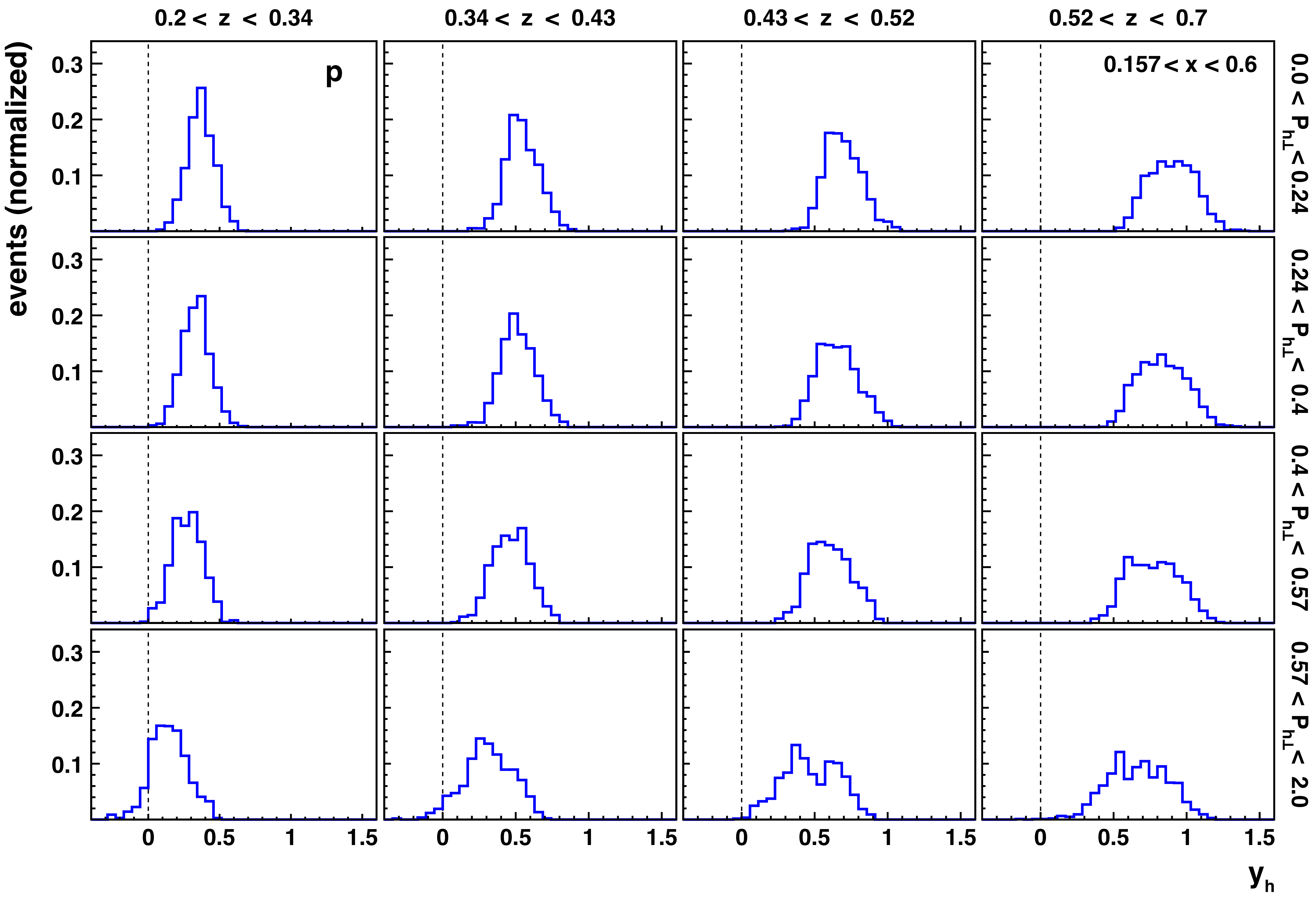
all other x-bins included in the Supplemental Material of JHEP12(2020)010

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)

“Qual der Wahl”

- SIDIS structure functions come with various kinematic prefactors
  - include in definition of asymmetries (“cross-section asym.”)

$$\text{M.L. pdf } \propto [1 + \mathcal{A}^{\sin(\phi+\phi_s)}(x, y, z, P_{h\perp}) + \ldots]$$

  - factor out from asymmetries (“structure-fct. asym.”)

$$\text{M.L. pdf } \propto [1 + D(y) A^{\sin(\phi+\phi_s)}(x, y, z, P_{h\perp}) + \ldots]$$

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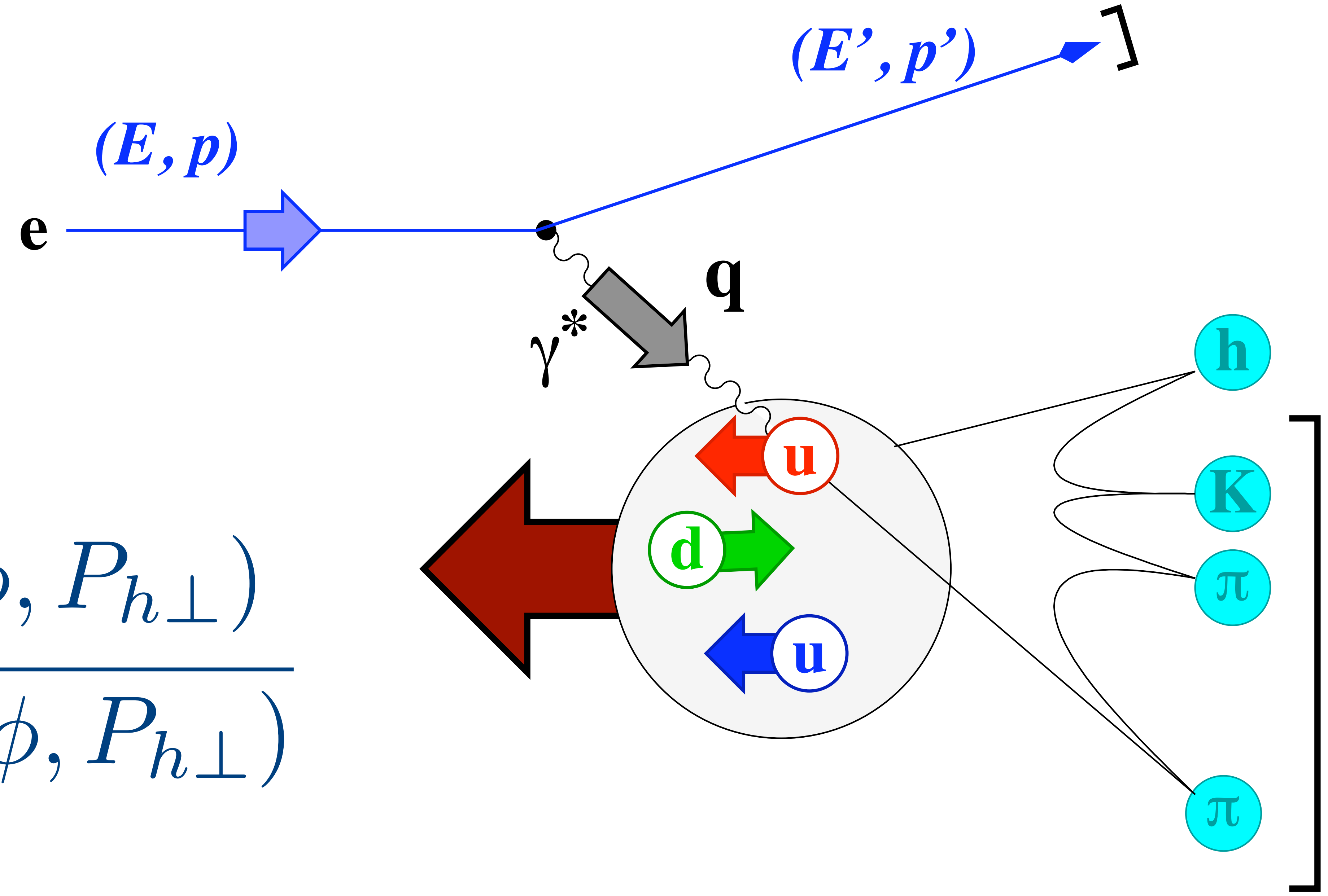
$$\text{M.L. pdf } \propto [1 + D(y) A^{\sin(\phi+\phi_s)}(x, y, z, P_{h\perp}) + \ldots]$$

- latter facilitates comparisons between experiments and simplifies kinematic dependences by removing known dependences
  - but what about twist suppression, also factor out?
  - and what about other kinematically suppressed contributions?

detector effects in SIDIS

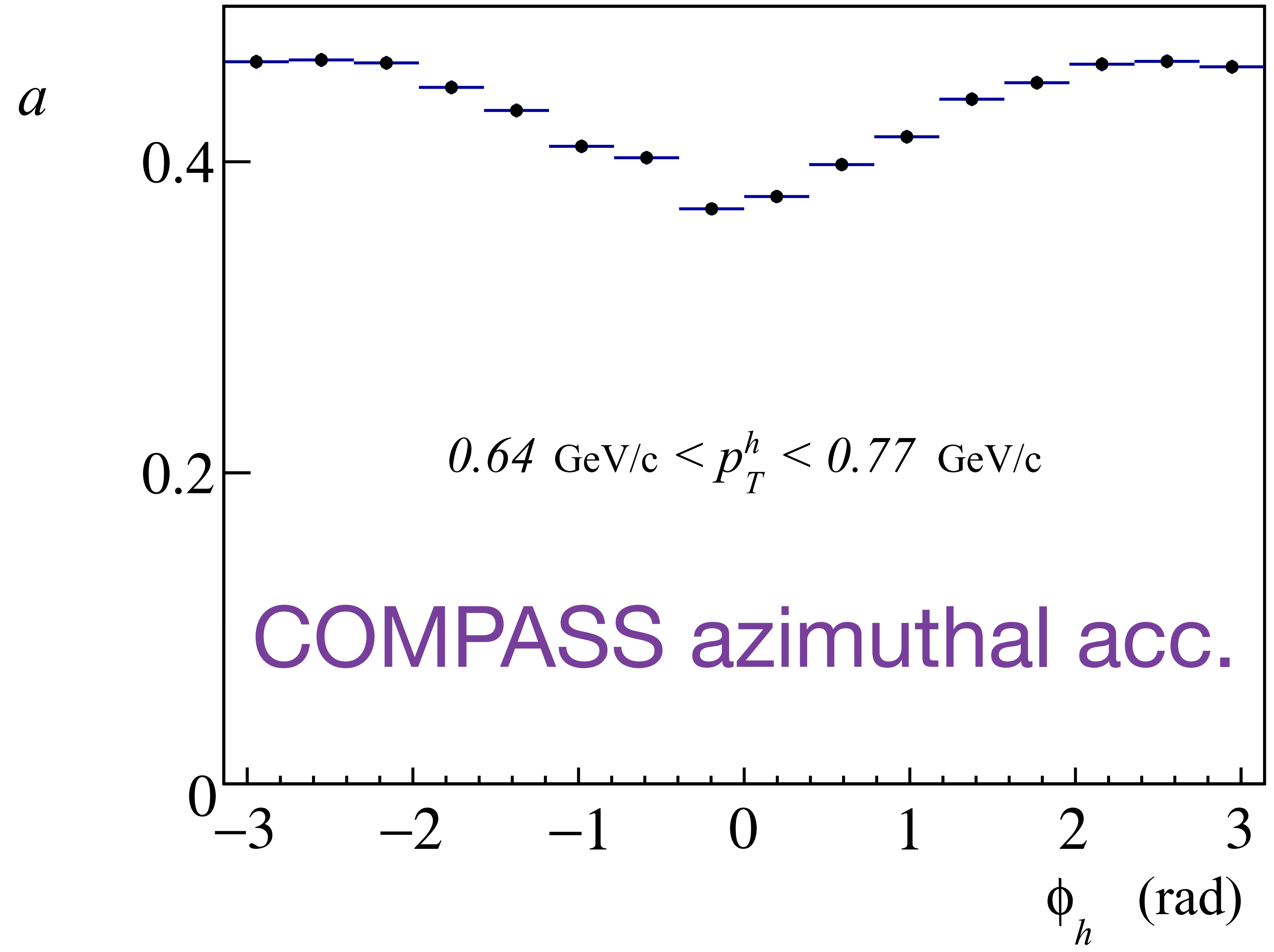
- one example of "collinear case": $A_{||}(x,z,Q^2)$
  - involves integration over typical TMD variables

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



  - both cross sections depend on TMD variables, and this correlated with kinematics
    - ➥ couples to acceptance dependence on those variables
    - ➥ can easily reduce/increase observed asymmetry [same is true for hadron multiplicities]

[Nucl. Phys. B 886 (2014) 1046–1077]



- ideally, fully differential analysis
  - ➥ in practice, resort to more approximate methods with reliable systematics

double-spin asymmetry $A_{||}$

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

double-spin asymmetry $A_{||}$

azimuthal
correction

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

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

double-spin asymmetry $A_{||}$

azimuthal correction

luminosities

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

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polarization-weighted luminosities

double-spin asymmetry $A_{||}$

azimuthal correction

luminosities

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

polarization-weighted luminosities

unfolded for QED radiation to Born level

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 $A_{||}$

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

- 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

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

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

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:

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

hadron-charge difference asymmetries

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- assuming also isospin symmetry in fragmentation:

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

hadron-charge difference asymmetries

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

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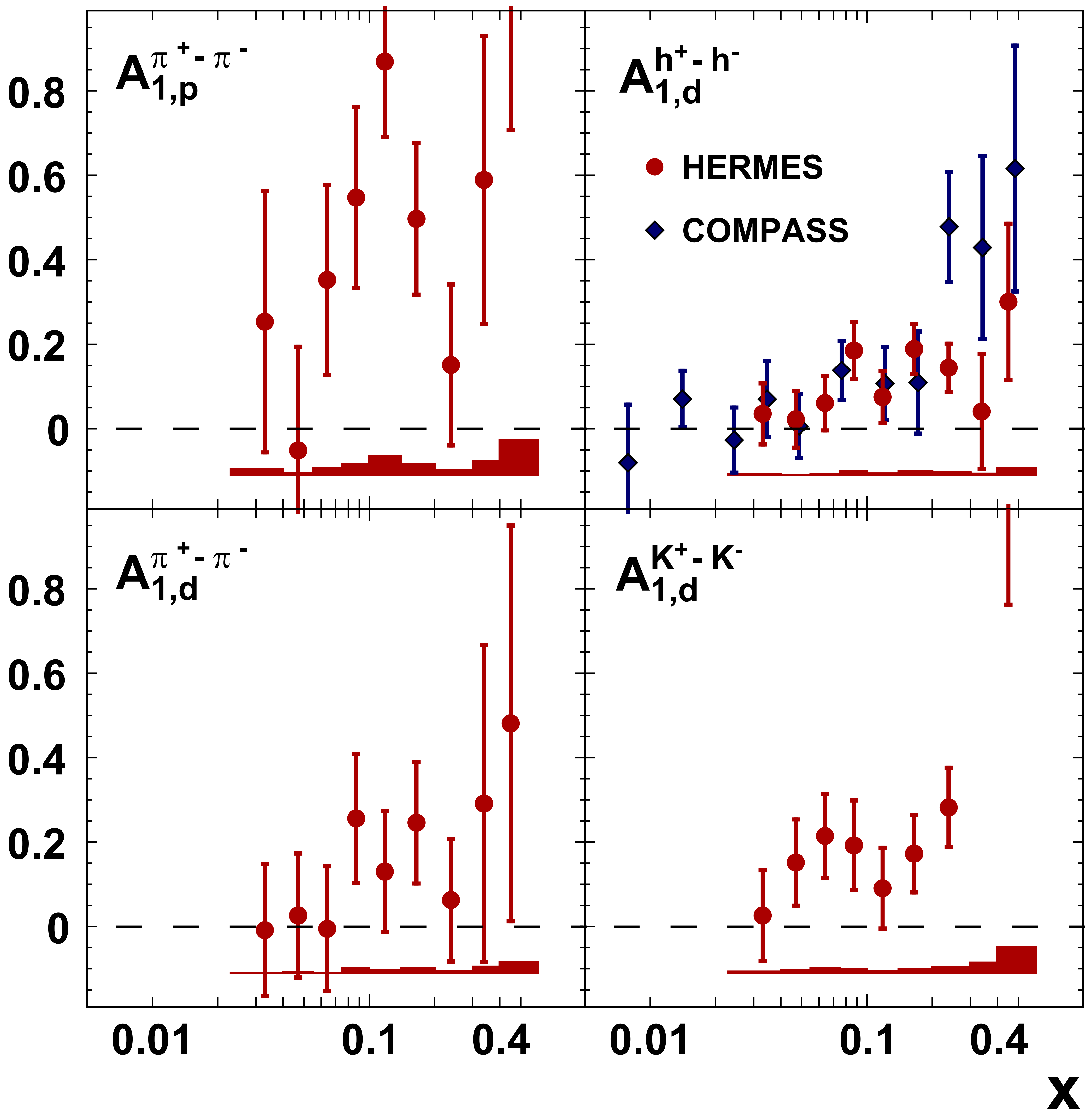
$$A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

- can be used to extract valence helicity distributions

hadron-charge difference asymmetries

[HERMES, PRD 99 (2019) 112001]

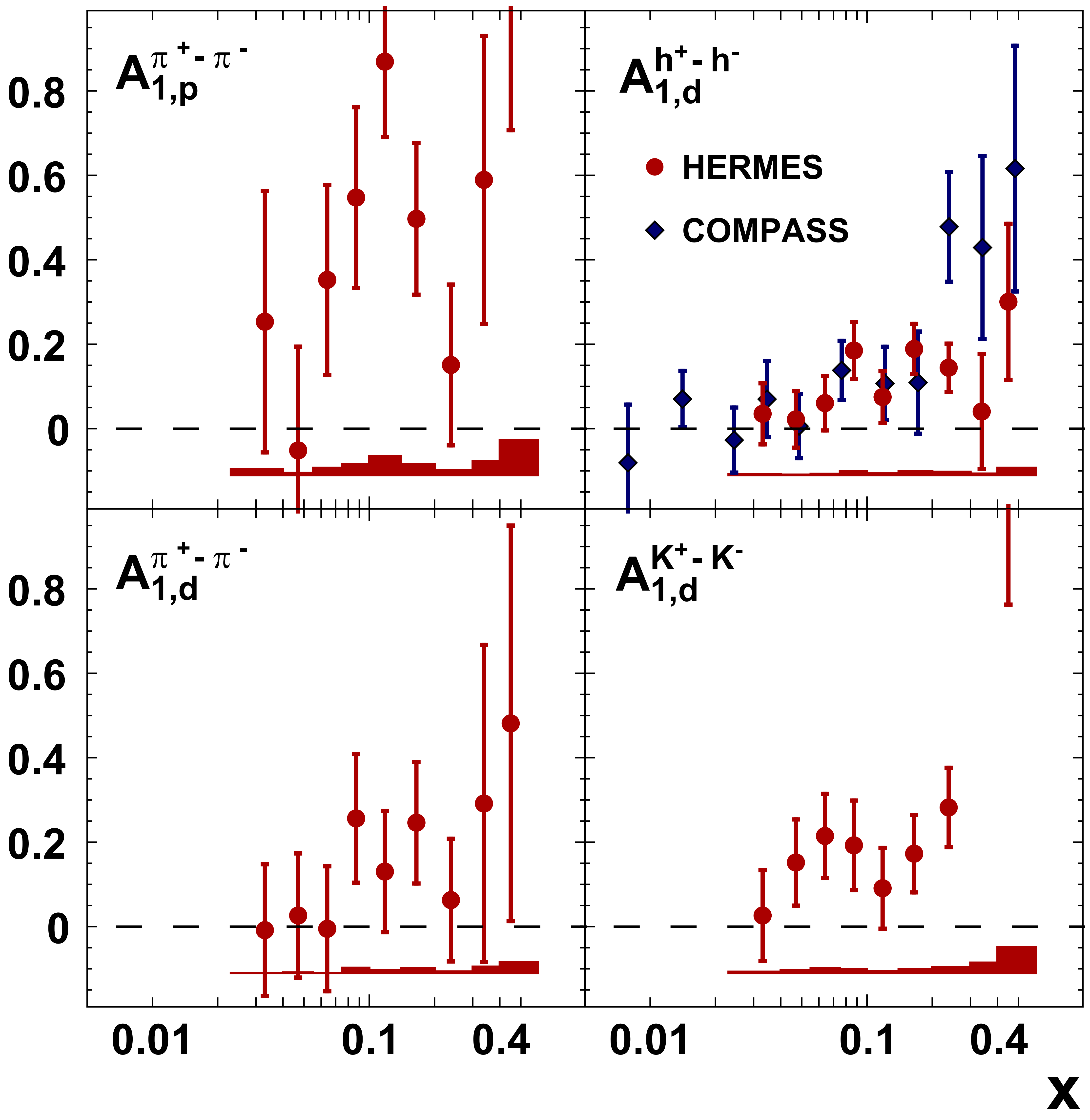


- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS

[HERMES, PRD 99 (2019) 112001]

hadron-charge difference asymmetries

[HERMES, PRD 99 (2019) 112001]



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

[HERMES, PRD 99 (2019) 112001]