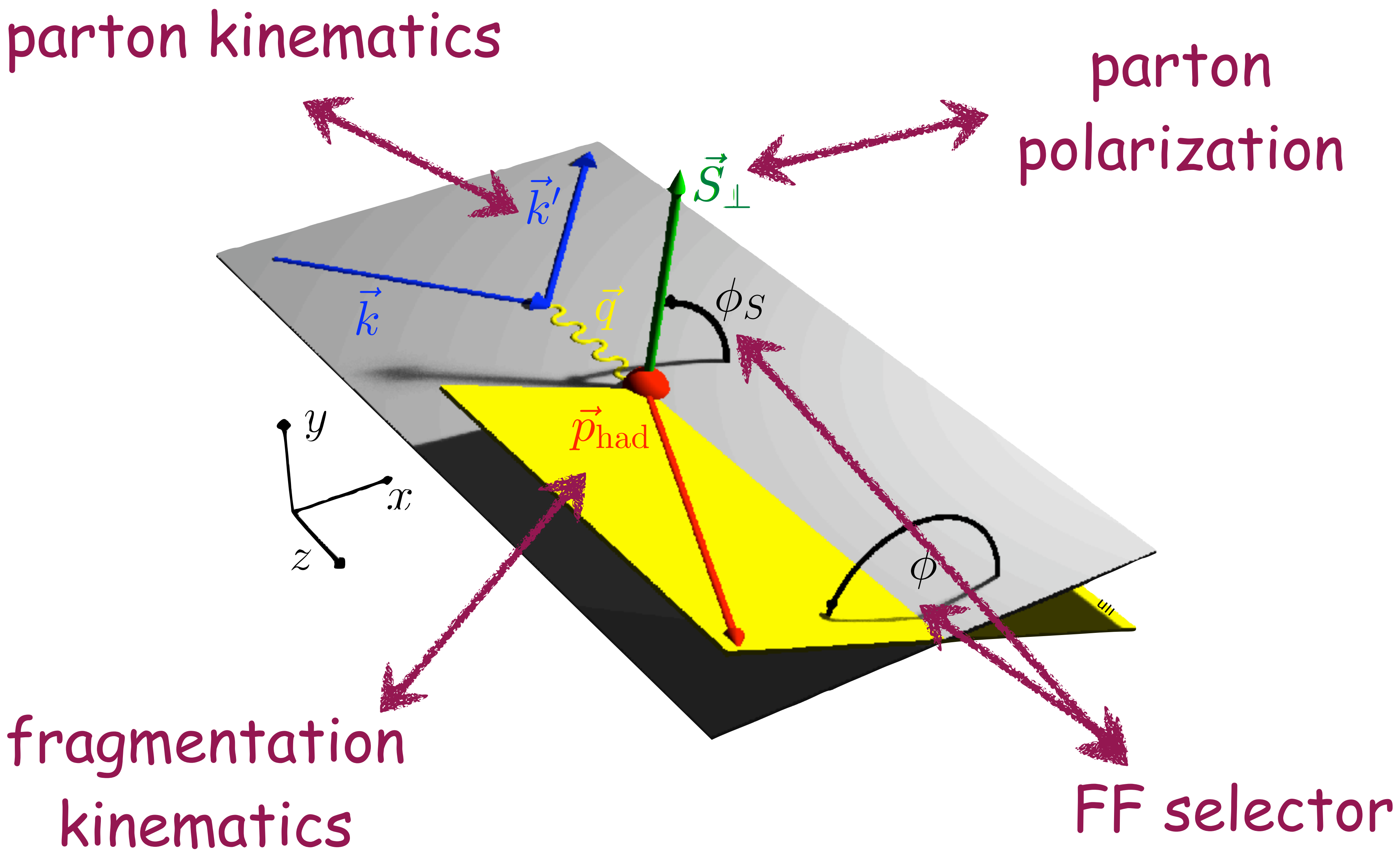
TMD Studies: from JLab to EIC

JLab (virtual) May 6-7, 2021



Pursuing TMD physics at HERMES kinematics

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ikerbasque Basque Foundation for Science

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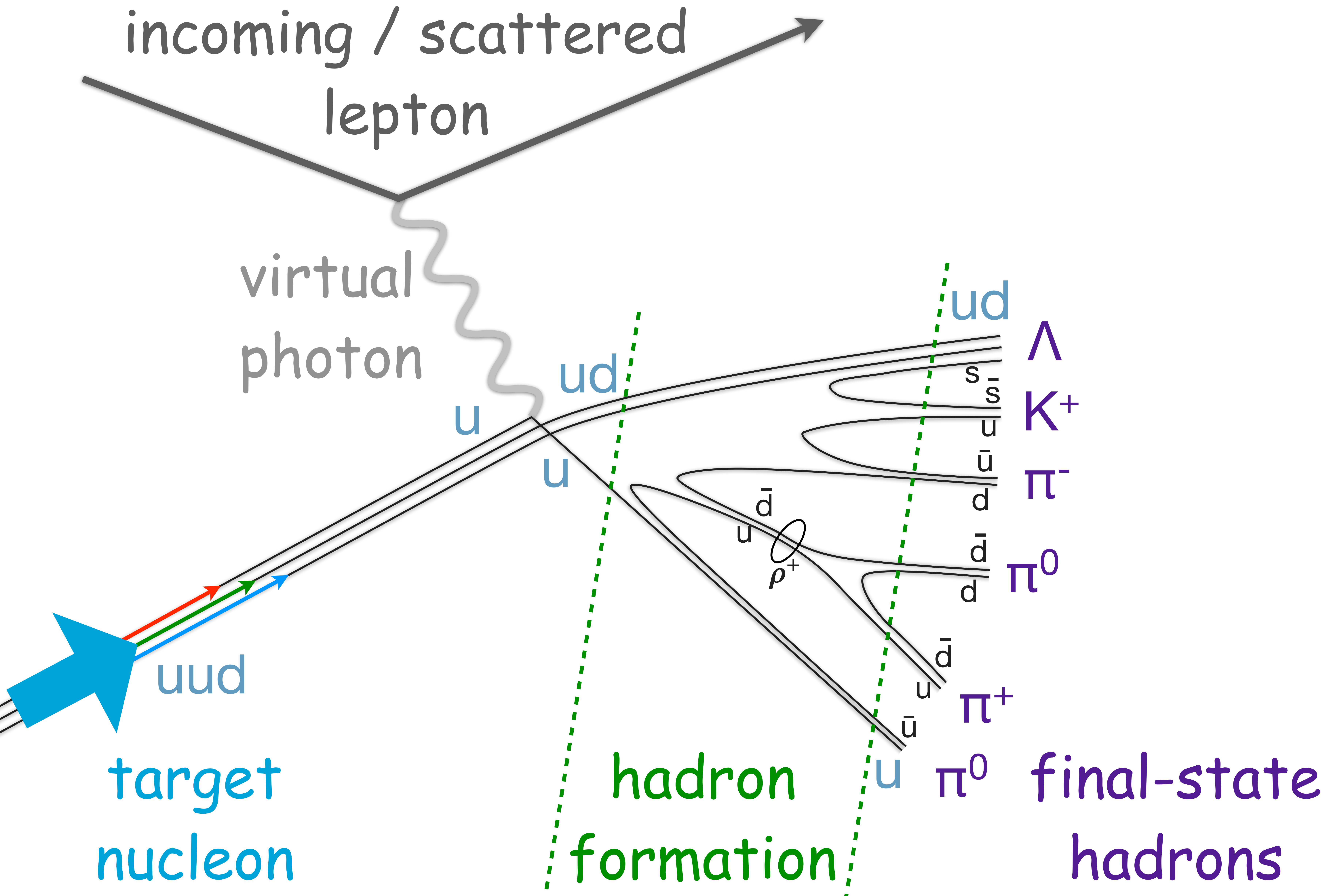
Universidad del País Vasco Euskal Herriko Unibertsitatea

SIDIS: probing TMD PDFs through fragmentation



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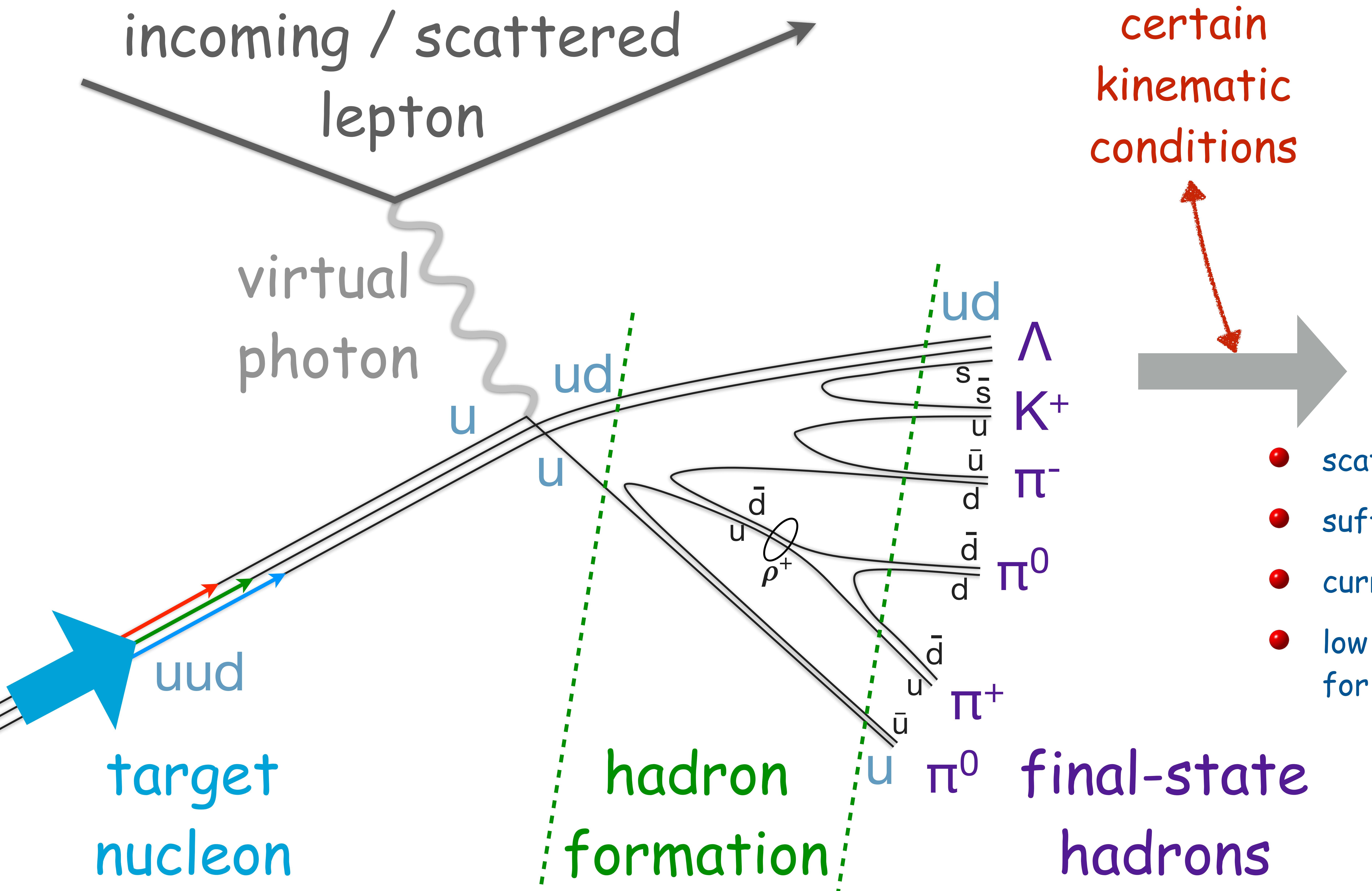
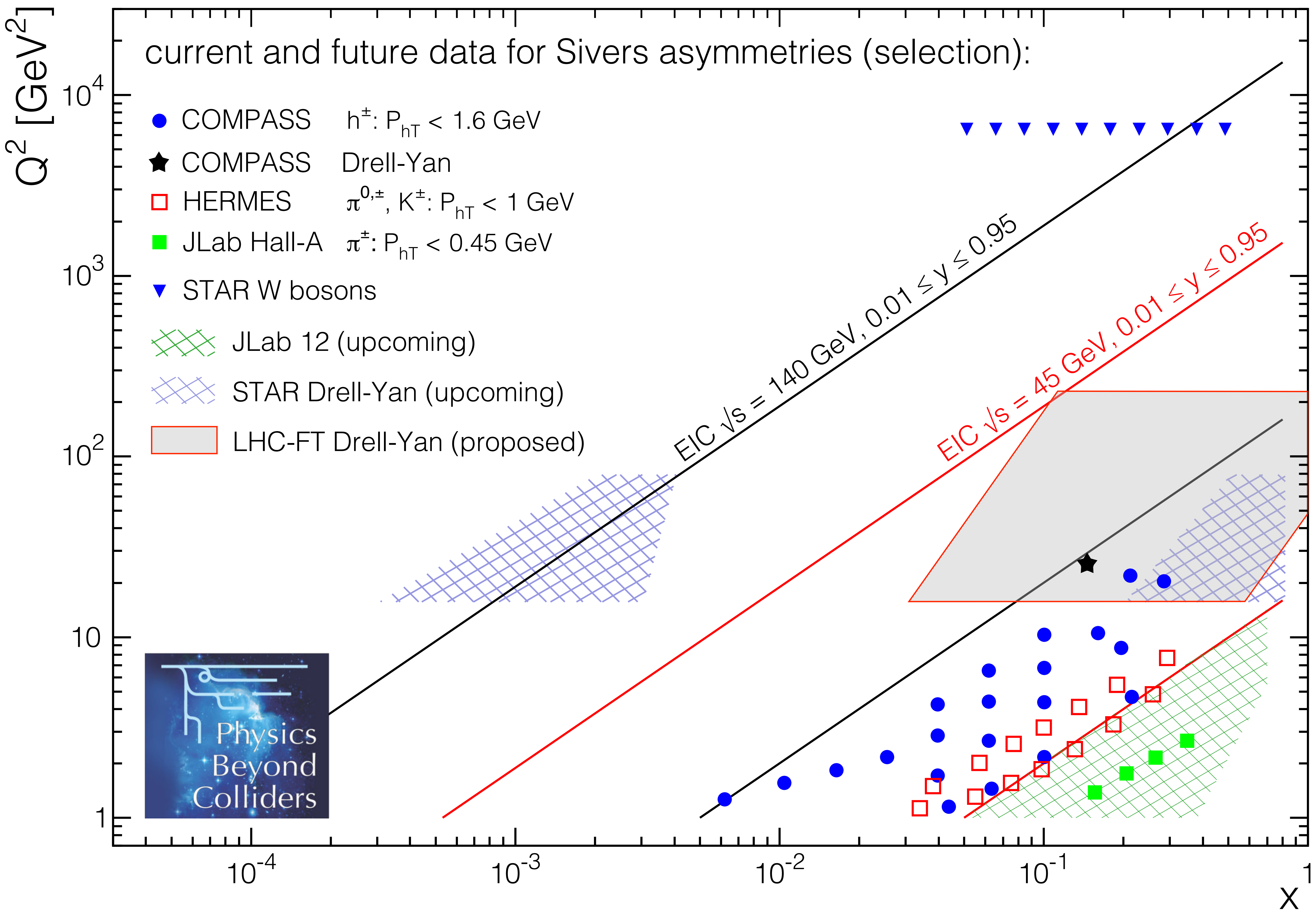


TMD PDF ⊗ TMD FF

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

2d kinematic phase space



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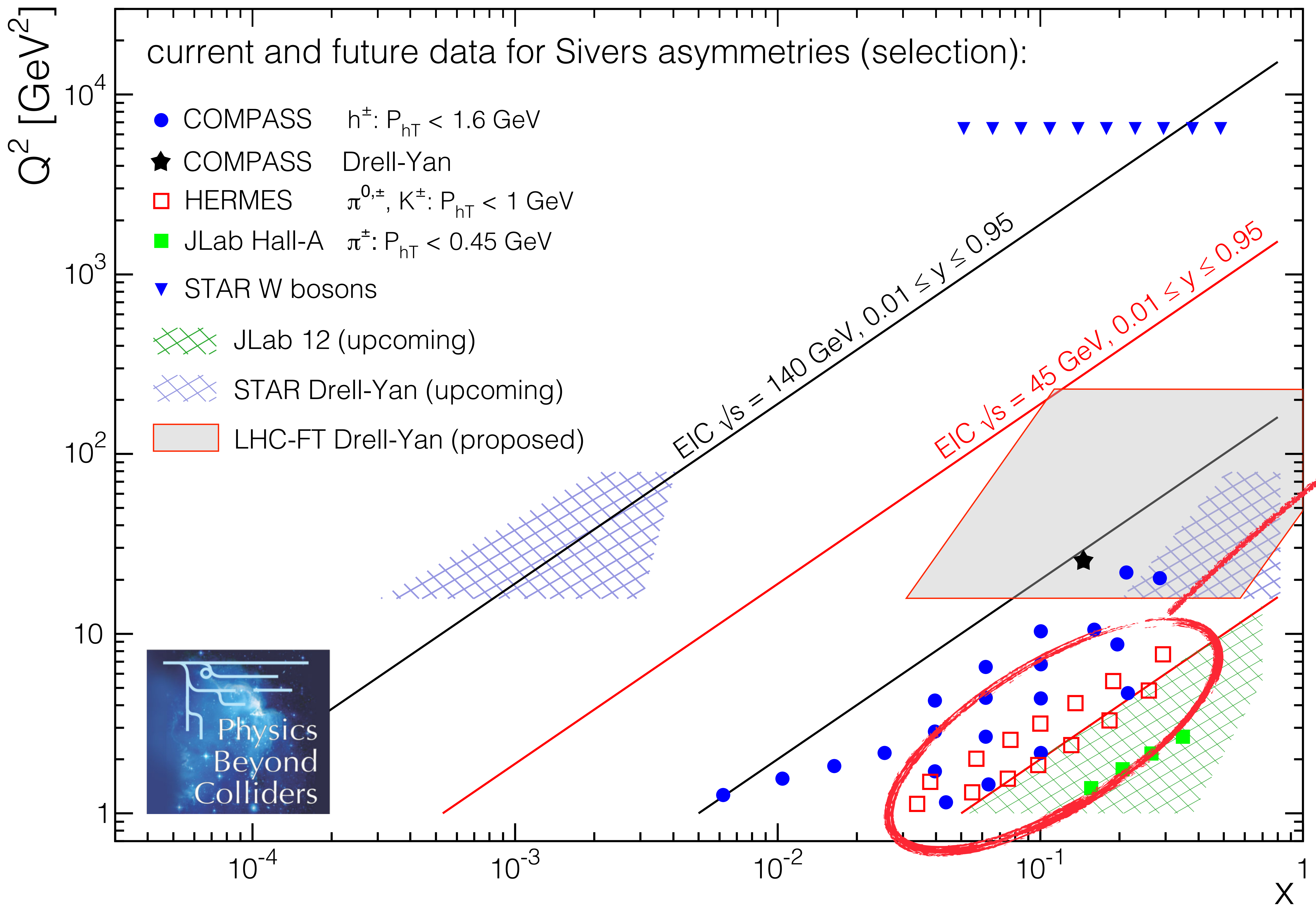
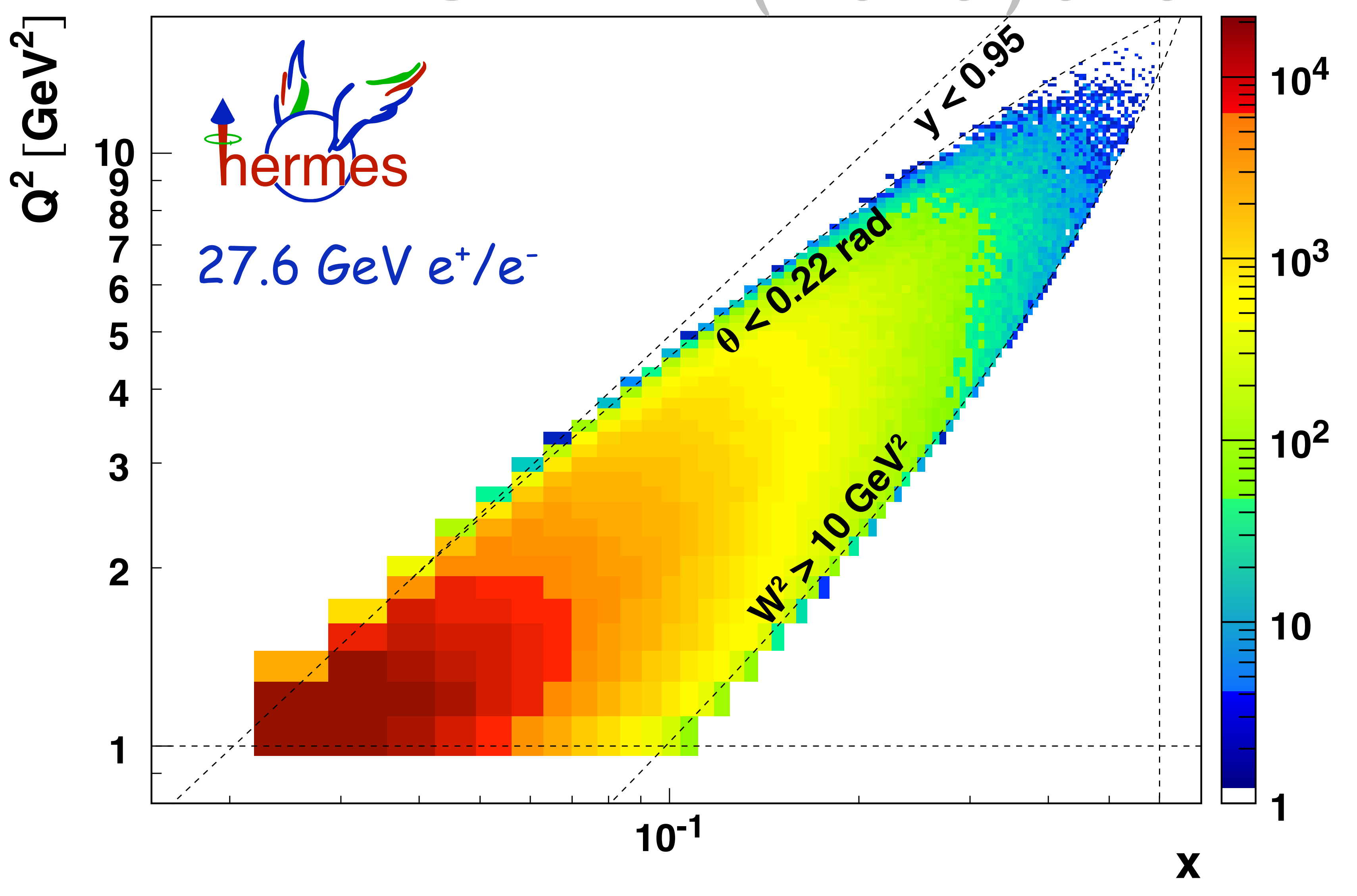


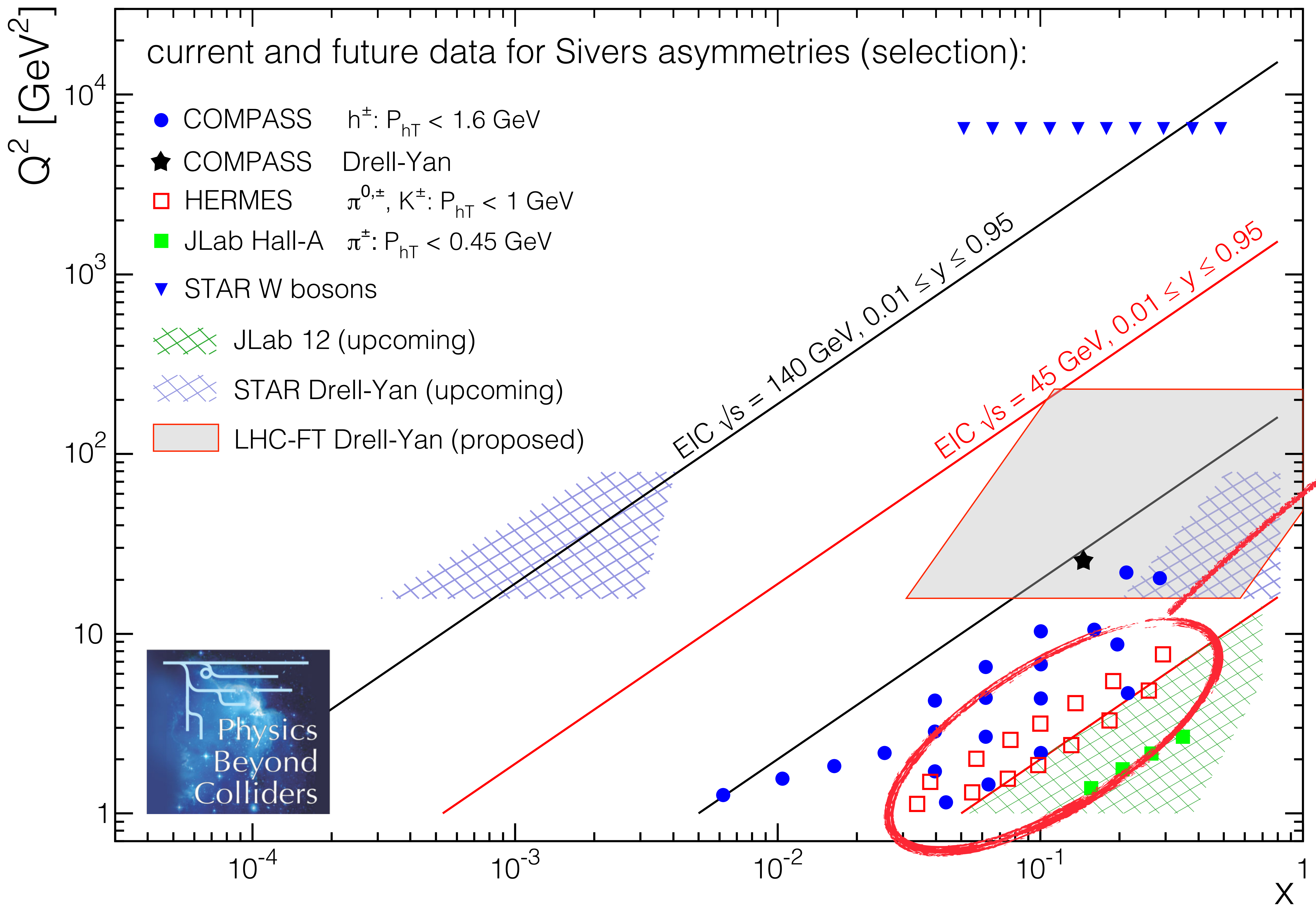
JHEP12(2020)010



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

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

2d kinematic phase space



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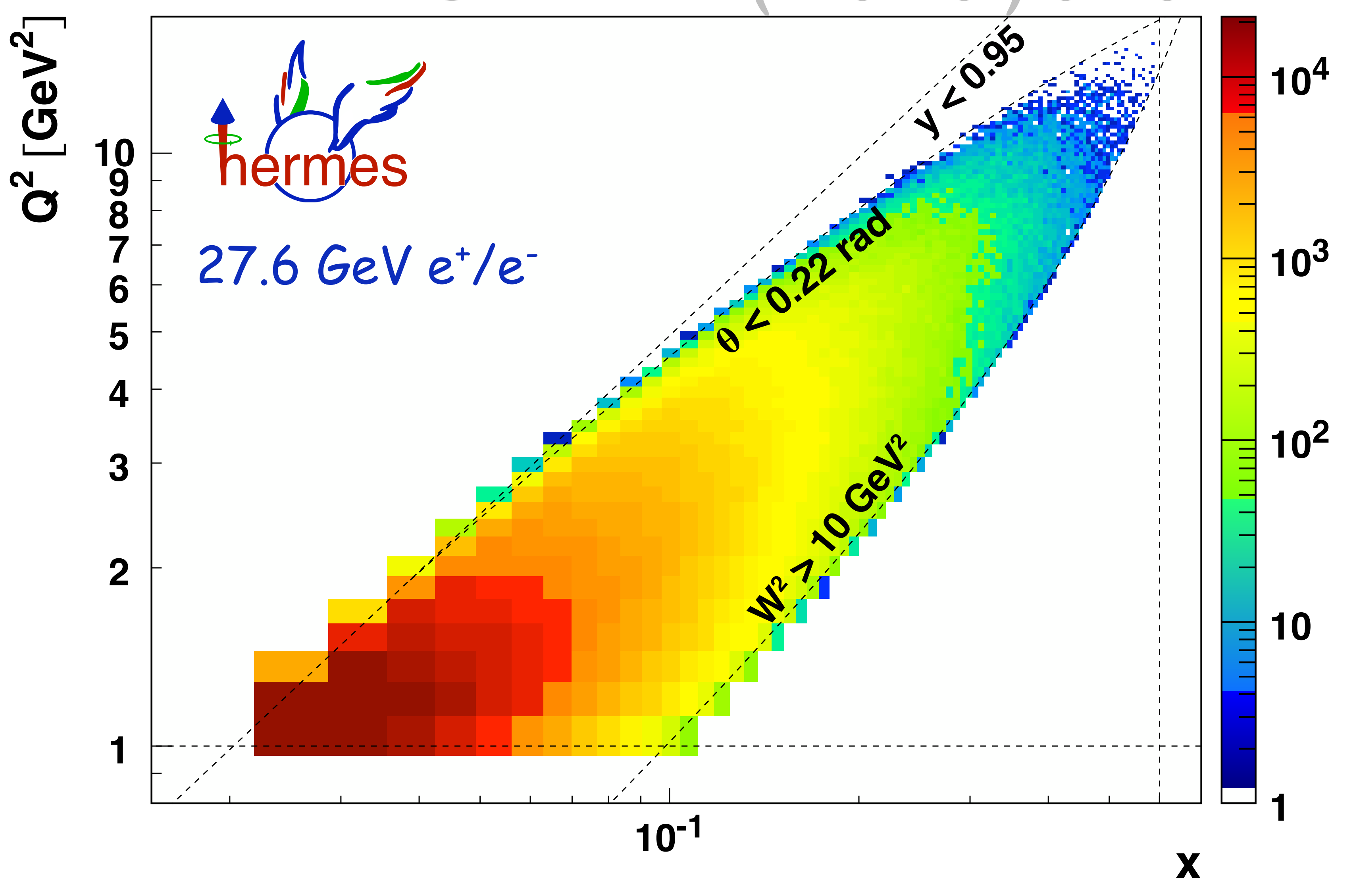
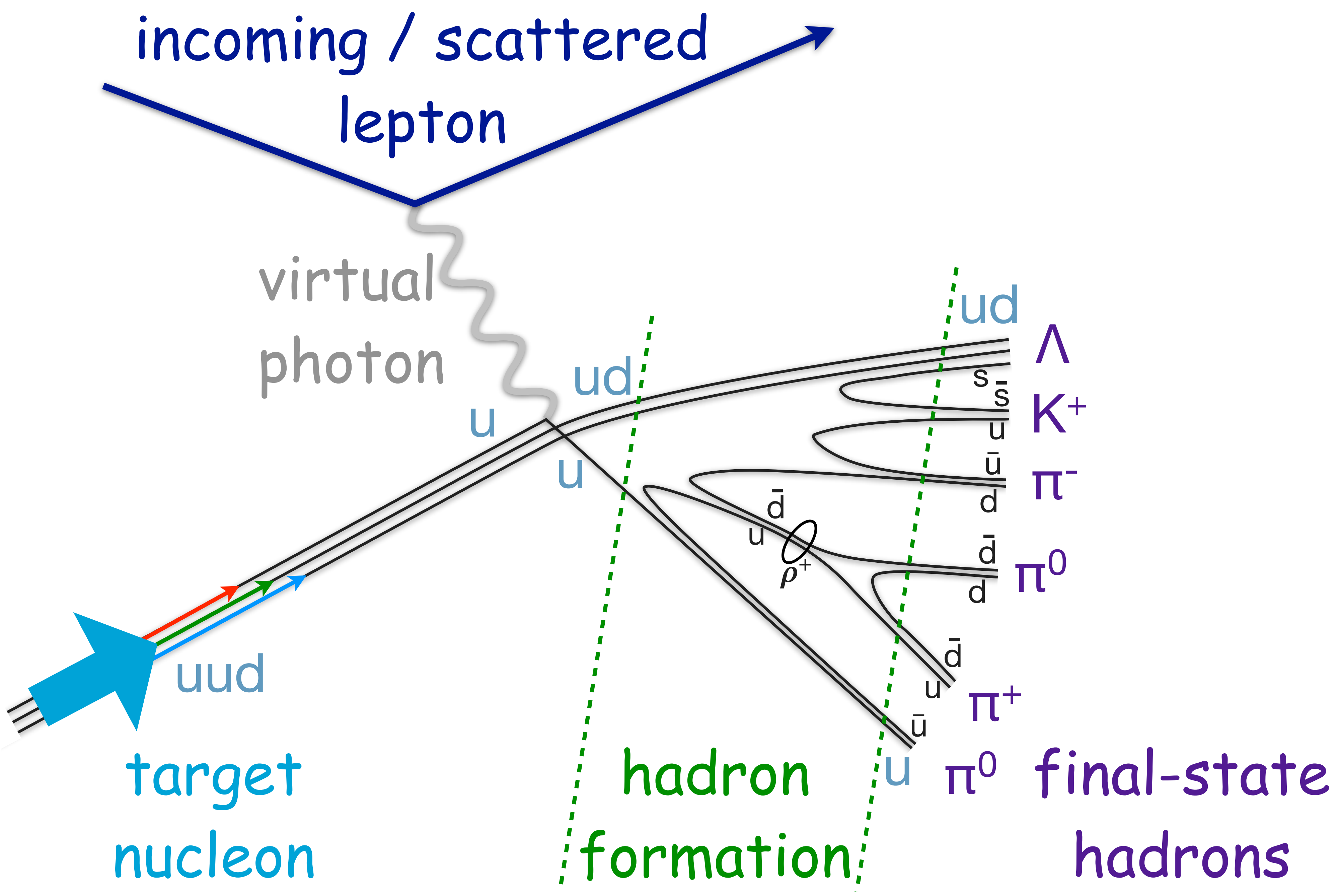
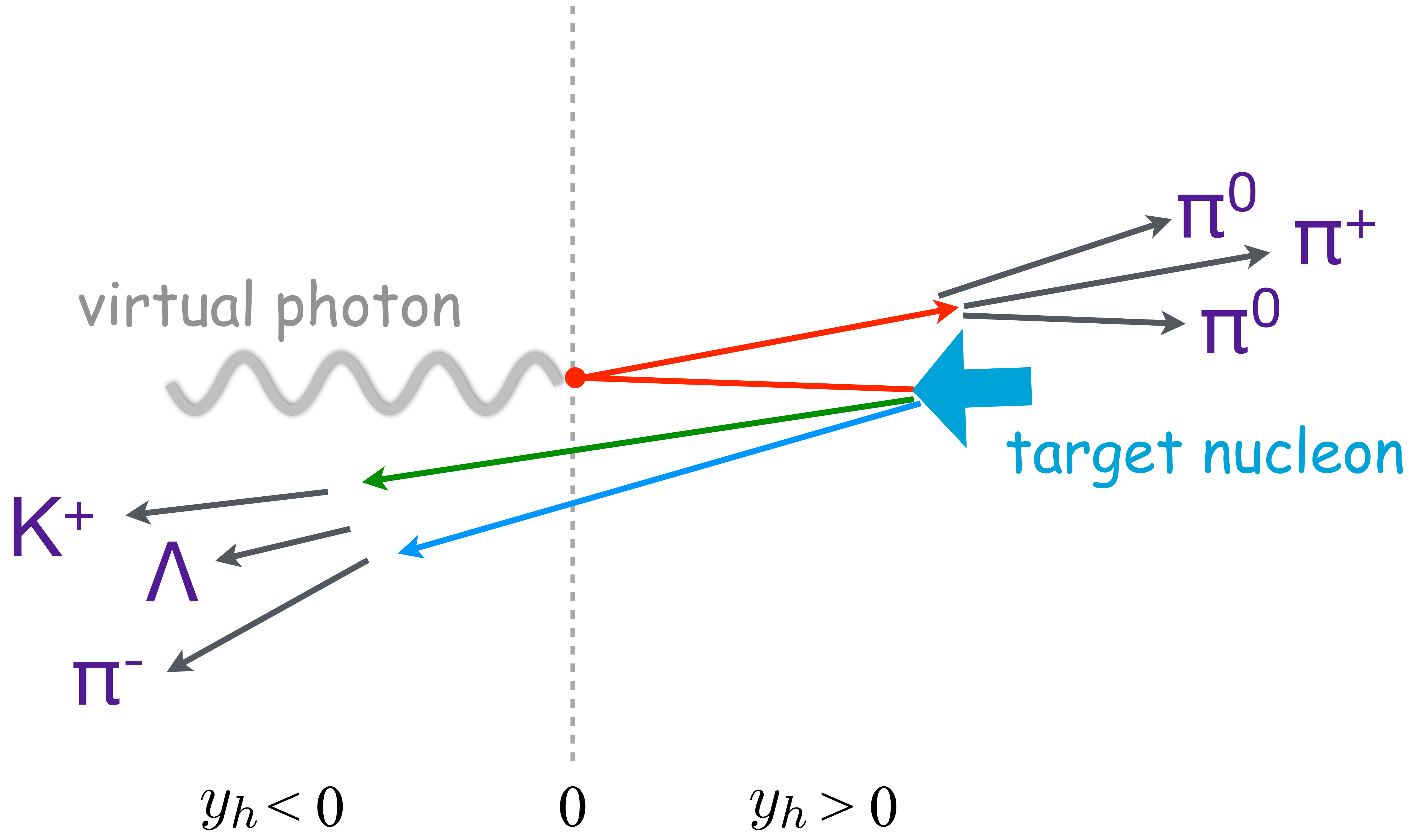


2d (x-Q^2) kinematic space not the only relevant one for SIDIS interpretation

current vs. target fragmentation



virtual-photon—nucleon c.m.s



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

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

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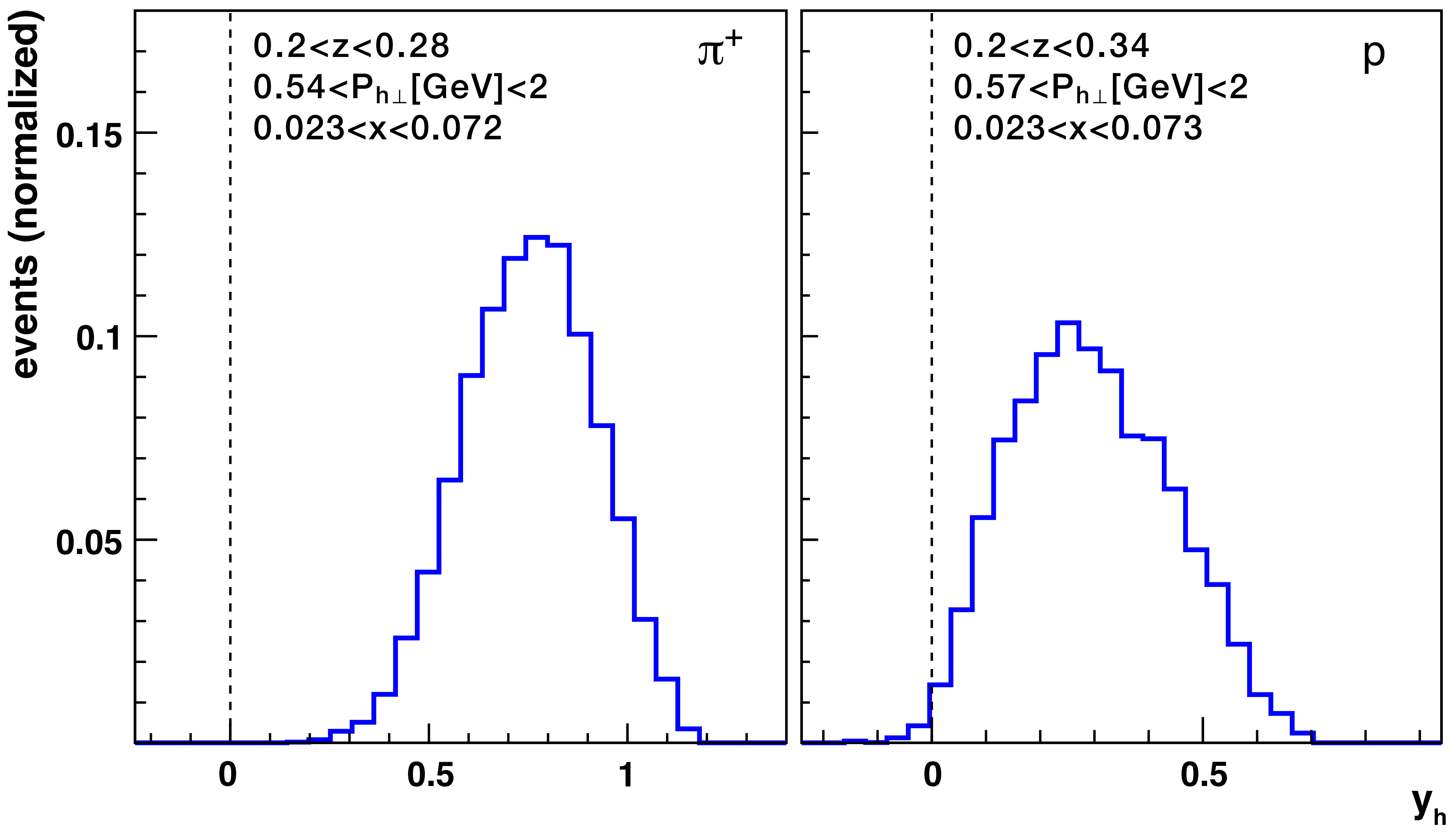

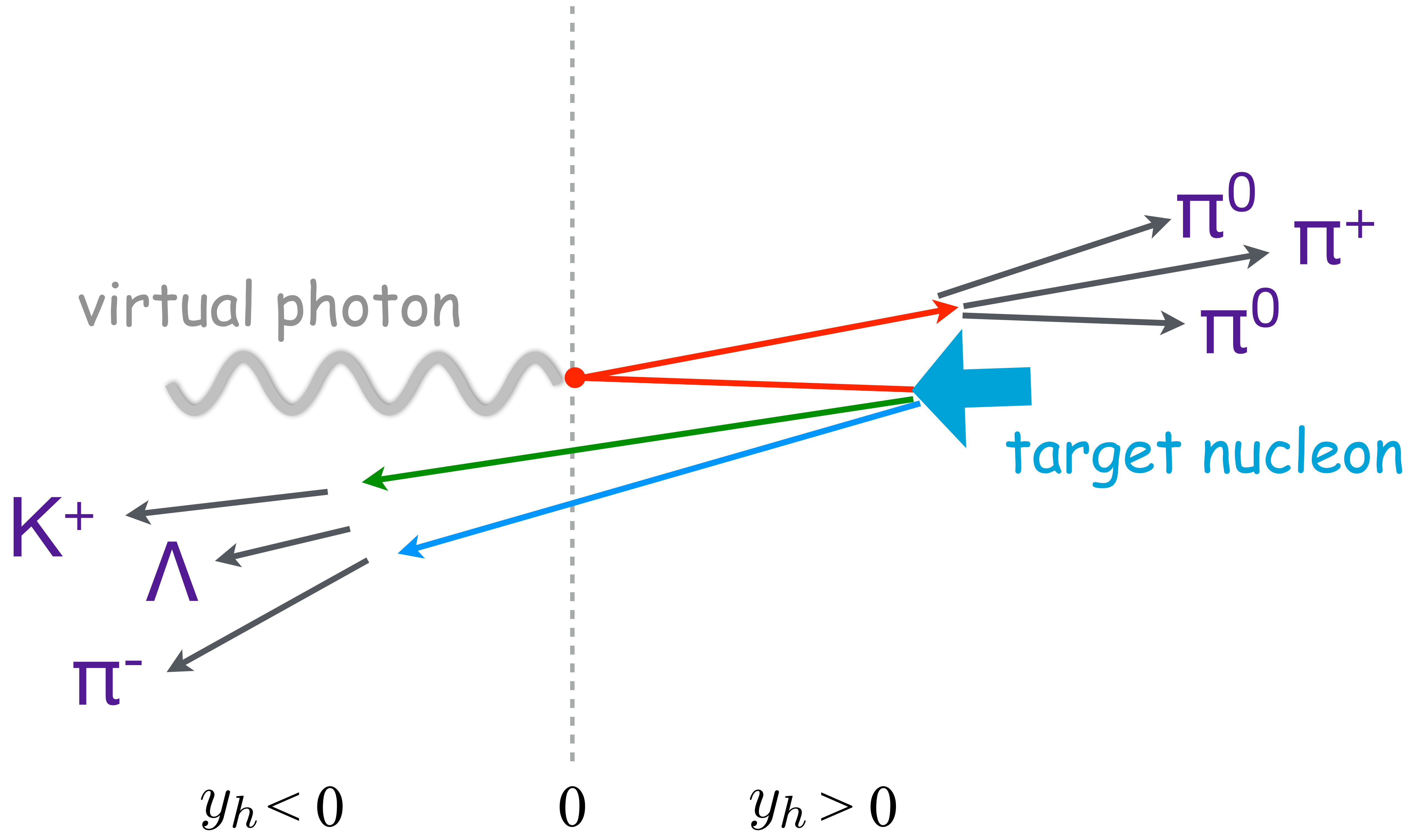

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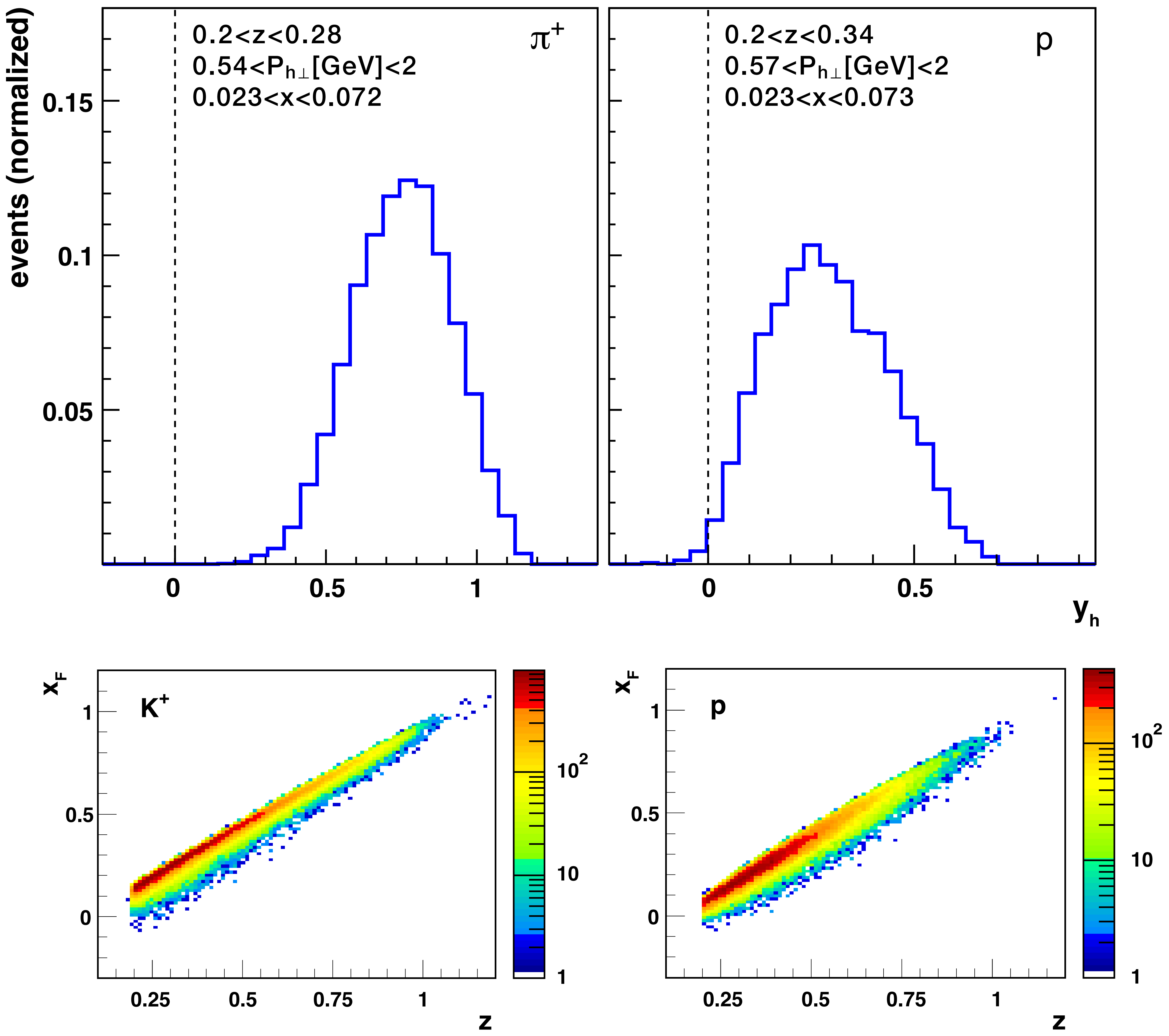
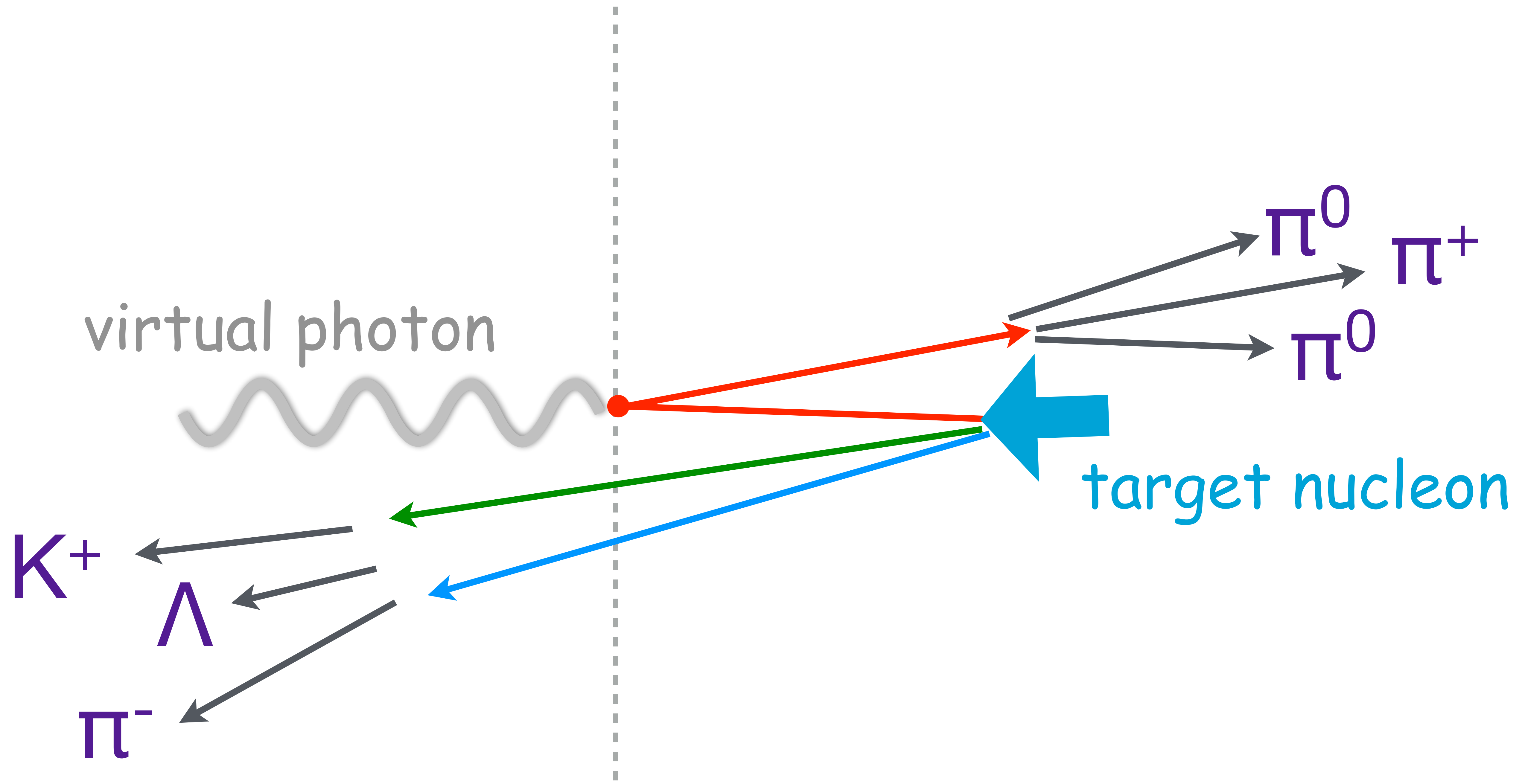


x_F ... Feynman x

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

virtual-photon—nucleon c.m.s



$y_h < 0$ $\quad 0 \quad$ $y_h > 0$

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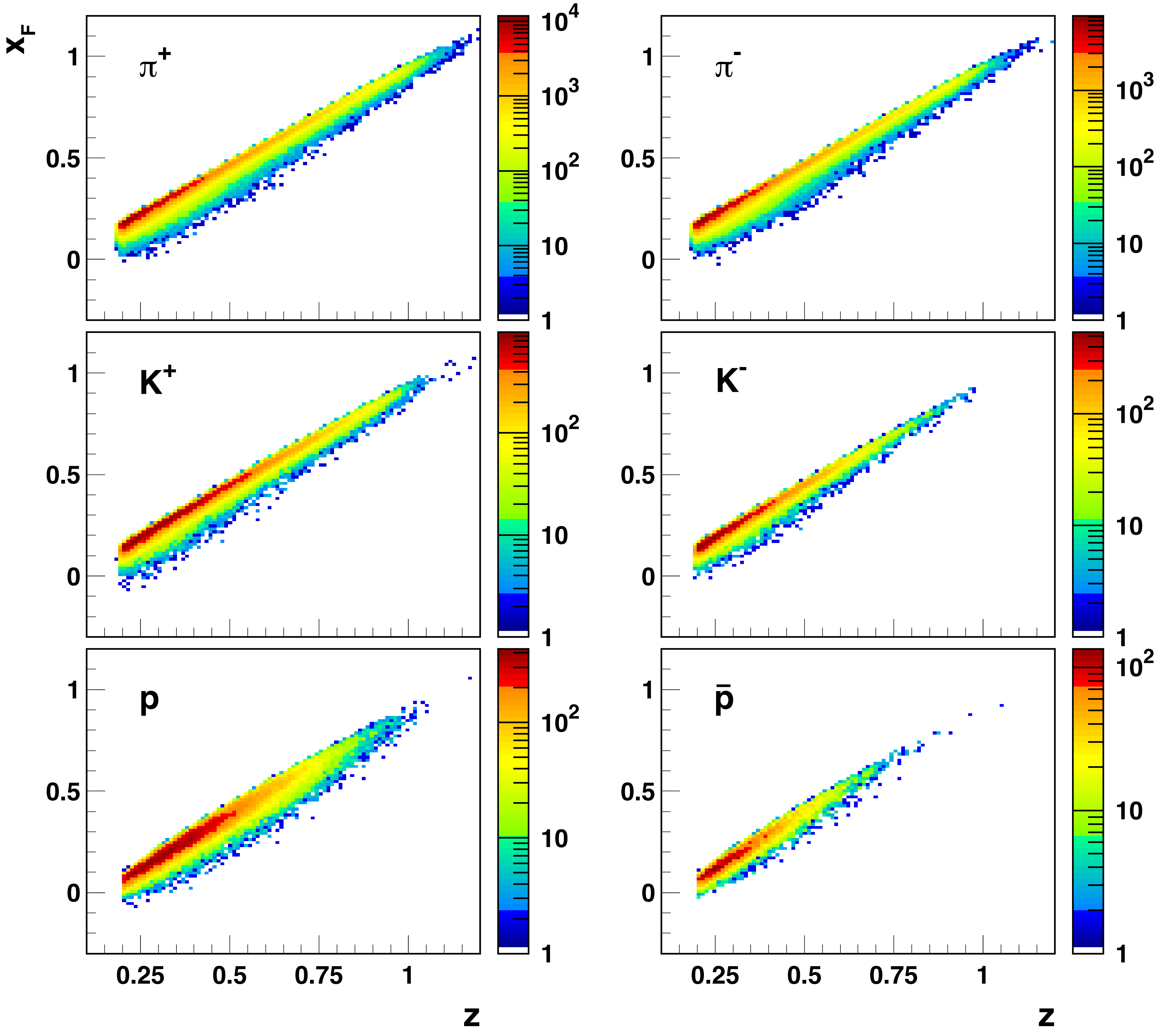
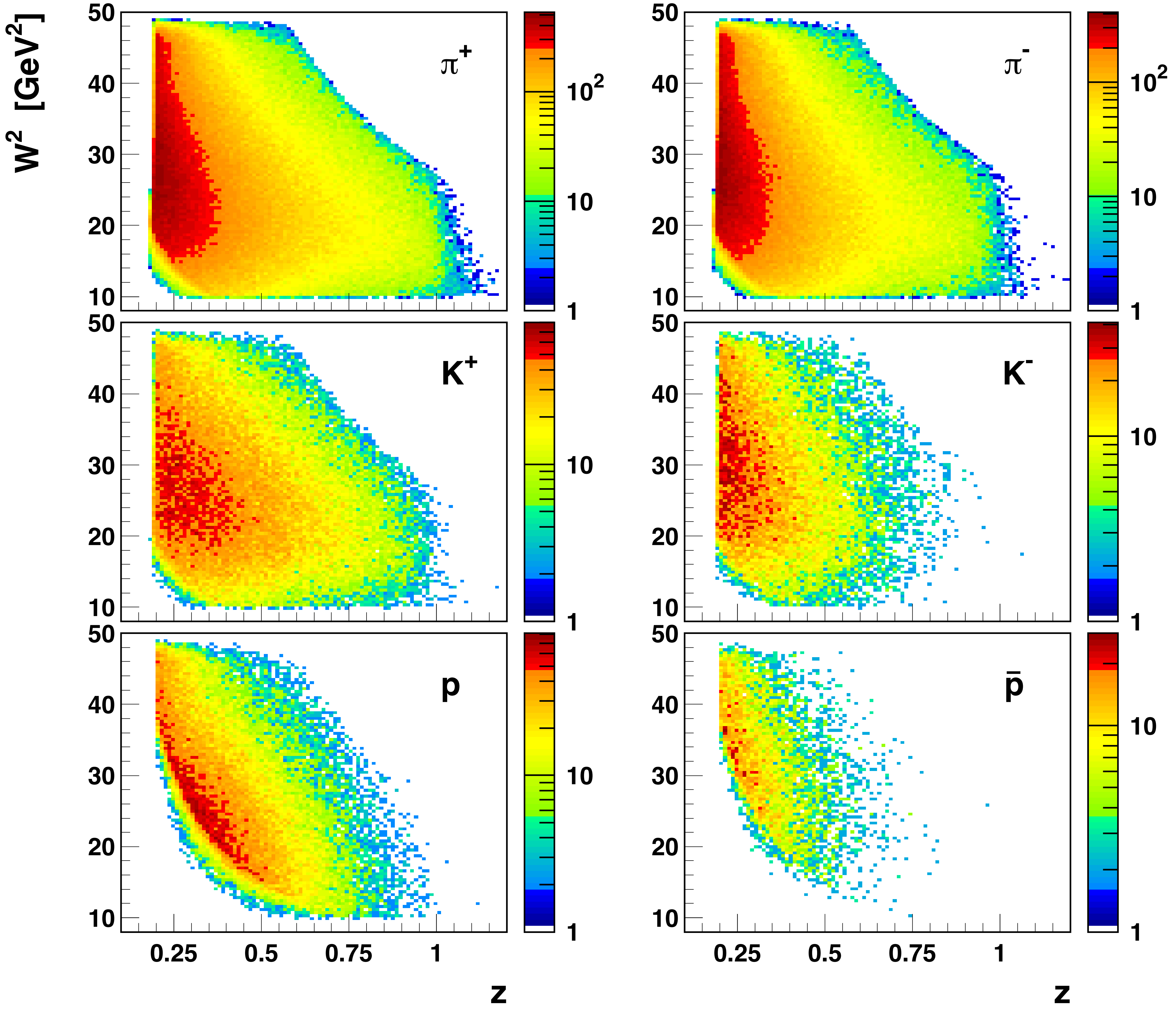
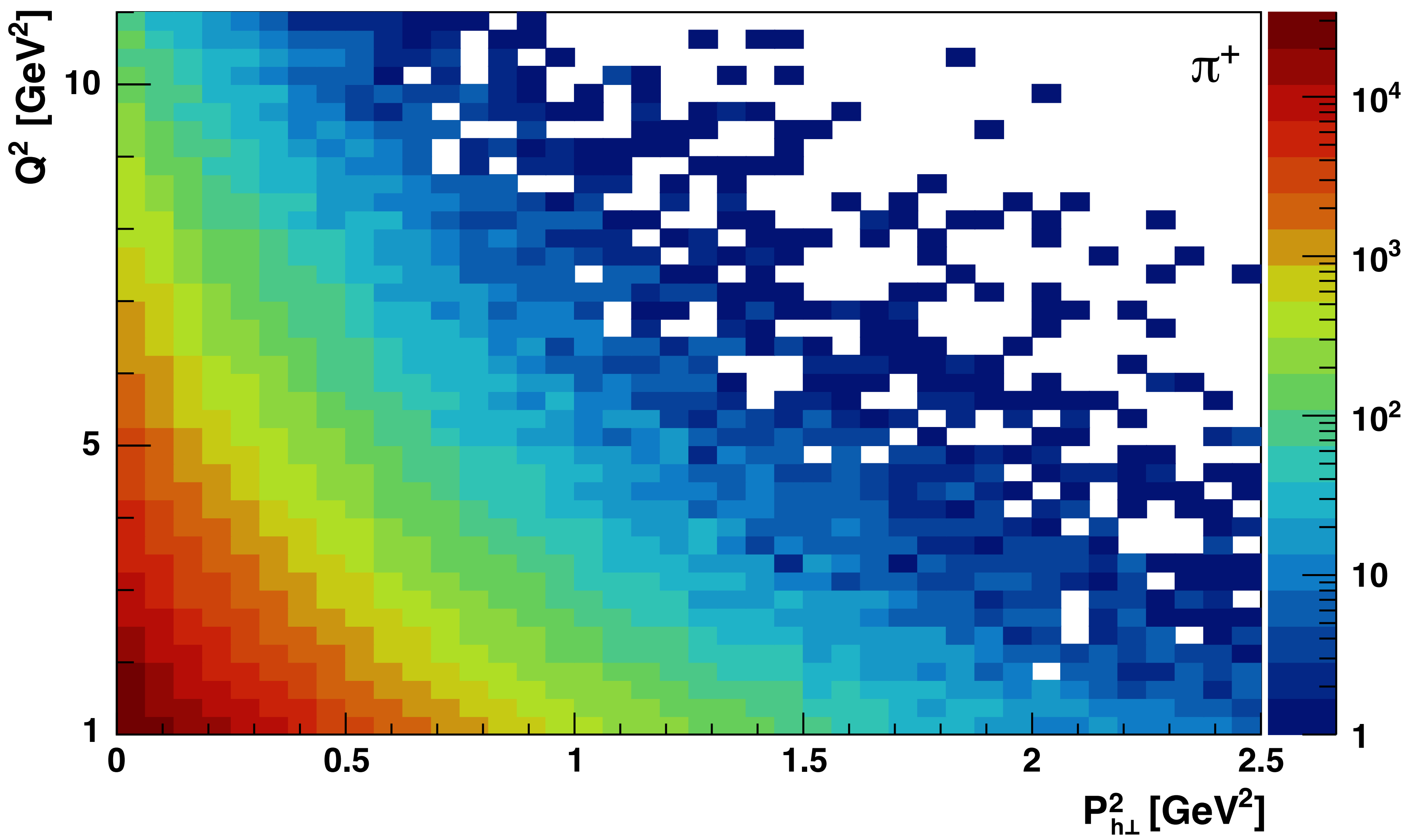




TMD factorization: a 2-scale problem

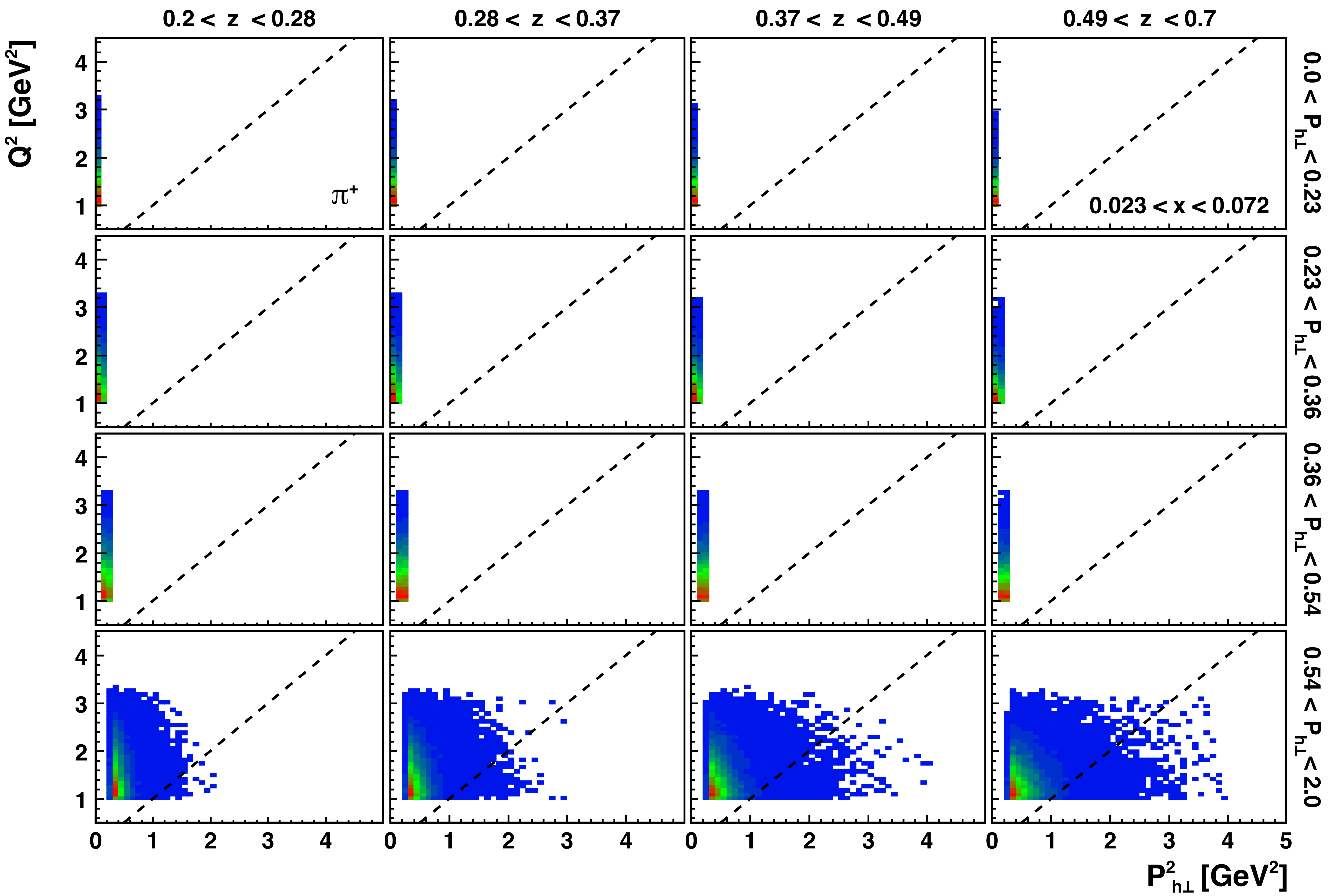
all events



- 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



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

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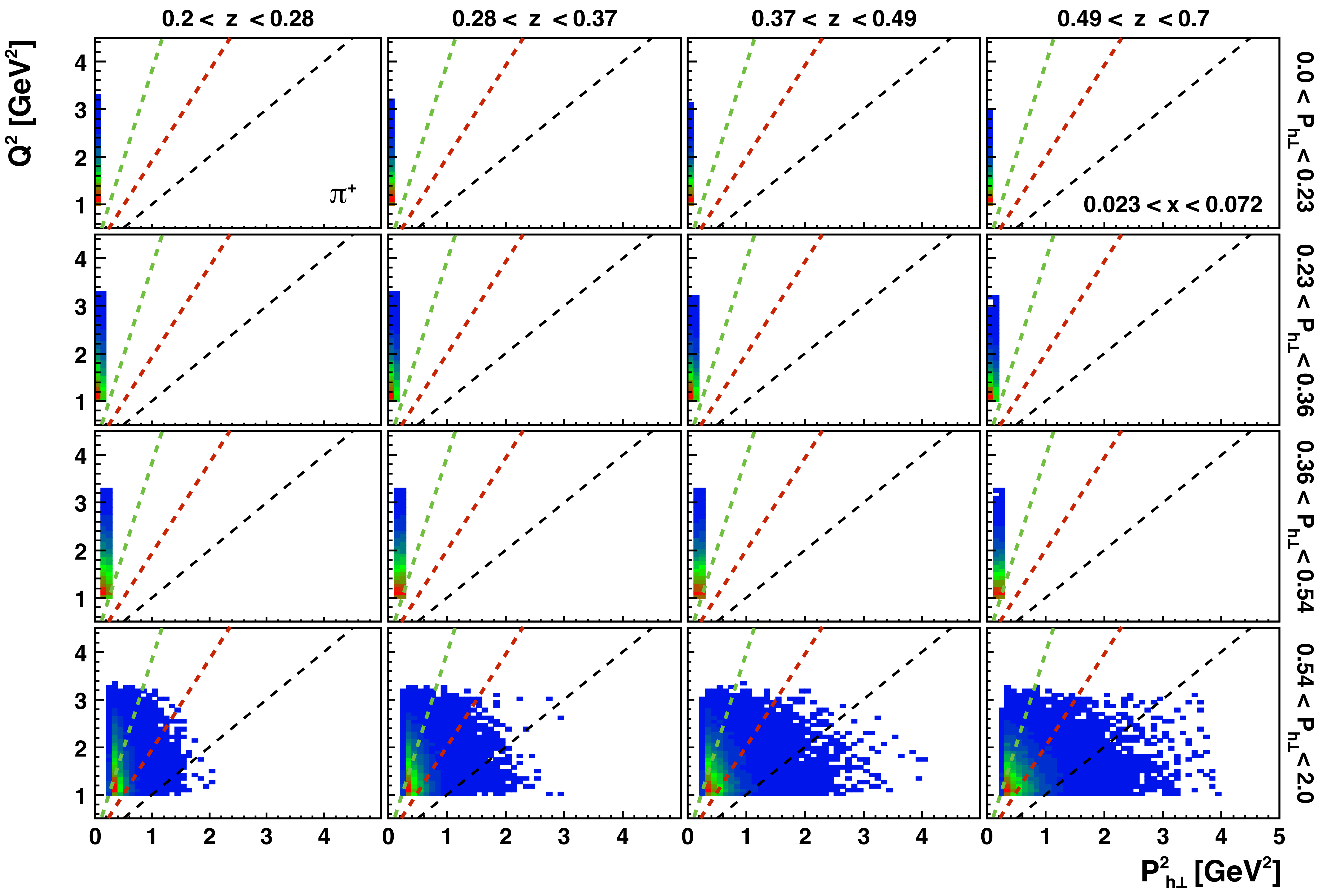

$Q^2 = P^2_{h\perp}$

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

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

disclaimer: coloured lines drawn by hand

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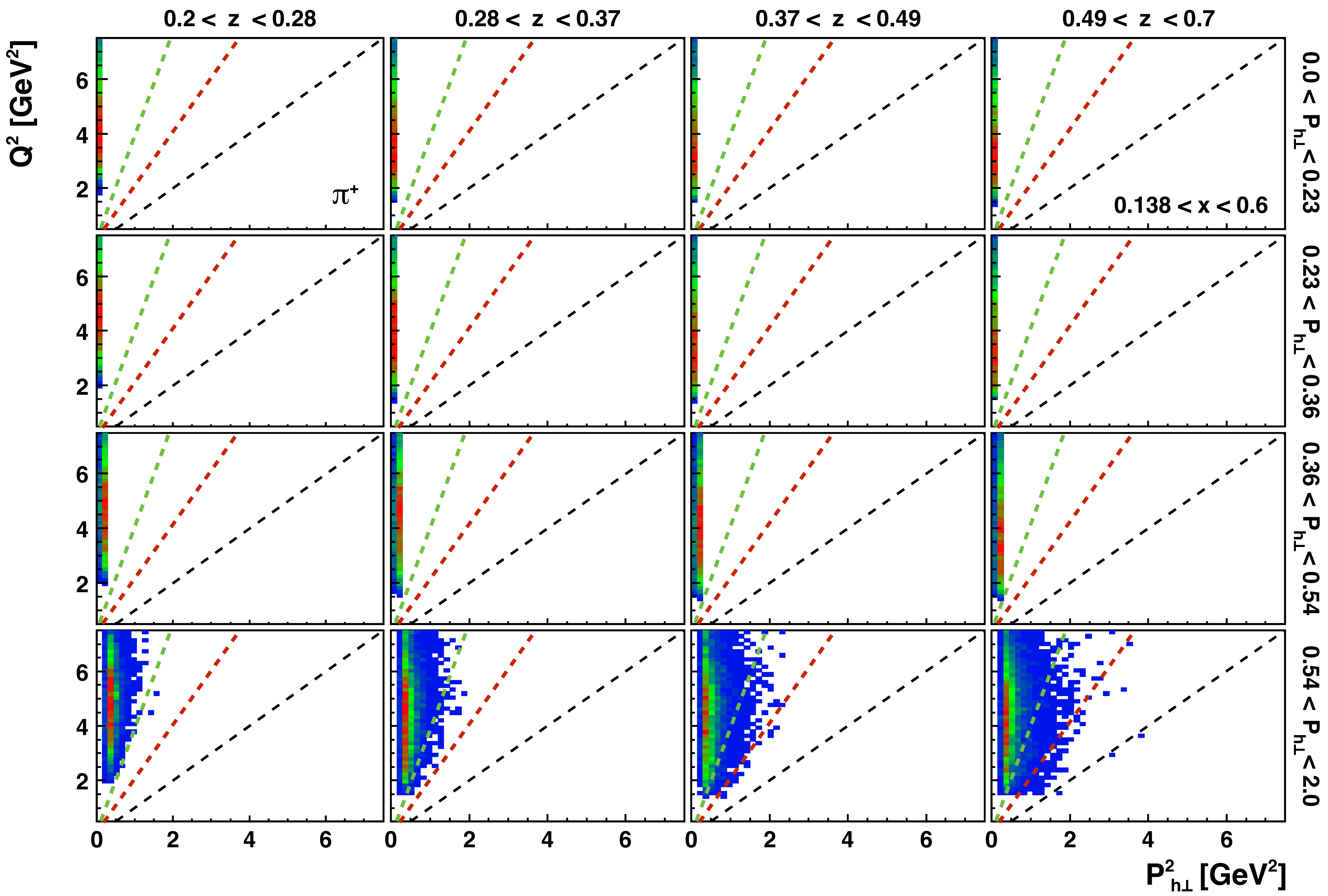

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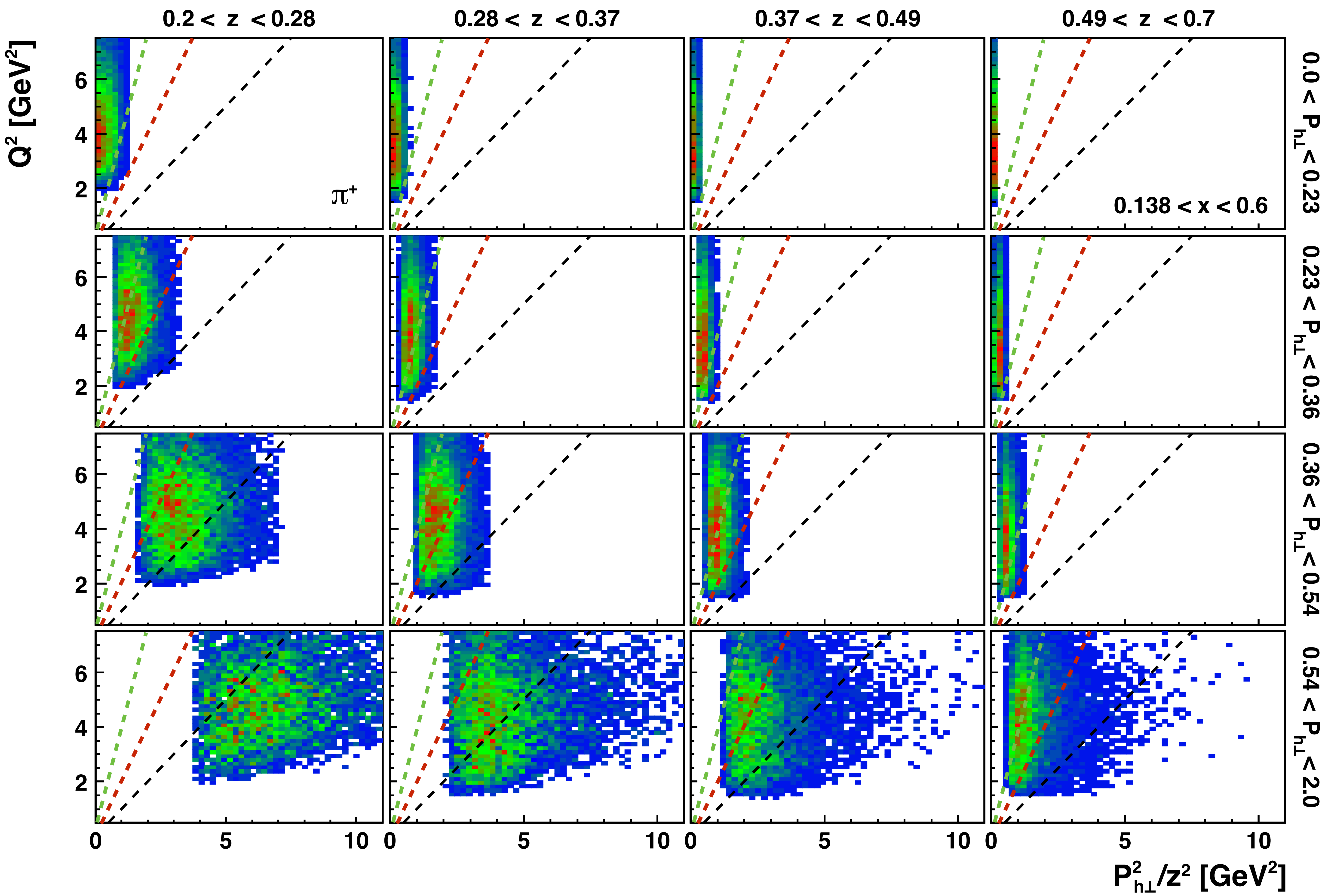

$Q^2 = P^2_{h\perp}/z^2$

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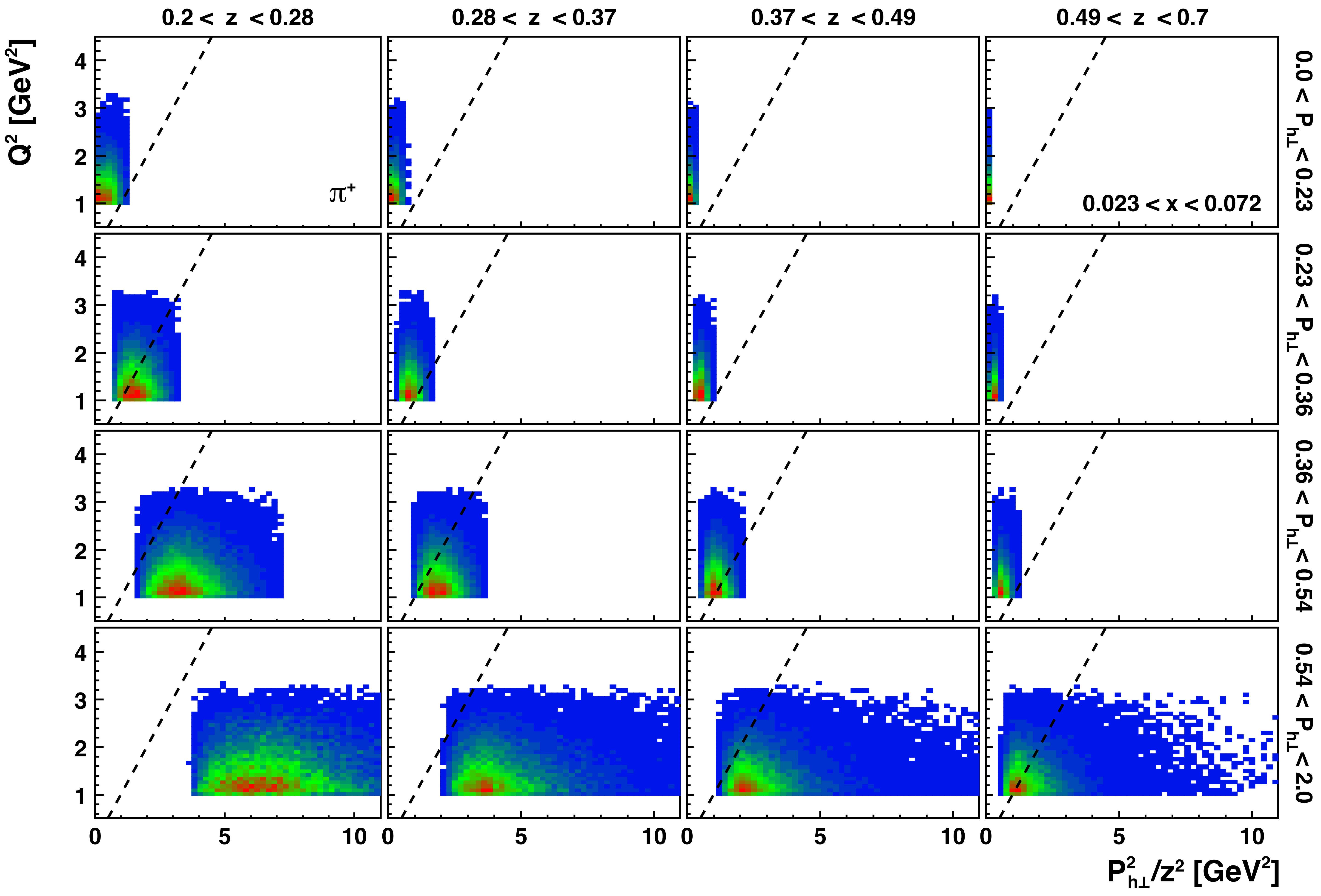

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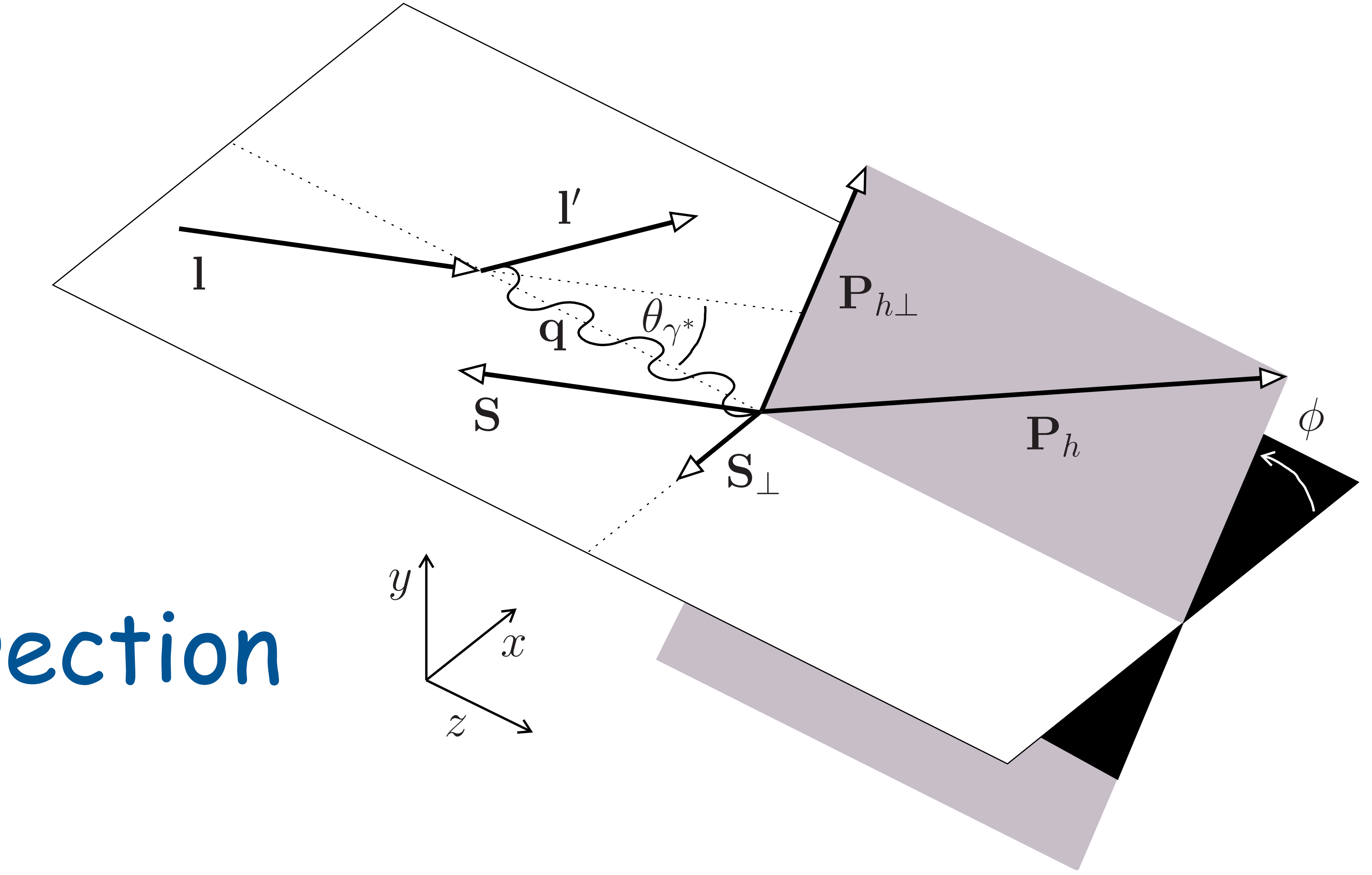
all other x-bins included in the Supplemental Material of JHEP12(2020)010

Mixing of target polarizations



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

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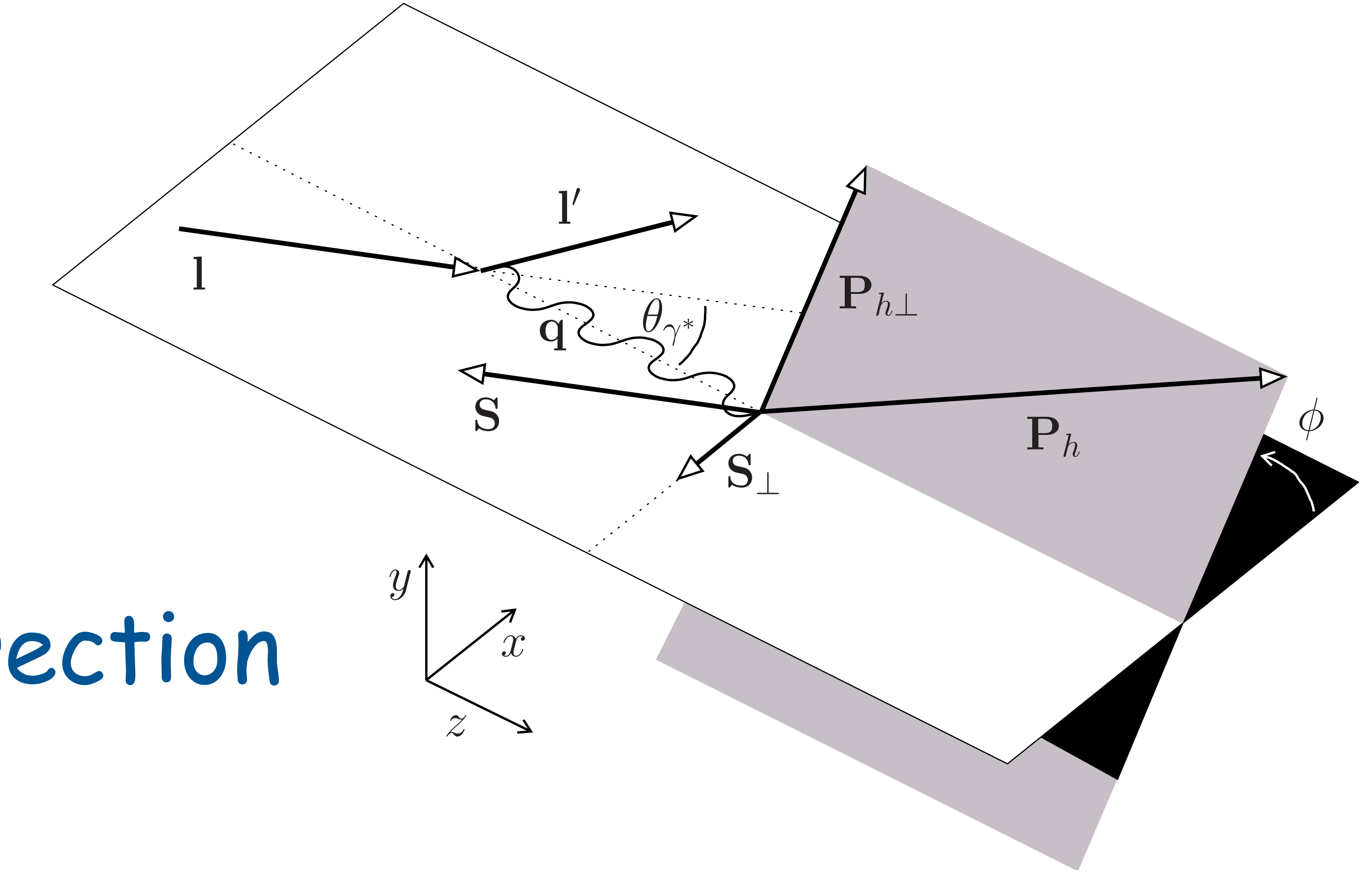

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➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

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

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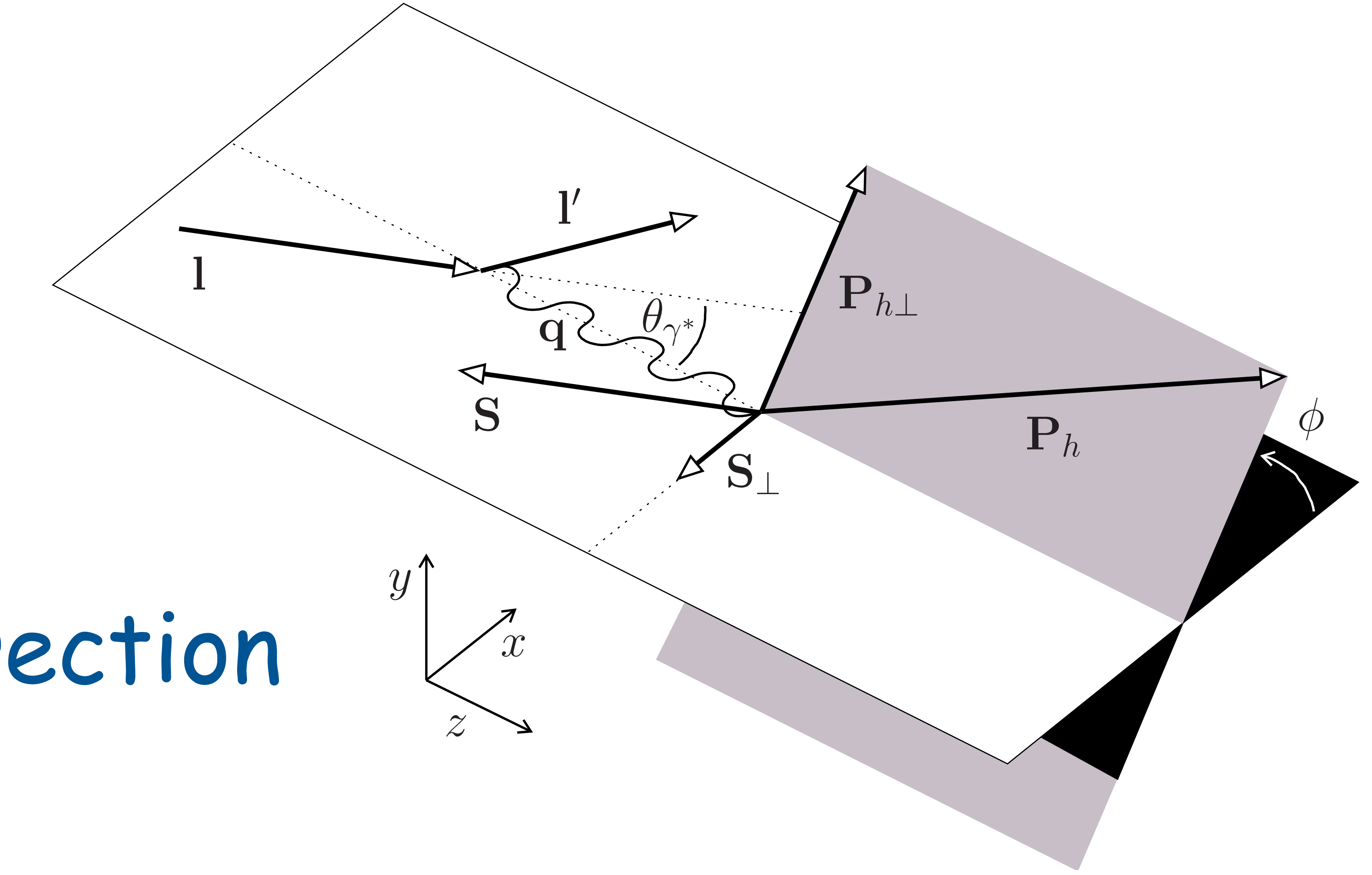

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➡ need data on same target for both polarization orientations!

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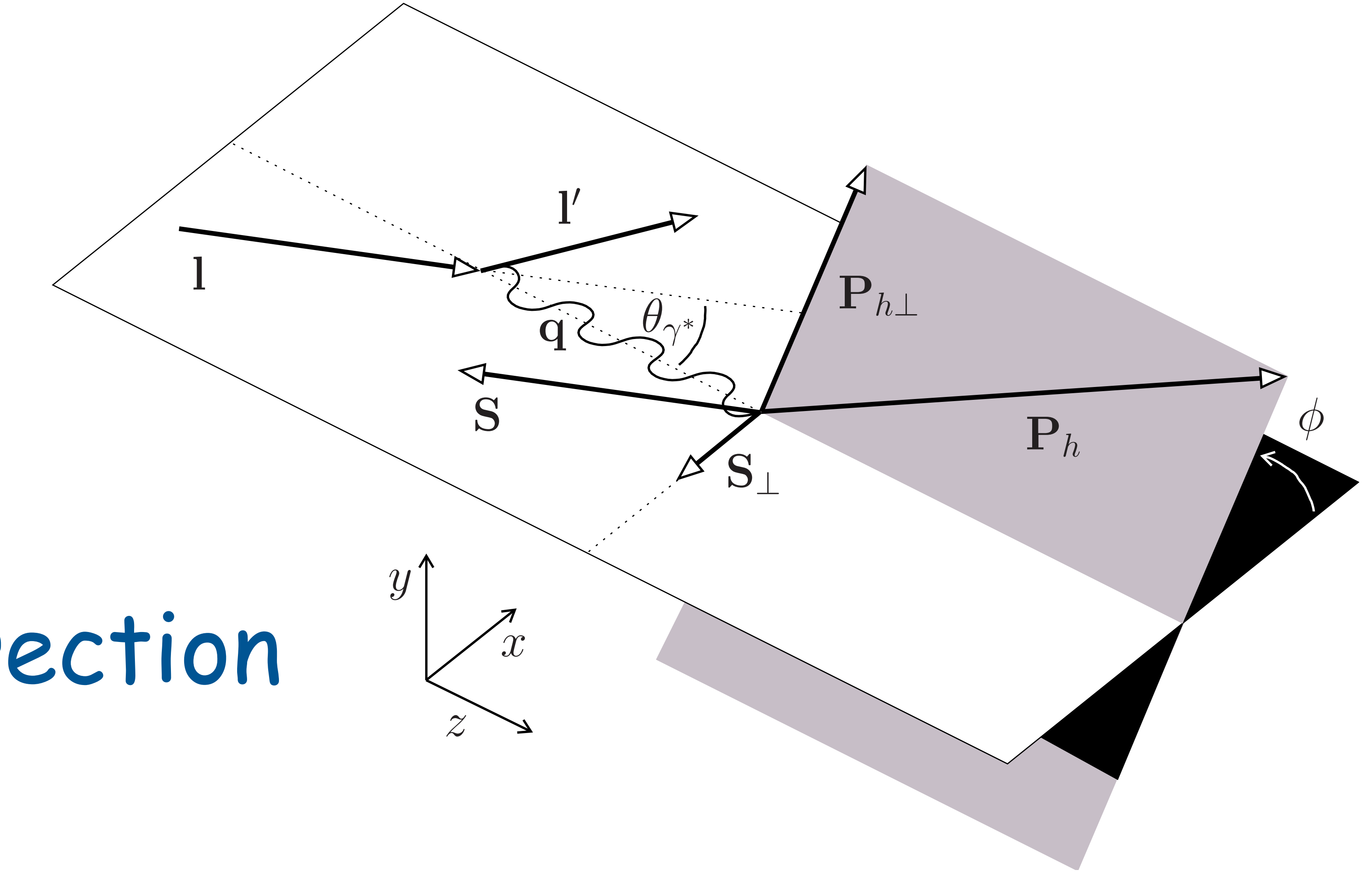

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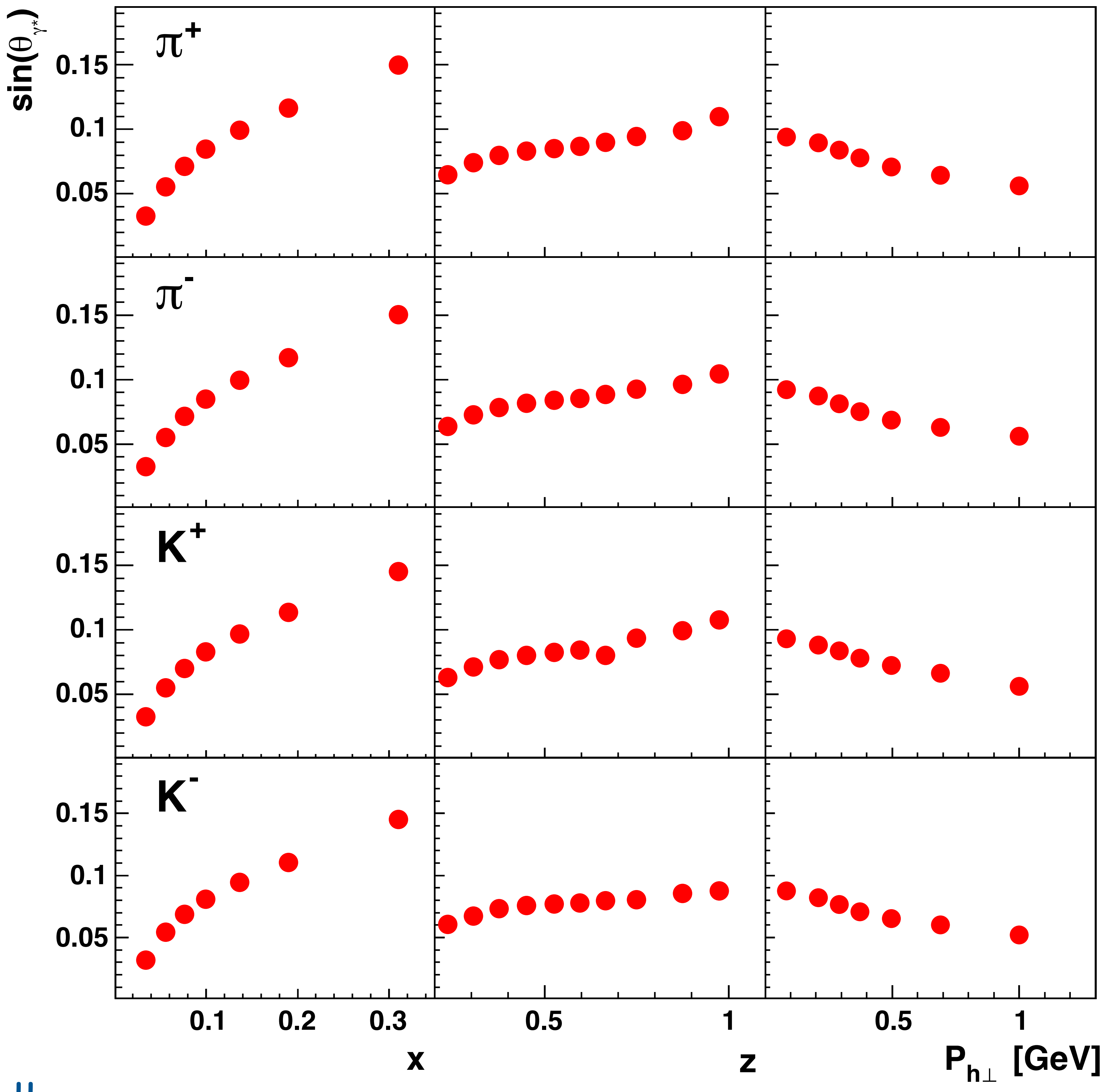

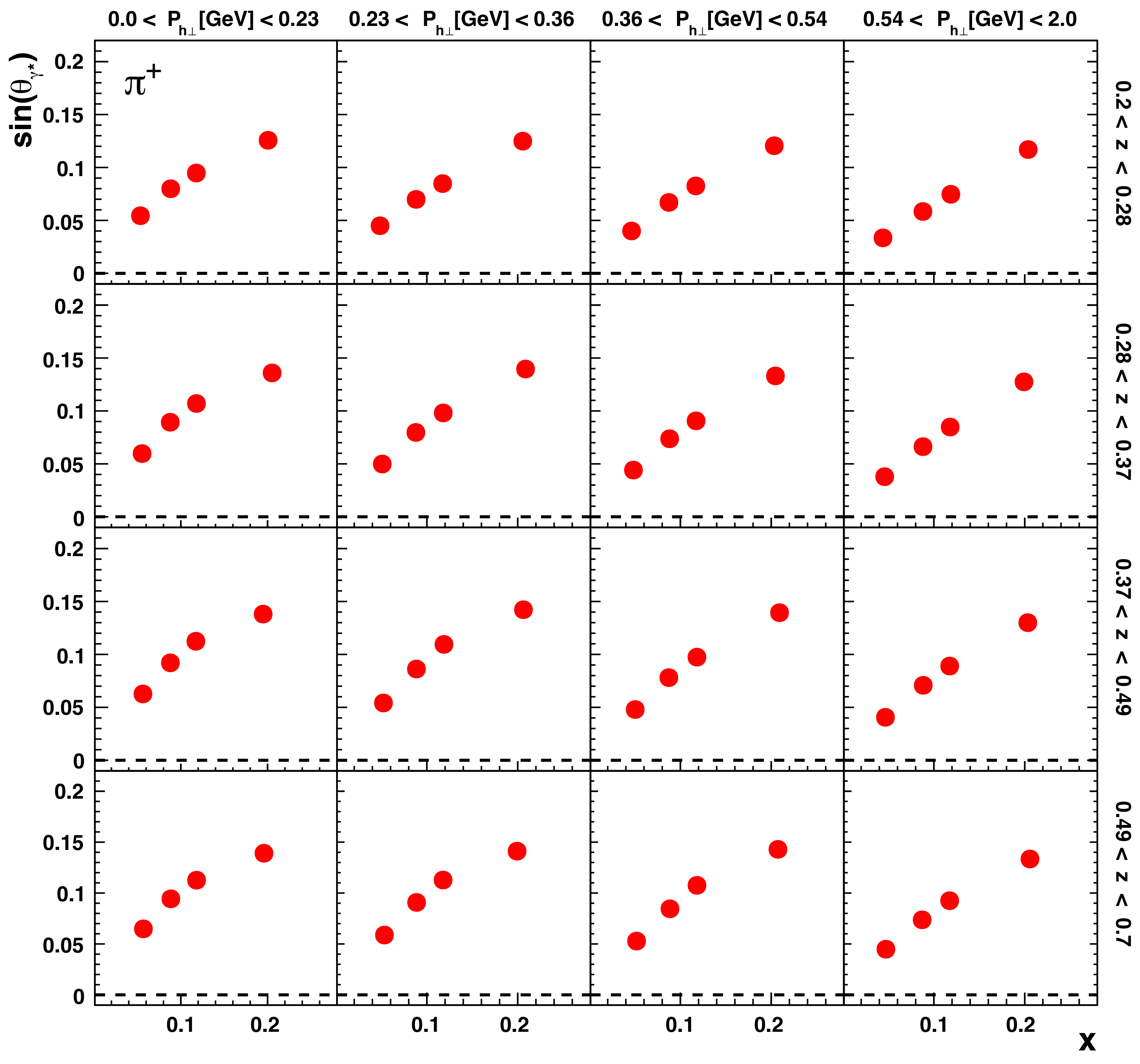

detector effects — need for multi-d analyses

$$\frac{N^+(x) - N^-(x)}{N^+(x) + N^-(x)} = \frac{\int \mathrm{d}\omega\, \epsilon(x,\omega)\, \Delta\sigma(x,\omega)}{\int \mathrm{d}\omega\, \epsilon(x,\omega)\, \sigma(x,\omega)}$$

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- measured cross sections / asymmetries often contain "remnants" of experimental acceptance ϵ
- difficult to evaluate precisely in absence of good physics model
  - general challenge to statistically precise data sets
  - avoid 1d binning/presentation of data
  - theorist: watch out for precise definition (if given!) of experimental results reported ... and try not to treat data points of different projections as independent

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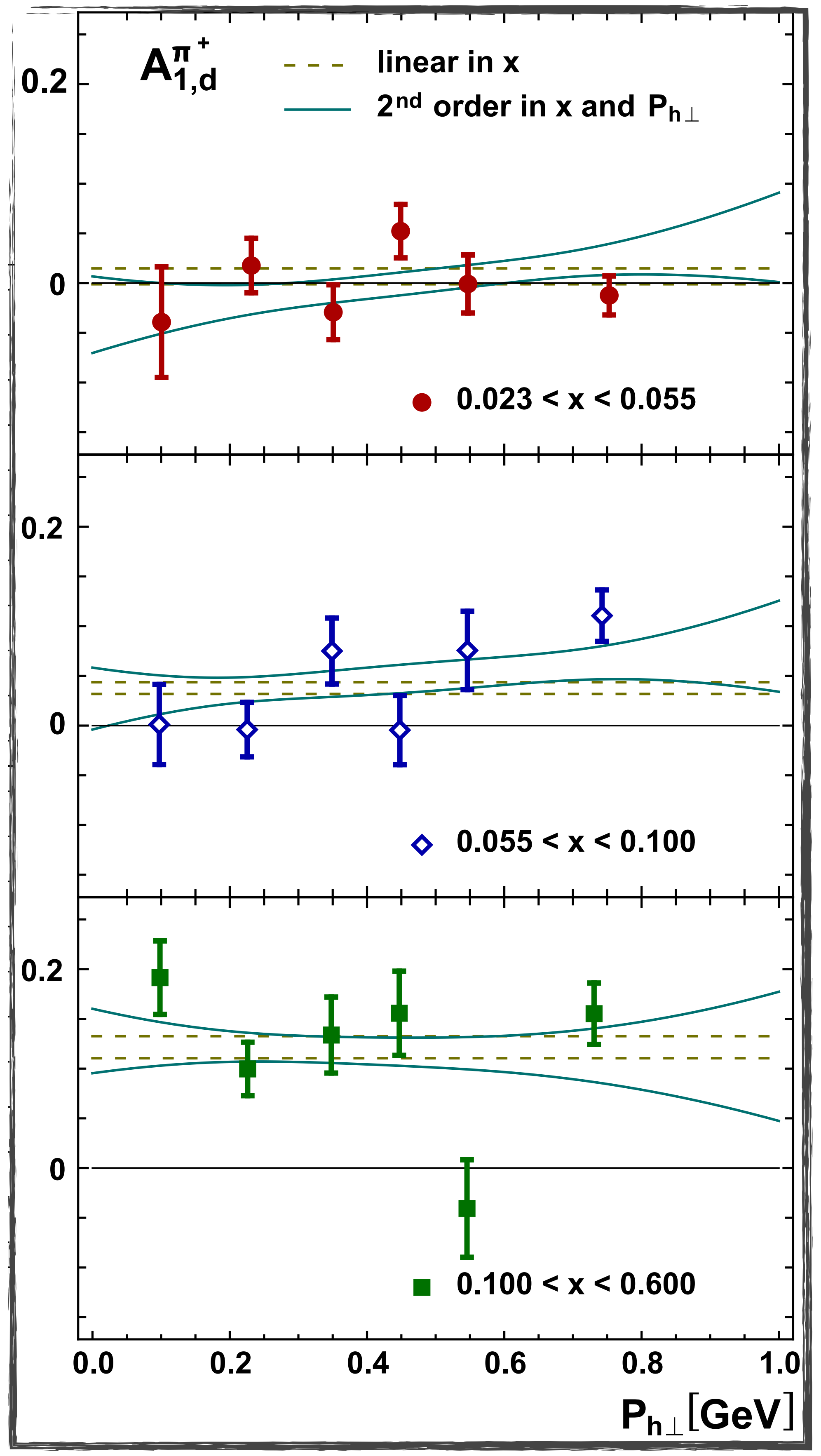
  - e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$
- further complication: physics (cross sections) folded with acceptance
  - NO experiment has flat acceptance in full multi-d kinematic space

detector effects — need for multi-d analyses

- Why have 1d projections survived for so long?
  - faster to catch features of functional dependence
  - most prominent asymmetry was A_{LL} (or A_1)
    - viewed with "collinear monocles" - thus blind for 3d effects
    - no strong dependence on hadron kinematics observed

[HERMES, PRD 99 (2019) 112001]



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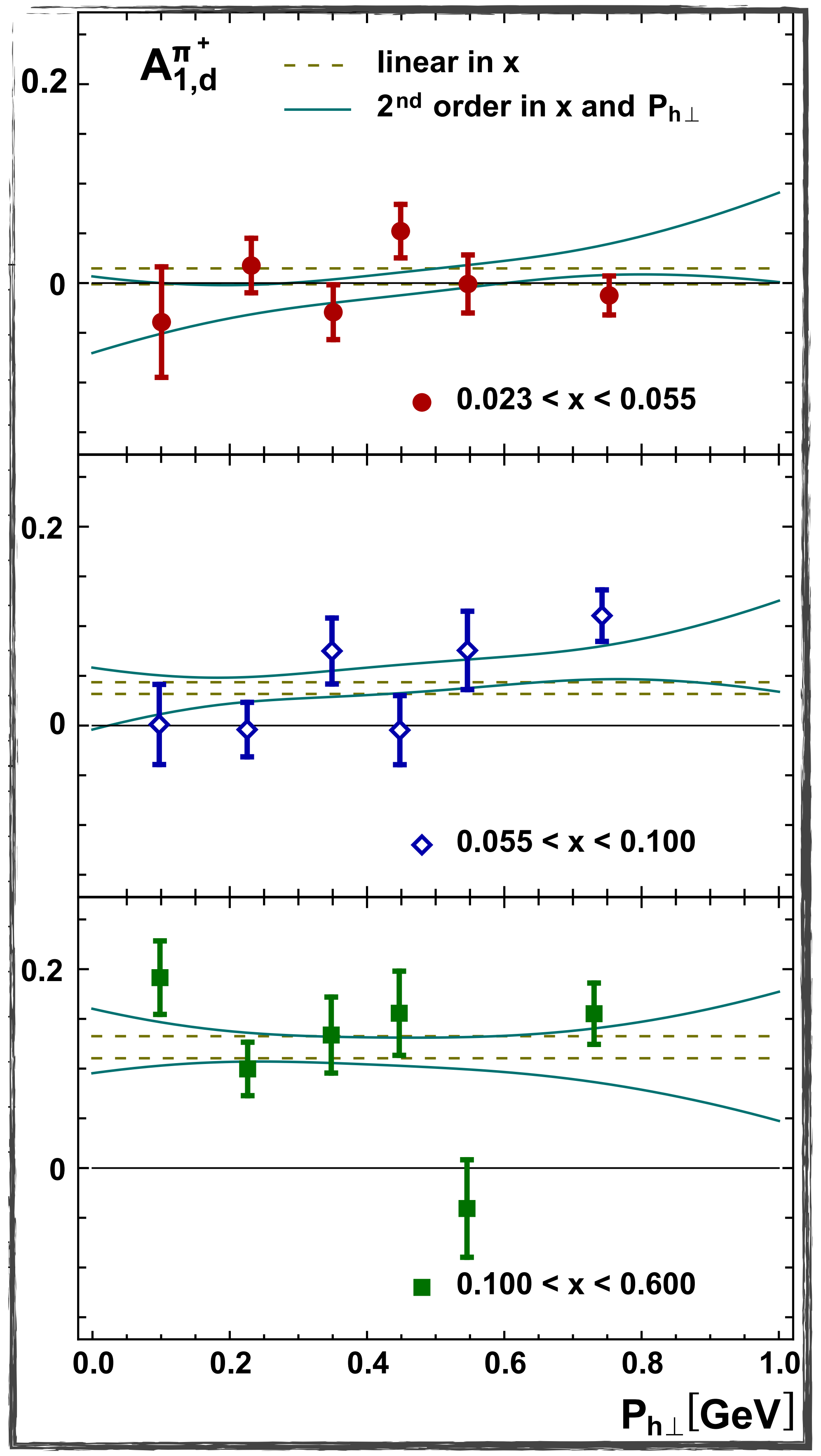

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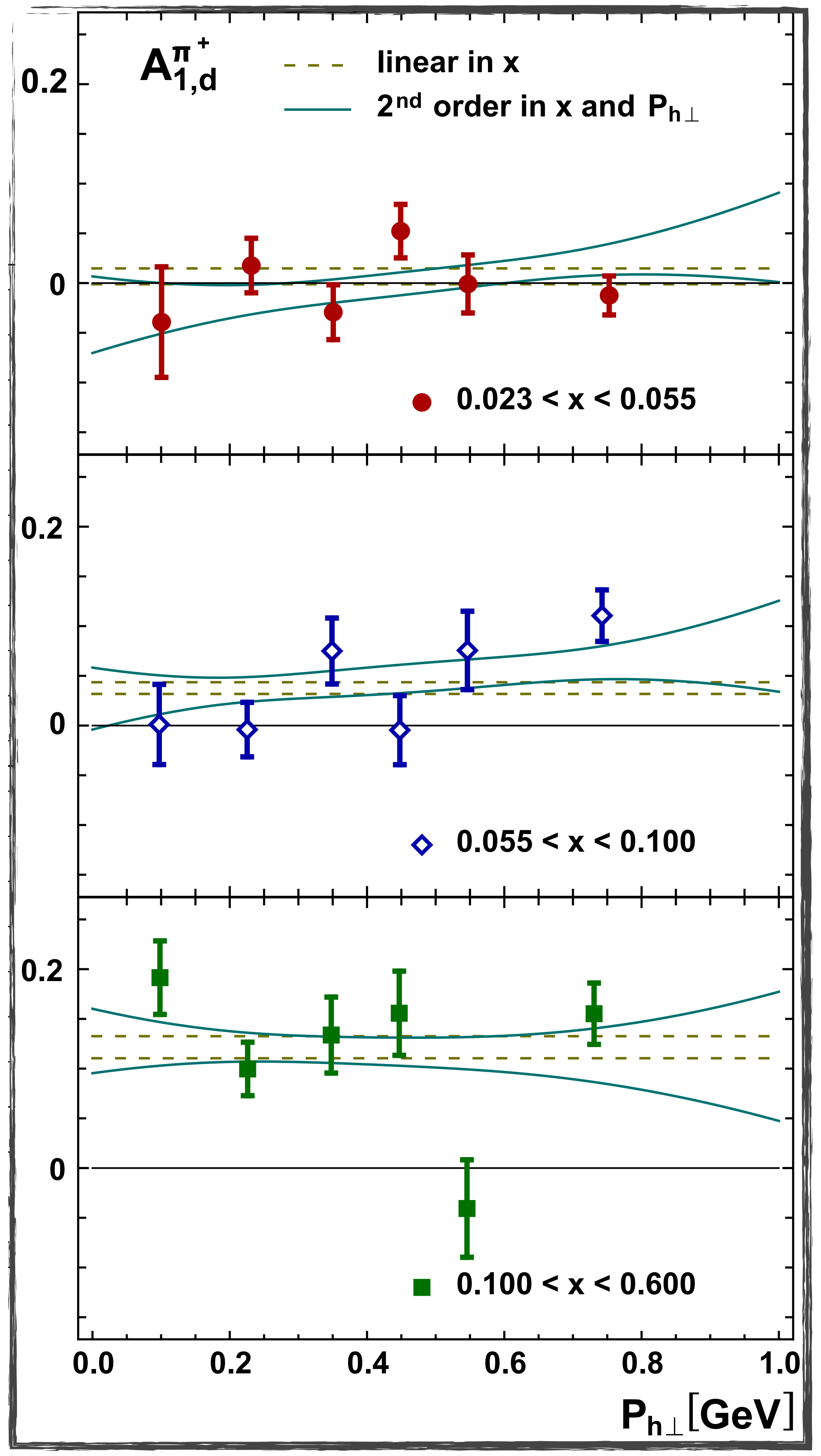

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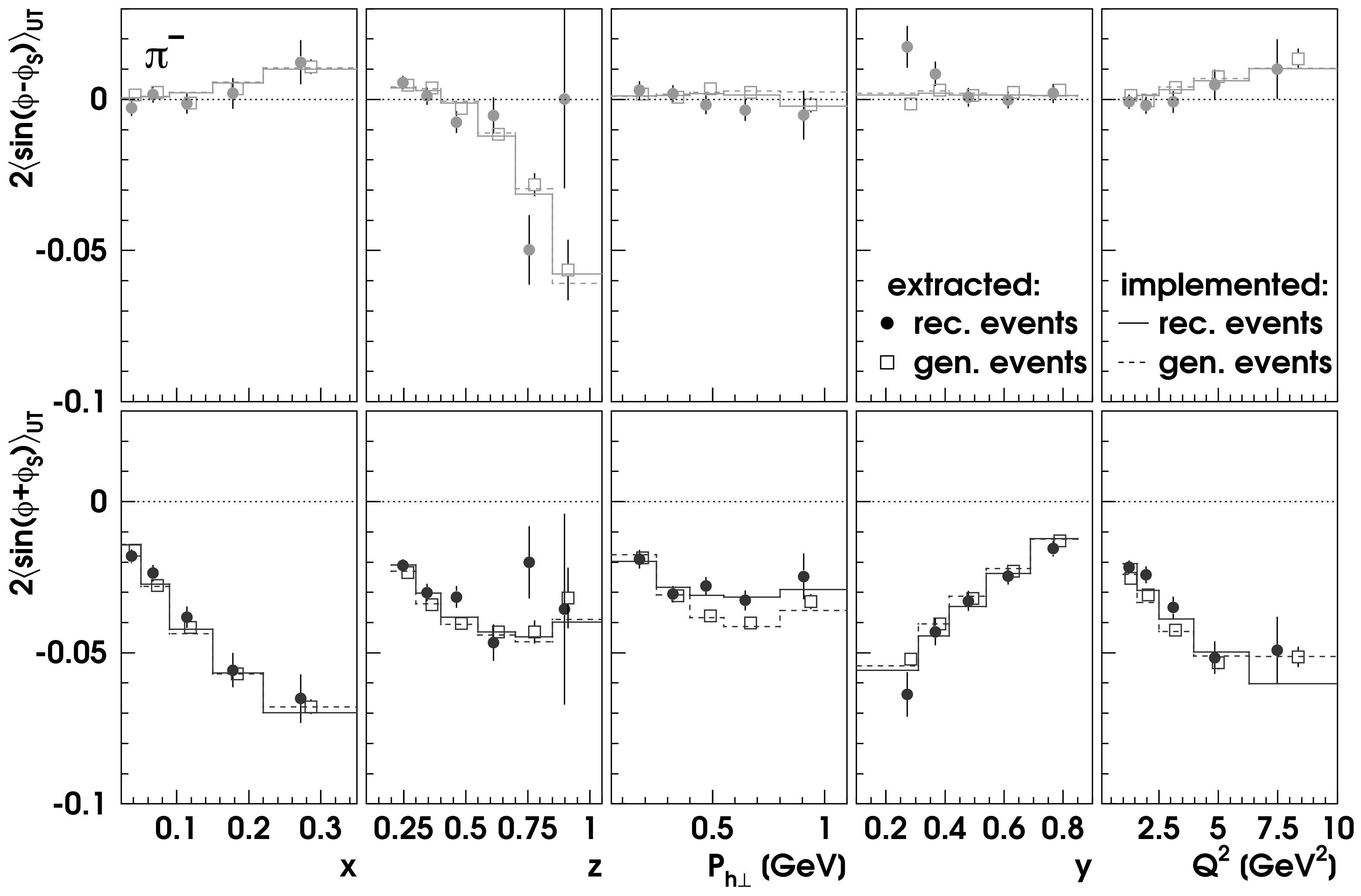
- need to evaluate systematics due to integration over phase space => Monte Carlo

Monte Carlo simulation for TMD analyses

- early Collins and Sivers analyses used dedicated TMD single-hadron MC: gmcTRANS based on Gaussian Ansatz
  - fully analytic, but no full-blown "event generator"



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$$\rho < \frac{1}{2}\left[1 + \mathcal{A}_{\mathrm{U}\perp}^{\sin(\phi-\phi_S)}(\Omega^i)\sin(\phi^i - \phi_S^i)\right] \quad \Rightarrow \quad \mathcal{P} = +1$$

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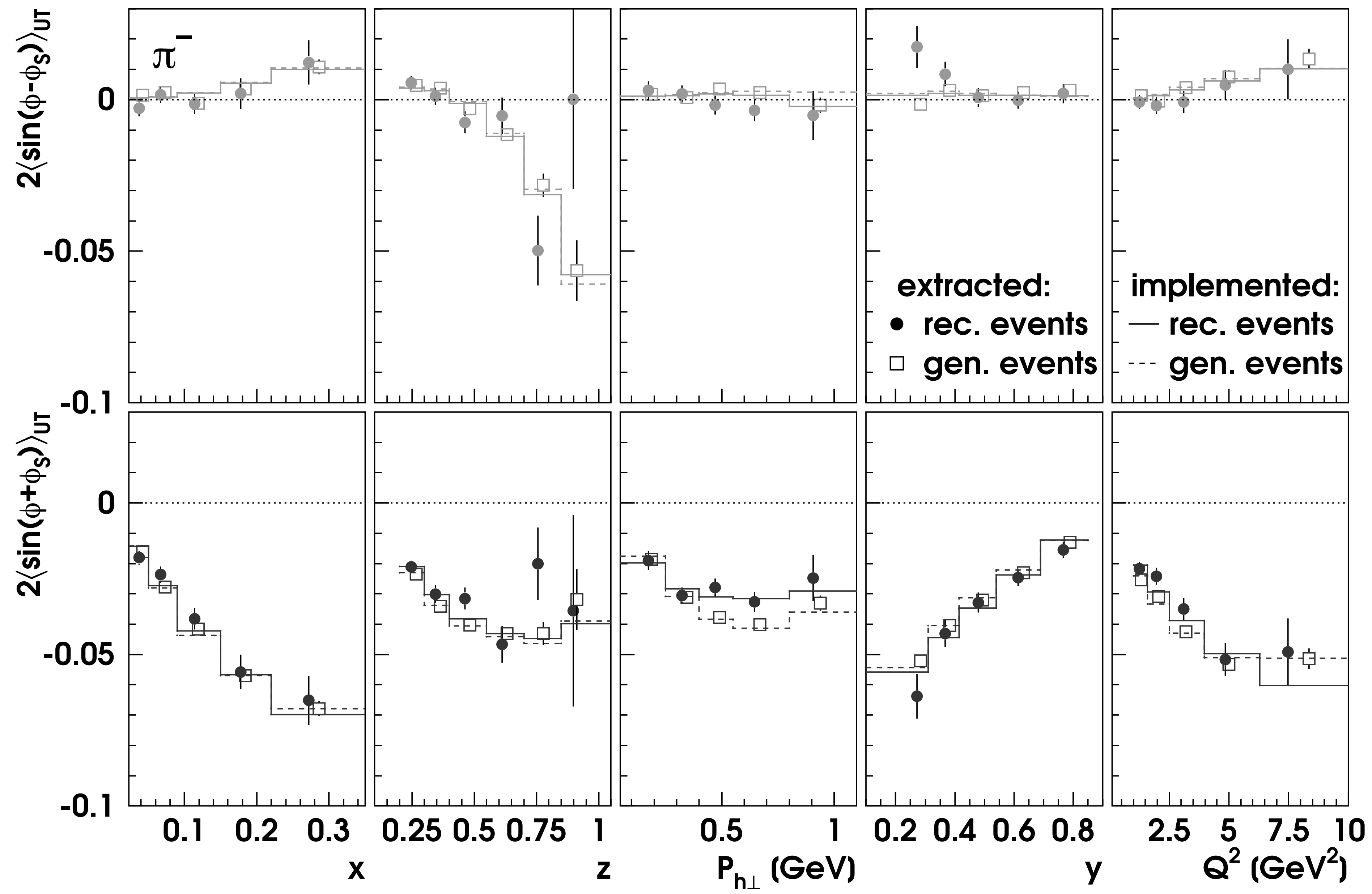
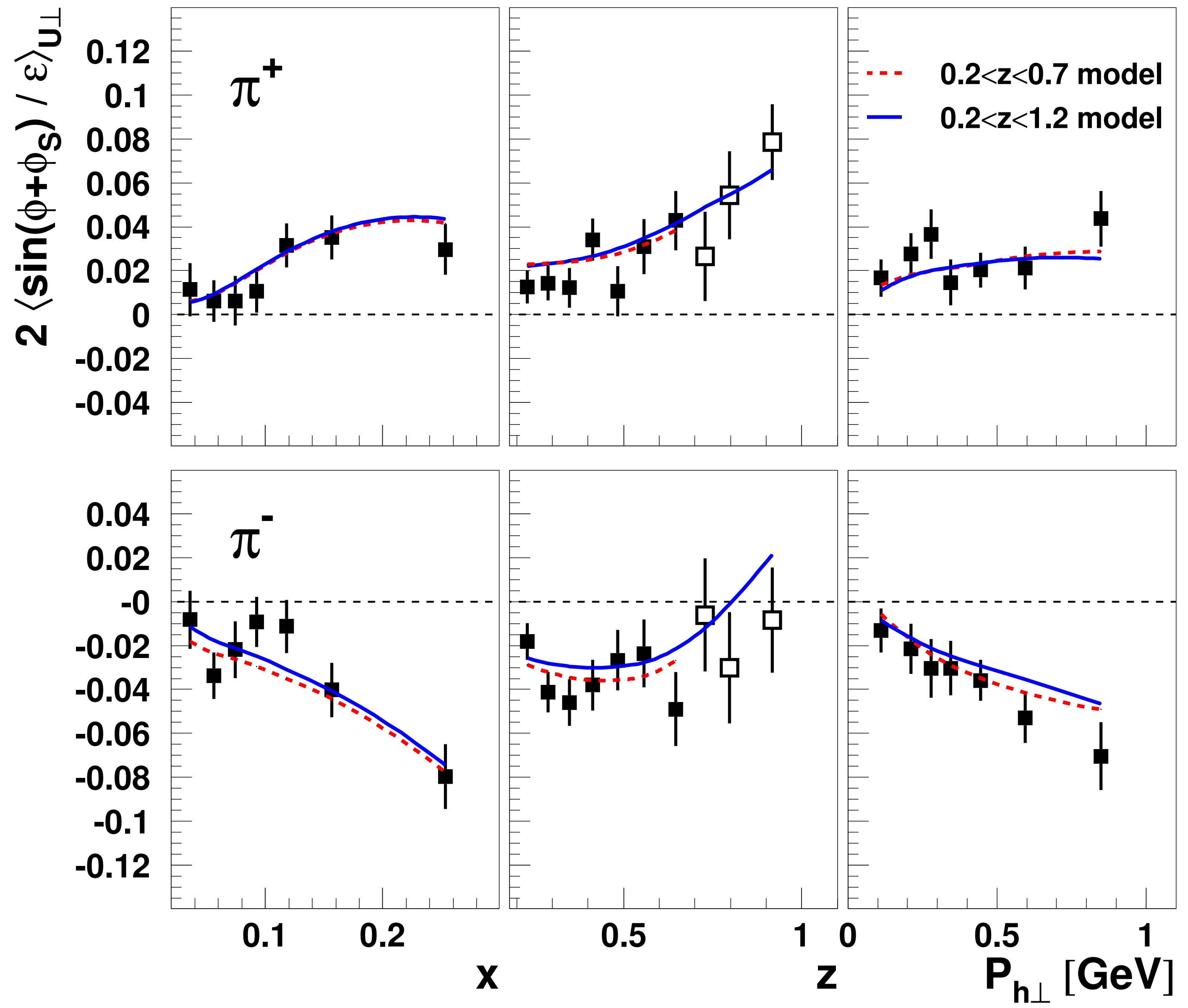
throwing a random variable $0<\rho<1$

  - model: fully differential Taylor series fit to HERMES data





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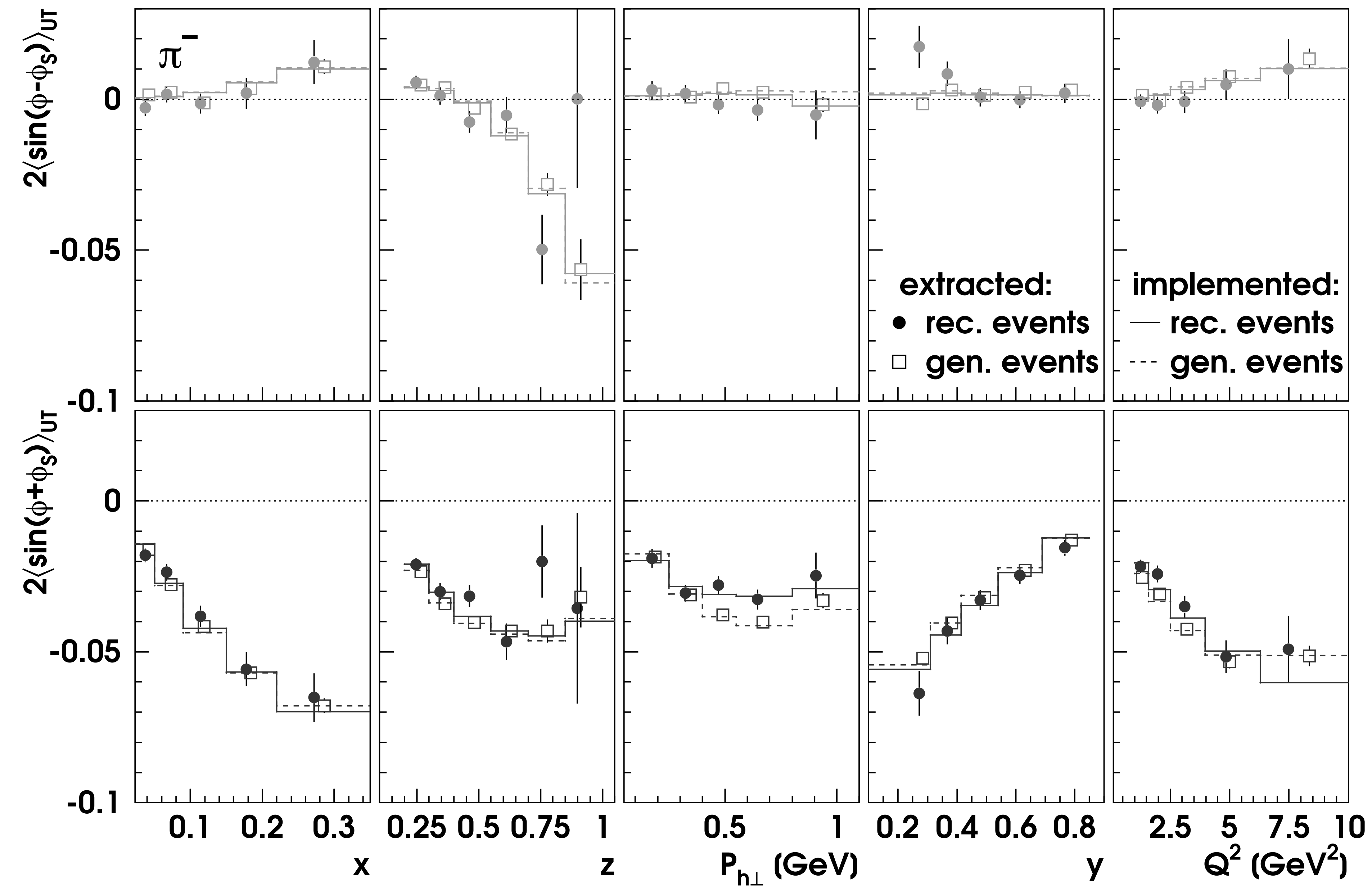
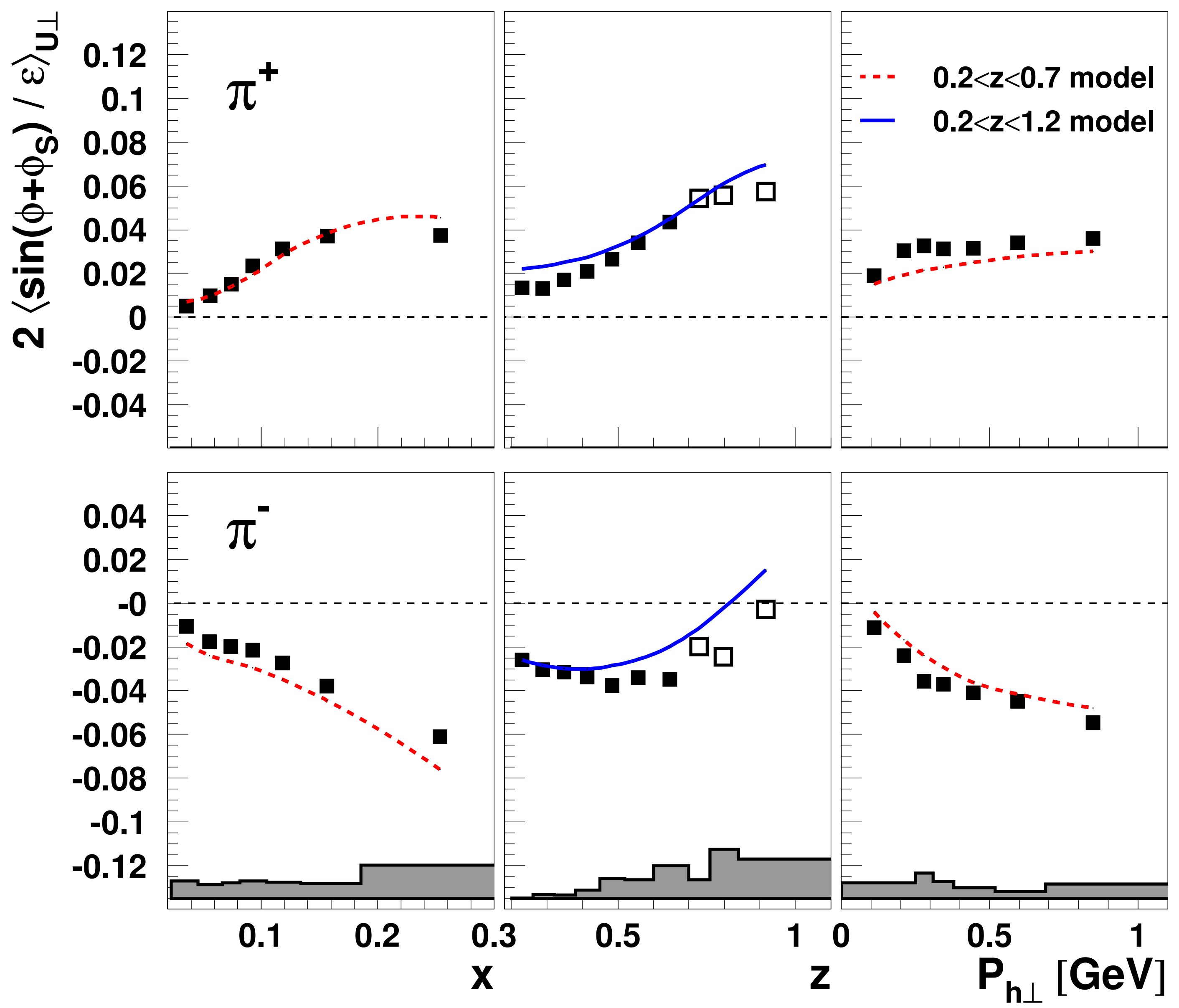
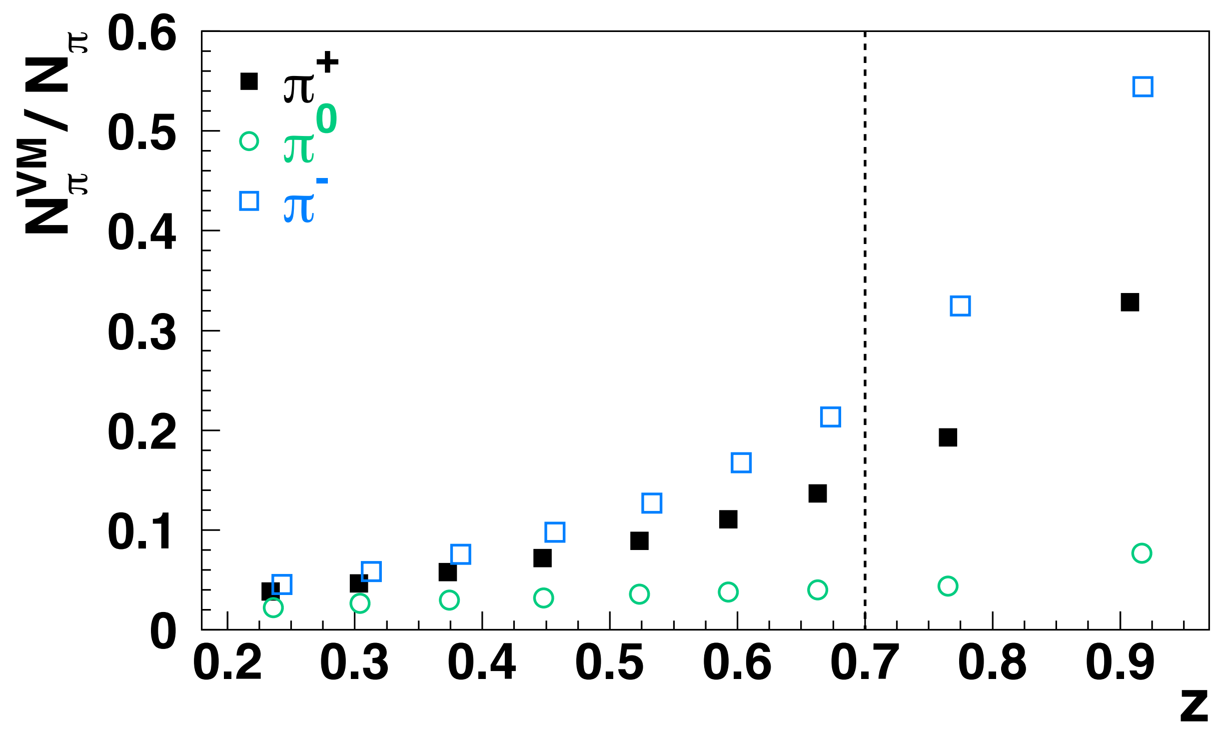
  - model: fully differential Taylor series fit to HERMES data
- systematics: extracted asymmetry vs. asymmetry model evaluated at average kinematics





some highlights

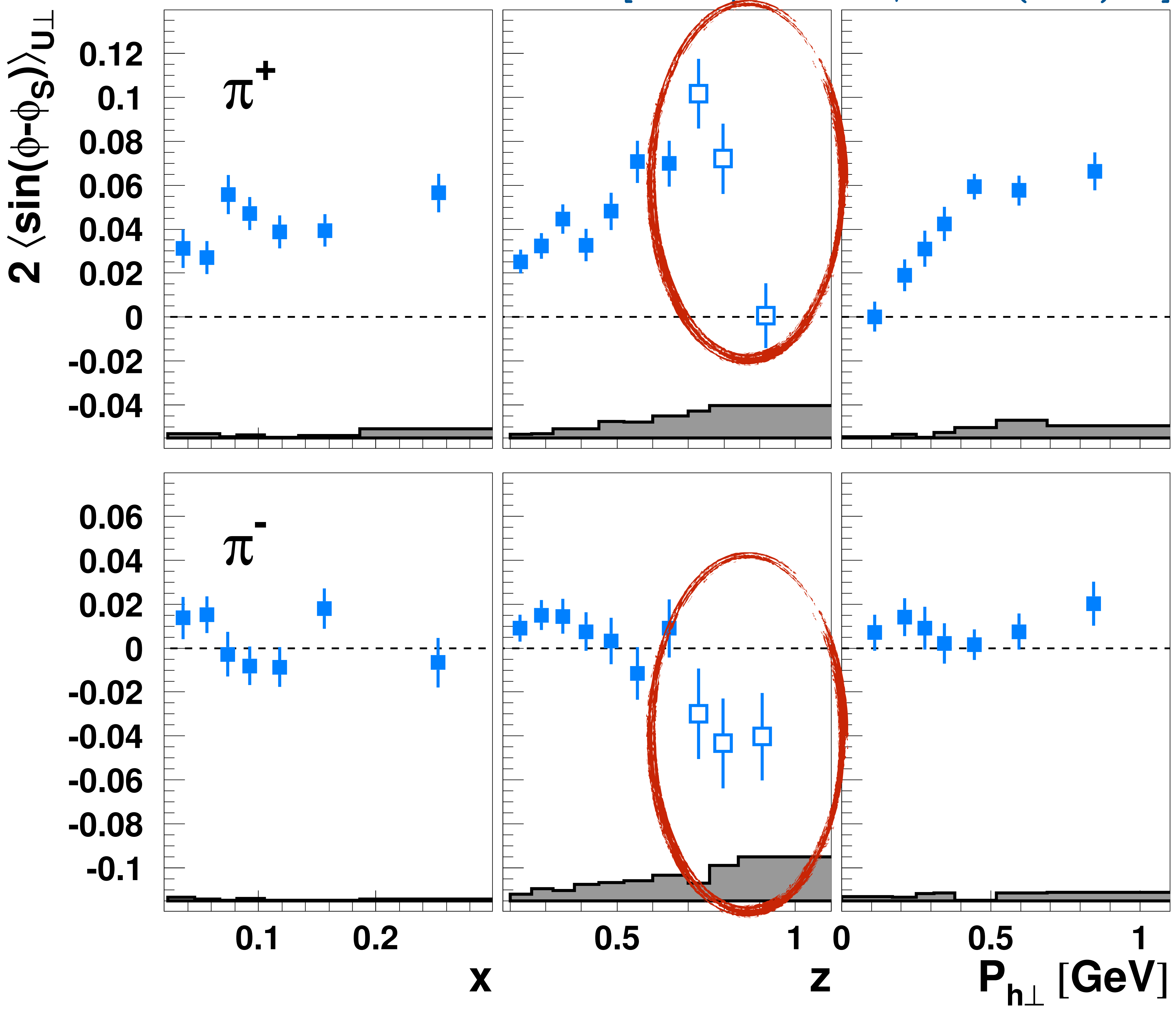
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

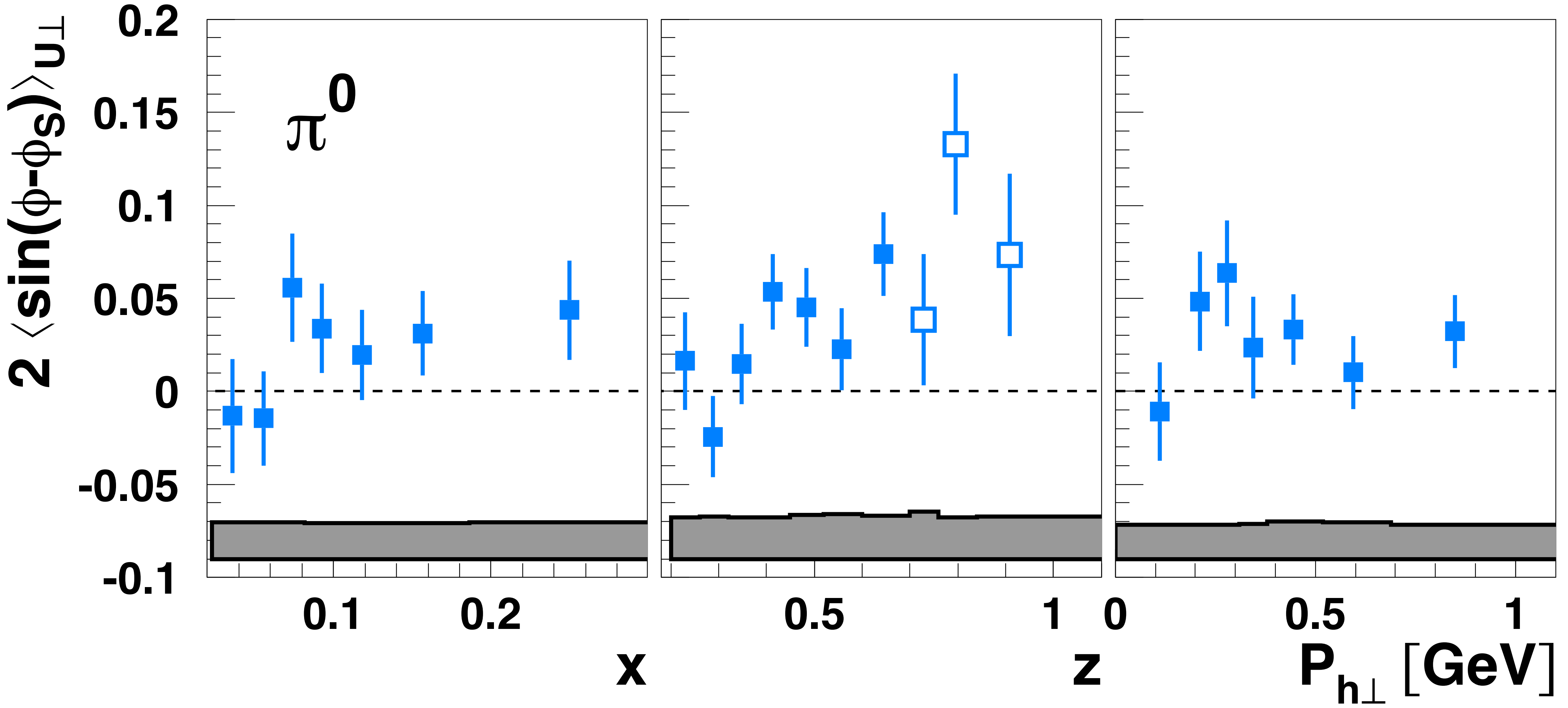


Sivers amplitudes for pions

- high-z data probes region where contributions from exclusive vector-meson production becomes significant
- only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)

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

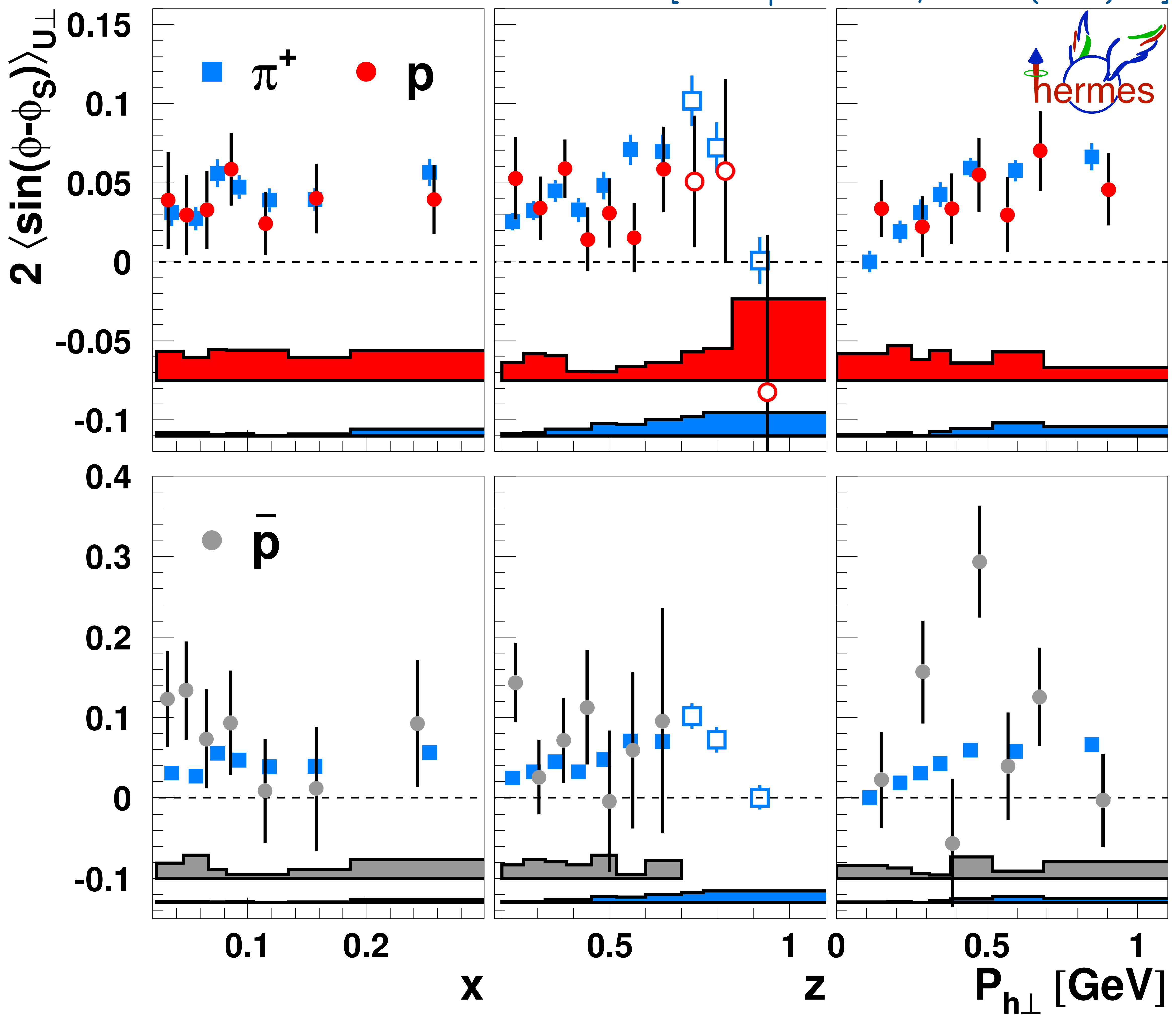




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes
pions vs. (anti)protons

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



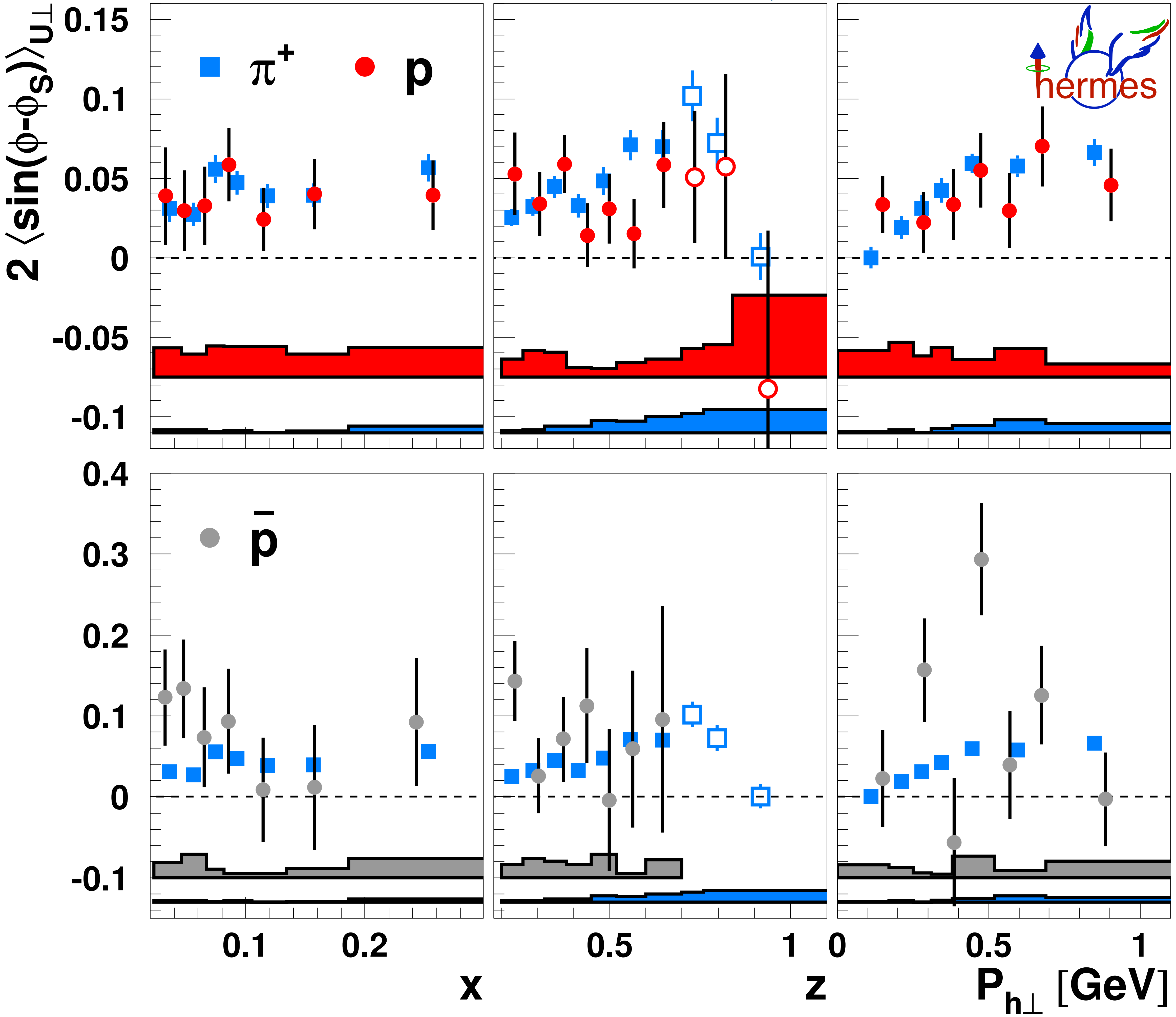
similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

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

Sivers amplitudes
pions vs. (anti)protons

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



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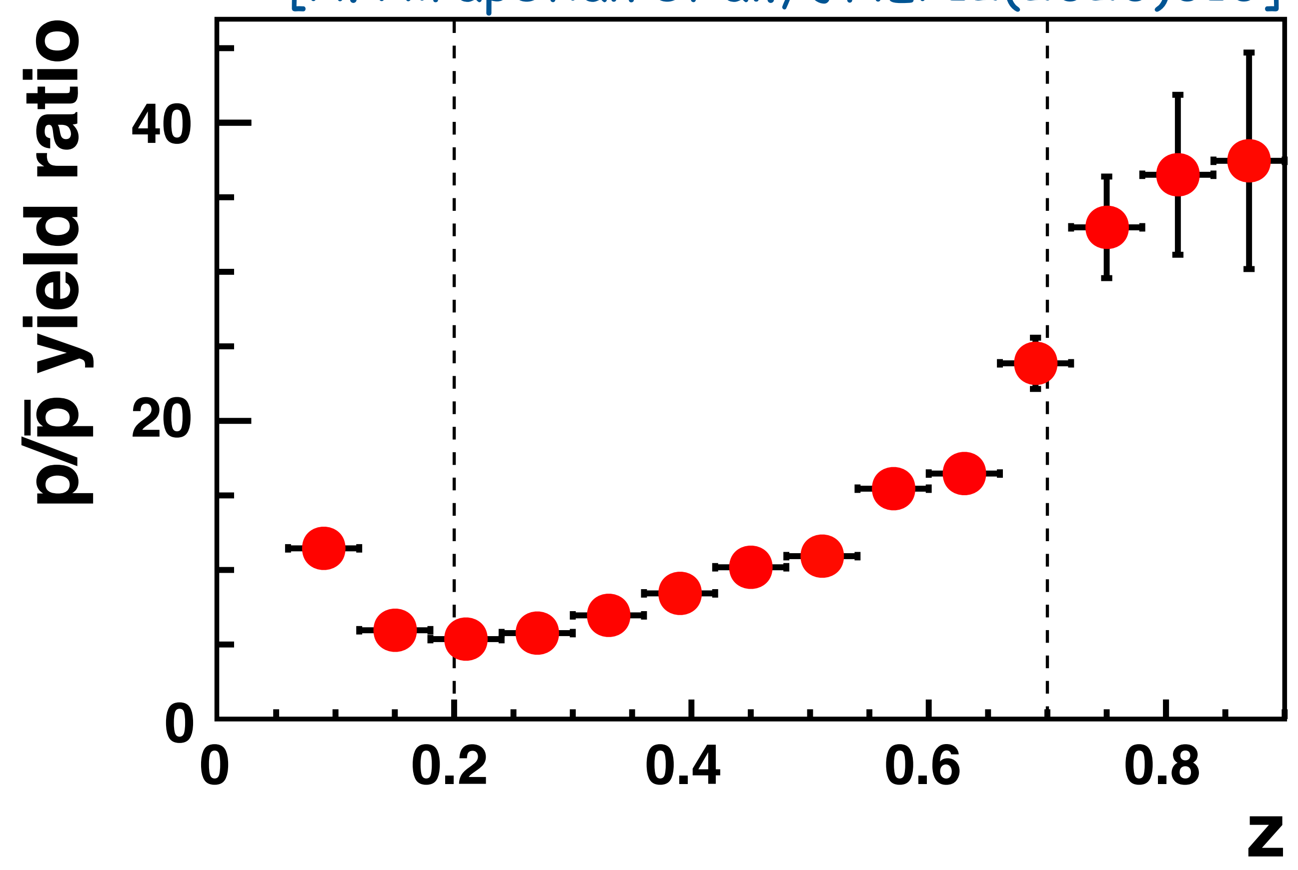

possibly, onset of target fragmentation only at lower z

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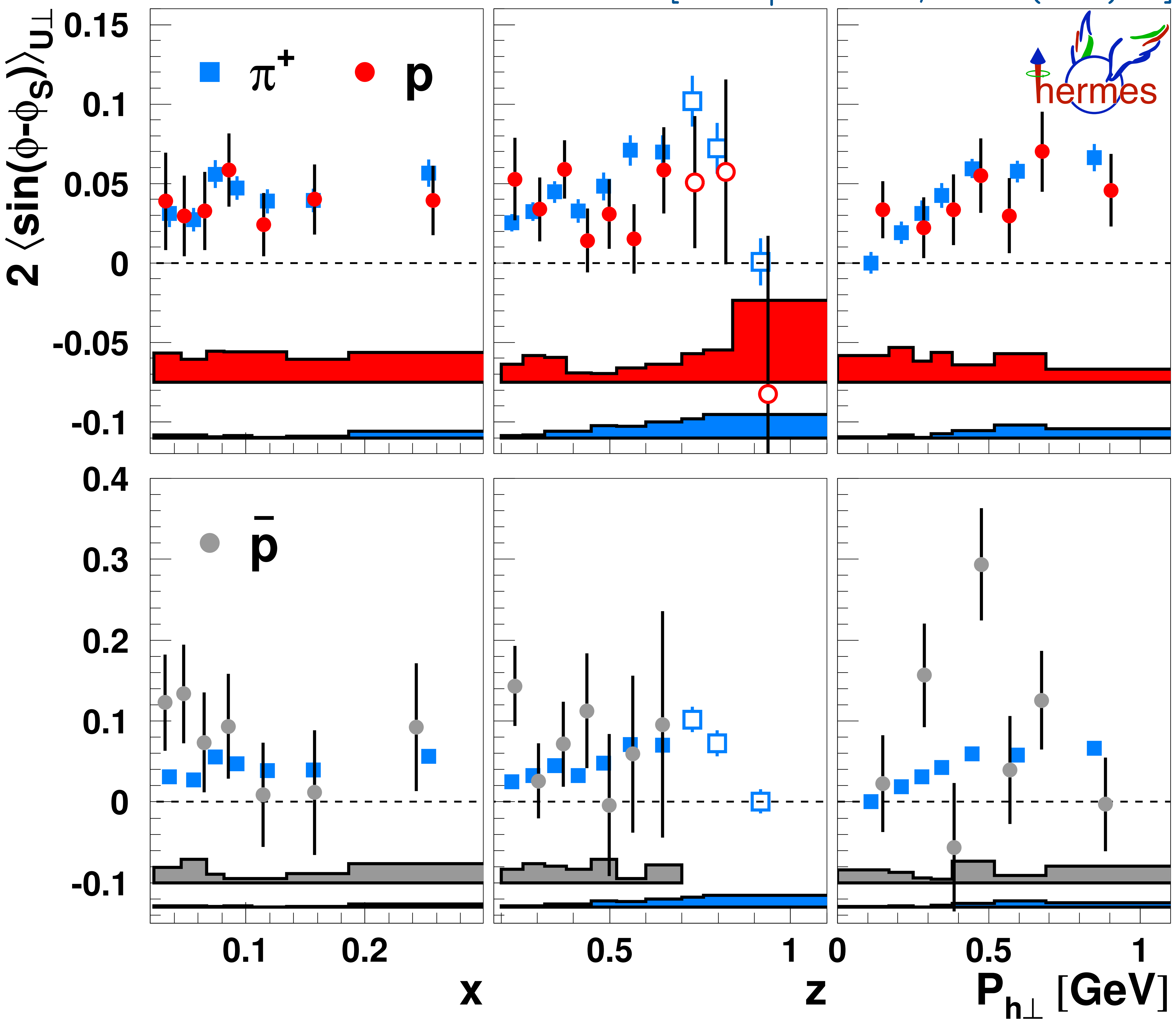

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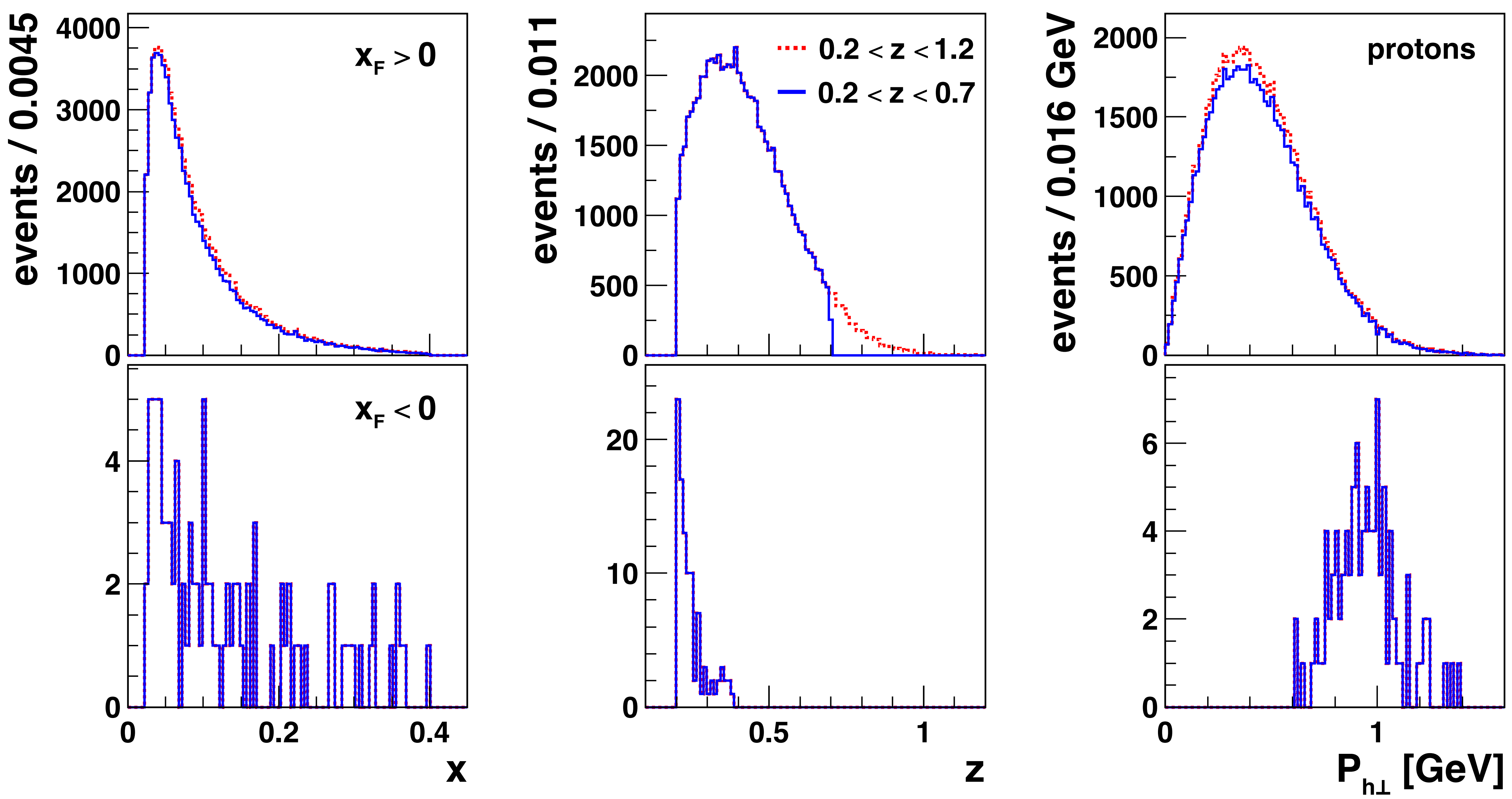

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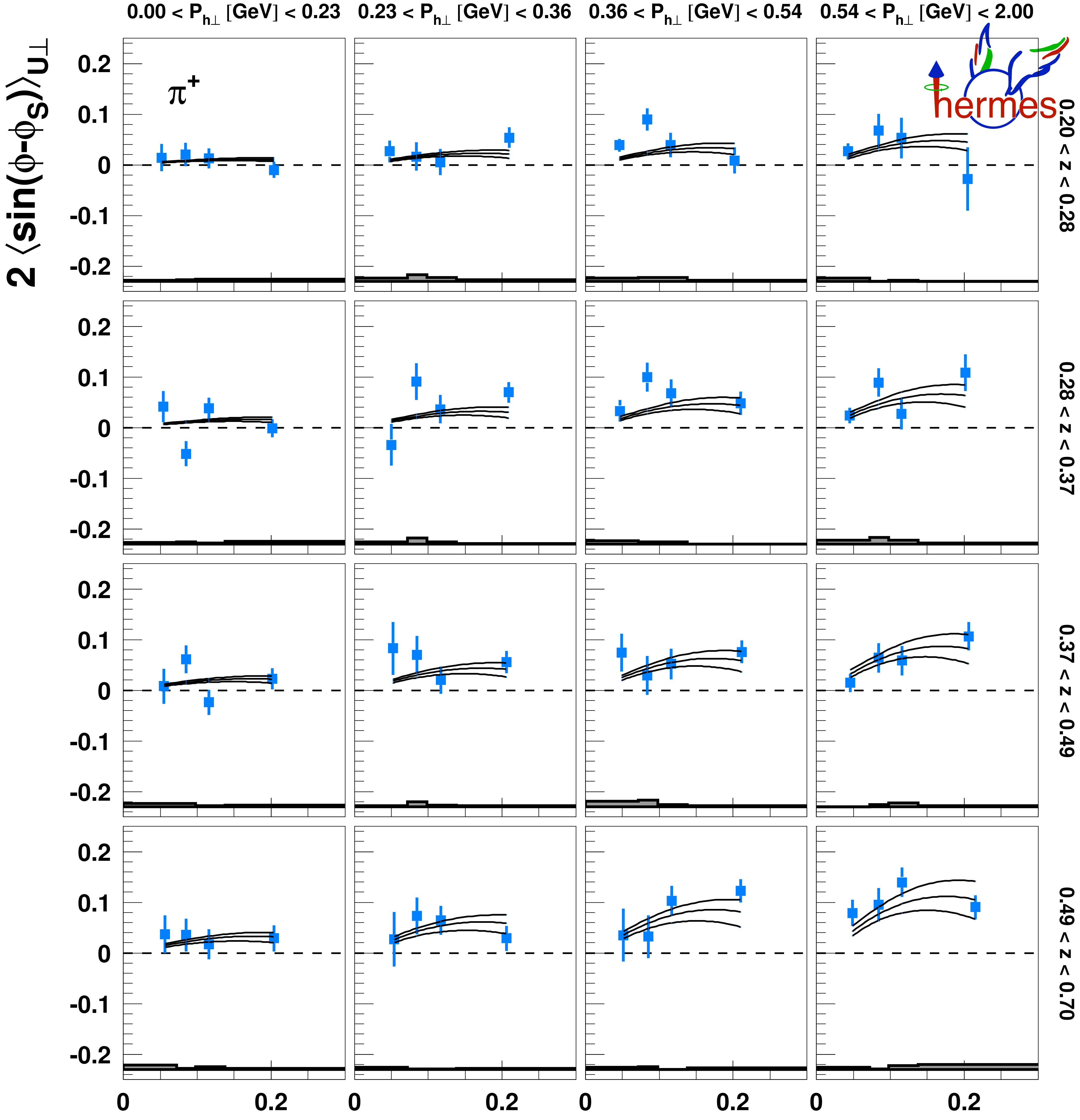
Sivers amplitudes multi-dimensional analysis

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



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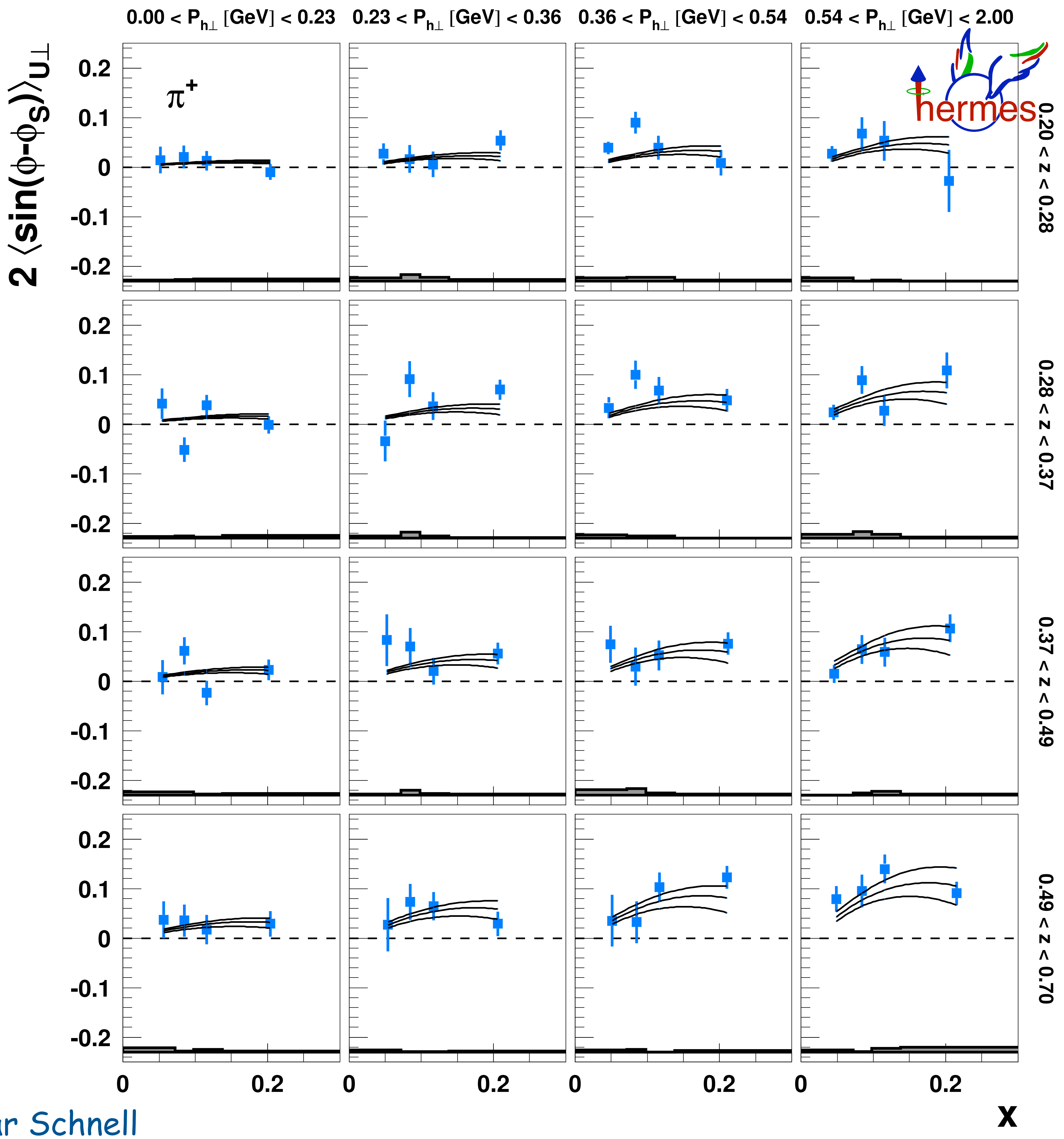
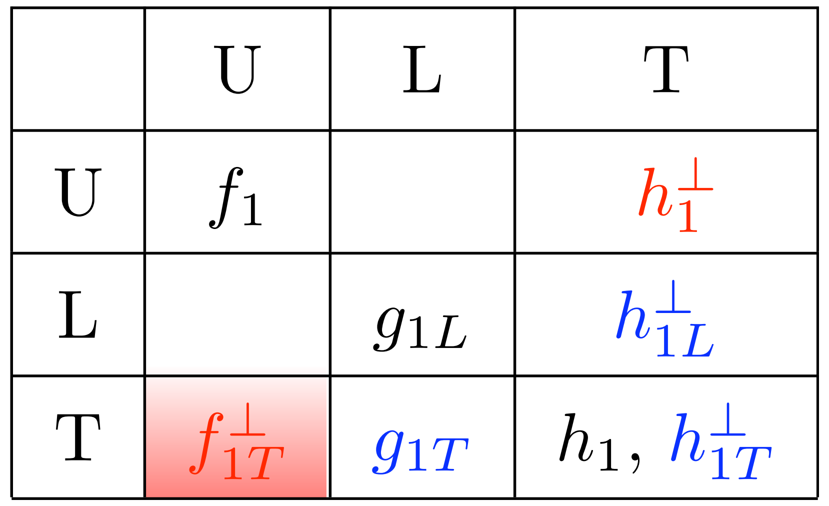


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$



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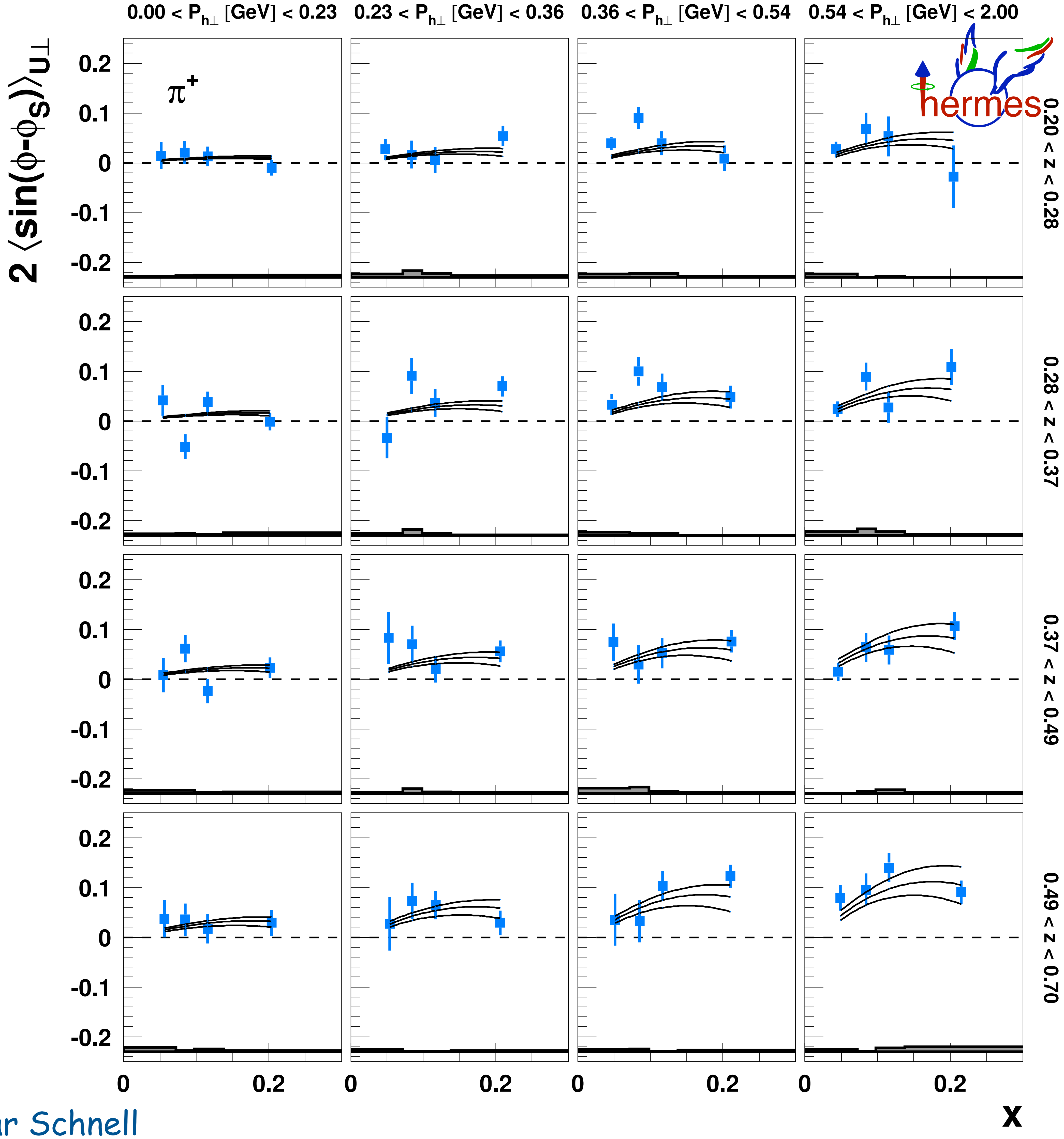

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength

Sivers amplitudes
multi-dimensional analysis

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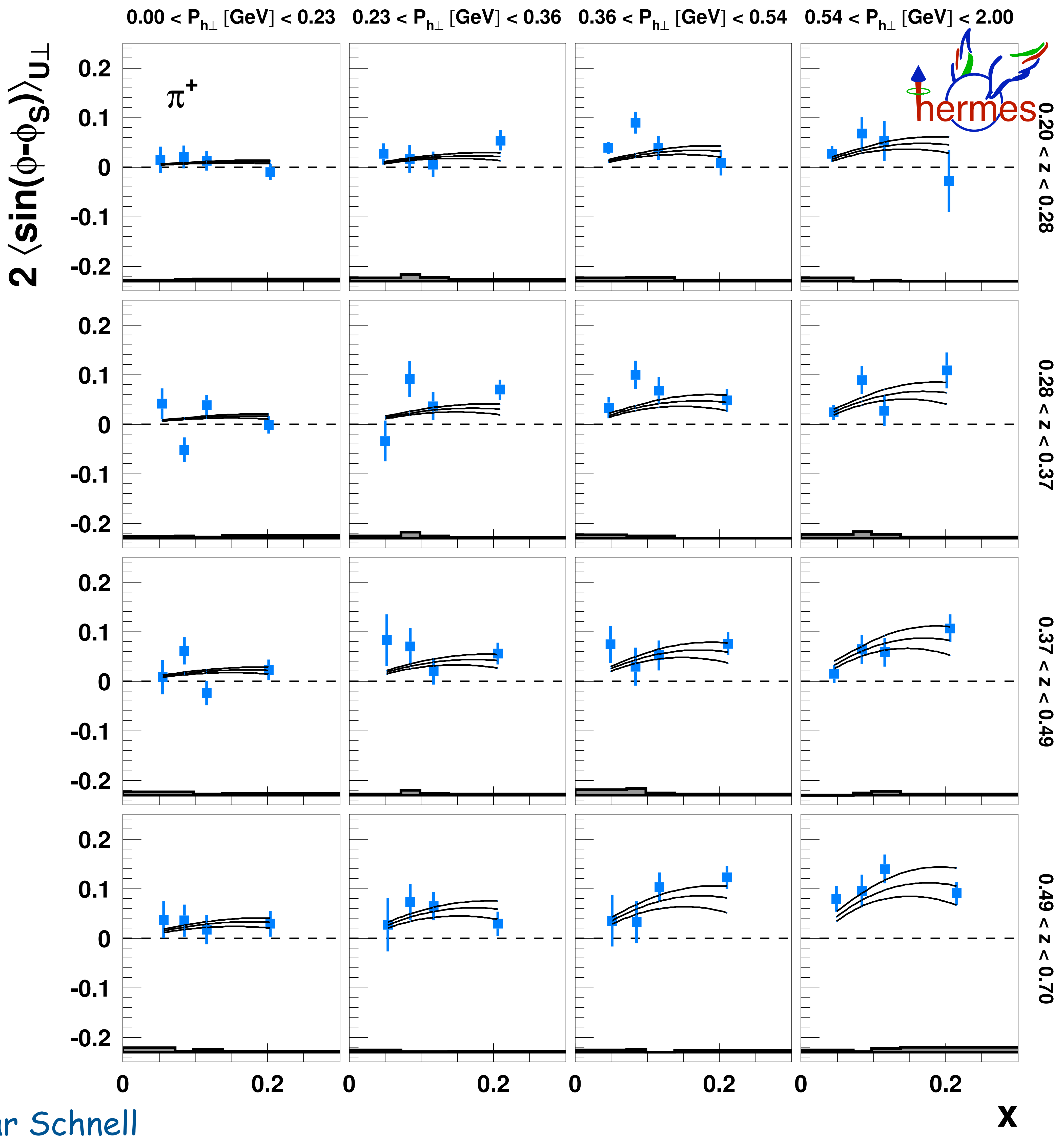

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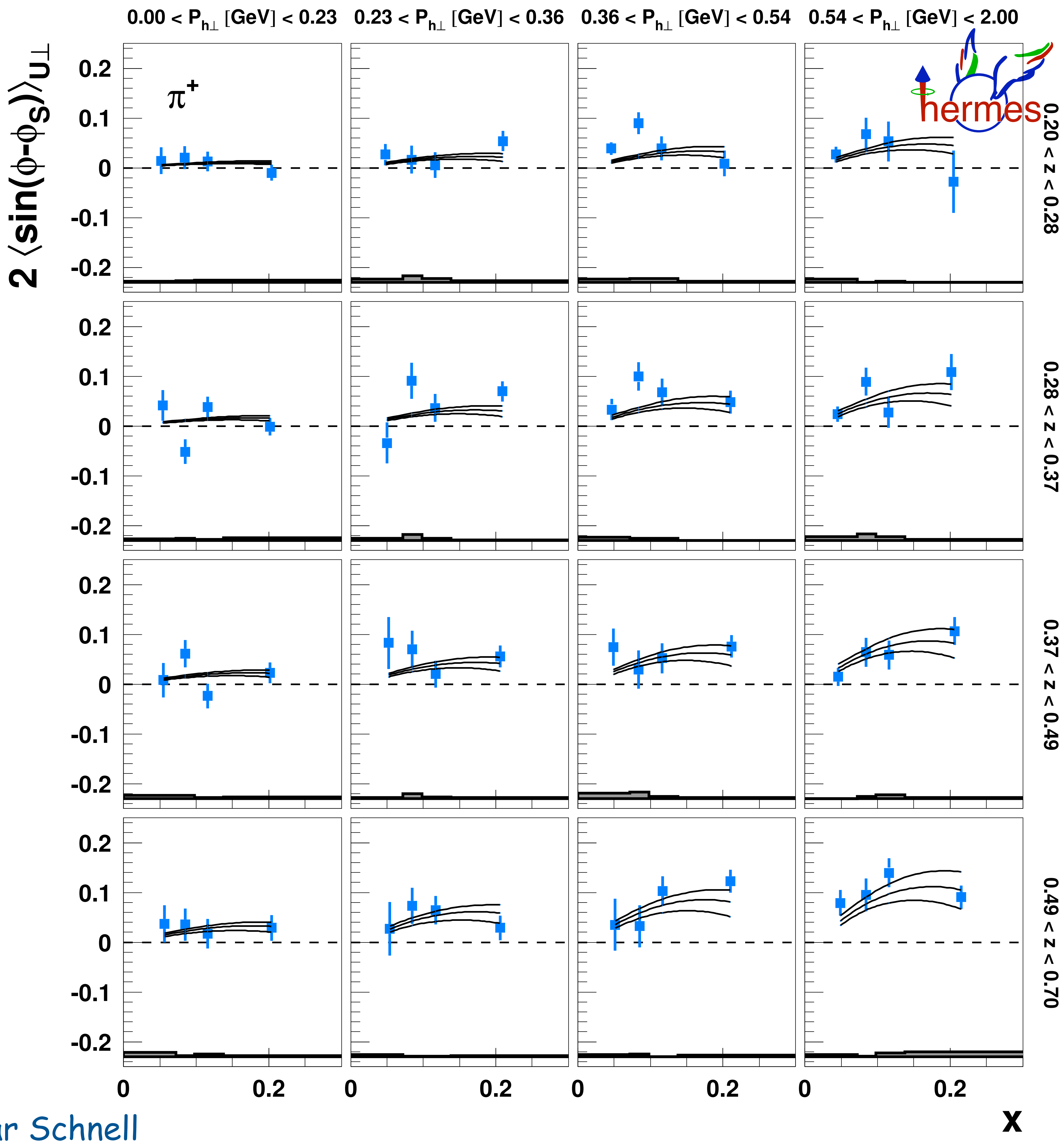

- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

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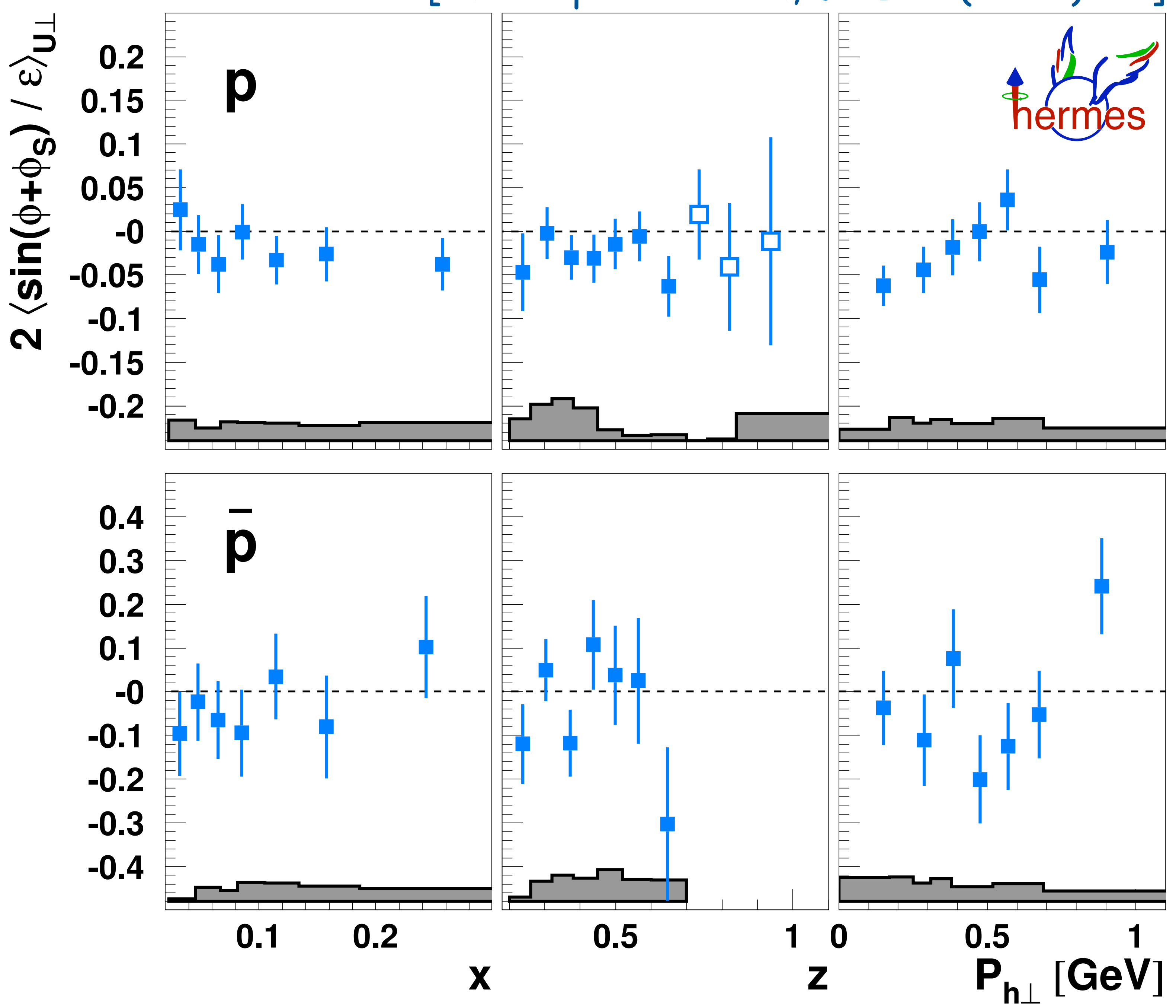
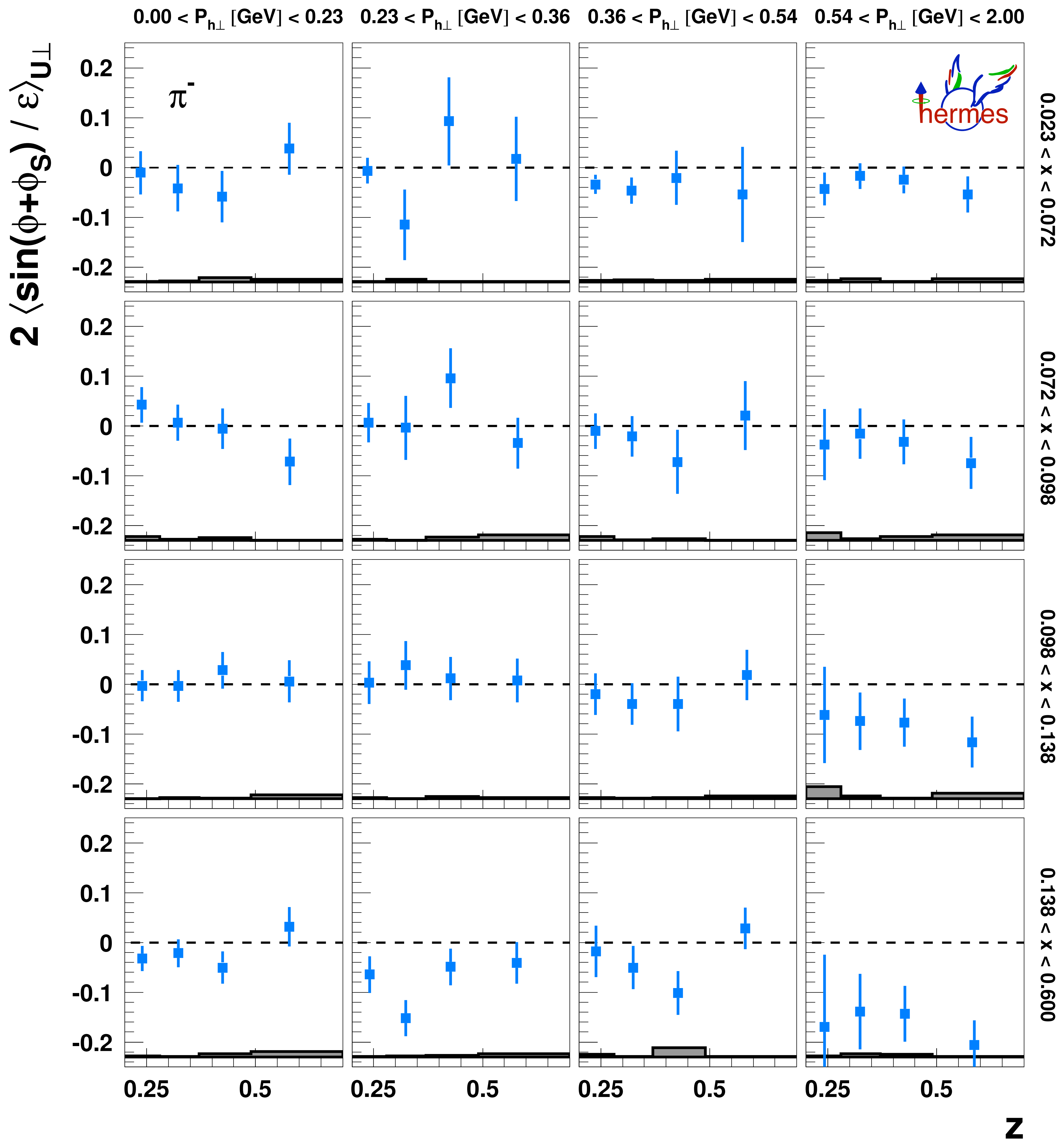
new HERMES results on Collins amplitudes

[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

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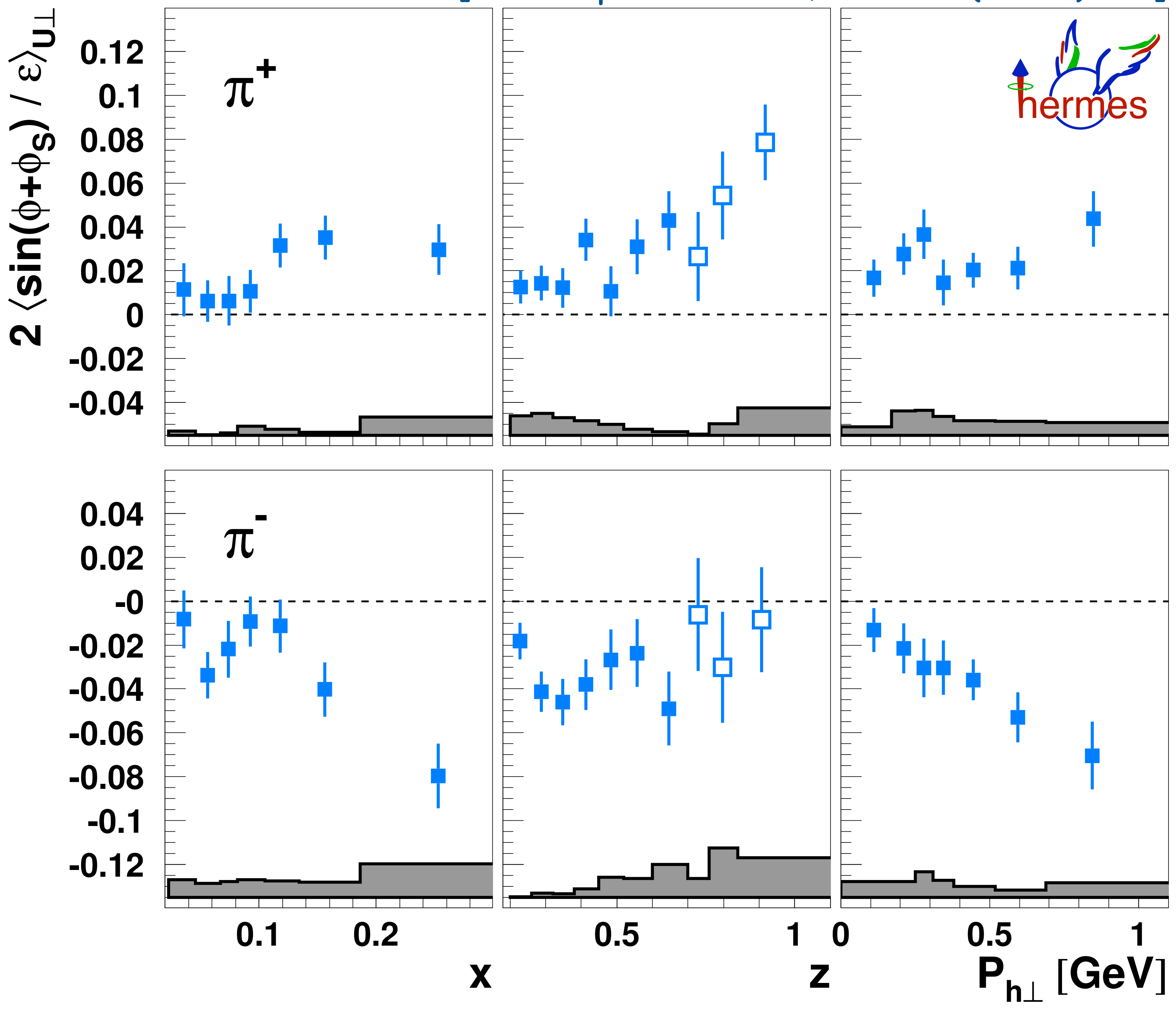

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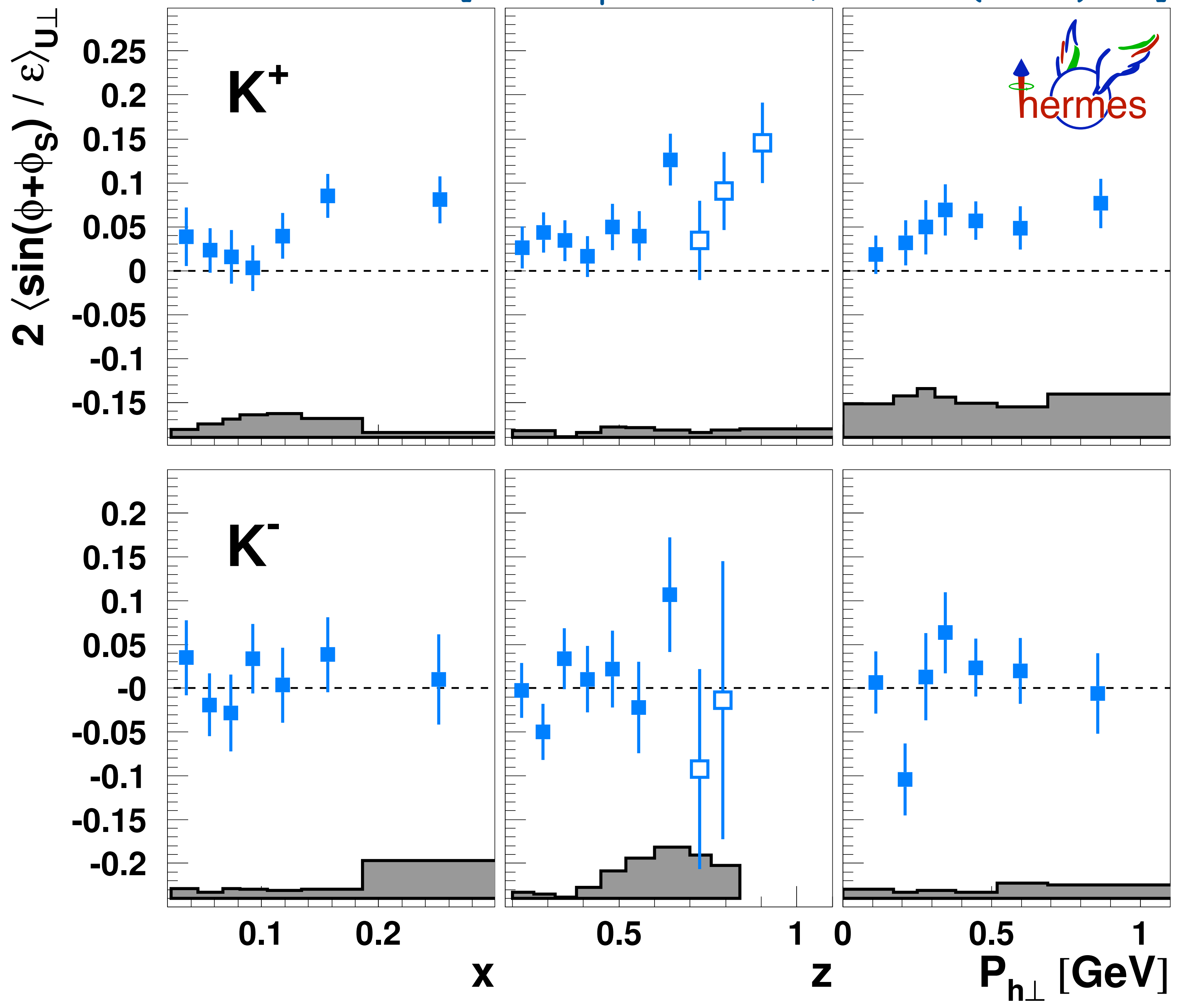
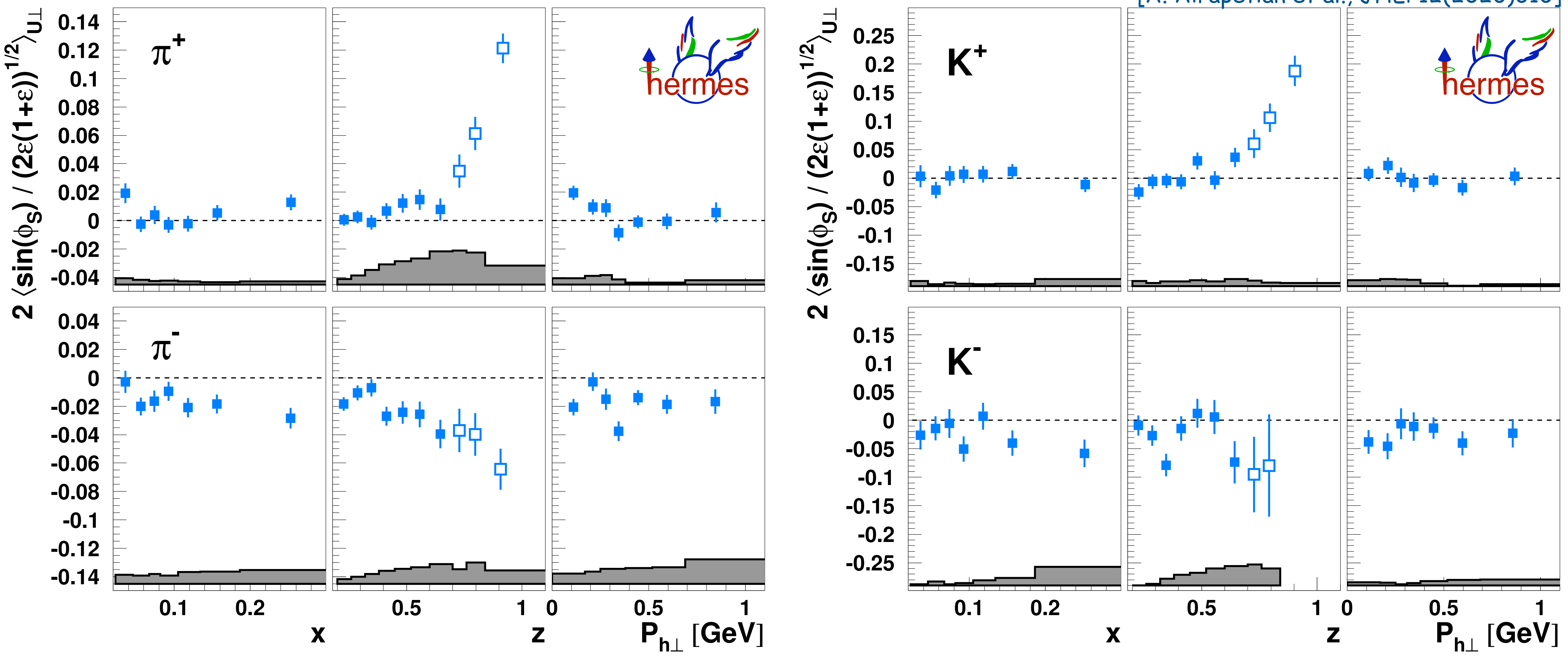


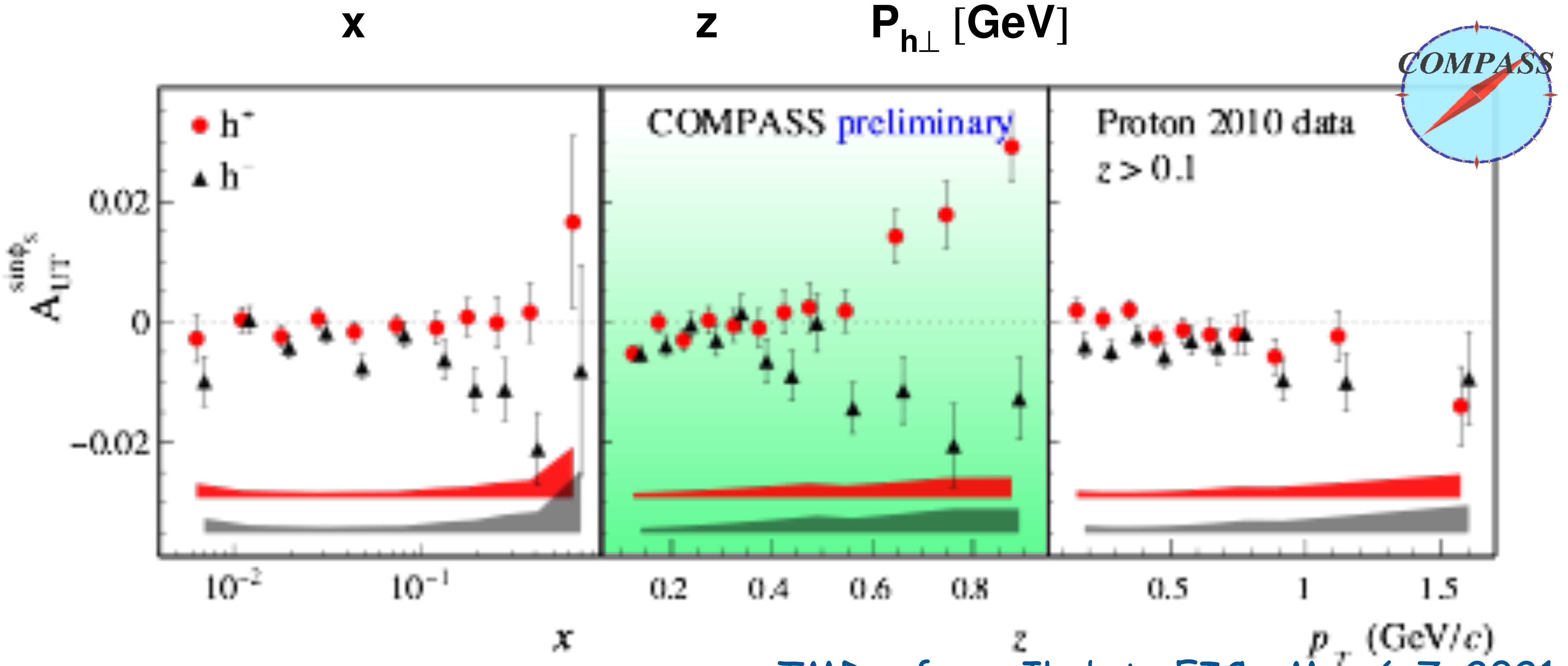
- results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic "depolarization" prefactor
- **high-z region** probes transition region to exclusive domain (with increasing amplitudes for positive pions and kaons)

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

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



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

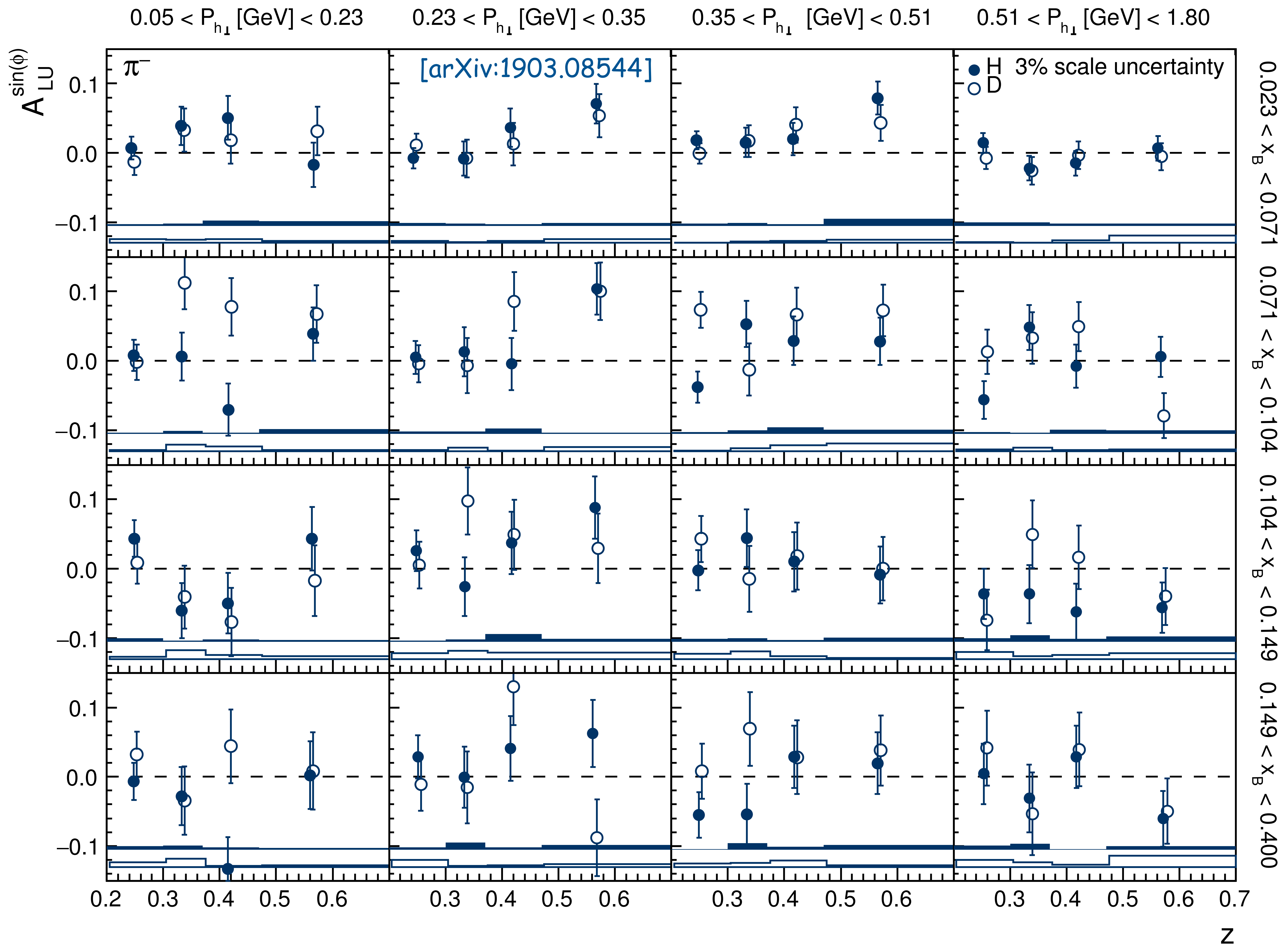


out of time … no specific conclusions

- check carefully acceptance effects (no experiment has perfect acceptance)
  - requires very good model of physics one is after
- do not exclude data just because some MC tells you the data are bad
  - rather include as much information in addition to your main results, in particular data-driven kinematic distributions
- bin in as many dimensions as possible (best fully differential)

backup slides

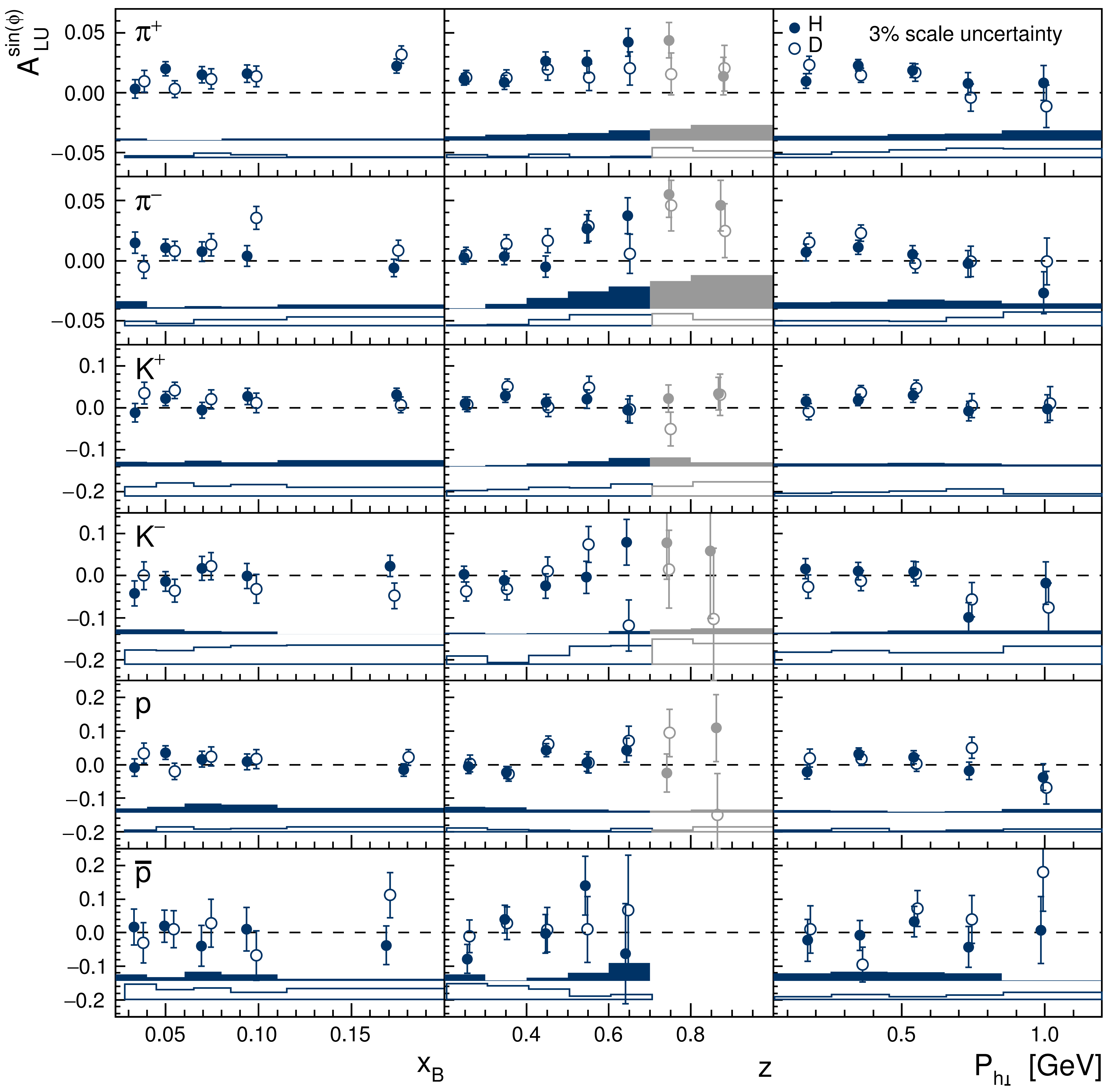
subleading twist II - <sin(ϕ)>$_{LU}$ HERMES 3d analysis



most comprehensive presentation, for discussion use 1d binning

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

[arXiv:1903.08544]



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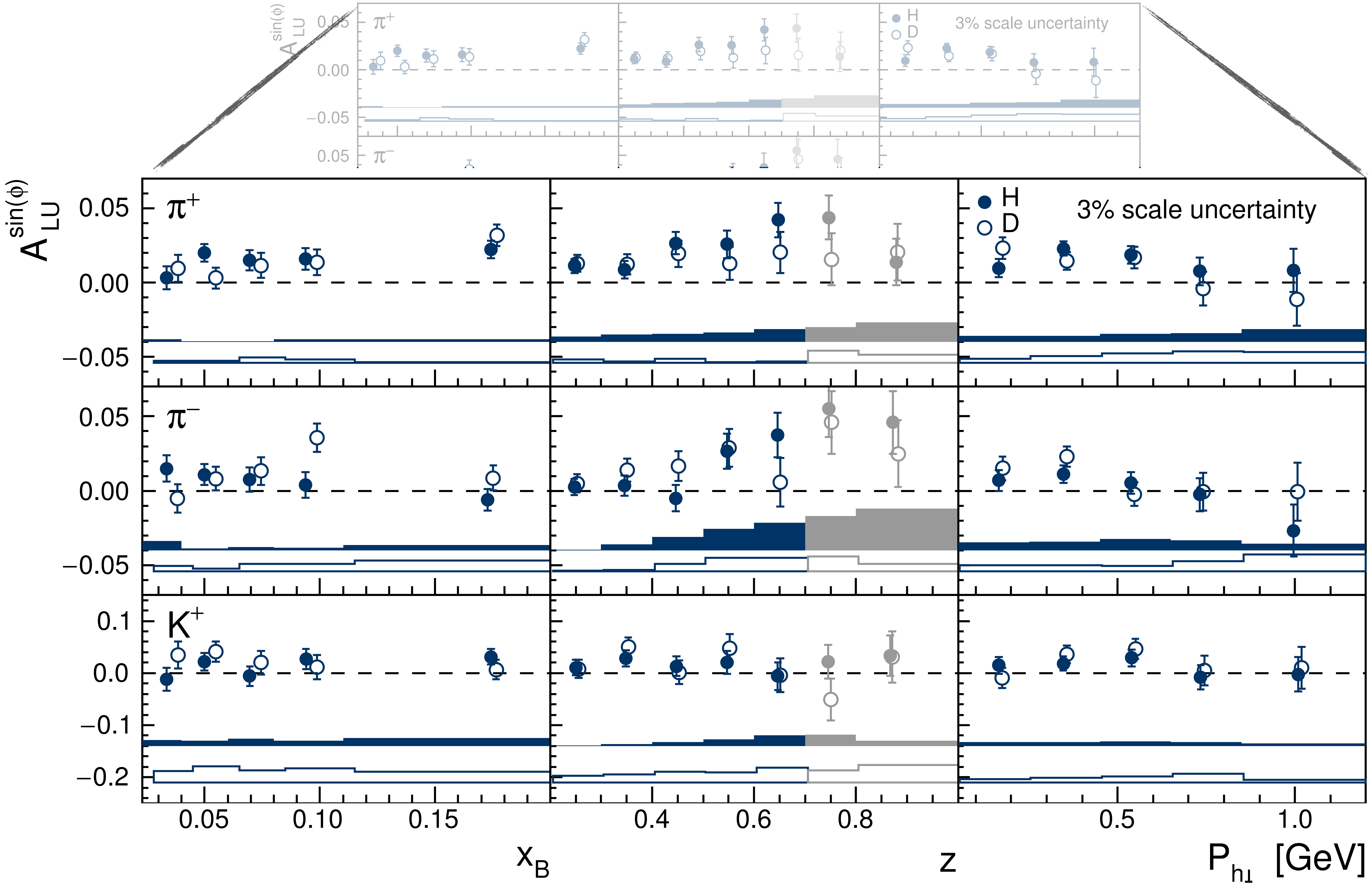

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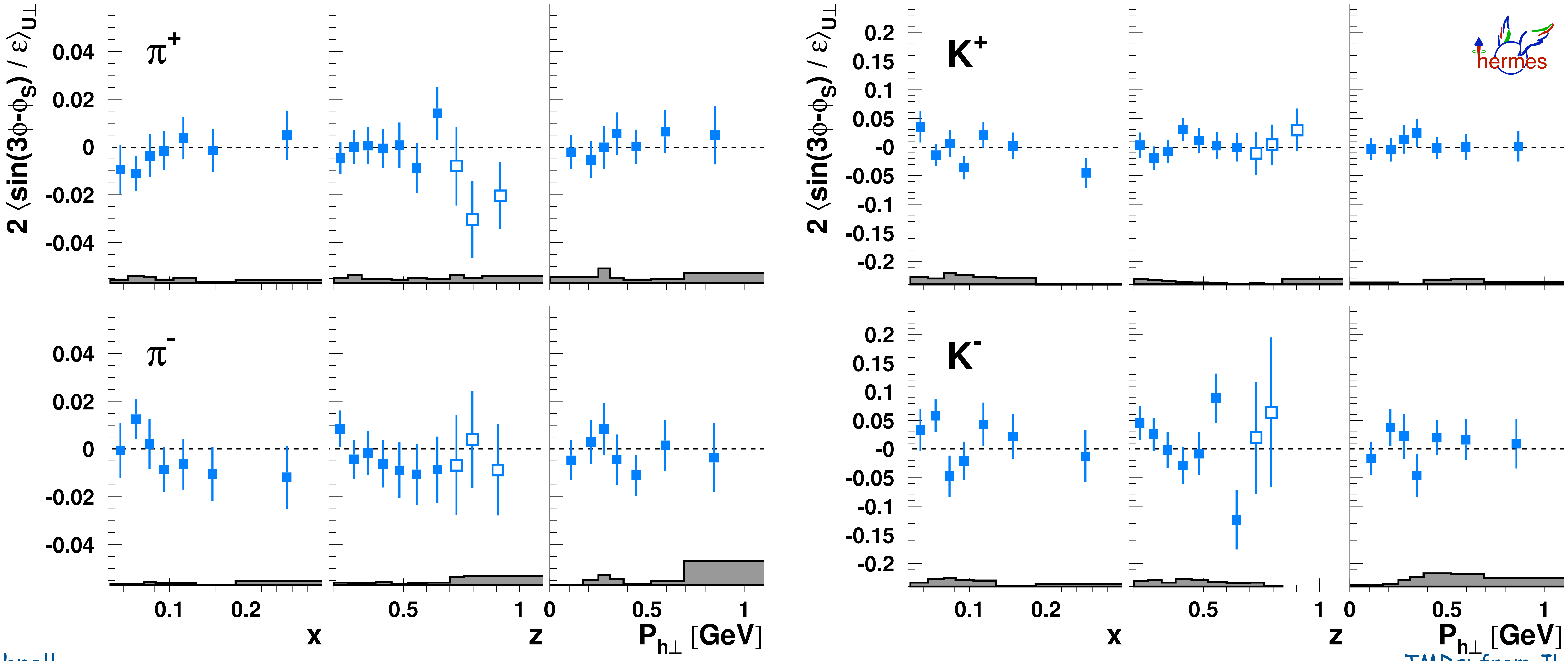
Pretzelosity

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

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



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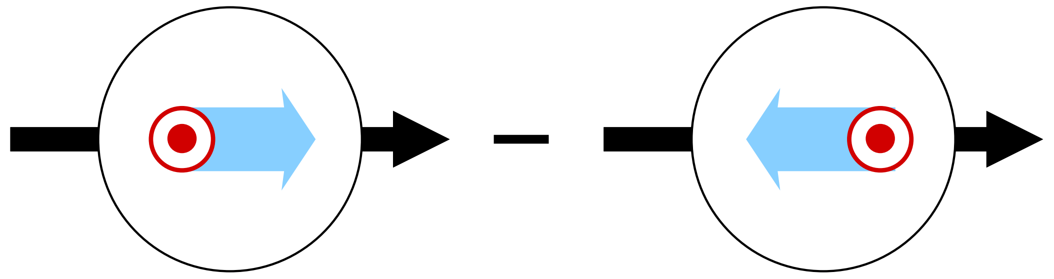
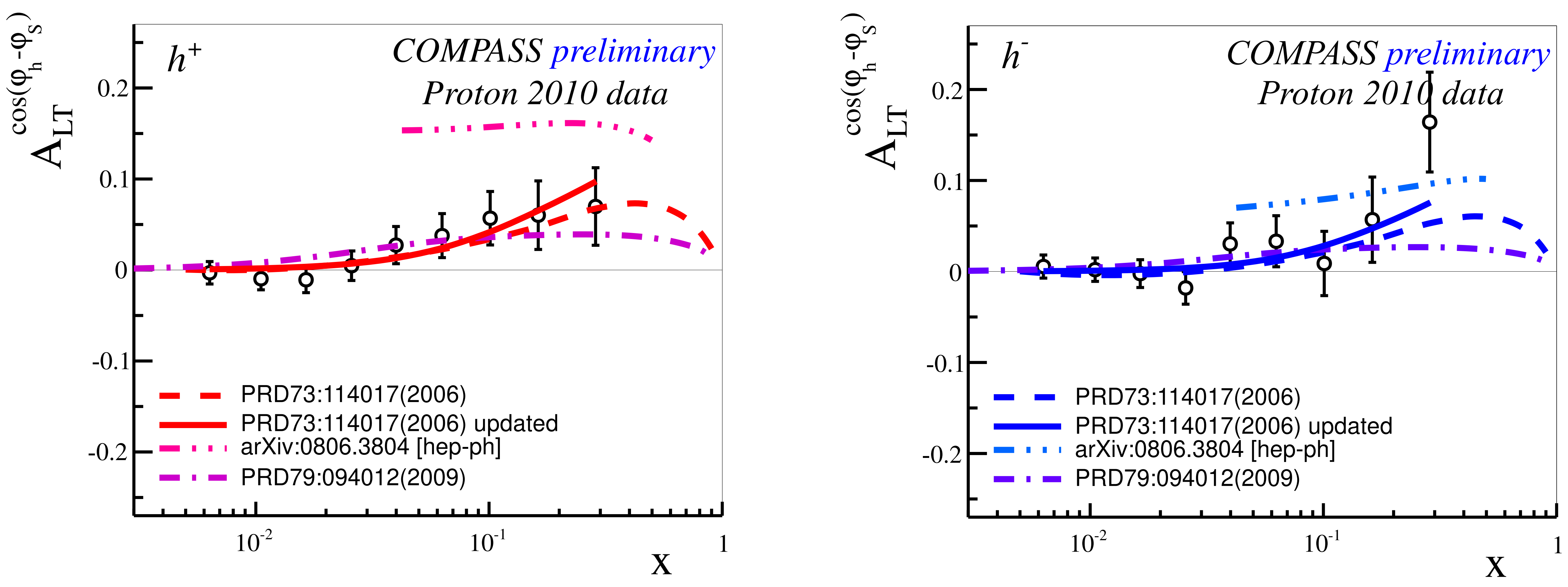
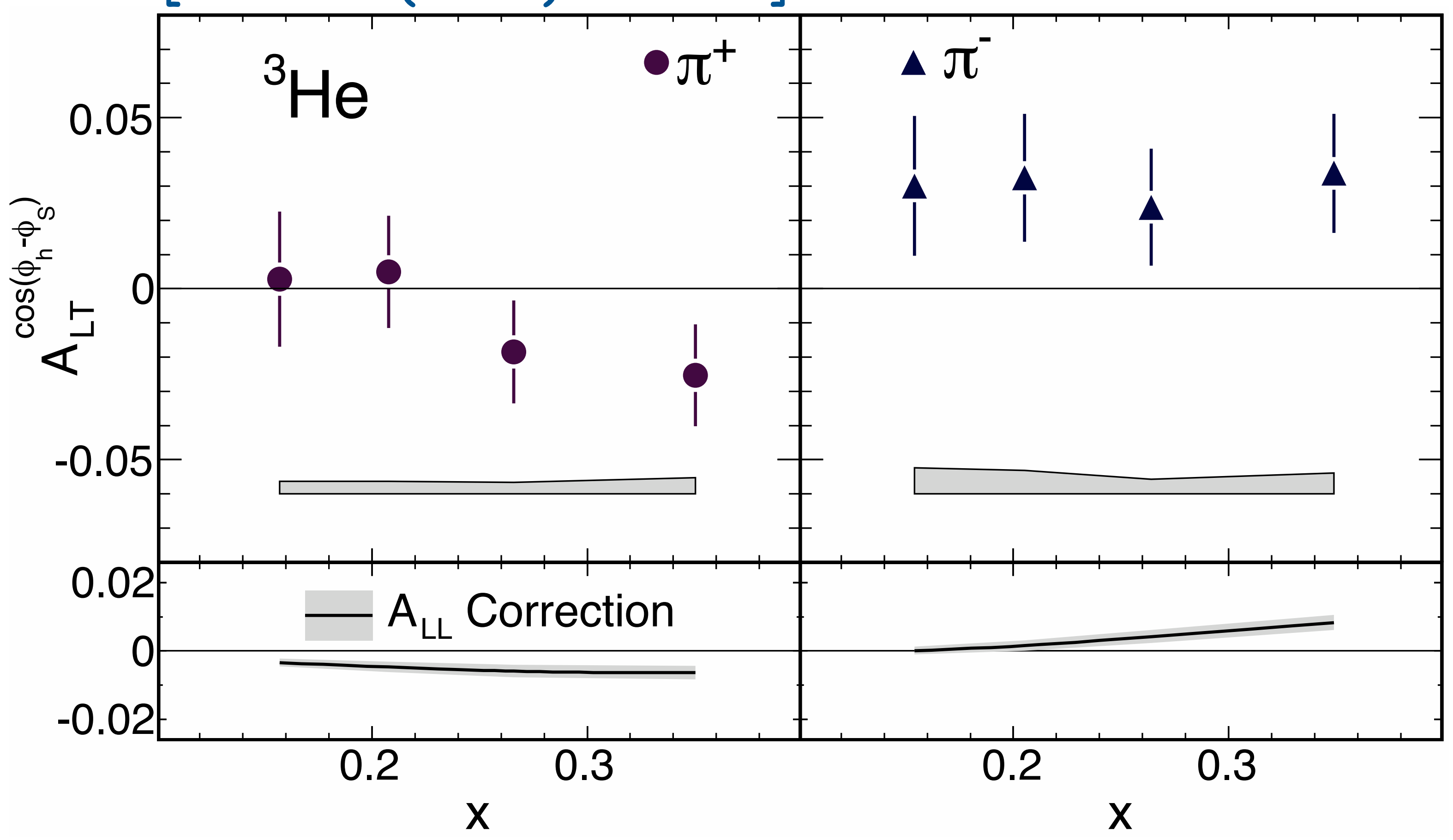


Worm-Gear II

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



[PRL 108 (2012) 052001]



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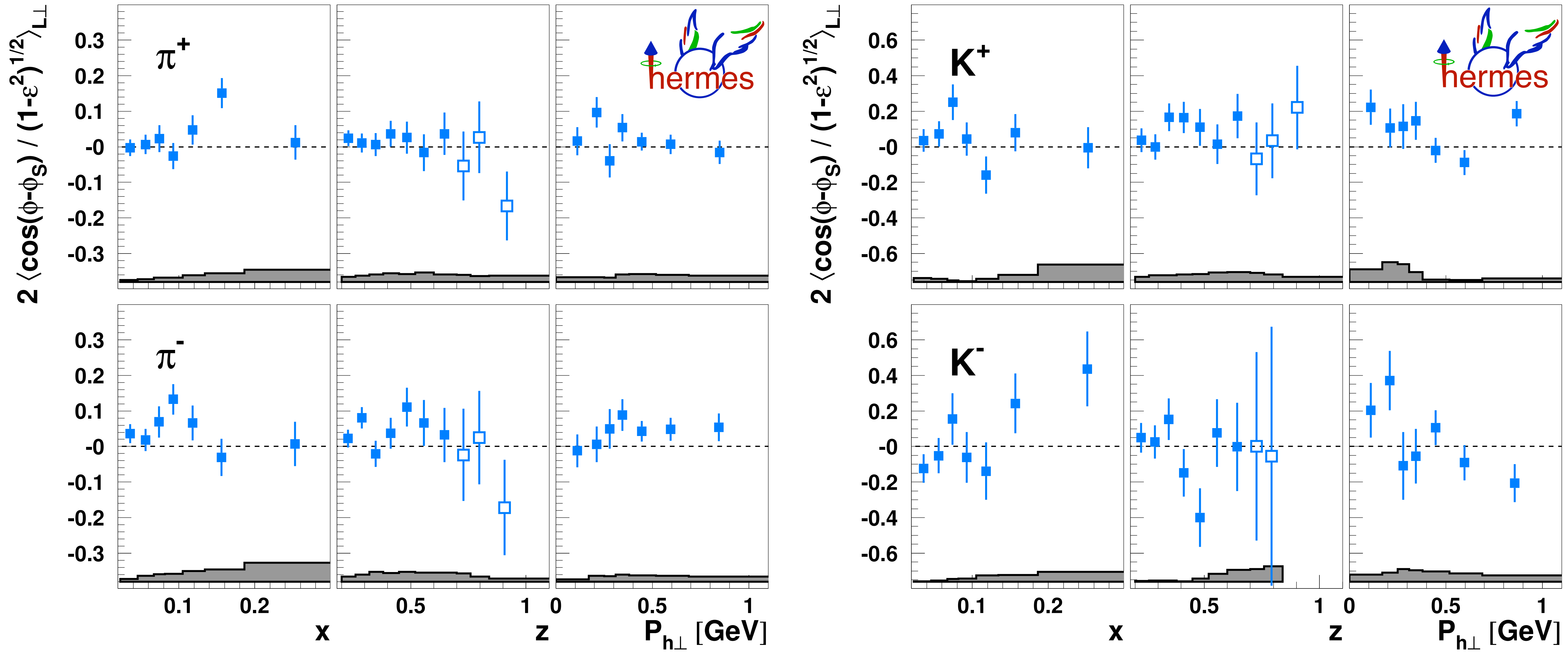
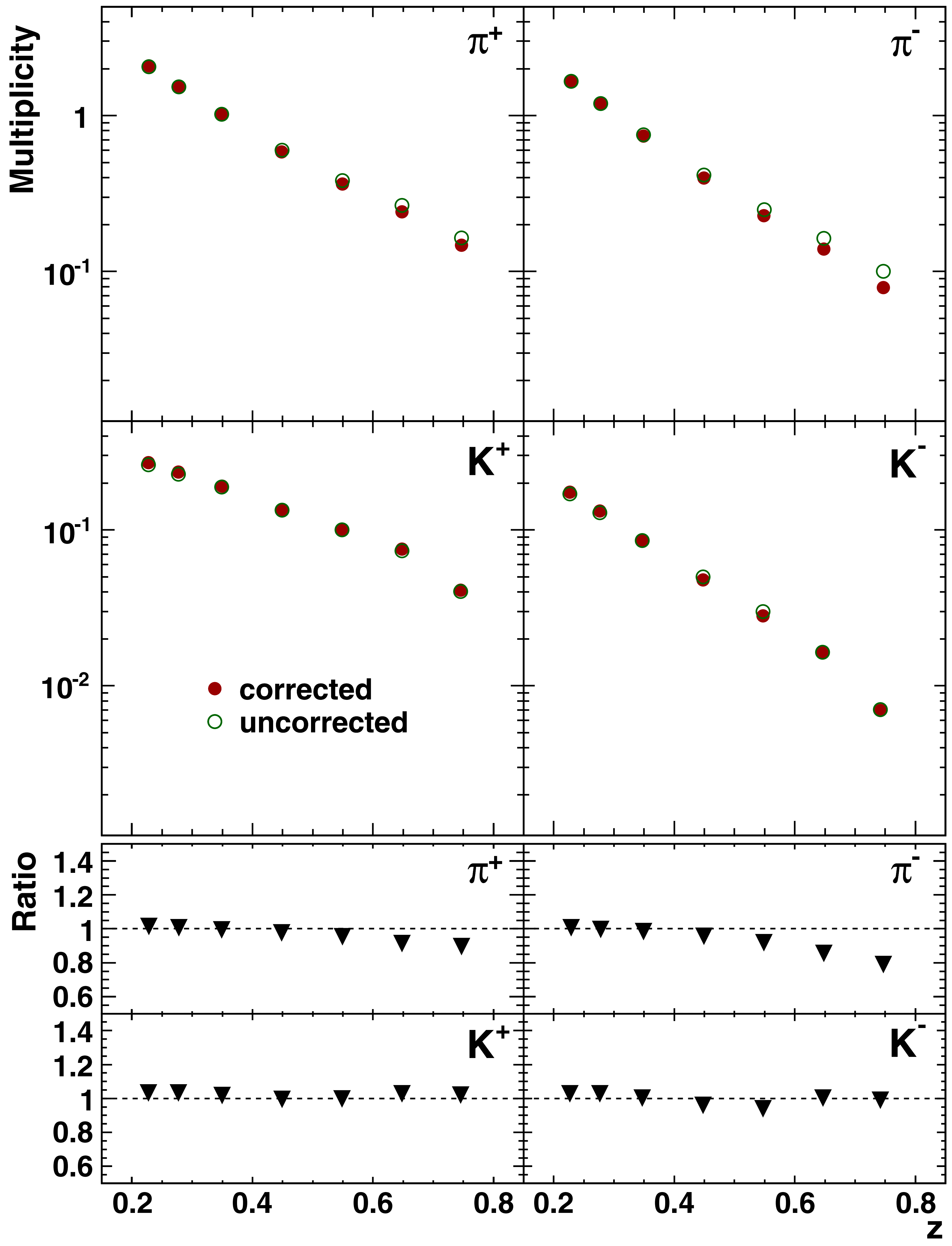


Subtracting mesons from decay of excl. VM production

PHYSICAL REVIEW D **87,** 074029 (2013)



- “corrected” should better read “VM subtracted”

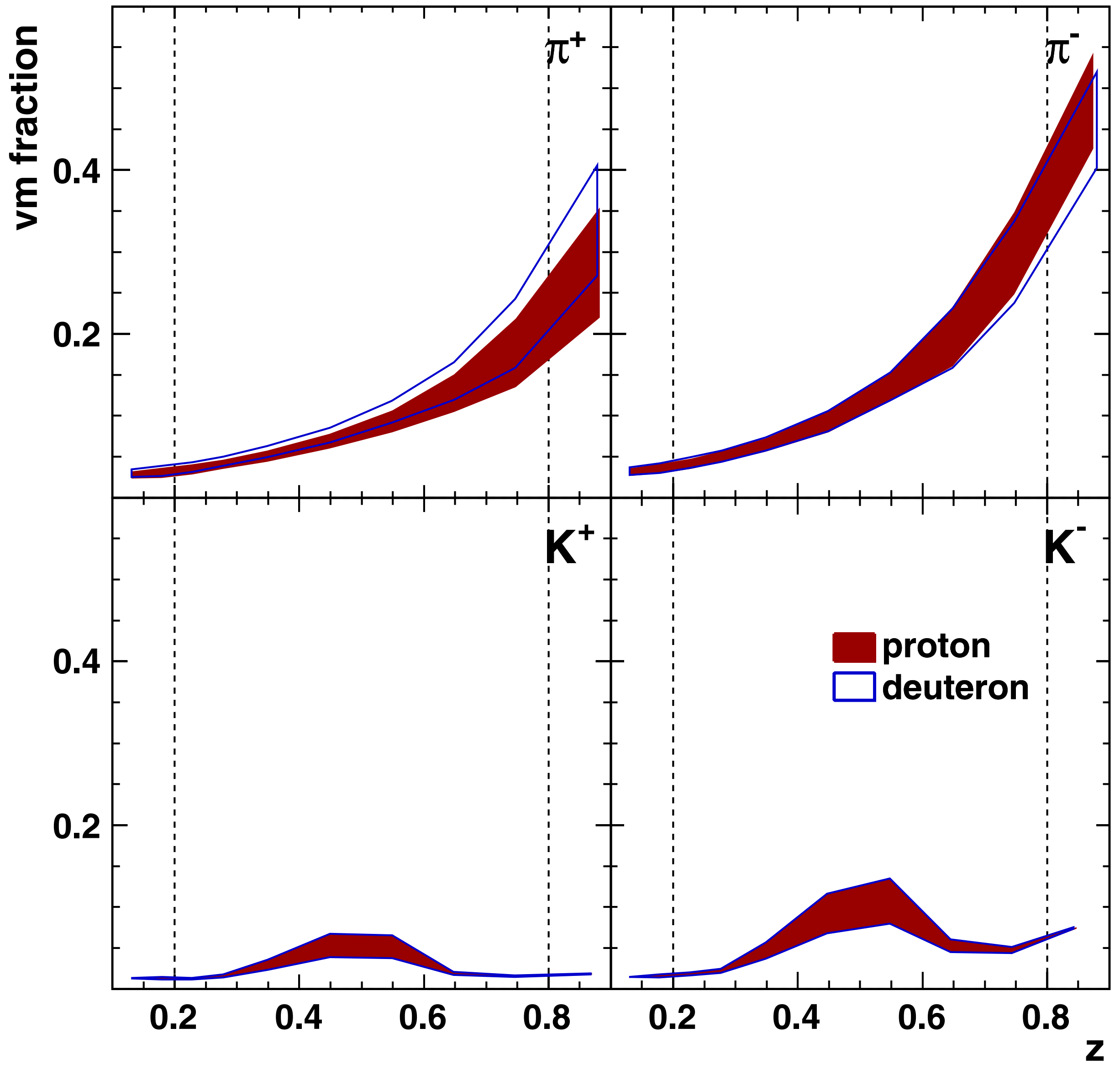
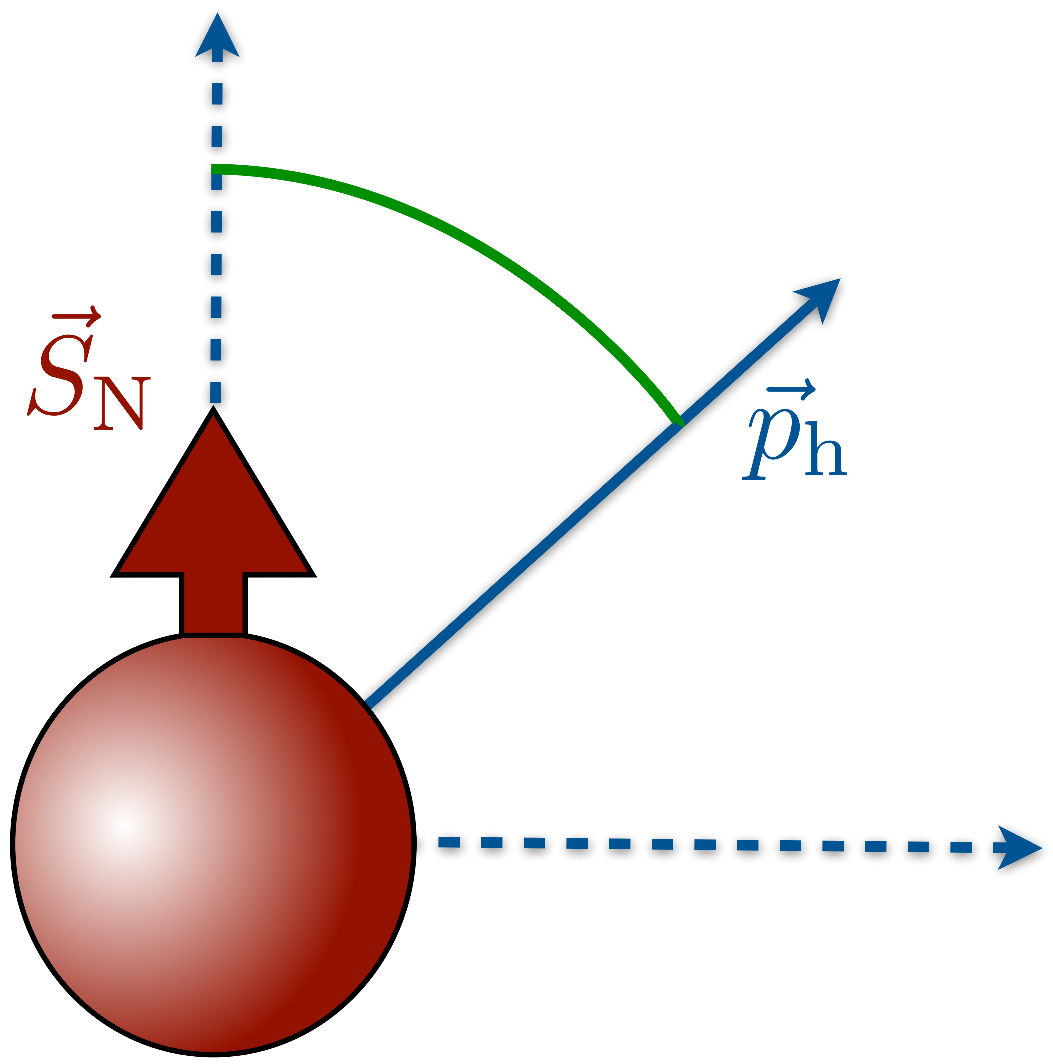


FIG. 3 (color online). Fraction of mesons generated by the decay of exclusive vector mesons as a function of z, from PYTHIA (see text). The widths of the bands indicate the uncertainty in the corresponding fractions. The vertical dashed lines are the limits in z used in the multiplicity extractions.

inclusive hadrons: A_{UT} sinψ amplitude

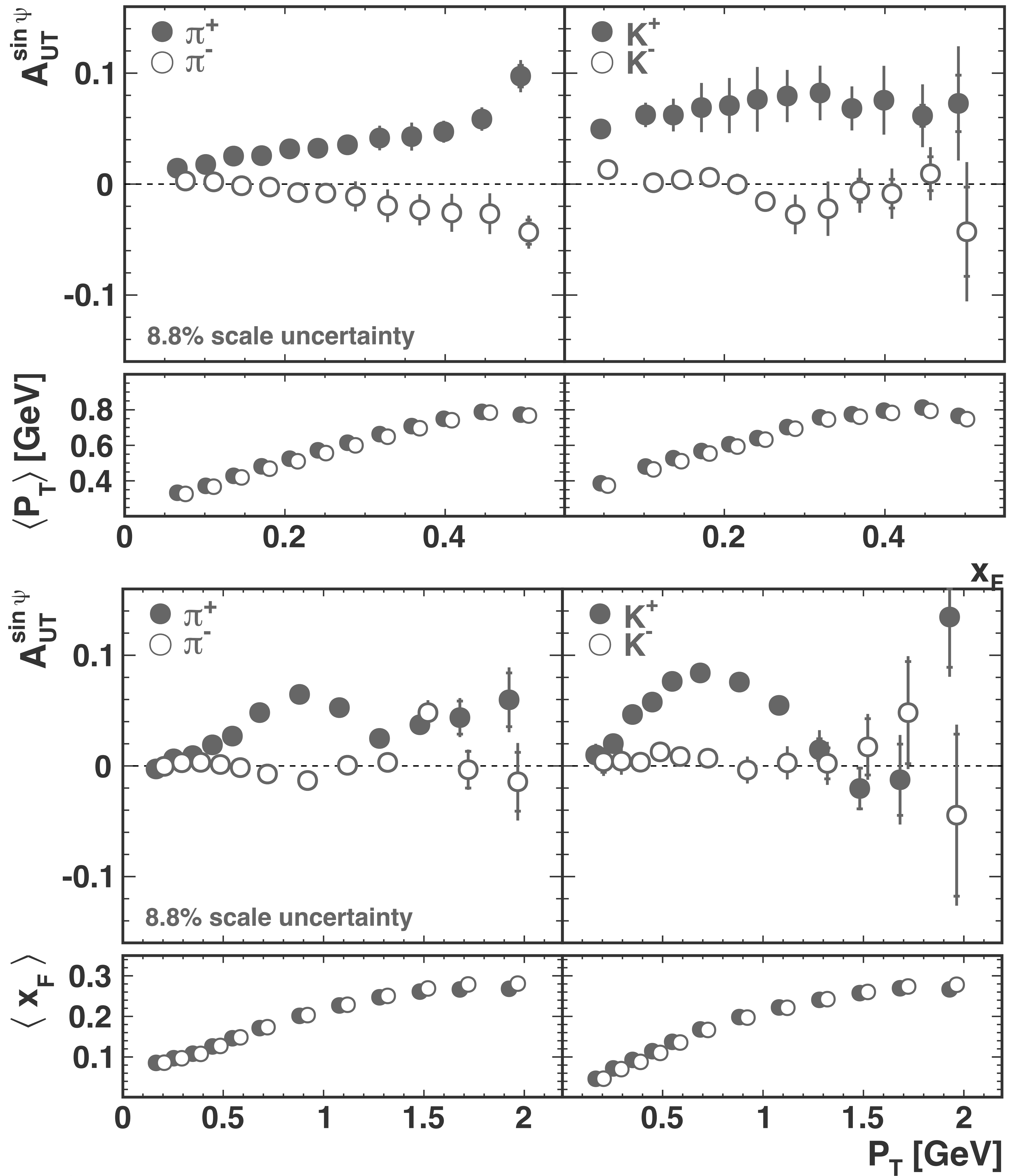
- clear left-right asymmetries for pions and positive kaons

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



lepton going into the plane

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



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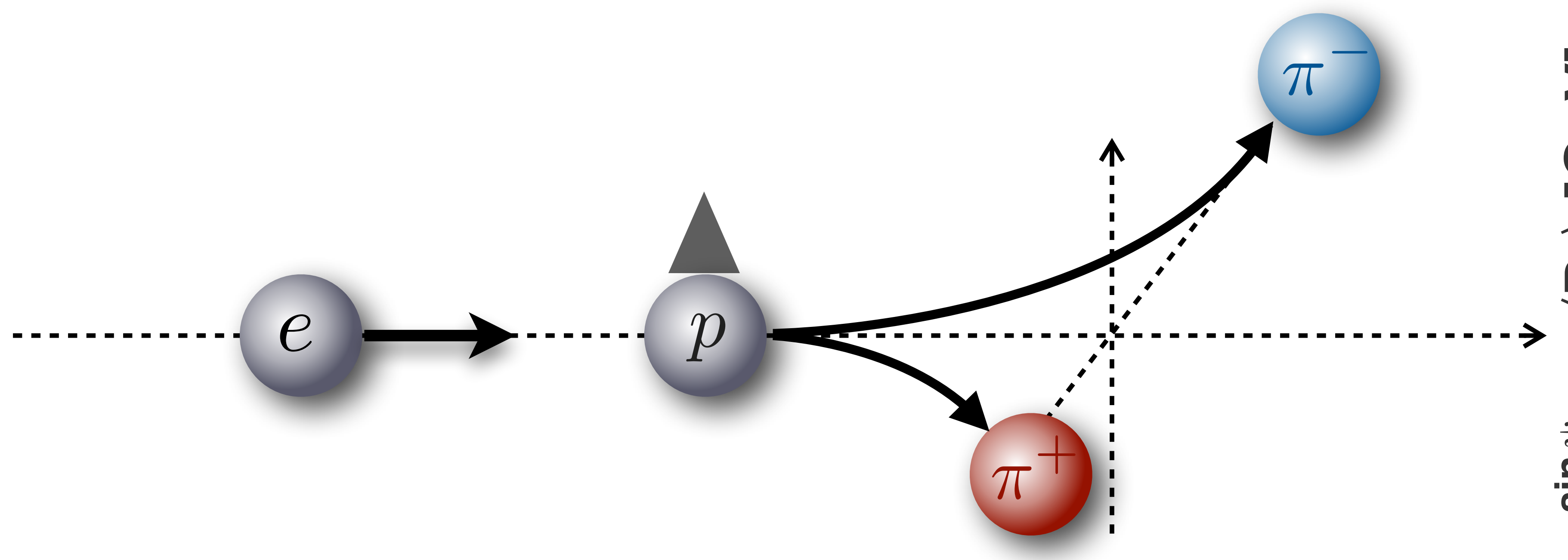

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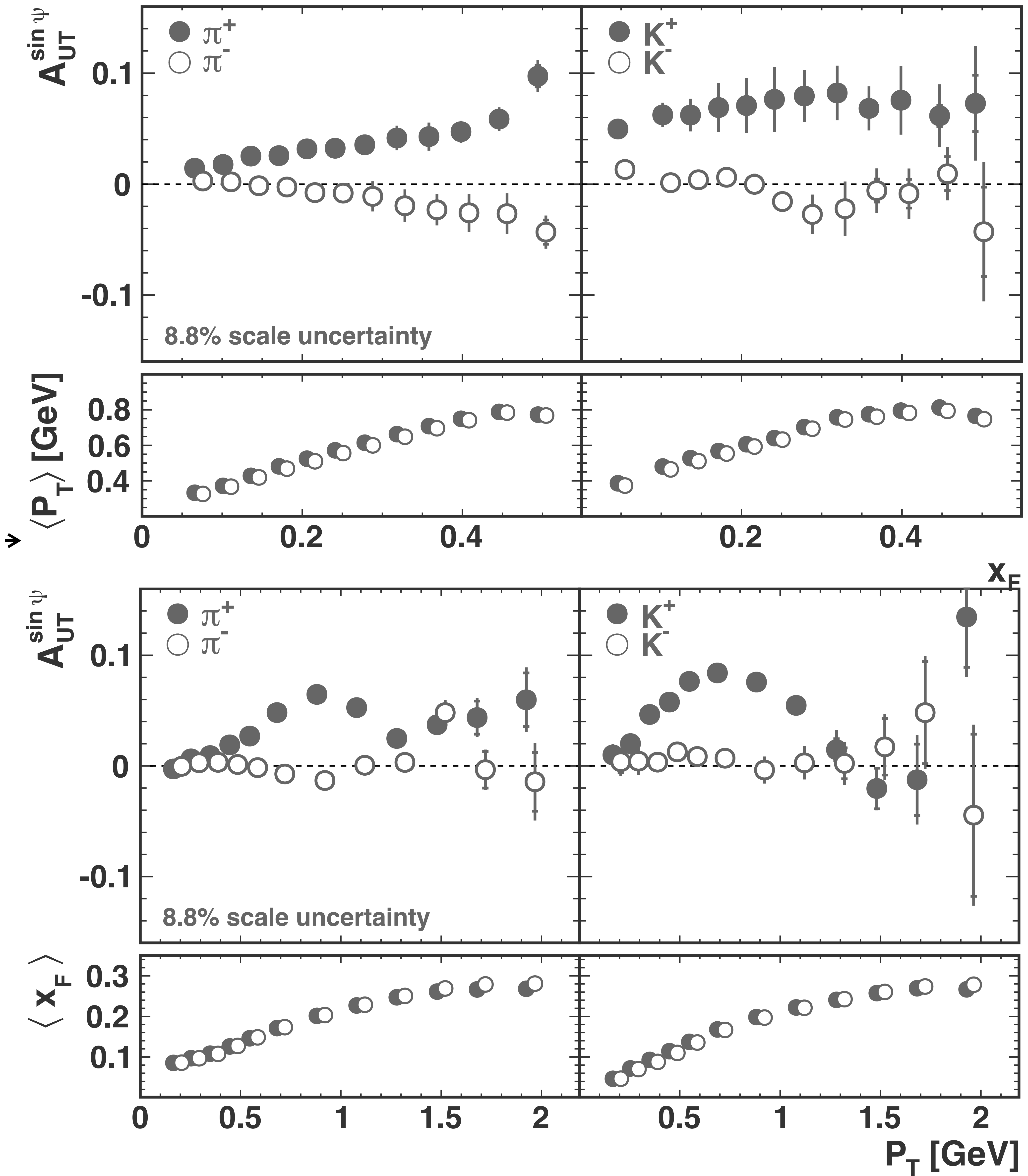

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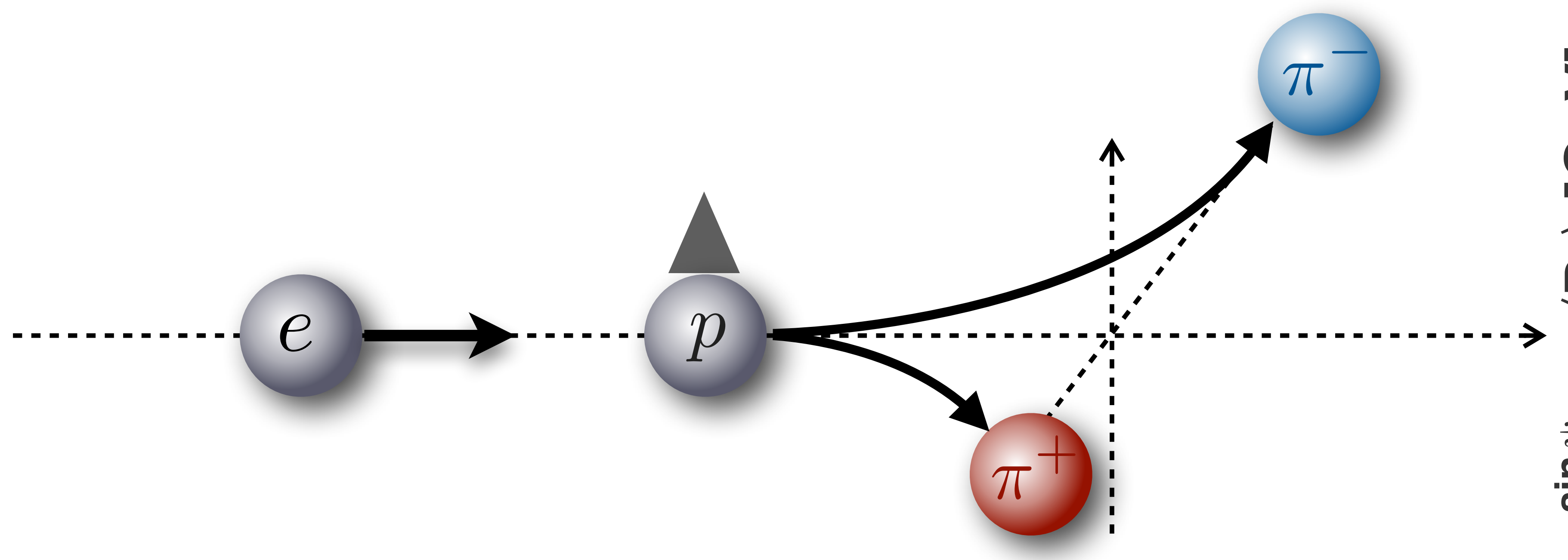

- initially increasing with P_T with a fall-off at larger P_T

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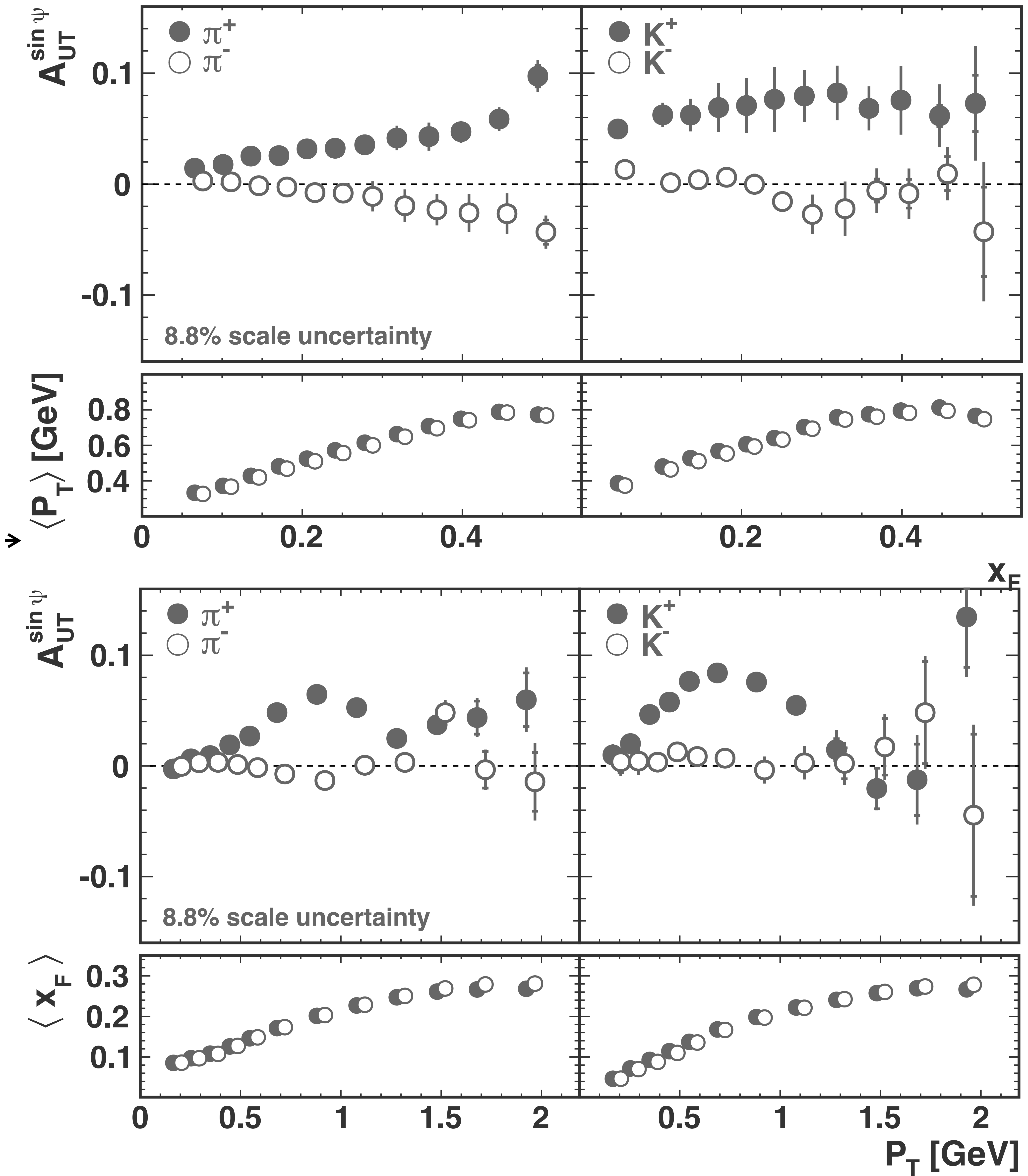

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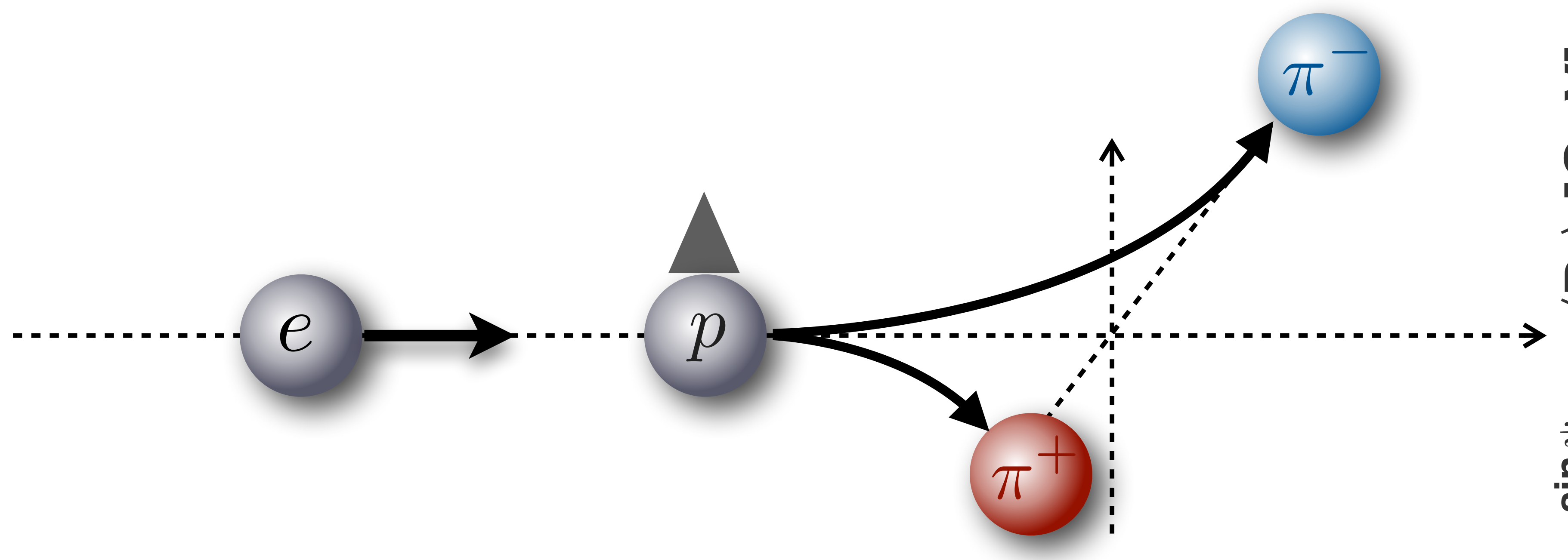
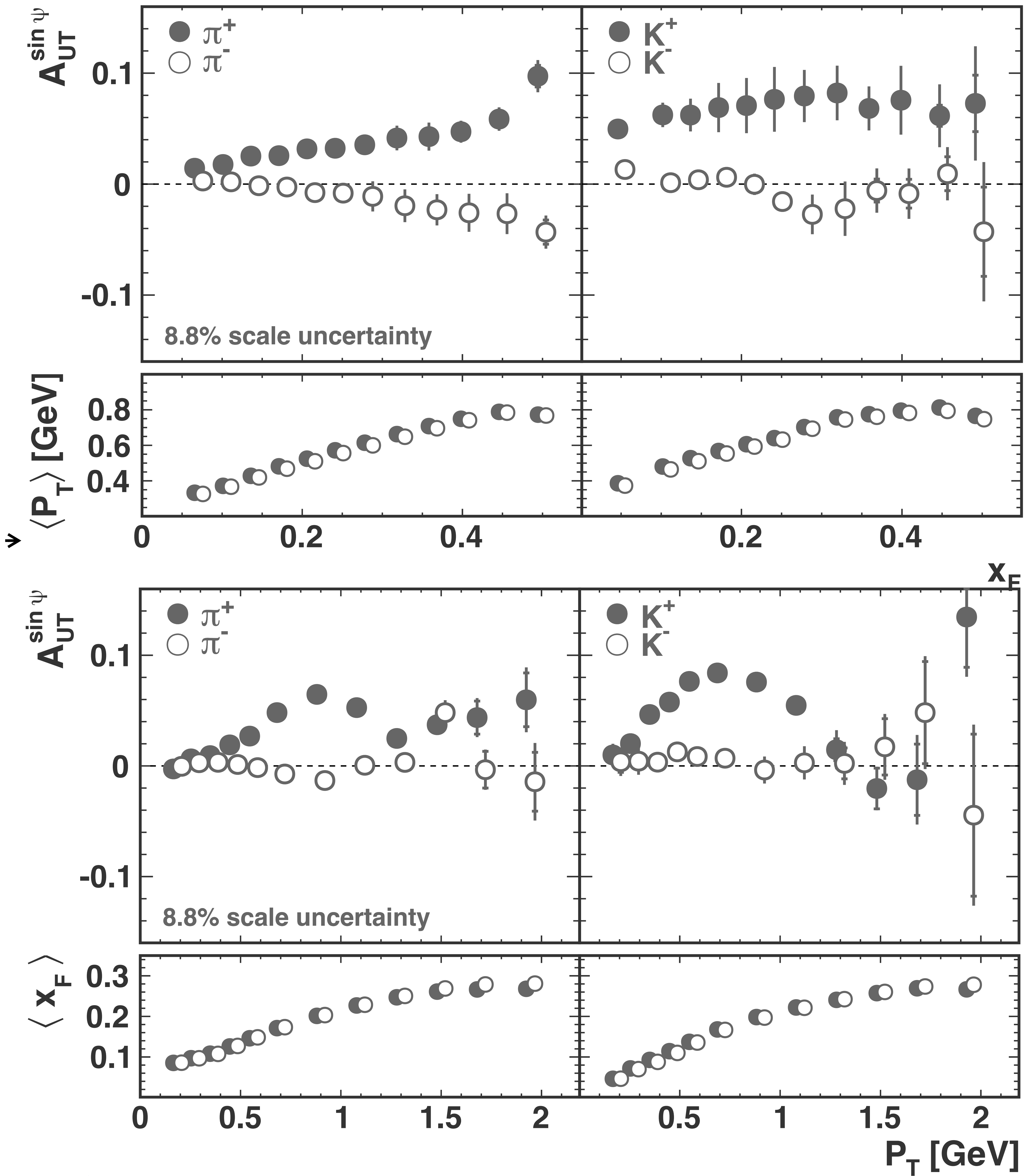


- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➥ look at 2D dependences

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



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