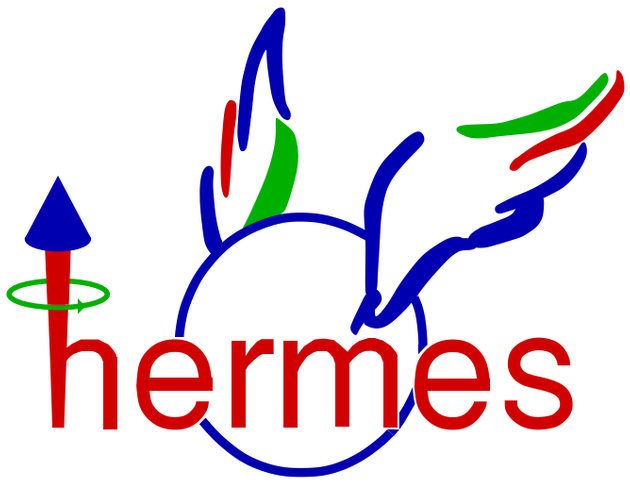
TMD measurements from



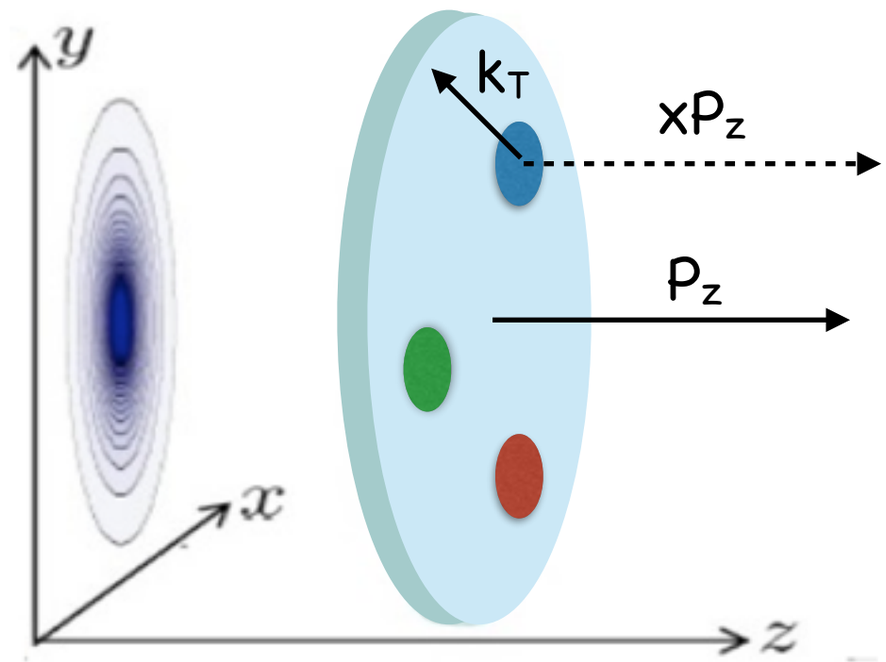
Charlotte Van Hulse, for the HERMES collaboration
University of the Basque Country UPV/EHU - Spain

QCD-N'16
11-15 July 2016
Bilbao, Spain

Outline

✳ Asymmetries A_{UT} and A_{LT}
- unpolarized & longitudinally polarized e^+/e^- beam
- transversely polarized H target

✳ Asymmetry A_{LU}
- longitudinally polarized e^+/e^- beam
- unpolarized H and D target



Semi-inclusive DIS cross section

$$\frac{d\sigma}{dxdydzd\phi_h dP_{h\perp}^2 d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)}$$

beam polarization

$$+\lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h) F_{LU}^{\sin(\phi_h)}$$

longitudinal target polarization

$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h) F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h) F_{UL}^{\sin(2\phi_h)}\Big]$$

$$+S_L\lambda_e\Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h) F_{LL}^{\cos(\phi_h)}\Big]$$

transverse target polarization

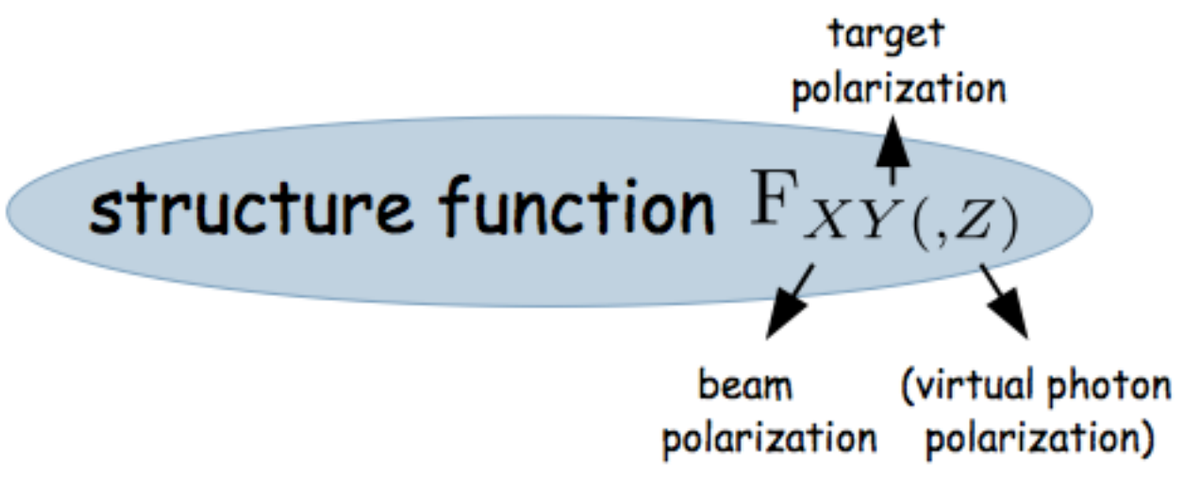
$$+S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

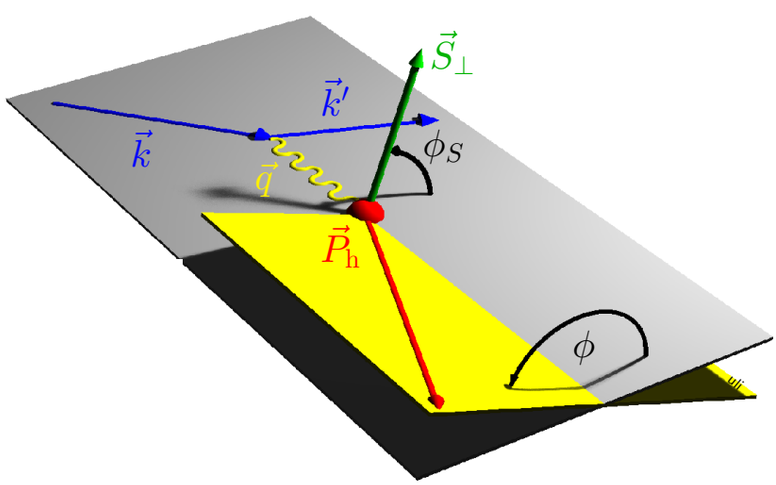
$$+ \quad \epsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$





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beam polarization

$$+\lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h) F_{LU}^{\sin(\phi_h)}$$

leading twist

longitudinal target polarization

$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h) F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h) F_{UL}^{\sin(2\phi_h)}\Big]$$

$$+S_L\lambda_e\Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h) F_{LL}^{\cos(\phi_h)}\Big]$$

transverse target polarization

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

$$+ \quad \epsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)}$$

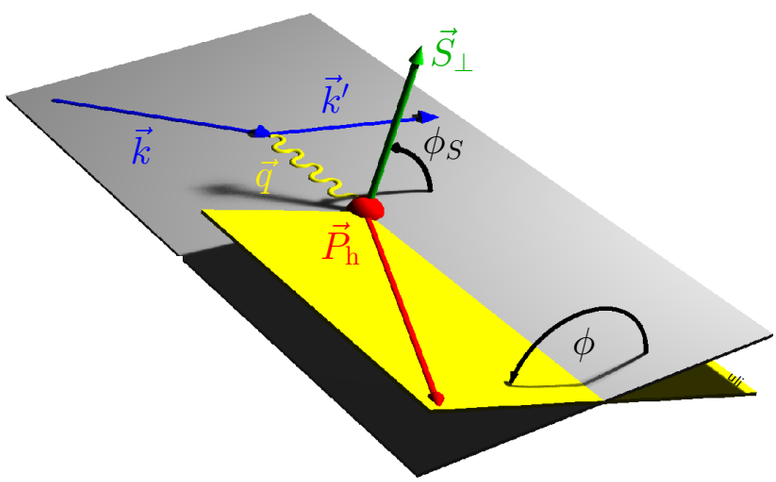
$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

target polarization

structure function $F_{XY(,Z)}$

beam polarization

(virtual photon polarization)



Semi-inclusive DIS cross section

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beam polarization

$$+\lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h) F_{LU}^{\sin(\phi_h)}$$

leading twist

longitudinal target polarization

$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h)F_{UL}^{\sin(\phi_h)} + \sin(2\phi_h) F^{\sin(2\phi_h)}\Big]$$

This talk

$$+S_L\lambda_e\Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h)F_{LL}^{\cos(\phi_h)}\Big]$$

transverse target polarization

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

$$+ \quad \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)}$$

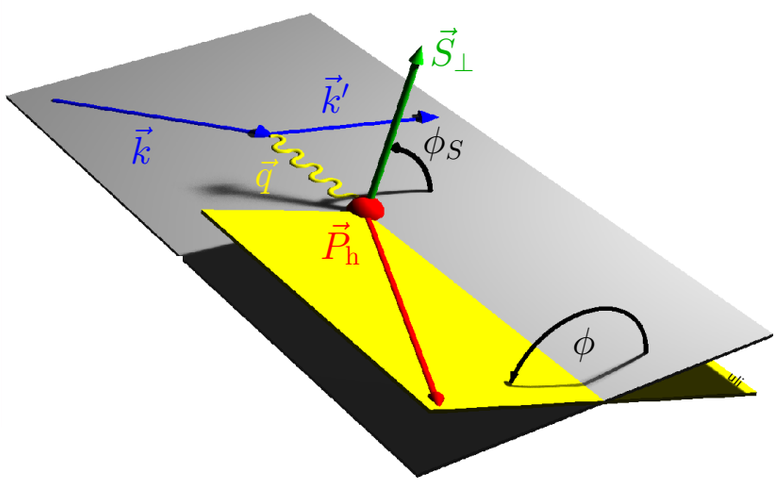
$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

target polarization

structure function $F_{XY(,Z)}$

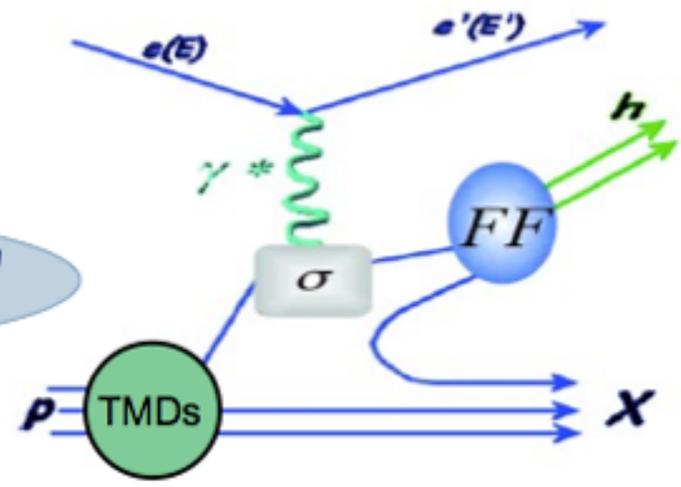
beam polarization

(virtual photon polarization)



Semi-inclusive DIS cross section

structure function $F_{XY} \propto TMD \otimes FF$



transverse momentum distributions (TMDs)

leading twist

fragmentation functions (FFs)

nucleon		quark U	quark L	quark T
	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

h	quark U	quark L	quark T
U	D_1		$H_1^\perp$

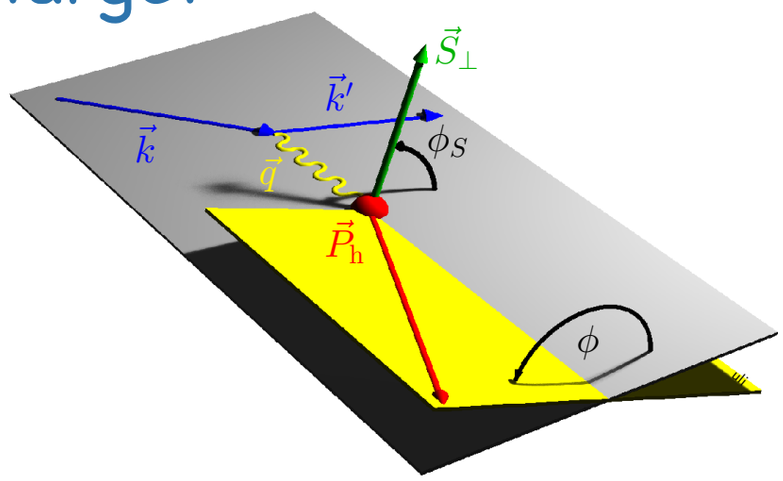
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

A_{UT} and A_{LT}

unpolarized & longitudinally polarized e^+/e^- beam
transversely polarized H target



Results for pions, kaons and protons

A_{UT} and A_{LT} fit simultaneously

$F_{UT}^{\sin(2\phi-\phi_S)}$

$F_{UT}^{\sin(\phi_S)}$

Sivers

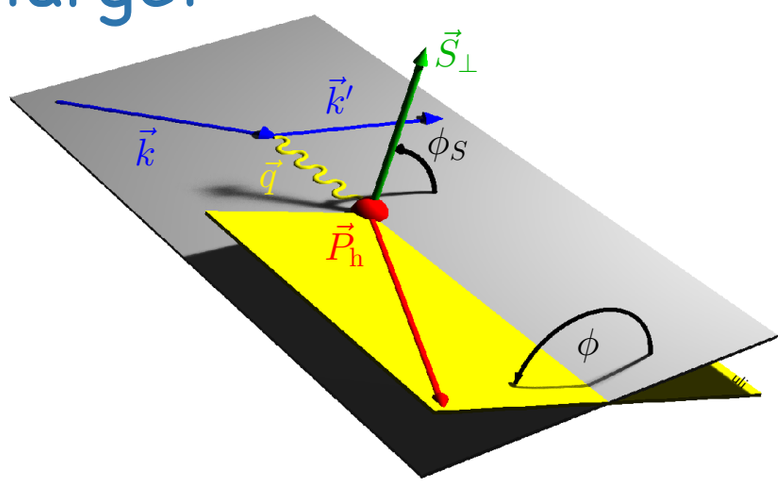
Collins

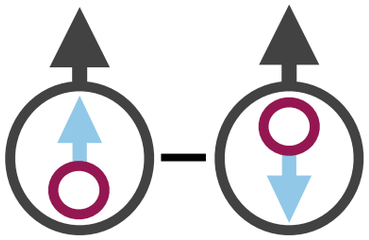
Pretzelosity

A_{UT}

unpolarized beam
transversely polarized H target

Results for pions, kaons and protons

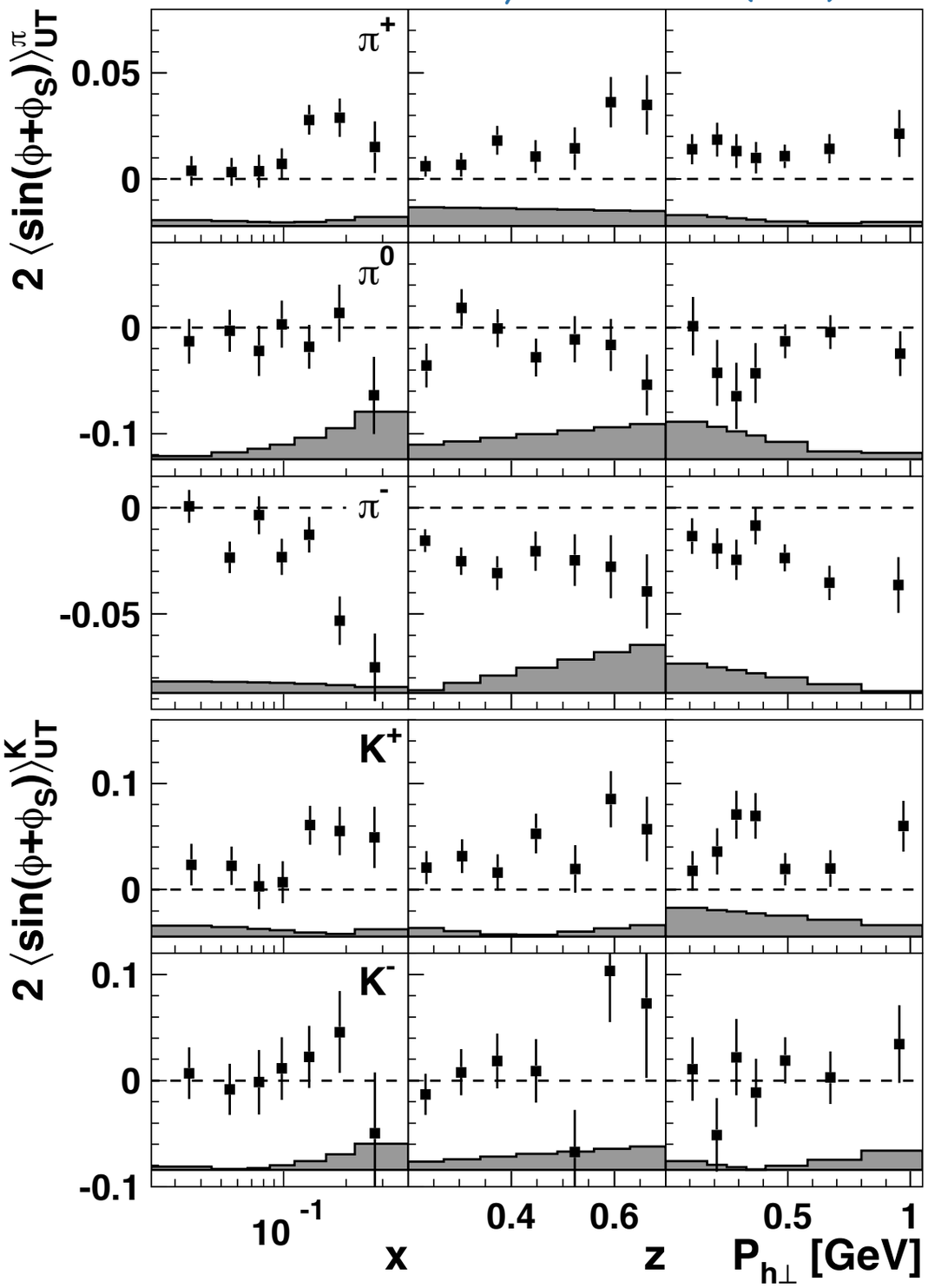




Collins amplitudes

$\propto h_{1T}^{q} \otimes H_1^{\perp,q}$

Phys. Lett. B 693 (2010) 11-16



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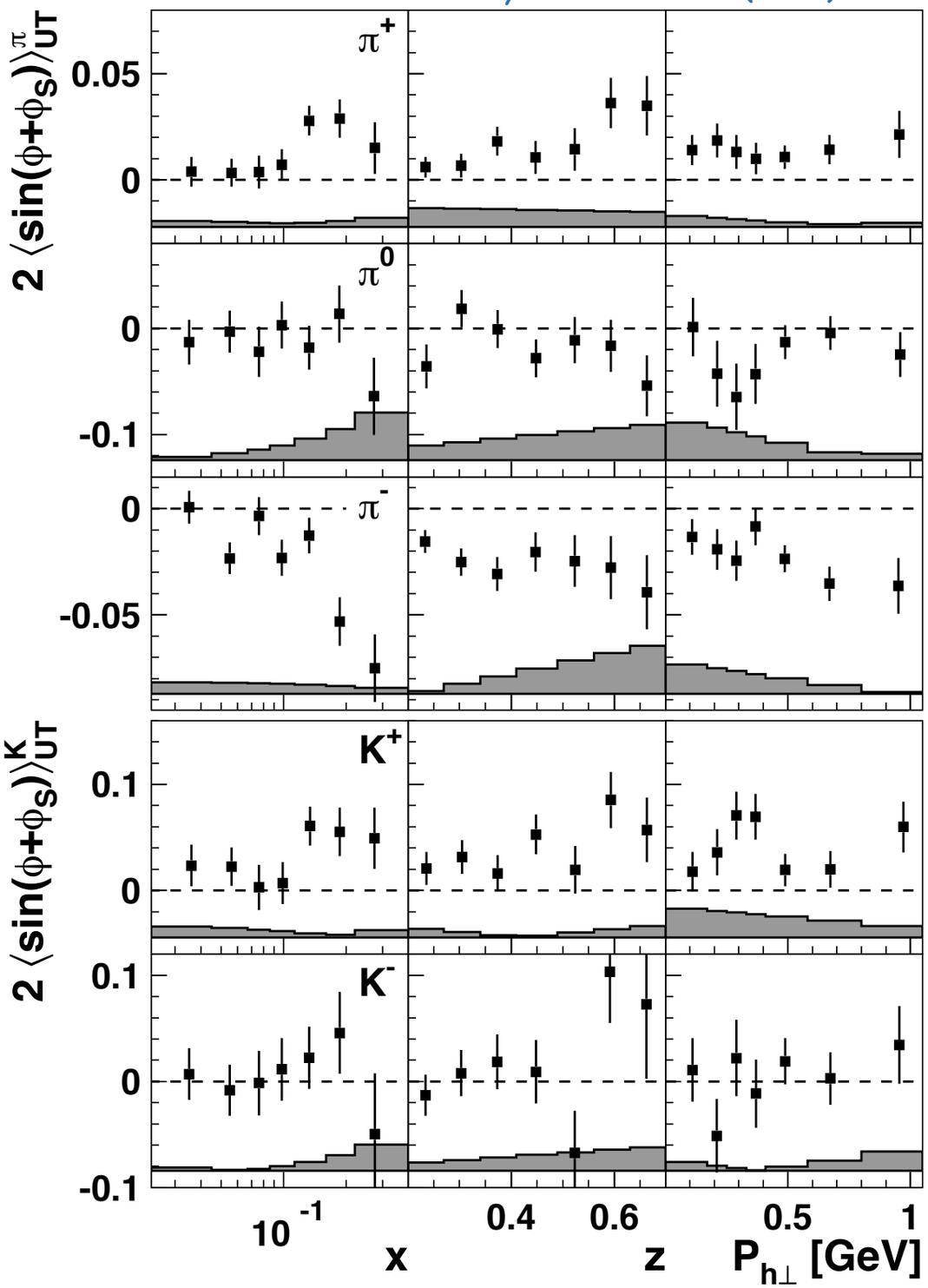
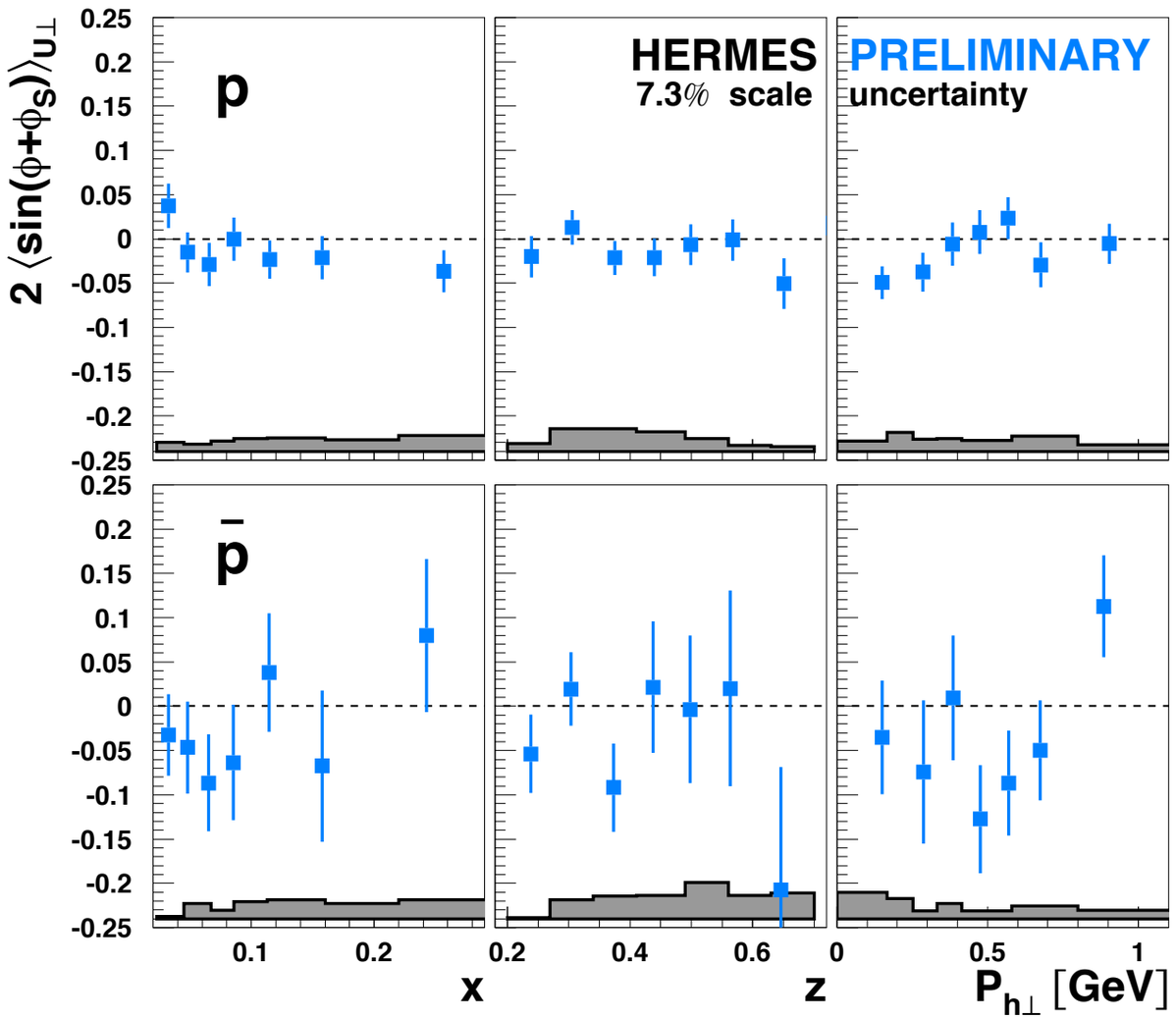
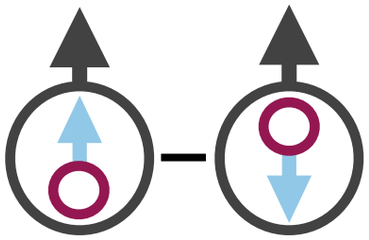
Phys. Lett. B 693 (2010) 11-16







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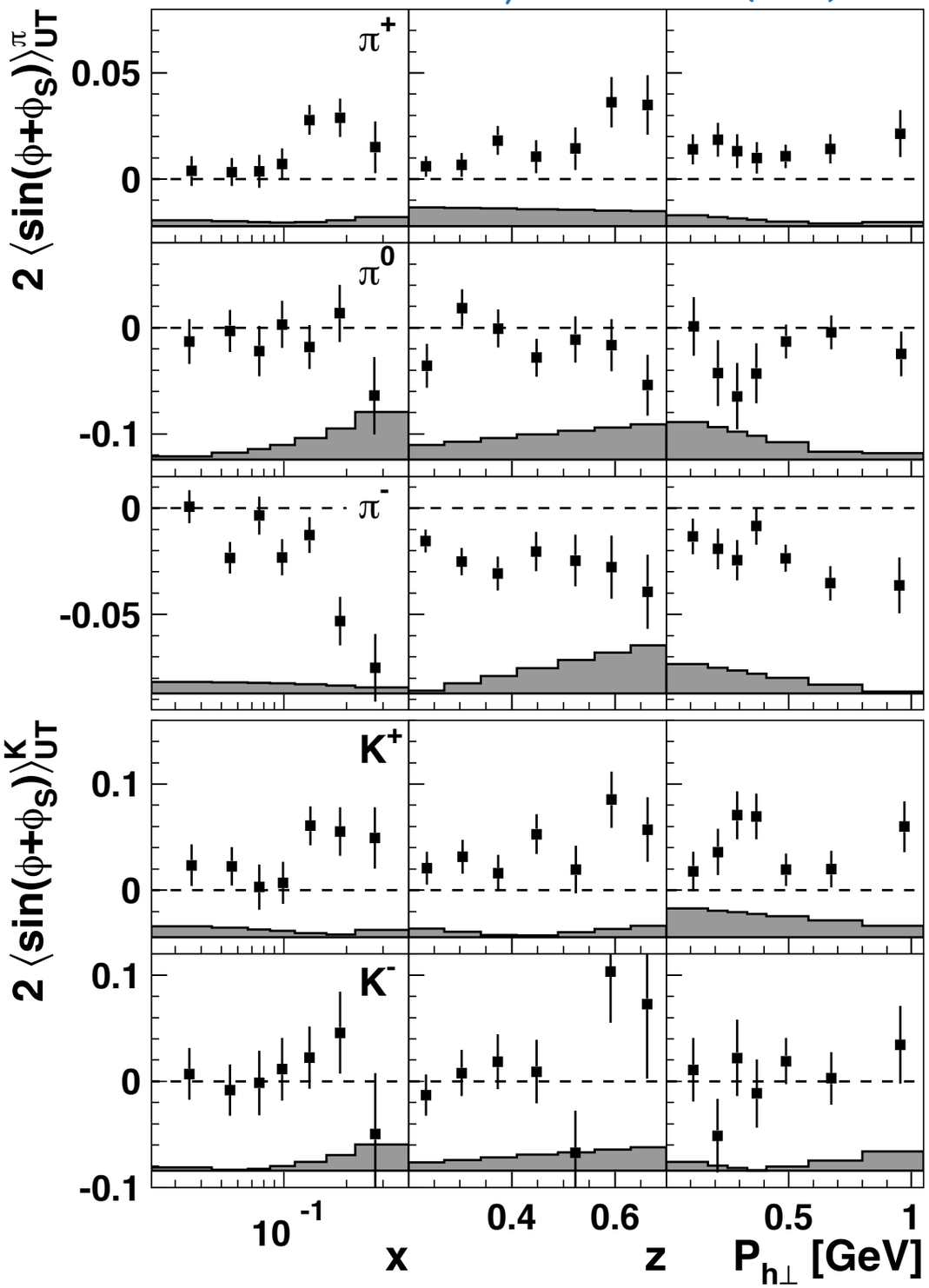
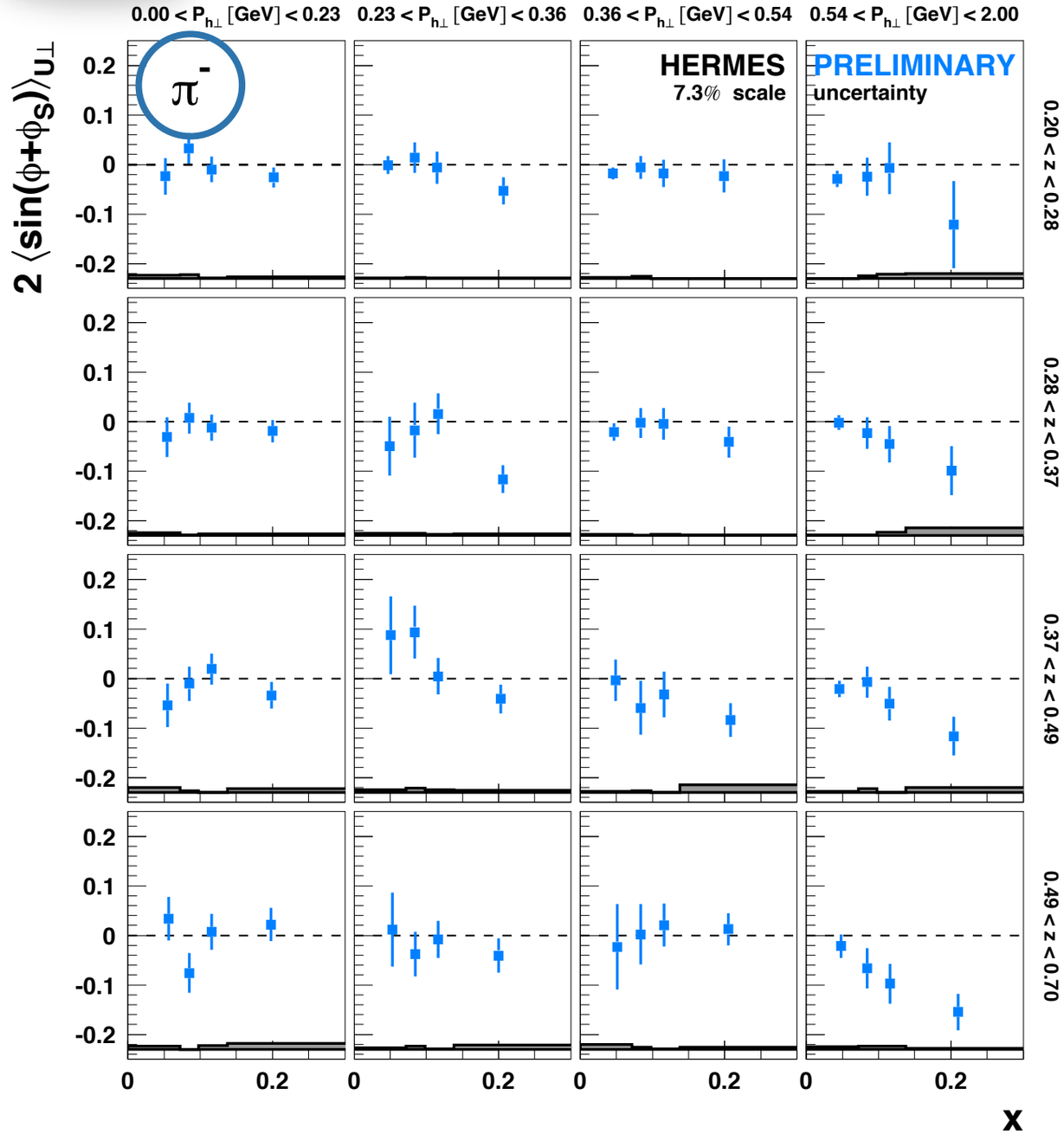
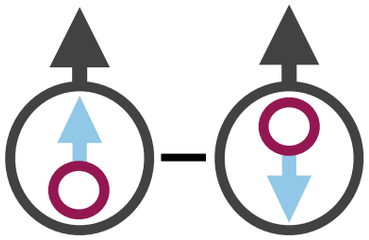
Phys. Lett. B 693 (2010) 11-16



3D





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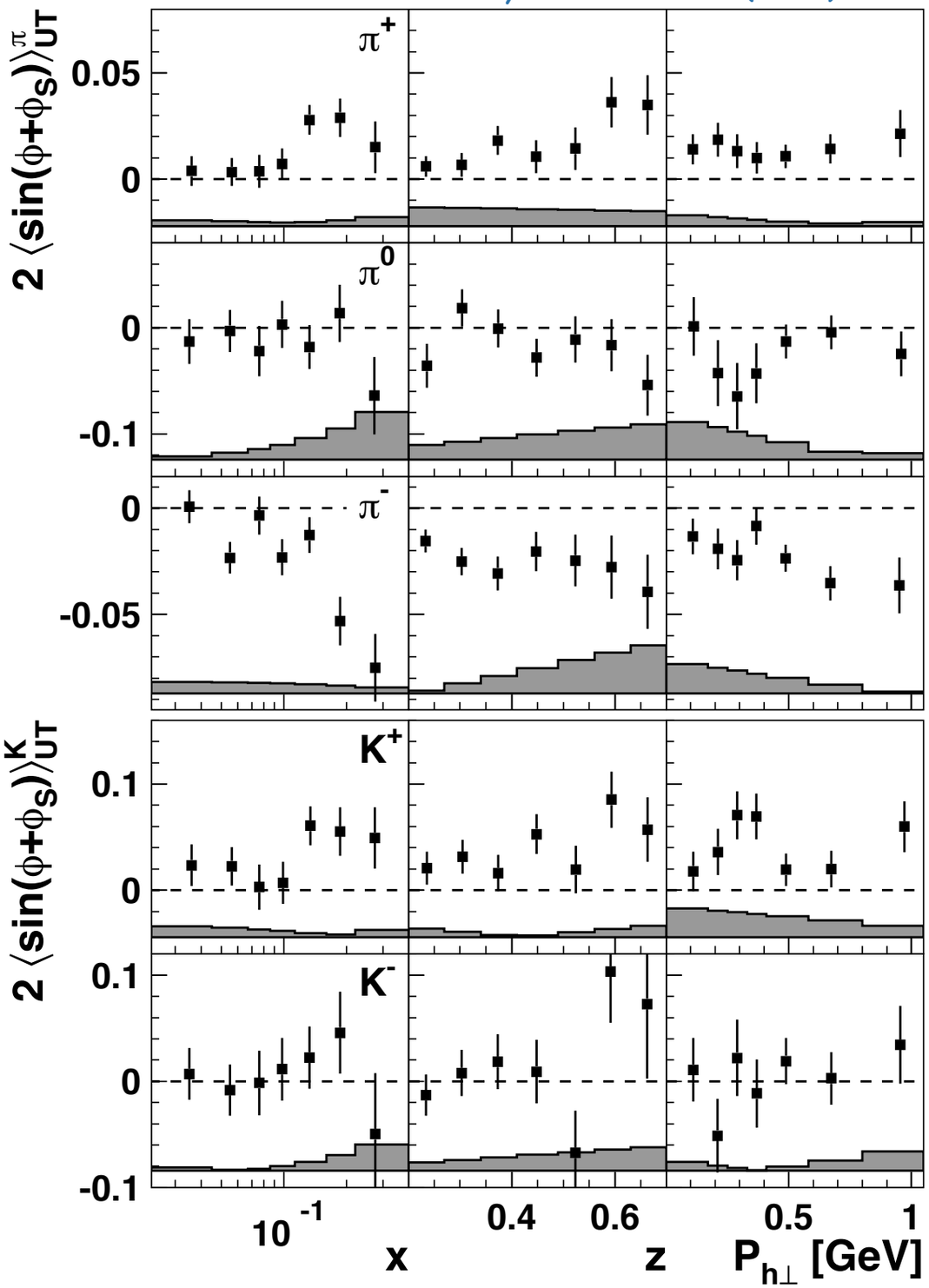
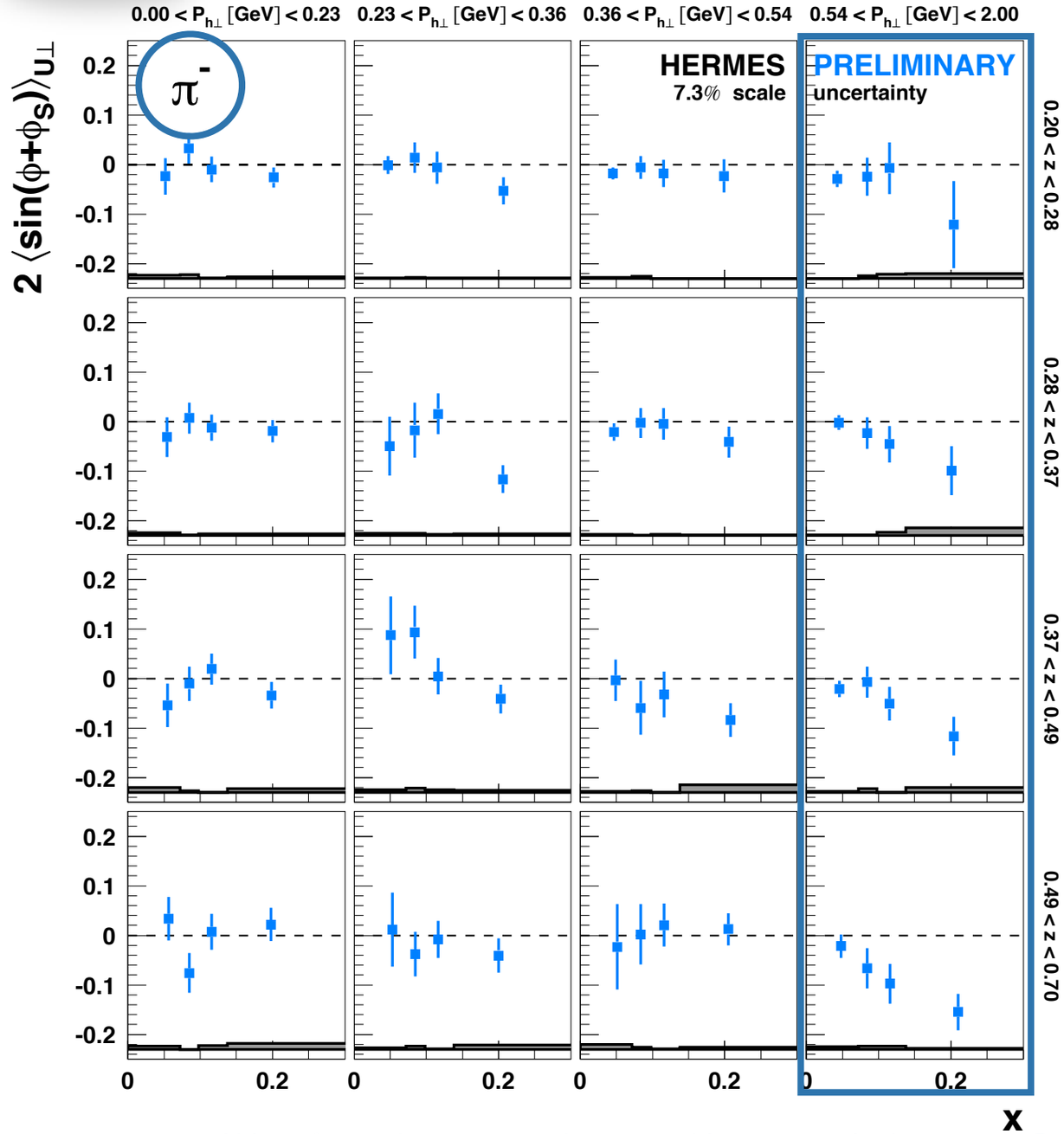
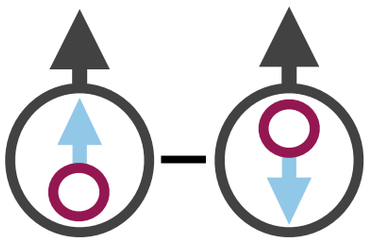
Phys. Lett. B 693 (2010) 11-16



3D



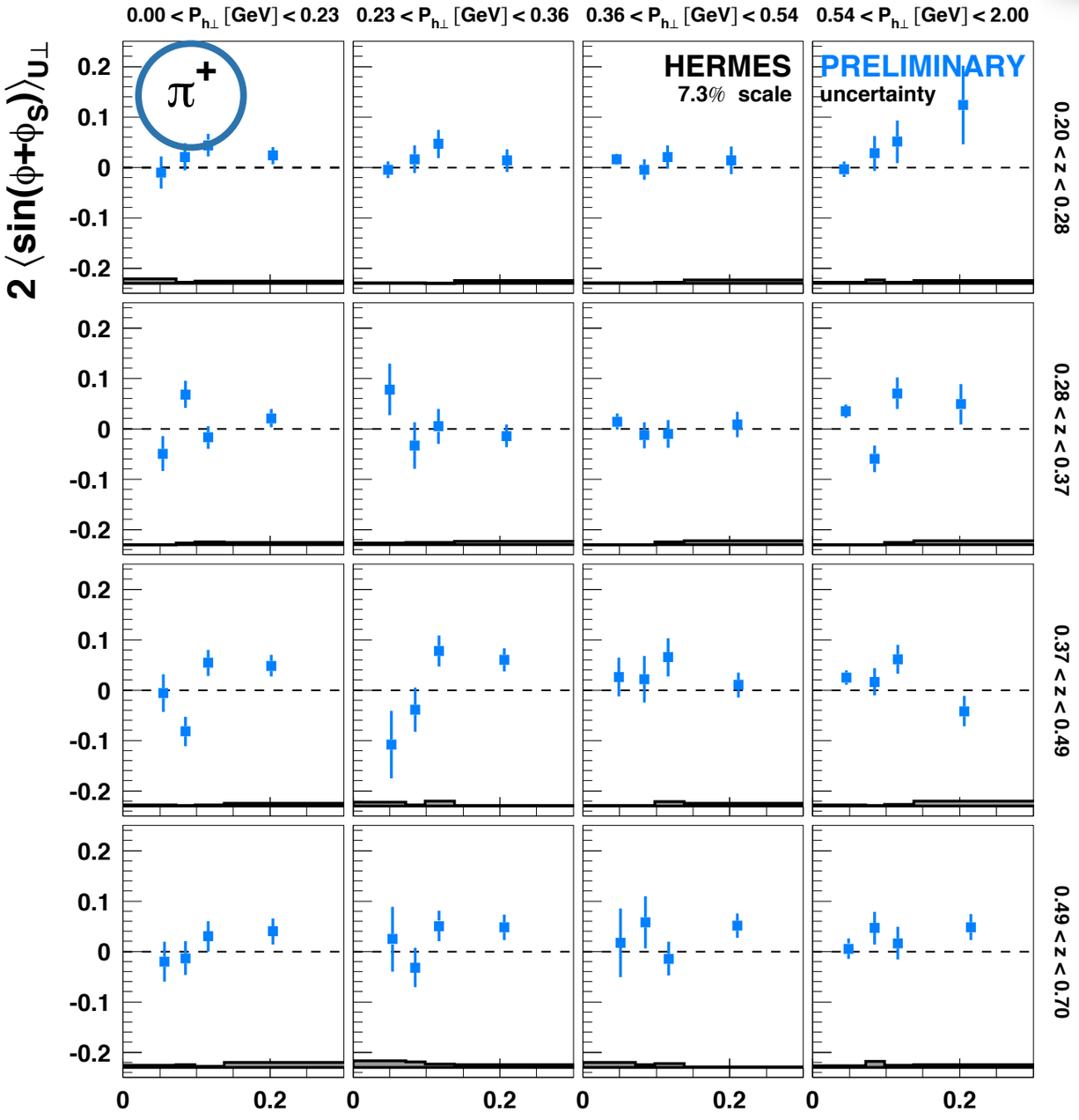
π^- amplitudes increasing with x at large $P_{h\perp}$

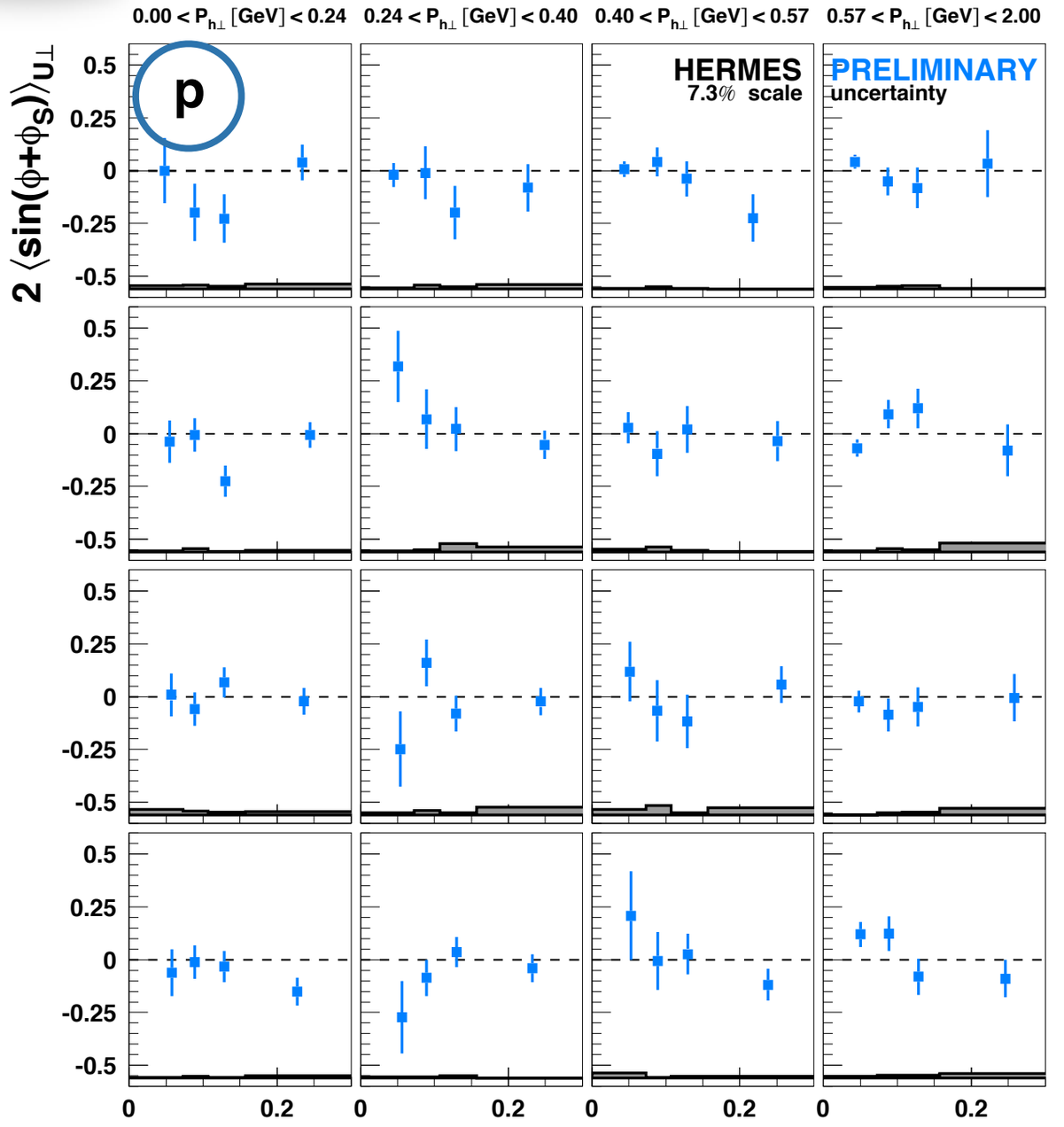


Collins amplitudes

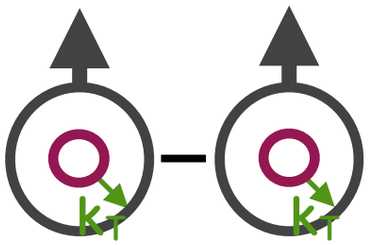
$$\propto h_{1T}^{q} \otimes H_1^{\perp,q}$$

3D



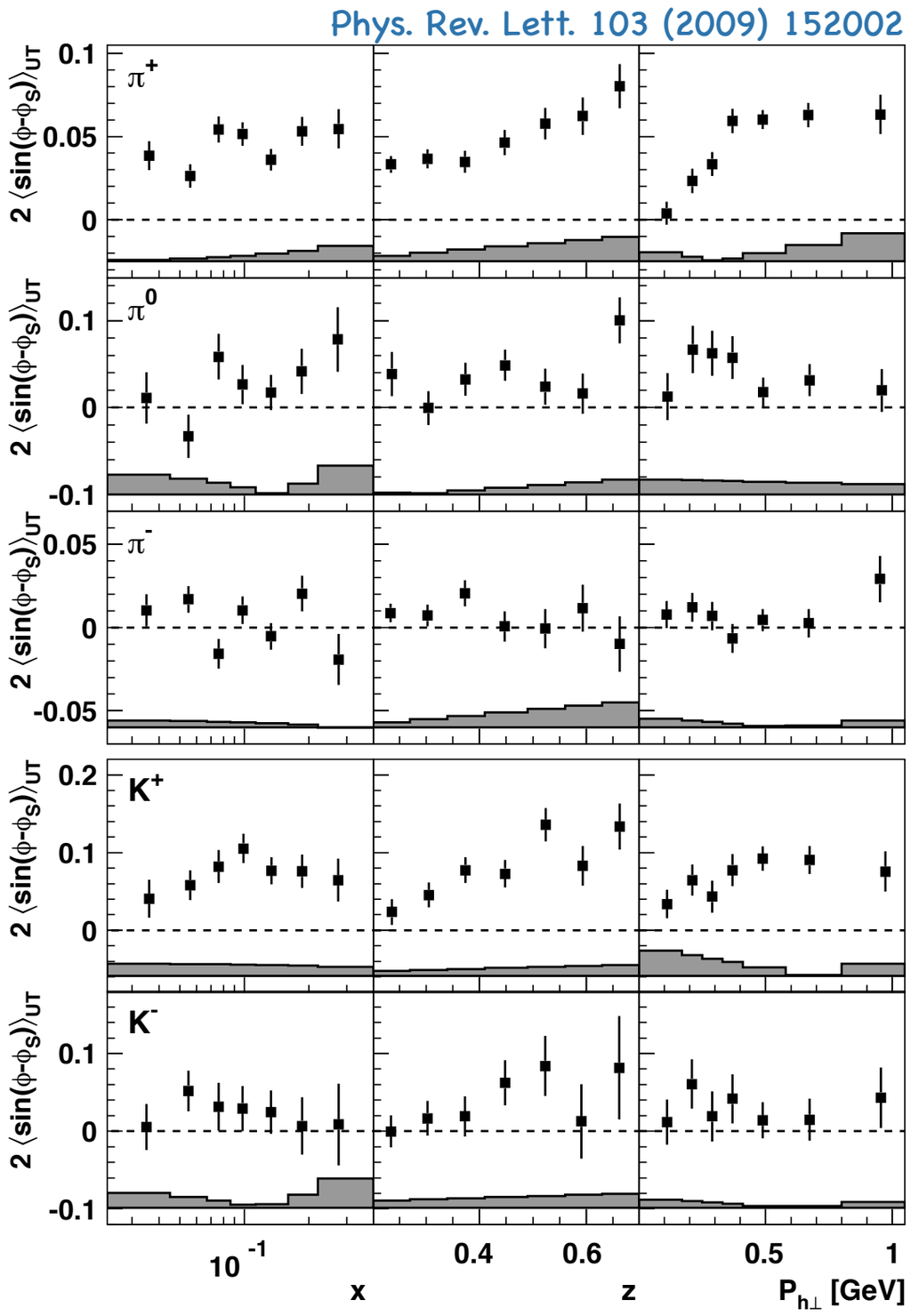


- Other hadrons, no clear kinematic dependencies in 3D
- No 3D for antiprotons



Sivers amplitudes $\propto f_{1T}^{\perp,q} \otimes D_1^q$

Phys. Rev. Lett. 103 (2009) 152002



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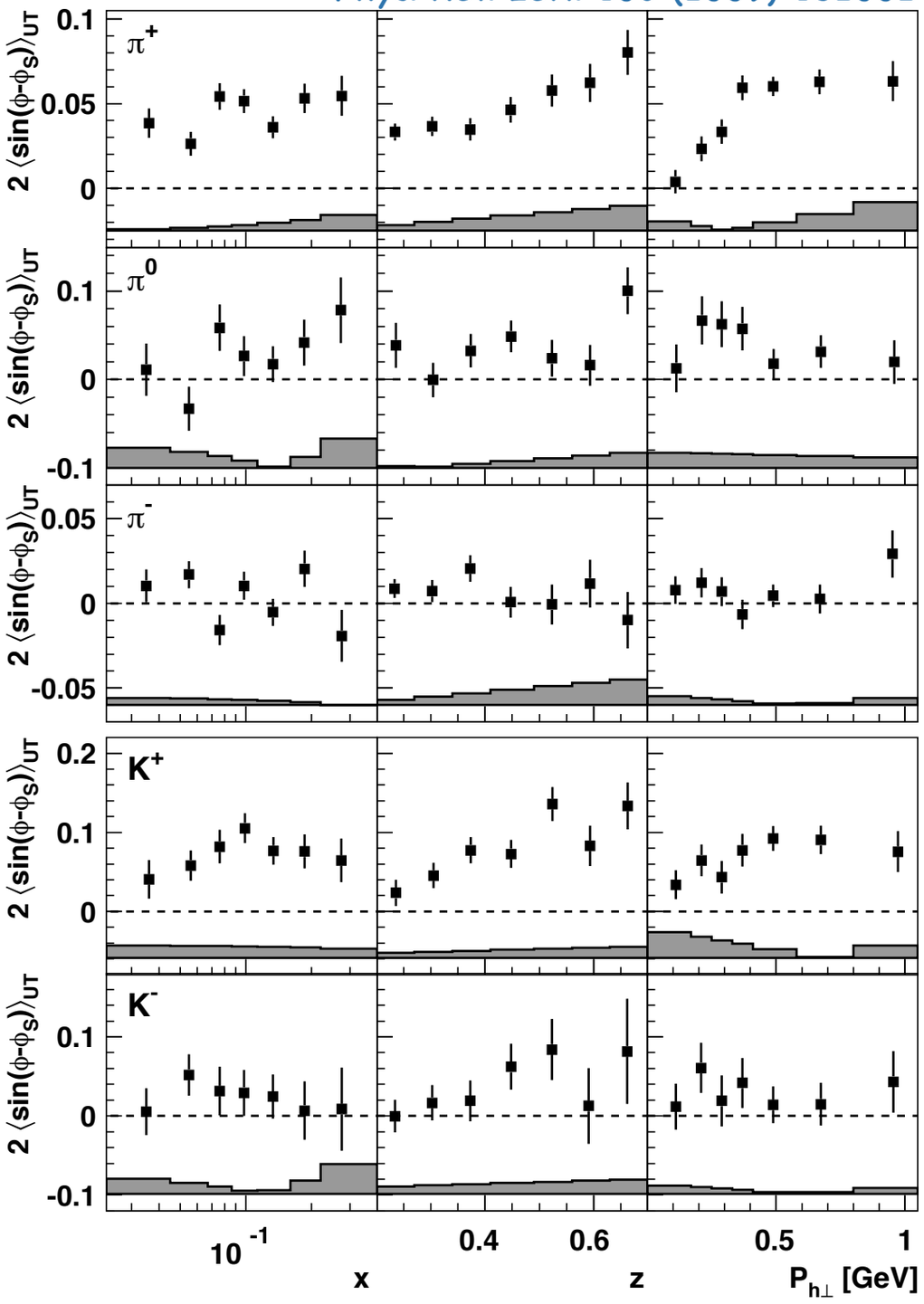
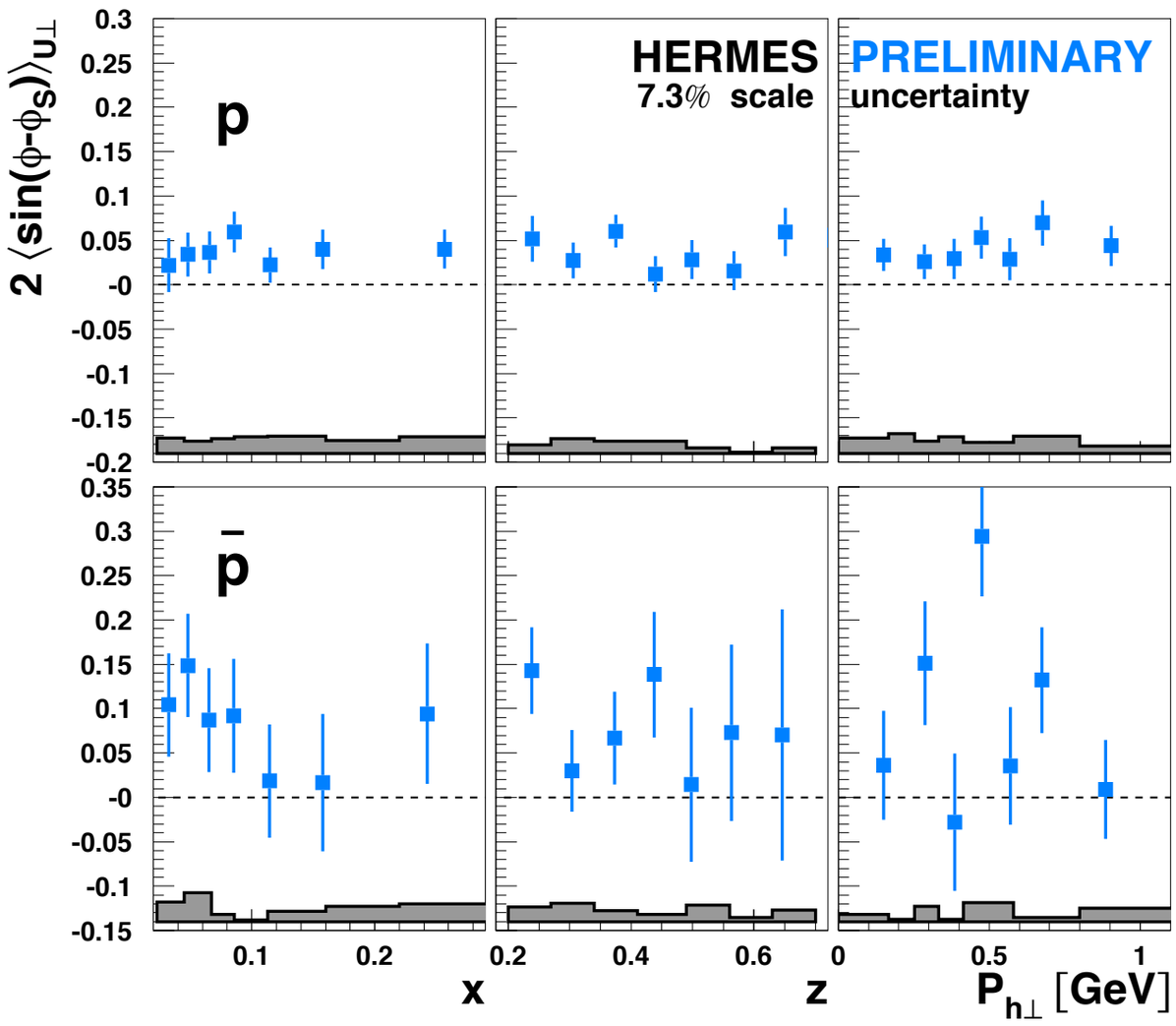
Phys. Rev. Lett. 103 (2009) 152002

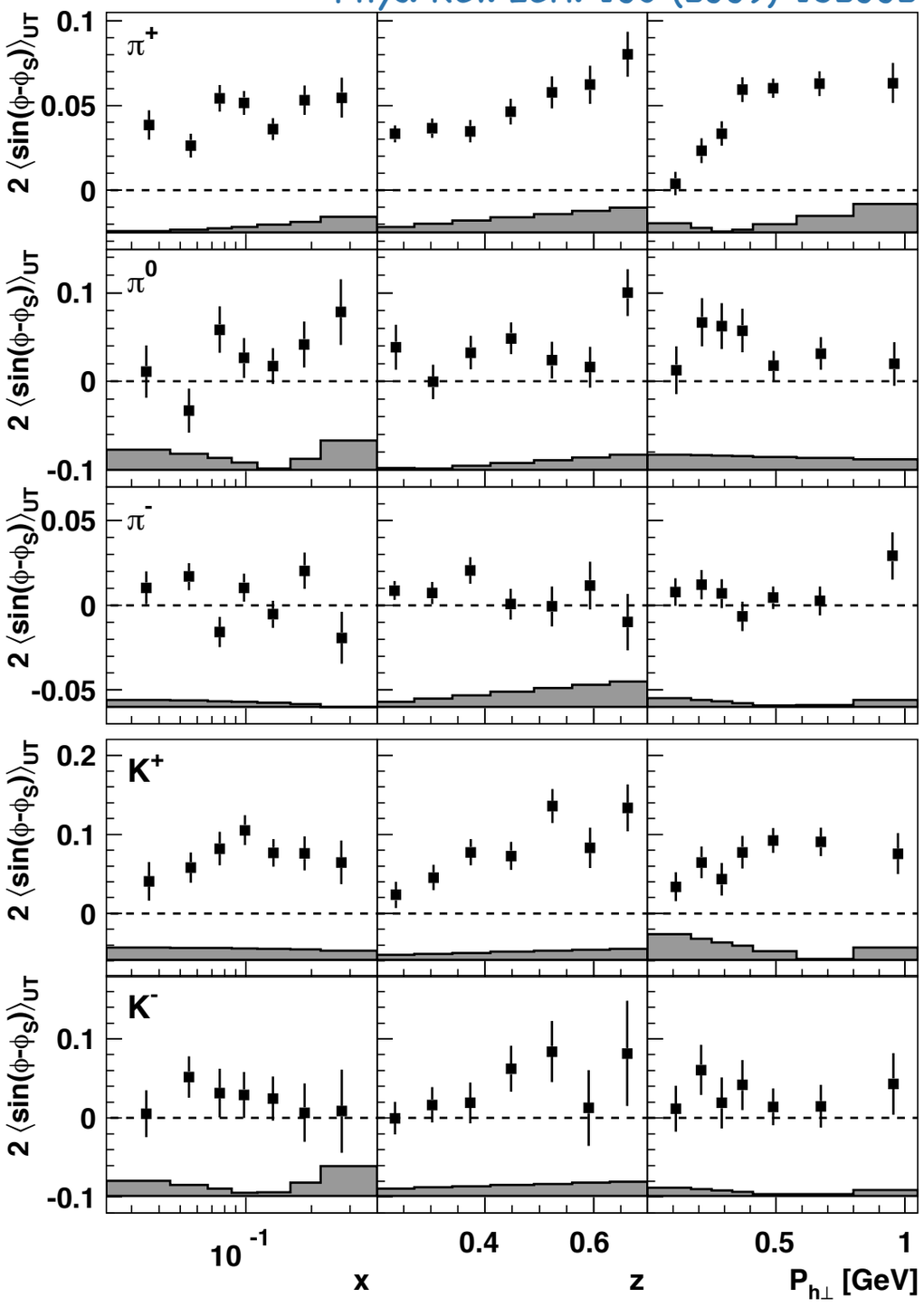




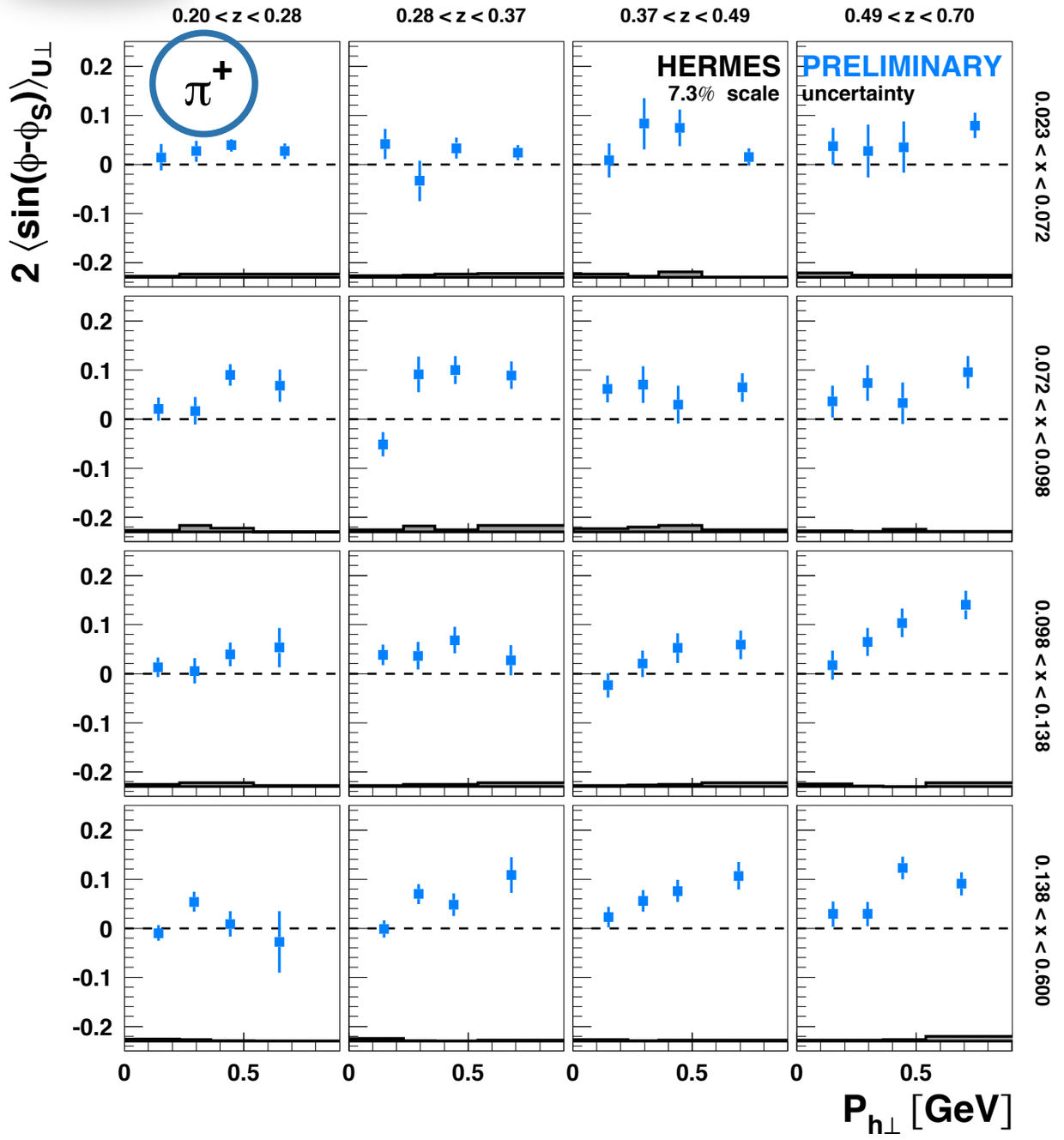
Positive Sivers amplitude for protons

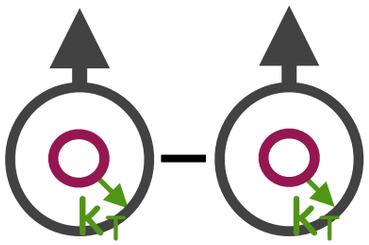
Sivers amplitudes $\propto f_{1T}^{\perp,q} \otimes D_1^q$

Phys. Rev. Lett. 103 (2009) 152002



3D





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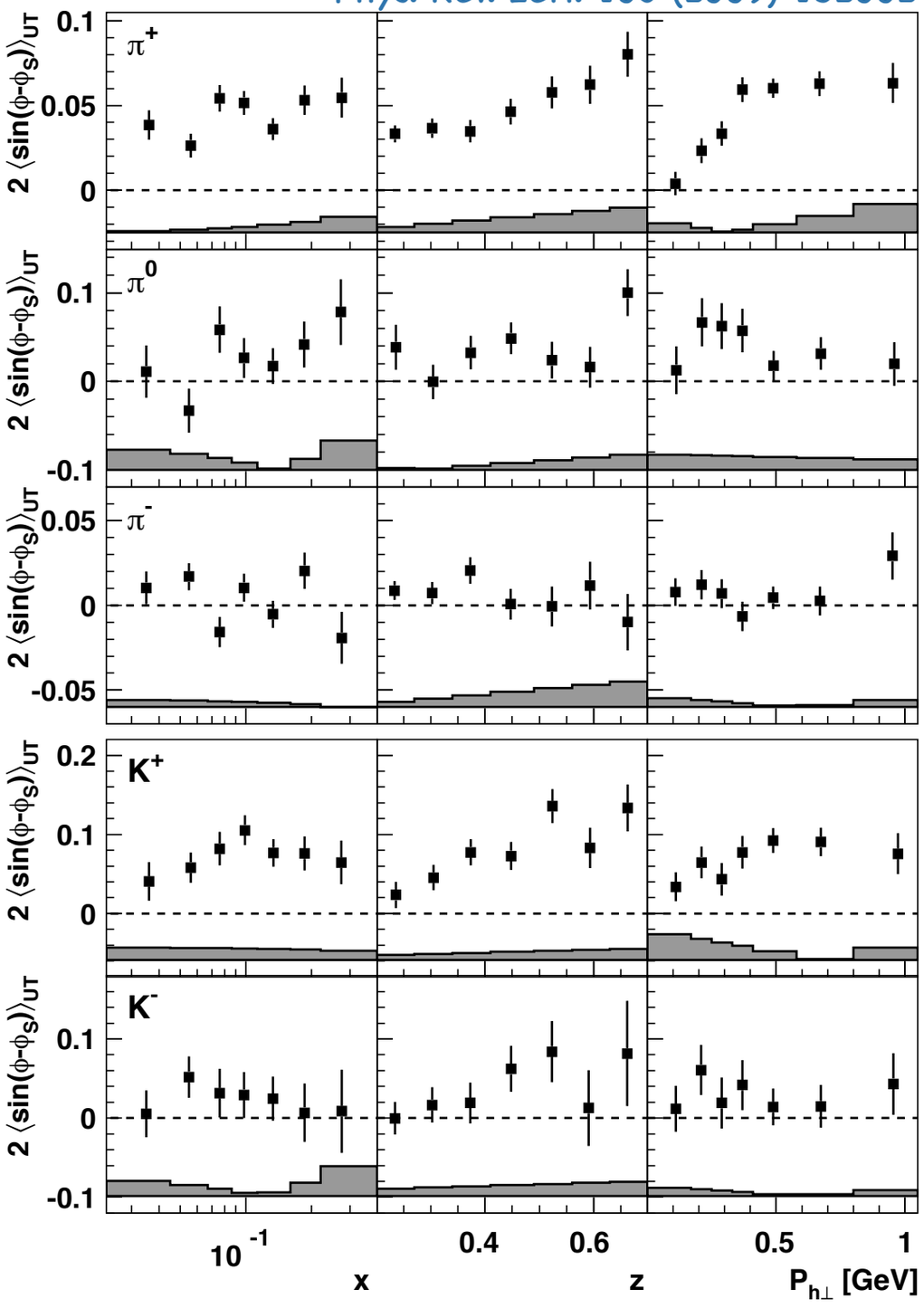
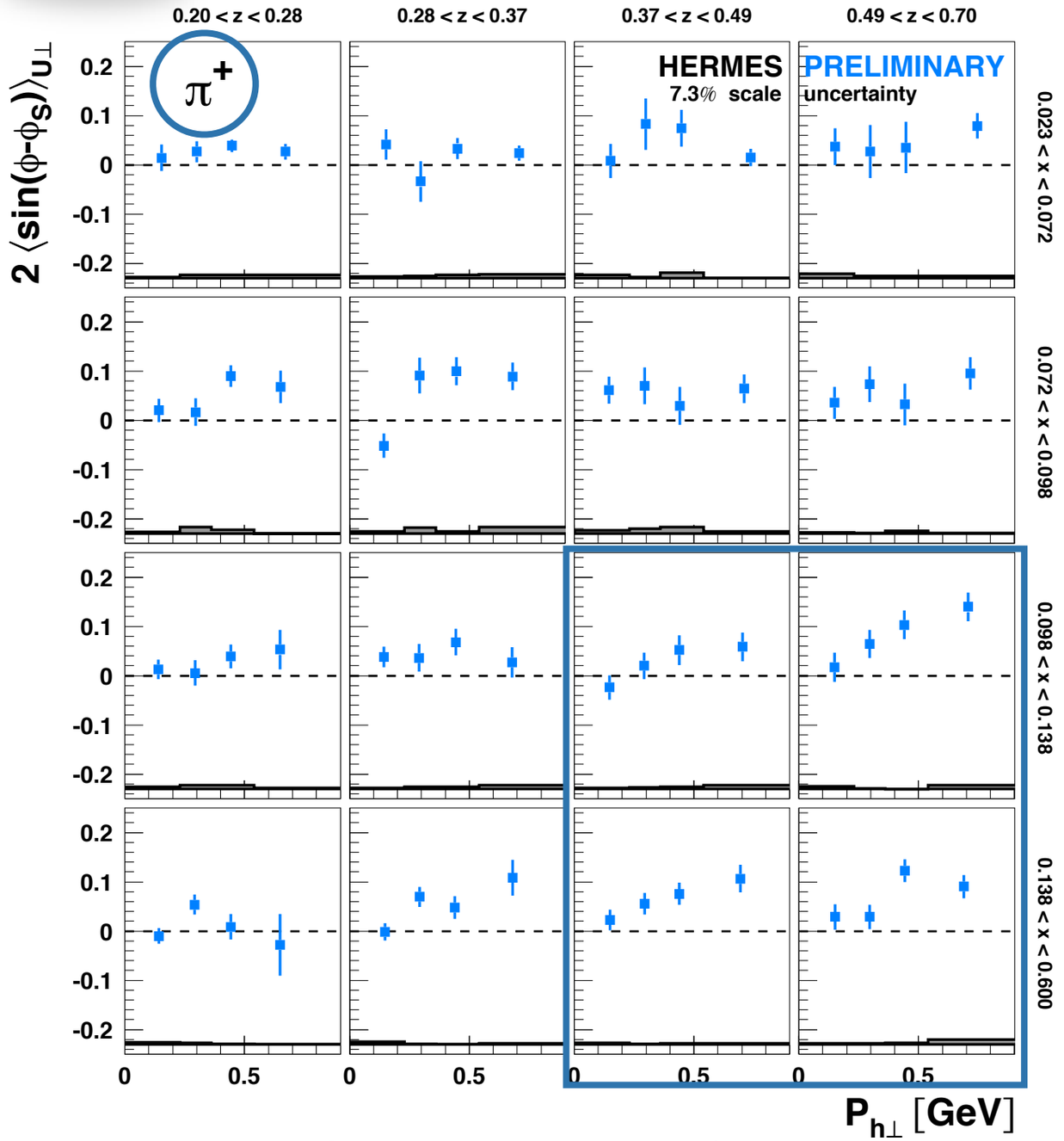
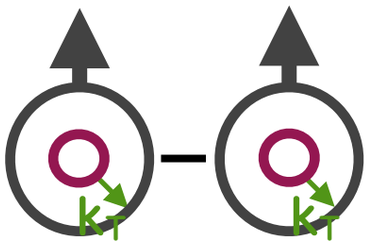
Phys. Rev. Lett. 103 (2009) 152002



3D



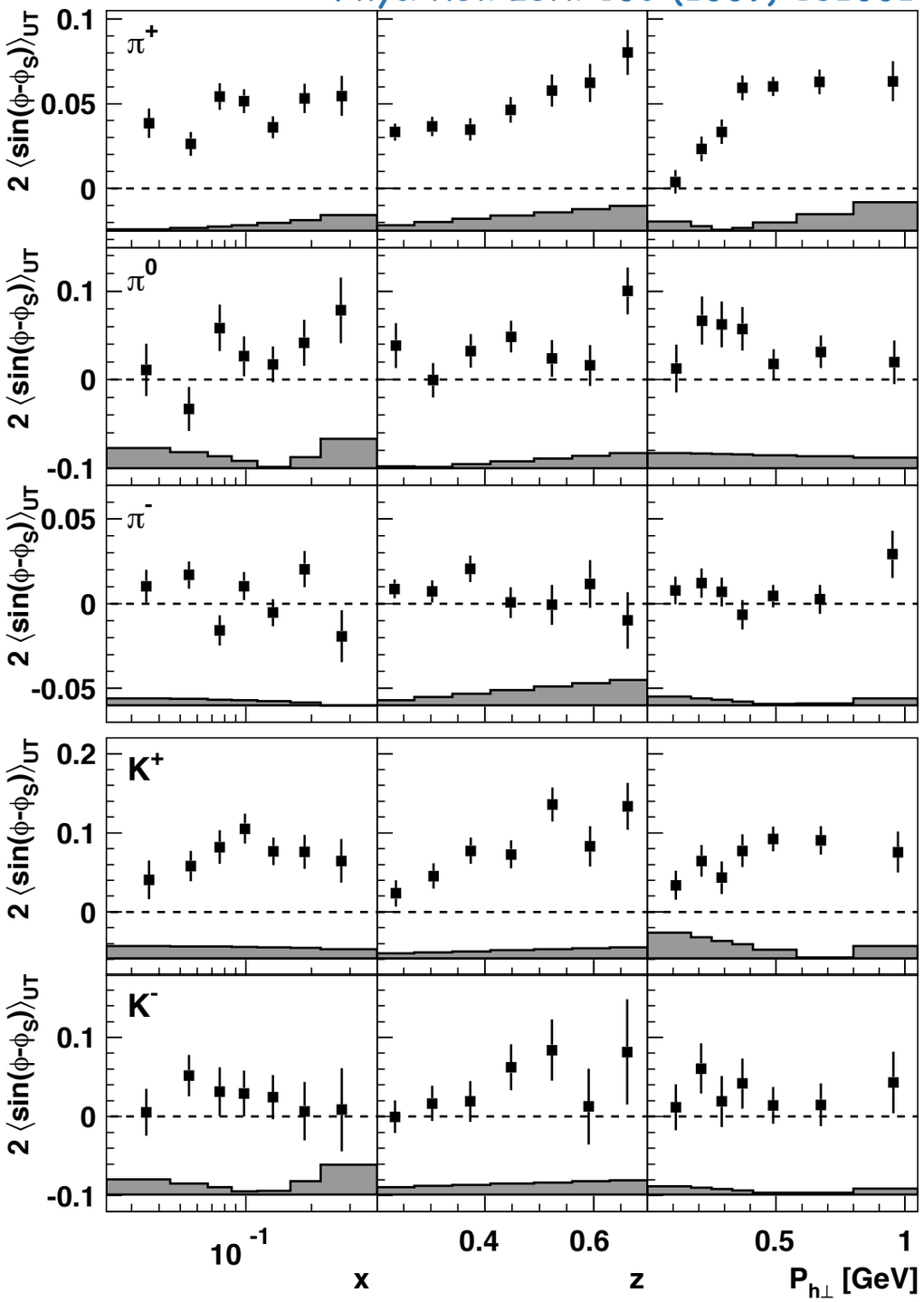
Increase with $P_{h\perp}$, concentrated at large x and z



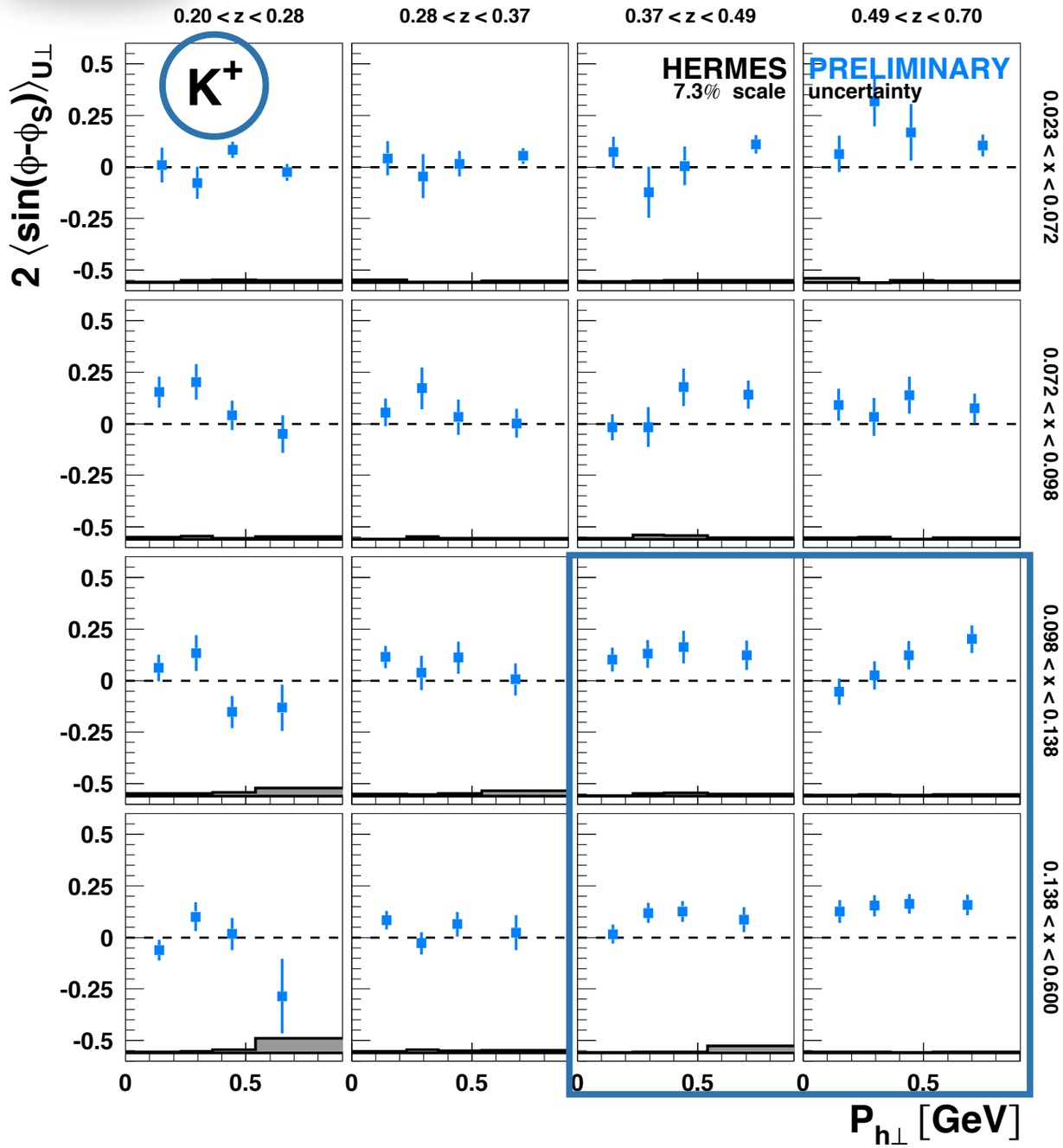
Sivers amplitudes

$$\propto f_{1T}^{\perp,q} \otimes D_1^q$$

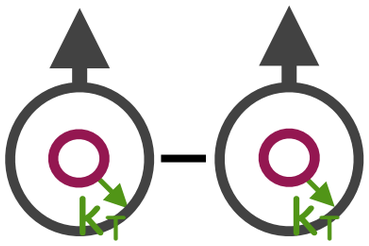
Phys. Rev. Lett. 103 (2009) 152002



3D



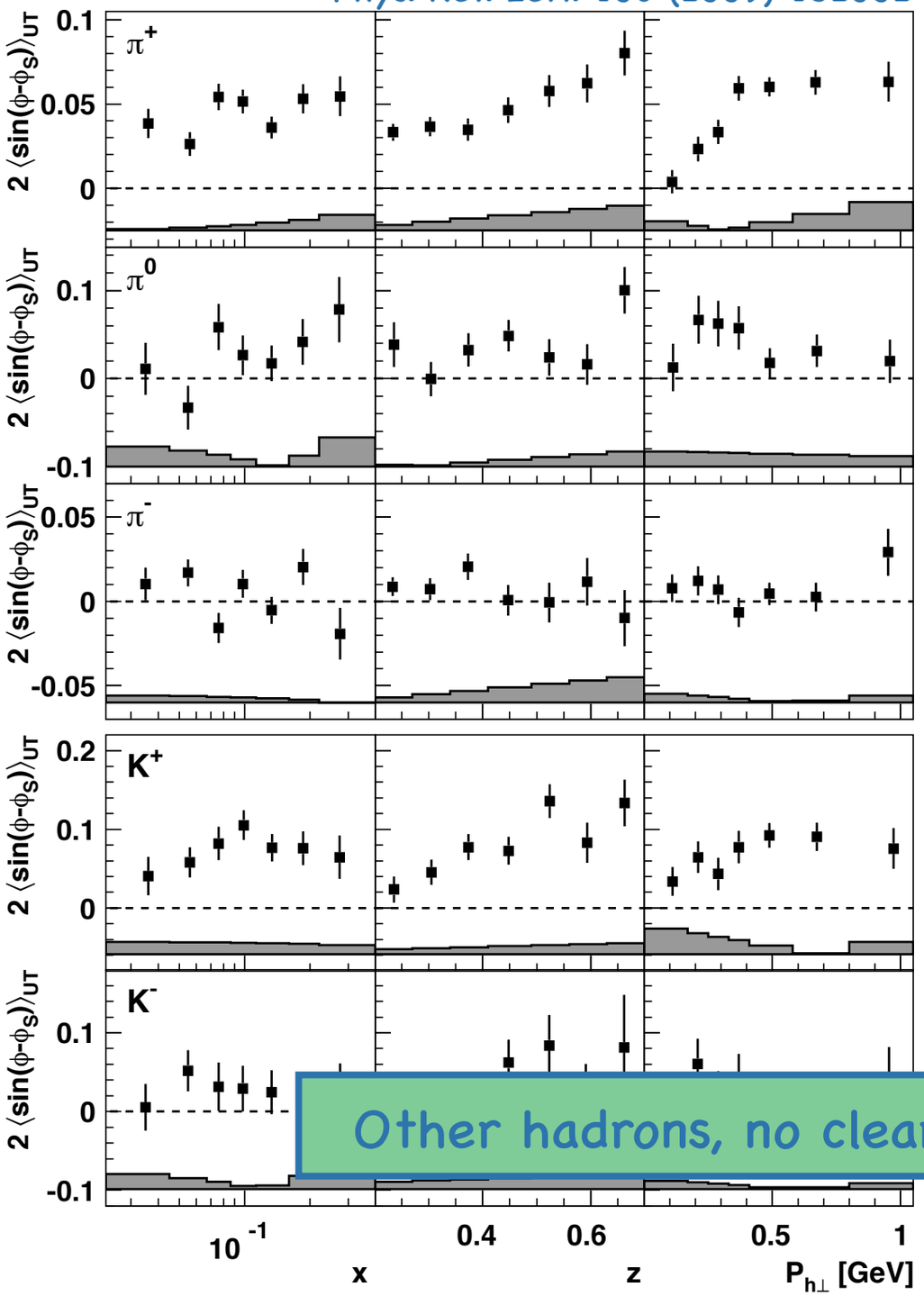
Increase with $P_{h\perp}$, concentrated at large x and z



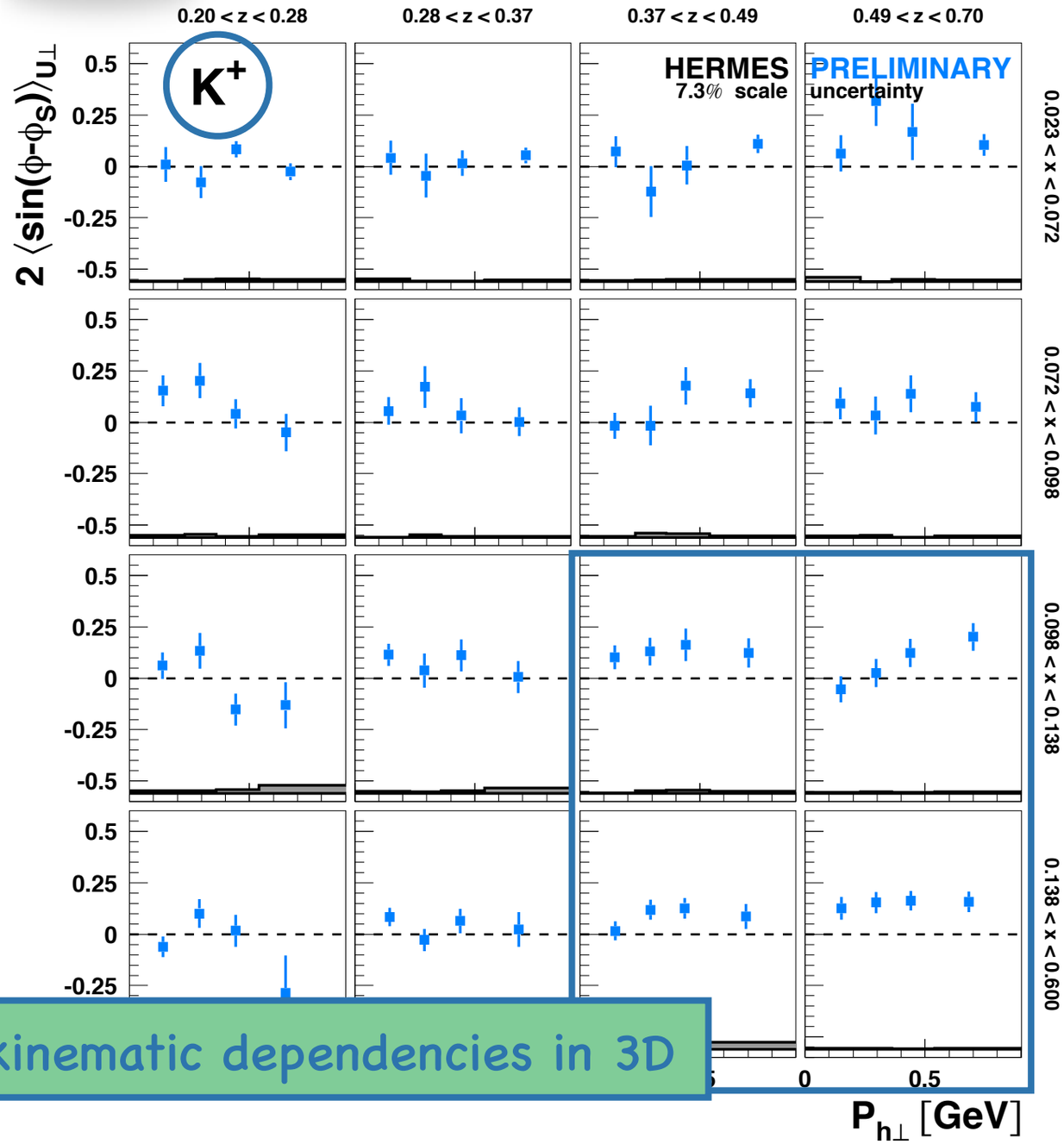
Sivers amplitudes

$\propto f_{1T}^{\perp,q} \otimes D_1^q$

Phys. Rev. Lett. 103 (2009) 152002

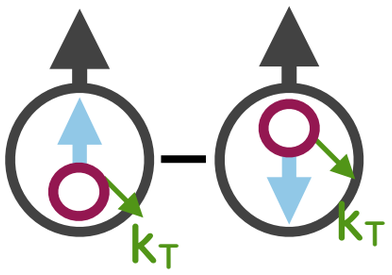


3D



Other hadrons, no clear kinematic dependencies in 3D

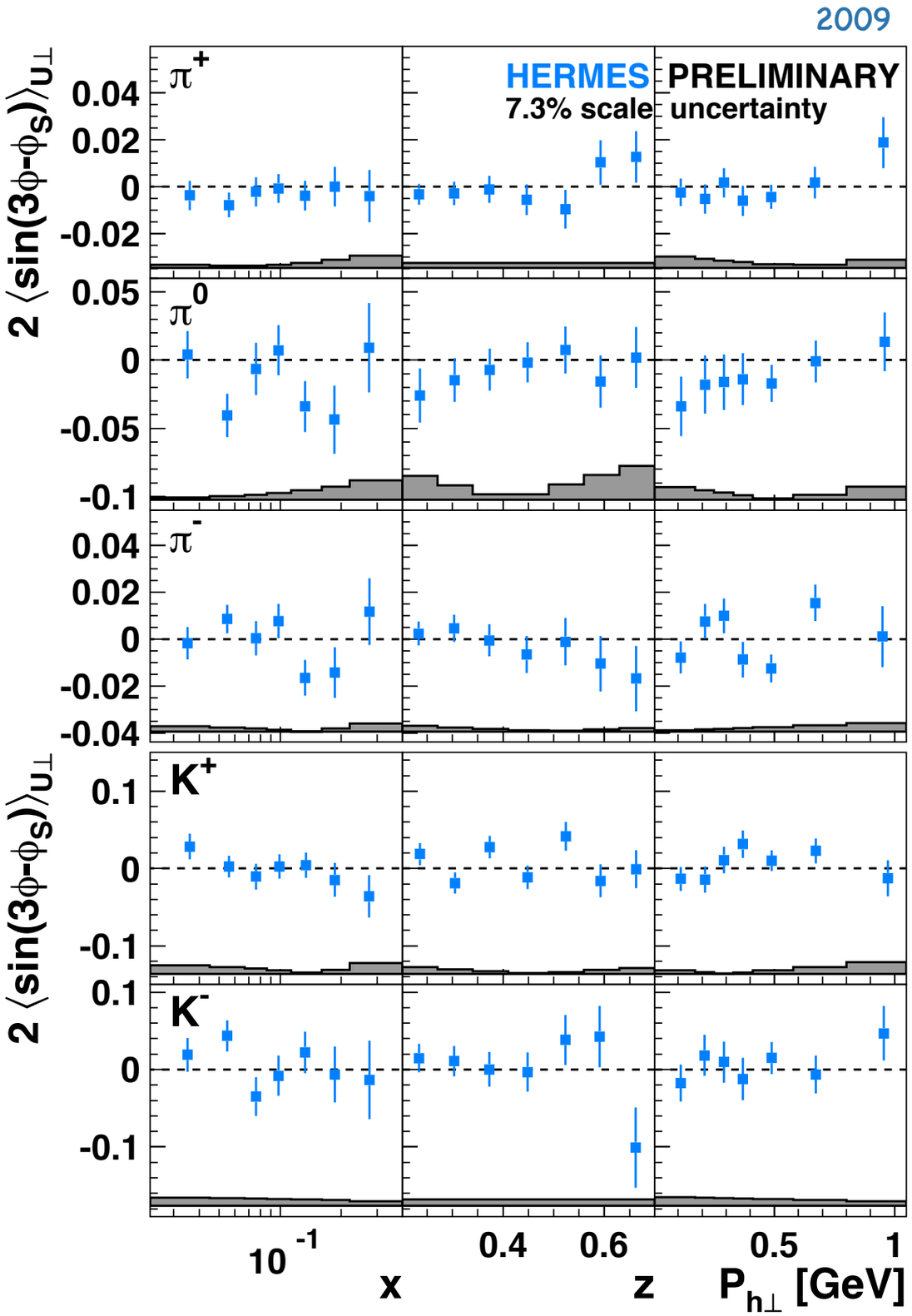
Increase with $P_{h\perp}$, concentrated at large x and z

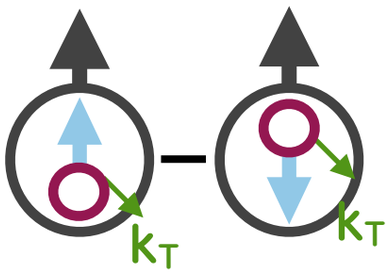


Pretzelosity amplitudes

$$\propto h_{1T}^{\perp,q} \otimes H_1^{\perp,q}$$

2009

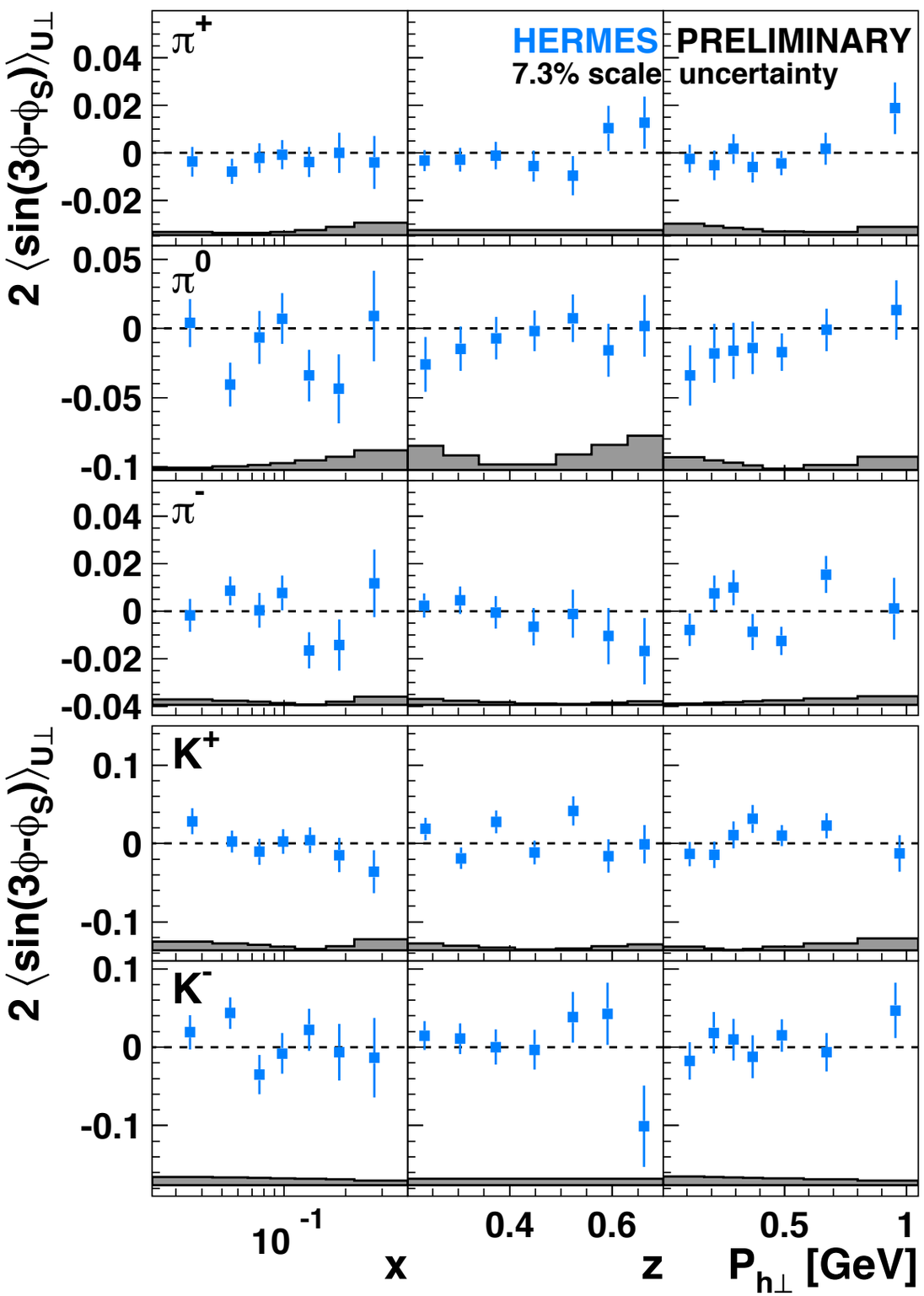


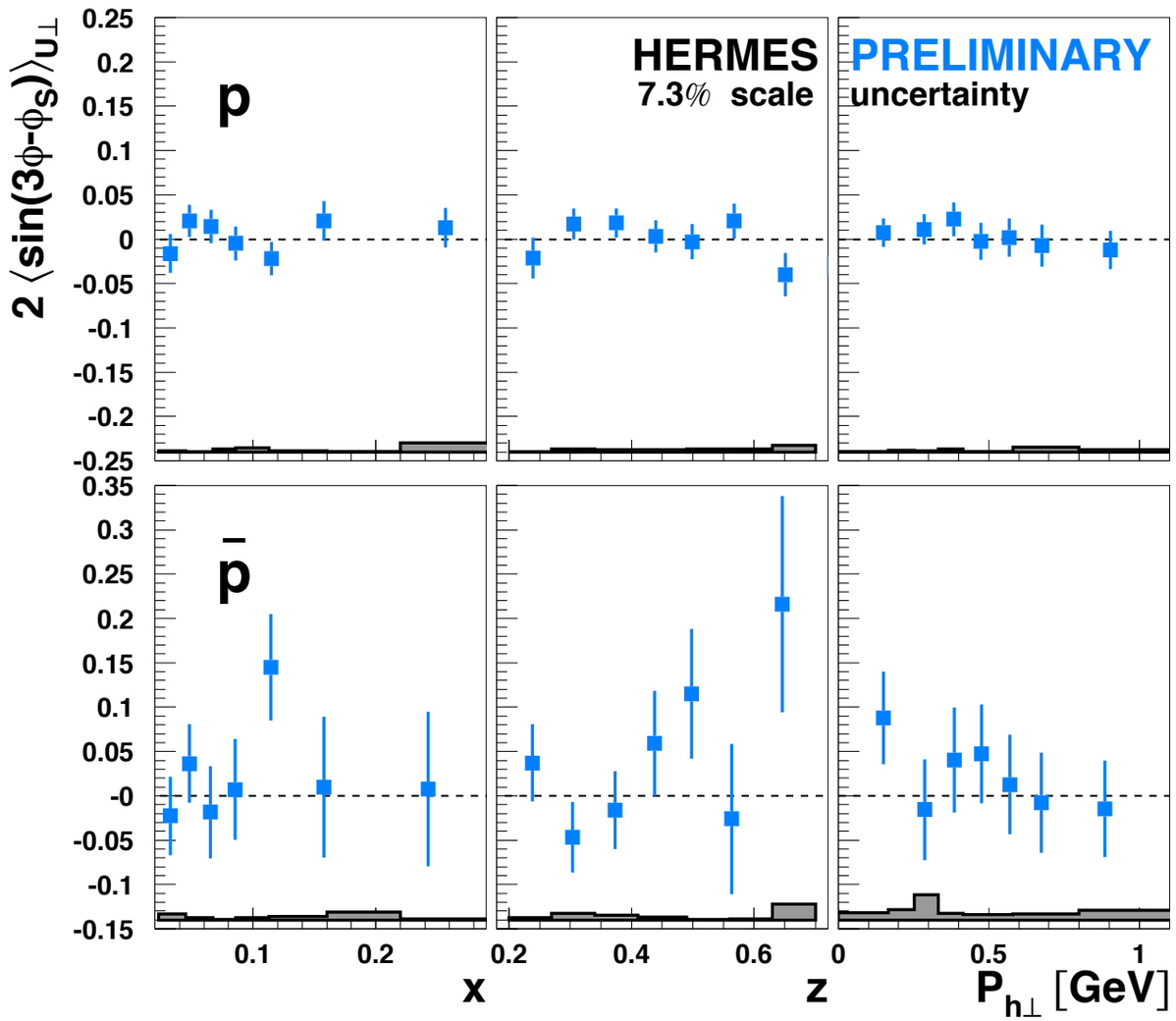


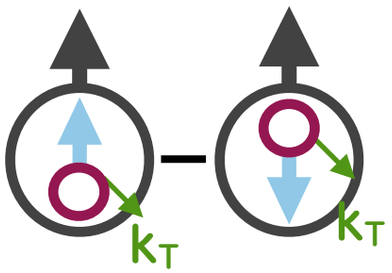
Pretzelosity amplitudes

$$\propto h_{1T}^{\perp,q} \otimes H_1^{\perp,q}$$

2009







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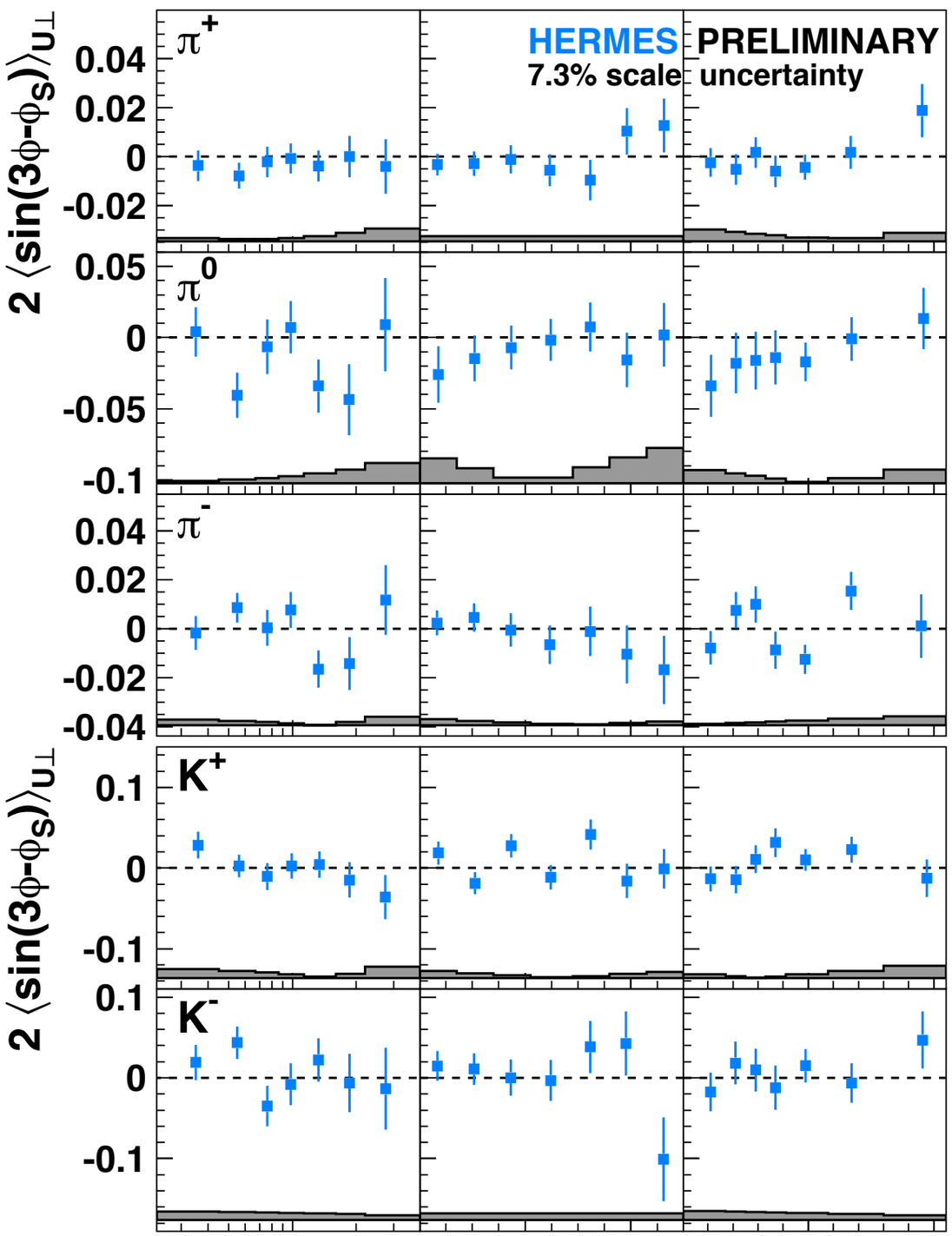
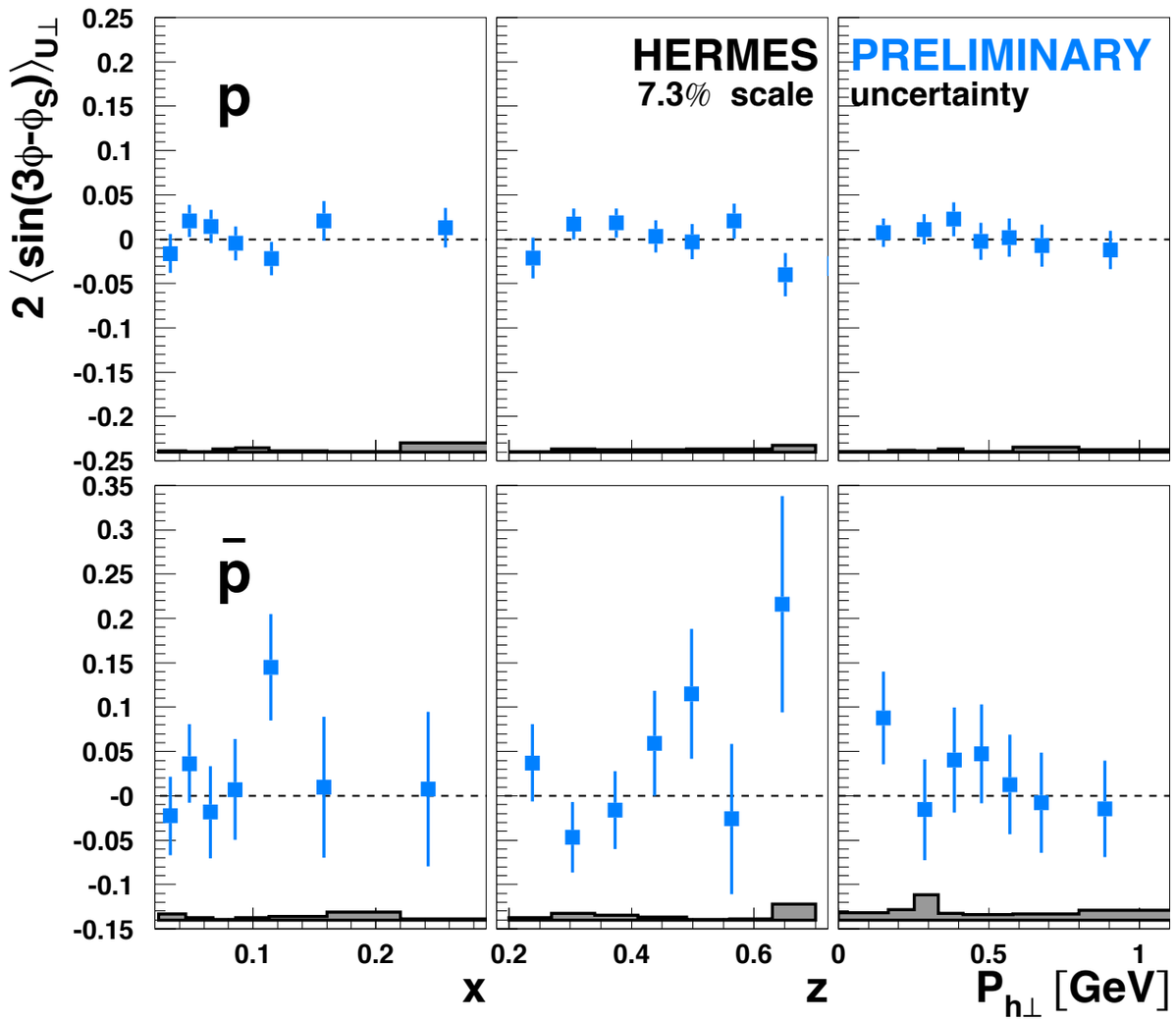
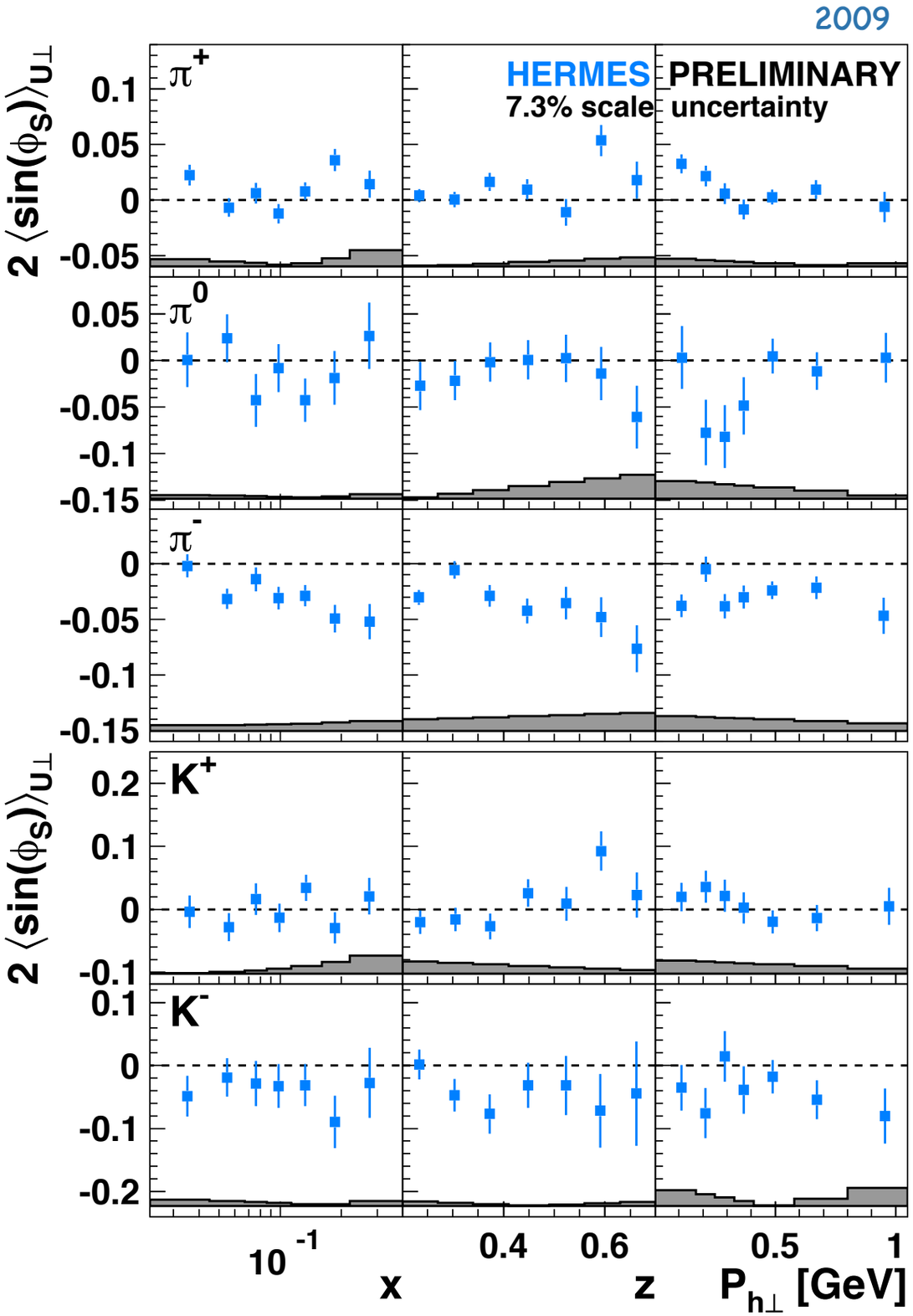




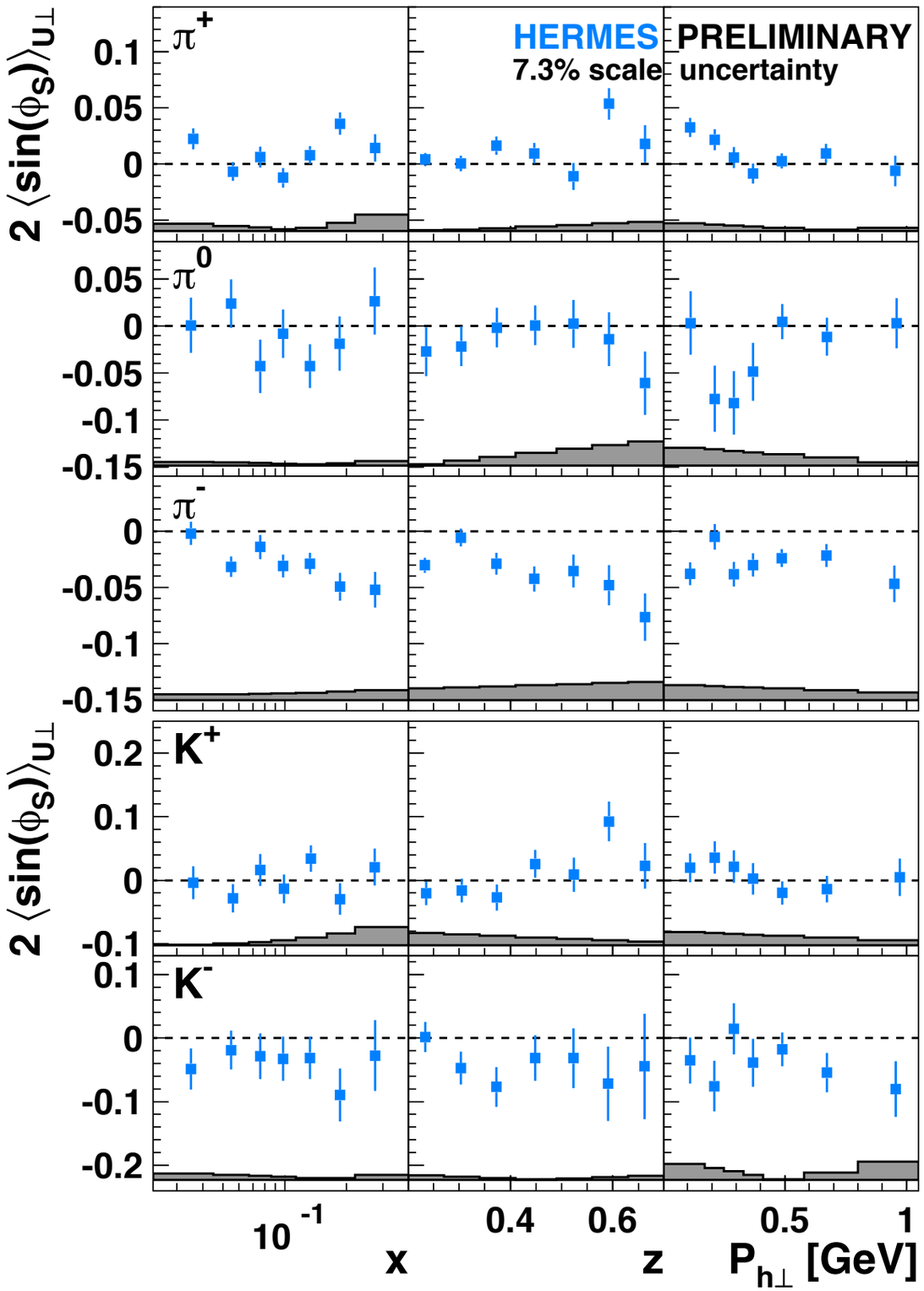
pions, kaons, protons: no underlying kinematic dependencies

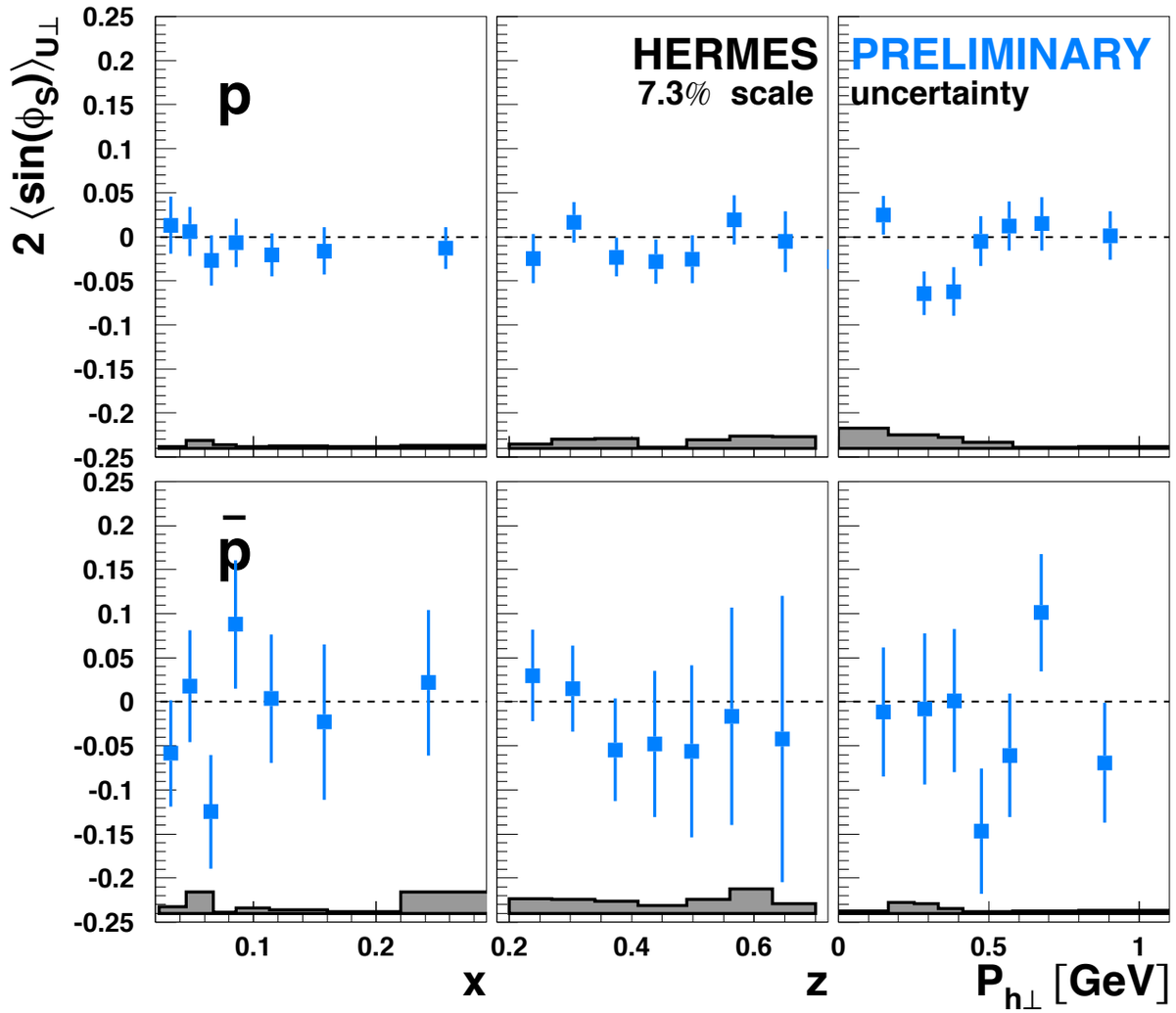
Twist-3: $F_{UT}^{\sin(\phi_S)}$



Twist-3: $F_{UT}^{\sin(\phi_S)}$

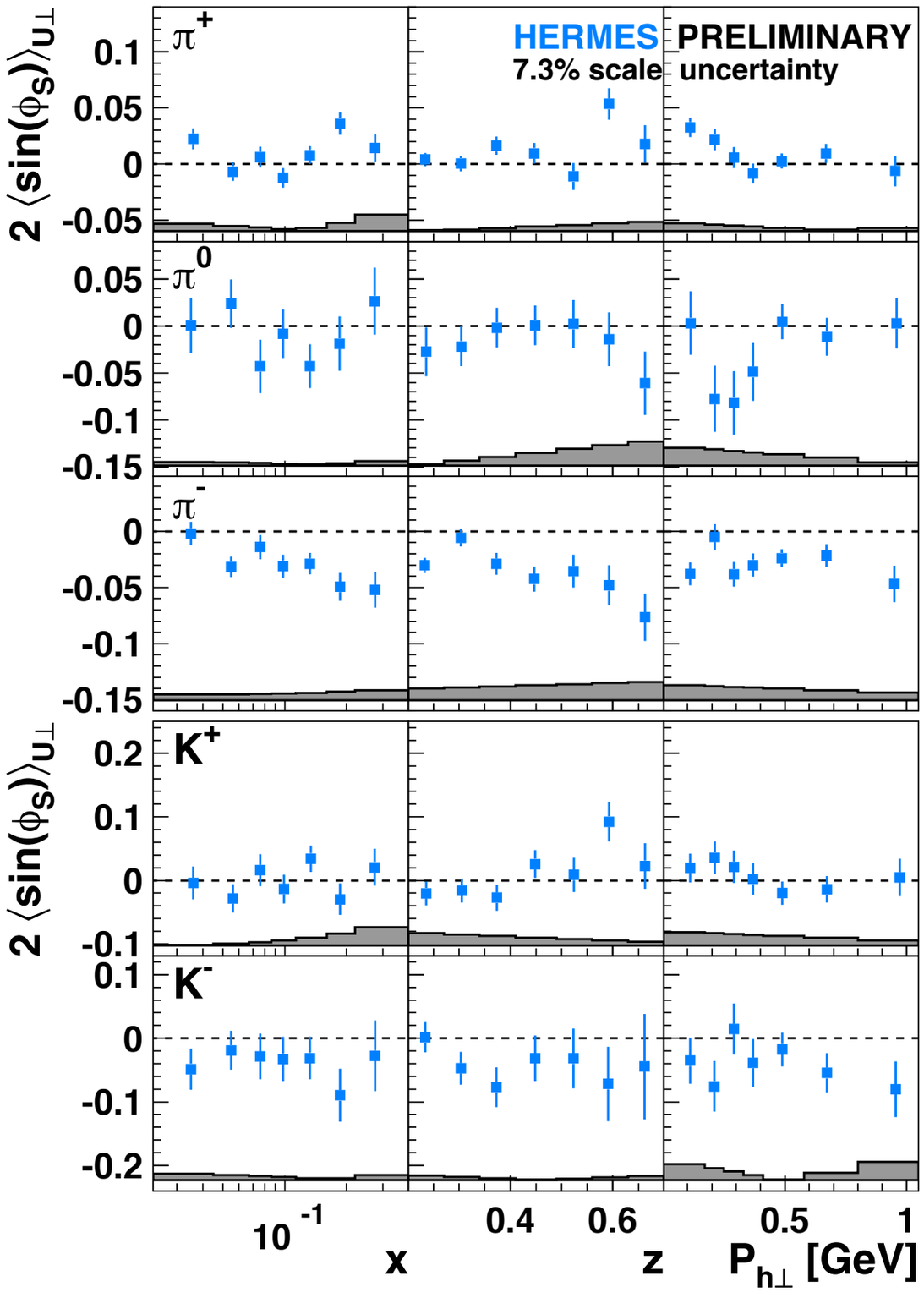
2009



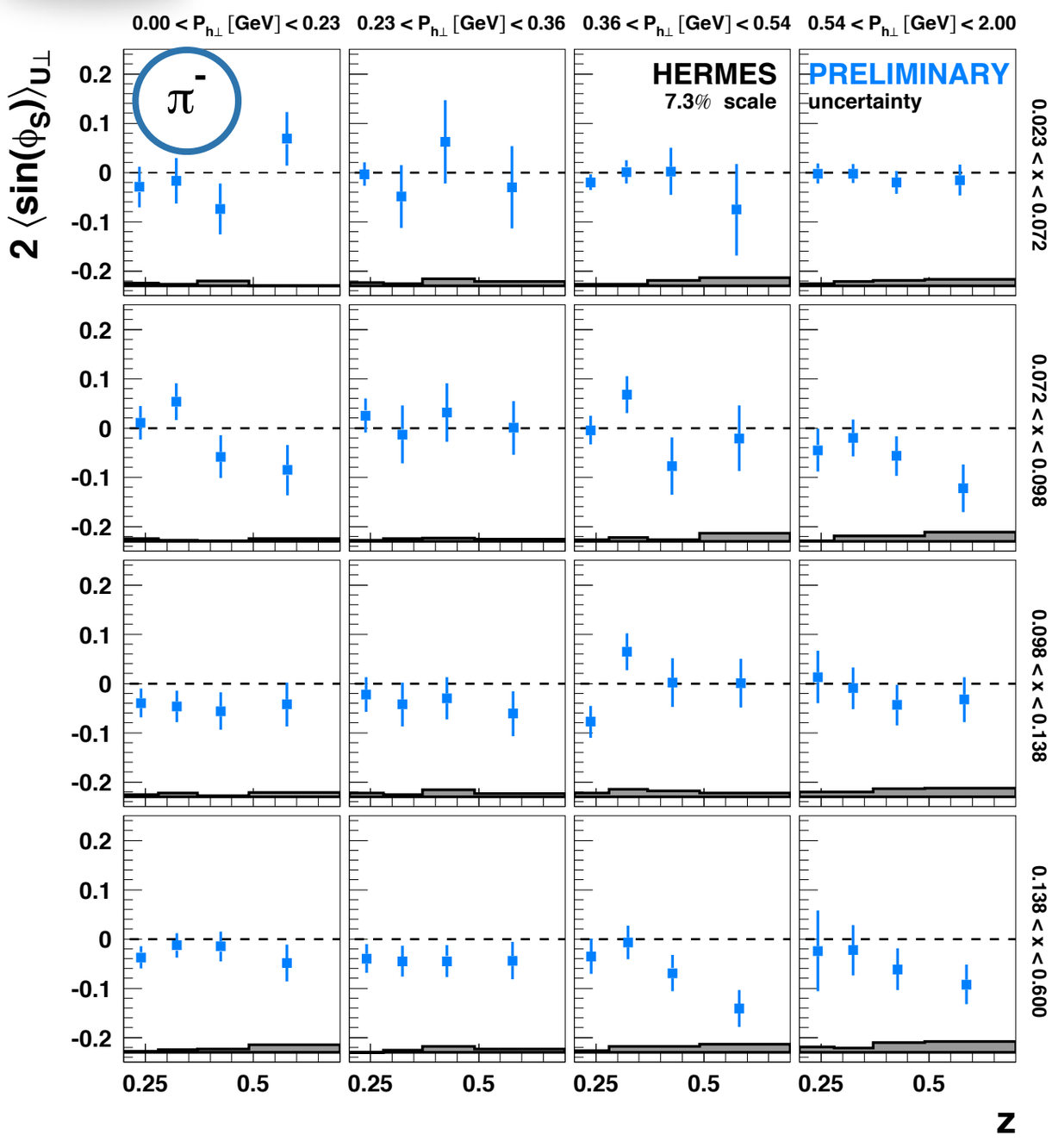


Twist-3: $F_{UT}^{\sin(\phi_S)}$

2009



3D



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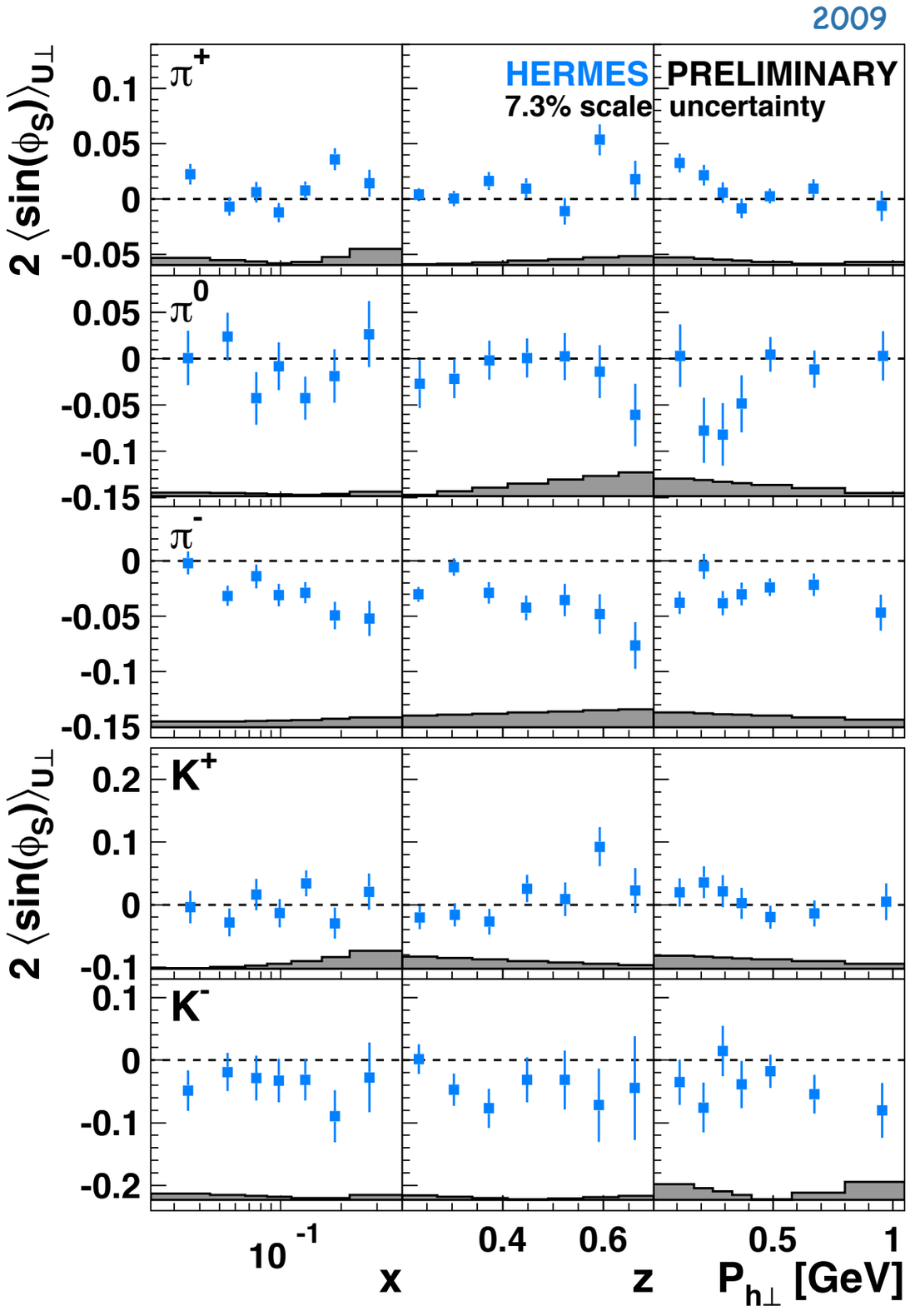
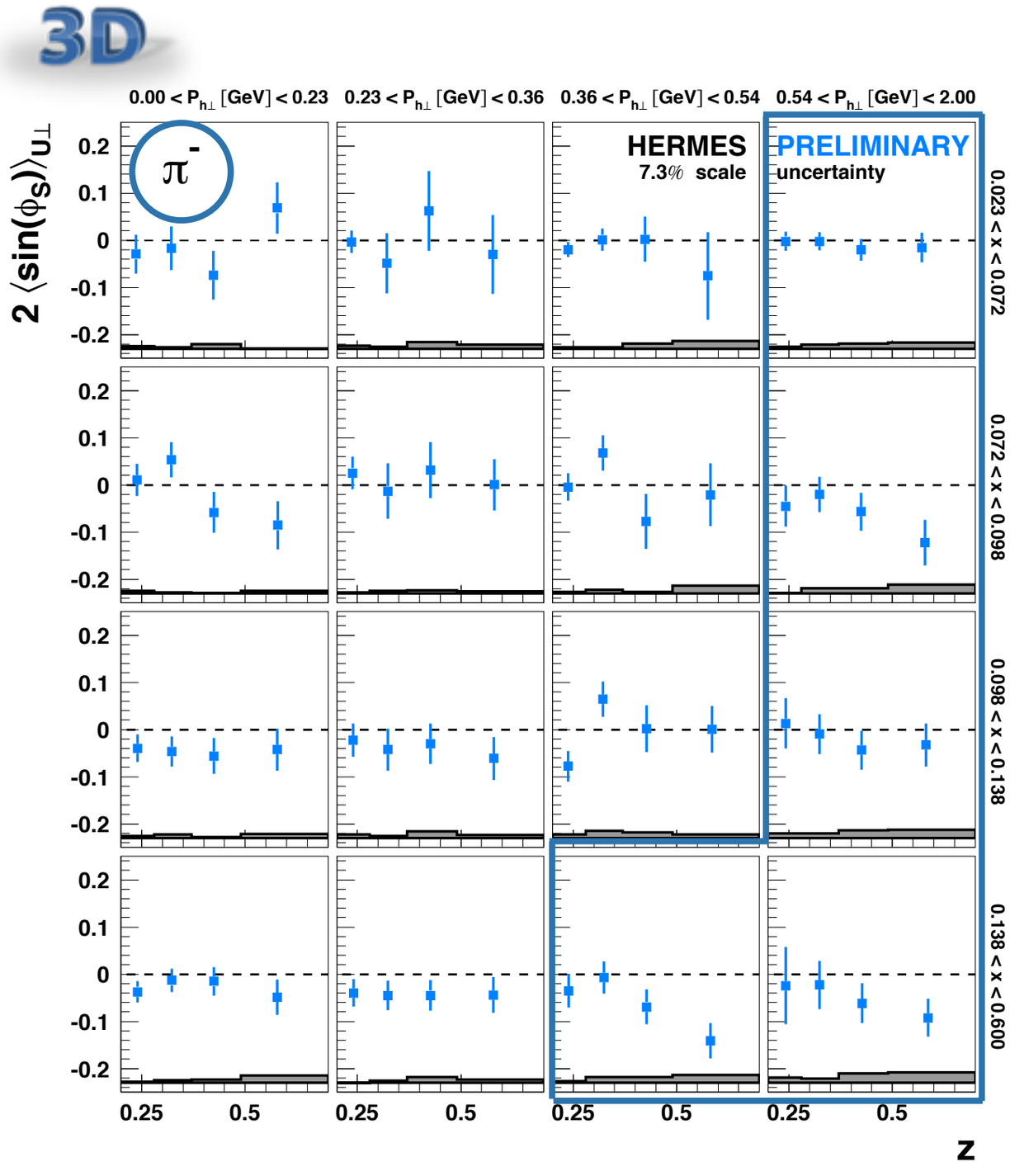
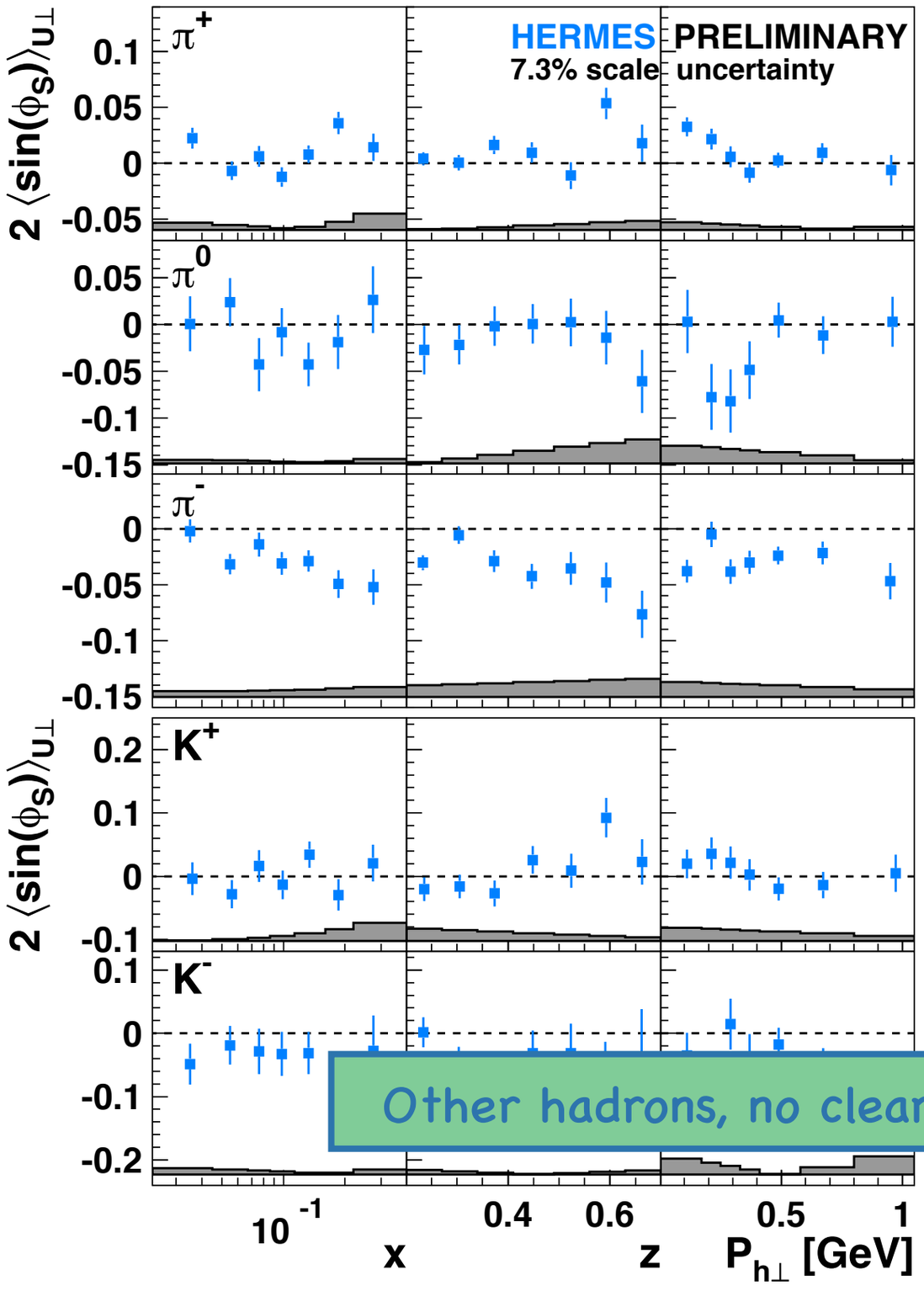




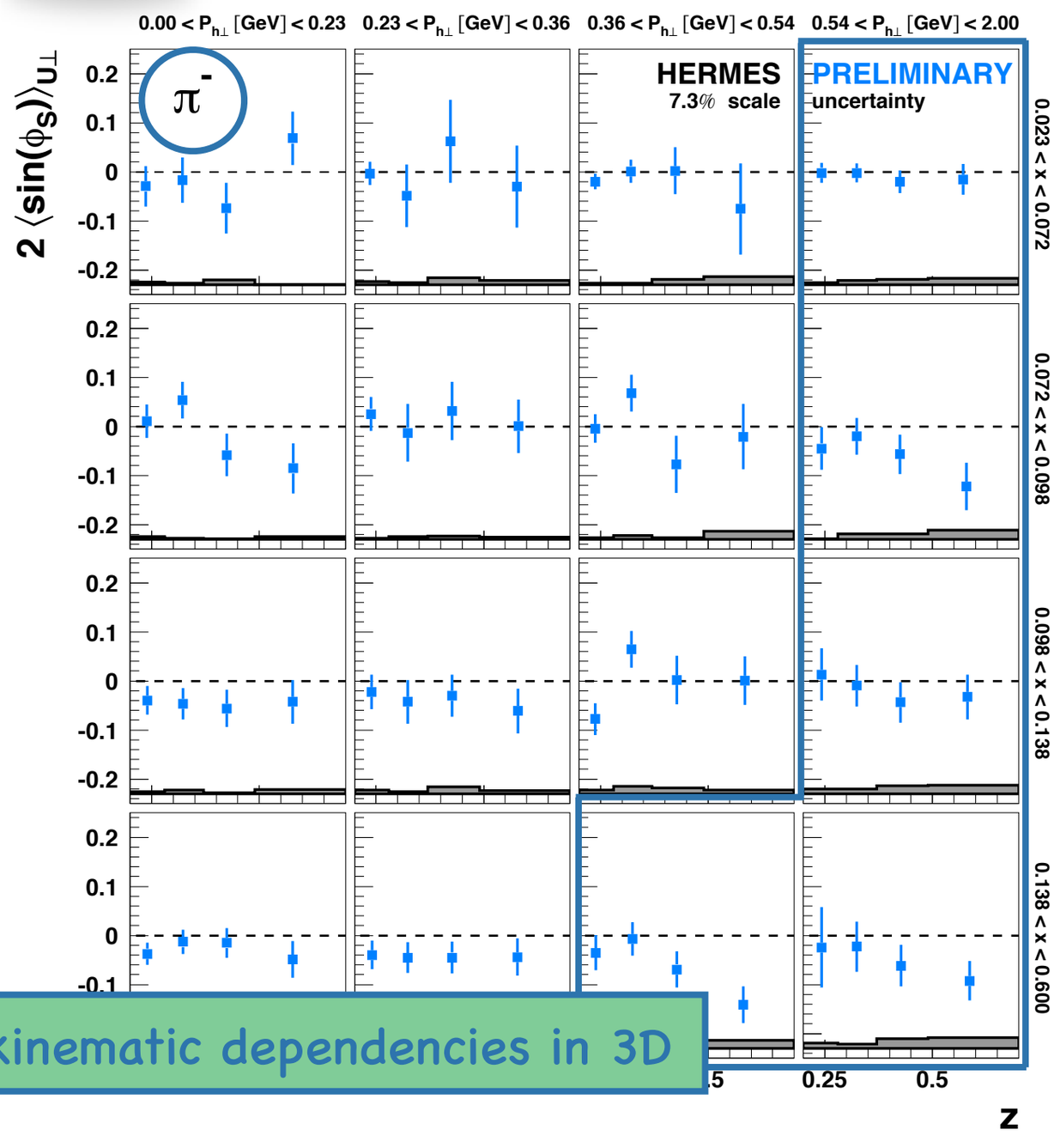
Increase with z, rather at larger x and $P_{h\perp}$

Twist-3: $F_{UT}^{\sin(\phi_S)}$

2009



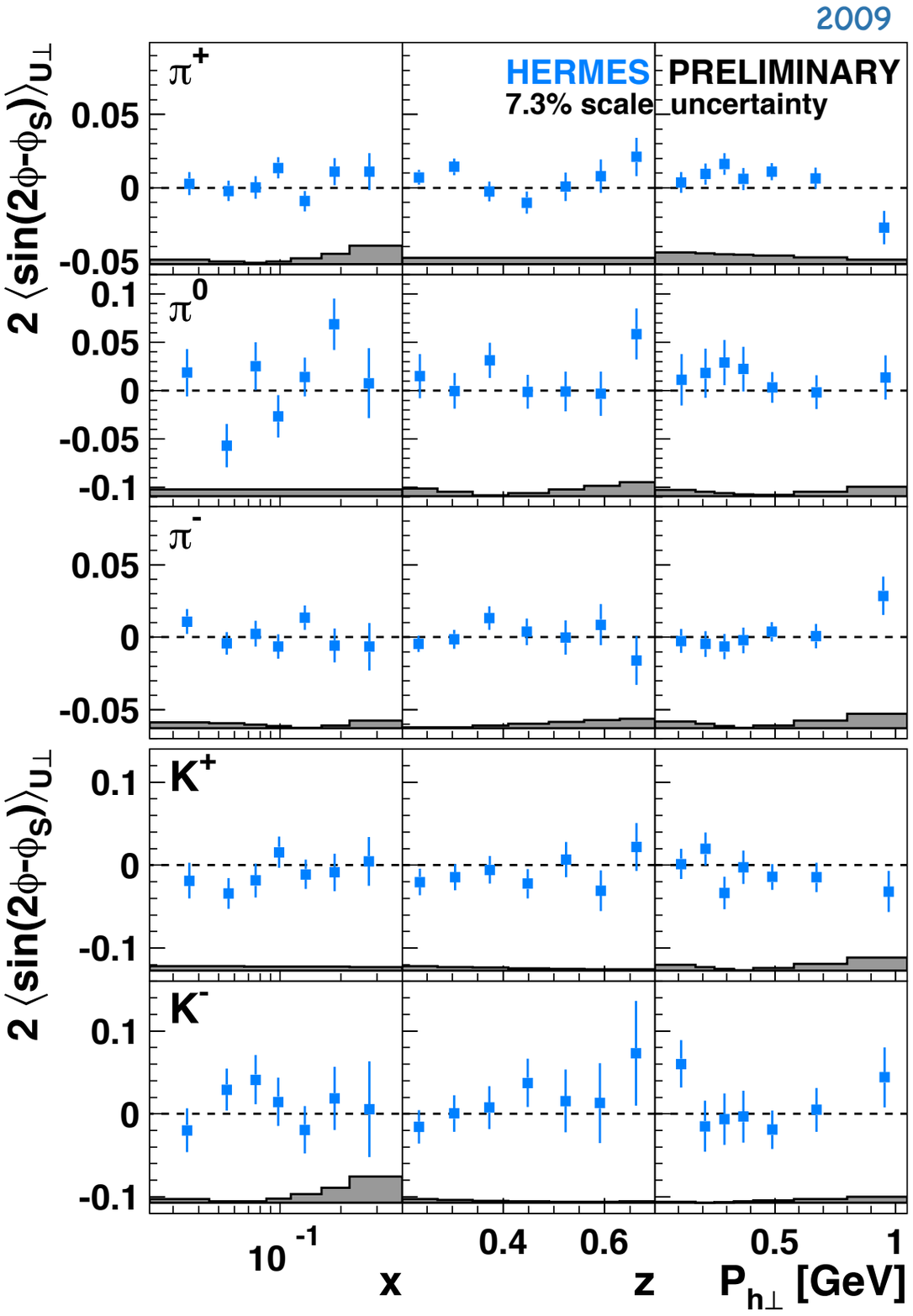
3D

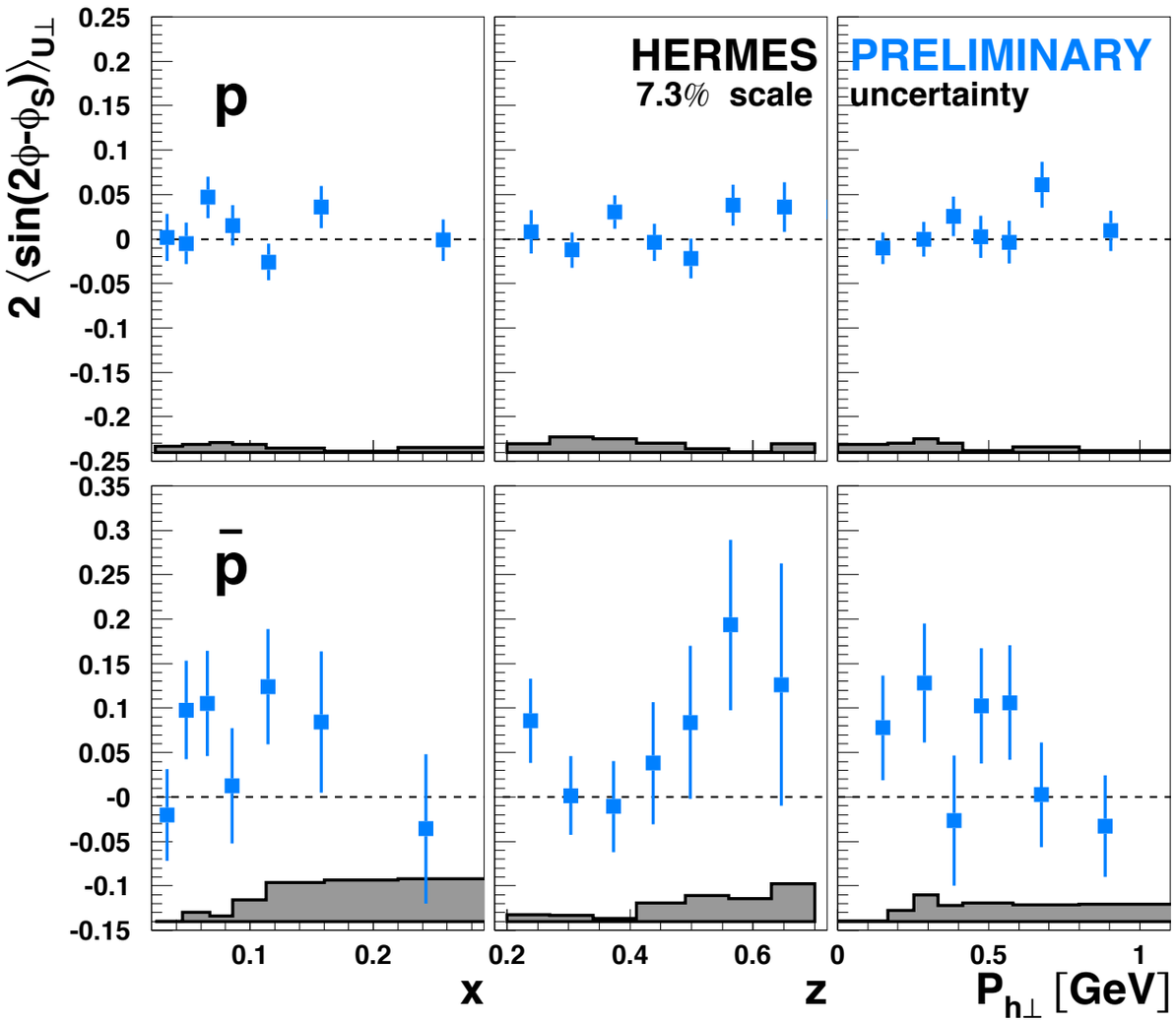


Other hadrons, no clear kinematic dependencies in 3D

Increase with z, rather at larger x and $P_{h\perp}$

Twist-3: $F_{UT}^{\sin(2\phi-\phi_S)}$





3D: no surprises

Worm-gear PDF

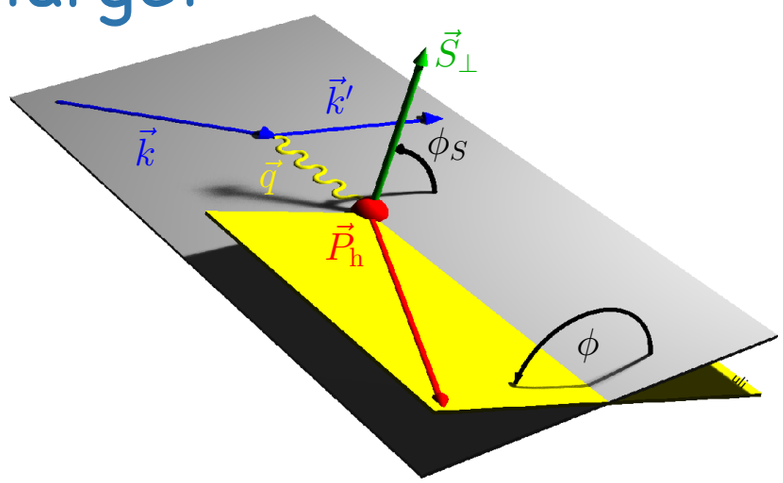
$F_{LT}^{\cos(2\phi-\phi_S)}$

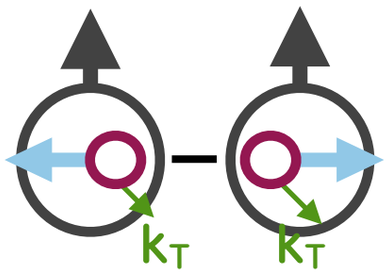
$F_{LT}^{\cos(\phi_S)}$

A_{LT}

longitudinally polarized beam
transversely polarized H target

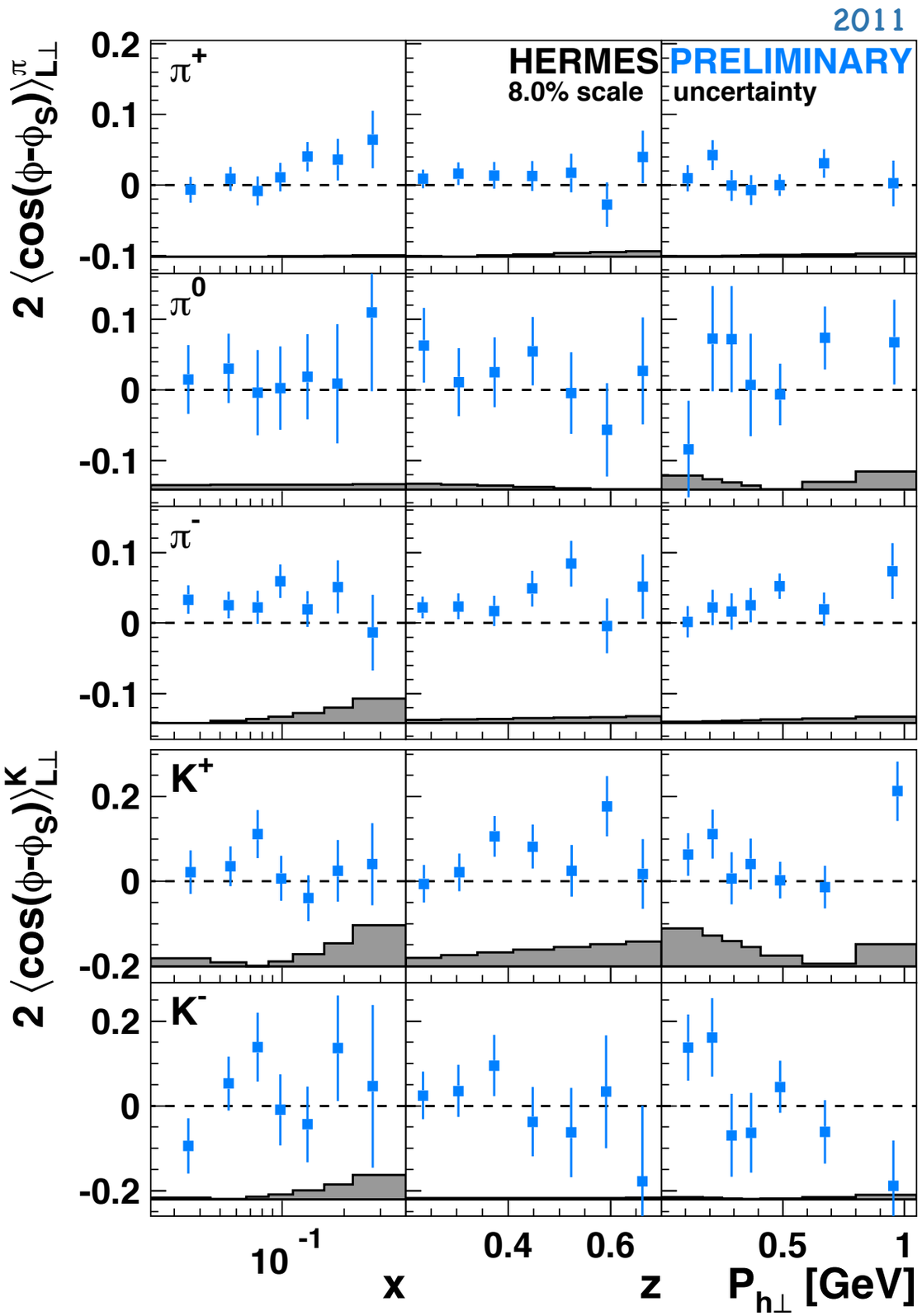
Results for pions, kaons and protons

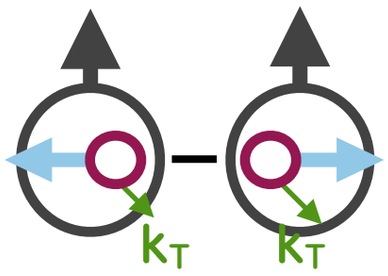




Worm-gear amplitudes

$\propto g_{1T}^{\perp,q} \otimes D_1^q$





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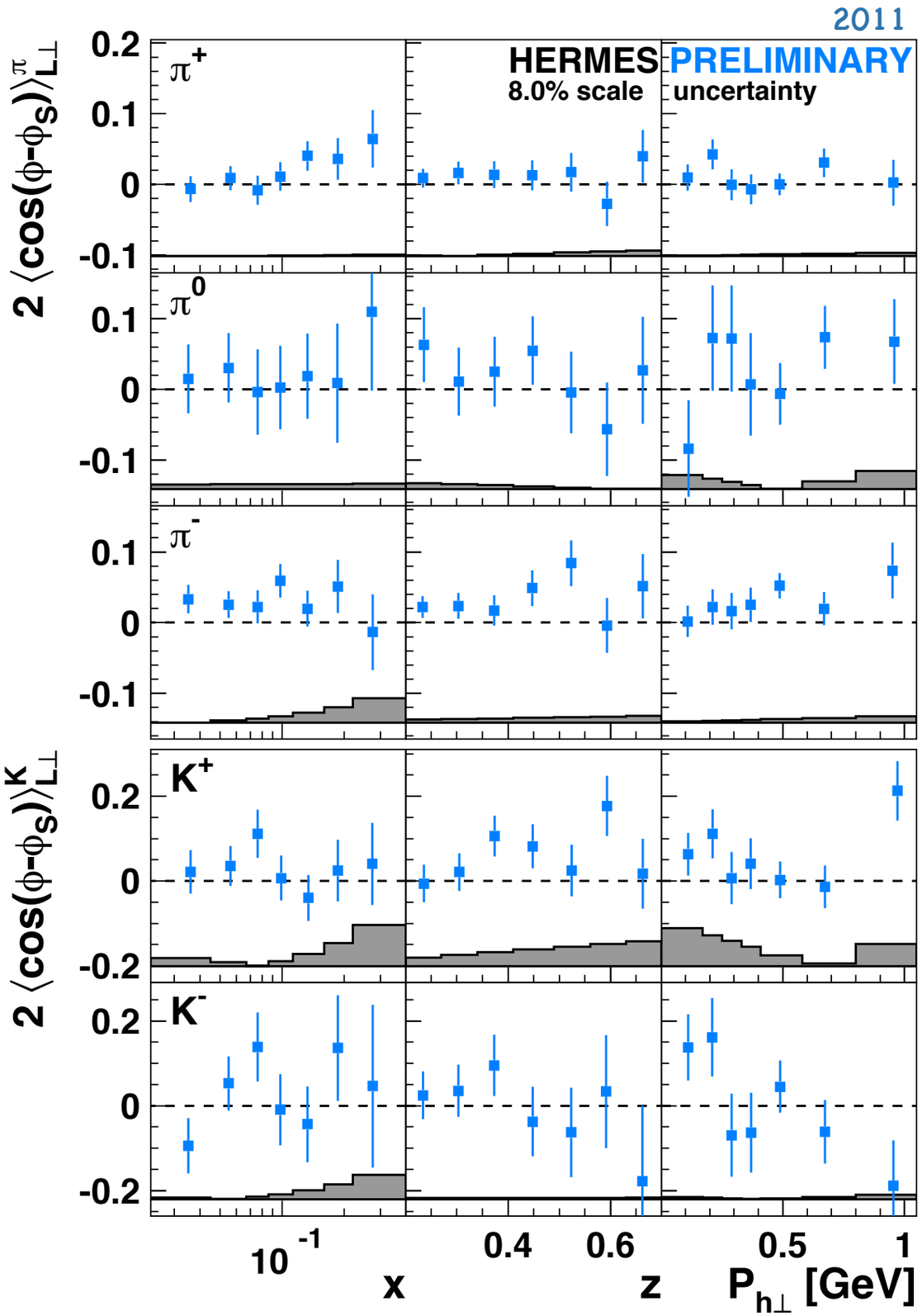
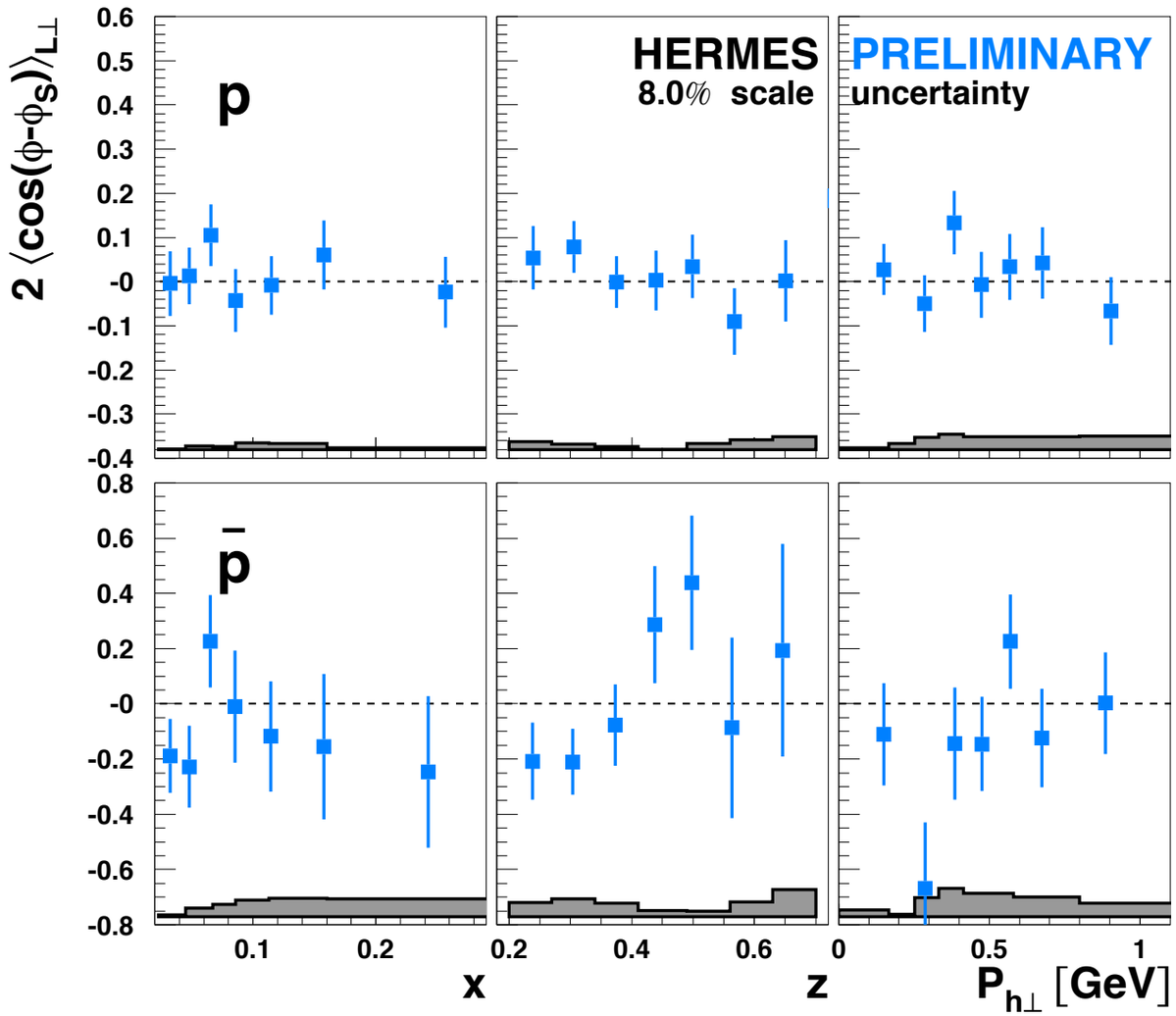
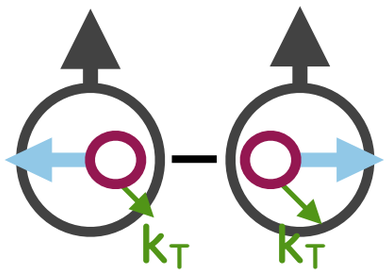


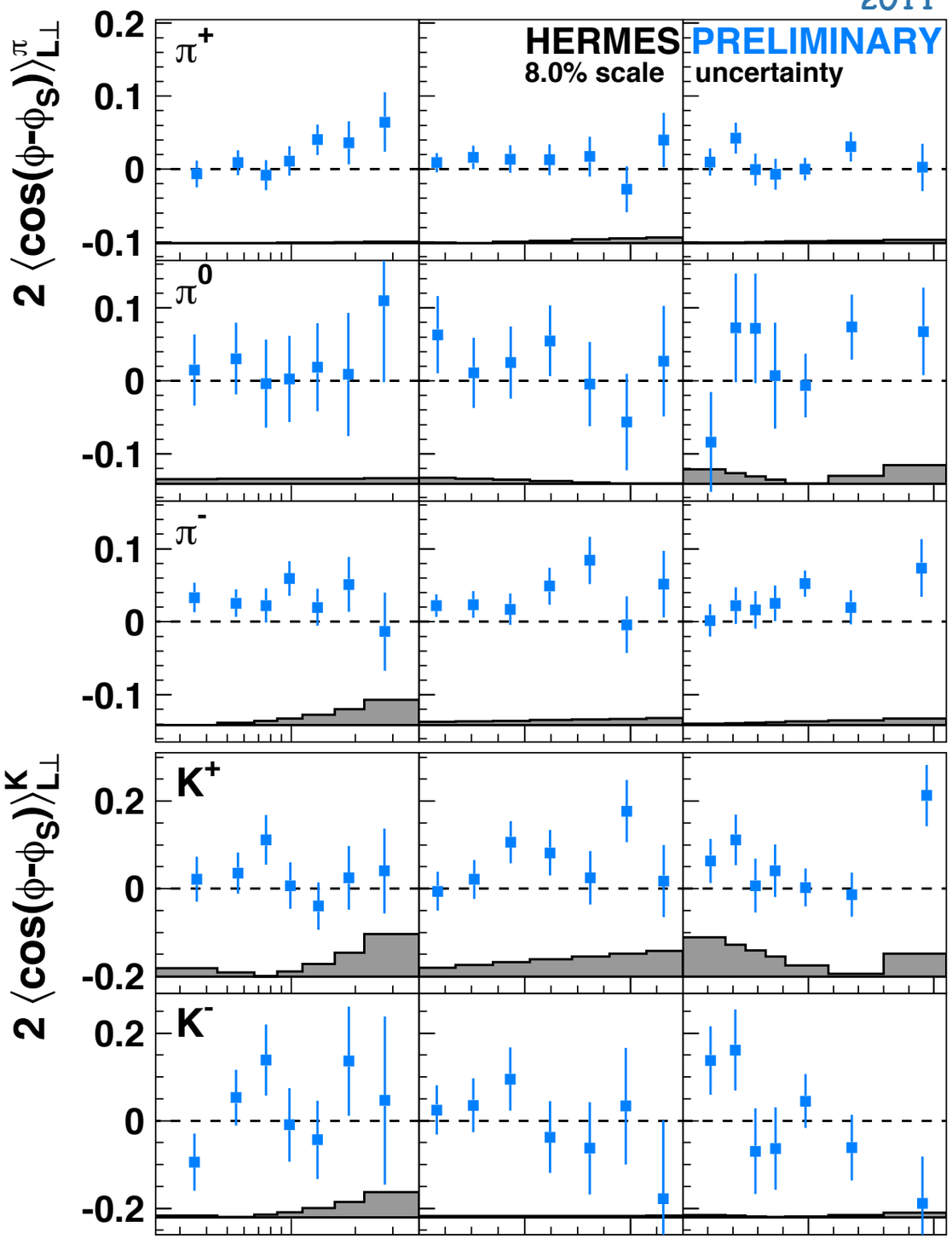




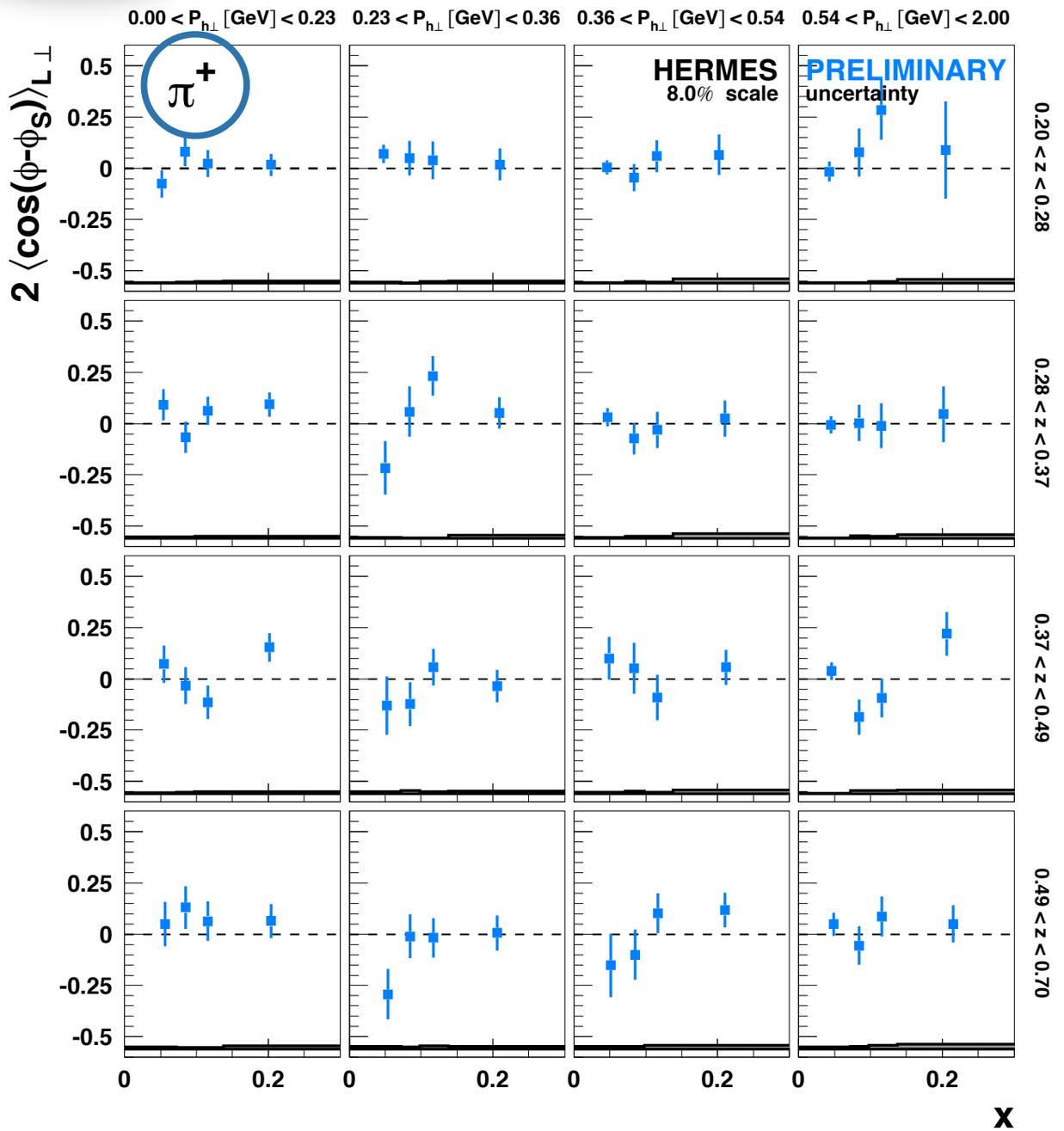
Worm-gear amplitudes

$\propto g_{1T}^{\perp,q} \otimes D_1^q$

2011

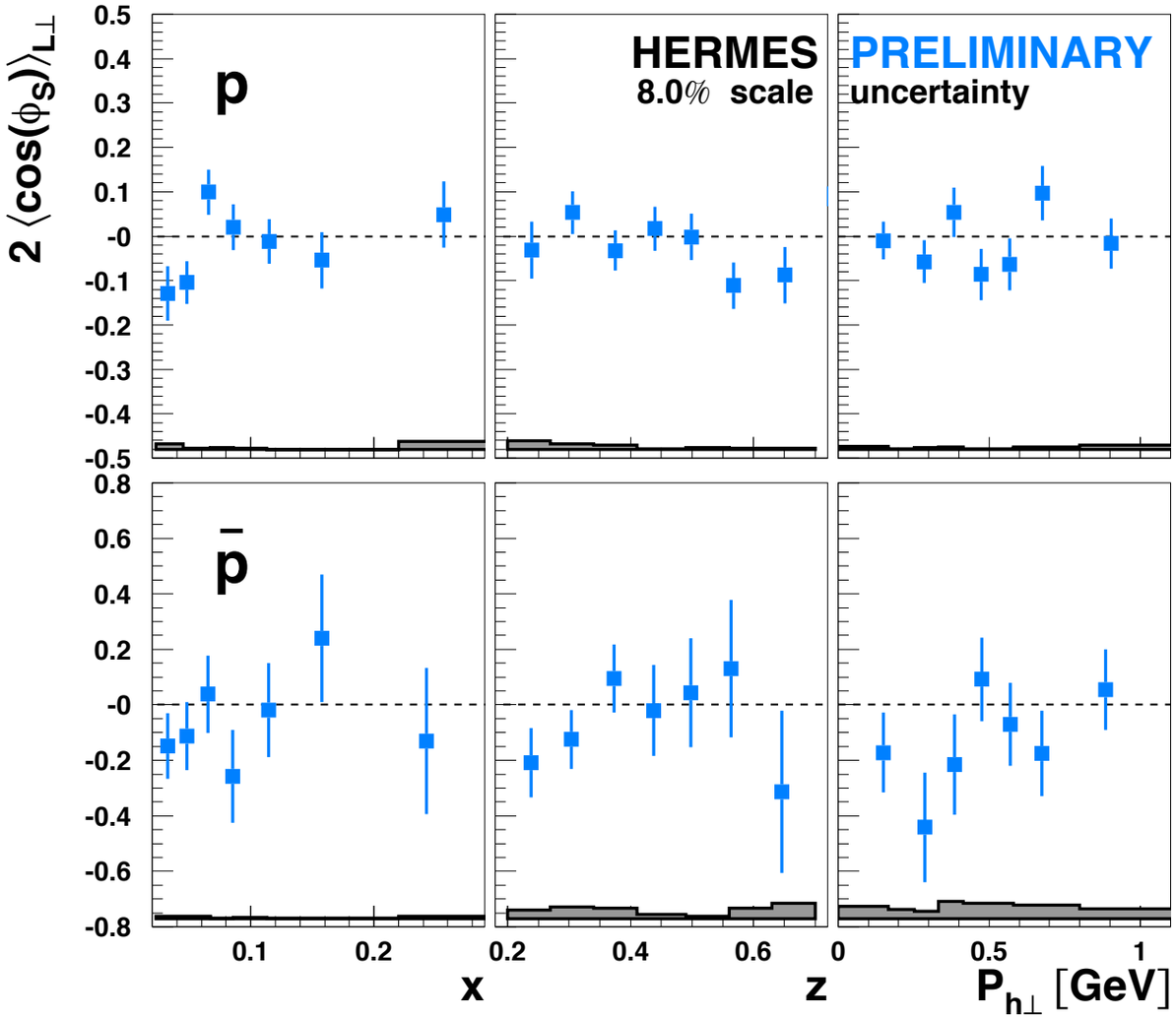


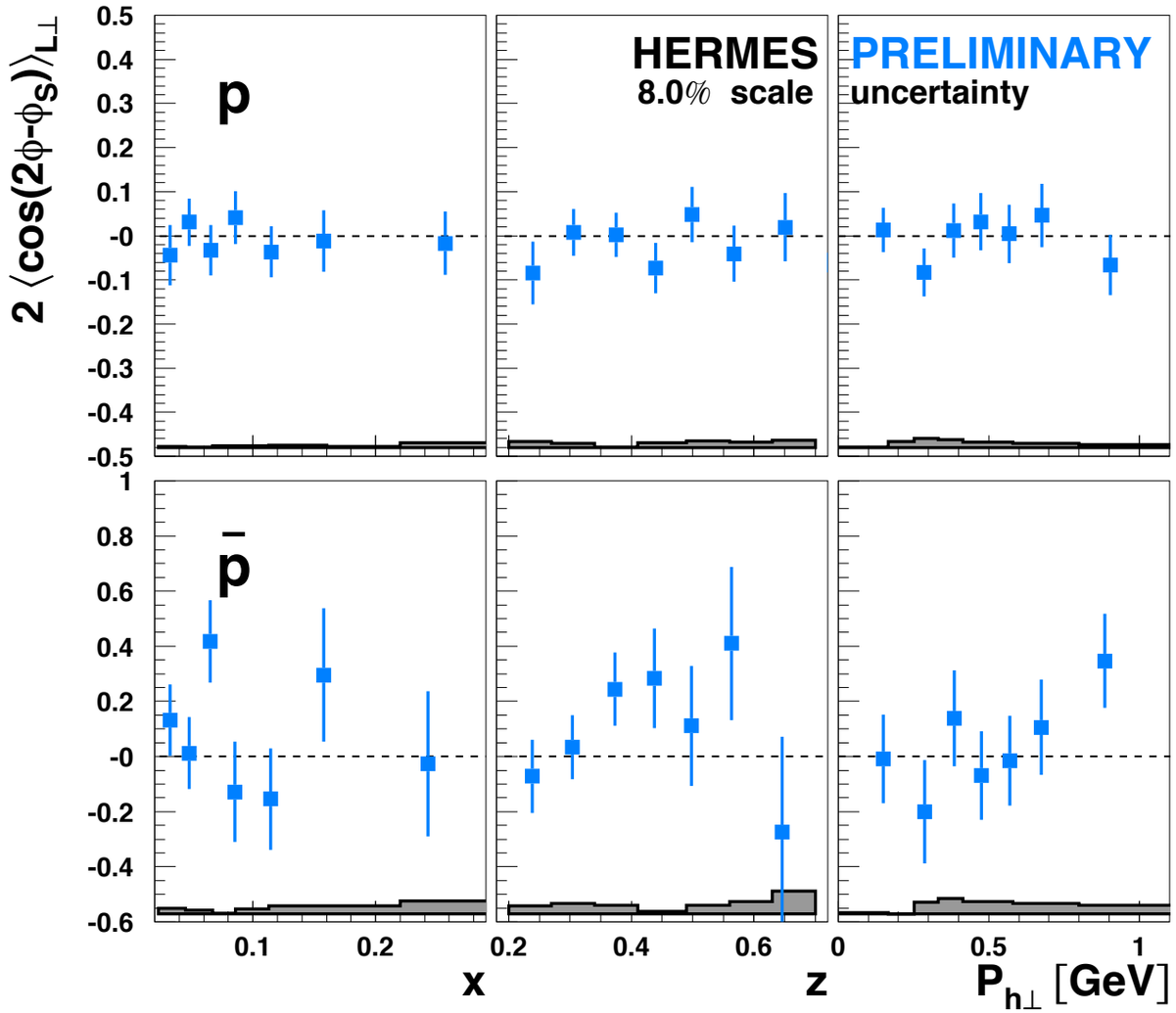
3D



pions, kaons, protons: no underlying kinematic dependencies

Twist-3: $F_{LT}^{\cos(\phi_S)}$ and $F_{LT}^{\cos(2\phi-\phi_S)}$



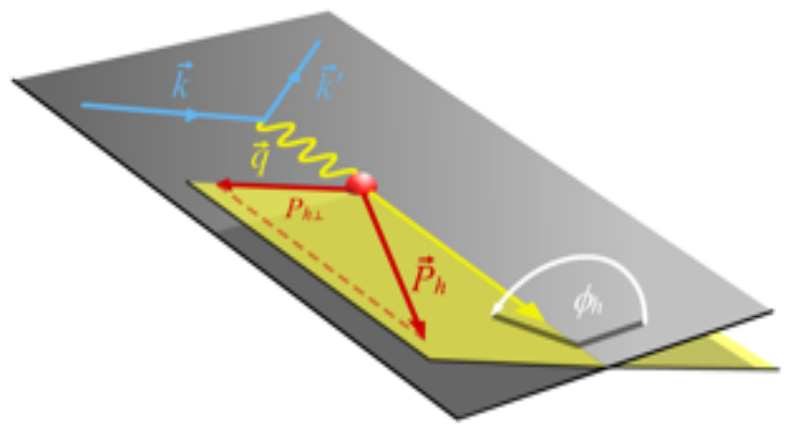


- Also for 1D pions & kaons (2011): compatible with zero
- 3D: no surprises

A_{LU}

longitudinally polarized e^+/e^- beam
unpolarized H & D target

Results for pions, kaons and protons



A_{LU}

Higher twist:

$$F_{LU}^{\sin\phi_h} \propto h_1^{\perp} \otimes \tilde{E},\ e \otimes H_1^{\perp},\ g^{\perp} \otimes D_1,\ f_1 \otimes \tilde{G}^{\perp}$$

A_{LU}

Higher twist:

$$F_{LU}^{\sin\phi_h} \propto h_1^{\perp} \otimes \tilde{E},\ e \otimes H_1^{\perp},\ g^{\perp} \otimes D_1,\ f_1 \otimes \tilde{G}^{\perp}$$

Chiral-odd T-even twist-3 FF

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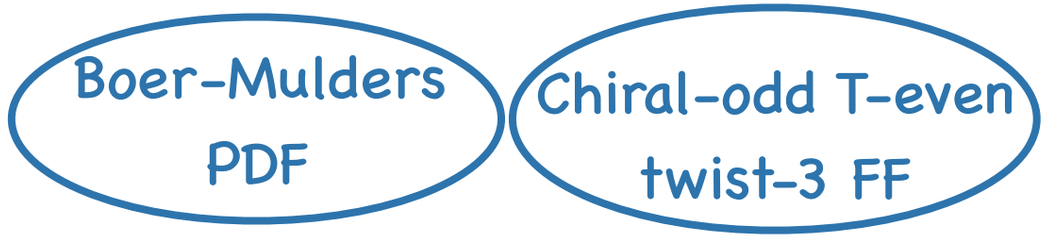

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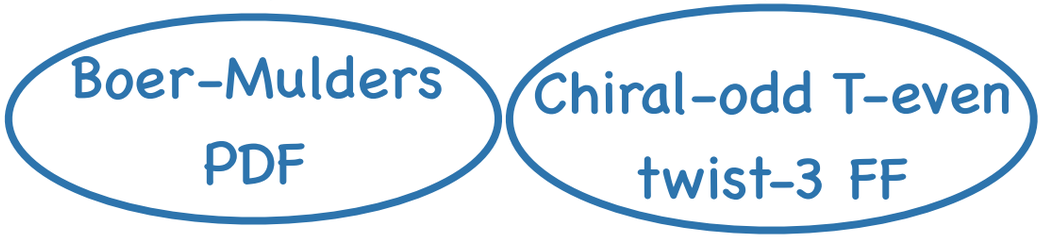
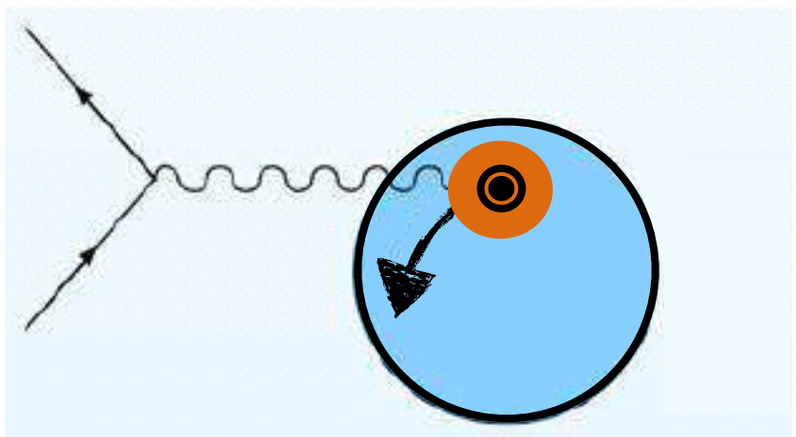


Boer-Mulders PDF



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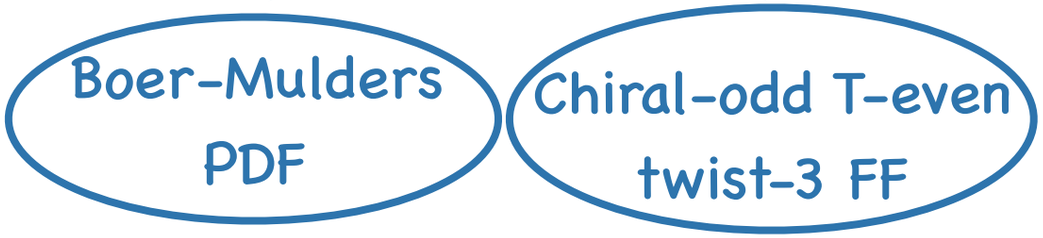
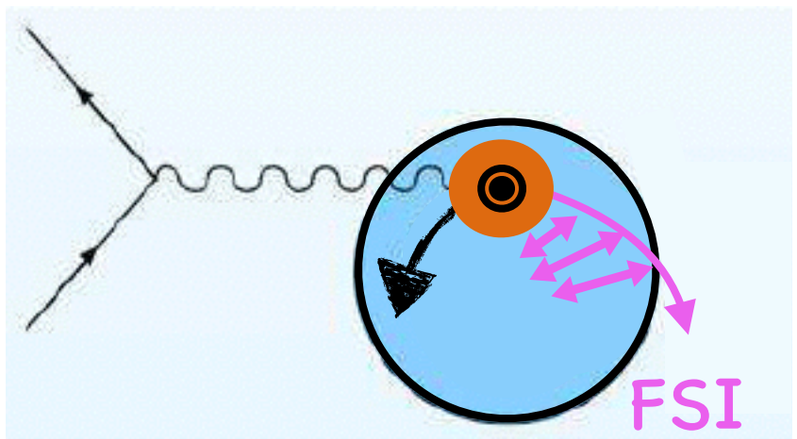


Boer-Mulders PDF



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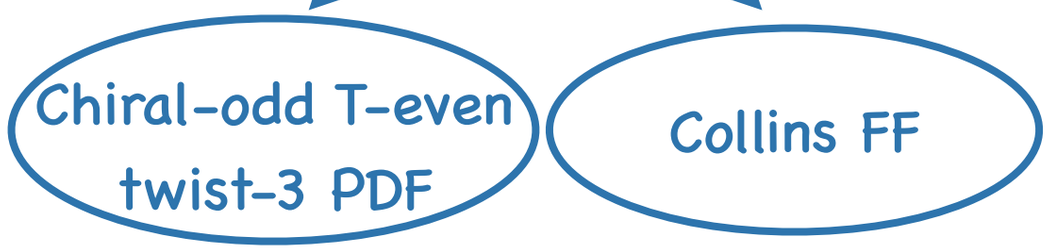

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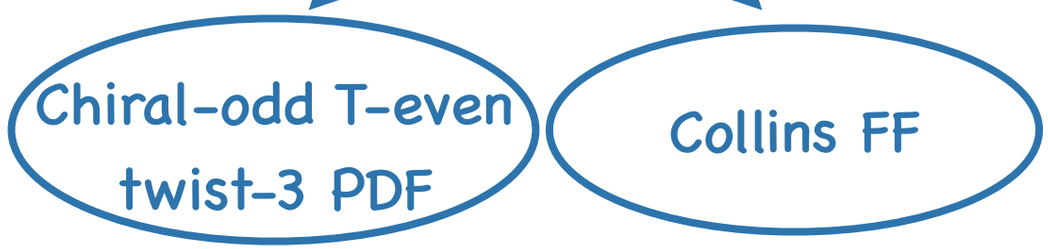


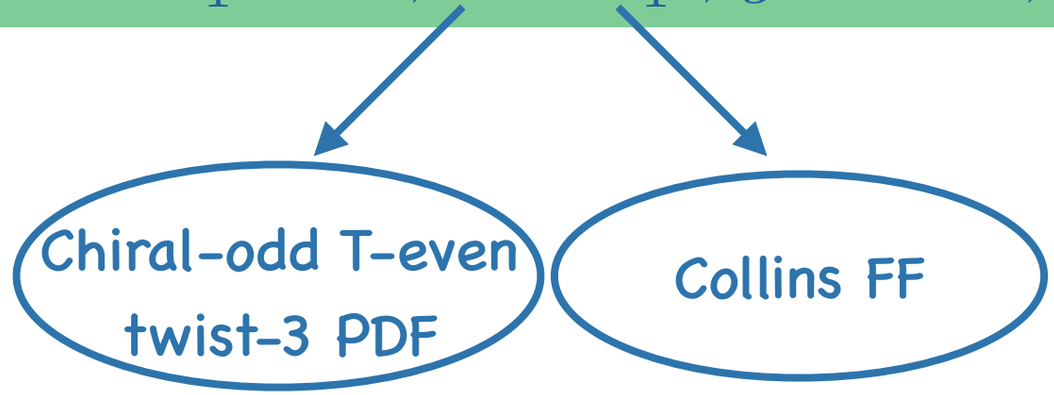
$$e(x) = e^{WW}(x) + \bar{e}(x)$$

$$e_2 \equiv \int_0^1 dx\, x^2 \bar{e}(x)$$

A_{LU}

Higher twist:

$$F_{LU}^{\sin\phi_h} \propto h_1^\perp \otimes \tilde{E},\ e \otimes H_1^\perp,\ g^\perp \otimes D_1,\ f_1 \otimes \tilde{G}^\perp$$



$$e(x) = e^{WW}(x) + \bar{e}(x)$$

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Force on struck quark at t=0 $\propto e_2$

M. Burkardt, arXiv:0810.3589

A_{LU}

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Chiral-odd T-even twist-3 PDF

Collins FF

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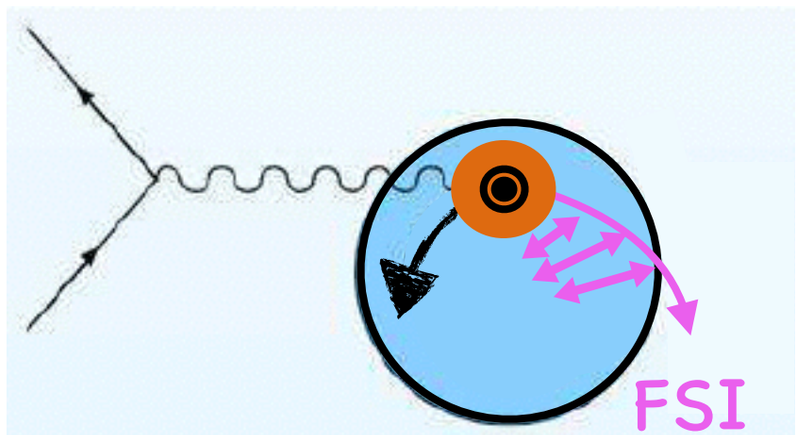
Boer-Mulders PDF



FSI: t=0→∞

A_{LU}

Higher twist:

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Chiral-odd T-even twist-3 PDF

Collins FF

$$e(x) = e^{WW}($$

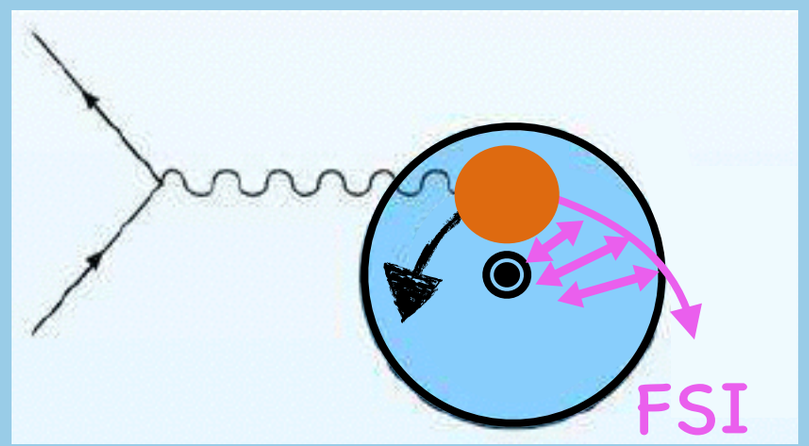
$$e_2 \equiv \int_0^1 dx$$

Force on struc

Analogously:

$$g_2(x) \Longleftrightarrow \text{Sivers PDF}$$

Sivers PDF



FSI: t=0→∞

M. Burkardt, arXiv:0810.3589

A_{LU}

Higher twist:

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spin-independent FF

A_{LU}

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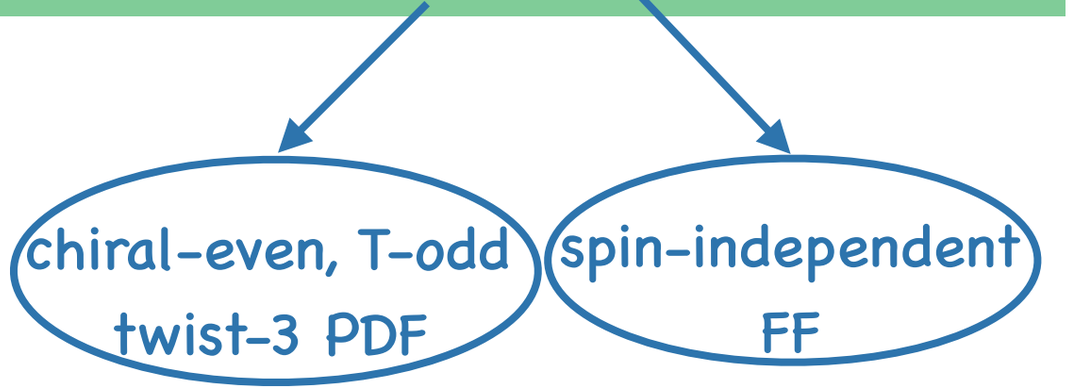

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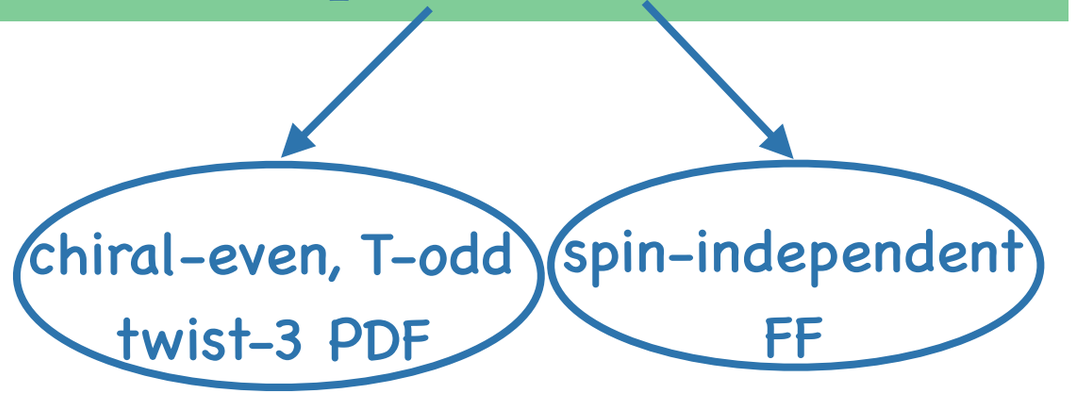

Only term to survive in TMD single-jet inclusive DIS

$$e + p \to e' + \text{jet} + X$$

A_{LU}

Higher twist:

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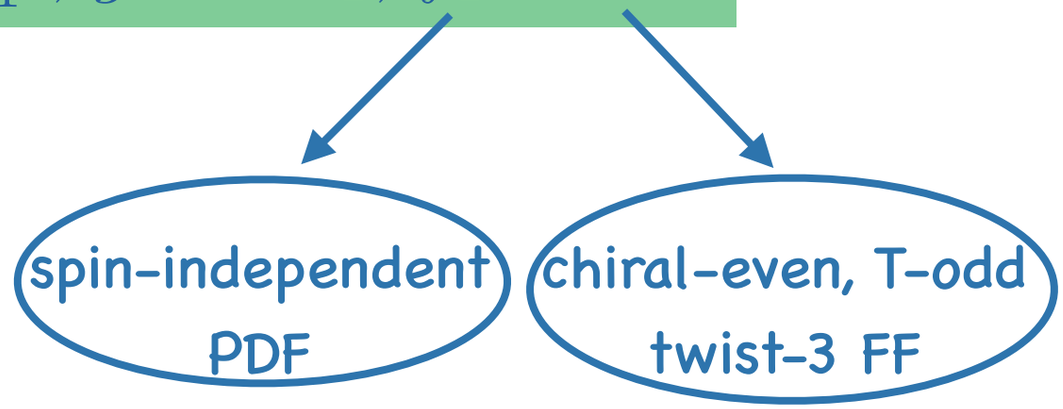

A_{LU}

Two-photon exchange: $A_{LU}^{\sin(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp}$

A. Metz and M. Schlegel, arXiv:0902.0781

Boer-Mulders PDF

Collins FF

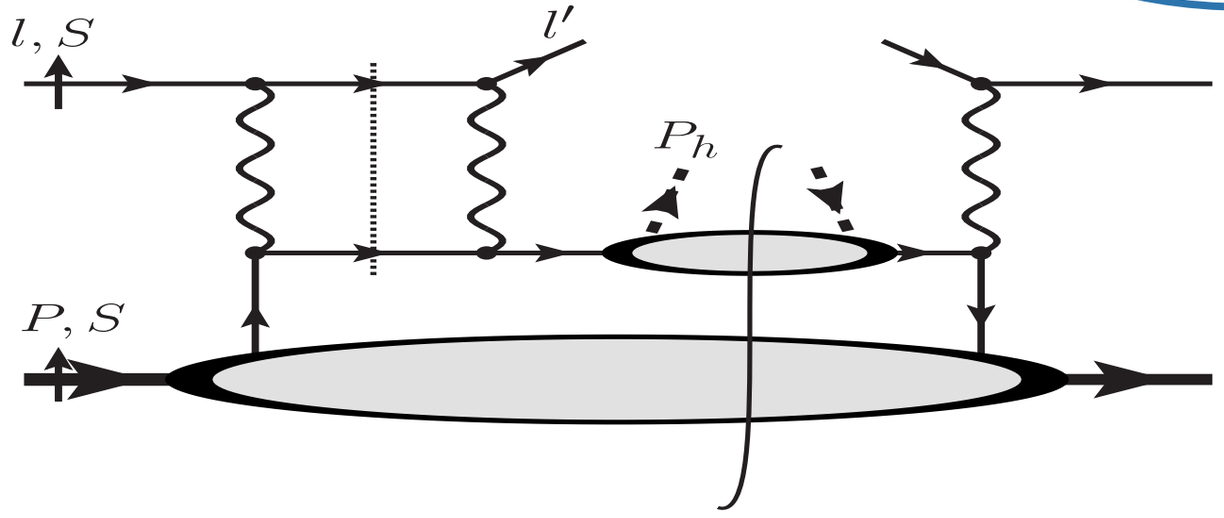

Fig. from A. Metz and M. Schlegel, arXiv:0902.0781

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Boer-Mulders PDF

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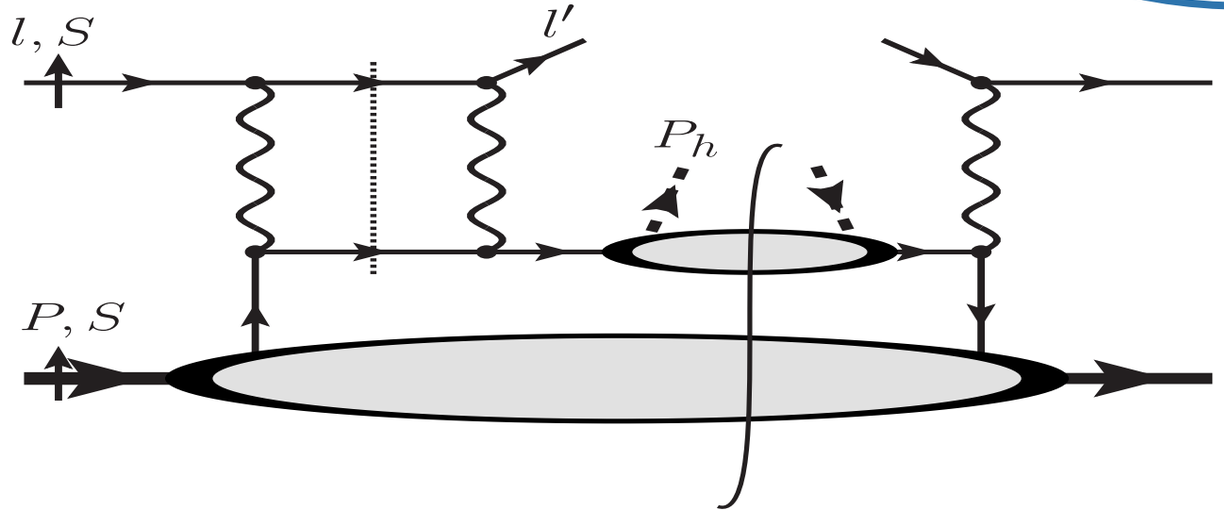
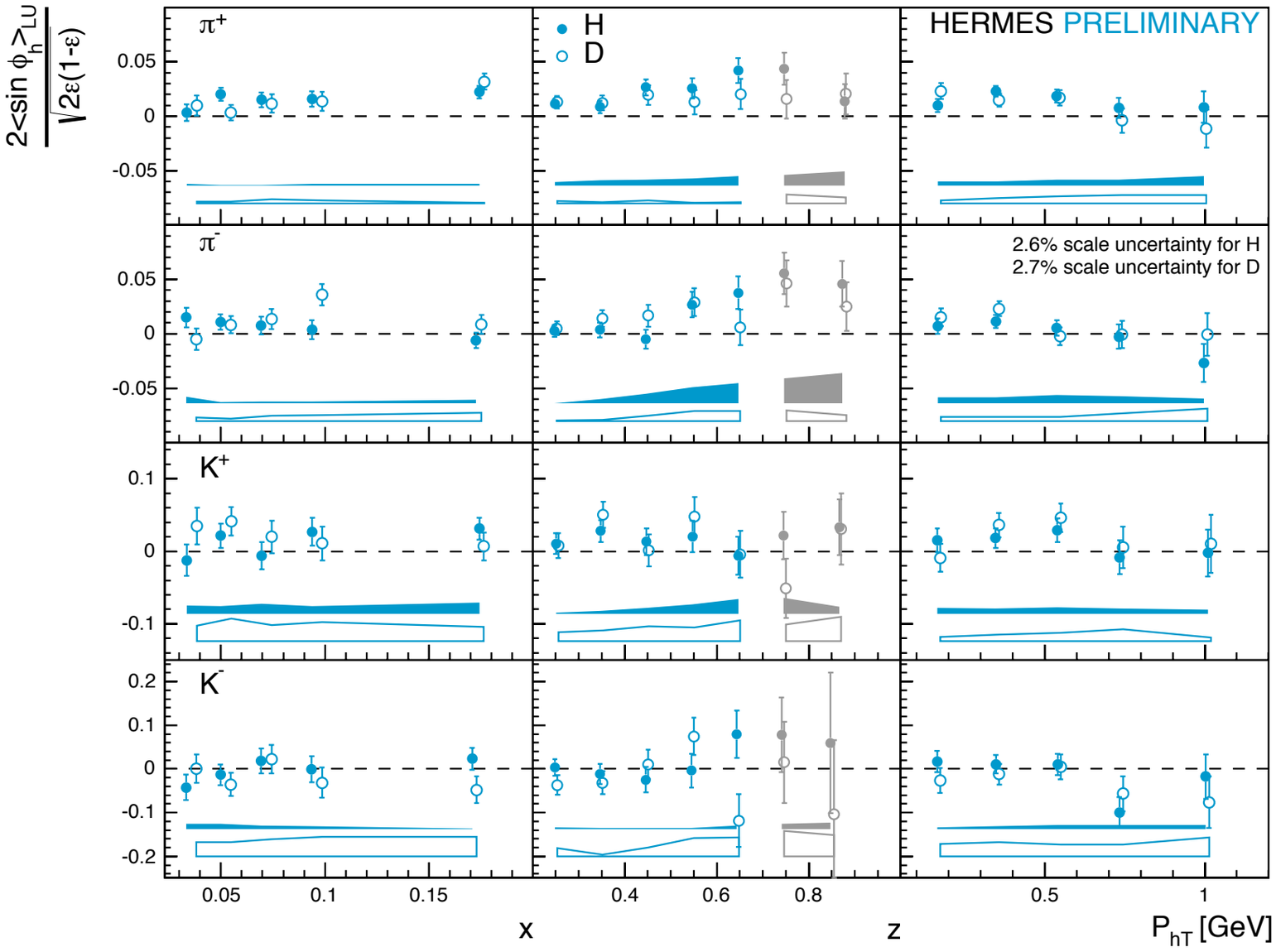


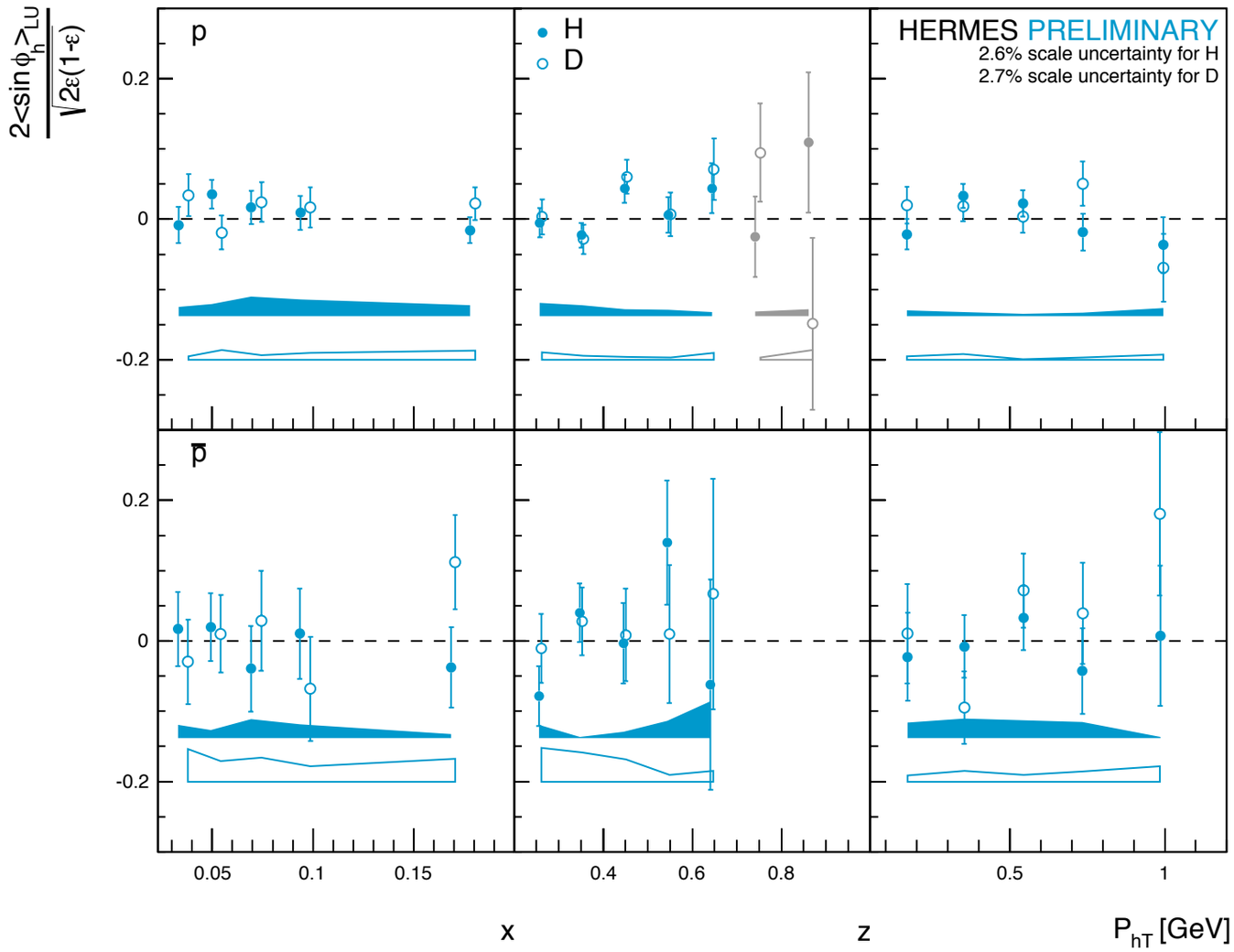
Fig. from A. Metz and M. Schlegel, arXiv:0902.0781

$A_{LU}^{\sin(2\phi)}$ **compatible with zero in present measurement**

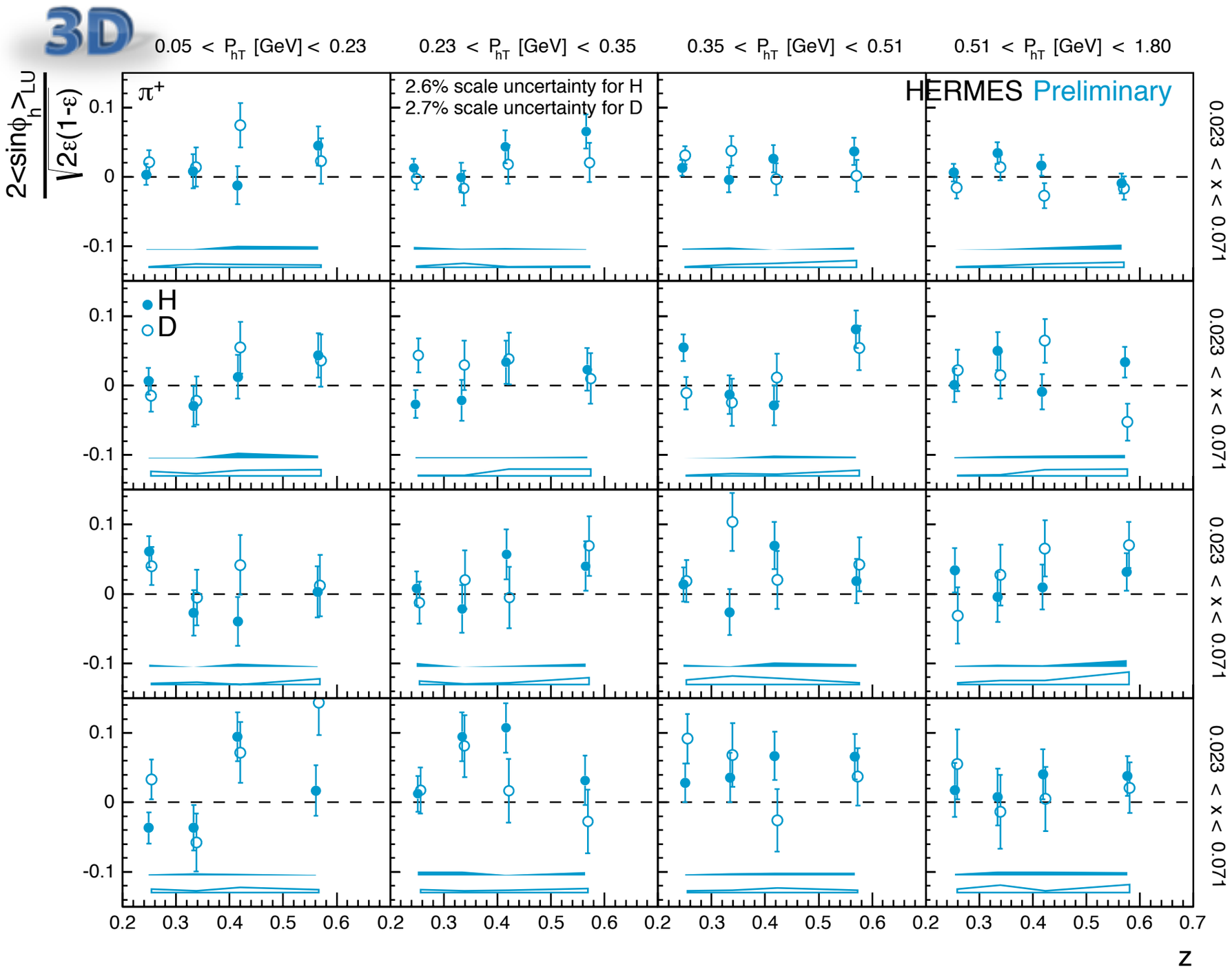
A_{LU} results pions & kaons 1D



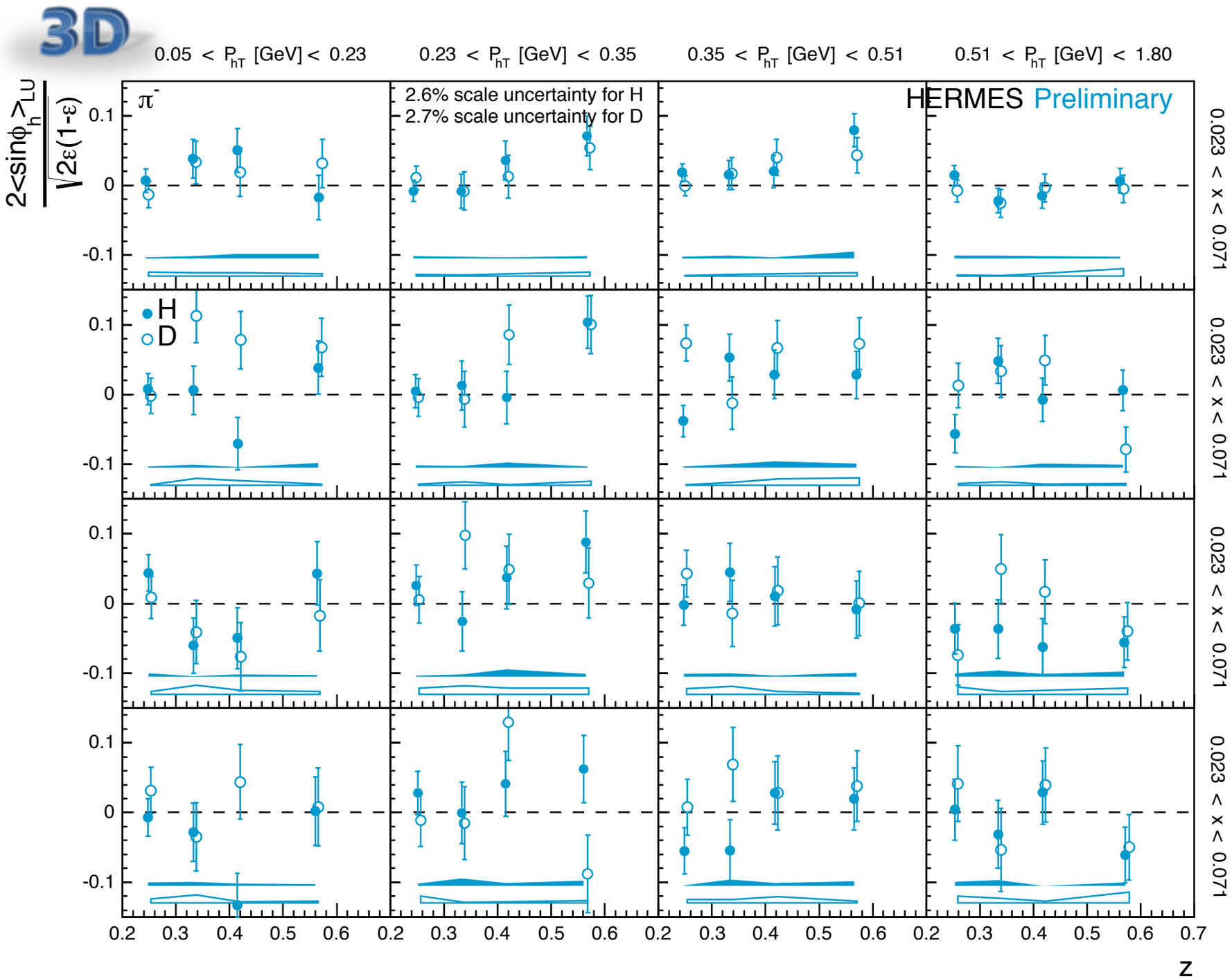
A_{LU} results protons 1D



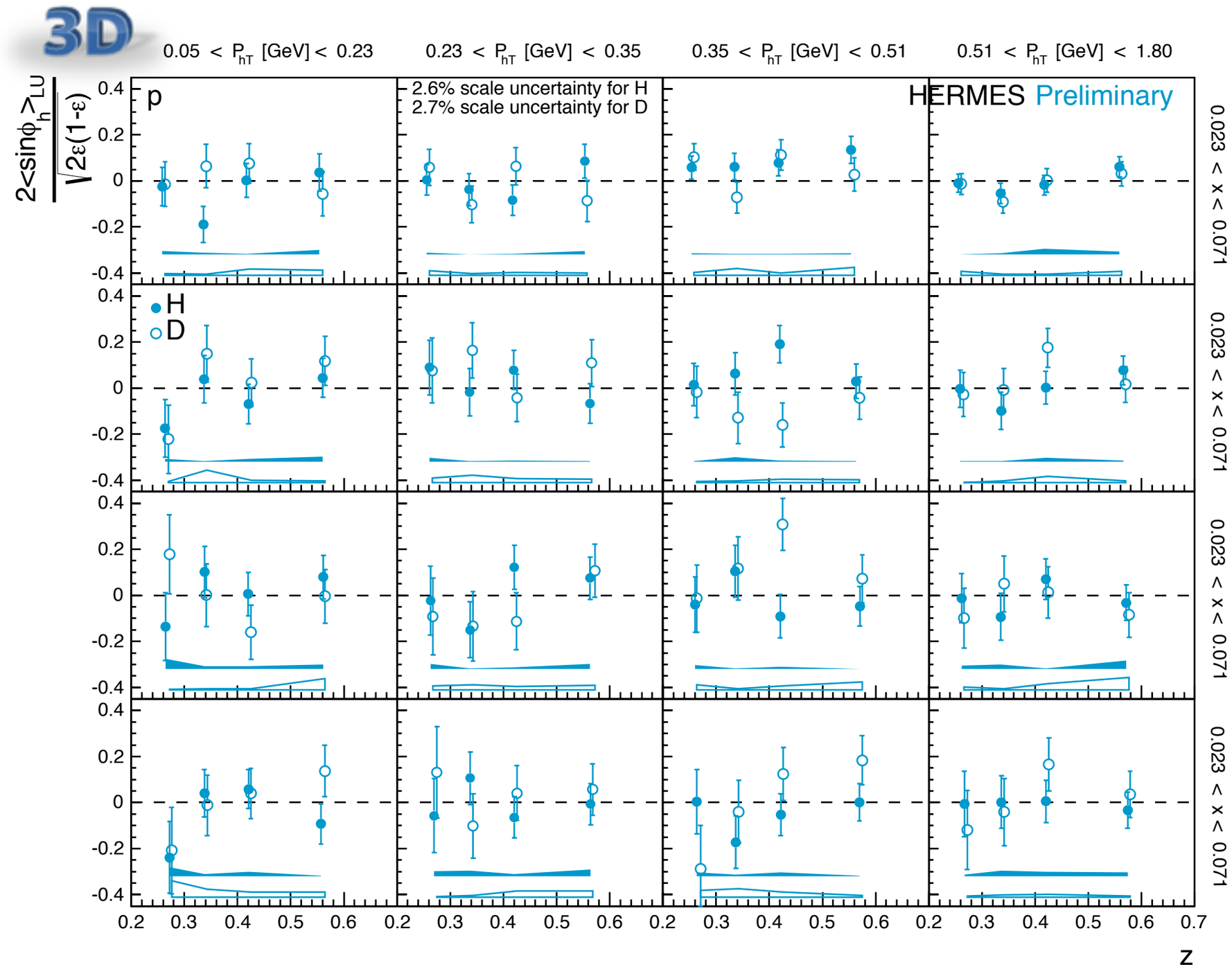
A_{LU} results pions 3D



A_{LU} results pions 3D



A_{LU} results protons 3D



Summary

- Twist-2 and twist-3 amplitudes in 3D on transversely polarized hydrogen target - beam longitudinally polarized and unpolarized:

  kinematic dependence of Collins, Sivers and $F_{UT}^{\sin(\phi_S)}$ located in certain kinematic corners

- Twist-3 non-zero A_{LU} observed for π^+, π^-, $K^+ \rightarrow$ access to twist-3 T-odd, T-even, chiral-odd, chiral-even PDFs and FFs

Thank you