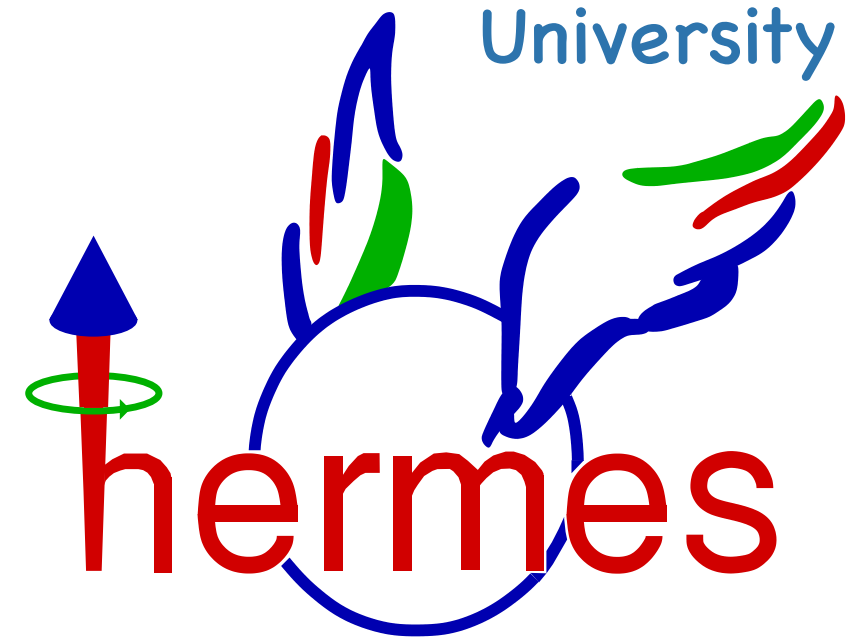


Transverse-momentum dependent semi-inclusive deep-inelastic scattering at HERMES

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



DIS 2016
11-15 April 2016
DESY-Hamburg, Germany

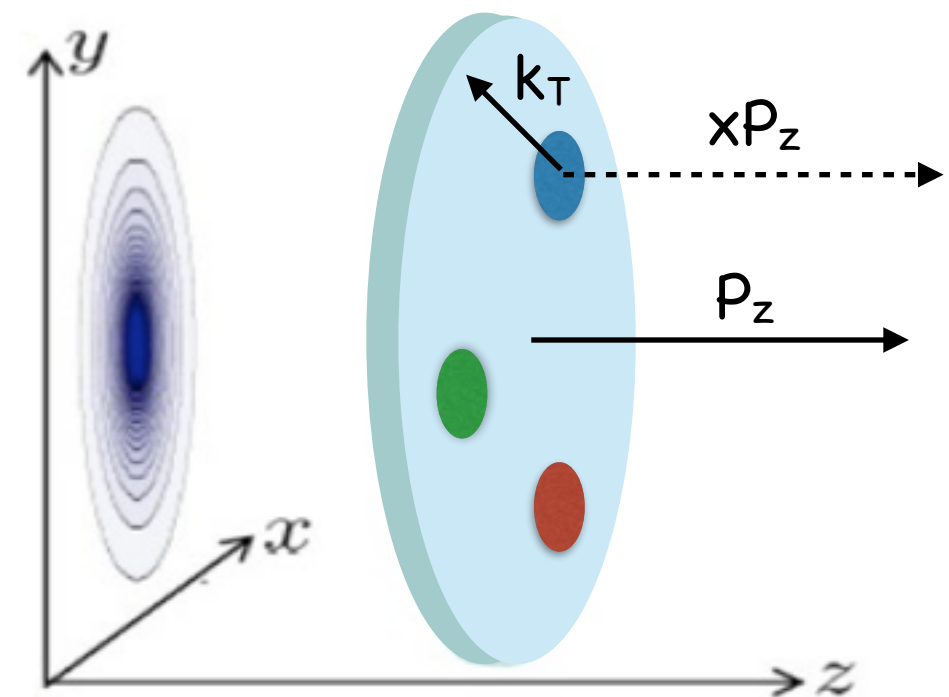
Outline

*Asymmetries A_{UT} and A_{LT}

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

*Asymmetry A_{LU}

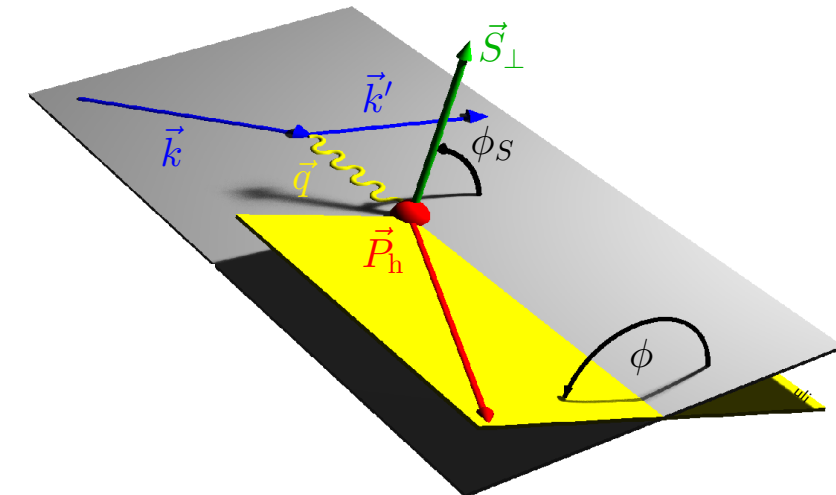
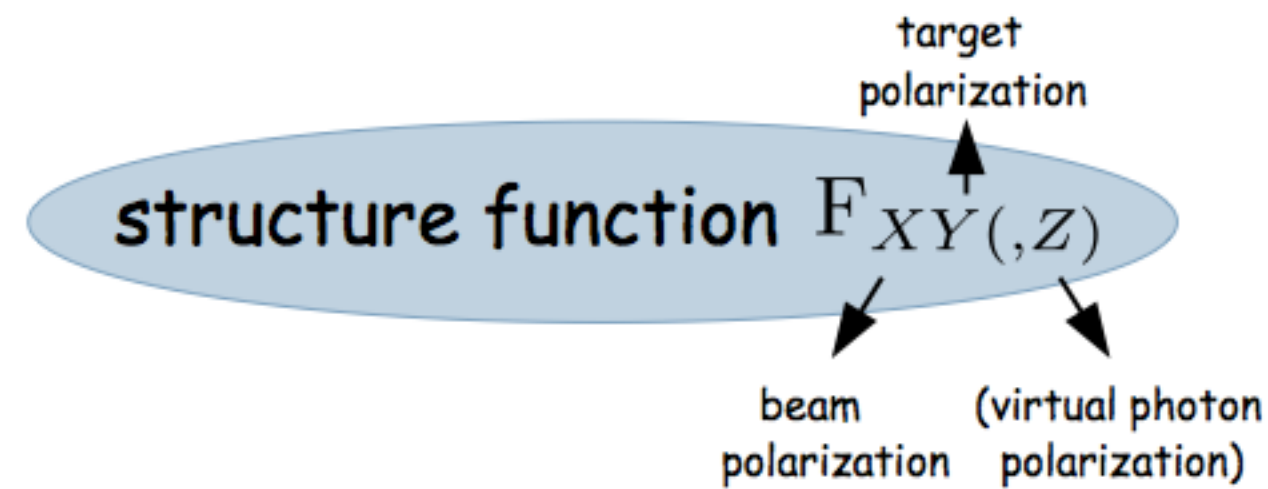
- longitudinally polarized e^+/e^- beam
- unpolarized H and D target



Semi-inclusive DIS cross section

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

$$\left\{ \begin{aligned} & F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} \\ & + \lambda_e \sqrt{2\epsilon(1-\epsilon)} \sin(\phi_h) F_{LU}^{\sin(\phi_h)} \\ & + S_L \left[\sqrt{2\epsilon(1+\epsilon)} \sin(\phi_h) F_{UL}^{\sin(\phi_h)} + \epsilon \sin(2\phi_h) F_{UL}^{\sin(2\phi_h)} \right] \\ & + S_L \lambda_e \left[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} \cos(\phi_h) F_{LL}^{\cos(\phi_h)} \right] \\ & + S_T \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\ & + \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\ & + \left. \sqrt{2\epsilon(1+\epsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\ & + S_T \lambda_e \left[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos(\phi_S) F_{LT}^{\cos(\phi_S)} \right. \\ & + \left. \left. \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\} \end{aligned} \right.$$



Semi-inclusive DIS cross section

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$$\left\{ \boxed{F_{UU,T}} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon \cos(2\phi_h) \boxed{F_{UU}^{\cos(2\phi_h)}} \right.$$

beam polarization

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

leading twist

longitudinal target polarization

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

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

transverse target polarization

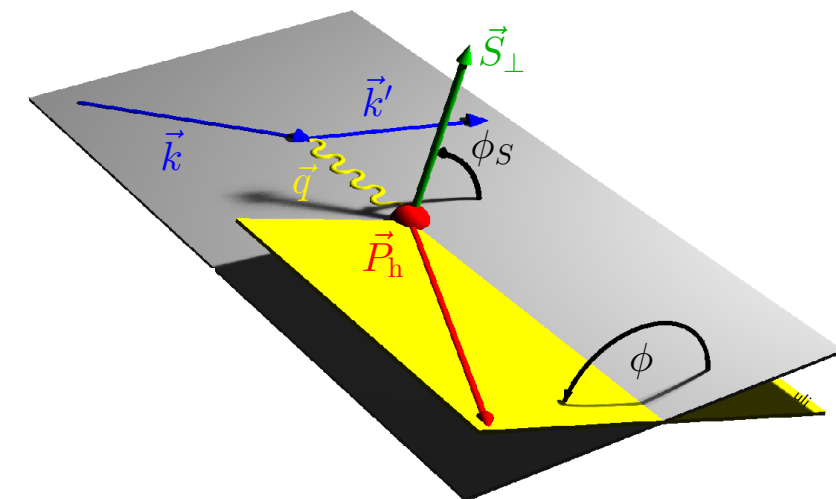
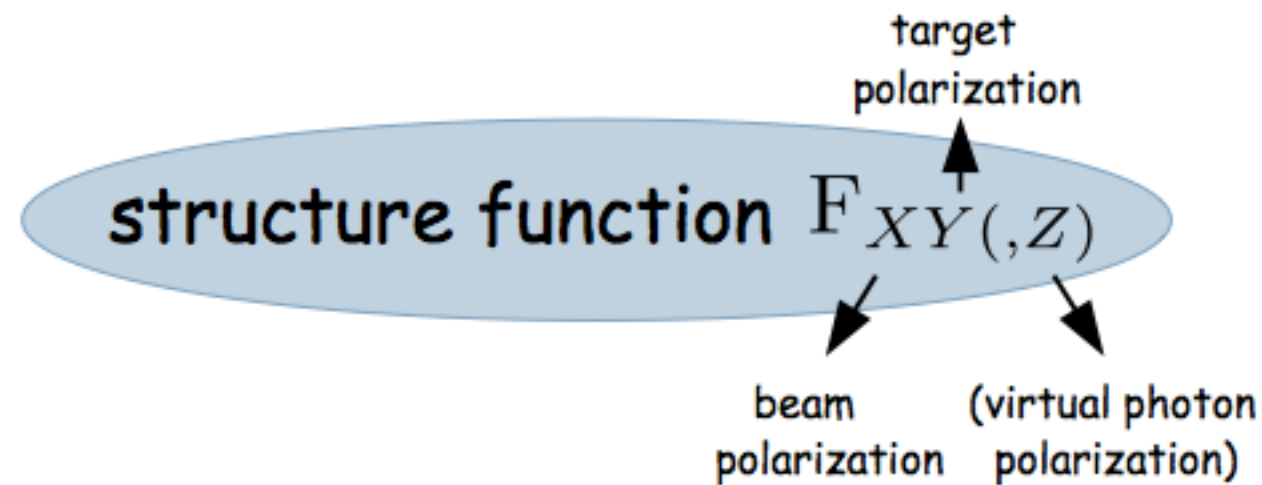
$$+ S_T \left[\sin(\phi_h - \phi_S) \left(\boxed{F_{UT,T}^{\sin(\phi_h - \phi_S)}} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right.$$

$$+ \epsilon \sin(\phi_h + \phi_S) \boxed{F_{UT}^{\sin(\phi_h + \phi_S)}} + \epsilon \sin(3\phi_h - \phi_S) \boxed{F_{UT}^{\sin(3\phi_h - \phi_S)}} \left. \right]$$

$$+ \left[\sqrt{2\epsilon(1+\epsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right]$$

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

$$\left. + \left[\sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\}$$



Semi-inclusive DIS cross section

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$$\left\{ \boxed{F_{UU,T}} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon \cos(2\phi_h) \boxed{F_{UU}^{\cos(2\phi_h)}} \right.$$

beam polarization

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

leading twist

longitudinal target polarization

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

This talk

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

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

transverse target polarization

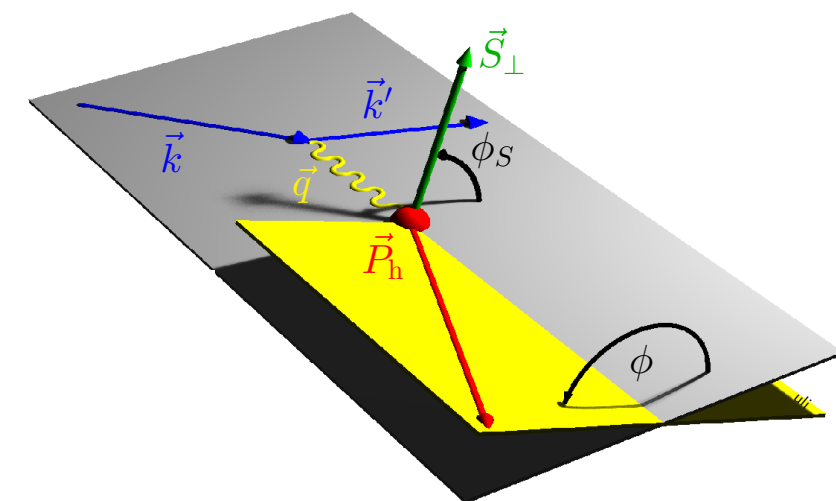
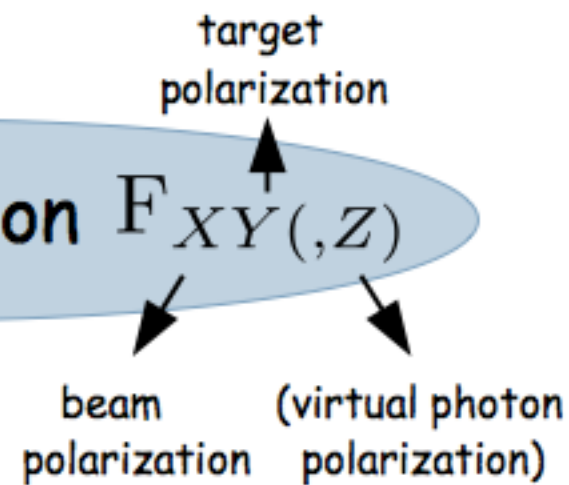
$$+ S_T \left[\sin(\phi_h - \phi_S) \left(\boxed{F_{UT,T}^{\sin(\phi_h - \phi_S)}} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right.$$

$$+ \epsilon \sin(\phi_h + \phi_S) \boxed{F_{UT}^{\sin(\phi_h + \phi_S)}} + \epsilon \sin(3\phi_h - \phi_S) \boxed{F_{UT}^{\sin(3\phi_h - \phi_S)}} \left. \right]$$

$$+ \left[\sqrt{2\epsilon(1+\epsilon)} \sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right]$$

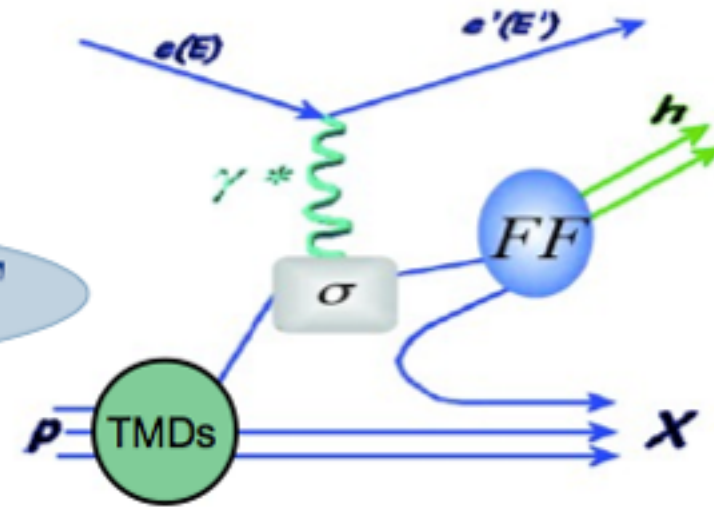
$$+ S_T \lambda_e \left[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) \boxed{F_{LT}^{\cos(\phi_h - \phi_S)}} + \sqrt{2\epsilon(1-\epsilon)} \cos(\phi_S) F_{LT}^{\cos(\phi_S)} \right.$$

$$\left. + \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right]$$



Semi-inclusive DIS cross section

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



transverse momentum distributions (TMDs)

fragmentation functions (FFs)

		quark			quark		
		U	L	T	U	L	T
nucleon	U	f_1		h_1^\perp	D_1		H_1^\perp
	L		g_1	h_{1L}^\perp			
	T	f_{1T}^\perp	g_{1T}^\perp	h_1 h_{1T}^\perp			

leading twist

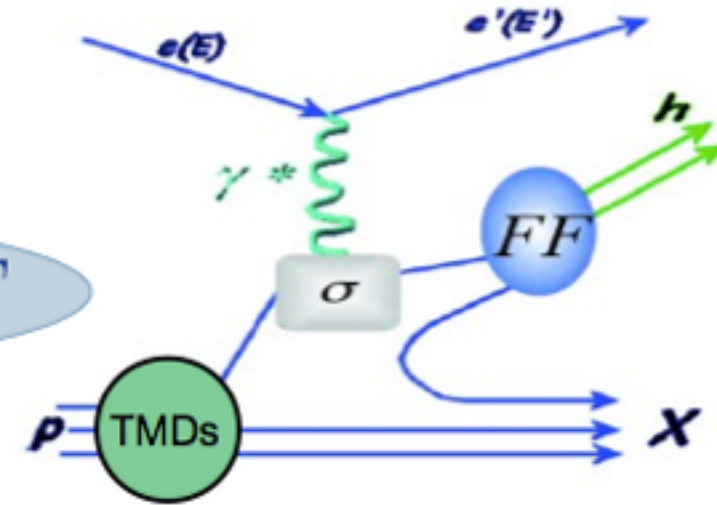
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

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transverse momentum distributions (TMDs)

fragmentation functions (FFs)

		quark			quark		
		U	L	T	U	L	T
nucleon	U	f_1		h_1^\perp	D_1		H_1^\perp
	L		g_1	h_{1L}^\perp			H_{1L}^\perp
	T	f_{1T}^\perp	g_{1T}^\perp	h_{1T}^\perp			

leading twist

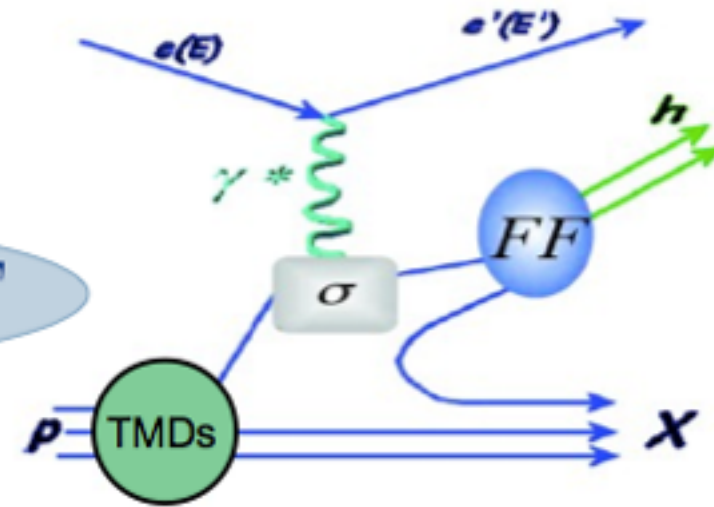
nucleon with transverse/longitudinal spin

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Semi-inclusive DIS cross section

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transverse momentum distributions (TMDs)

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		quark			quark		
		U	L	T	U	L	T
nucleon	U	f_1		h_1^\perp	D_1		H_1^\perp
	L		g_1	h_{1L}^\perp			
	T	f_{1T}^\perp	g_{1T}^\perp	h_1 h_{1T}^\perp			

leading twist

- 6 more leading-twist FFs
- 16 subleading-twist TMDs and FFs

nucleon with transverse/longitudinal spin

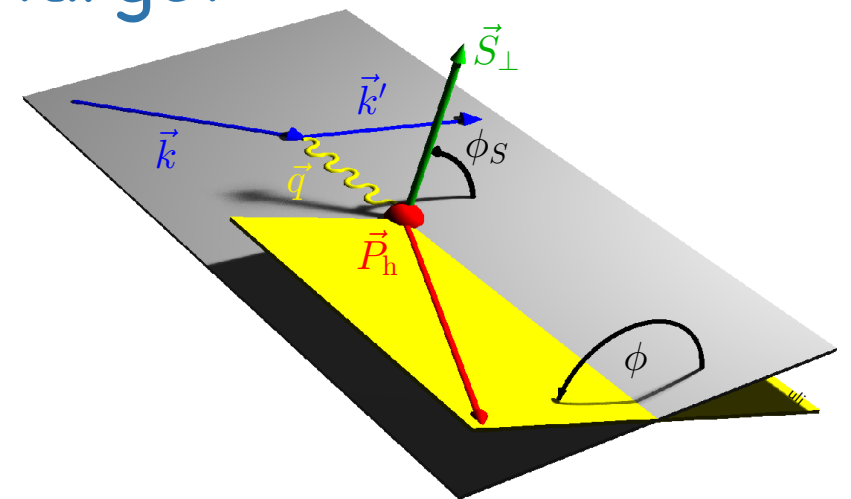
quark with transverse/longitudinal spin

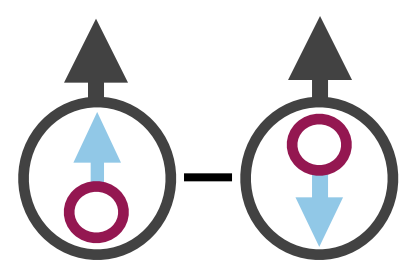
quark transverse momentum

A_{UT} and A_{LT}

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

Results for pions, kaons and protons



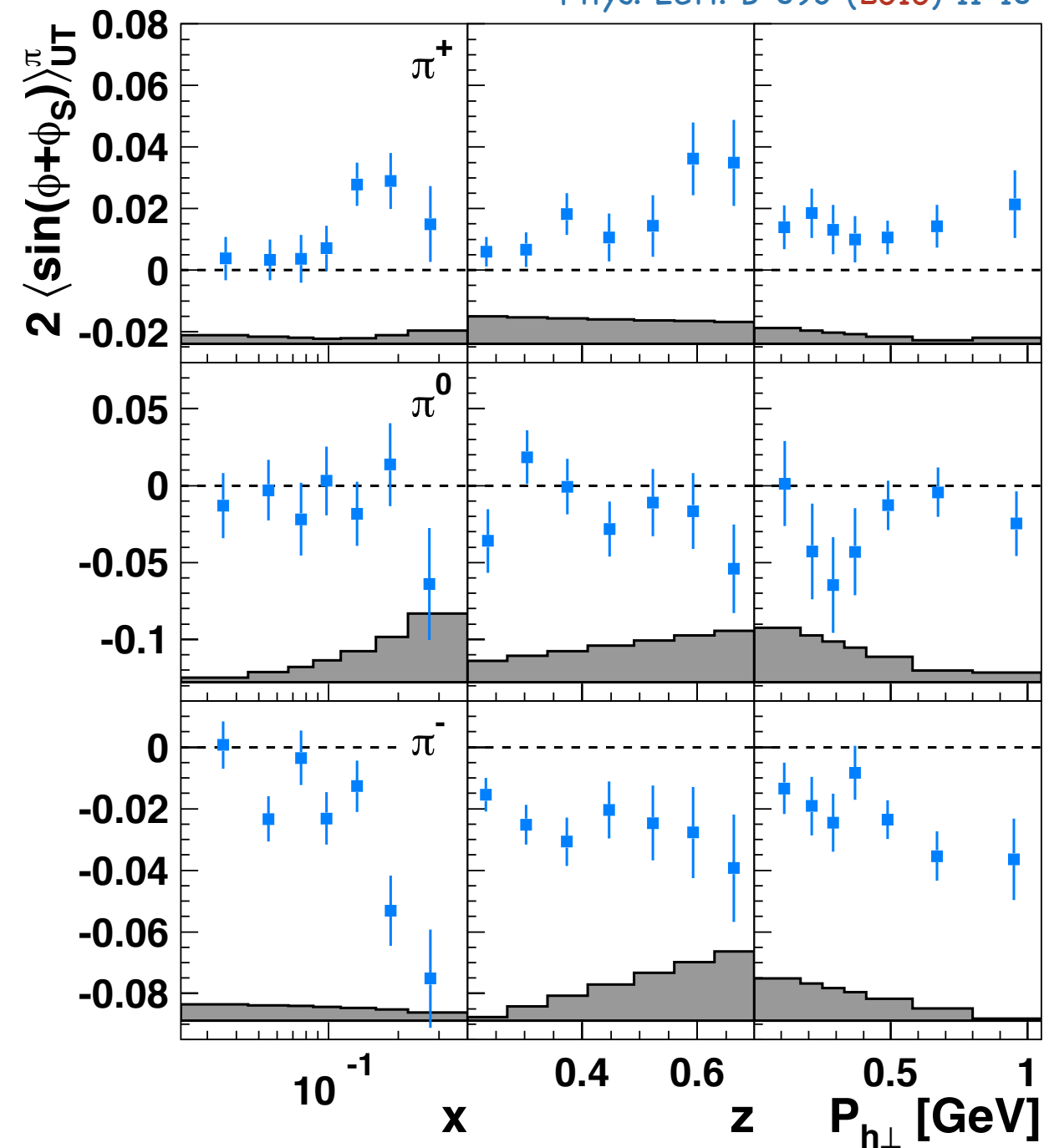


pions

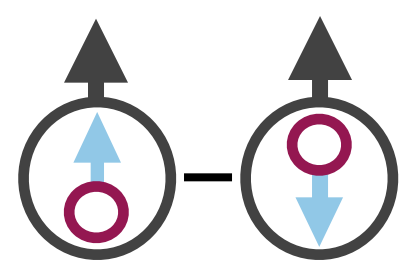
Collins amplitudes

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

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



- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x

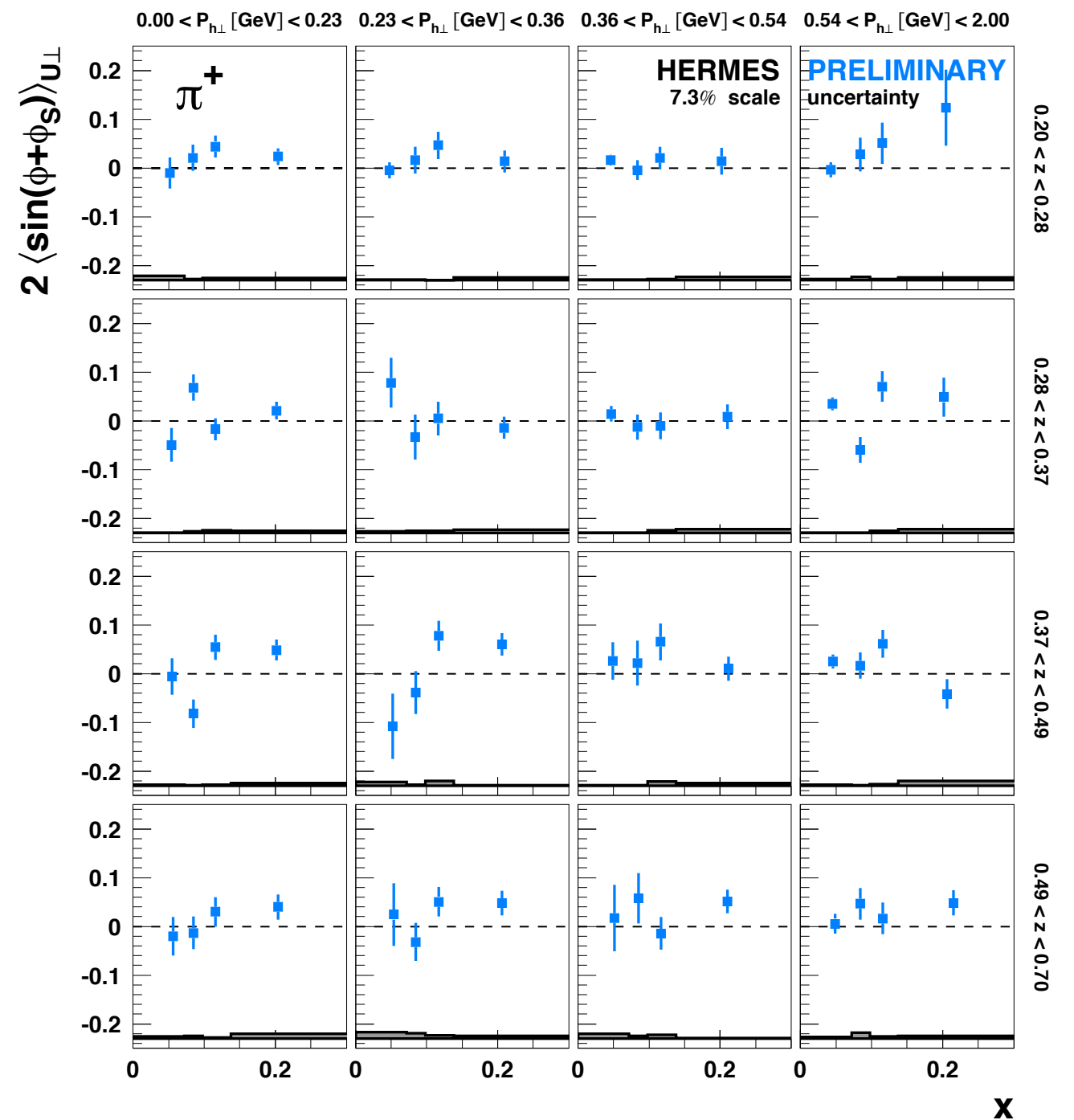
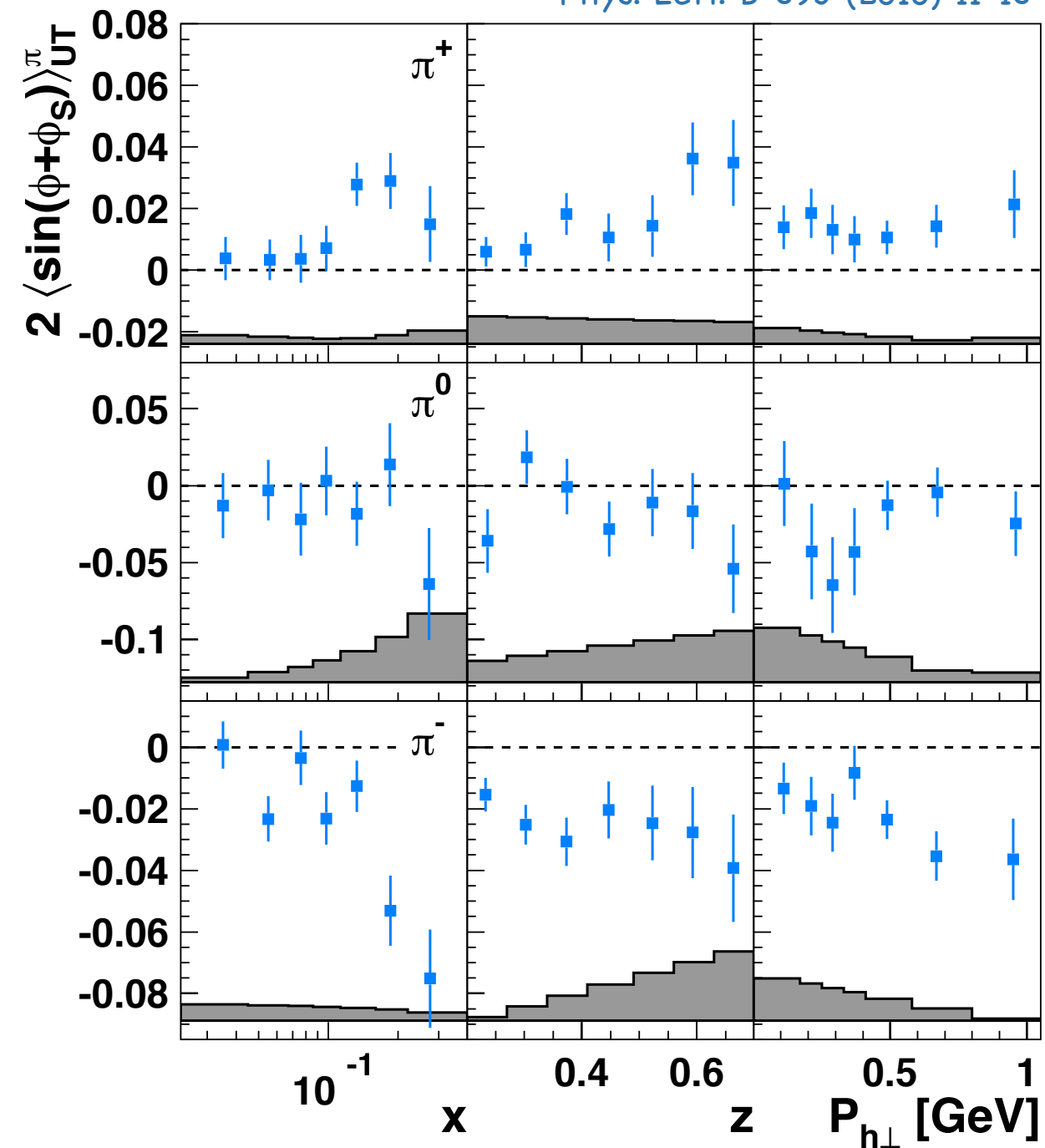


pions

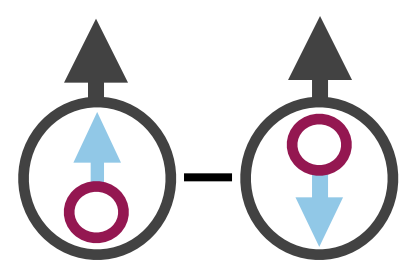
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Phys. Lett. B 693 (2010) 11-16



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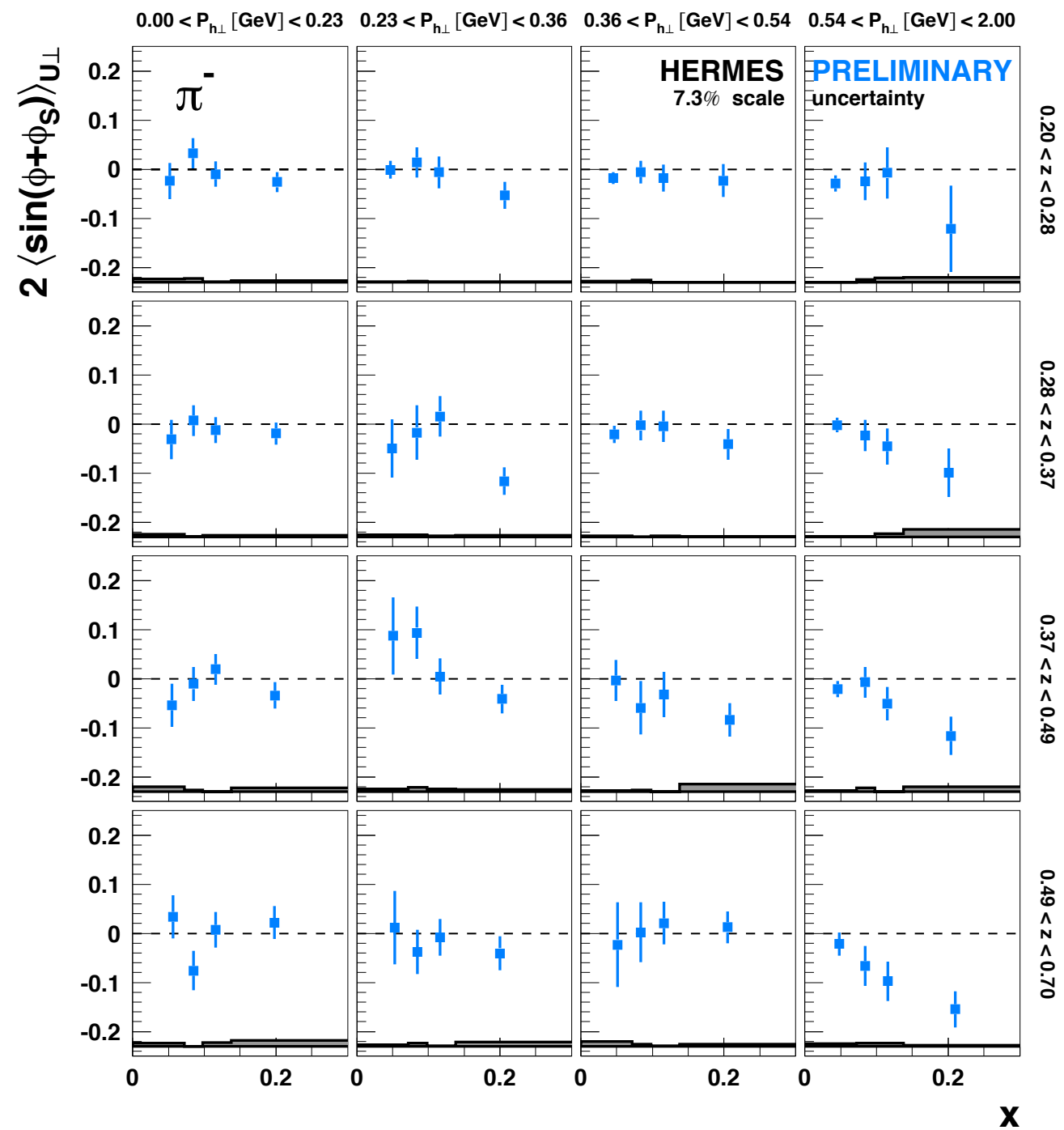
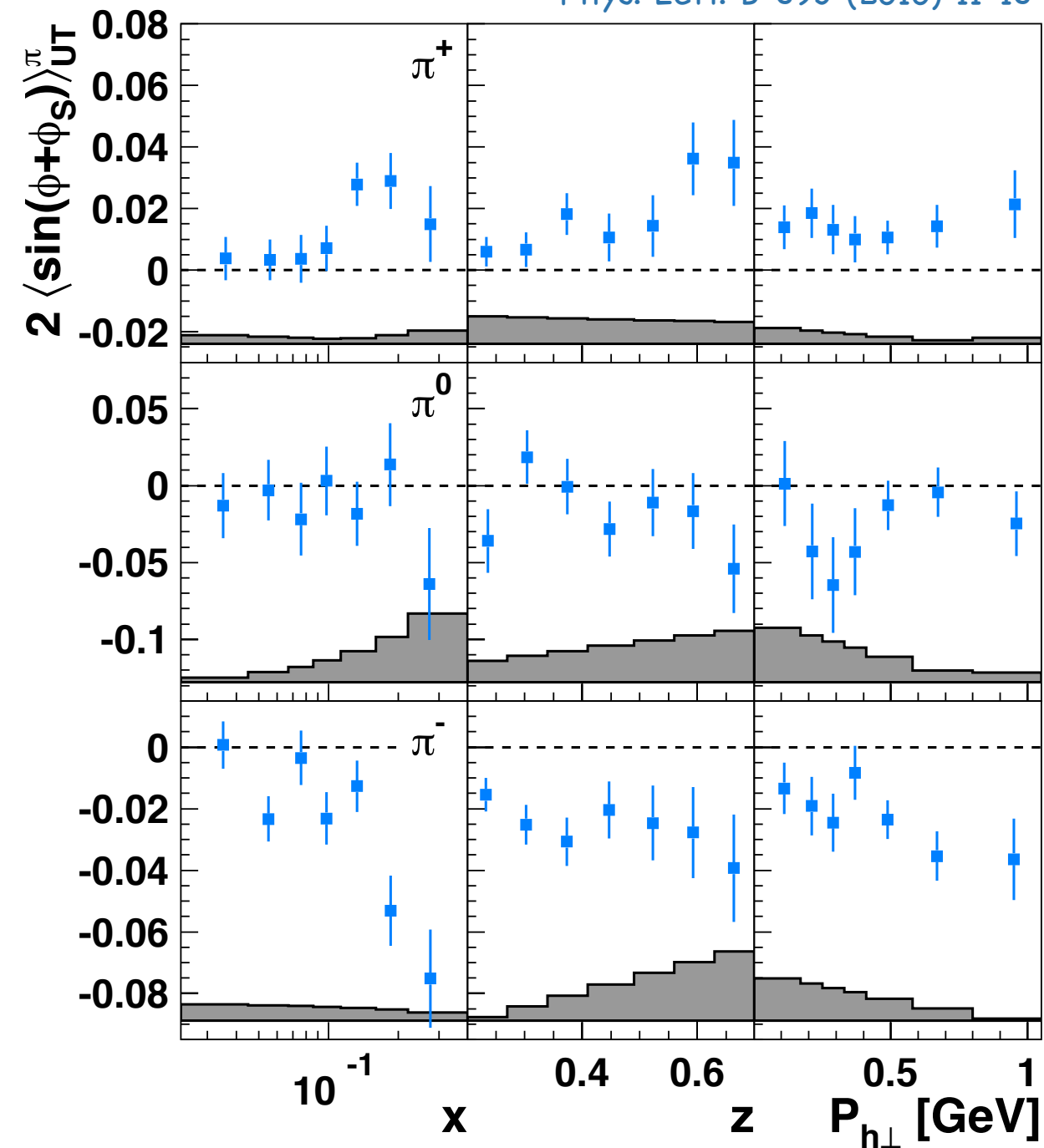


pions

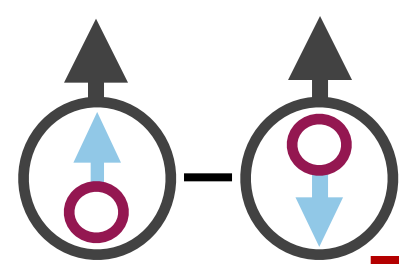
Collins amplitudes

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



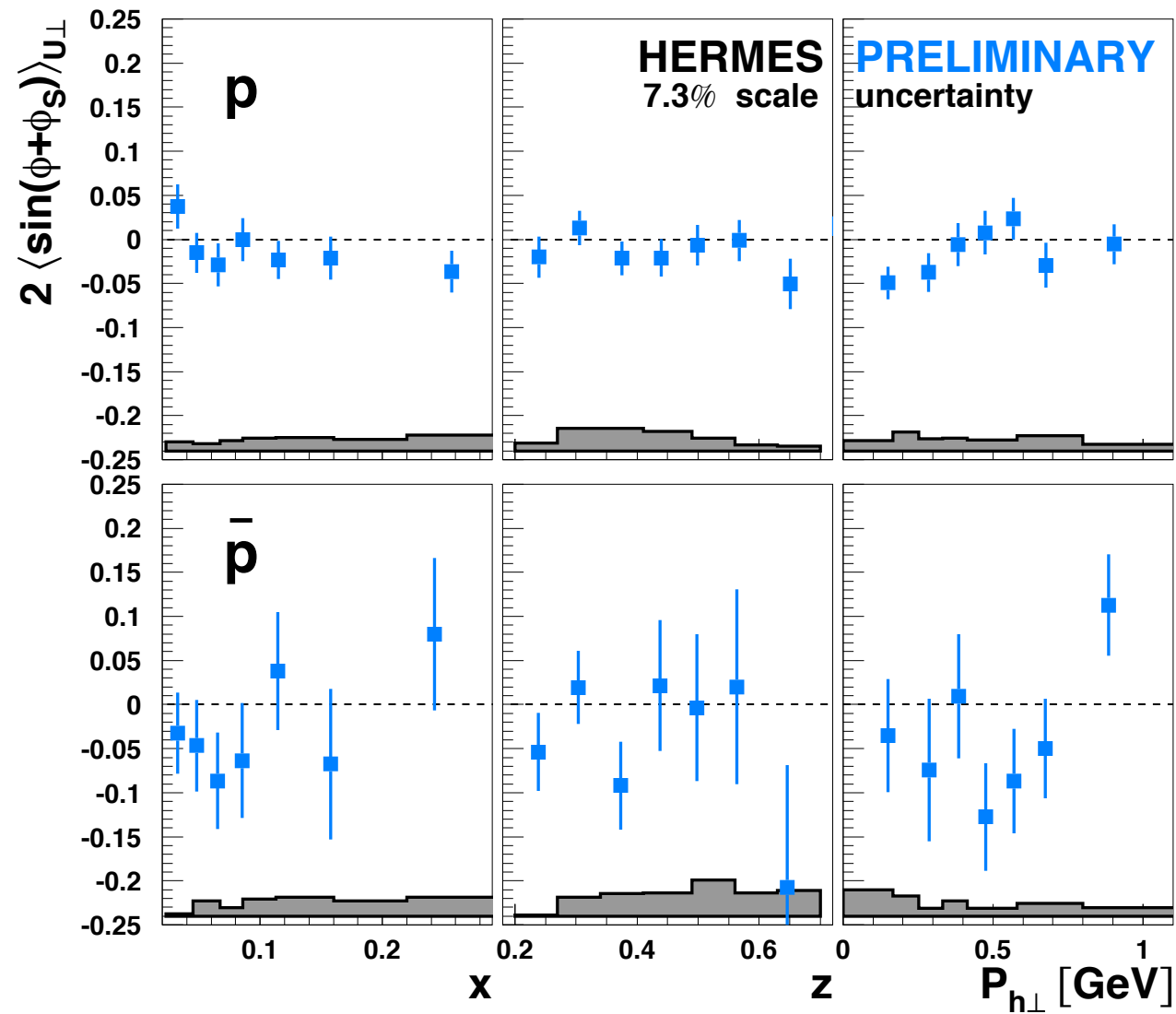
- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x at large $P_{h\perp}$

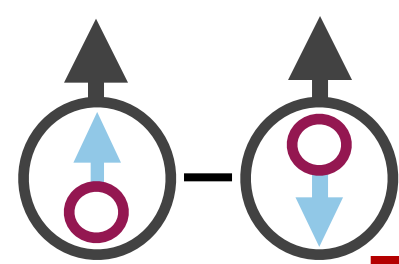


protons

Collins amplitudes

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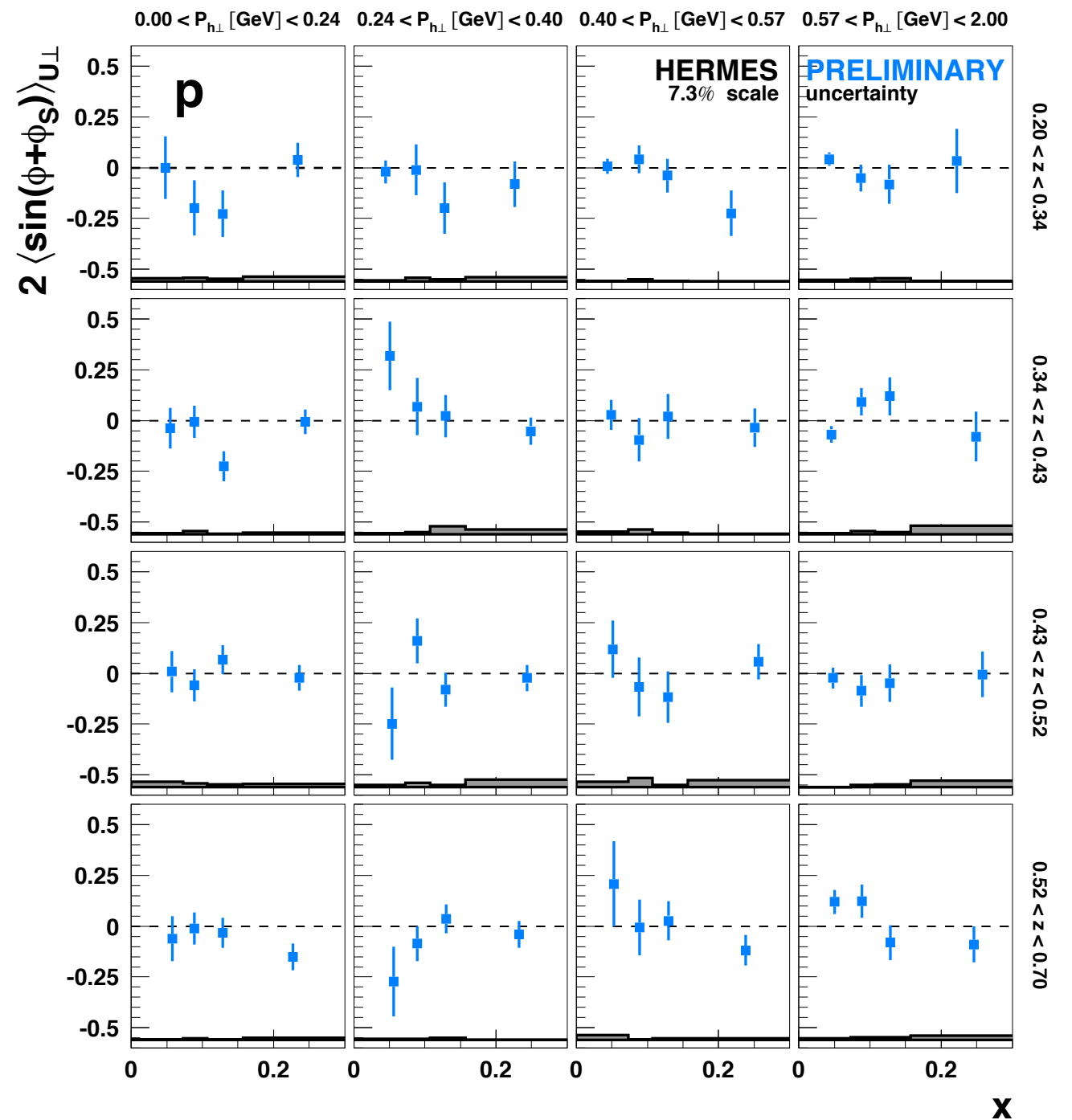
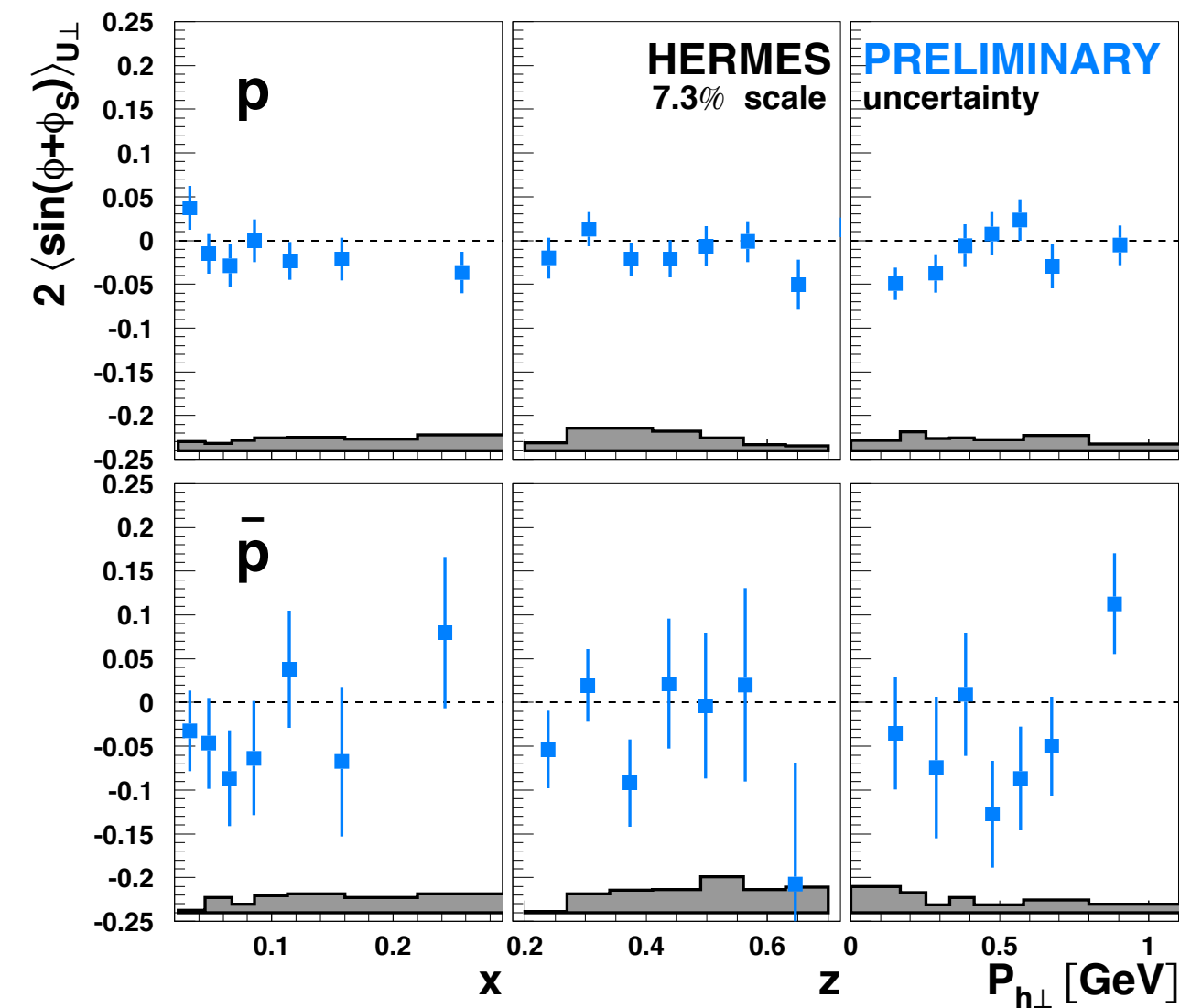


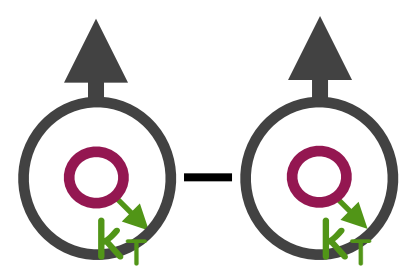


protons

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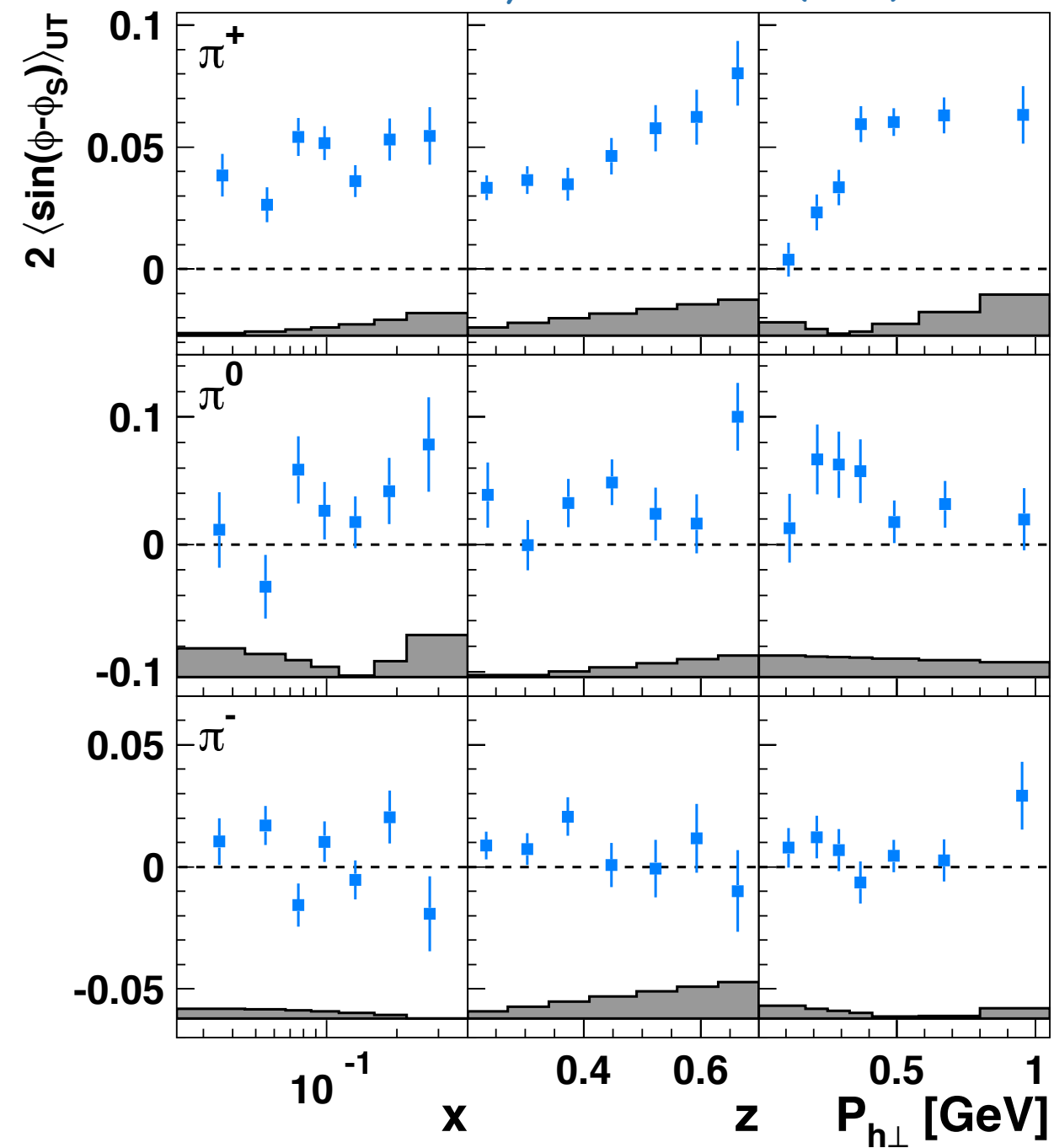


pions

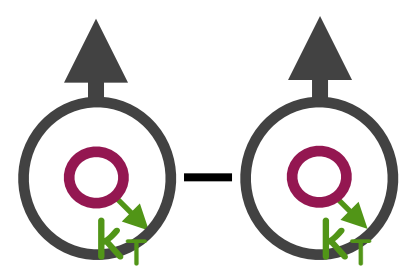
Sivers amplitudes

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

Phys. Rev. Lett. 103 (2009) 152002



- π^+ amplitudes > 0 ; increasing with $P_{h\perp}$ up to 0.4 GeV

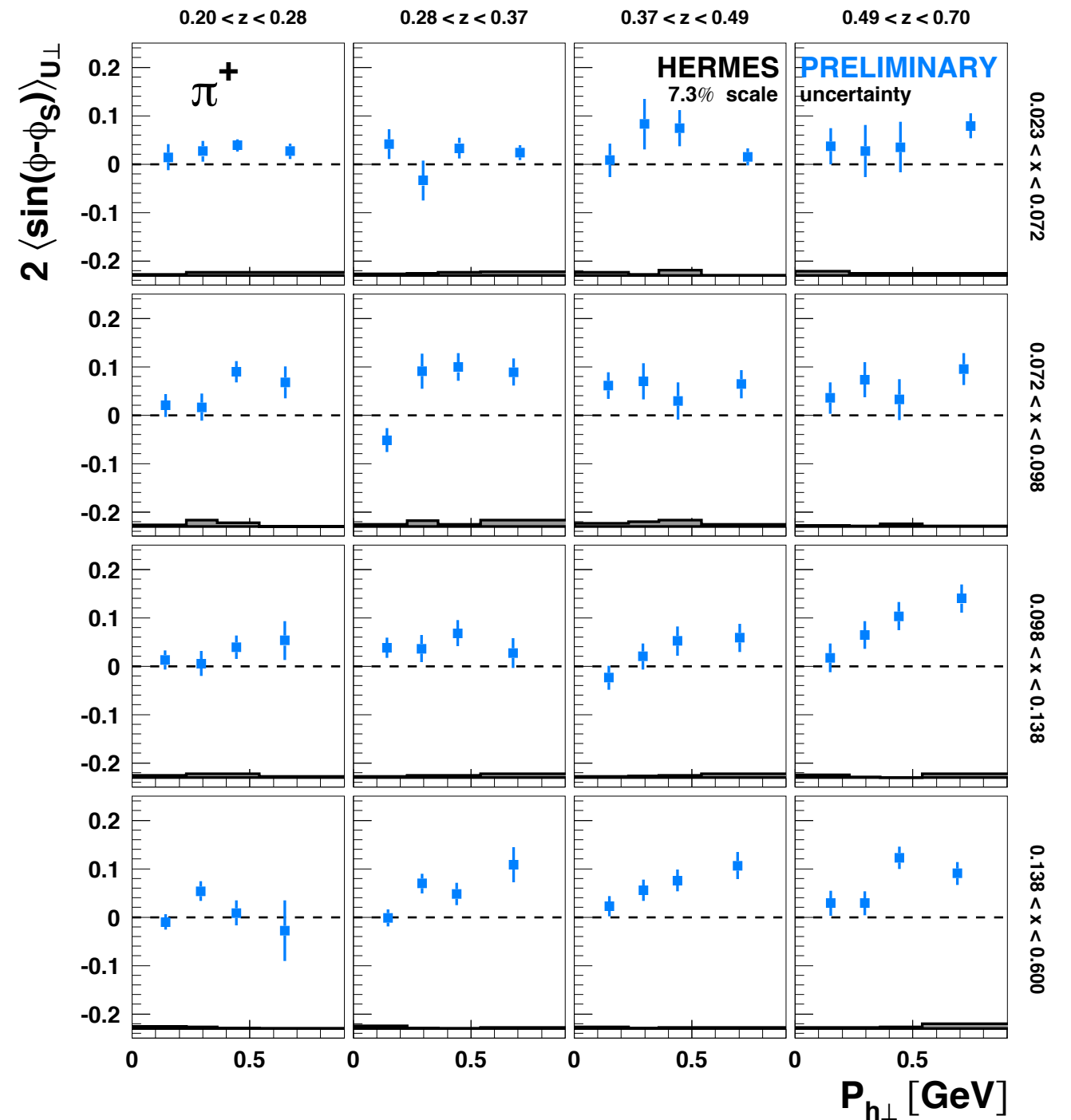
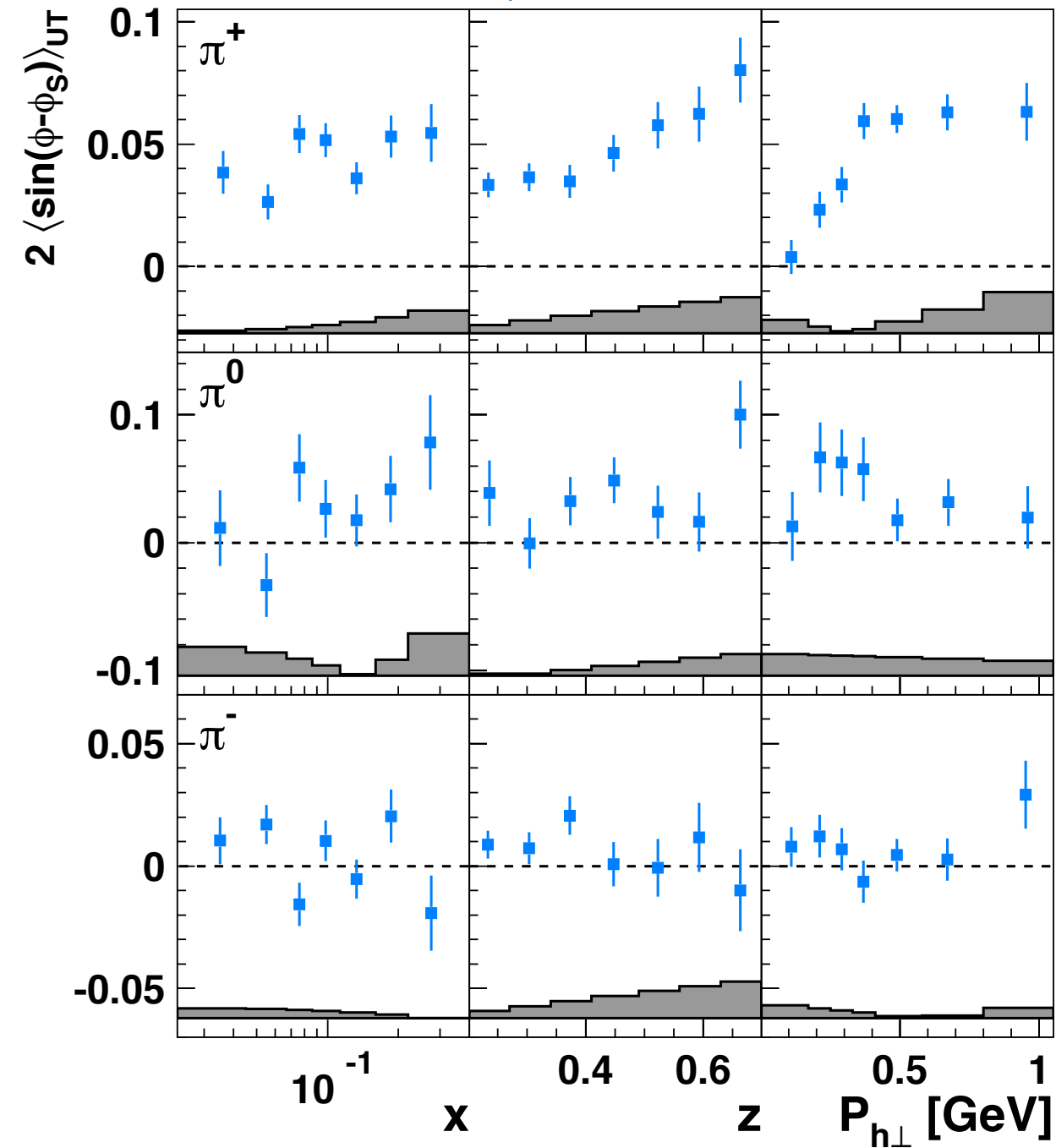


pions

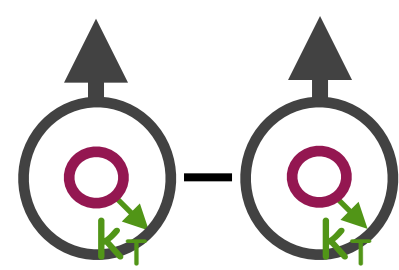
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Phys. Rev. Lett. 103 (2009) 152002



- π^+ amplitudes > 0 ; increasing with $P_{h\perp}$ up to 0.4 GeV: concentrated at large x and z

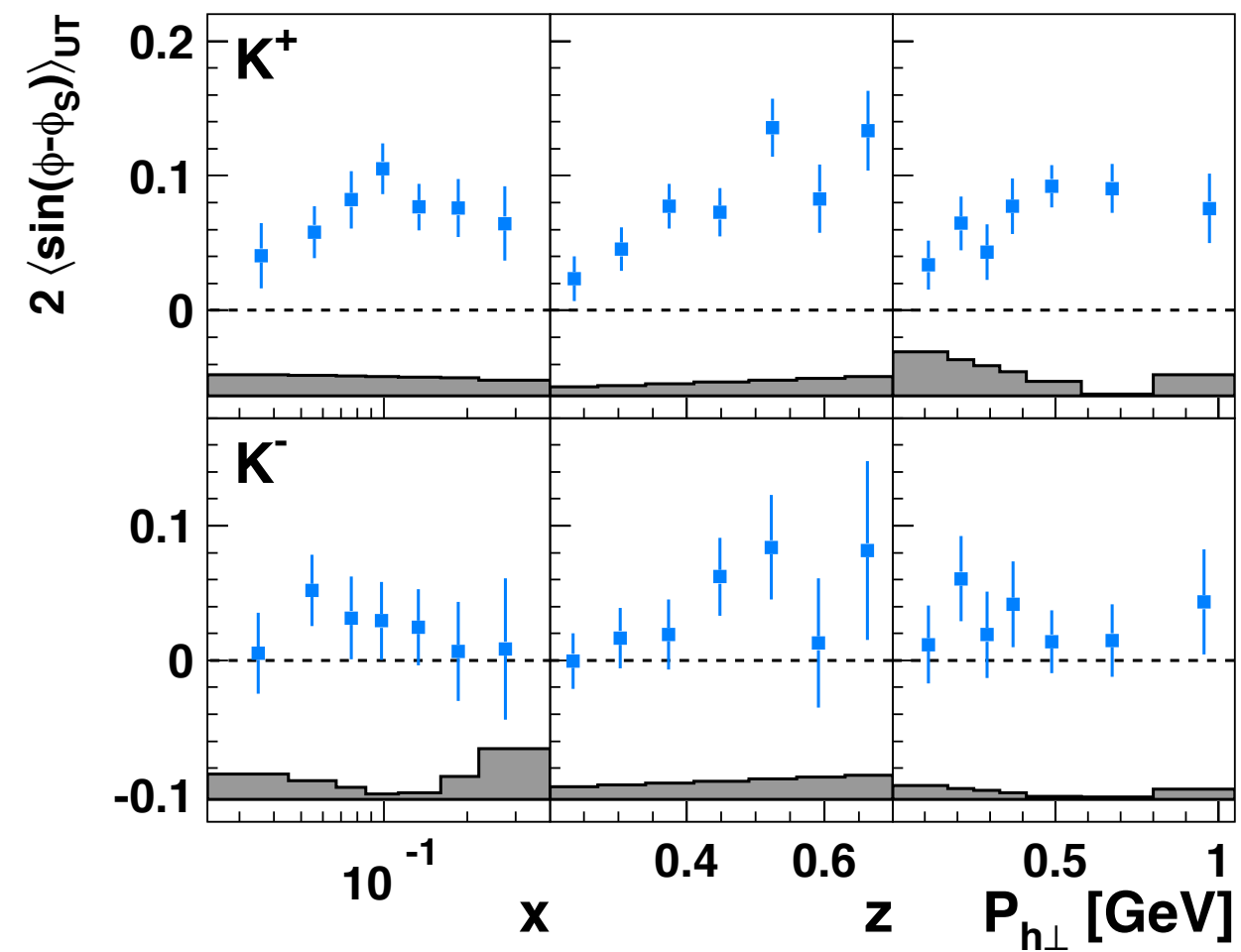


kaons

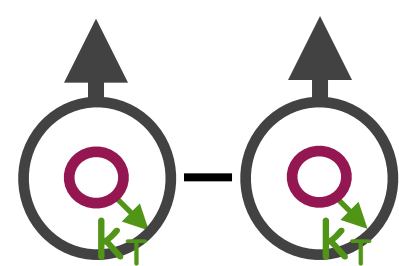
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Phys. Rev. Lett. 103 (2009) 152002



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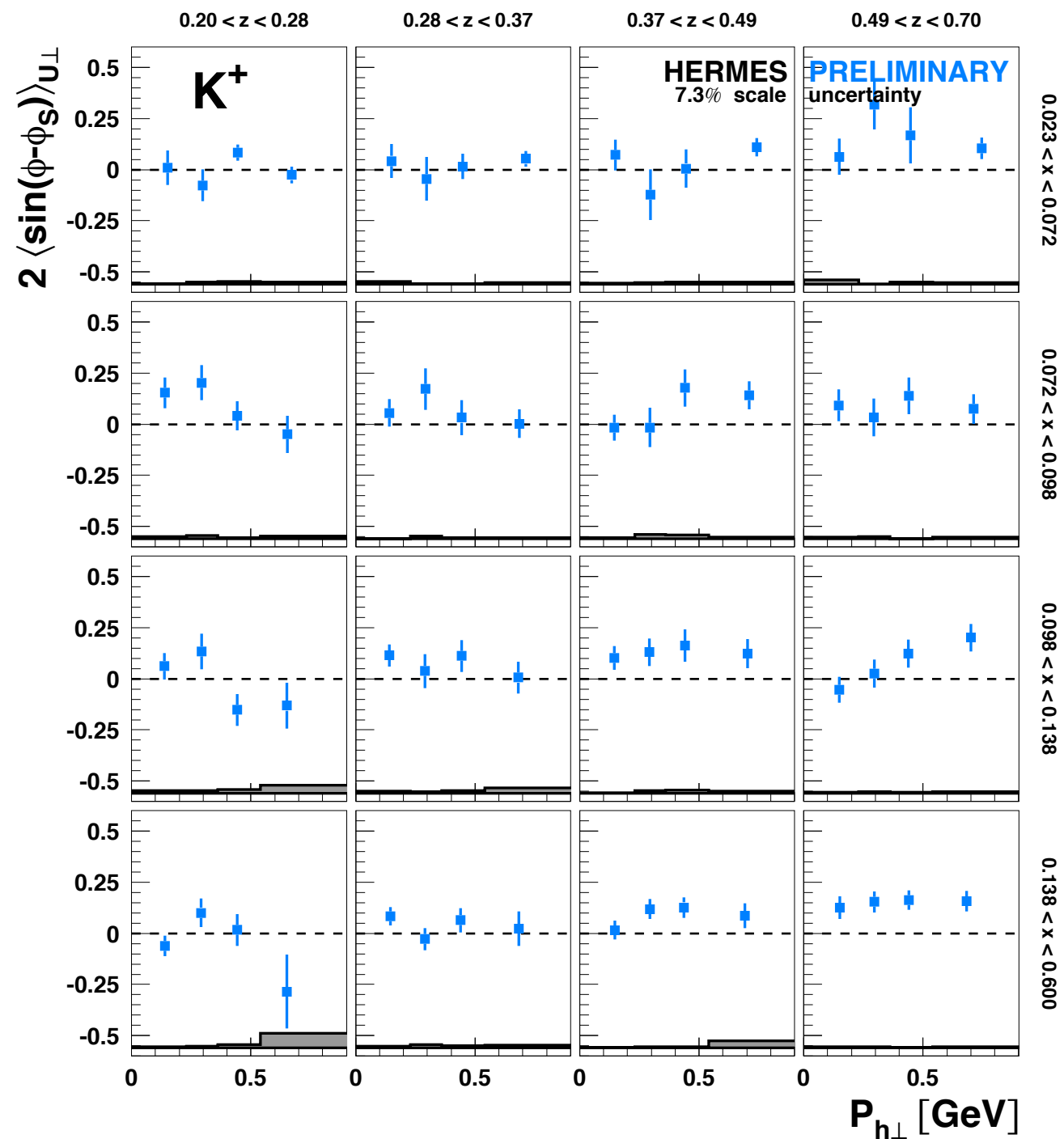
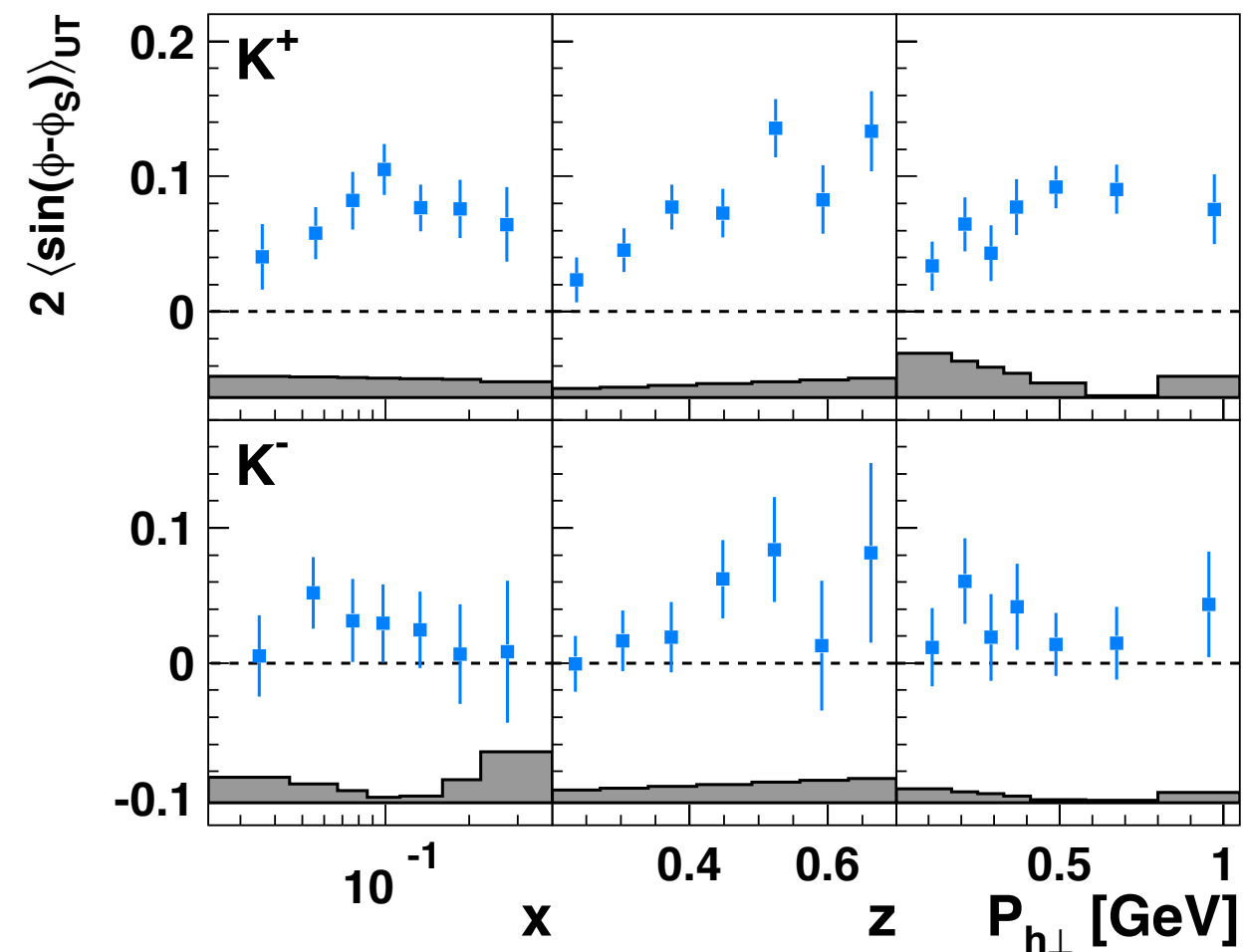


kaons

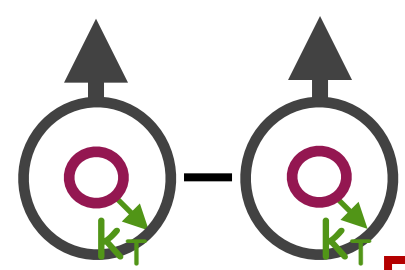
Sivers amplitudes

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

Phys. Rev. Lett. 103 (2009) 152002



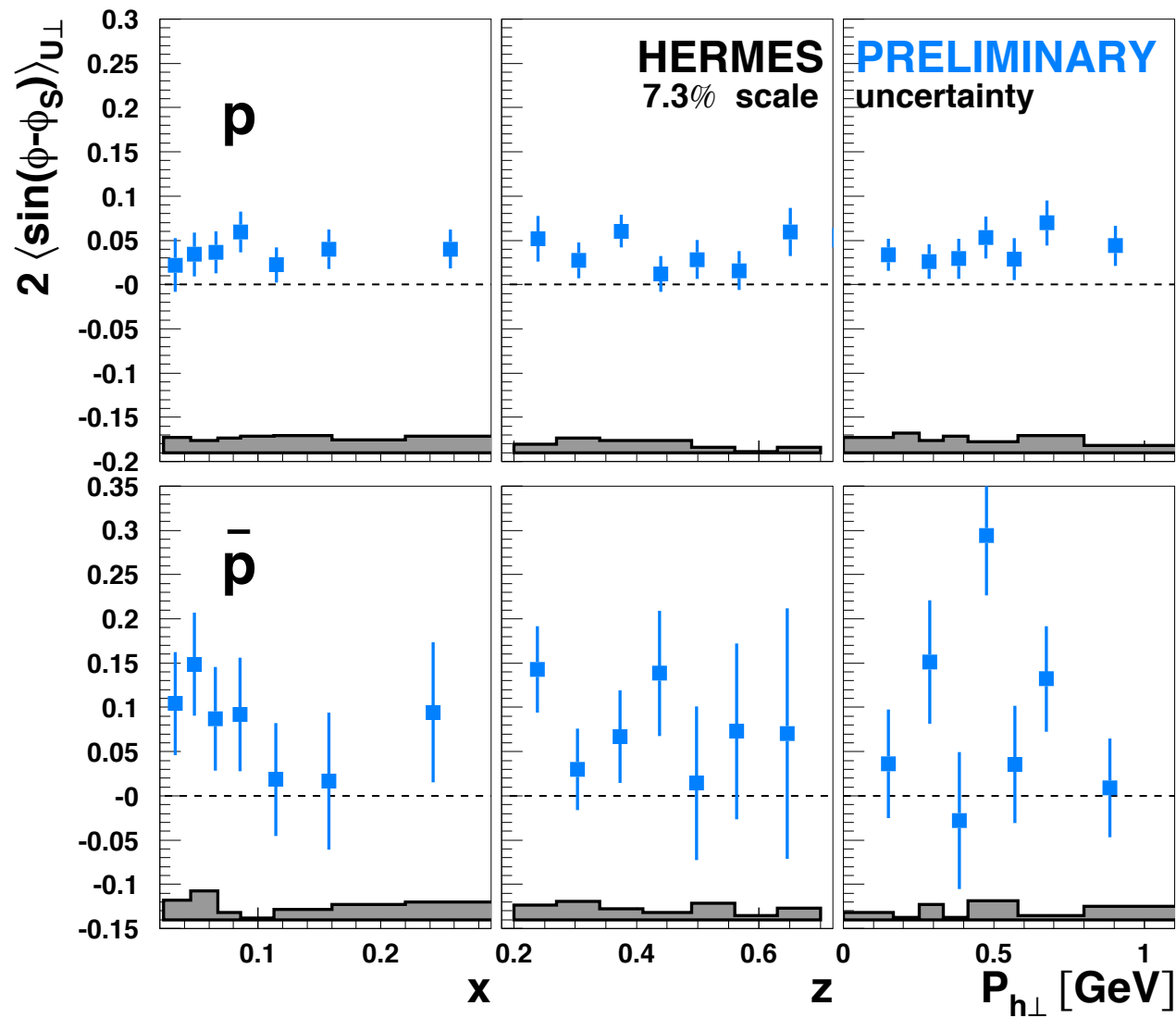
- K^+ amplitudes >0 ; increasing with $P_{h\perp}$ up to 0.4 GeV: concentrated at large x and z



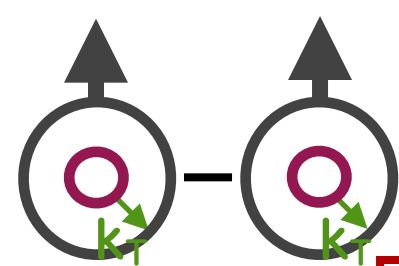
protons

Sivers amplitudes

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



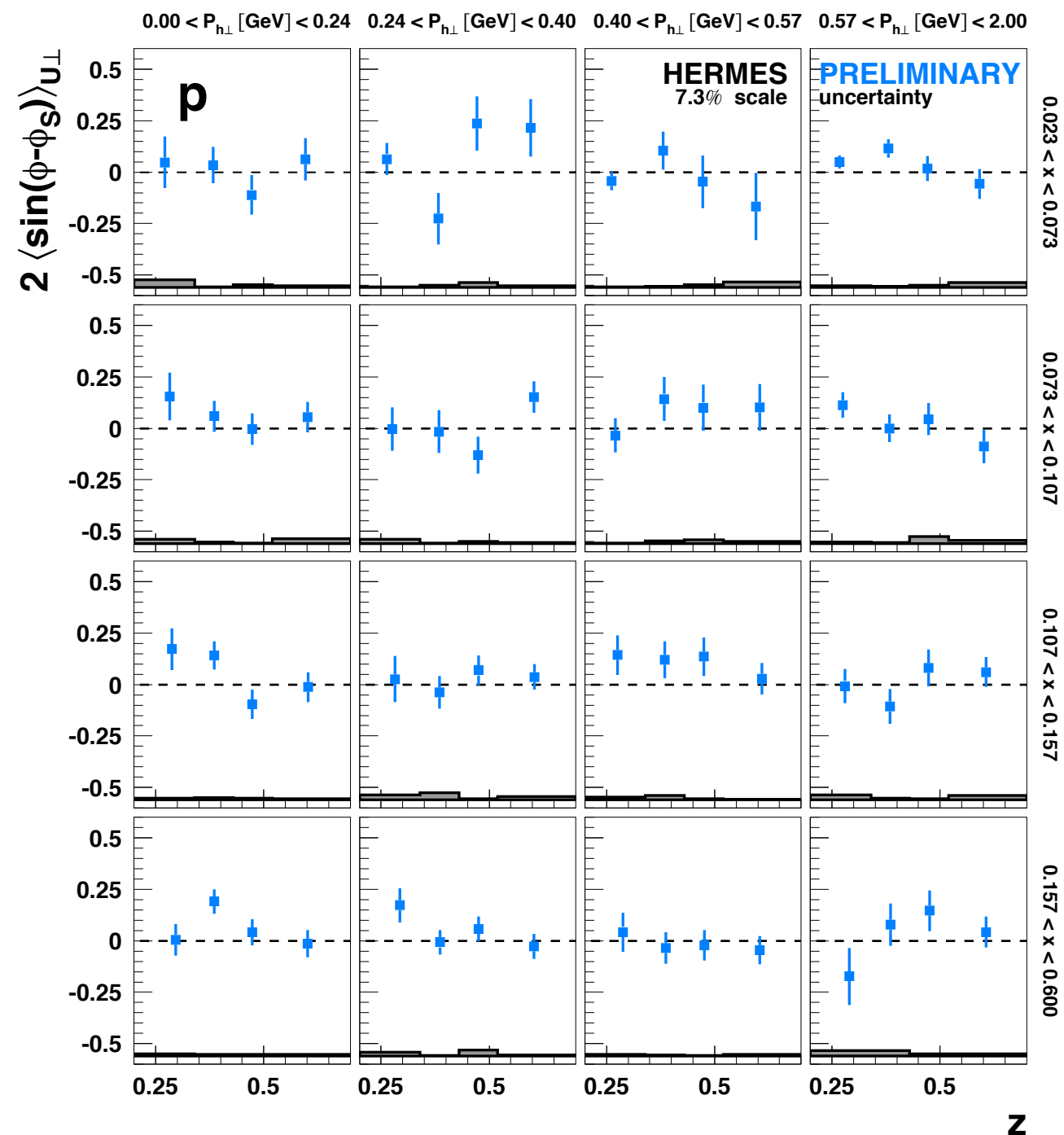
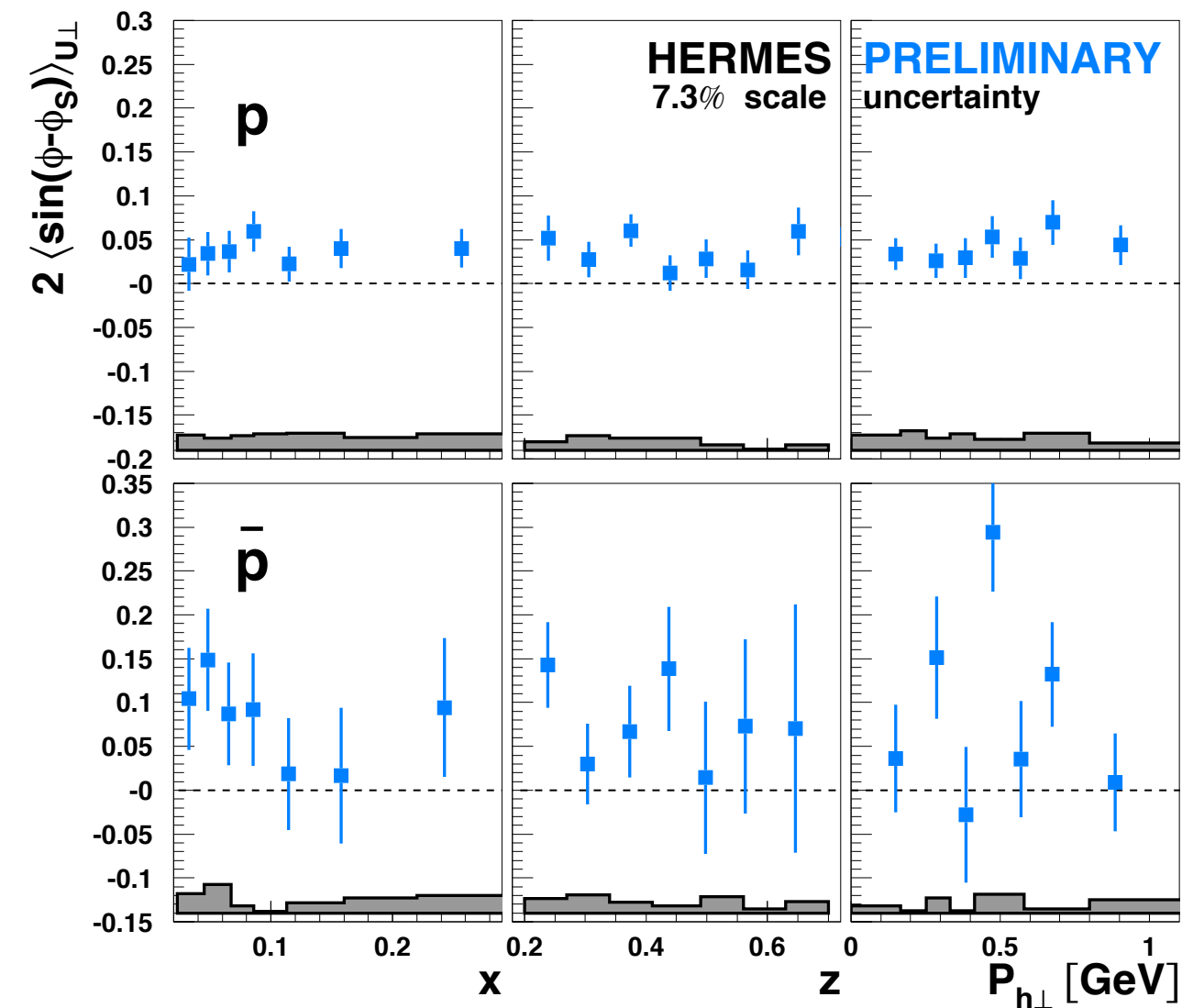
- Positive Sivers amplitude for protons!

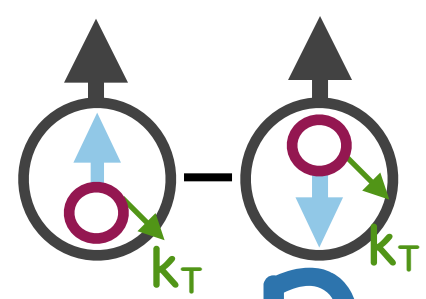


protons

Sivers amplitudes

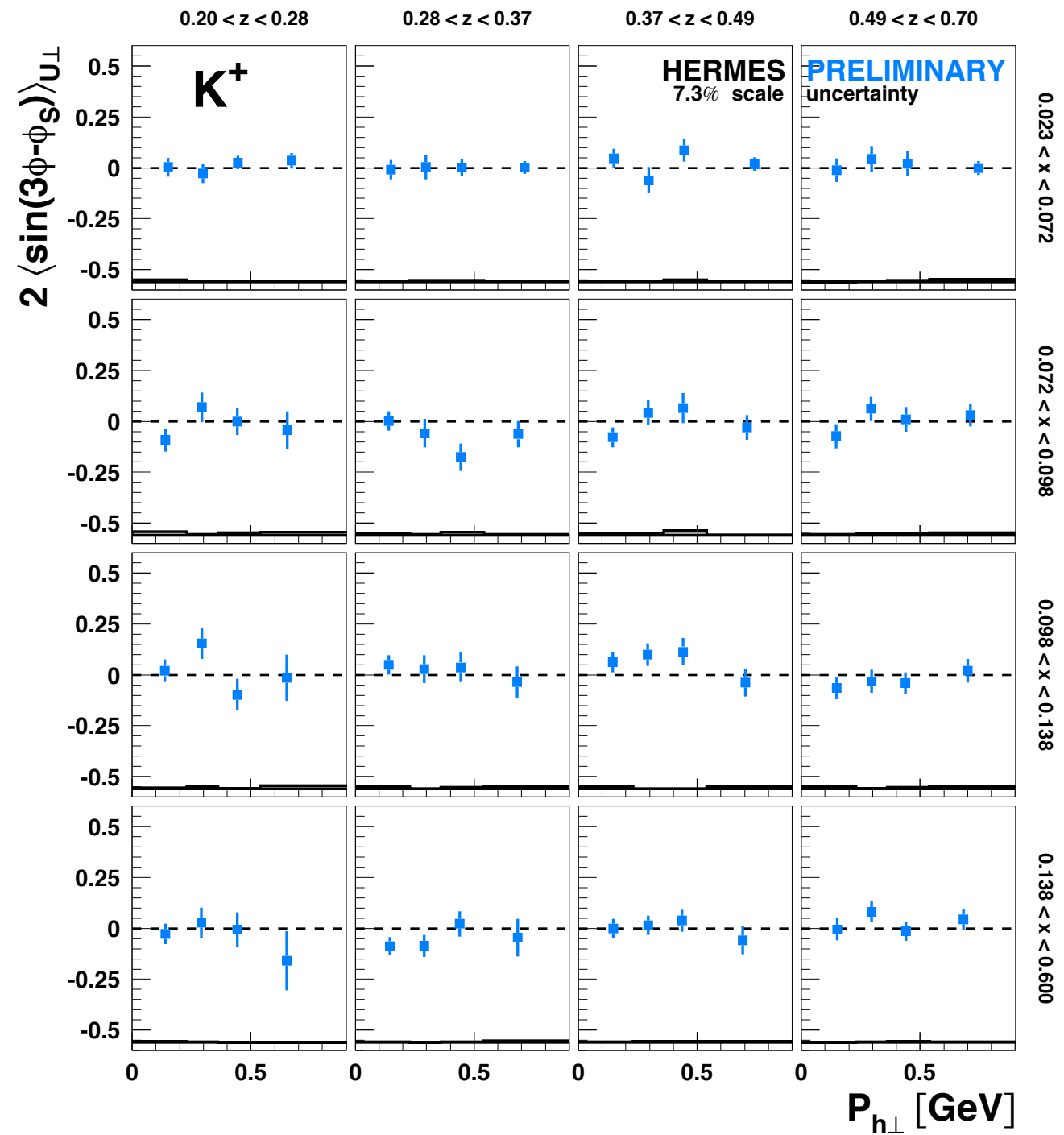
$$\propto f_{1T}^{\perp,q} \otimes D_1^q$$





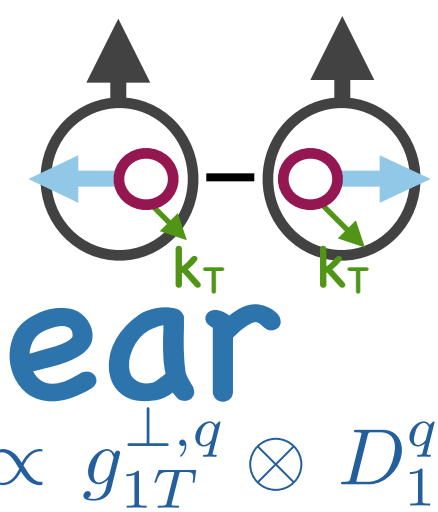
Pretzelosity

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

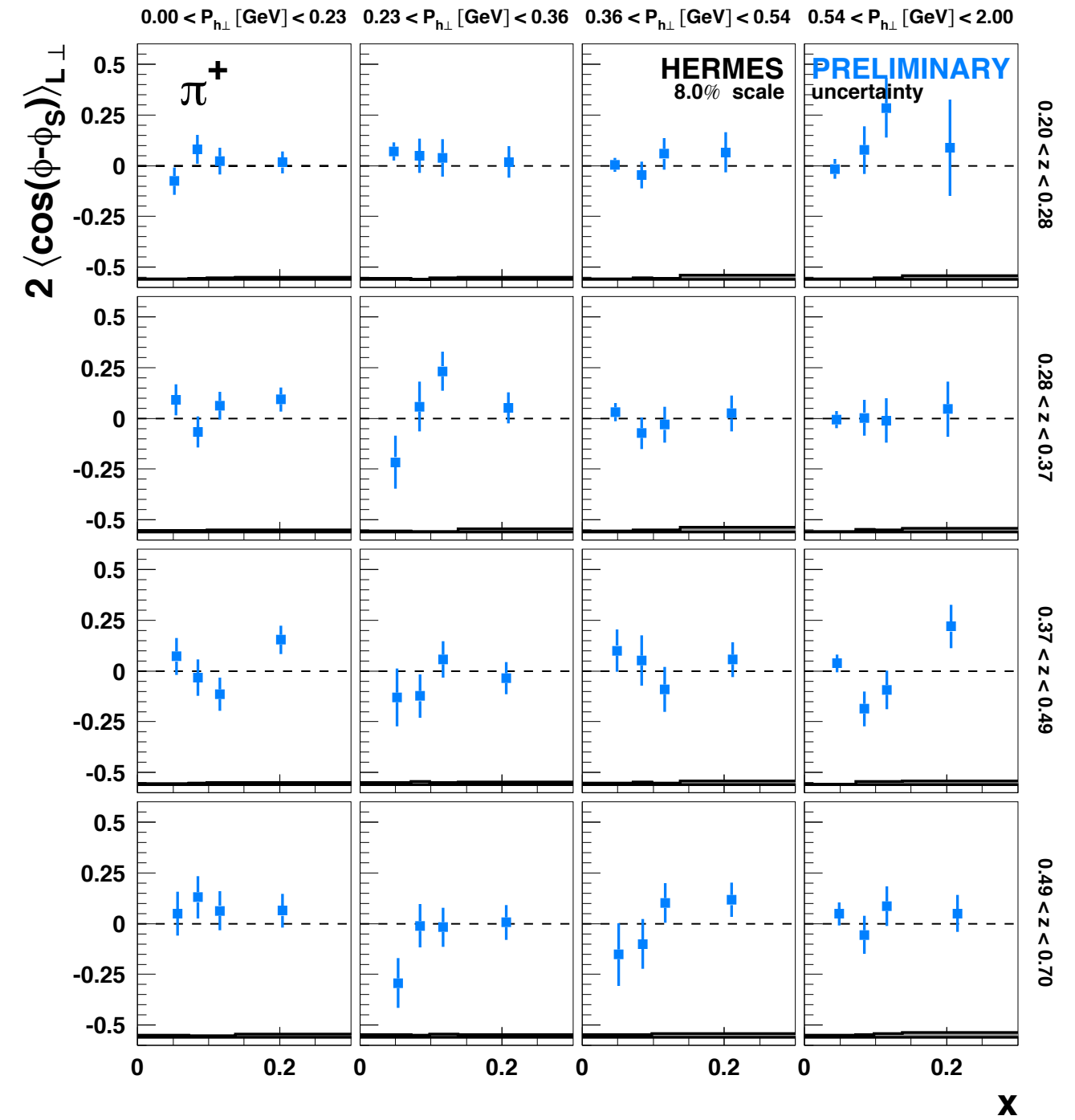
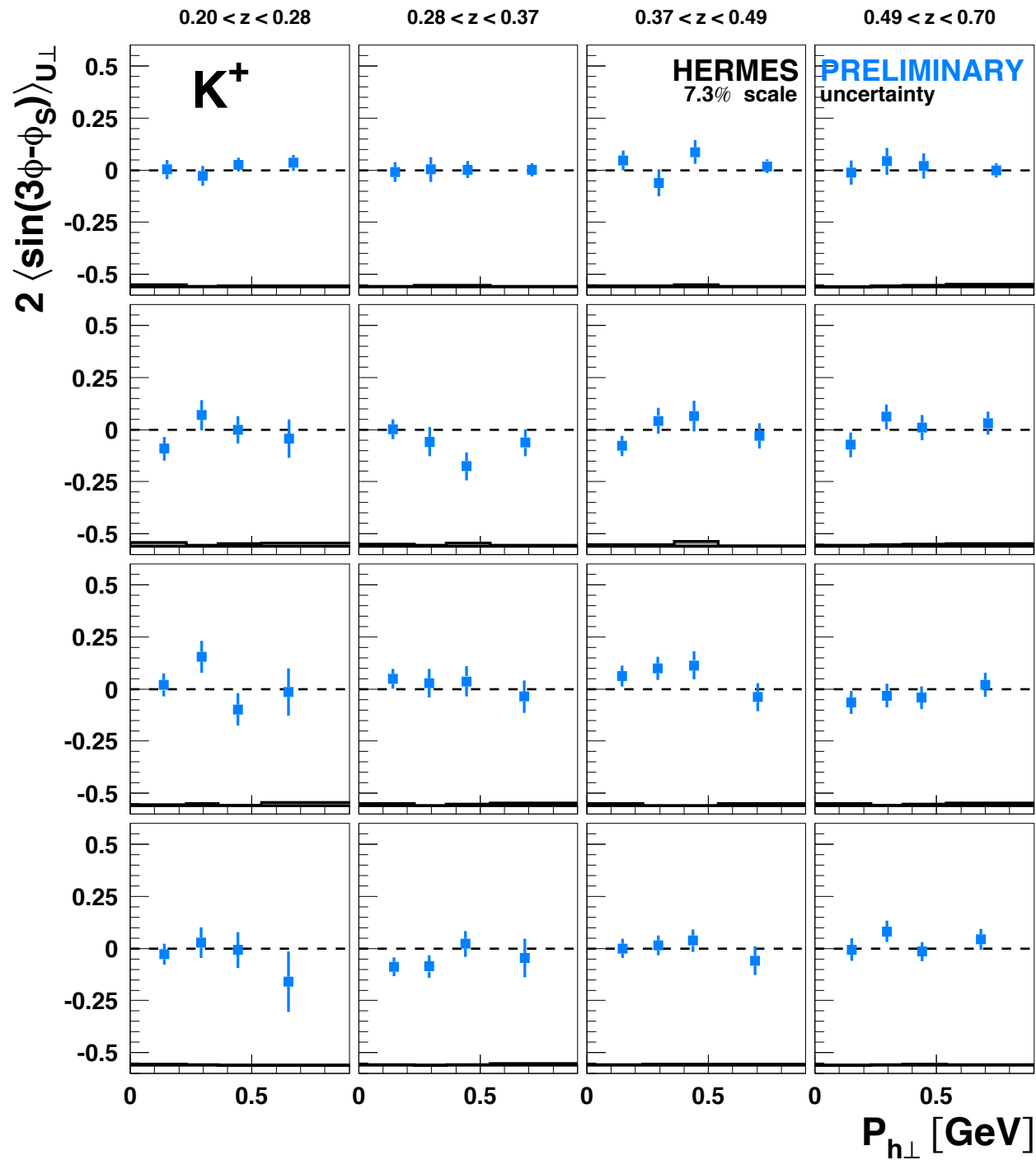




$$\propto h_{1T}^{\perp,q} \otimes H_1^{\perp,q}$$



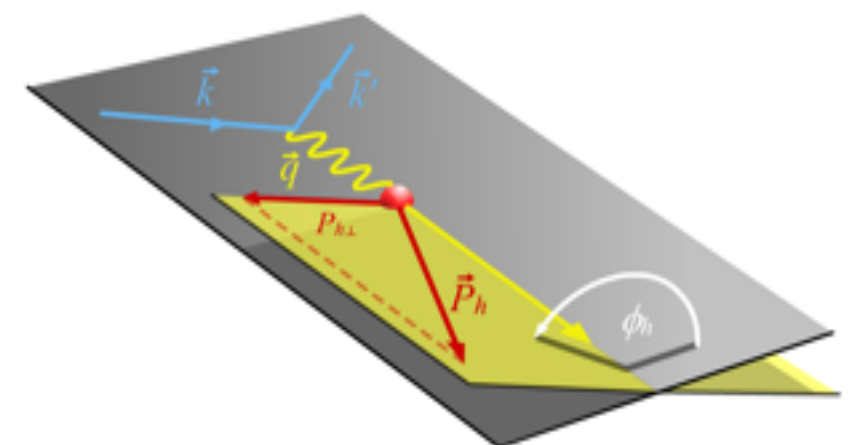
$$\propto g_{1T}^{\perp,q} \otimes D_1^q$$



A_{LU}

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

Results for pions, kaons and protons

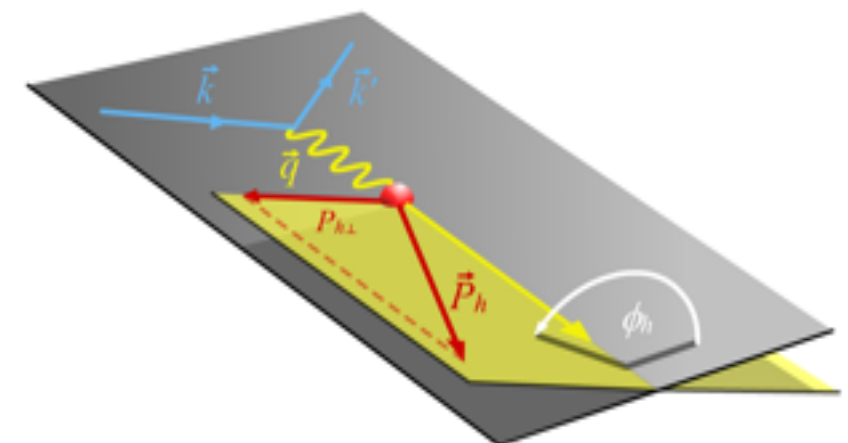


A_{LU}

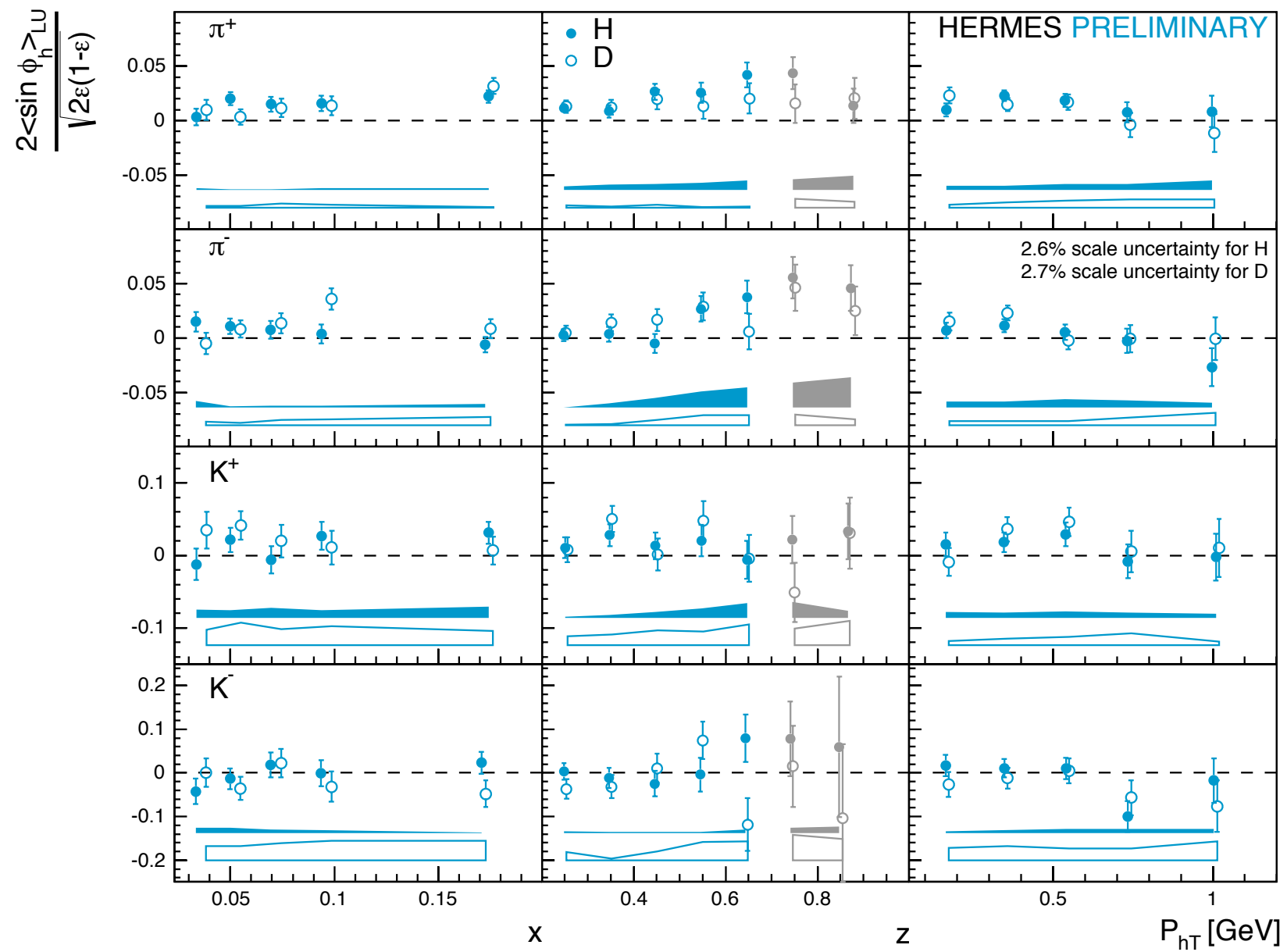
Higher twist:

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

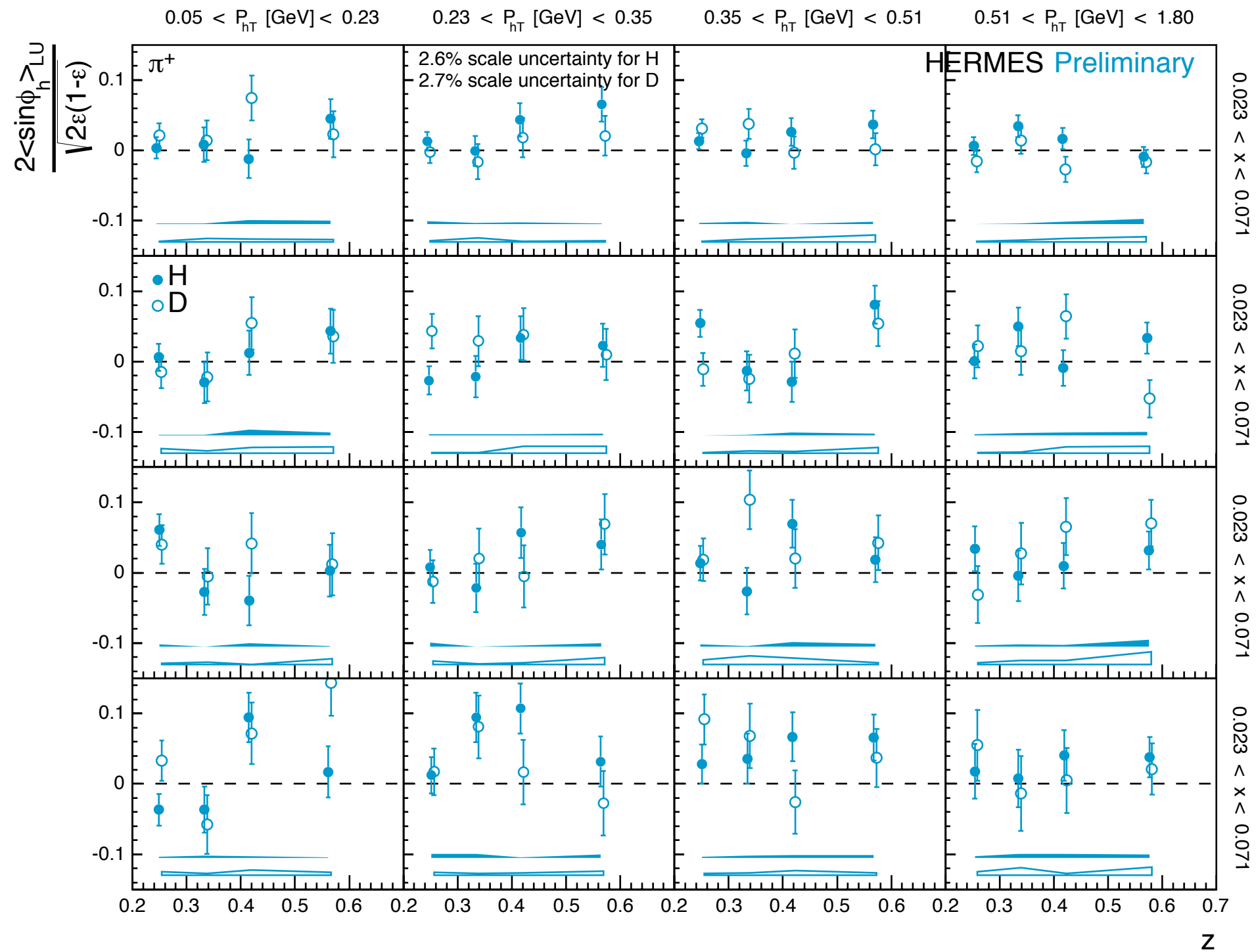
Results for pions, kaons and protons



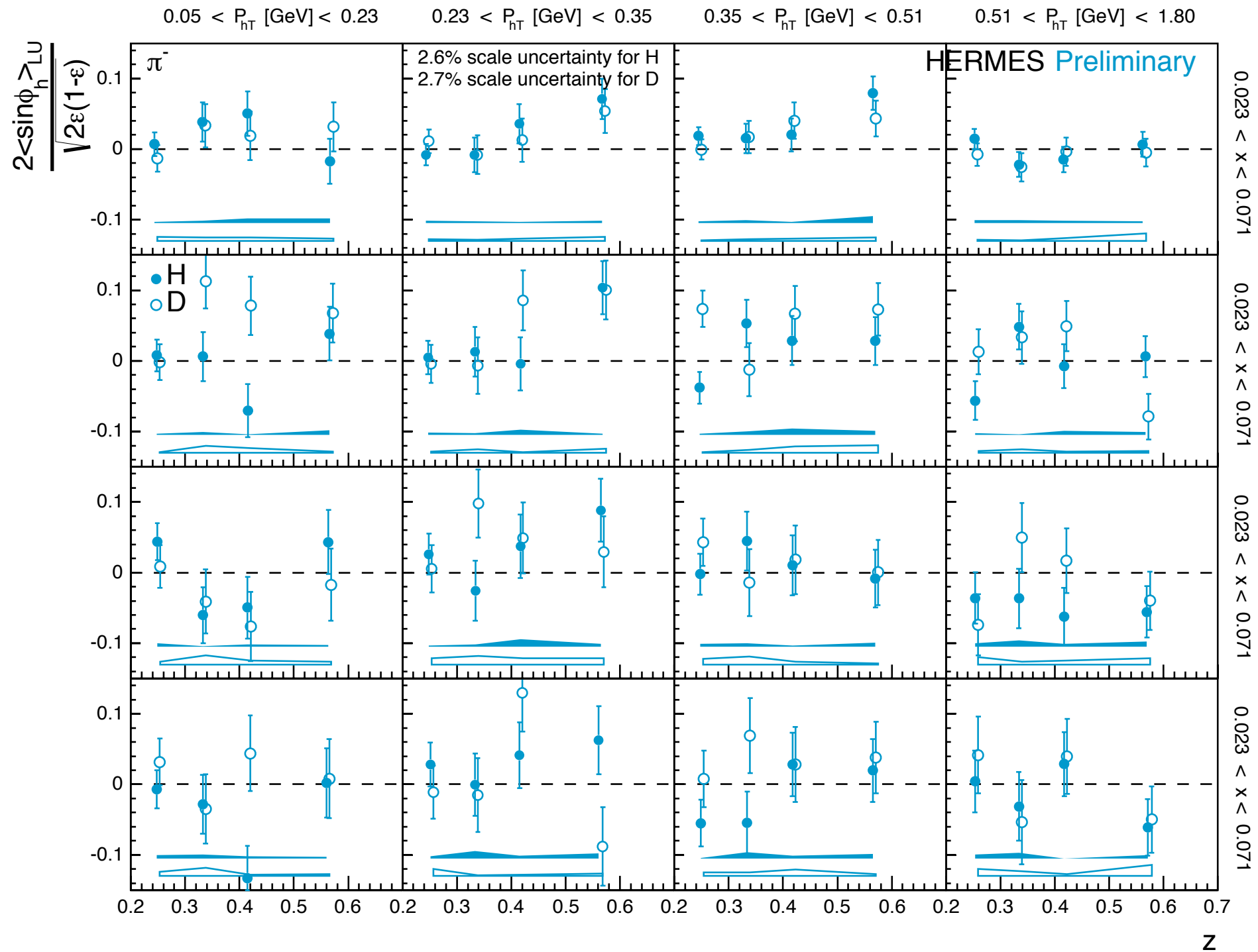
A_{LU} results pions & kaons 1D



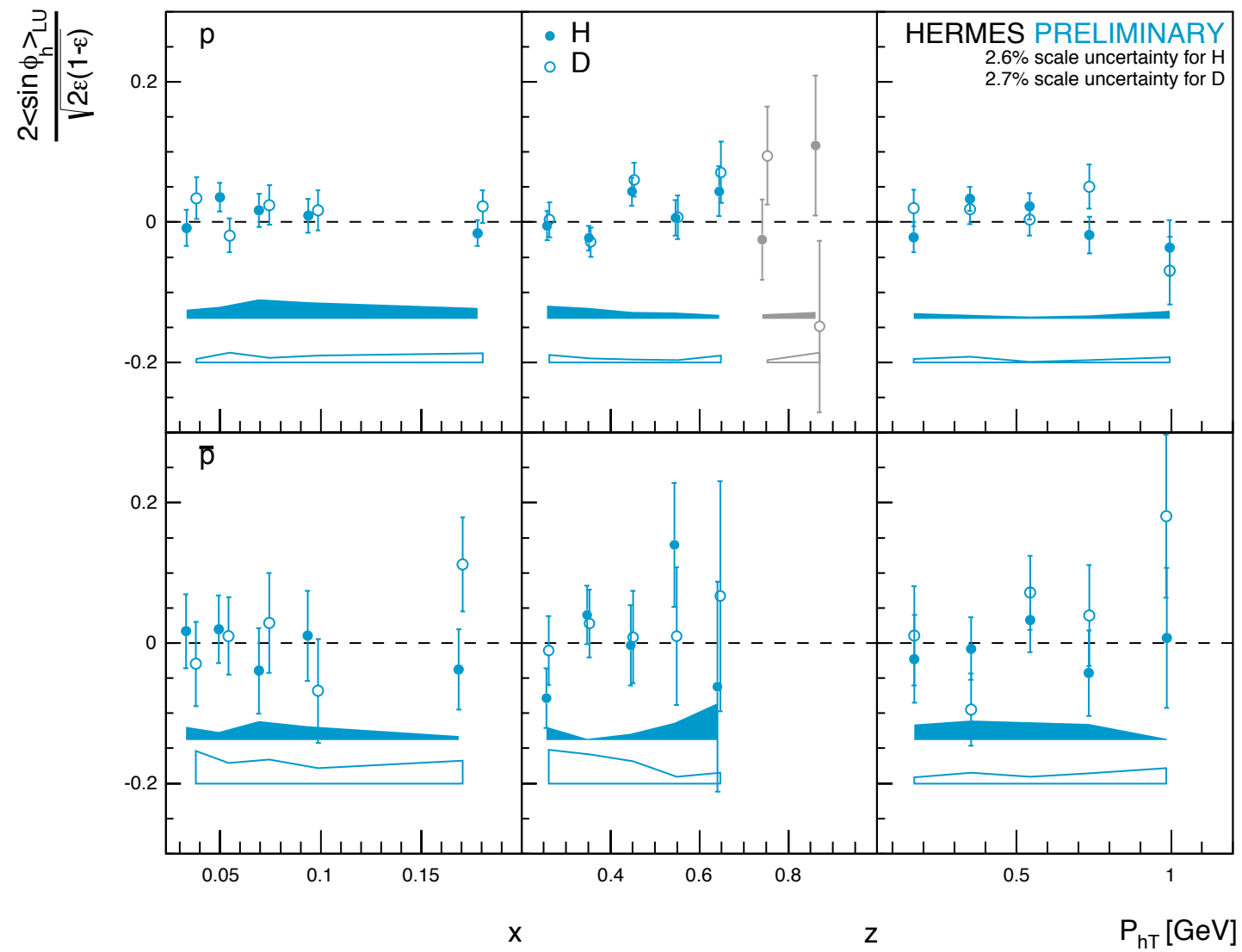
A_{LU} results pions 3D



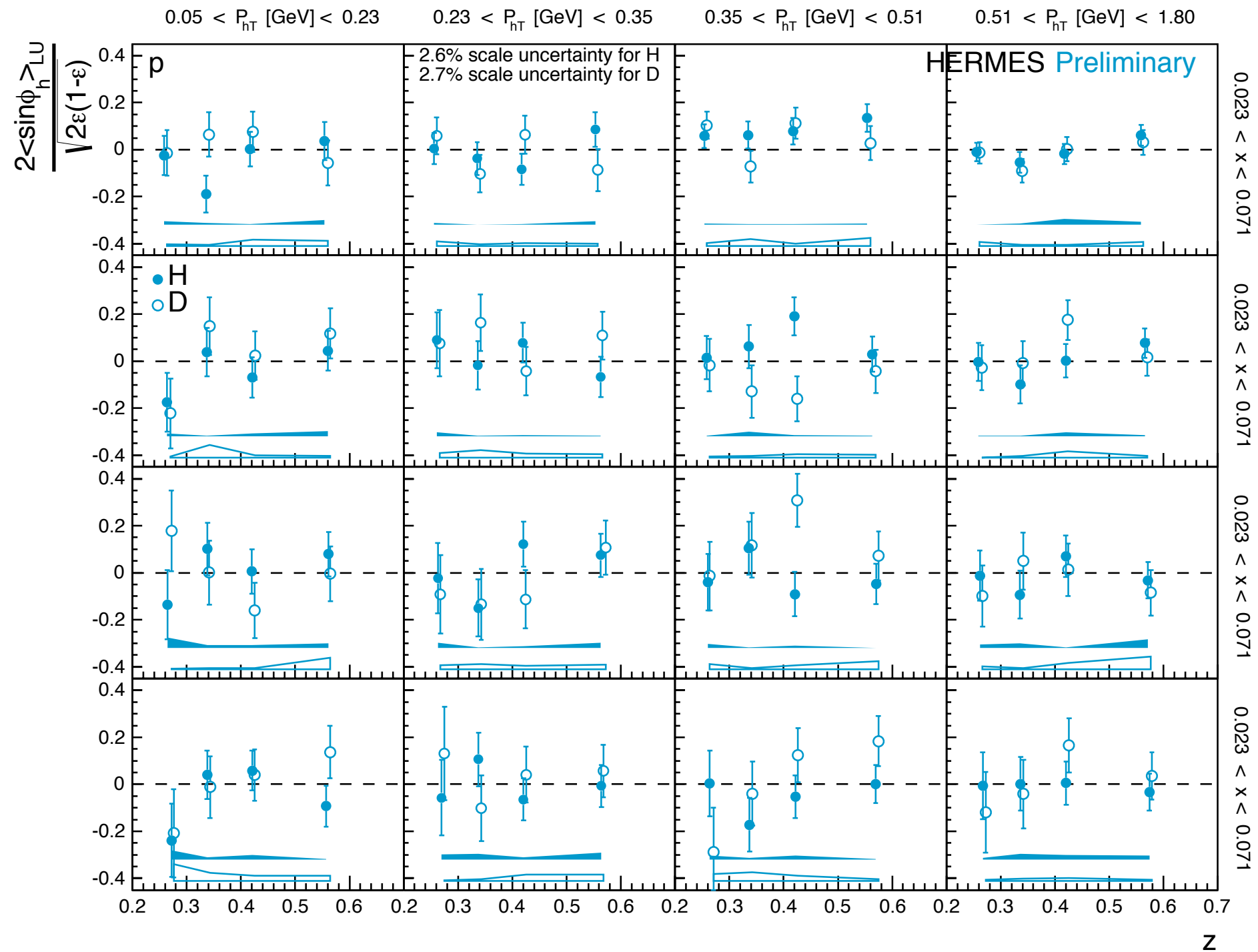
A_{LU} results pions 3D



A_{LU} results protons 1D



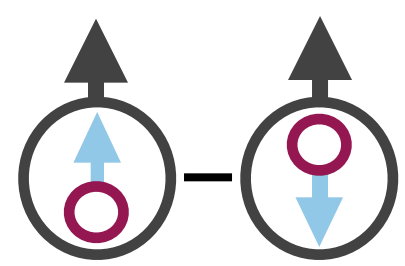
A_{LU} results protons 3D



Summary

- Twist-2 and twist-3 amplitudes in 3D on transversely polarized hydrogen target – beam longitudinally polarized and unpolarized:
kinematic dependence of Collins and Sivers located in certain kinematic corners
- Twist-3 non-zero A_{LU} observed for π^+ , π^- , K^+

Back up



Collins amplitudes

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

