22nd International Spin Symposium
September 25th-30th, 2016 - iHotel Conference Center, Champaign, IL

Spin'16

Overview of TMD results

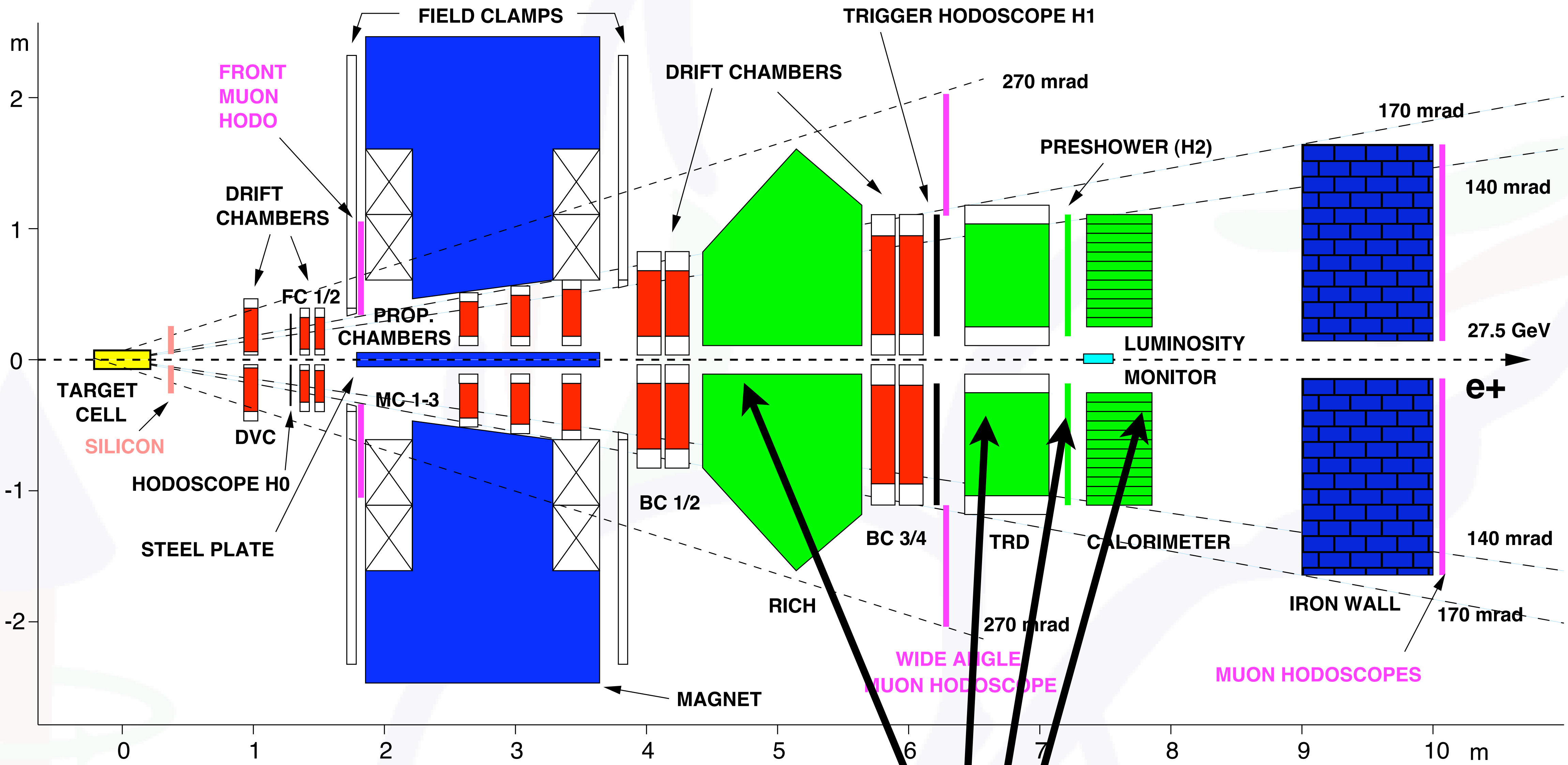
from hermes

ikerbasque
Basque Foundation for Science

Gunar.Schnell @ desy.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

HERMES schematically

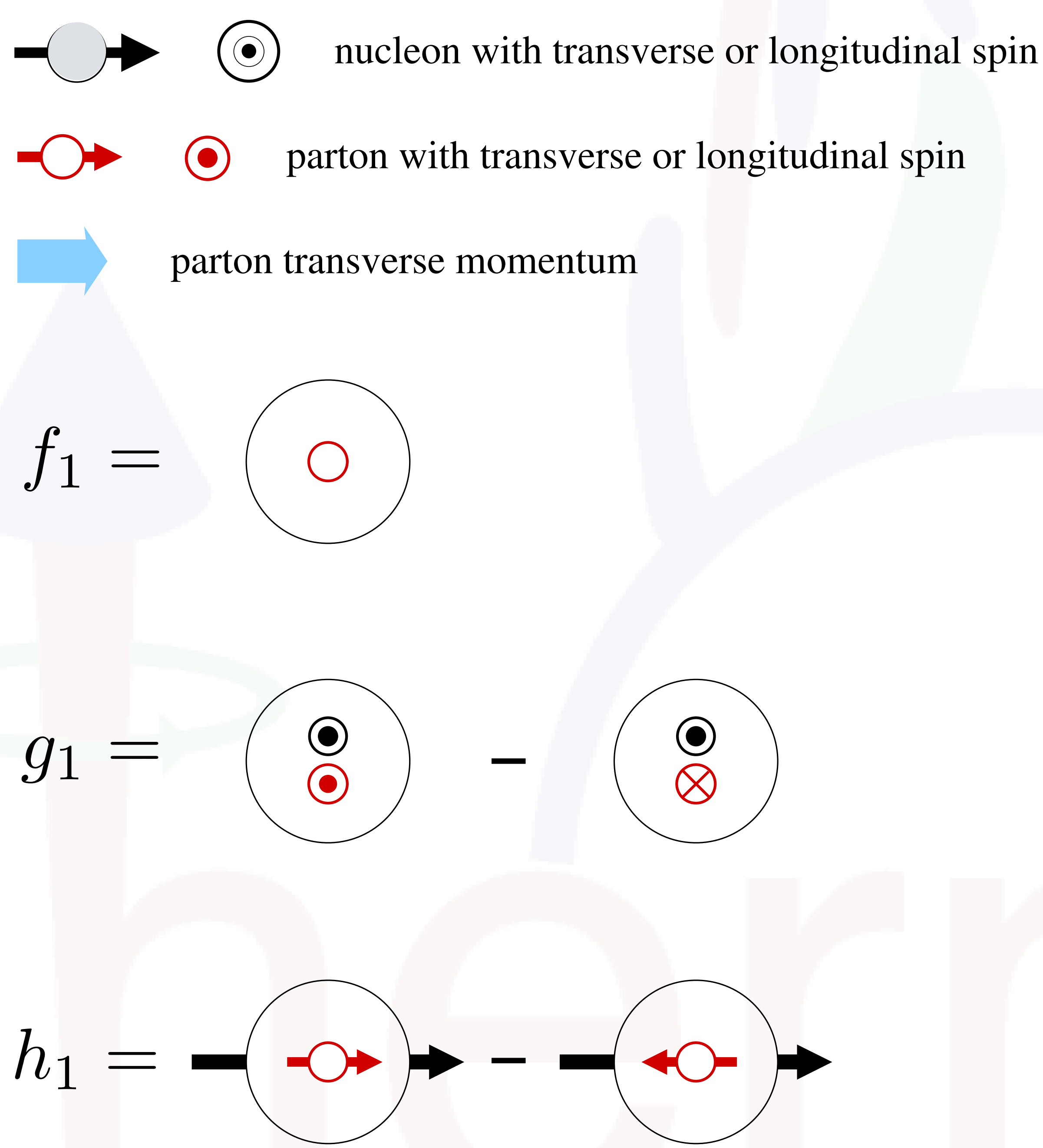


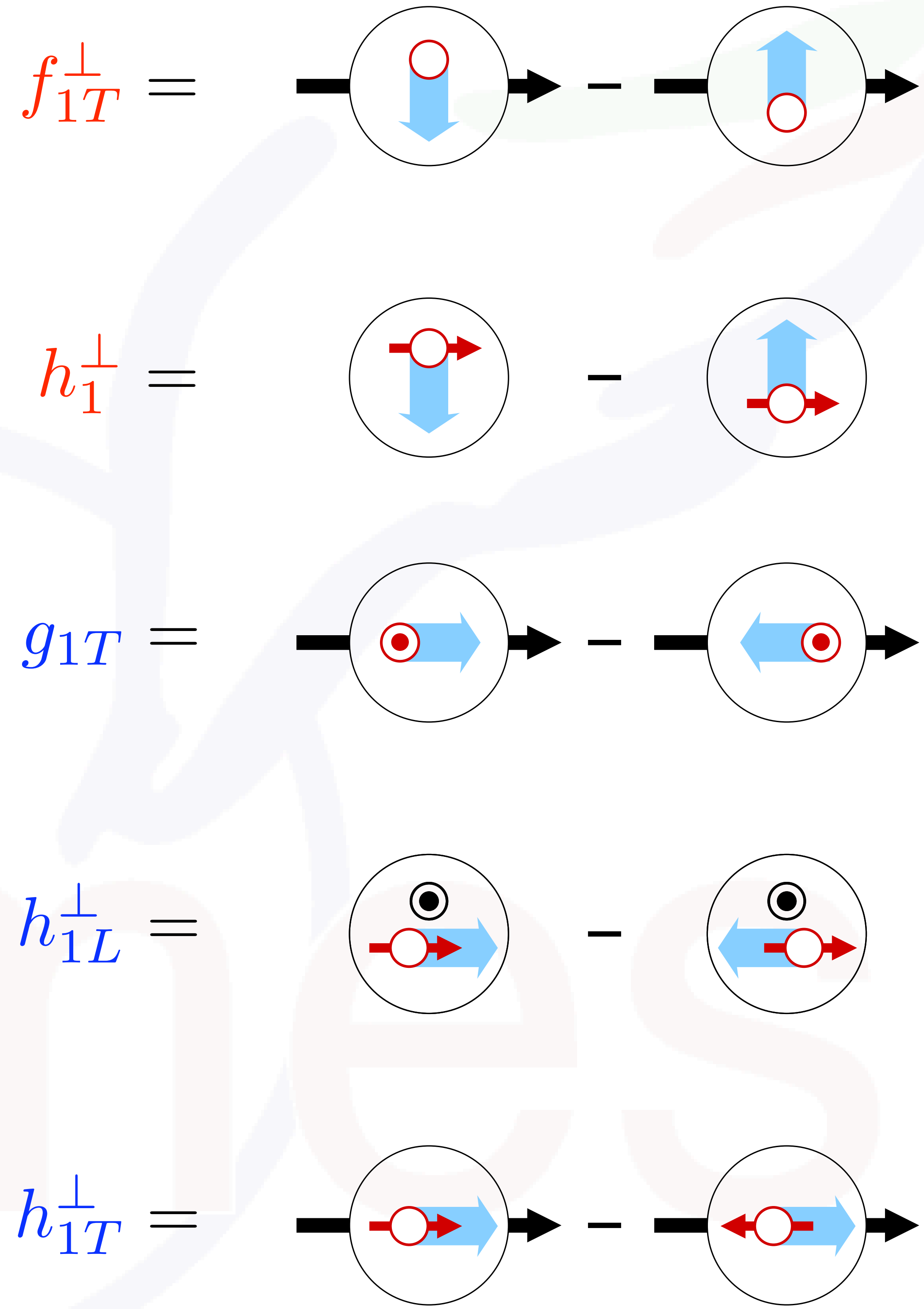
- pure gas targets internal to HERA 27.6 GeV lepton ring
- unpolarized (^{1}H ... Xe)
- long. polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

TMDs - probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen





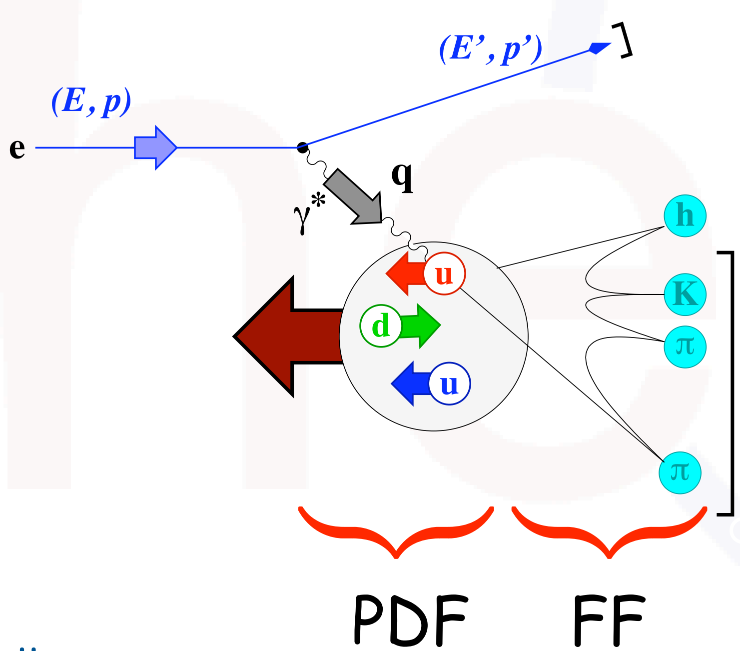
[courtesy of A. Bacchetta]

Probing TMDs in semi-inclusive DIS

quark pol. / nucleon pol.

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

in SIDIS*) couple PDFs to:



*) semi-inclusive DIS with unpolarized final state

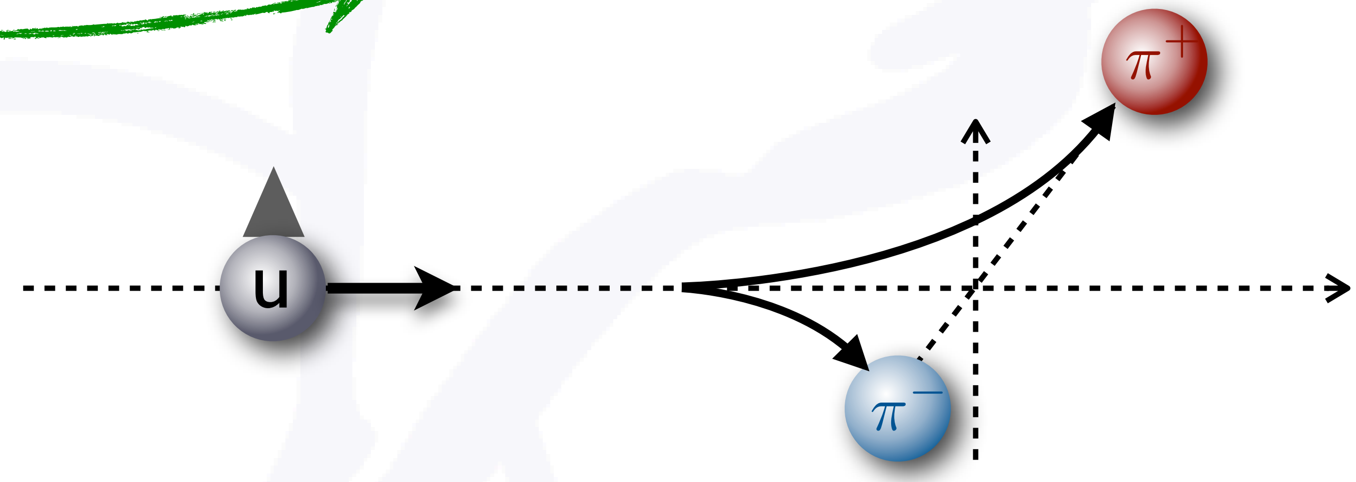
Probing TMDs in semi-inclusive DIS

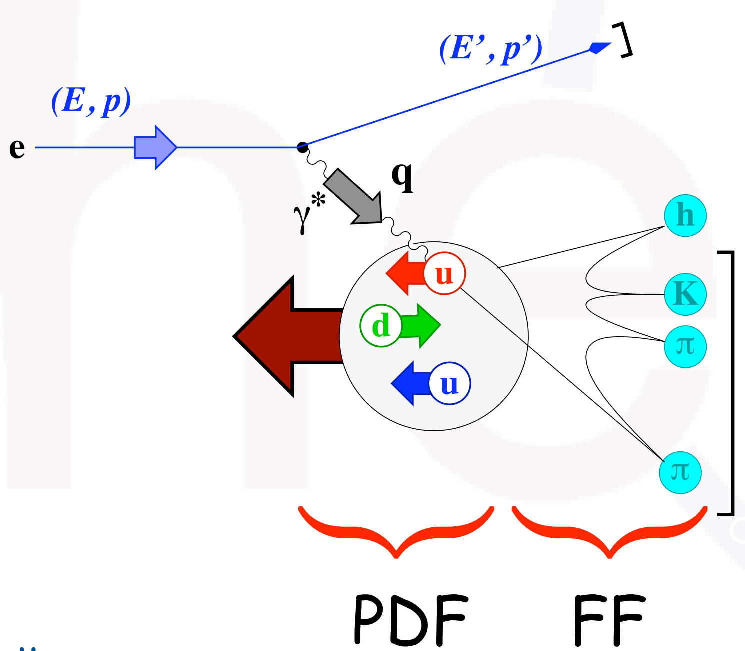
quark pol. (columns) / nucleon pol. (rows)

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

in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$





*) semi-inclusive DIS with unpolarized final state

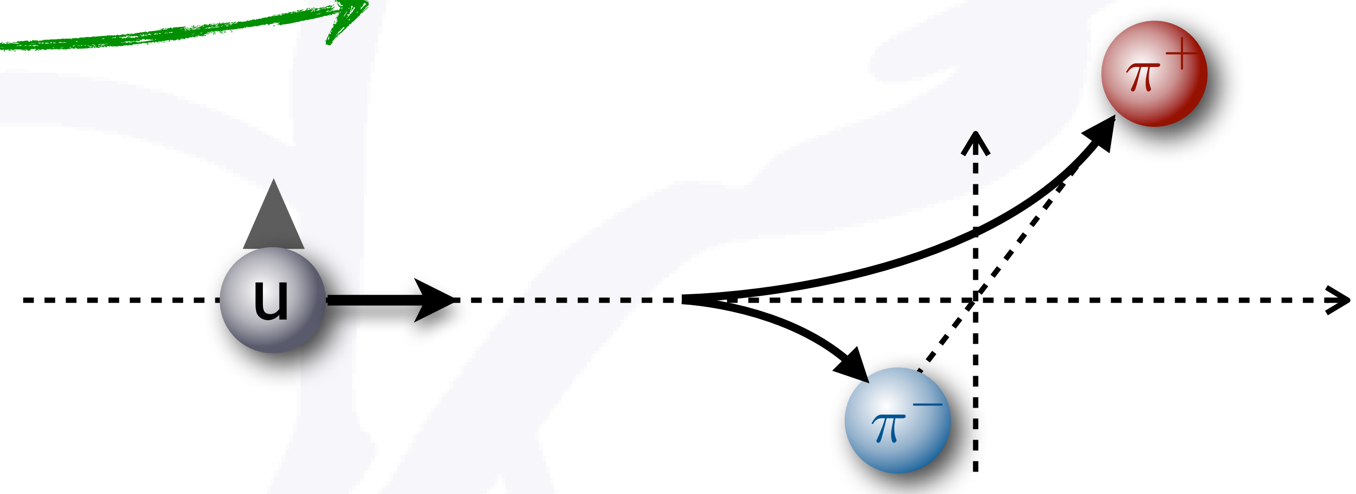
Probing TMDs in semi-inclusive DIS

quark pol. (columns) / nucleon pol. (rows)

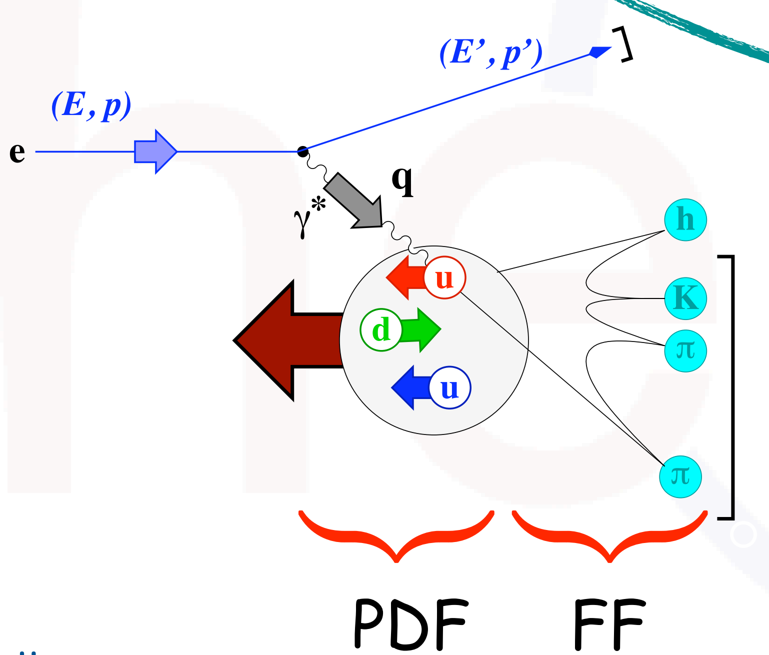
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$



ordinary FF: $D_1^{q\to h}$



*) semi-inclusive DIS with unpolarized final state

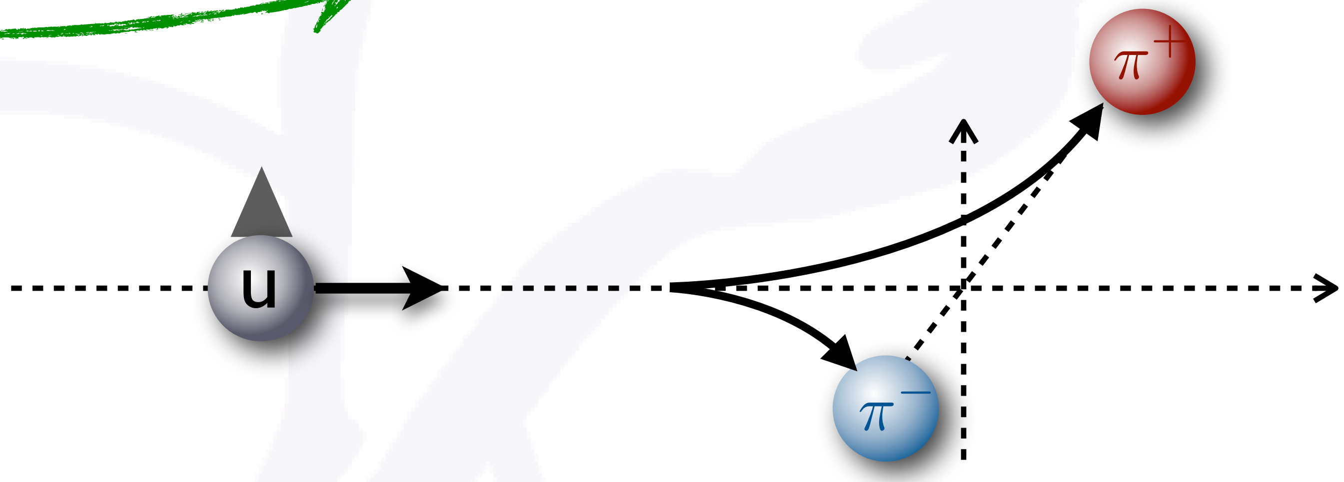
Probing TMDs in semi-inclusive DIS

quark pol. (columns) / nucleon pol. (rows)

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

in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$



ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

1-Hadron production (ep→ehX)

$$d\sigma = d\sigma_{UU}^{0} + \cos 2\phi \, d\sigma_{UU}^{1} + \frac{1}{Q} \cos\phi \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma_{LU}^{3}$$

$$+ S_L \left\{ \sin 2\phi \, d\sigma_{UL}^{4} + \frac{1}{Q} \sin\phi \, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q} \cos\phi \, d\sigma_{LL}^{7} \right] \right\}$$

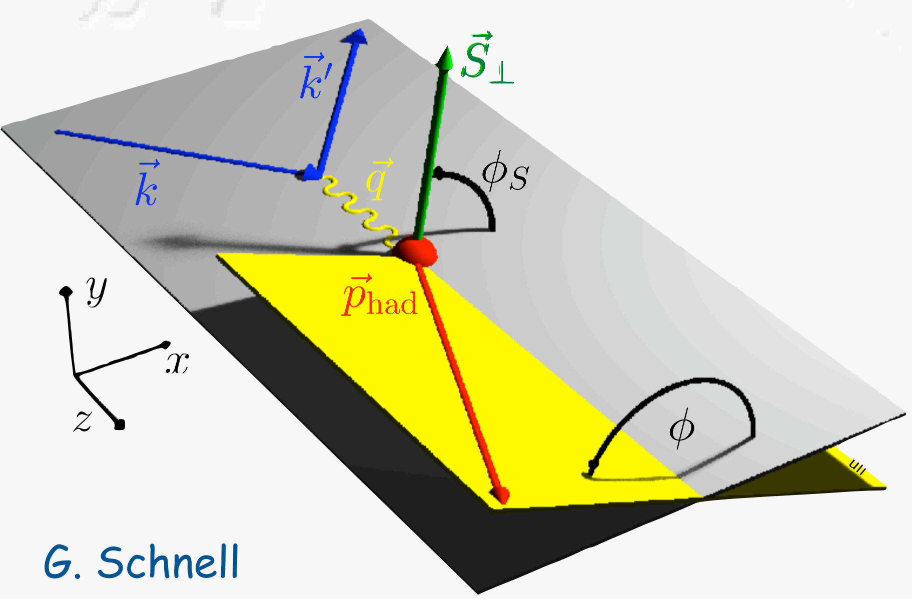
$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^{8} + \sin(\phi + \phi_S) \, d\sigma_{UT}^{9} + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right.$$

$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}$$

σ_{XY}

Beam Target
Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197
Boer and Mulders, Phys. Rev. D 57 (1998) 5780
Bacchetta et al., Phys. Lett. B 595 (2004) 309
Bacchetta et al., JHEP 0702 (2007) 093
“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

1-Hadron production (ep→ehX)

$$d\sigma = d\sigma_{UU}^{0} + \cos 2\phi \, d\sigma_{UU}^{1} + \frac{1}{Q} \cos\phi \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma_{LU}^{3}$$

$$+ S_L \left\{ \sin 2\phi \, d\sigma_{UL}^{4} + \frac{1}{Q} \sin\phi \, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q} \cos\phi \, d\sigma_{LL}^{7} \right] \right\}$$

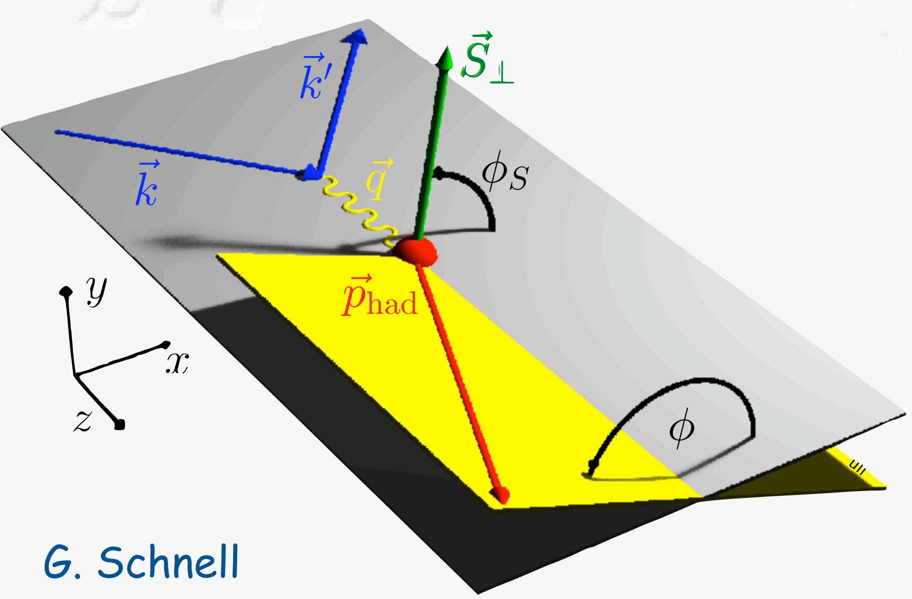
$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^{8} + \sin(\phi + \phi_S) \, d\sigma_{UT}^{9} + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right.$$

$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

$$\left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}$$

σ_{XY}

Beam Target
Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504

1-Hadron production (ep→ehX)

$$d\sigma = d\sigma_{UU}^{0} + \cos 2\phi\, d\sigma_{UU}^{1} + \frac{1}{Q}\cos\phi\, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma_{LU}^{3}$$

$$+S_L \left\{ \sin 2\phi\, d\sigma_{UL}^{4} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}^{5} + \lambda_e \left[d\sigma_{LL}^{6} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}^{7} \right] \right\}$$

$$+S_T \left\{ \sin(\phi-\phi_S)\, d\sigma_{UT}^{8} + \sin(\phi+\phi_S)\, d\sigma_{UT}^{9} + \sin(3\phi-\phi_S)\, d\sigma_{UT}^{10} \right.$$

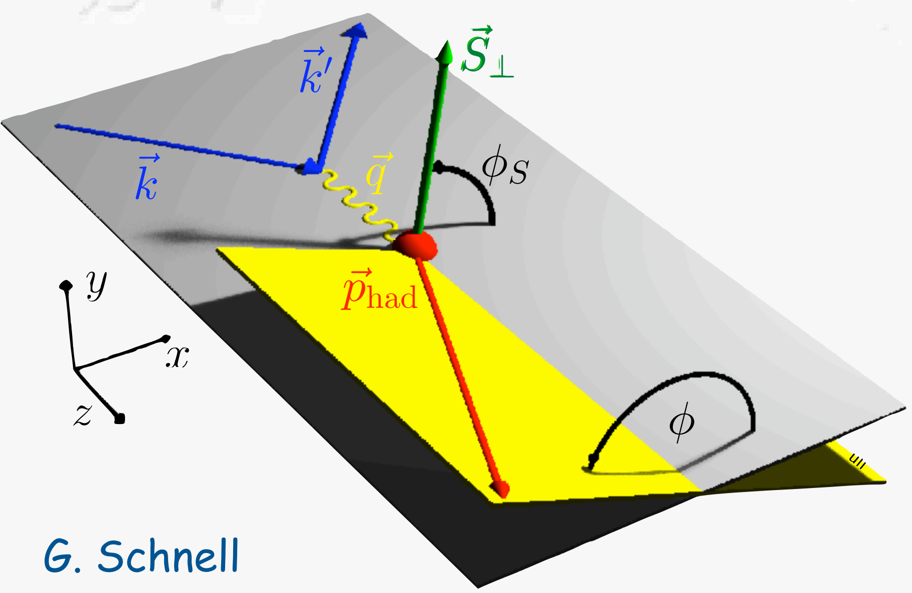
$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma_{UT}^{11} + \sin\phi_S\, d\sigma_{UT}^{12}\right)$$

$$\left. +\lambda_e \left[\cos(\phi-\phi_S)\, d\sigma_{LT}^{13} + \frac{1}{Q}\left(\cos\phi_S\, d\sigma_{LT}^{14} + \cos(2\phi-\phi_S)\, d\sigma_{LT}^{15}\right) \right] \right\}$$

σ_{XY}

Beam **Target**

Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504

Hadron multiplicities in DIS

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

$$+ \sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

beam polarization; virtual-photon polarization

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

Hadron multiplicities in DIS

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dx\,dy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dx\,dy\,dz\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon F_{UU,L}}{F_T+\epsilon F_L}$$

$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

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

$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

$$F_{XY,Z} = F_{XY,Z}(x,y,z,P_{h\perp})$$

(X: beam polarization; Y: target polarization; Z: virtual-photon polarization)

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

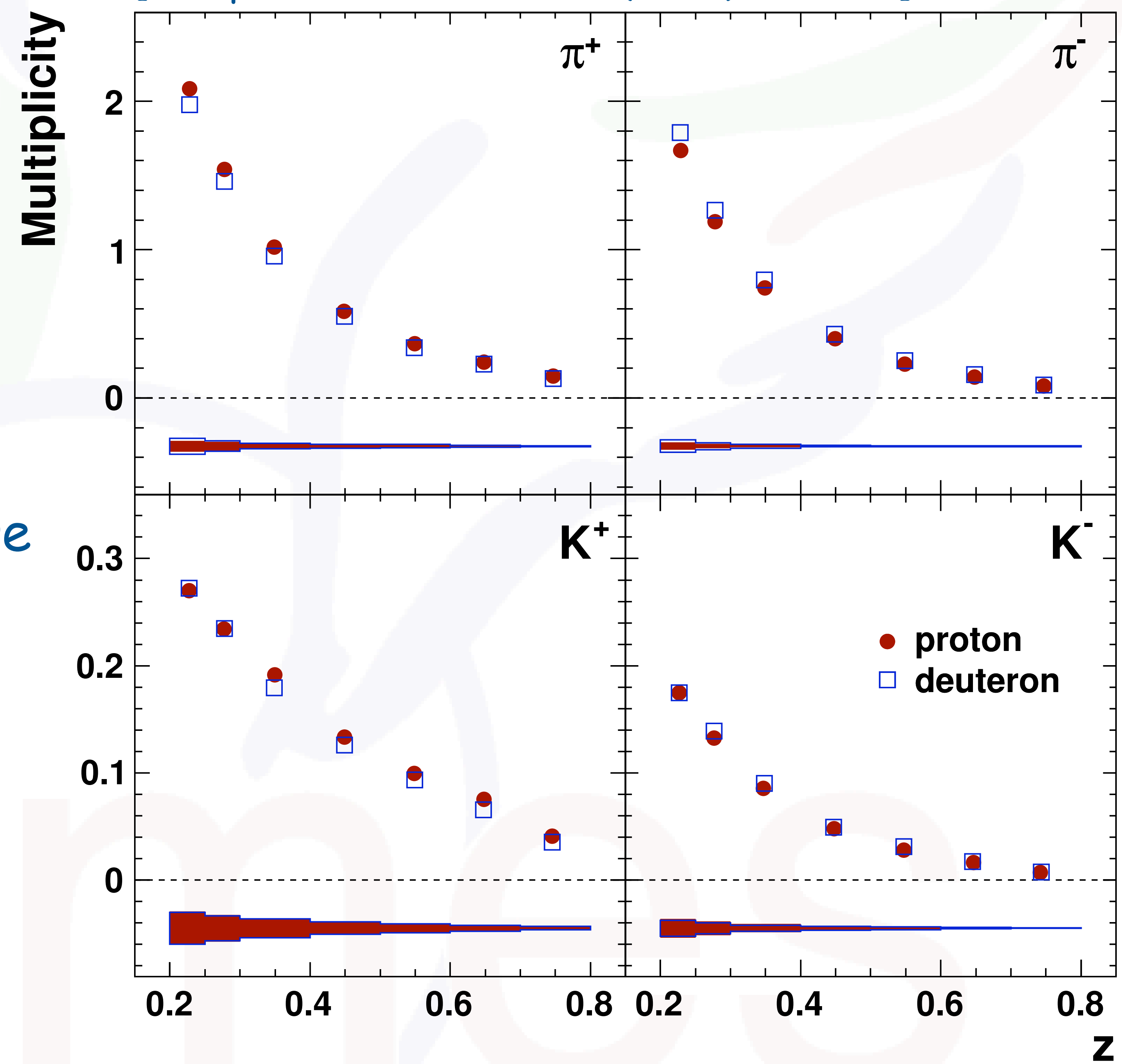
$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

Multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons http://www-hermes.desy.de/multiplicities
- extracted in a multi-dimensional unfolding procedure

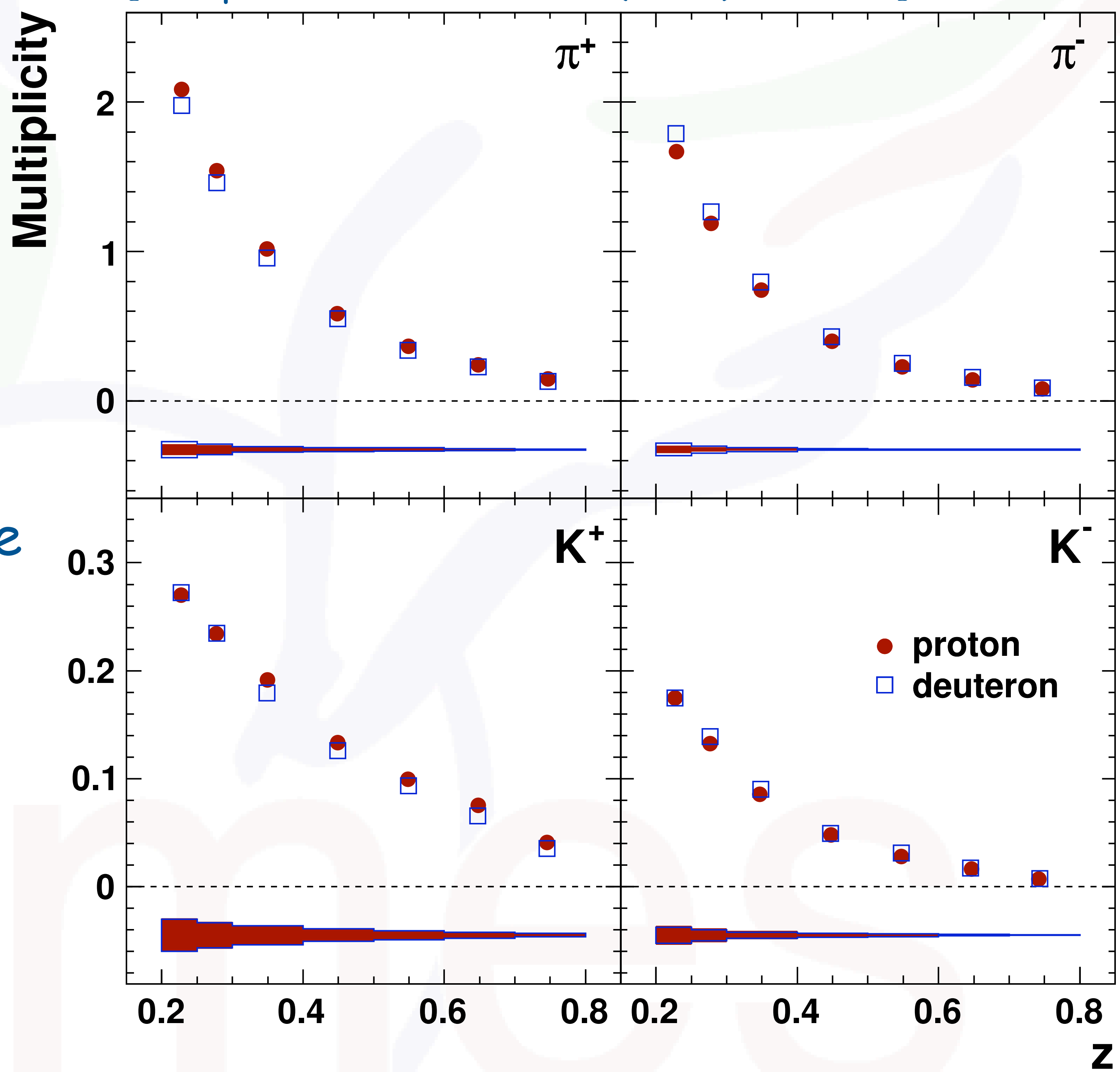
[Airapetian et al., PRD 87 (2013) 074029]



Multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons
  http://www-hermes.desy.de/multiplicities
- extracted in a multi-dimensional unfolding procedure
- access to flavor dependence of fragmentation through different mesons and targets

[Airapetian et al., PRD 87 (2013) 074029]

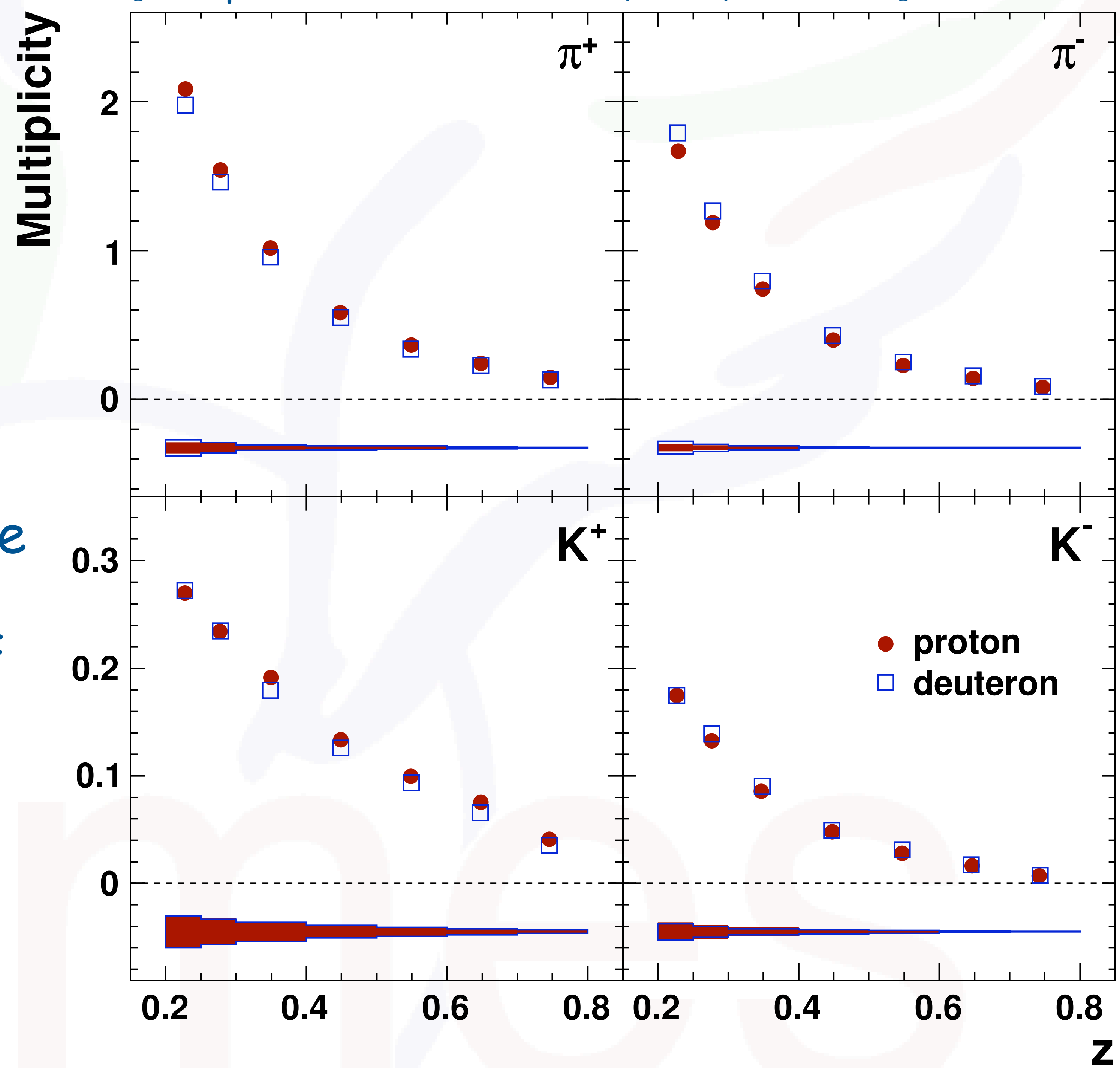


Multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons
  http://www-hermes.desy.de/multiplicities
- extracted in a multi-dimensional unfolding procedure
- access to flavor dependence of fragmentation through different mesons and targets

☛ Helicity VI session

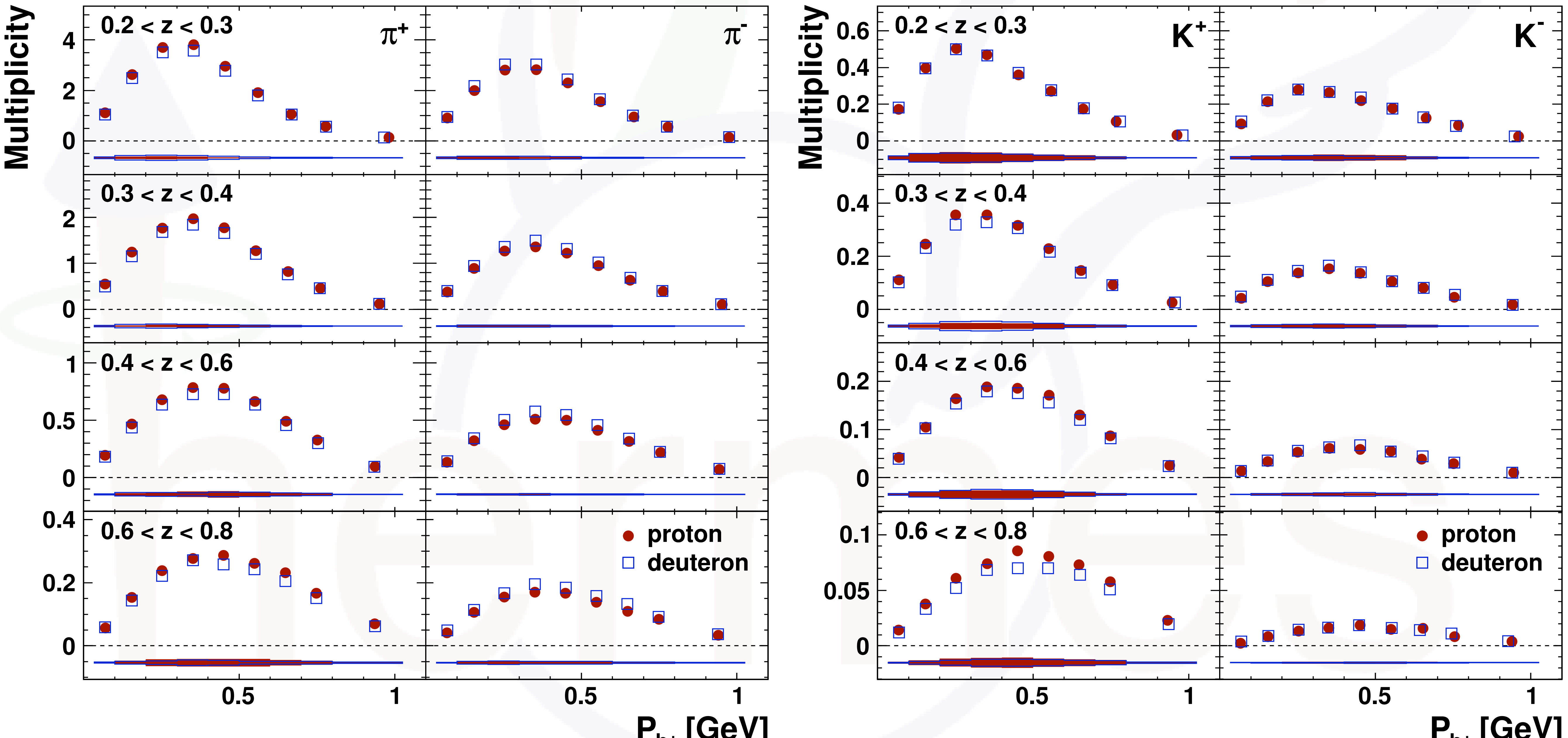
[Airapetian et al., PRD 87 (2013) 074029]



Transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

[Airapetian et al., PRD 87 (2013) 074029]

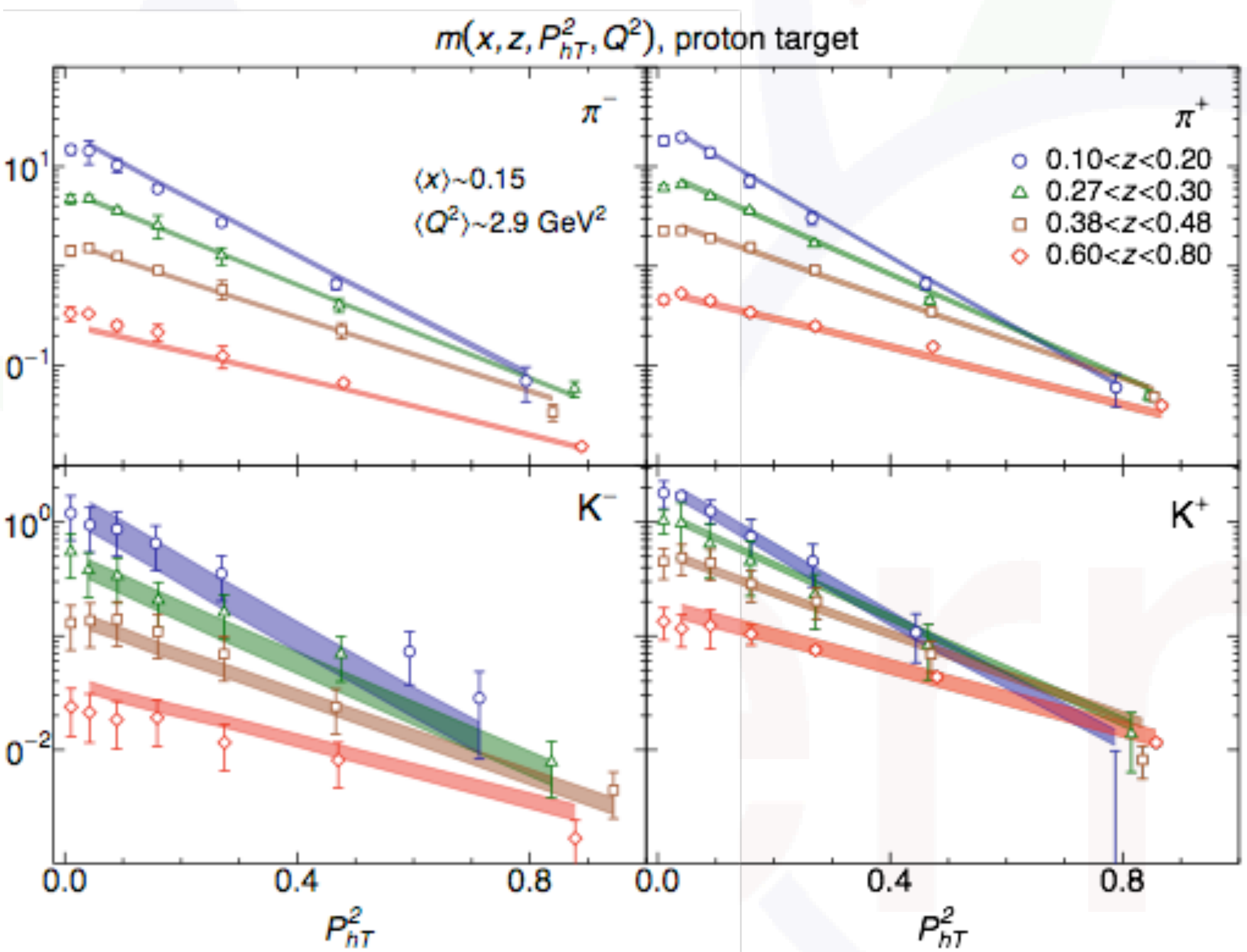


FF TMD flavor dependence

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

- fit to HERMES multiplicity data:

$$m_N^h(x,z,\boldsymbol{P}_{hT}^2;Q^2) = \frac{\pi}{\sum_q e_q^2\, f_1^q(x;Q^2)} \sum_q e_q^2\, f_1^q(x;Q^2)\, D_1^{q\to h}(z;Q^2)\, \frac{e^{-\boldsymbol{P}_{hT}^2/\langle \boldsymbol{P}_{hT,q}^2\rangle}}{\pi\langle \boldsymbol{P}_{hT,q}^2\rangle}$$



$$f_1^q(x,\boldsymbol{k}_\perp^2;Q^2) = f_1^q(x;Q^2)\, \frac{e^{-\boldsymbol{k}_\perp^2/\langle \boldsymbol{k}_{\perp,q}^2\rangle}}{\pi\langle \boldsymbol{k}_{\perp,q}^2\rangle}$$

$$D_1^{q\to h}(z,\boldsymbol{P}_\perp^2;Q^2) = D_1^{q\to h}(z;Q^2)\, \frac{e^{-\boldsymbol{P}_\perp^2/\langle \boldsymbol{P}_{\perp,q\to h}^2\rangle}}{\pi\langle \boldsymbol{P}_{\perp,q\to h}^2\rangle}$$

$$\langle \boldsymbol{P}_{hT,q}^2\rangle = z^2\langle \boldsymbol{k}_{\perp,q}^2\rangle + \langle \boldsymbol{P}_{\perp,q\to h}^2\rangle$$

[A. Signori, A. Bacchetta, M. Radici and GS, JHEP 11(2013)194]

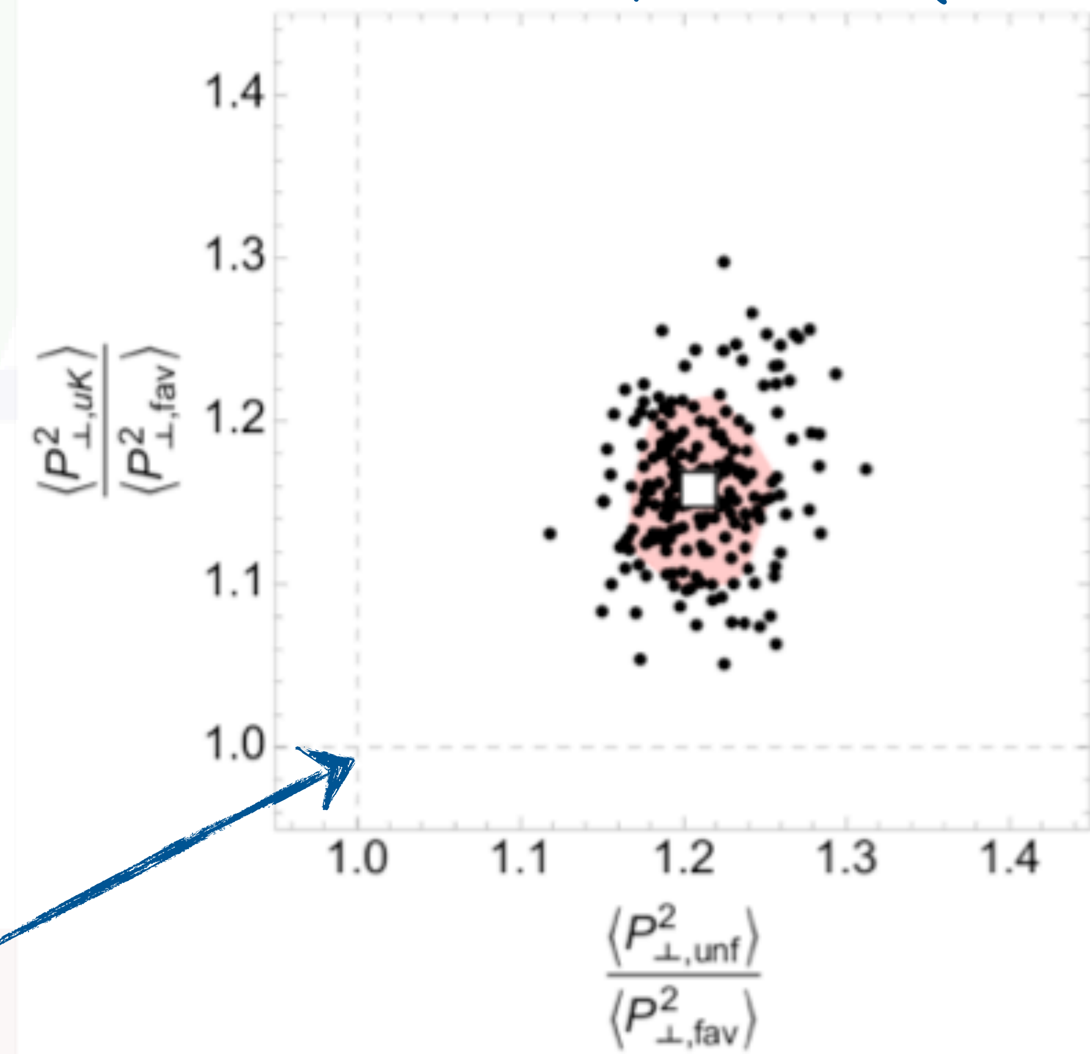
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

FF TMD flavor dependence

- fit to HERMES multiplicity data:

[A. Signori, A. Bacchetta, M. Radici and GS, JHEP 11(2013)194]

q→π favored width
<
q→K favored width



point of
no flavor dep.

q→π favored width < unfavored

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

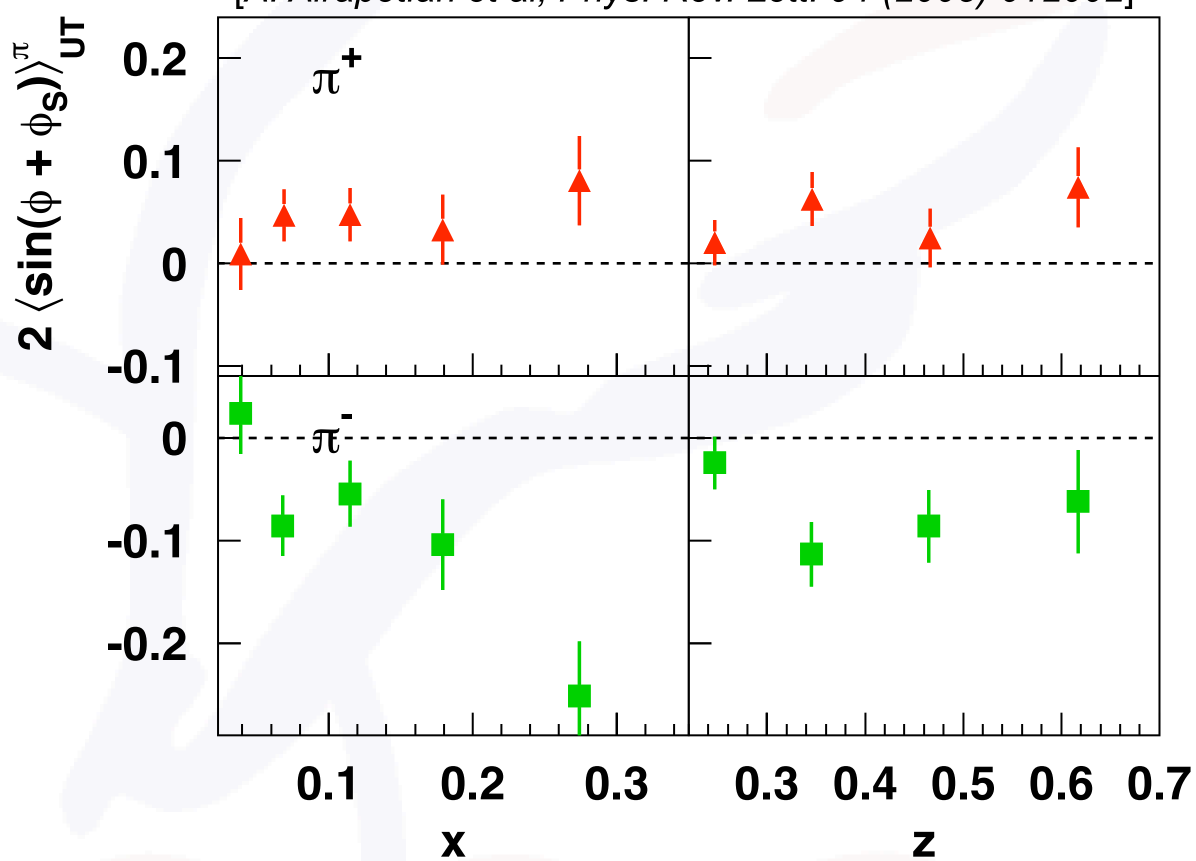
Transversely polarized quarks?

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

Transversely polarized quarks?

- transverse polarization of quarks leads to large effects!

[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

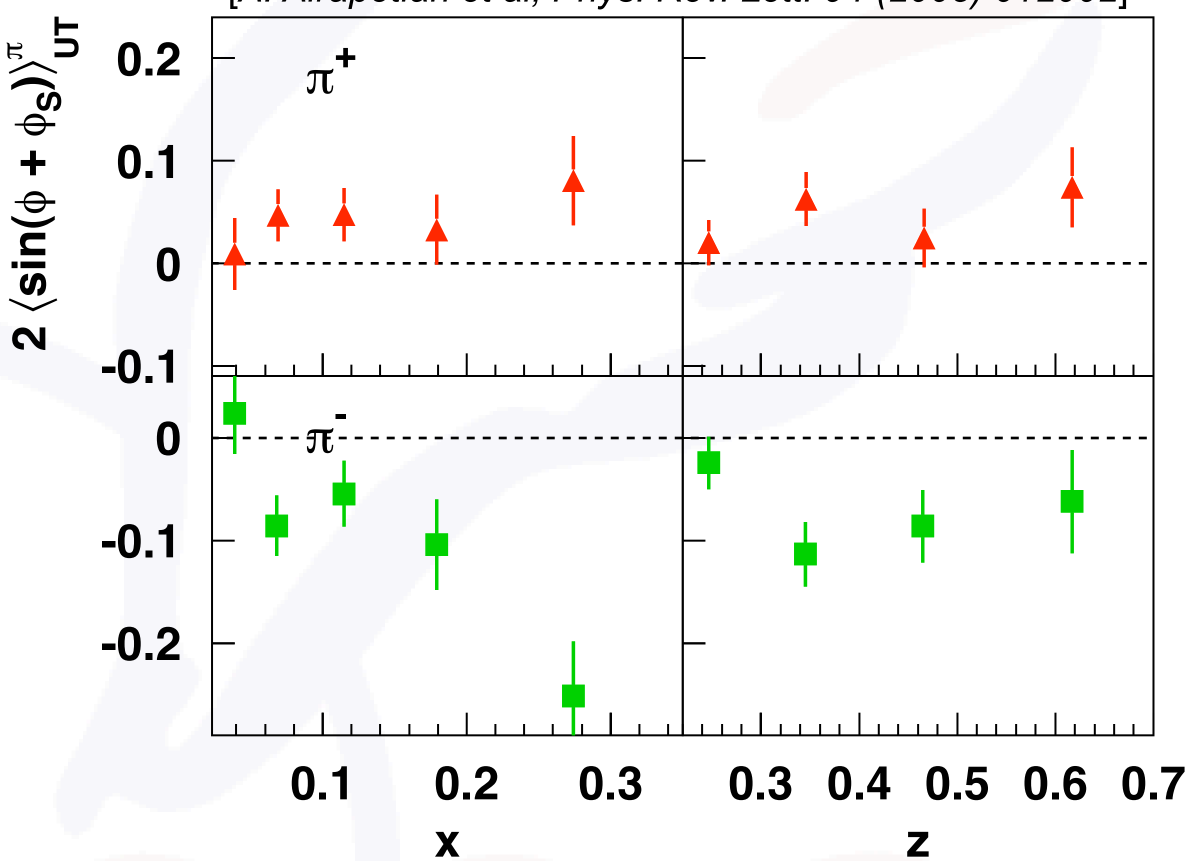
Non-zero transversity
Non-zero Collins function

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

Transversely polarized quarks?

- transverse polarization of quarks leads to large effects!
- opposite in sign for charged pions

[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



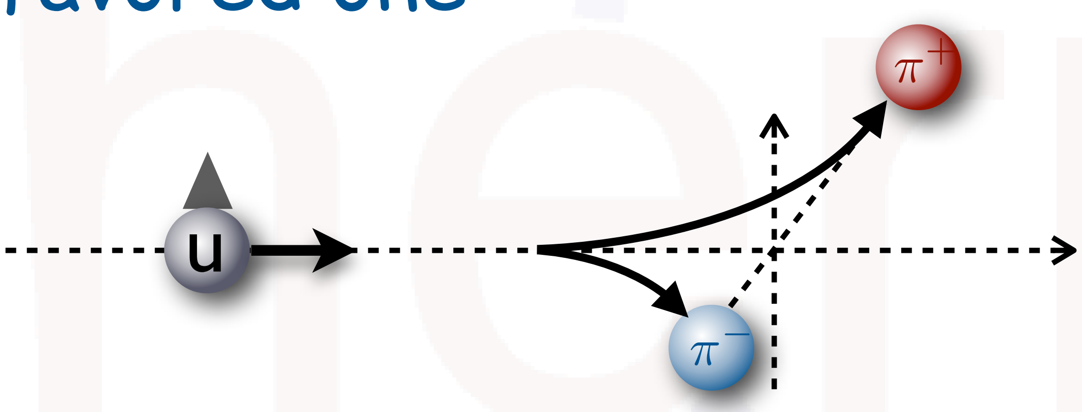
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

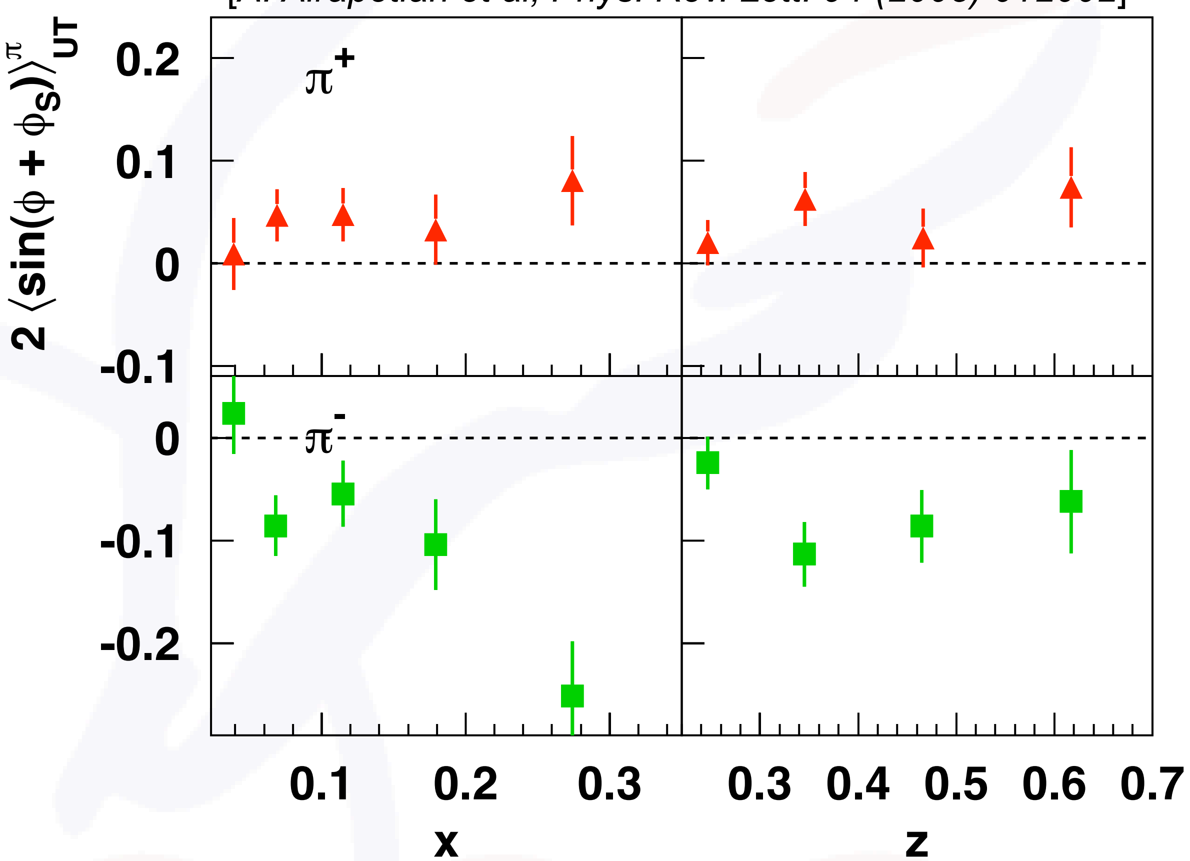
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversely polarized quarks?

- transverse polarization of quarks leads to large effects!
- opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one



[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

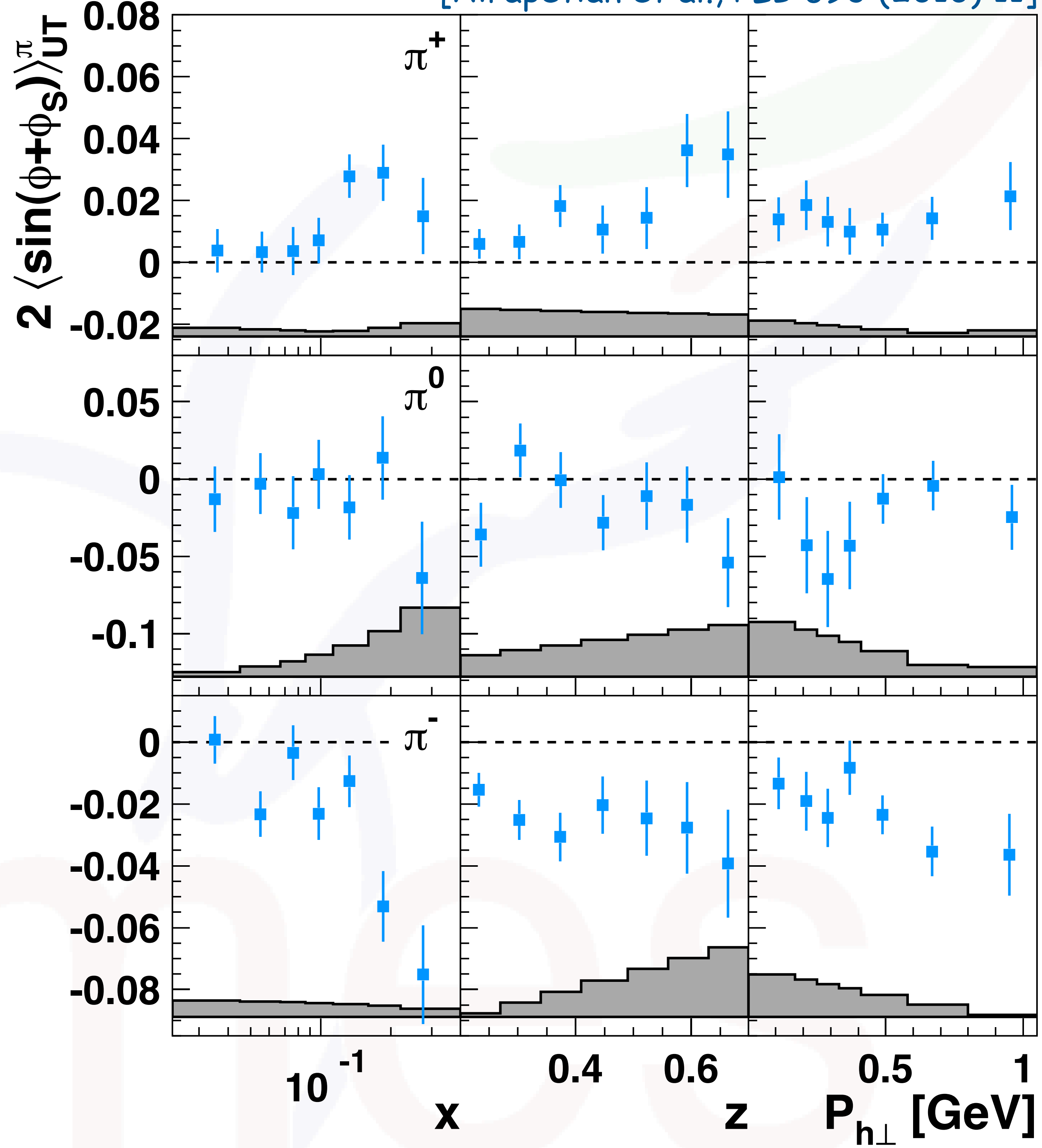
Non-zero transversity
Non-zero Collins function

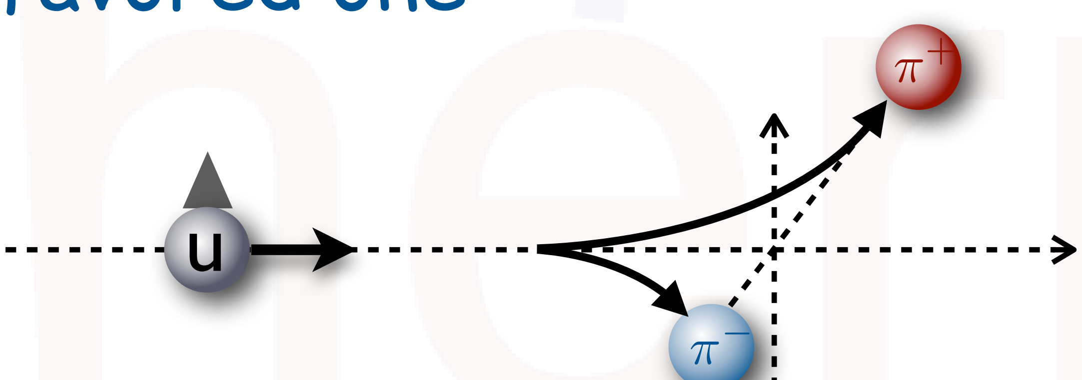
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversely polarized quarks?

- transverse polarization of quarks leads to large effects!
- opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one

[Airapetian et al., PLB 693 (2010) 11]

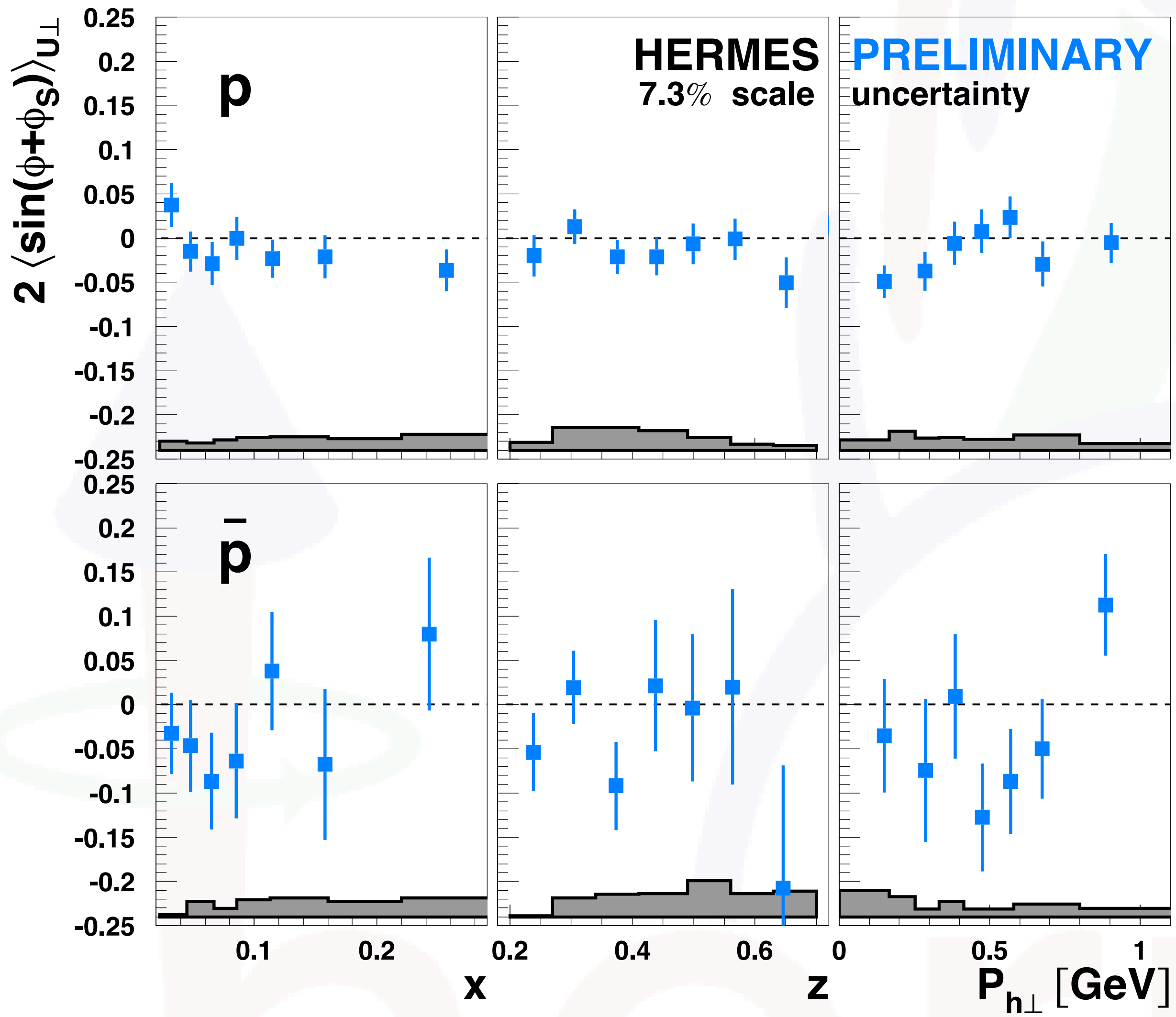


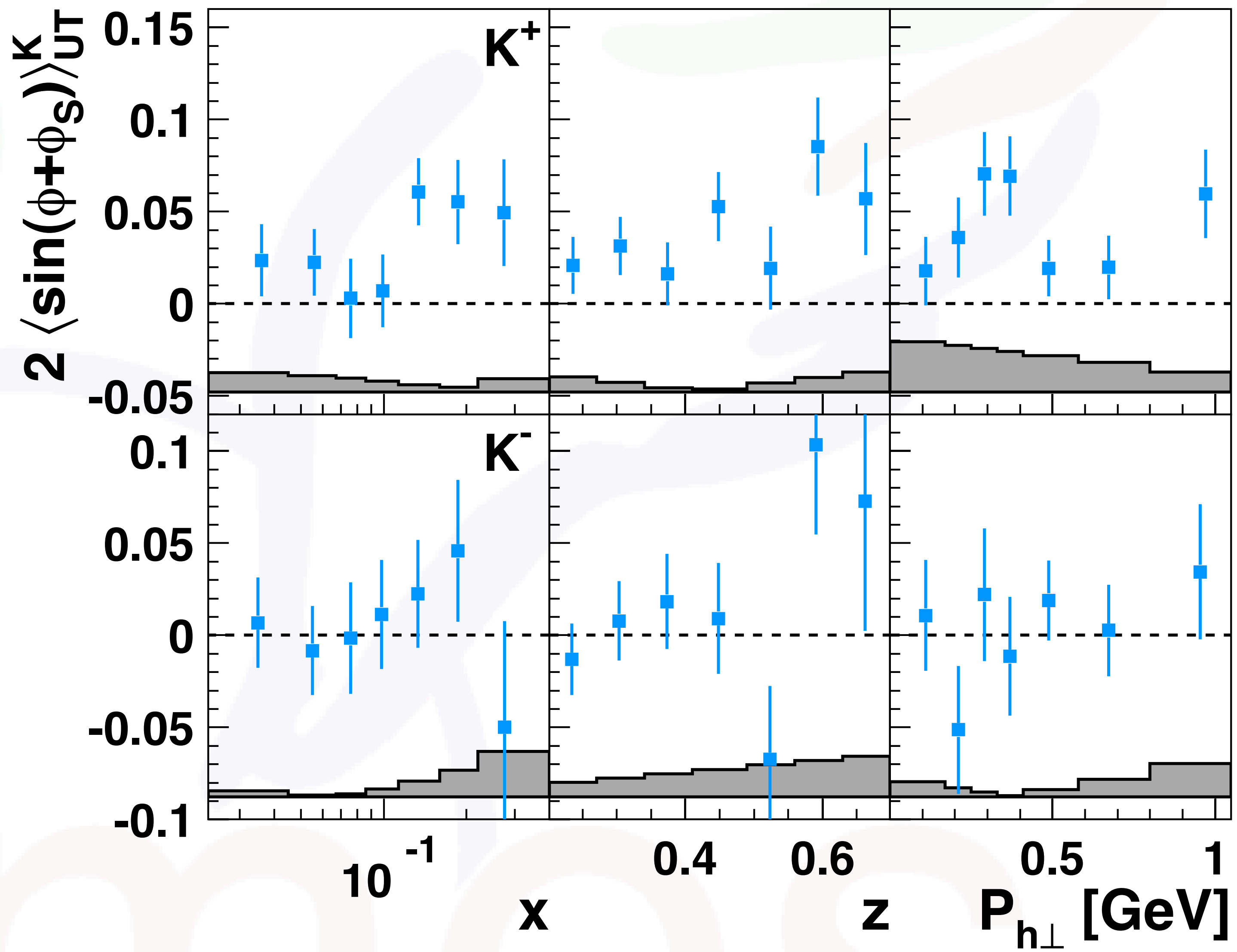


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins effect for kaons and (anti) protons

[Airapetian et al., PLB 693 (2010) 11]



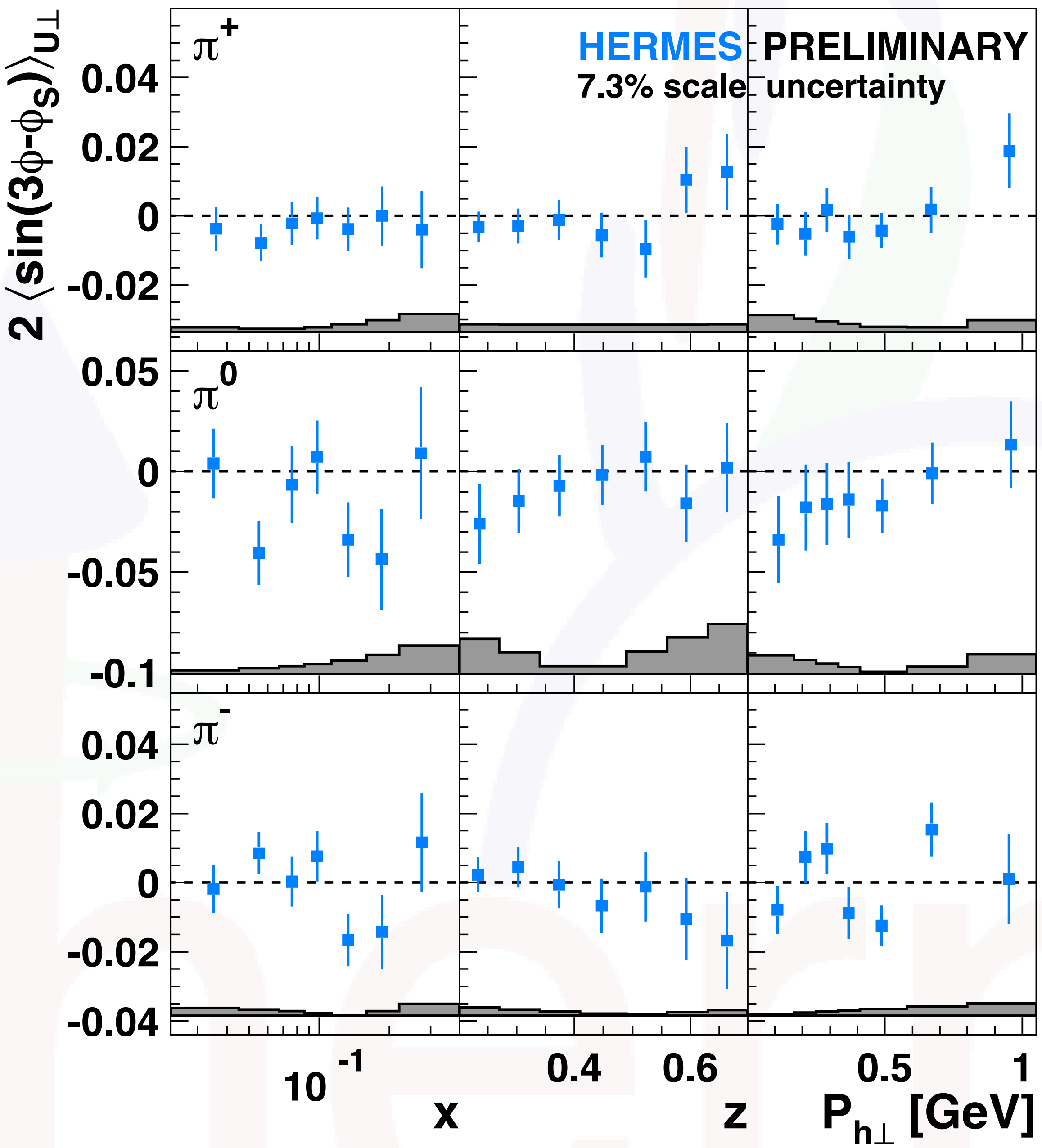


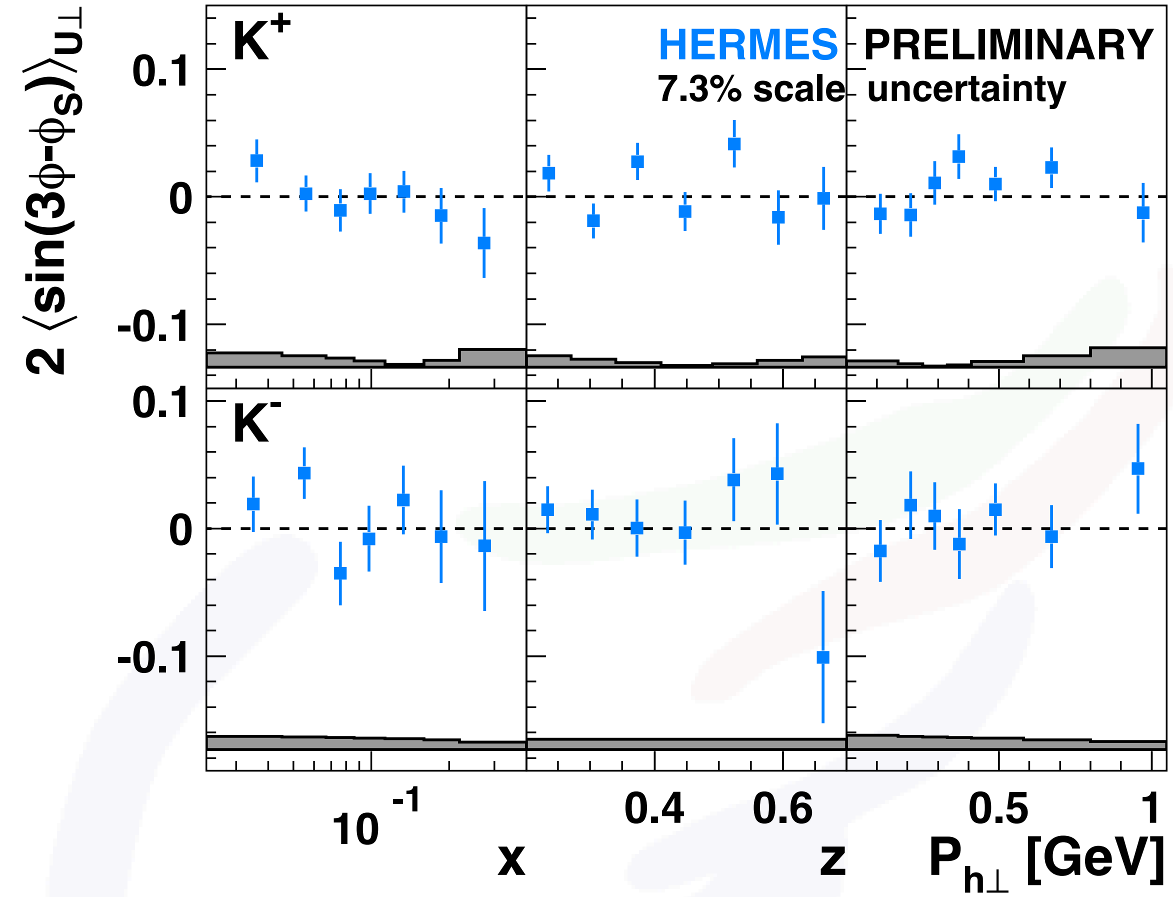
- positive Collins SSA amplitude for positive kaons
- consistent with zero for negative kaons and (anti)protons

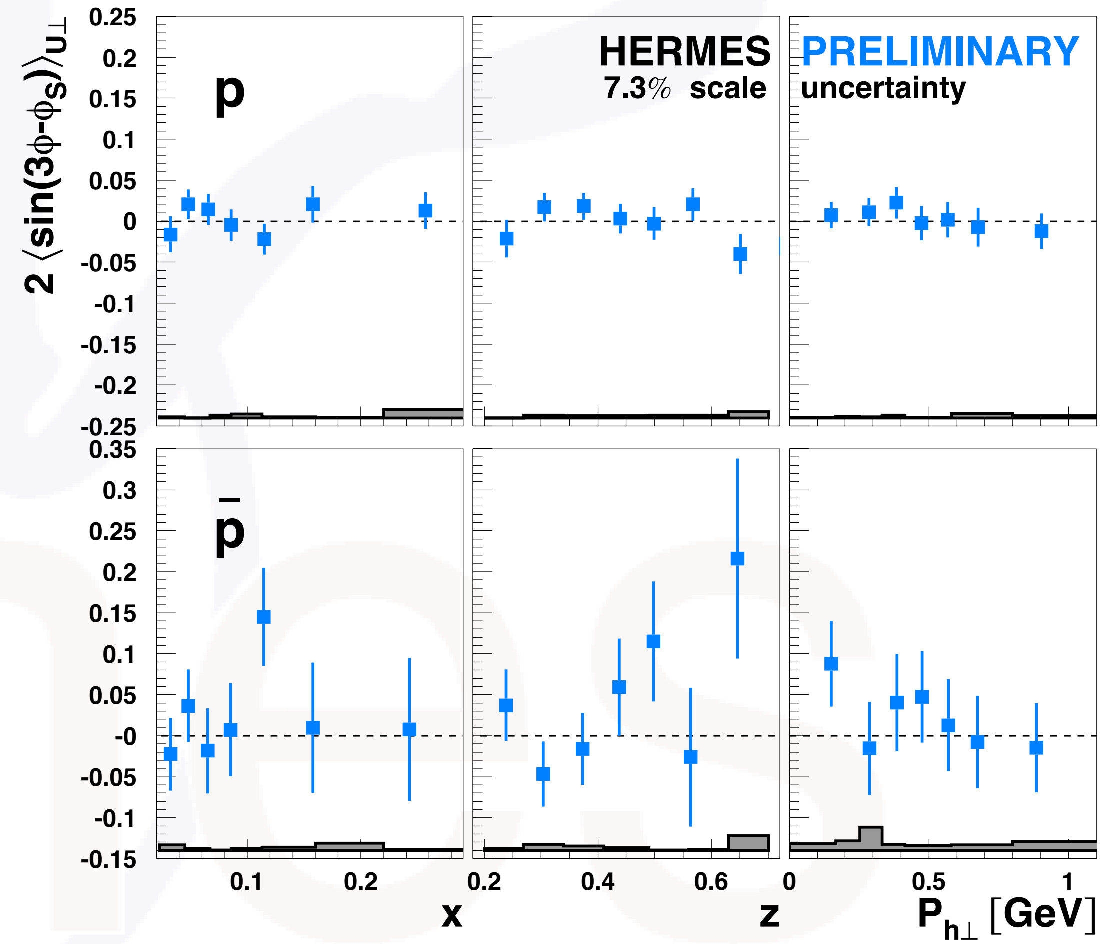
➡vanishing sea-quark transversity and baryon Collins effect?

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

Pretzelosity?

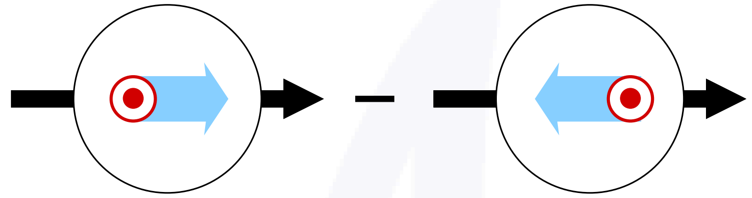






- consistent with zero; but suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Collins)

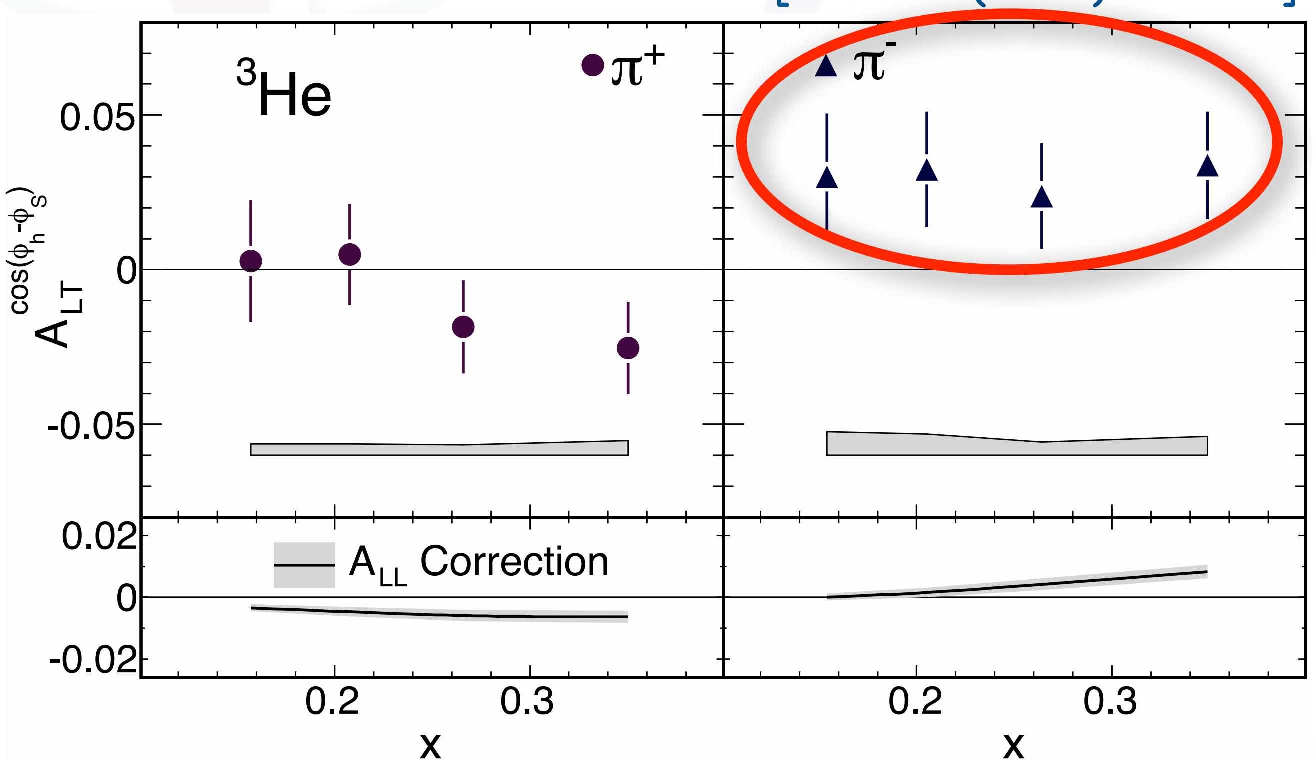
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

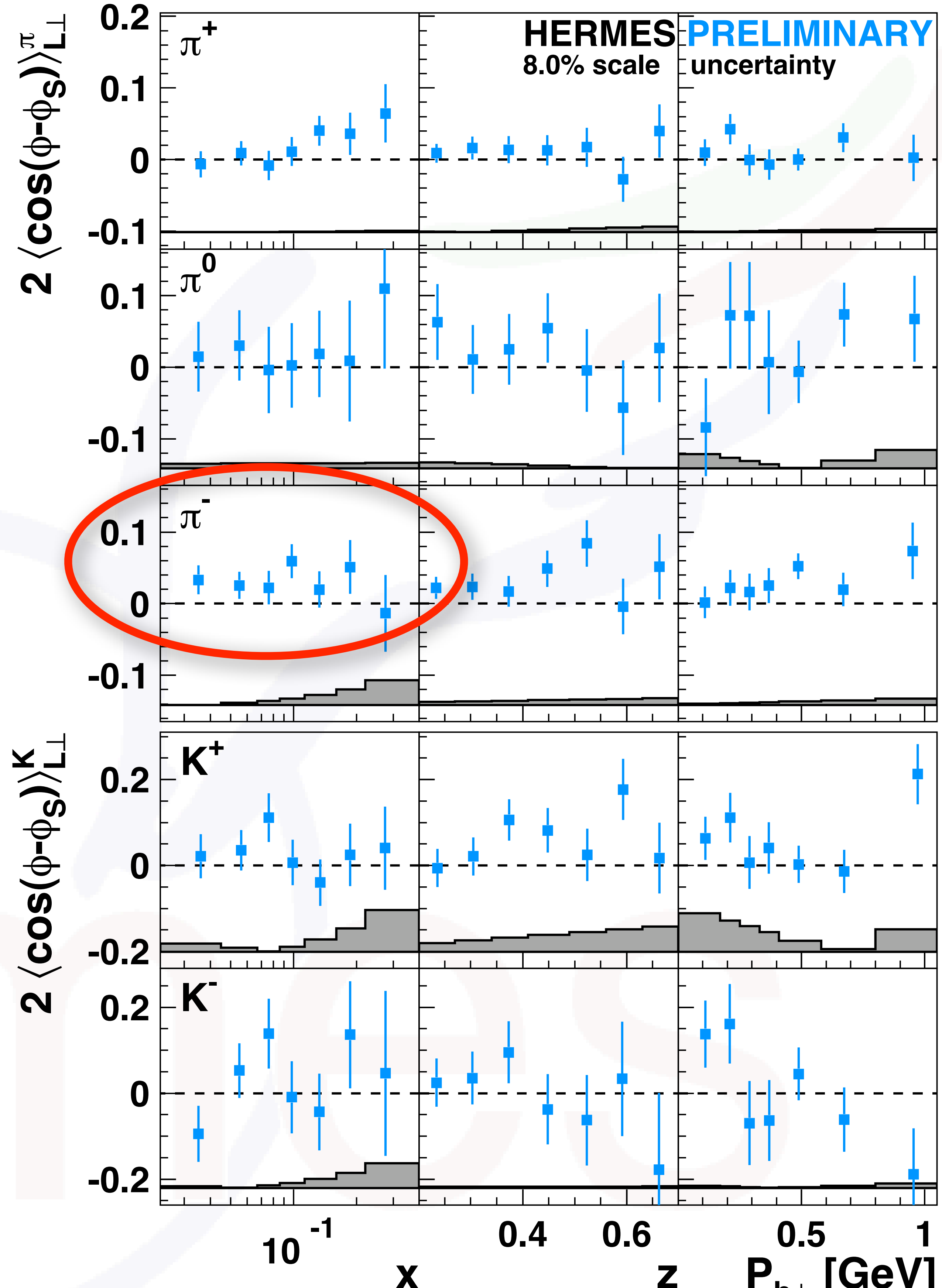


Worm-Gear

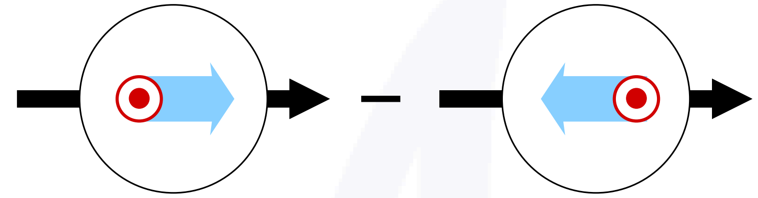
- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES

[PRL 108 (2012) 052001]



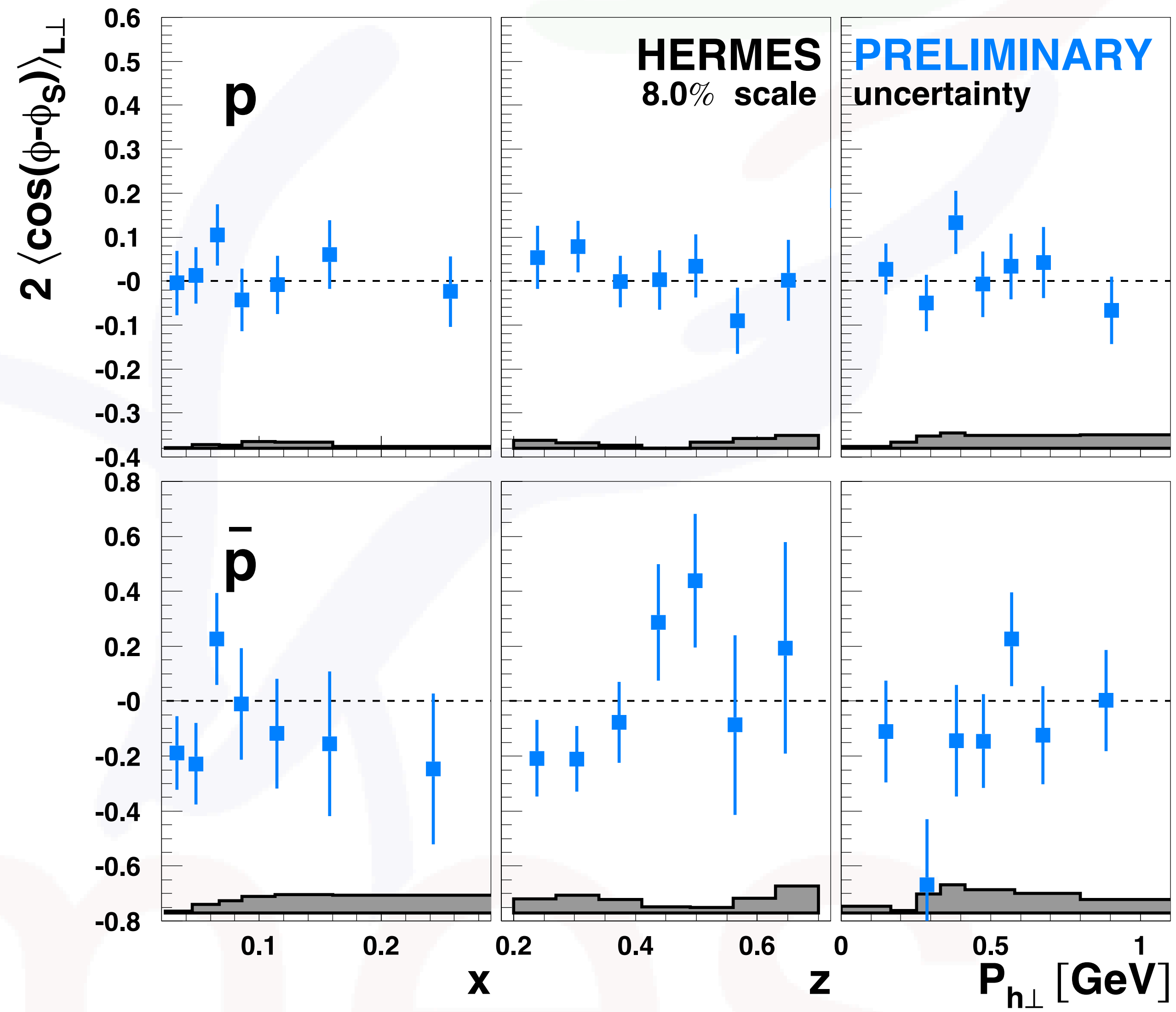


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



Worm-Gear

- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES
- results for protons and anti-protons consistent with zero

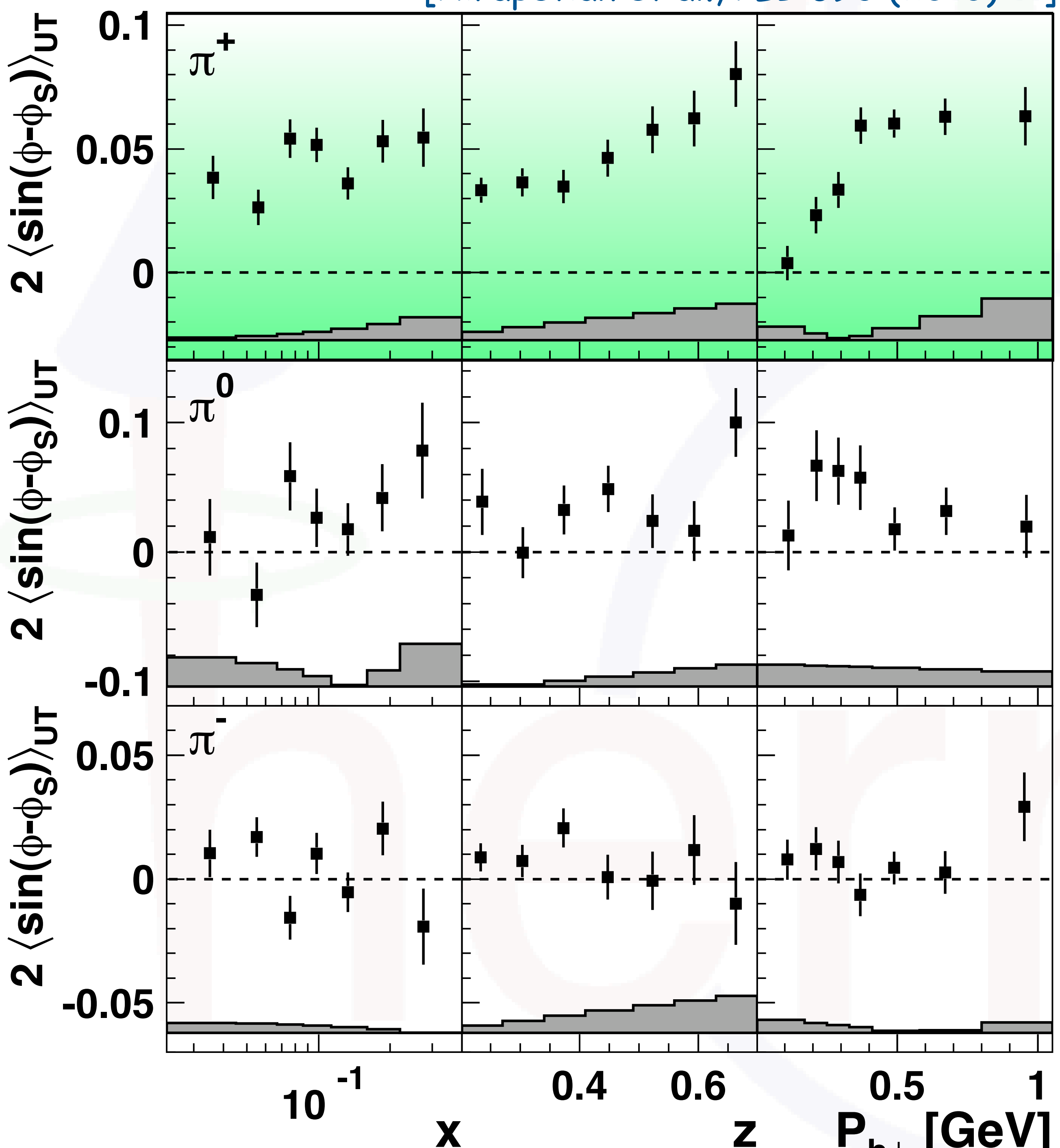


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes for pions

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

[Airapetian et al., PLB 693 (2010) 11]

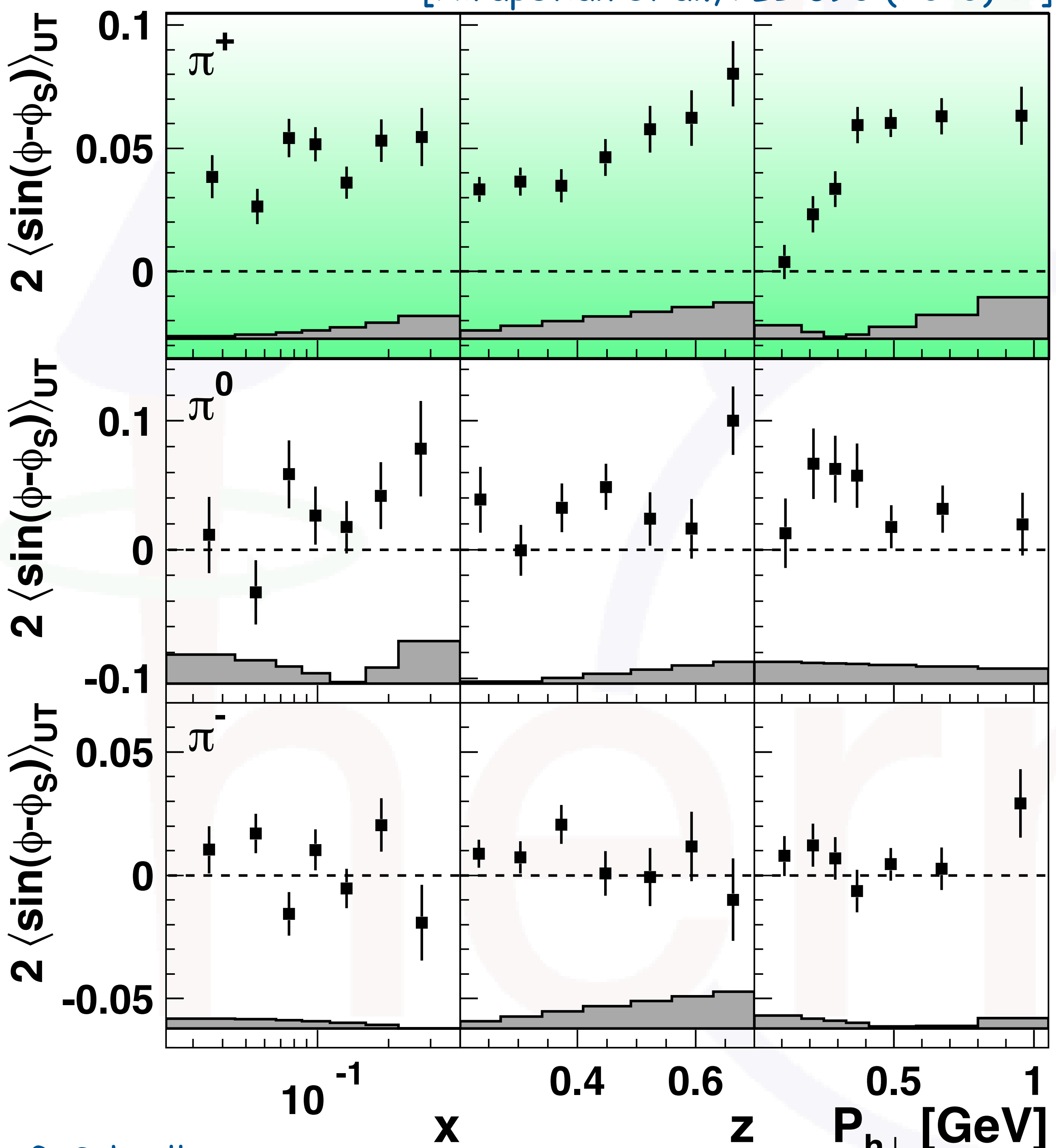


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

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

[Airapetian et al., PLB 693 (2010) 11]



π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1\rm T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

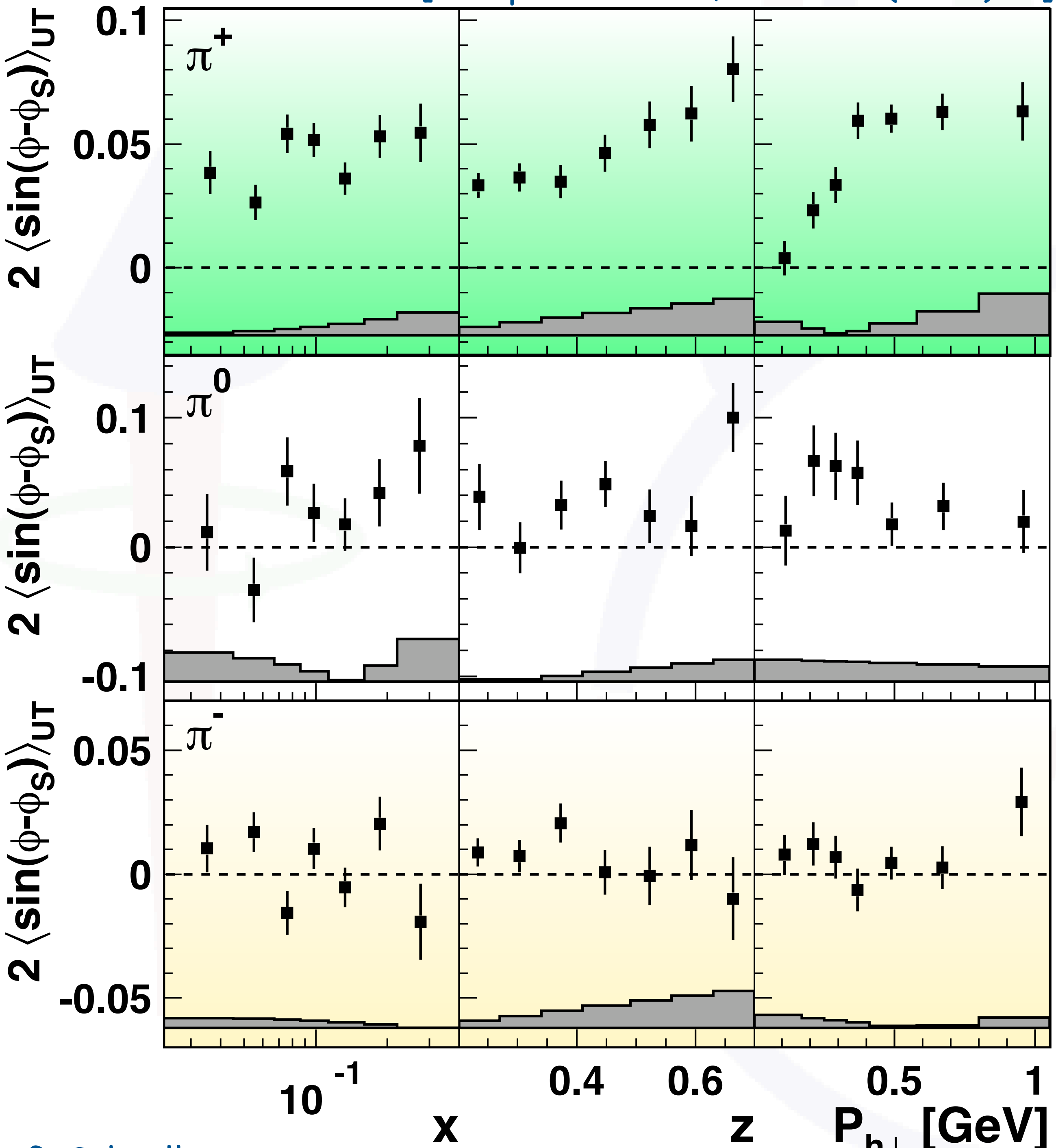
☛ **u-quark Sivers DF < 0**

	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

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

[Airapetian et al., PLB 693 (2010) 11]



π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{\rm 1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

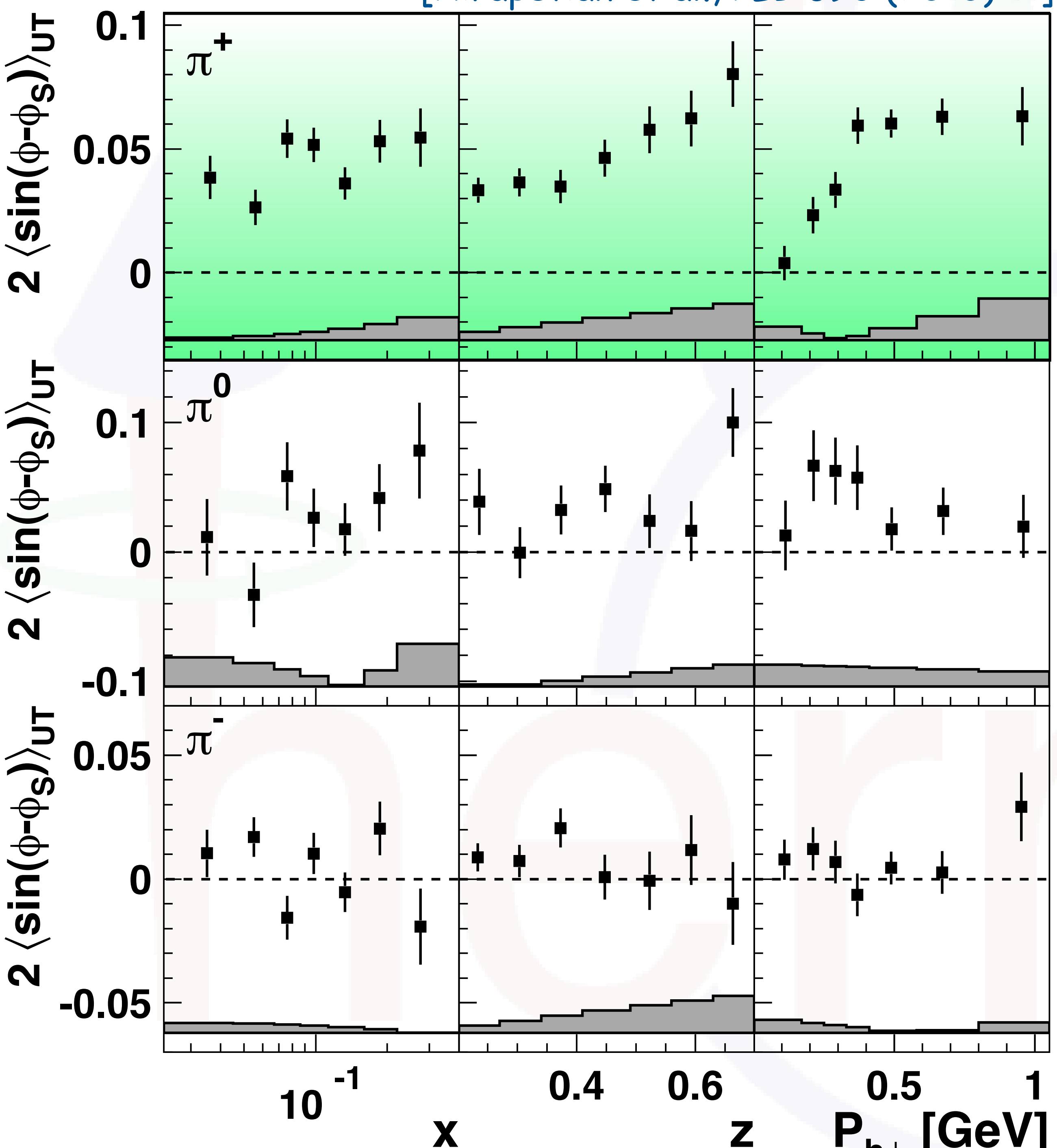
☛ d-quark Sivers DF > 0 (cancelation for π^-)

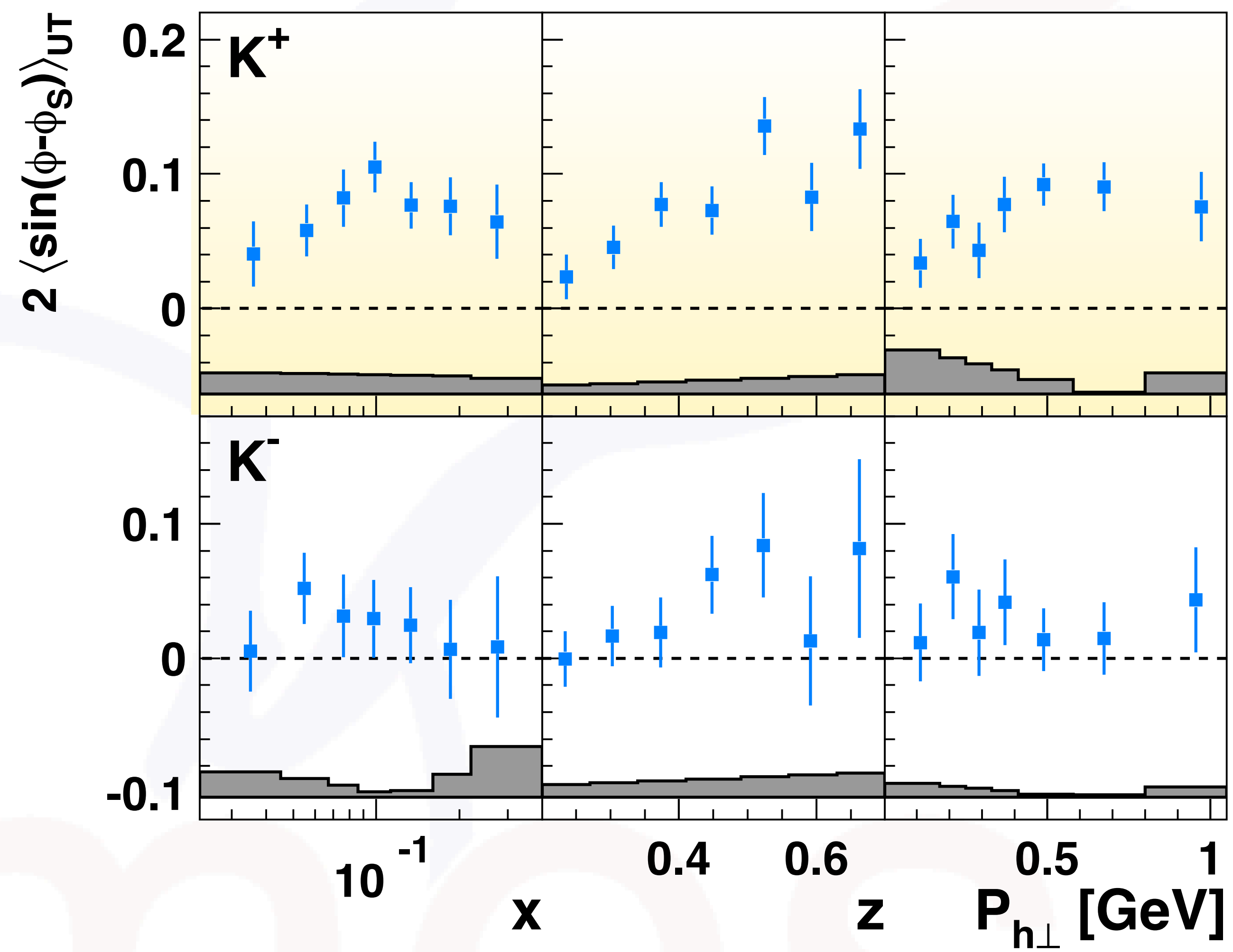
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes for mesons

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

[Airapetian et al., PLB 693 (2010) 11]





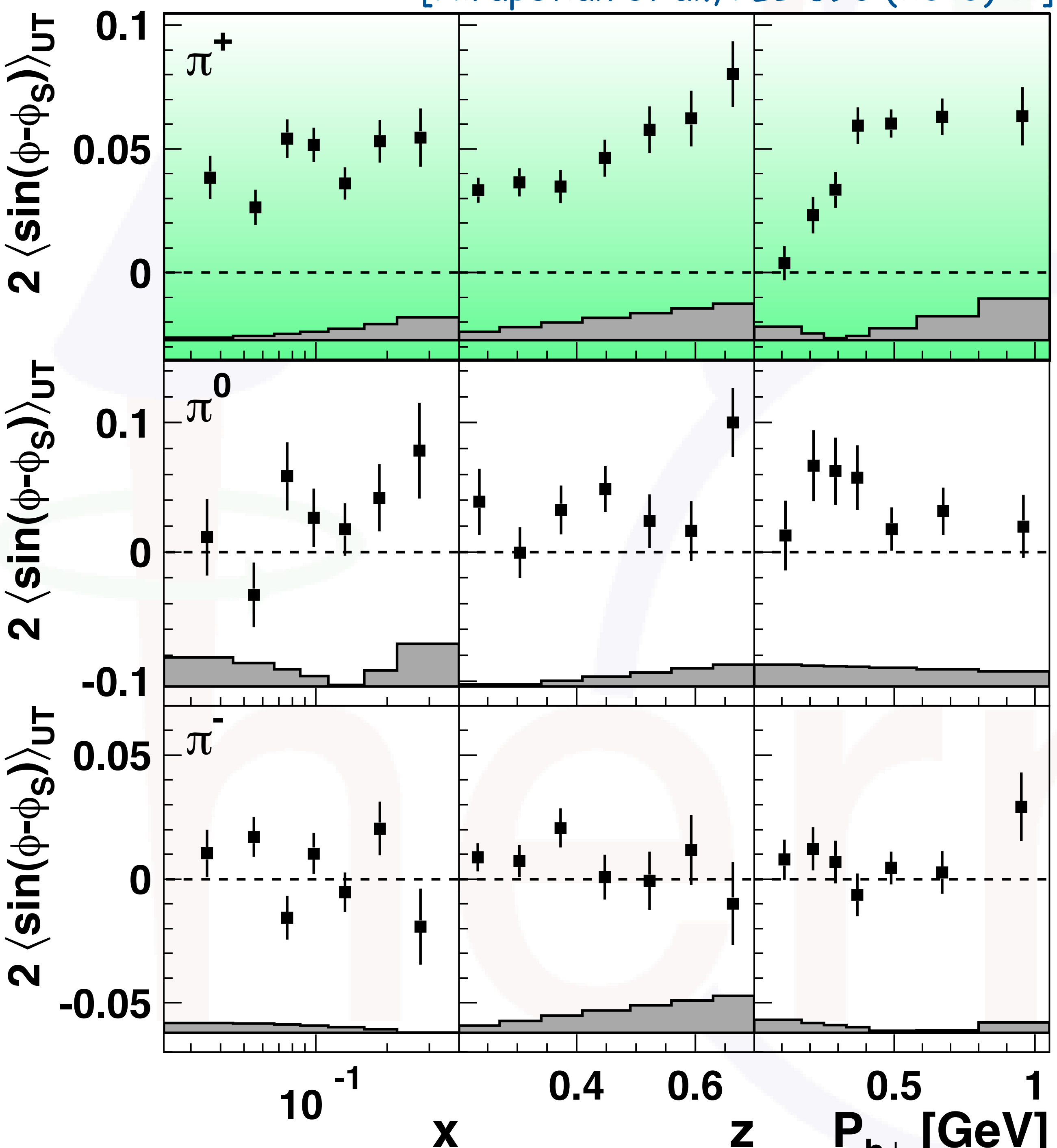
☛ larger amplitudes for positive kaons vs. pions

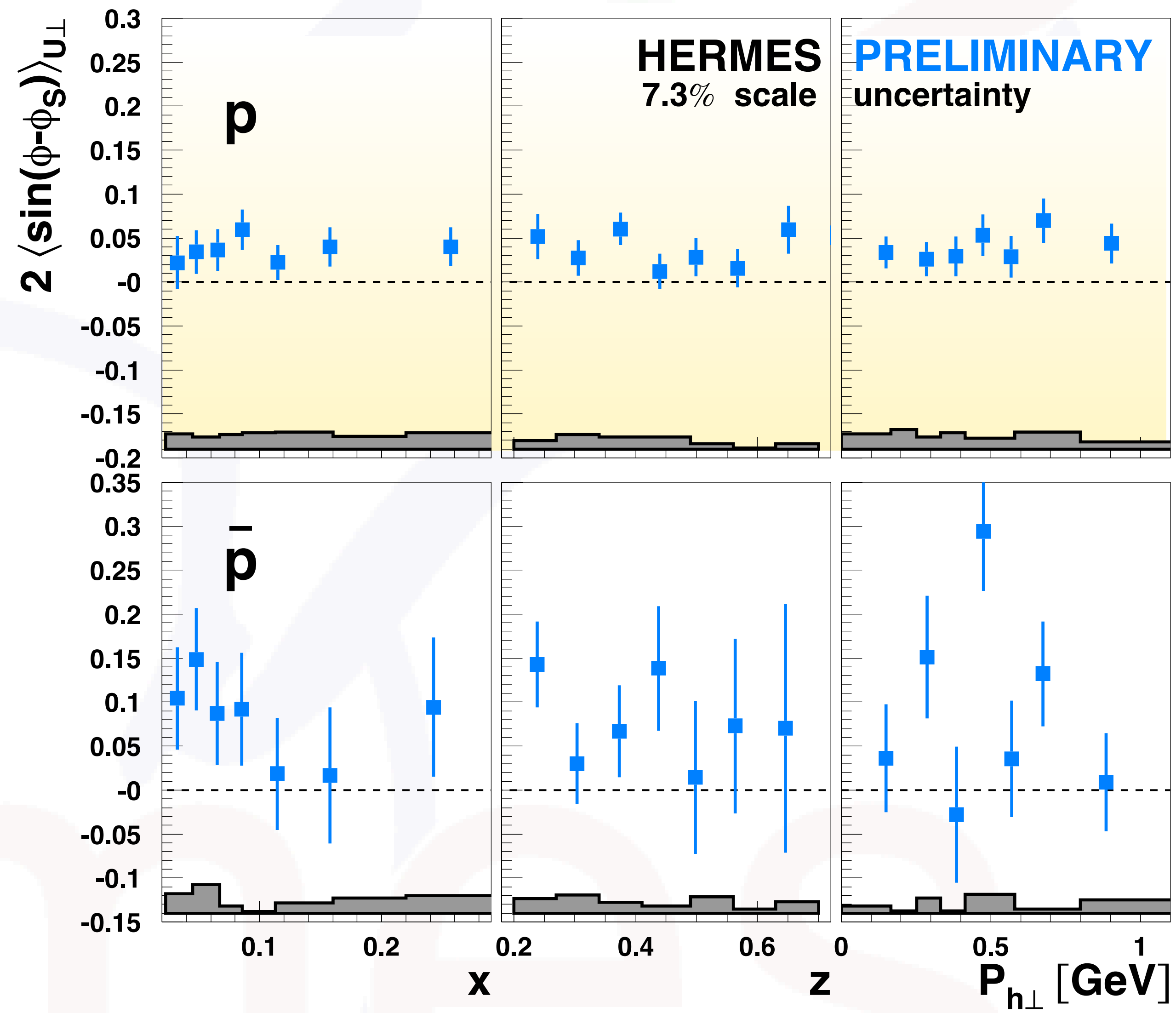
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for baryons

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

[Airapetian et al., PLB 693 (2010) 11]

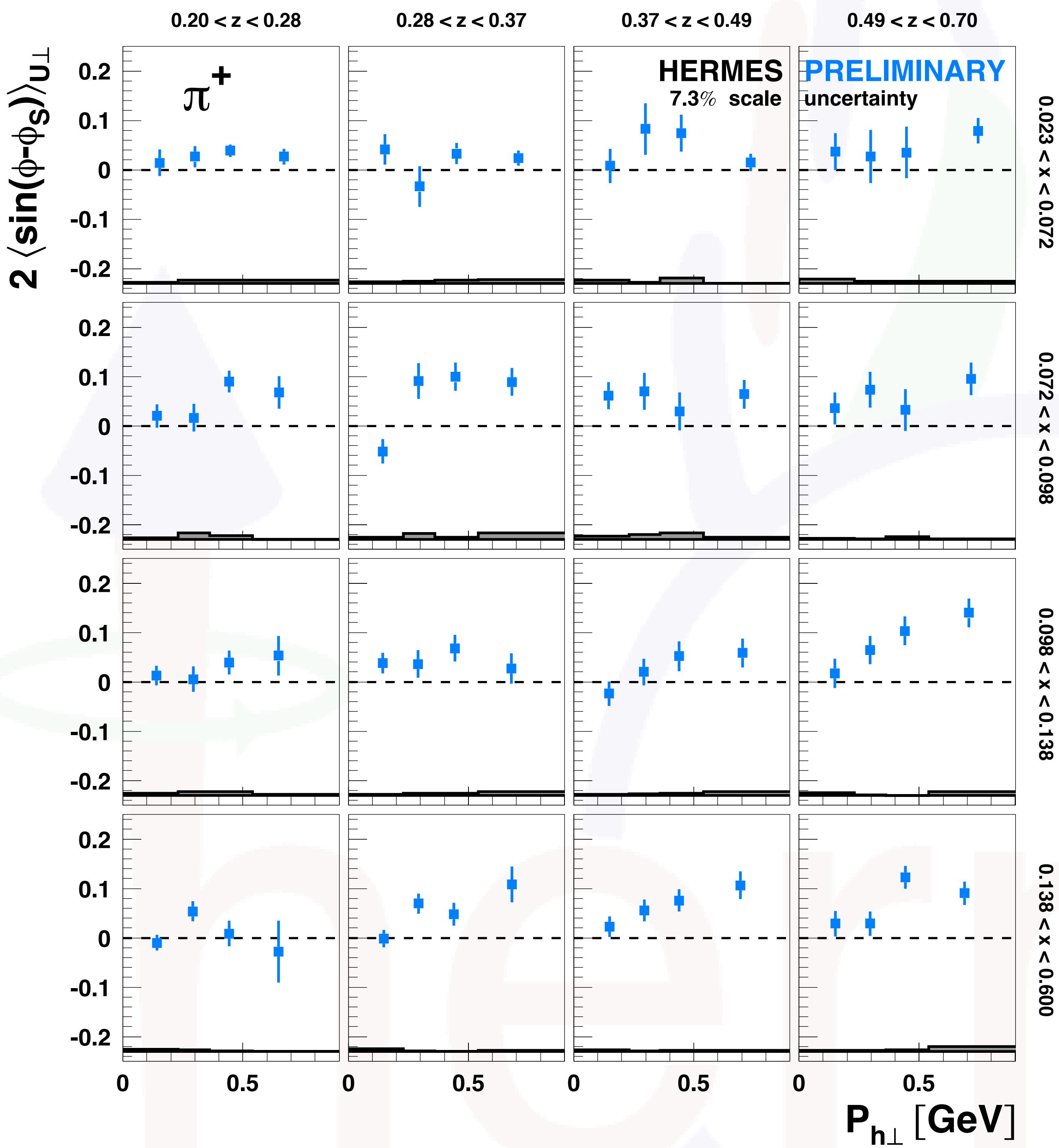




similar amplitudes for positive pions and protons ☛ u-quark dominance (and not a FF effect)?

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

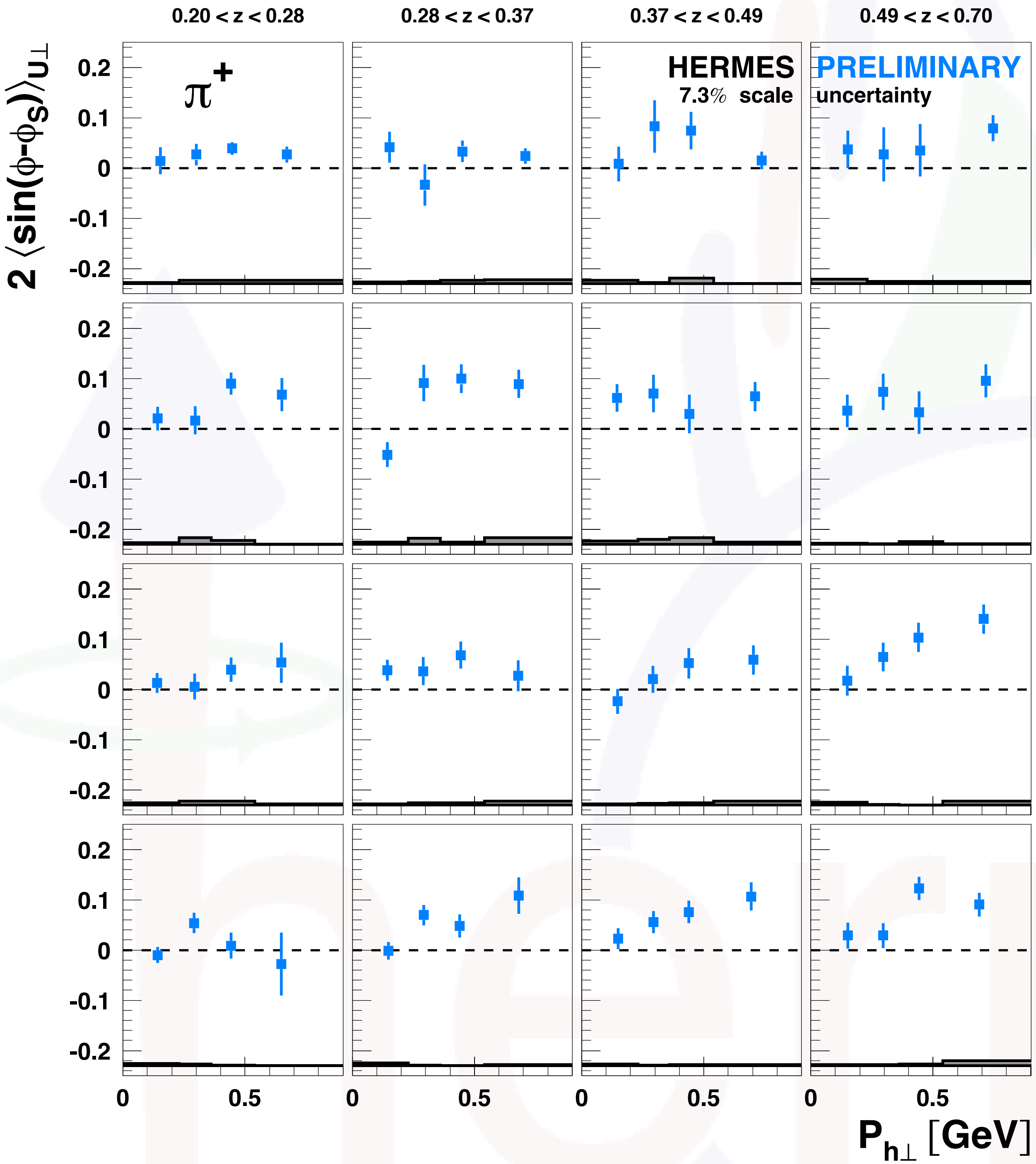
Sivers amplitudes - 3d binning

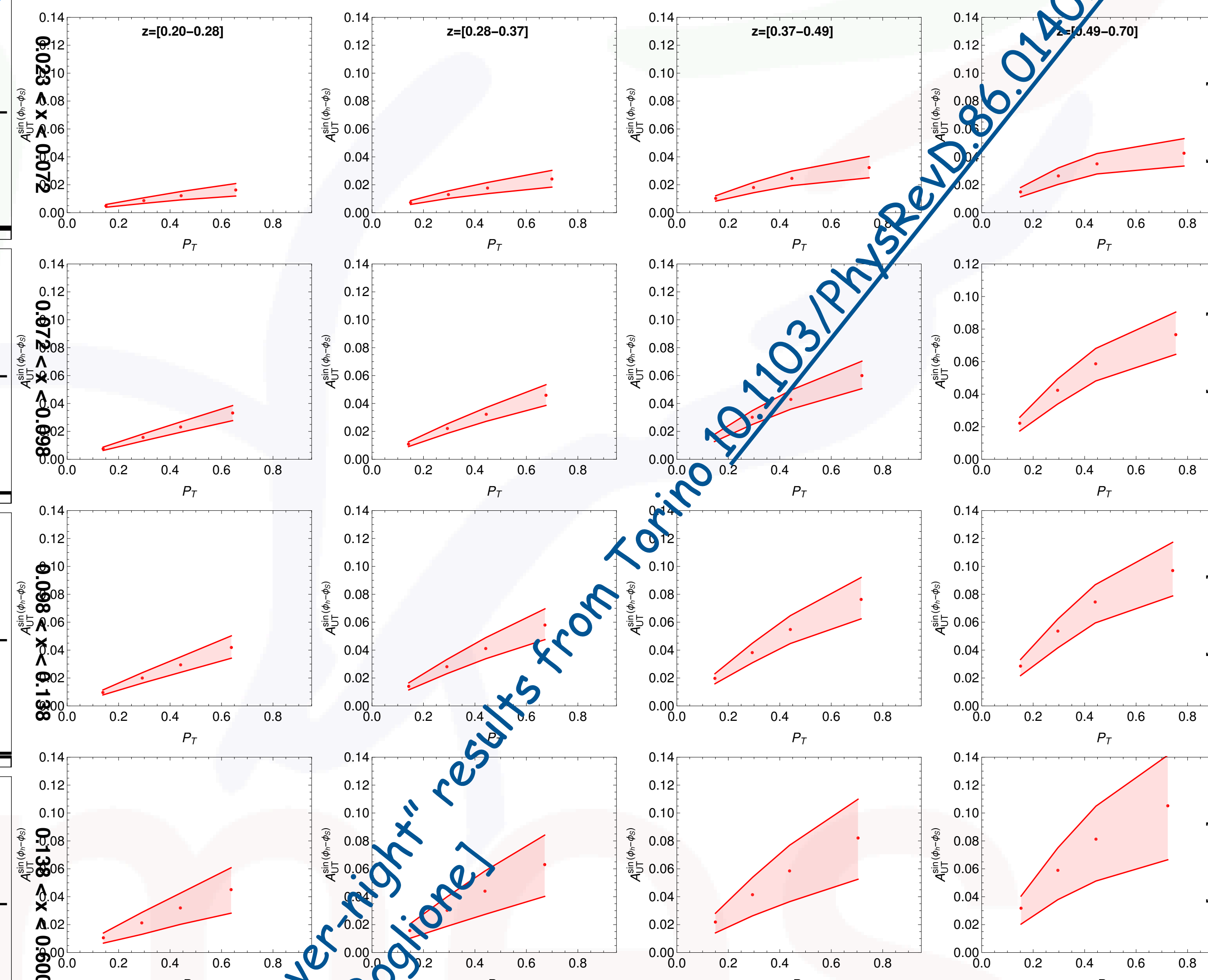


- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- disentangle correlations
- isolate phase-space region with strong signal strength
- allows more detailed comparison with calculations (e.g., unofficial "over-night" results from Torino 10.1103/PhysRevD.86.014028 fit - courtesy M. Boglione)

Sivers amplitudes - 3d binning

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



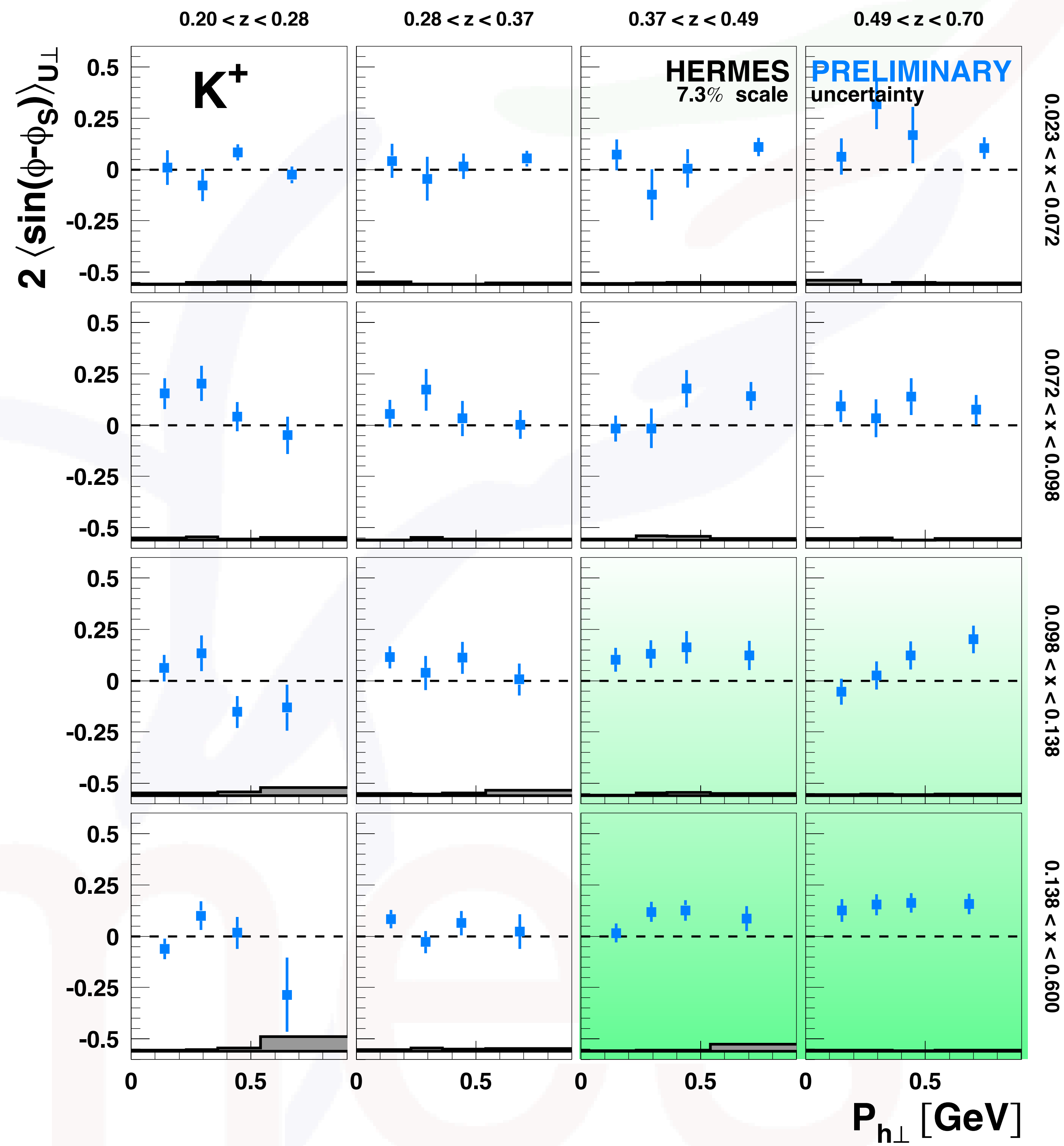


[unofficial "over-right" results from Torino 10.1103/PhysRevD.86.014028 fit - courtesy M. Boglione]

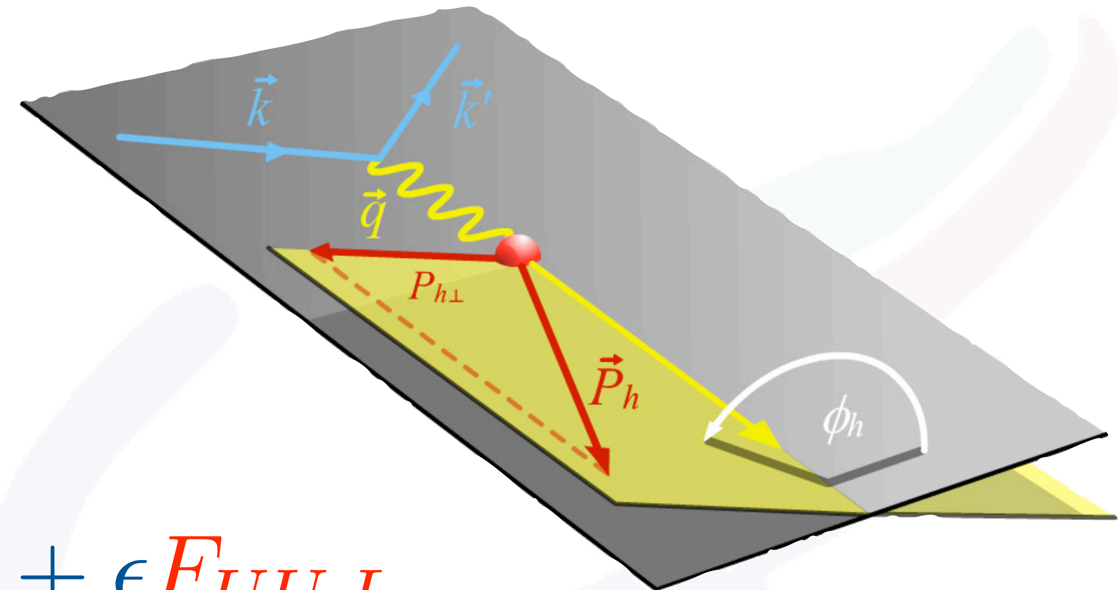
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes - 3d binning

- large K+ amplitudes O(20%) seen at large values of (x, z)
- region of purest "u-quark probe"



Cross section without polarization



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

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

target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

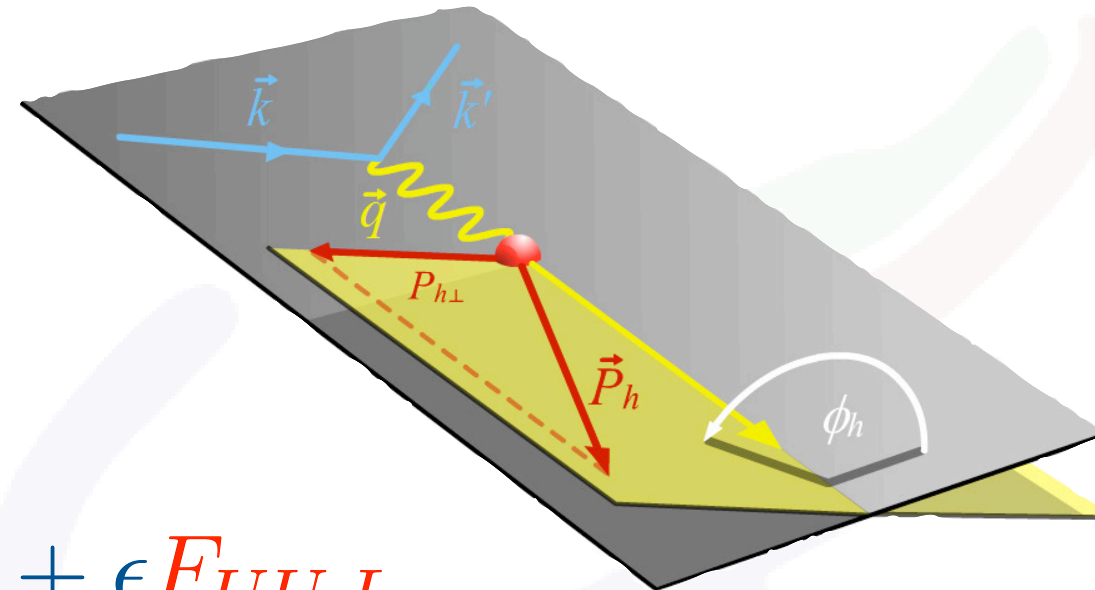
beam polarization; virtual-photon polarization

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

Cross section without polarization



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

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

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp\right]$$

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\;h_1^\perp H_1^\perp-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\;f_1 D_1+\ldots\right]$$

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

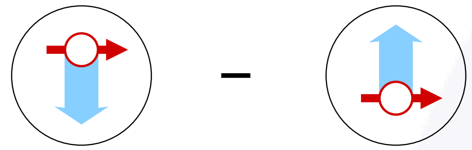
(Implicit sum over quark flavours)

$$\gamma=\frac{2Mx}{Q}$$

$$\varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

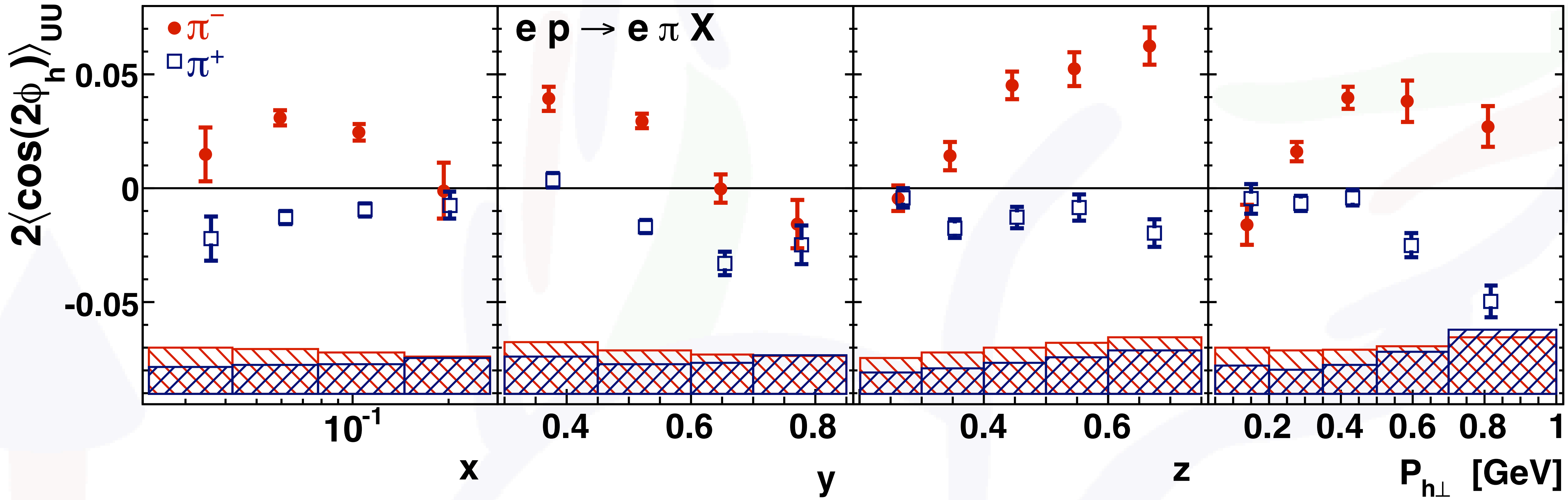
[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

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

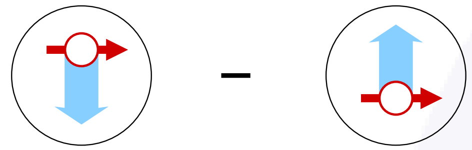


signs of Boer-Mulders

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

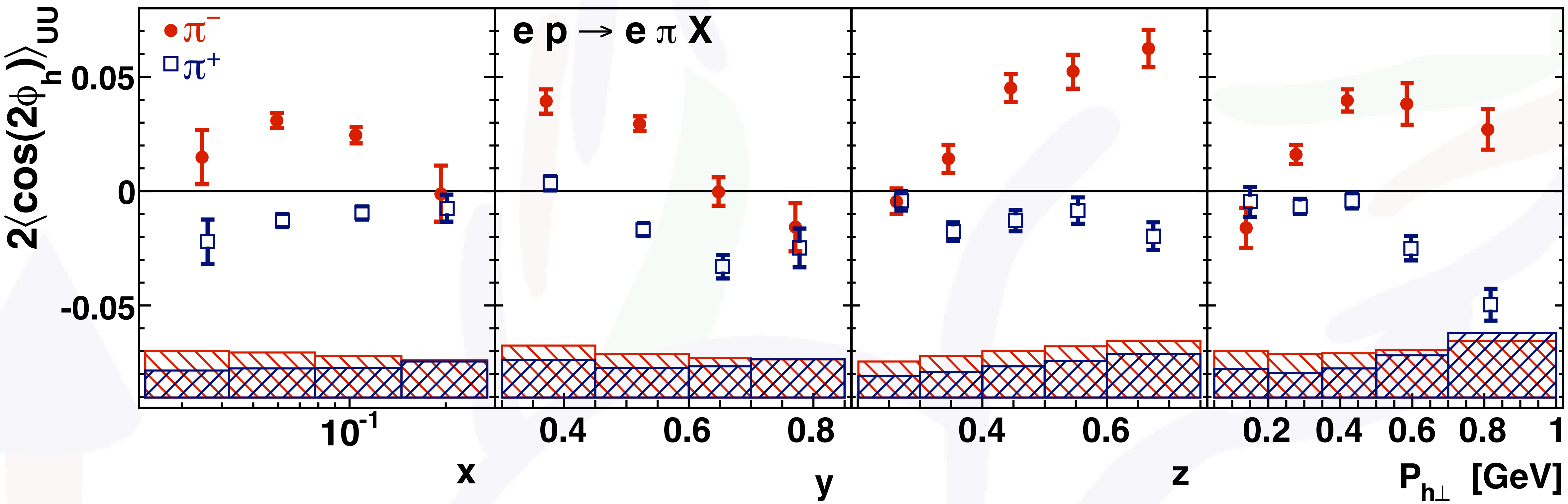


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



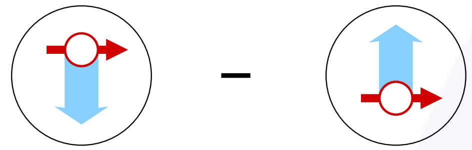
signs of Boer-Mulders

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



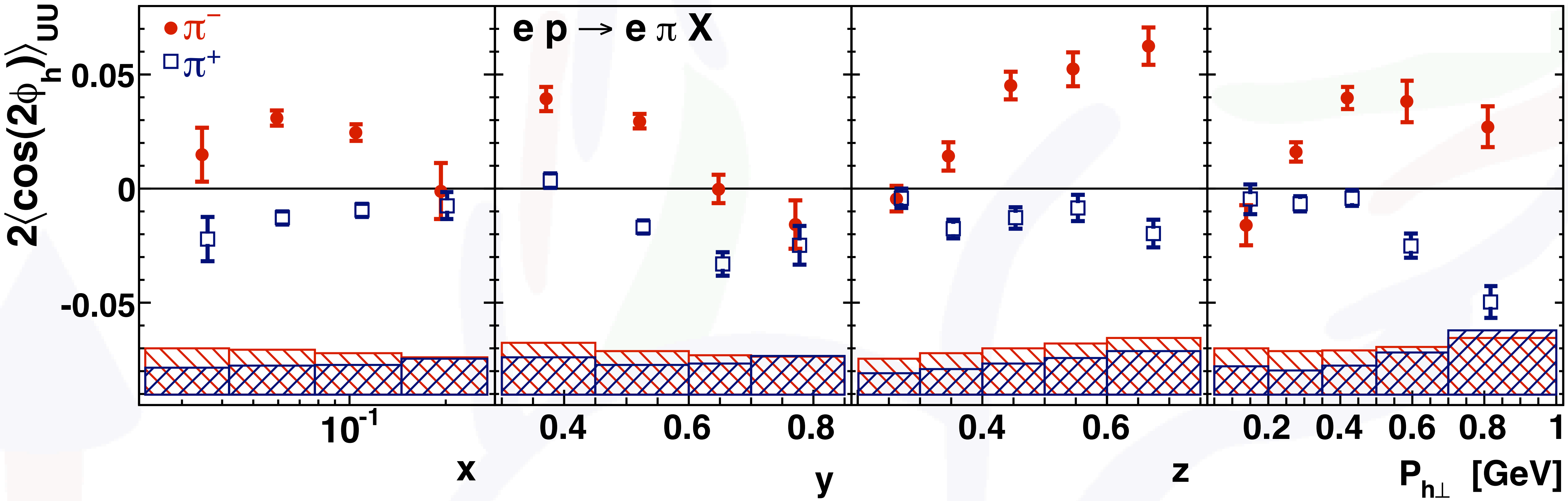
- modulations are not zero!

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



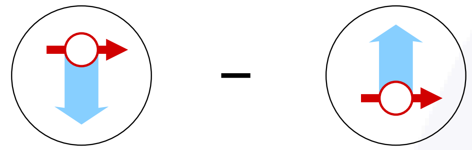
signs of Boer-Mulders

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



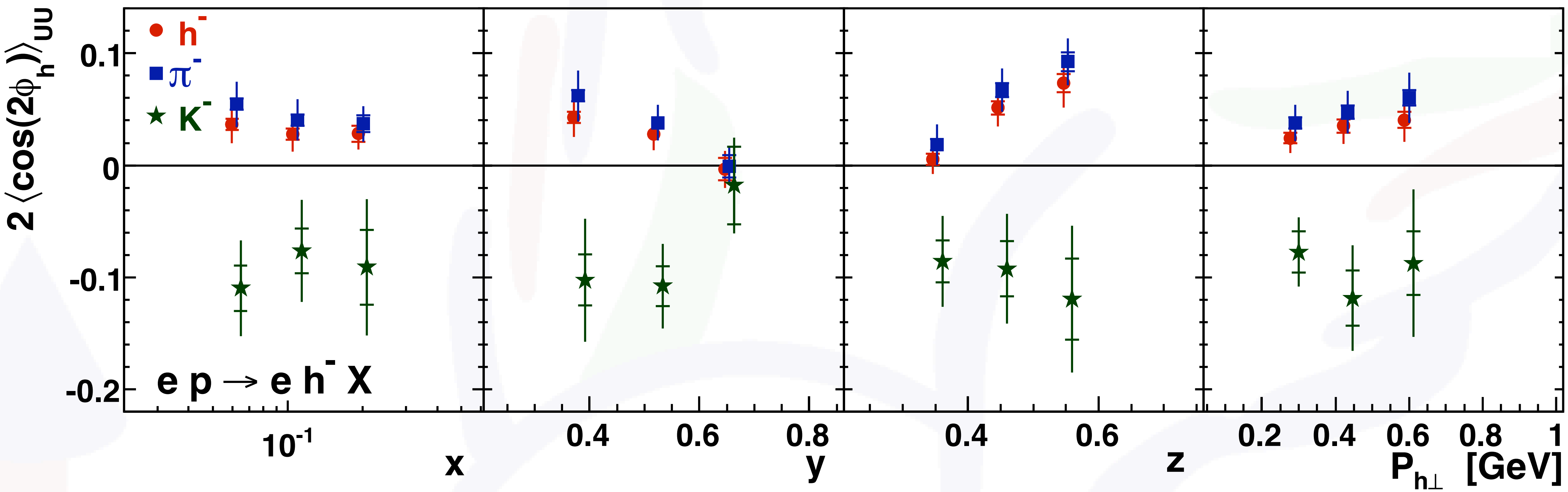
- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-

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



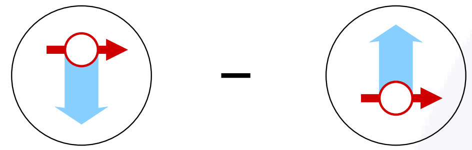
signs of Boer-Mulders

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



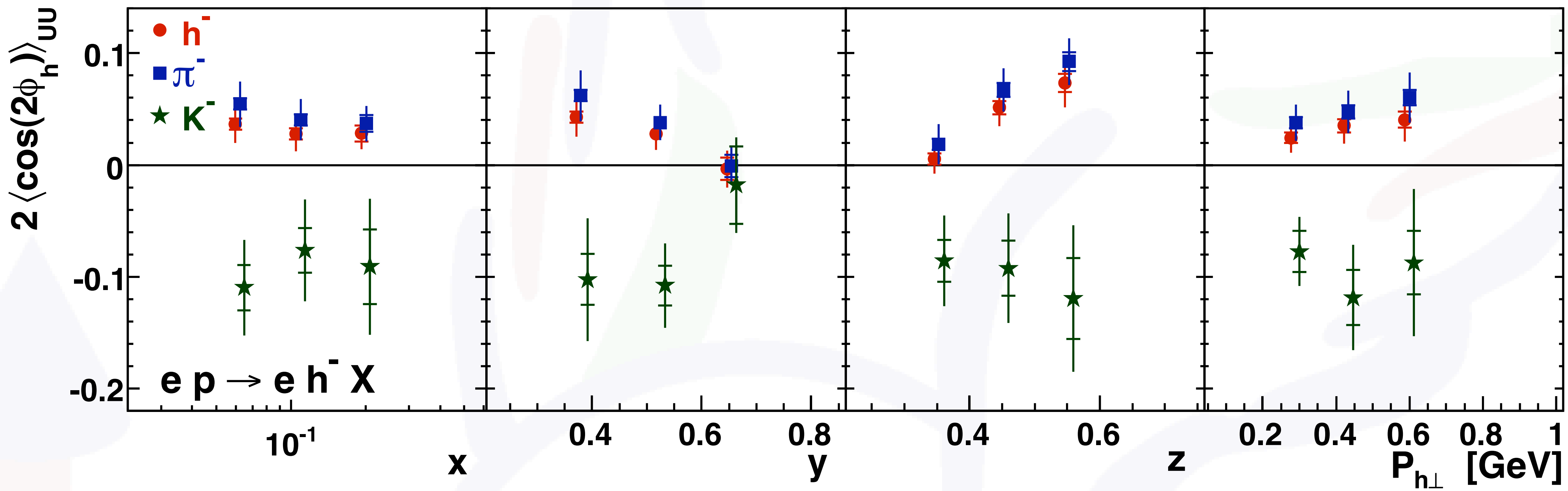
- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons

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



signs of Boer-Mulders

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



- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons
- available in multidimensional binning: http://www-hermes.desy.de/cosnphi/

Cahn effect?

next to leading twist

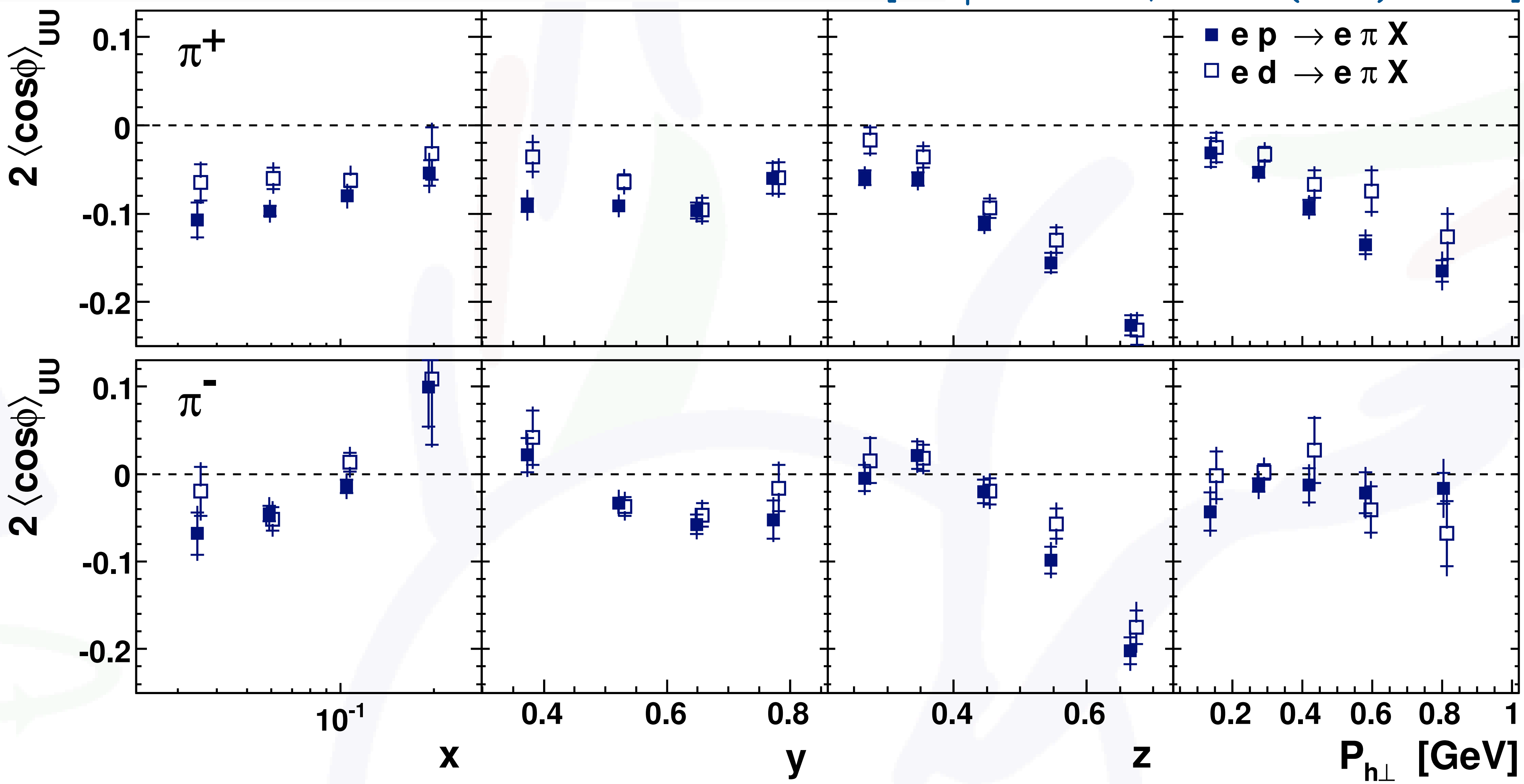
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

BOER-MULDERS EFFECT

CAHN EFFECT

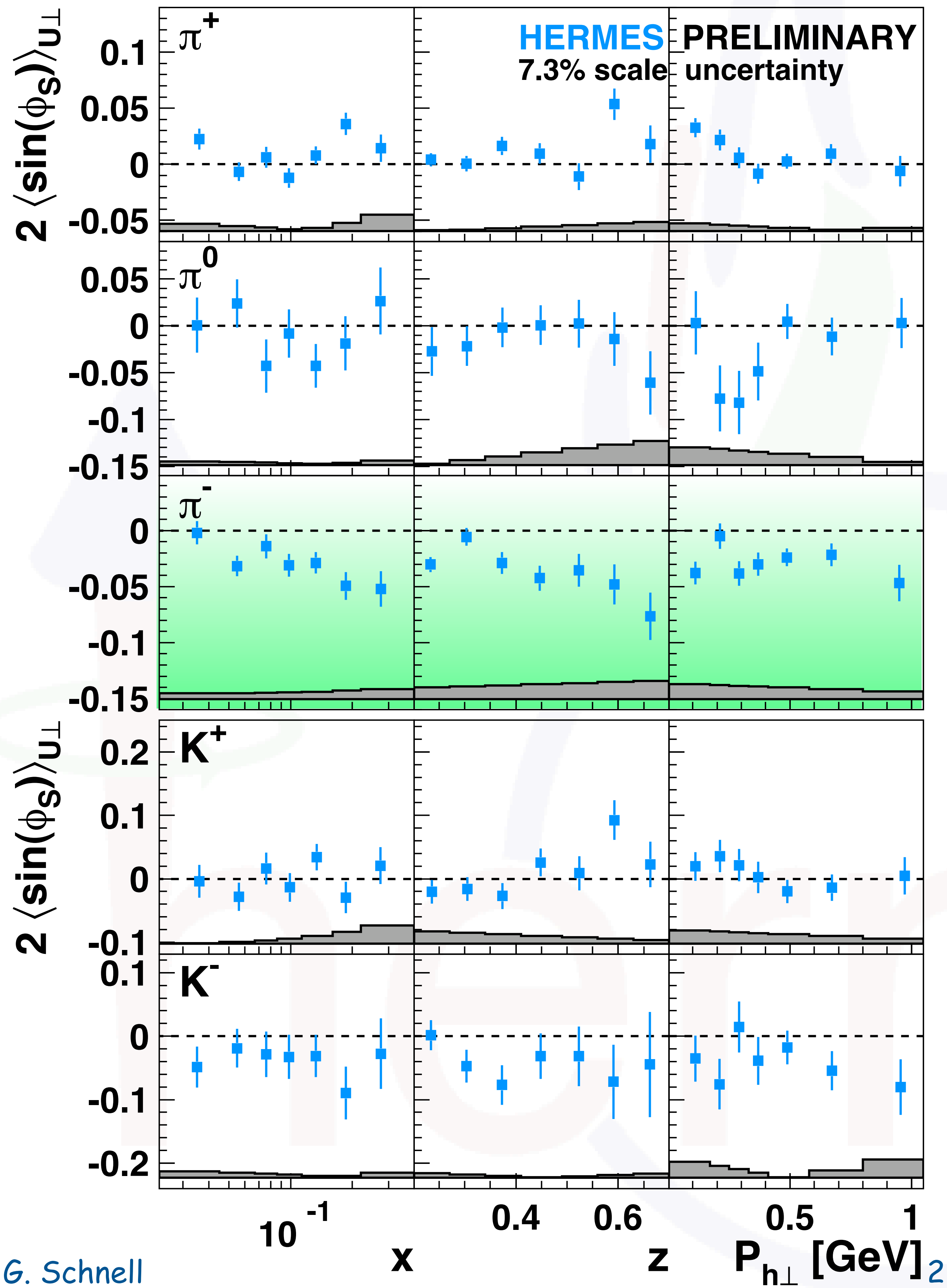
Interaction dependent terms neglected

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



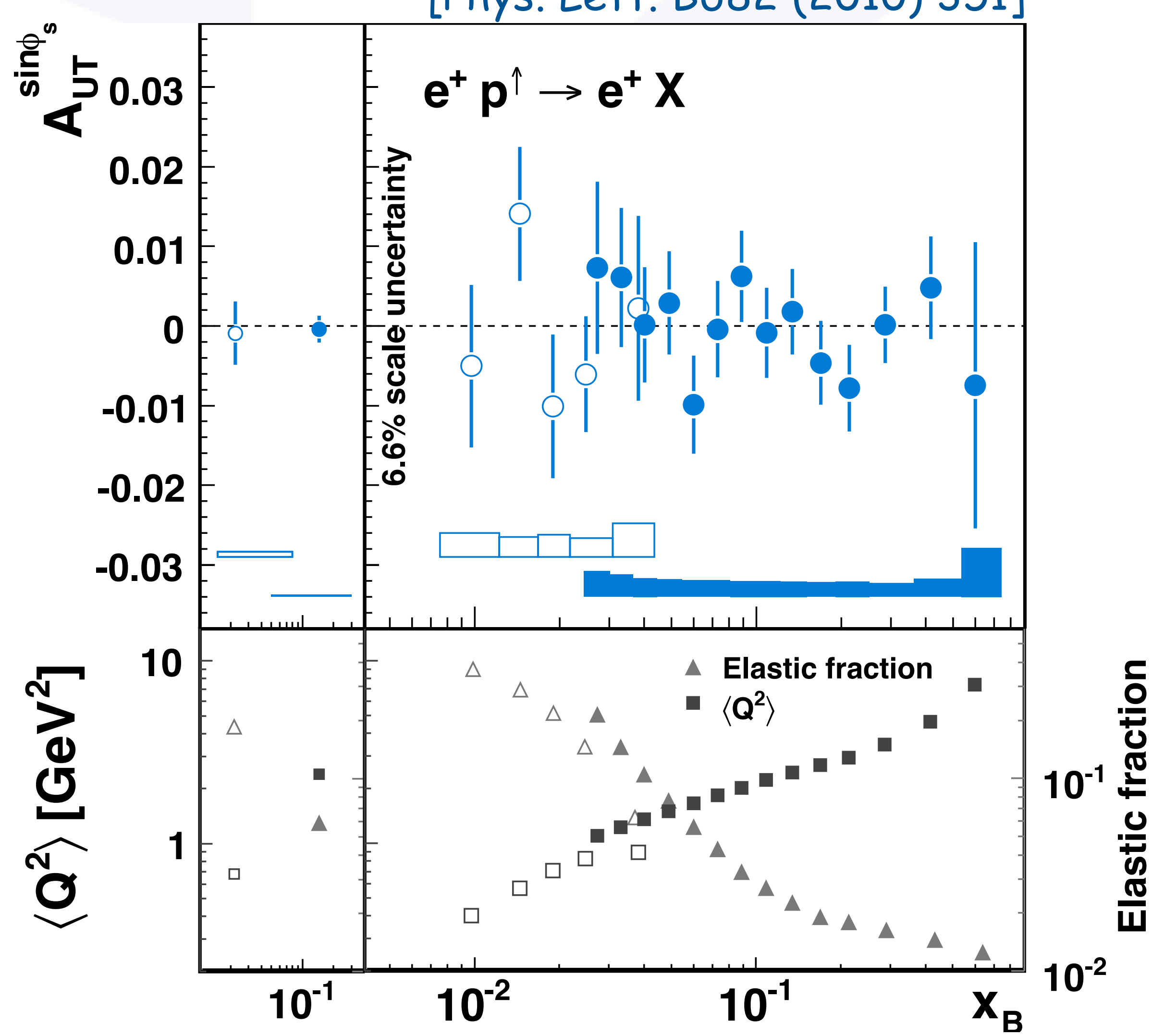
- no dependence on hadron charge **expected** for Cahn effect
- ➡ flavor dependence of transverse momentum
- ➡ sign of Boer-Mulders in $\cos\phi$ modulation
  (indeed, overall pattern resembles B-M modulations)
- ➡ additional “genuine” twist-3 contributions?

Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

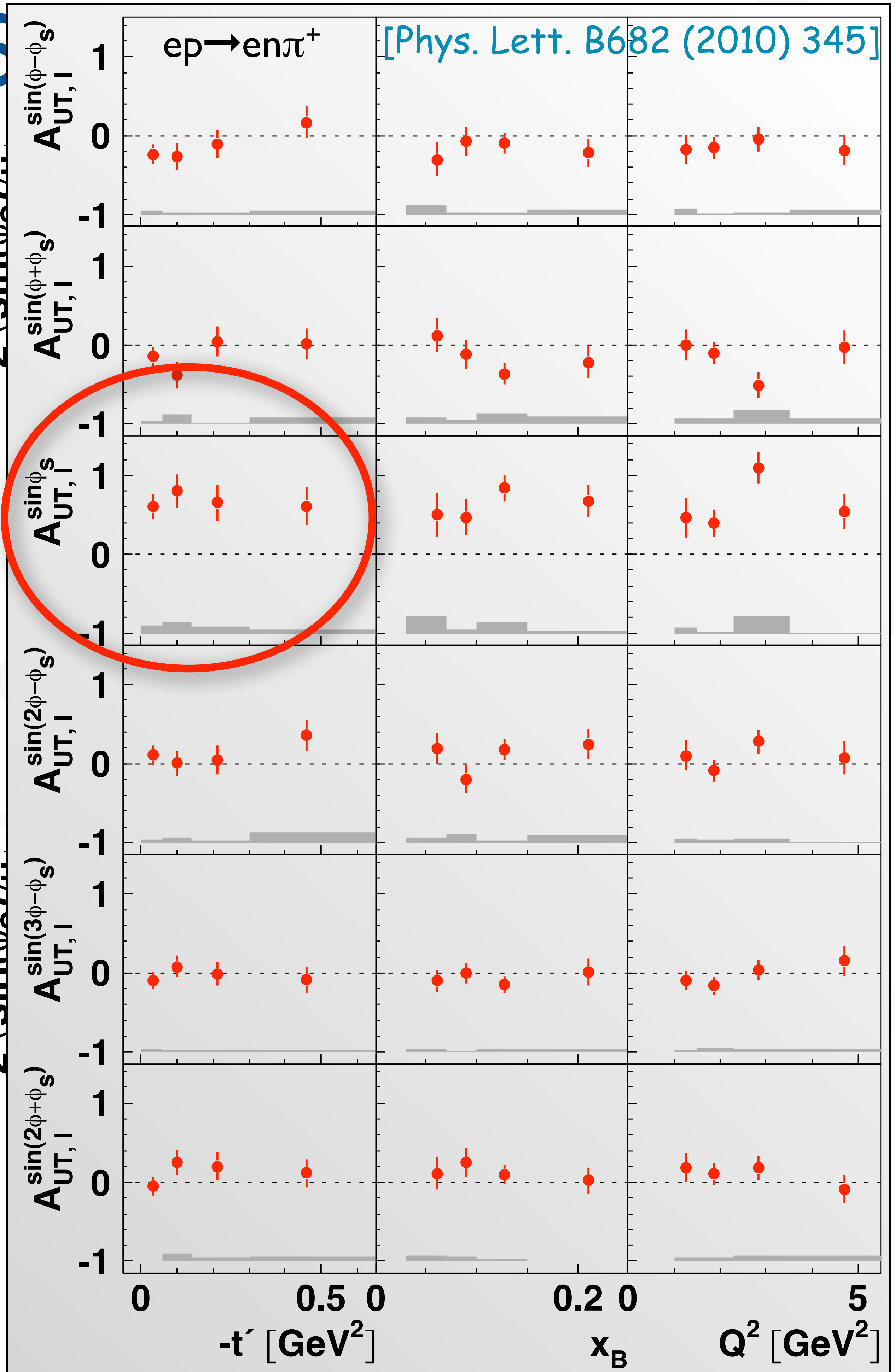


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons

[Phys. Lett. B682 (2010) 351]

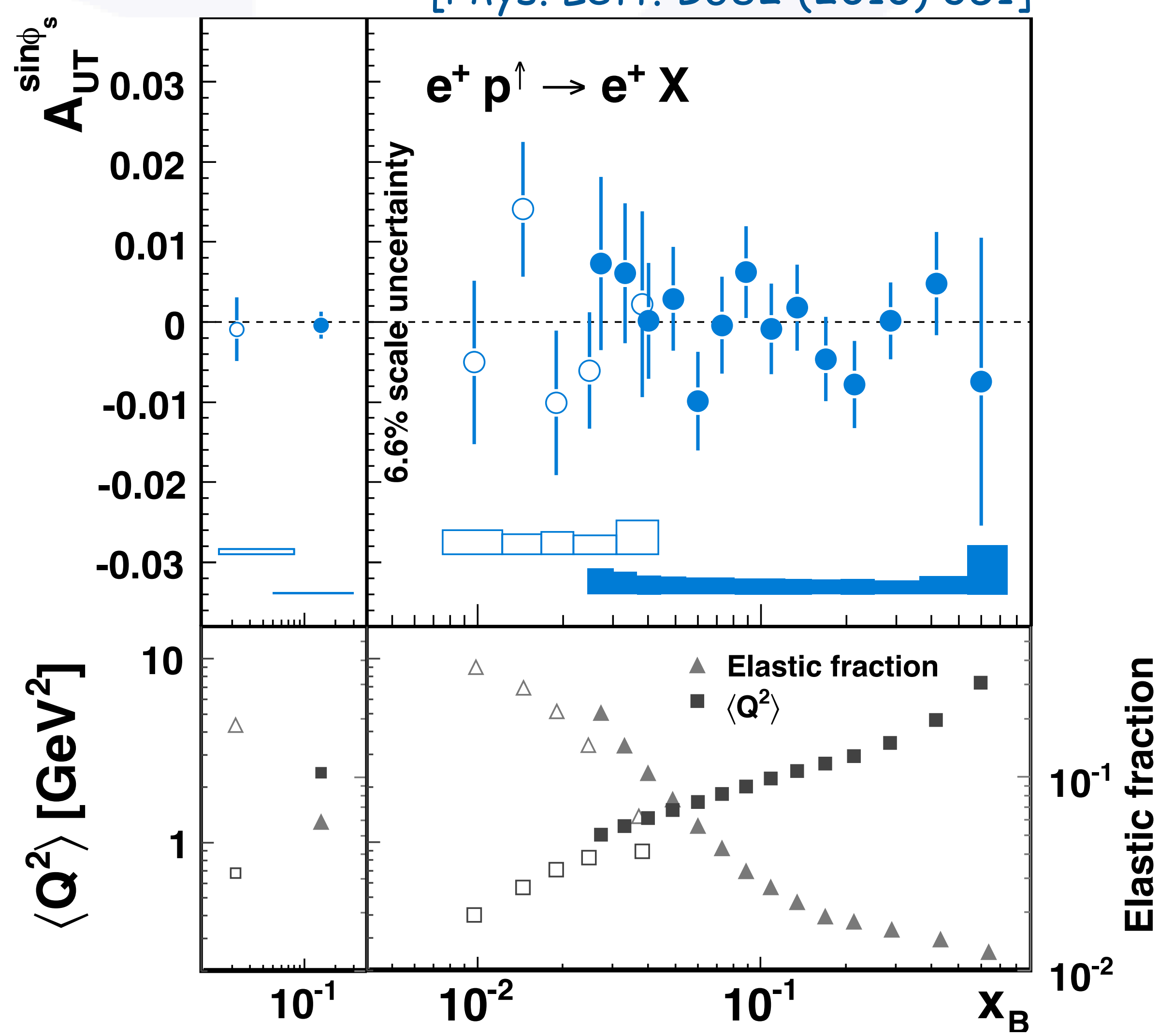


S... - $\langle \sin(\phi_s)\rangle_{UT}$

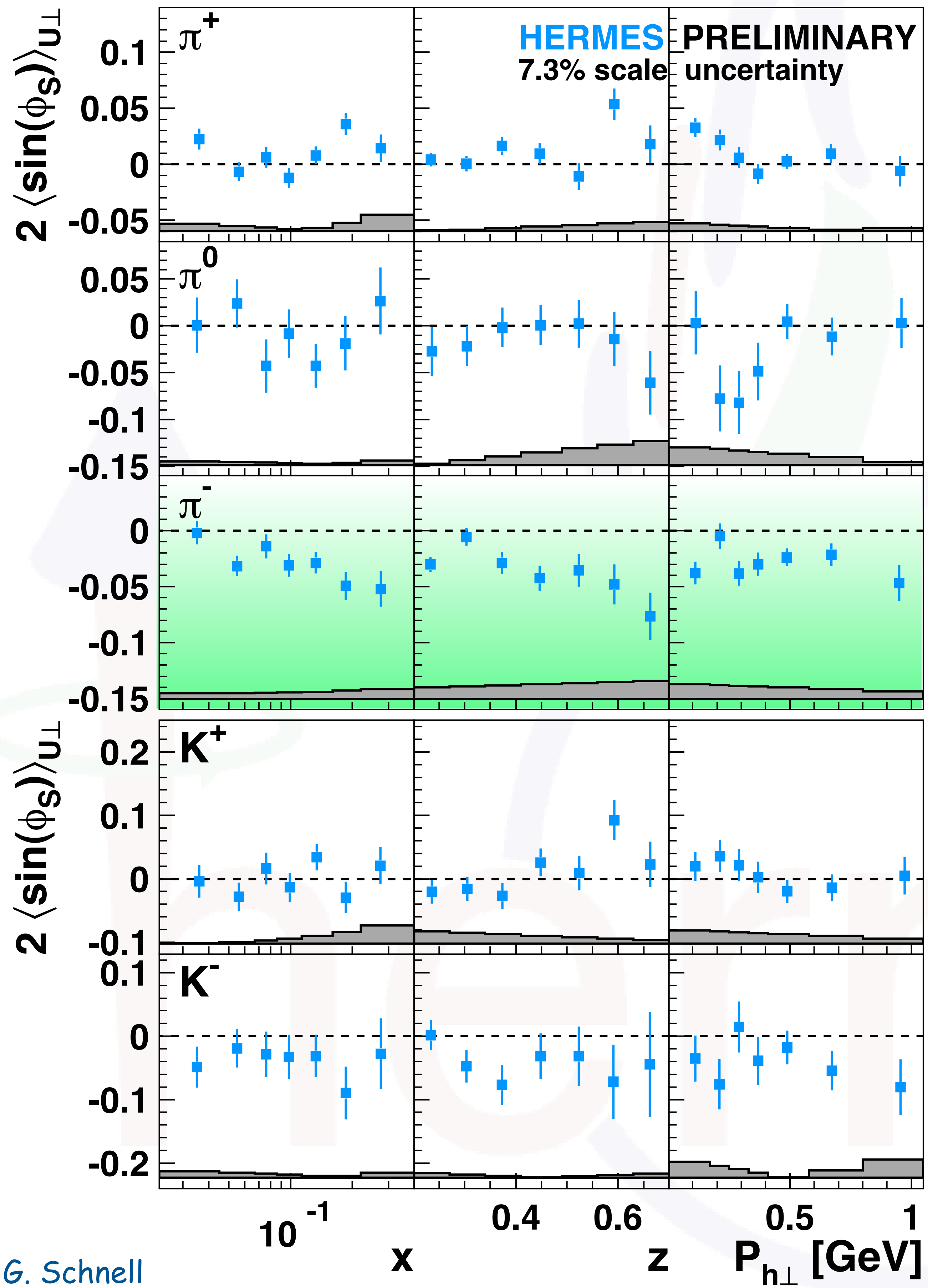


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons

[Phys. Lett. B682 (2010) 351]



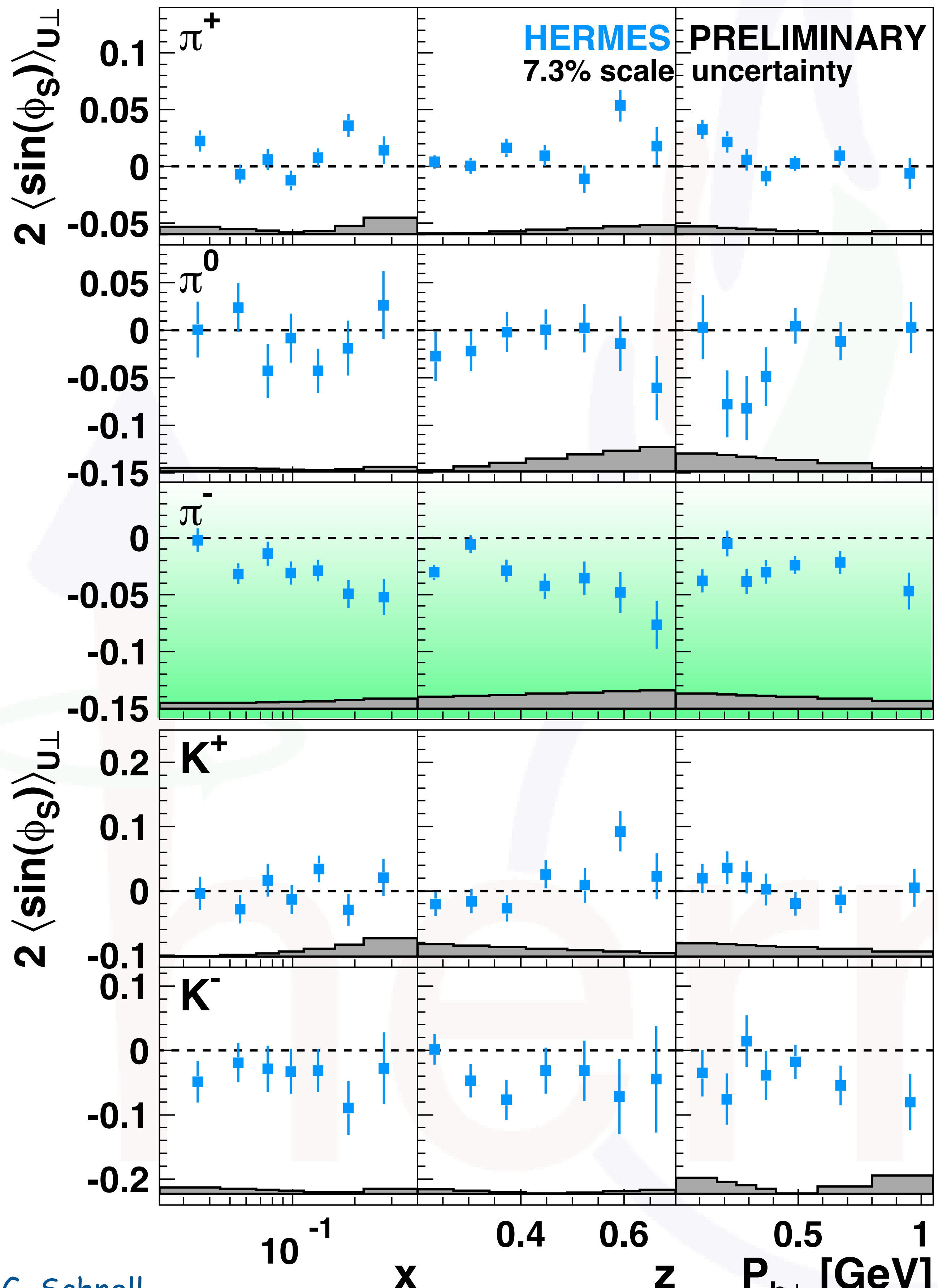
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

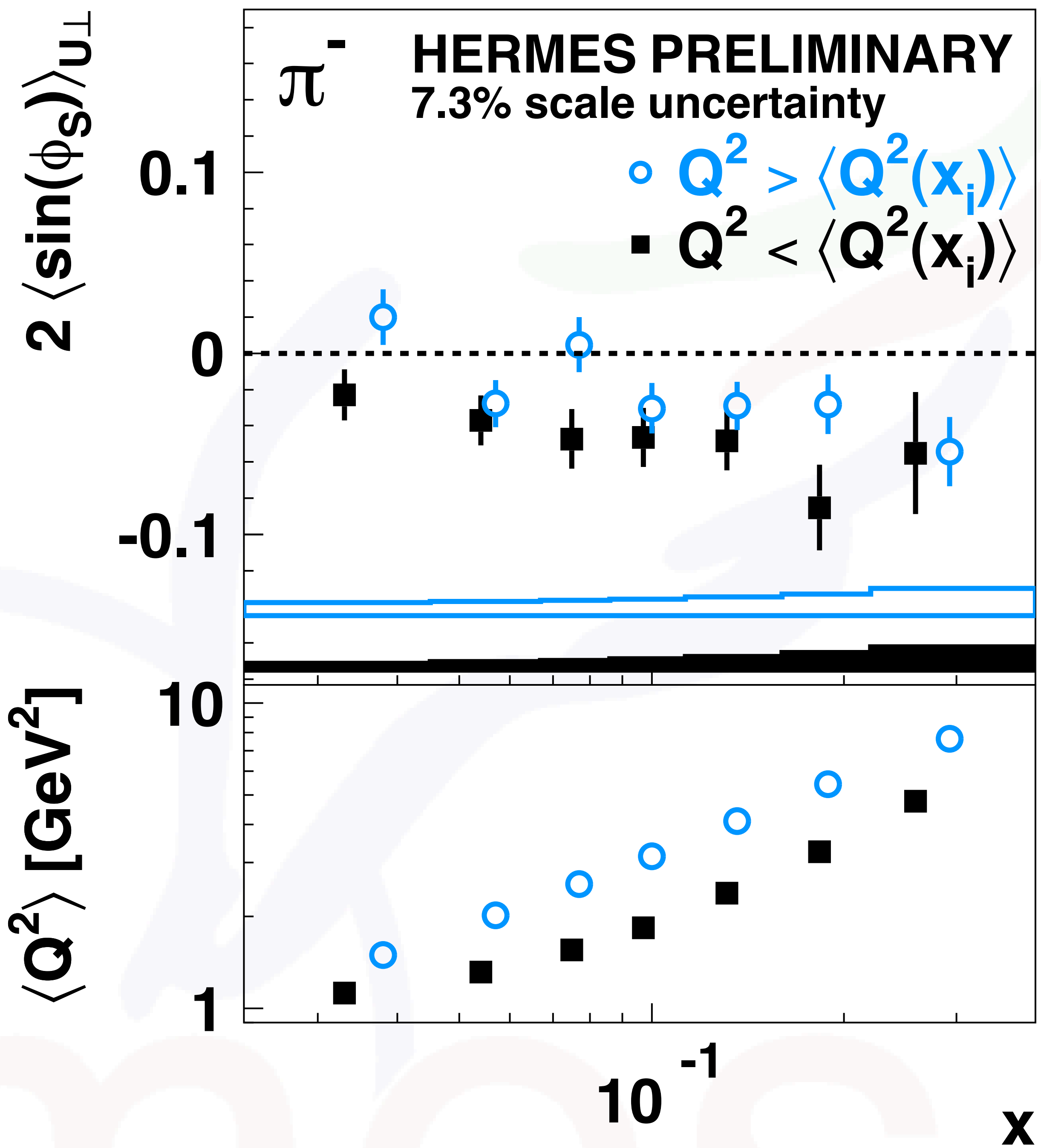


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

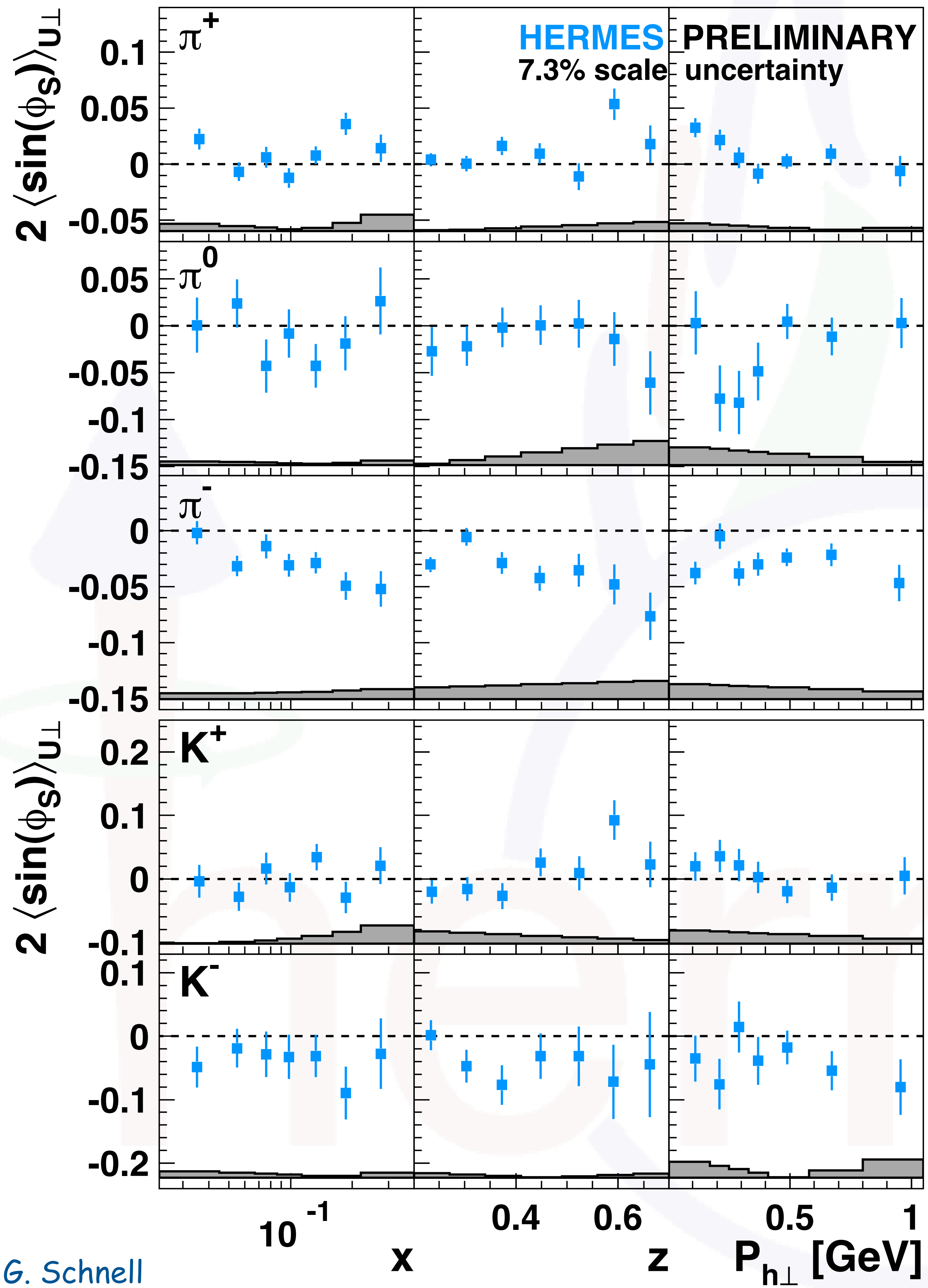
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

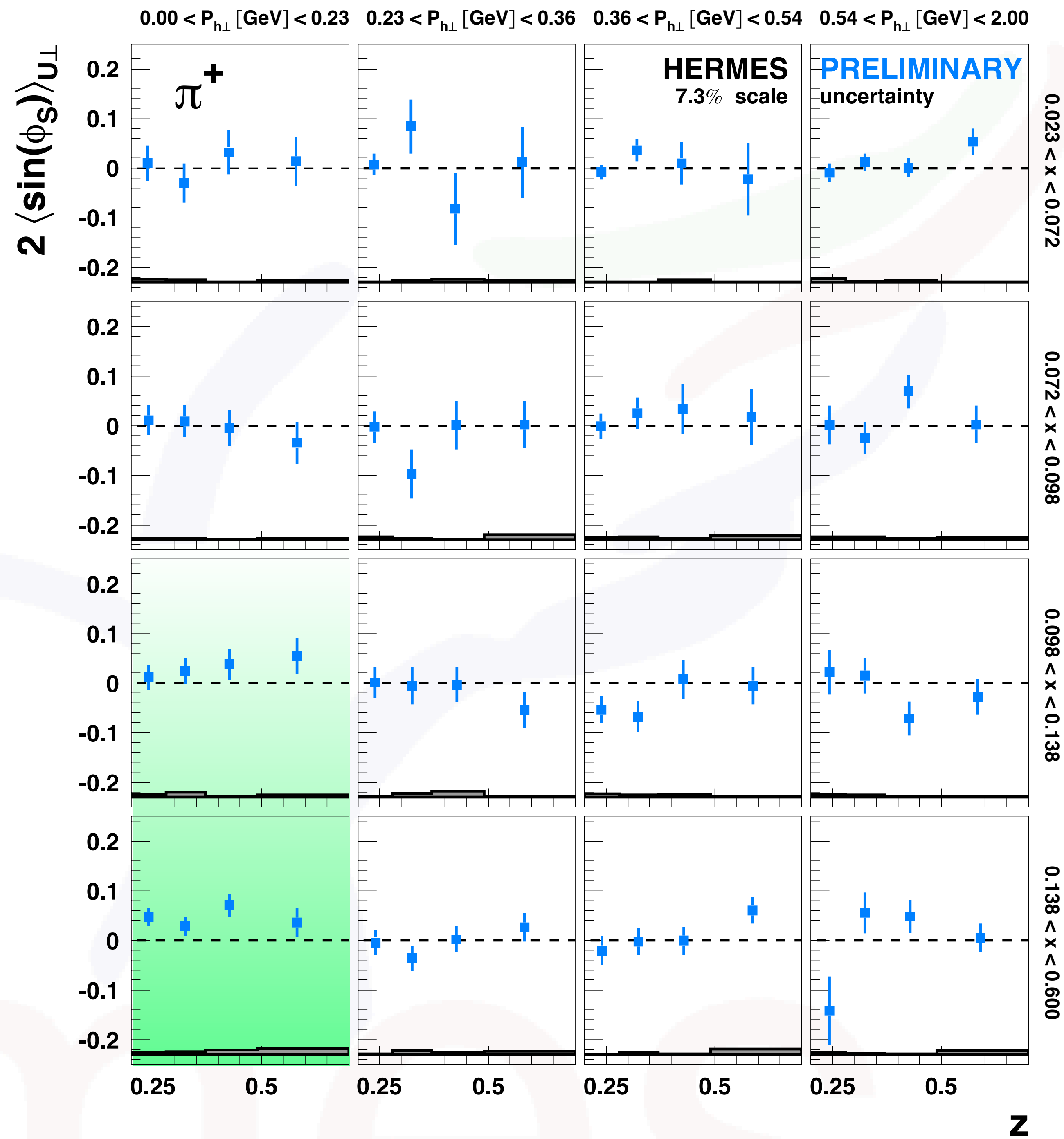




- hint of Q^2 dependence seen in signal for negative pions

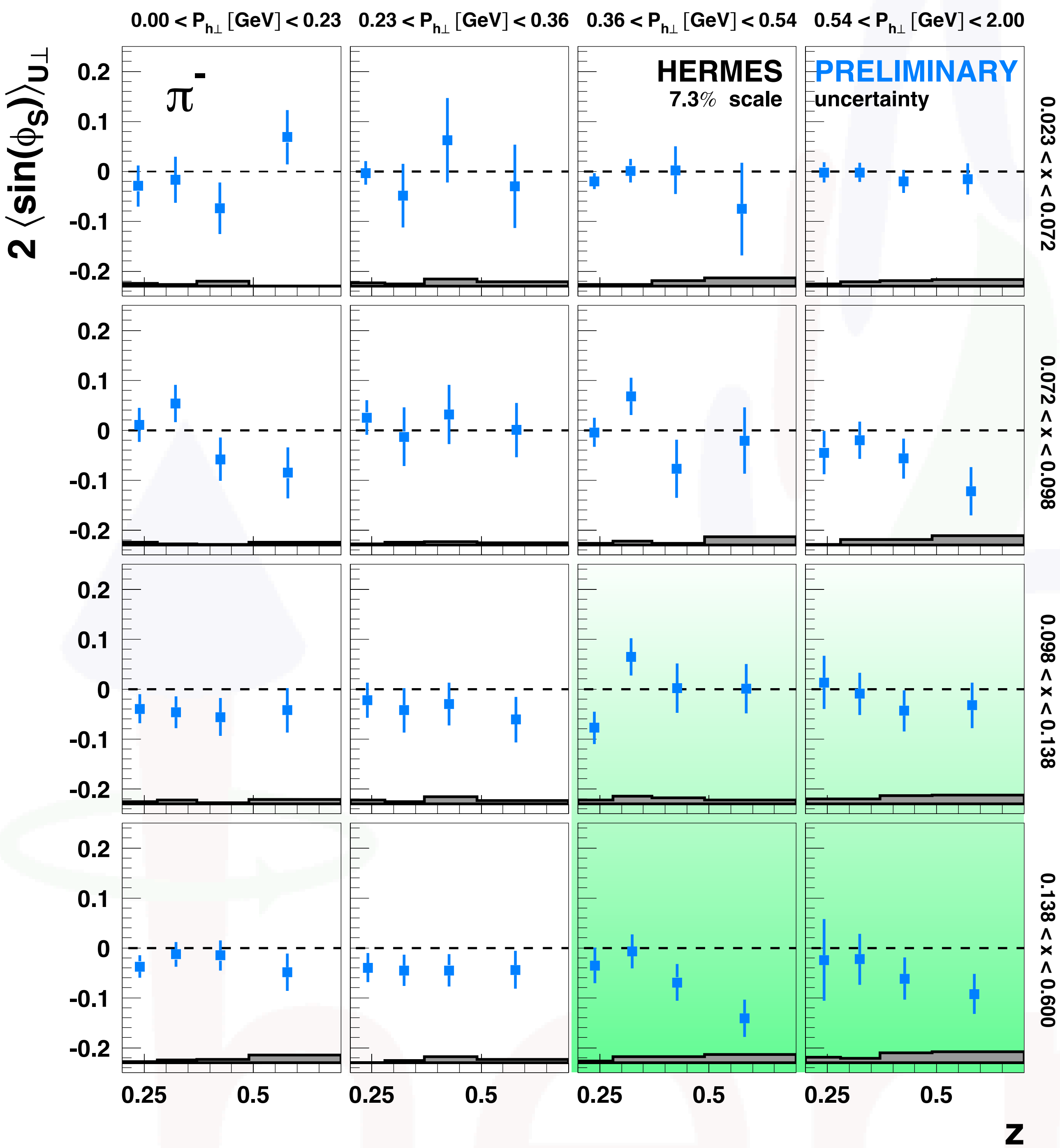
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

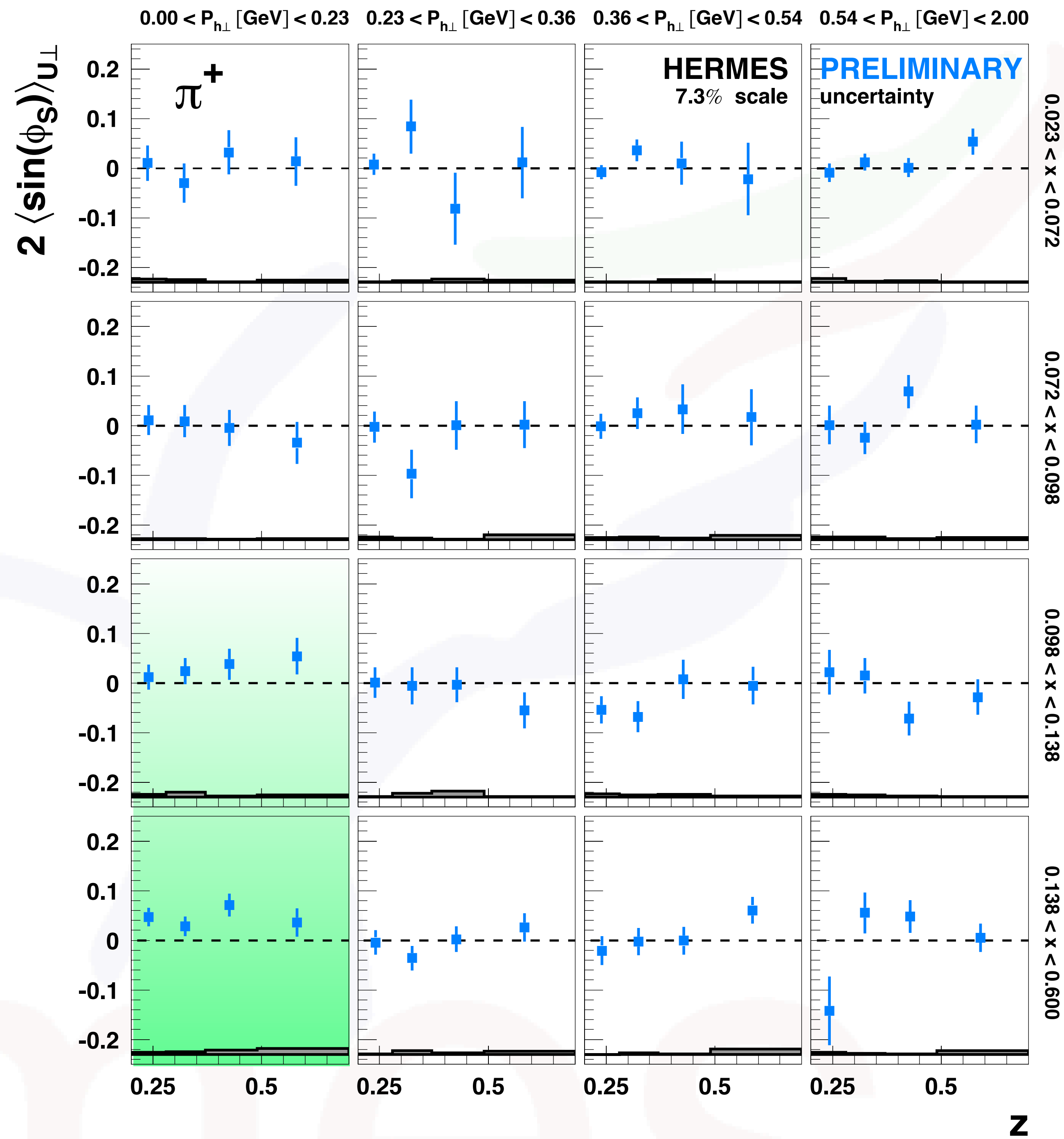




- positive amplitudes at low $P_{h\perp}$ also for positive pions

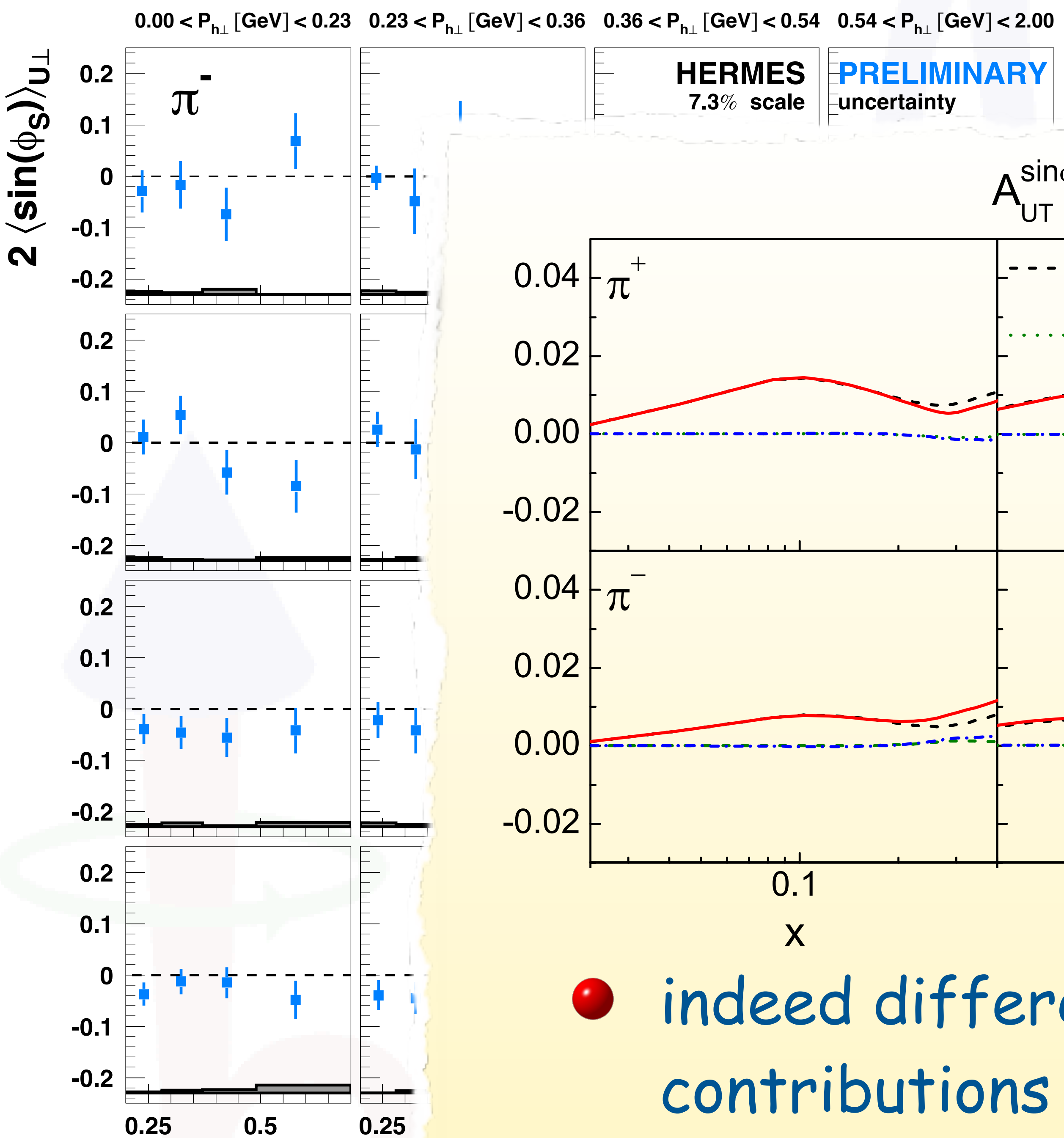
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

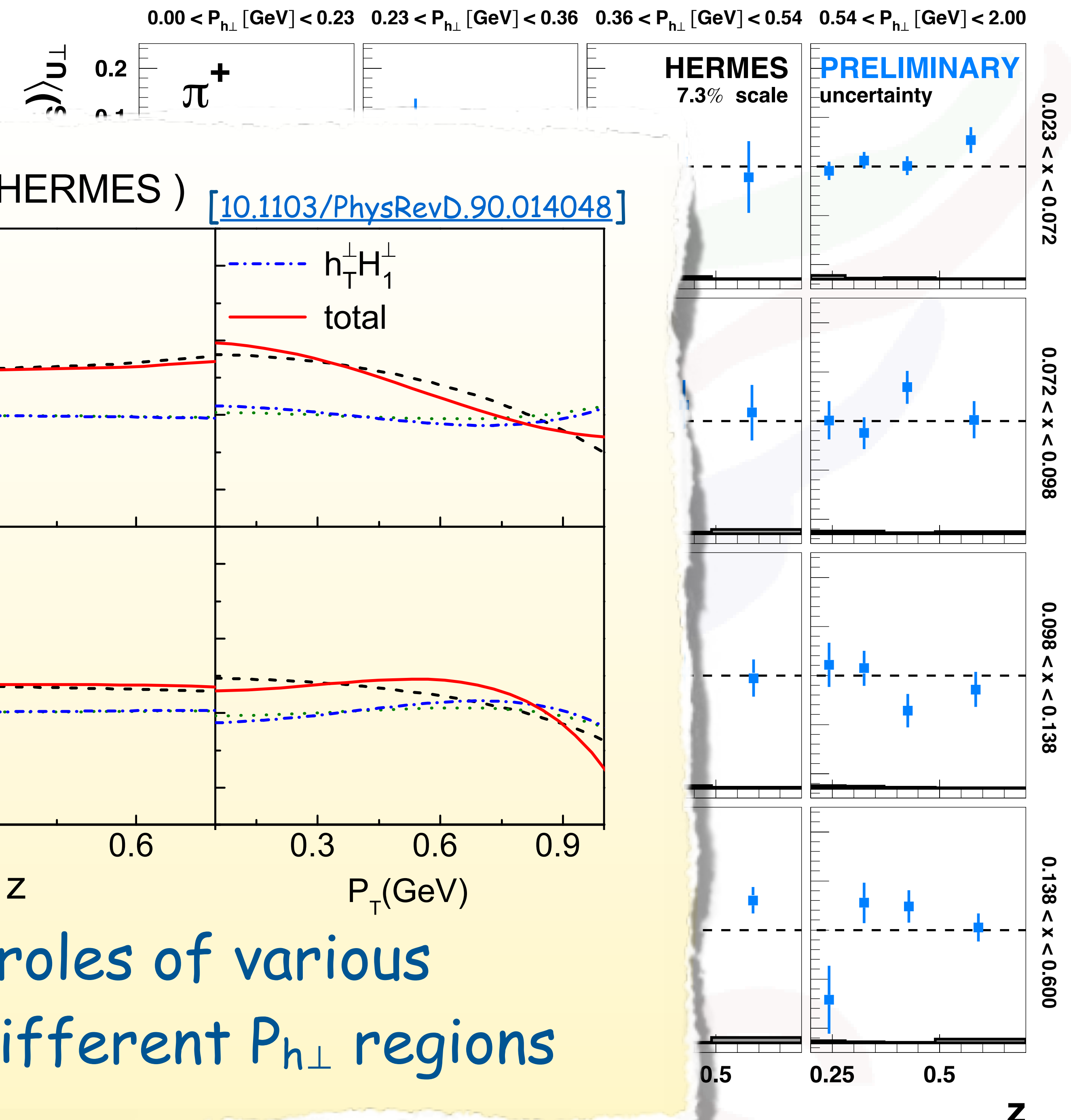


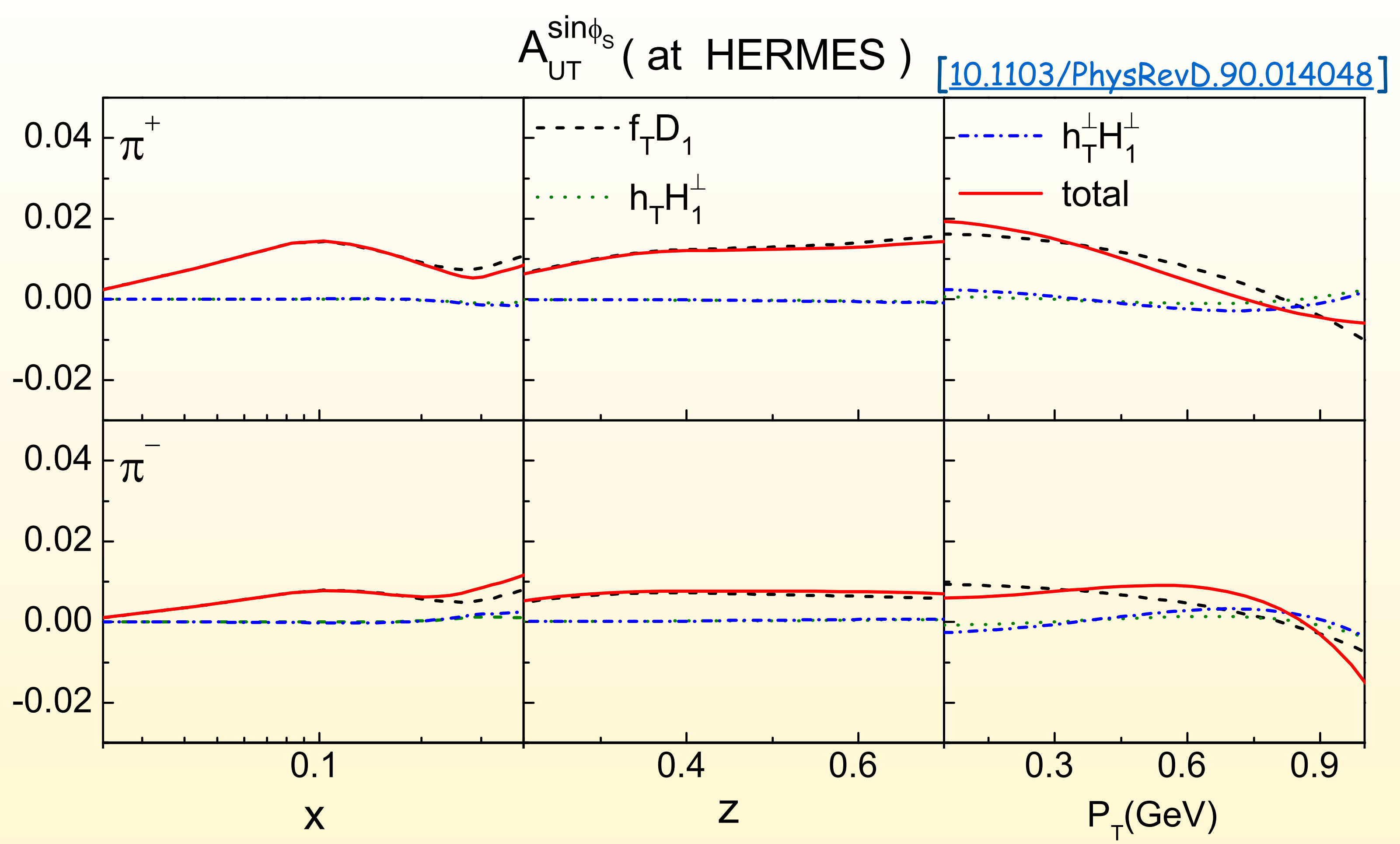


- nonzero amplitudes mainly at large $P_{h\perp}$ in case of negative pions
- positive amplitudes at low $P_{h\perp}$ also for positive pions

Subleading twist II - <sin(ϕ_S)>$_{UT}$





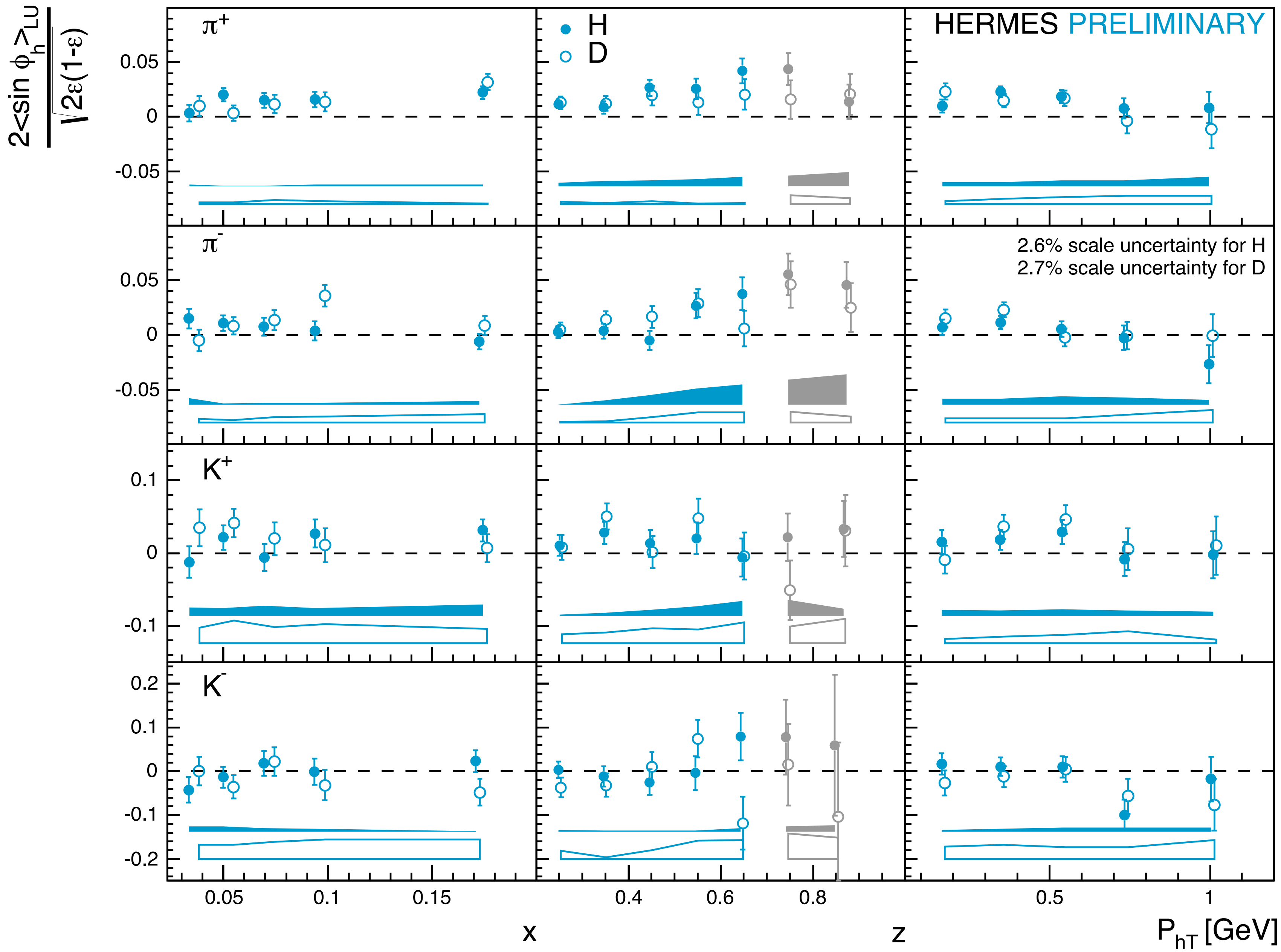


- indeed different roles of various contributions in different $P_{h\perp}$ regions

- nonzero amplitudes mainly at large $P_{h\perp}$ in case of negative pions
- positive amplitudes at low $P_{h\perp}$ also for positive pions

Subleading twist III - <sin(φ)>$_{LU}$

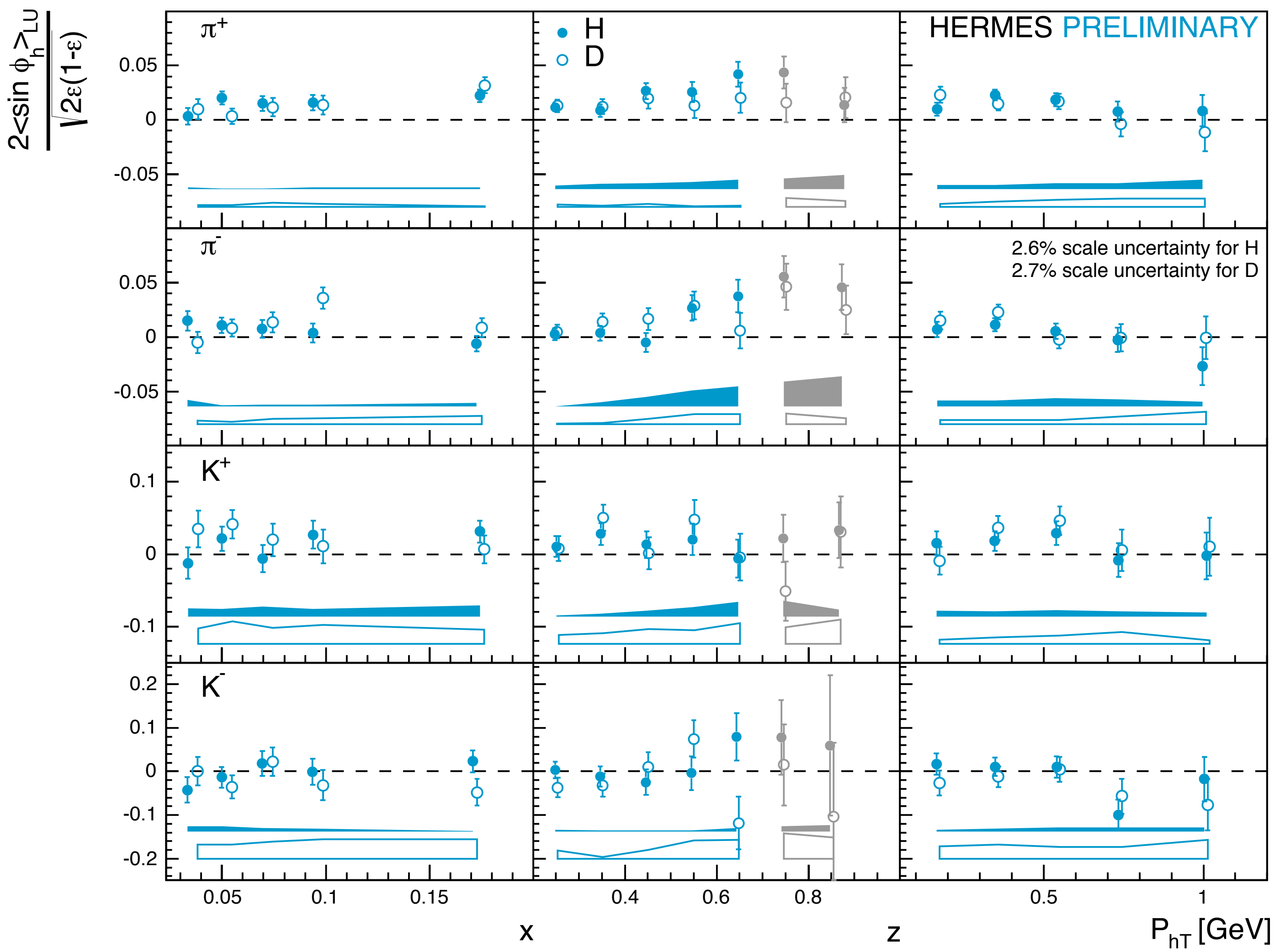
$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus xeH_1^{\perp}$$

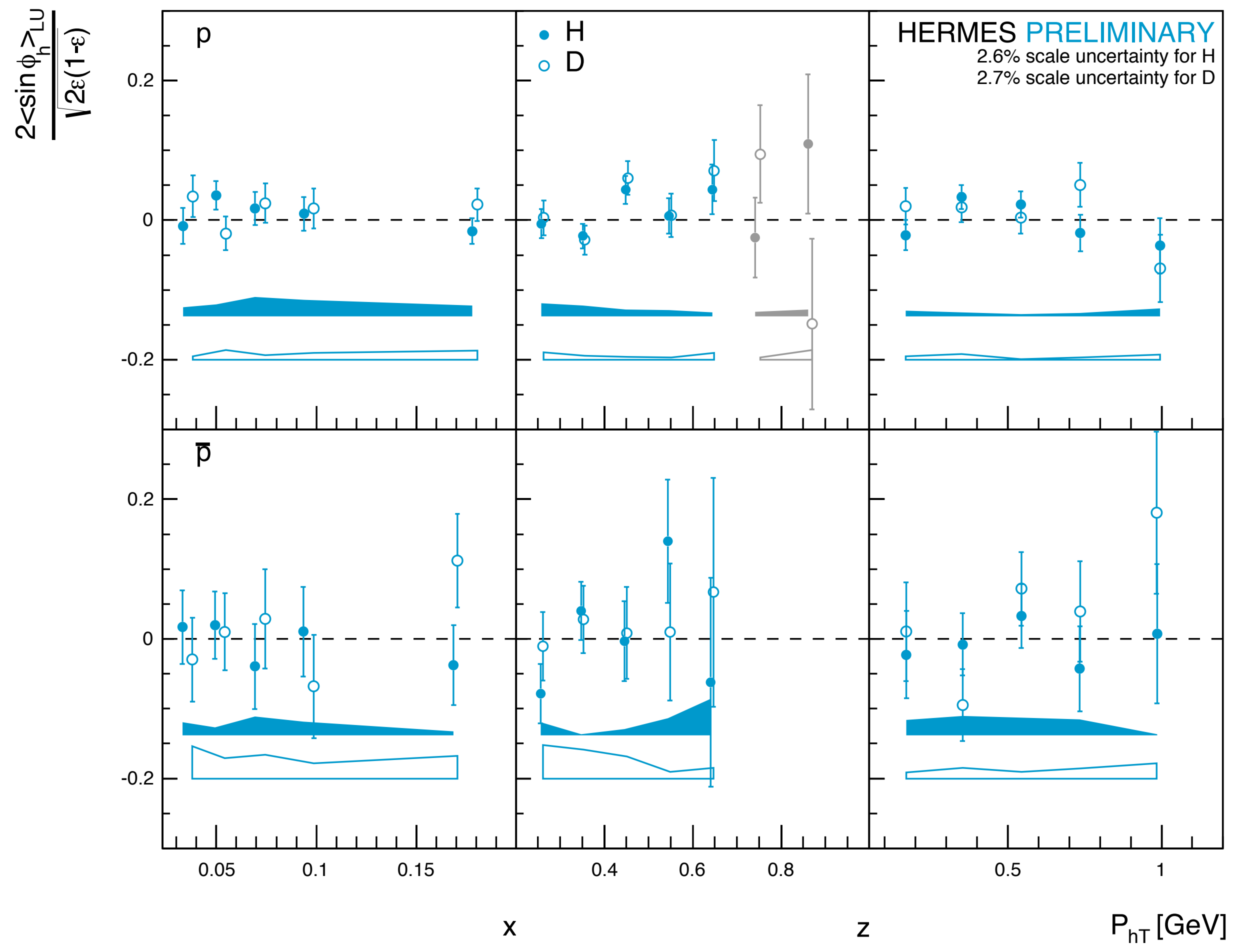


- significant positive amplitudes for (in particular positive) pions

Subleading twist III - $\langle\sin(\phi)\rangle_{LU}$

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

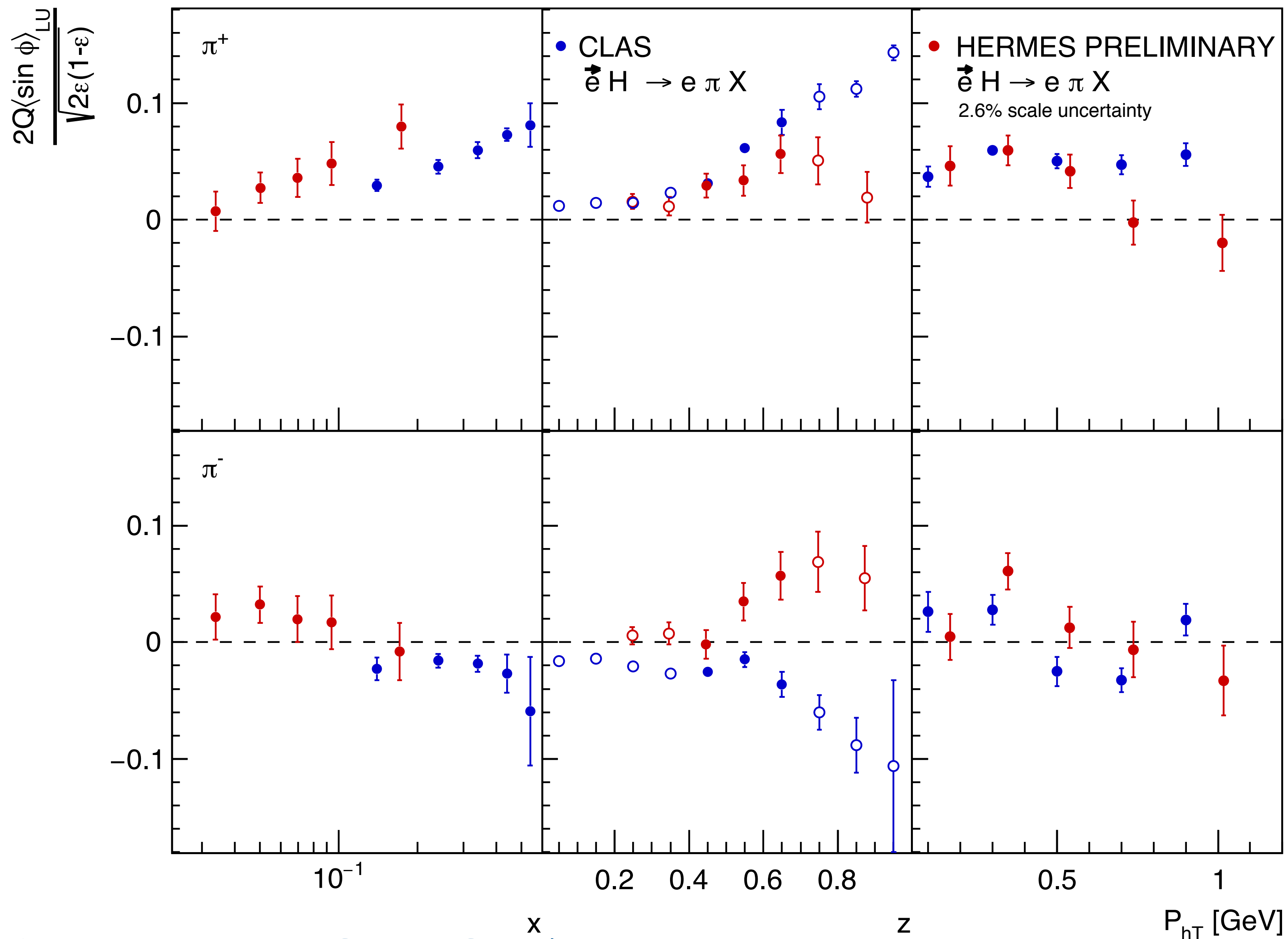




- mostly consistent w/ zero for other hadrons (except maybe K⁺)

Subleading twist III - <sin(φ)>$_{LU}$

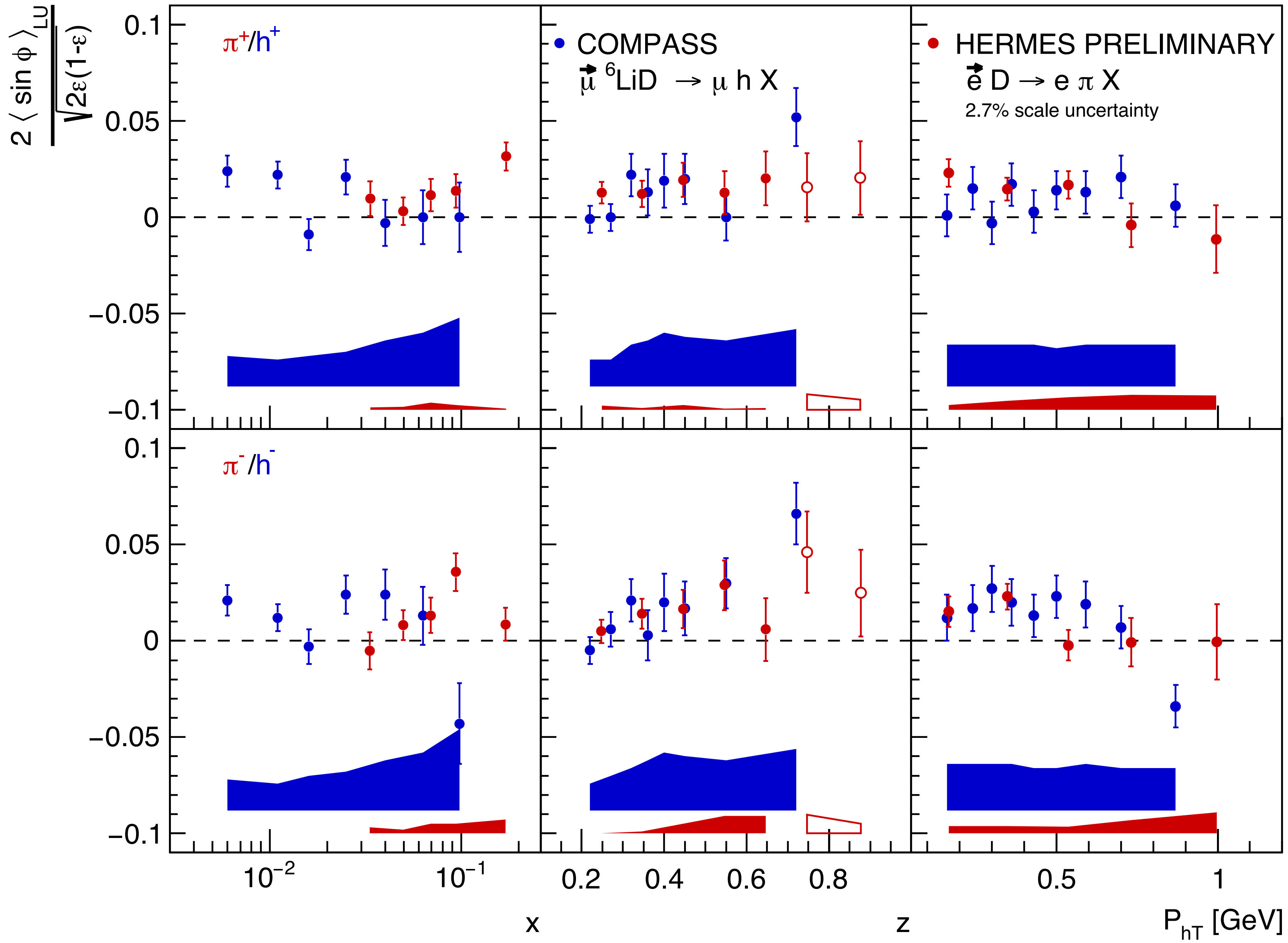
$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus x e H_1^{\perp}$$



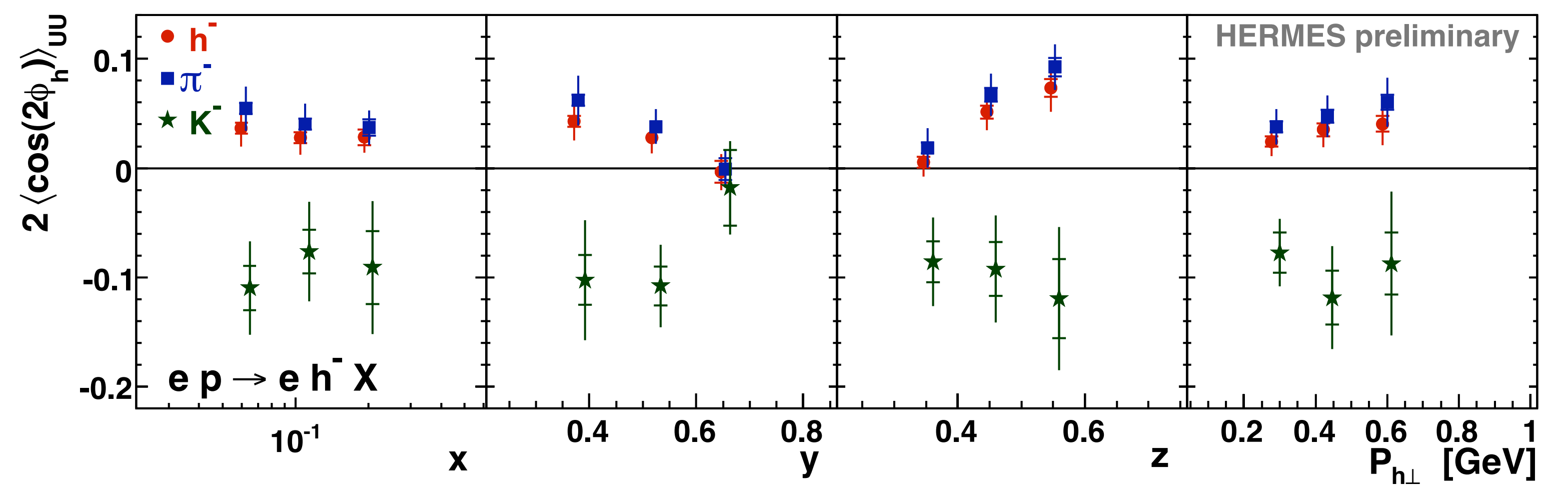
- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x)Collins term due to higher x probed?

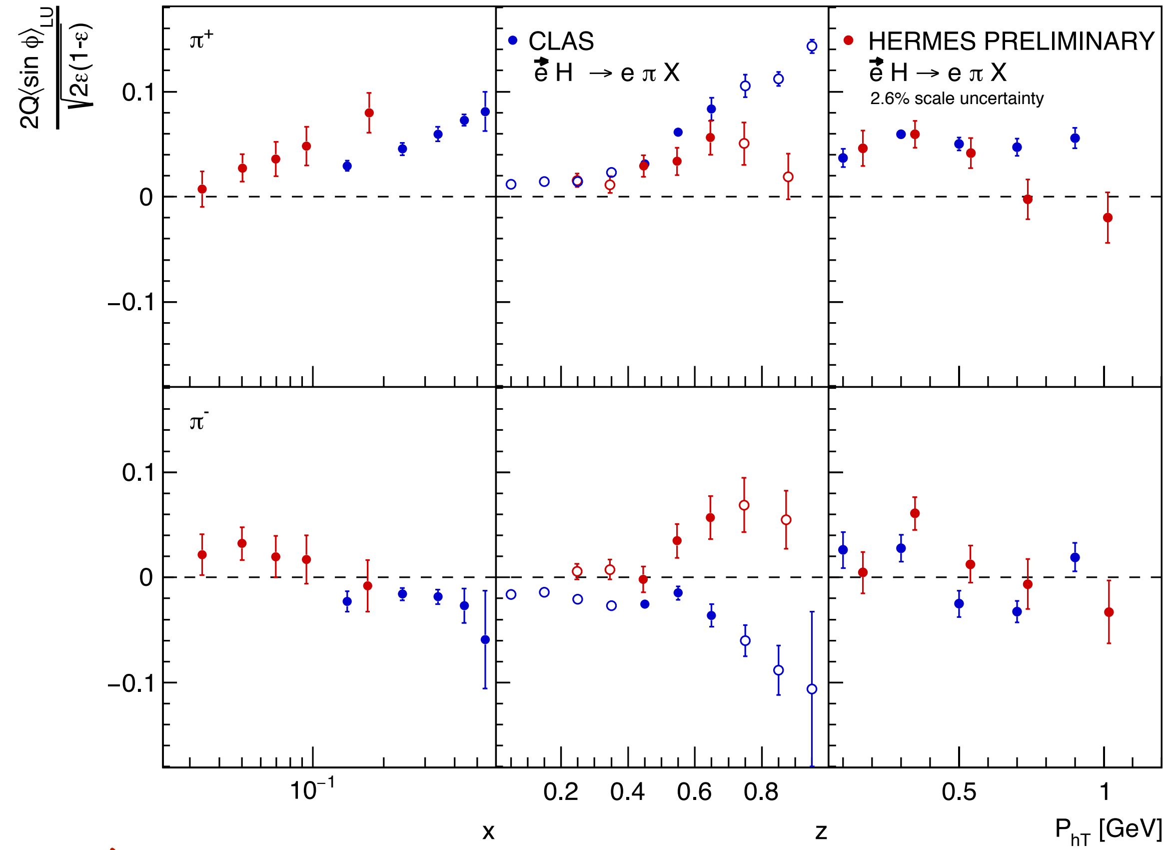
Subleading twist III - ⟨sin(φ)⟩$_{LU}$

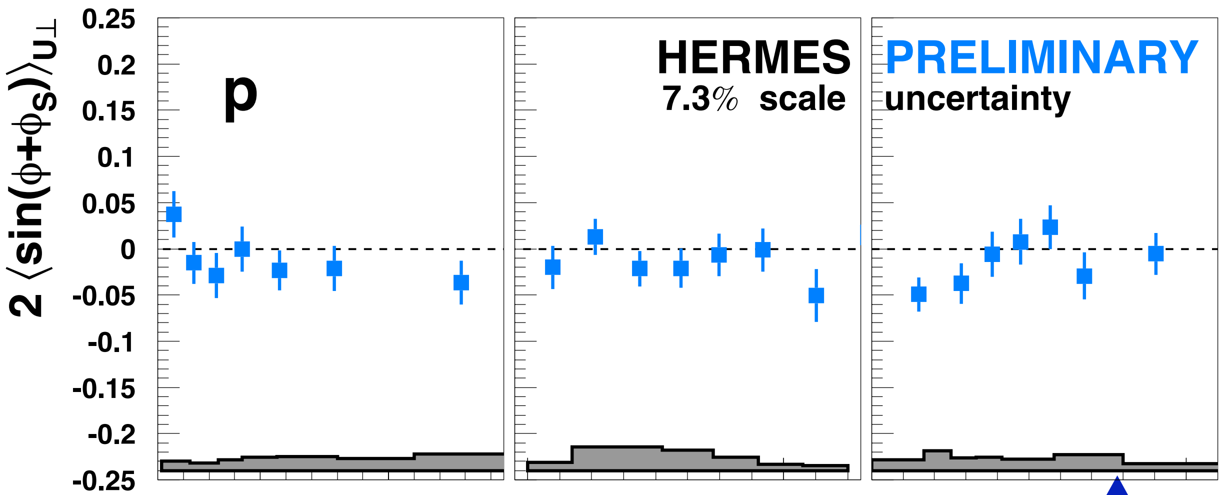
$$\frac{M_h}{Mz} h_1^\perp E \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 G^\perp \oplus x e H_1^\perp$$

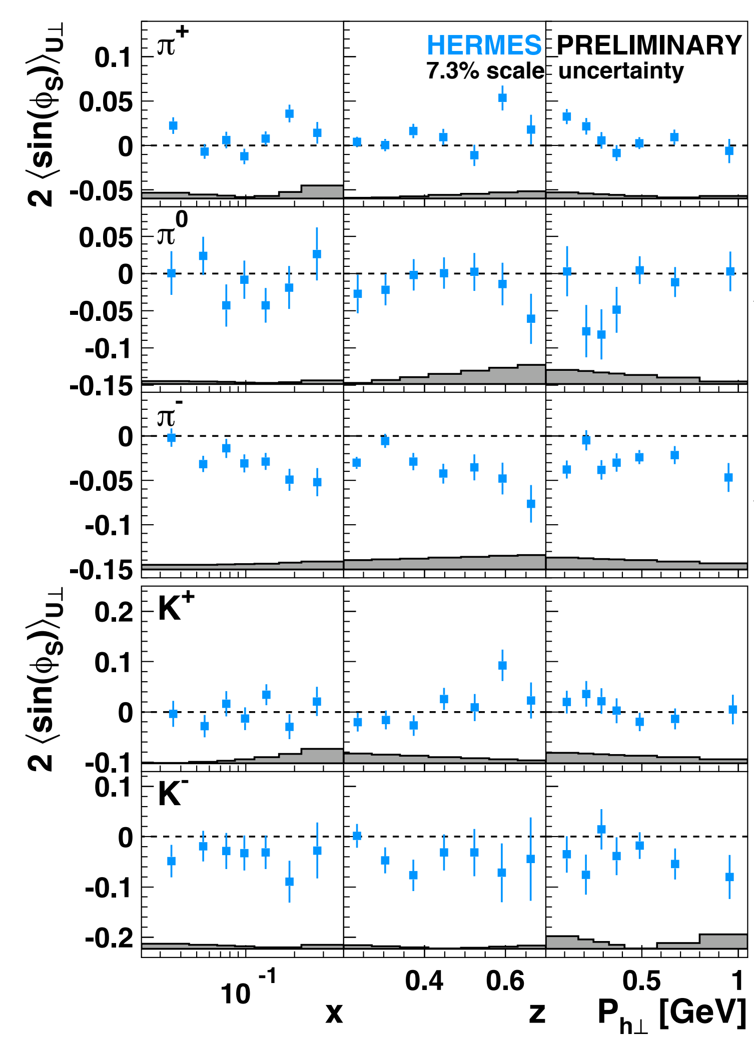


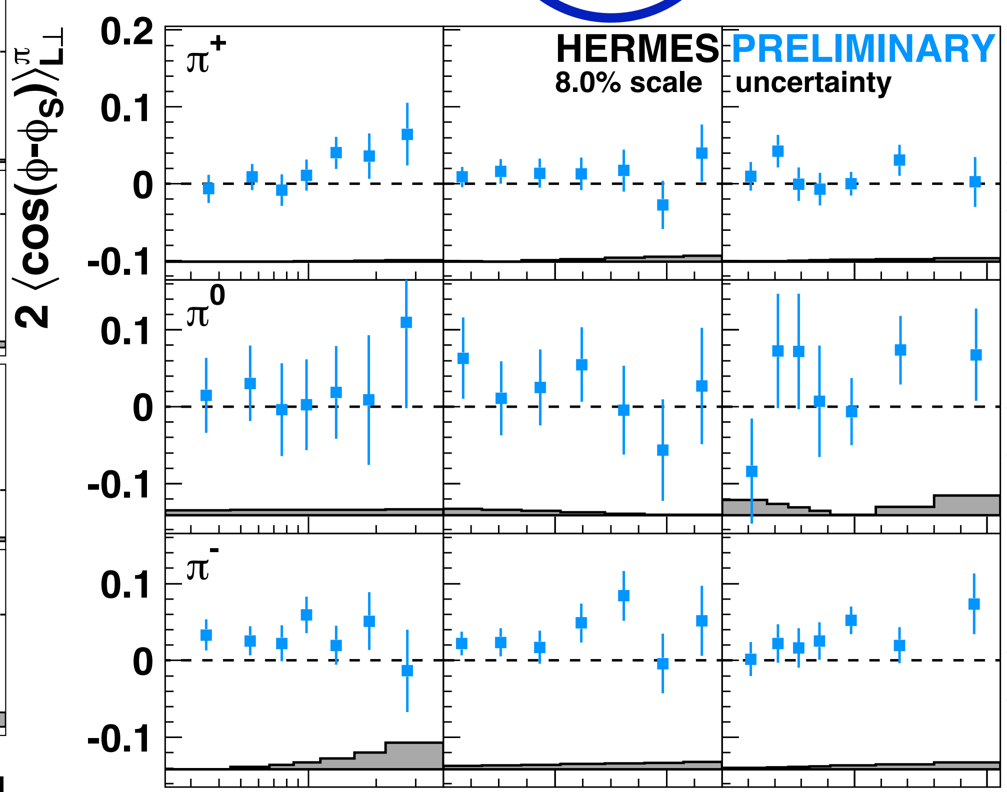
- consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets

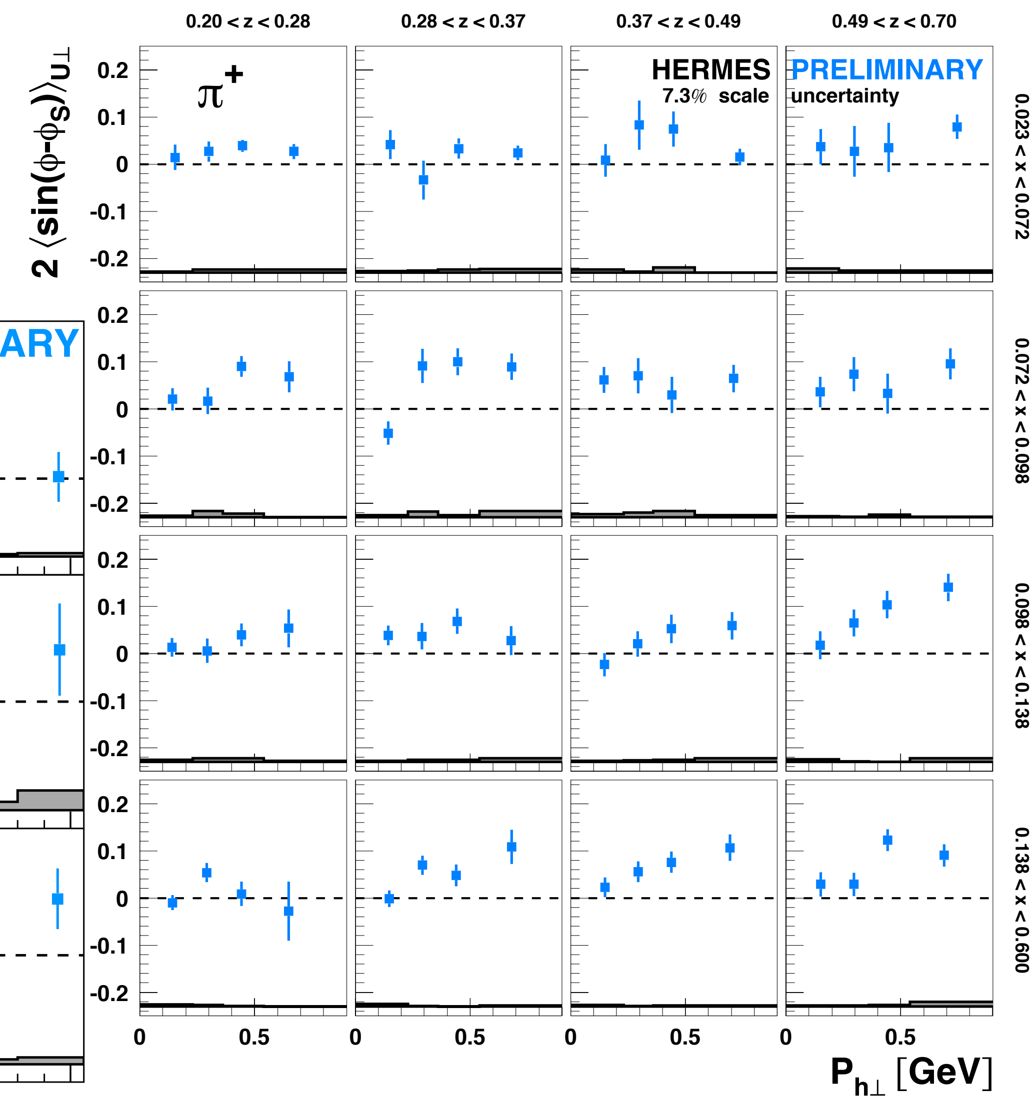

HERMES preliminary
h-
π-
K-
e p → e h- X
2 ⟨cos(2φh)⟩UU
x
y
z
Ph⊥ [GeV]


CLAS
e H → e π X
HERMES PRELIMINARY
e H → e π X
2.6% scale uncertainty
π+
π-
x
z
PhT [GeV]


p
HERMES
7.3% scale
PRELIMINARY
uncertainty
2 ⟨sin(φ+φS)⟩U⊥

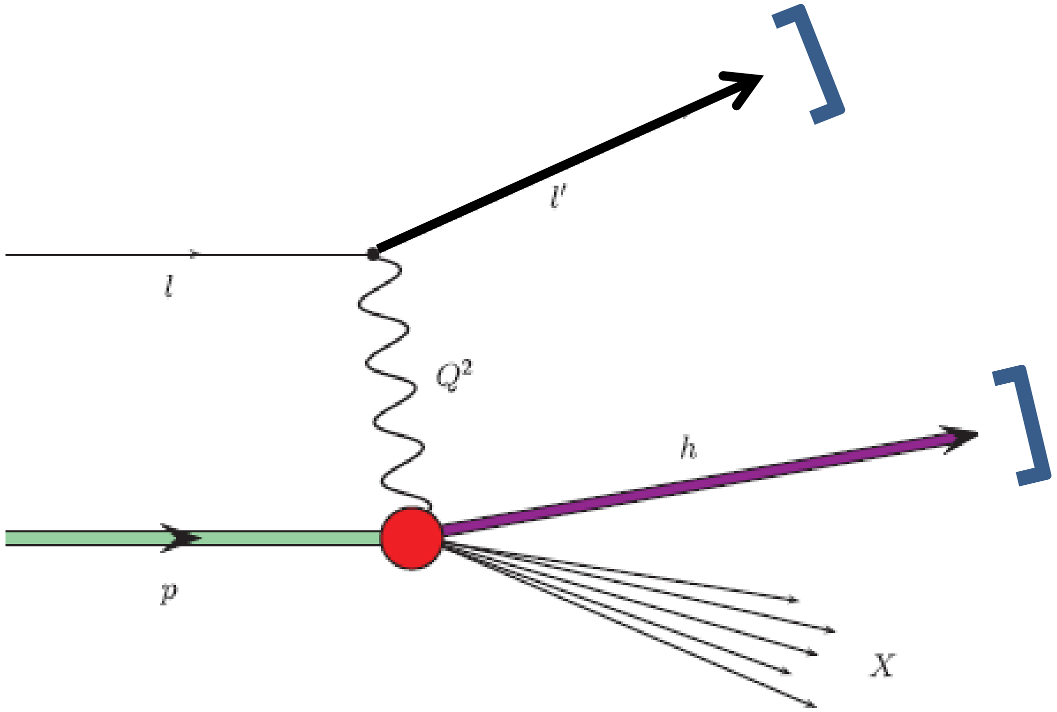

HERMES
7.3% scale
PRELIMINARY
uncertainty
π+
π0
π-
K+
K-
2 ⟨sin(φS)⟩U⊥
x
z
Ph⊥ [GeV]


HERMES
8.0% scale
PRELIMINARY
uncertainty
π+
π0
π-
2 ⟨cos(φ-φS)⟩L⊥


0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
π+
HERMES
7.3% scale
PRELIMINARY
uncertainty
2 ⟨sin(φ-φS)⟩U⊥
Ph⊥ [GeV]

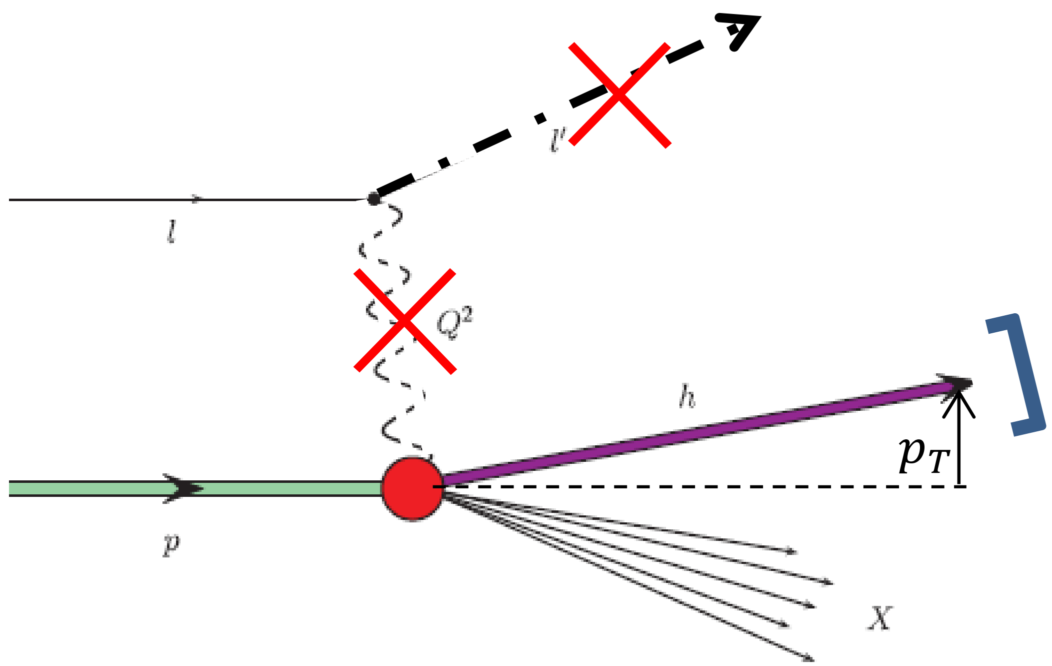
Backup slides

Semi-inclusive hadrons



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

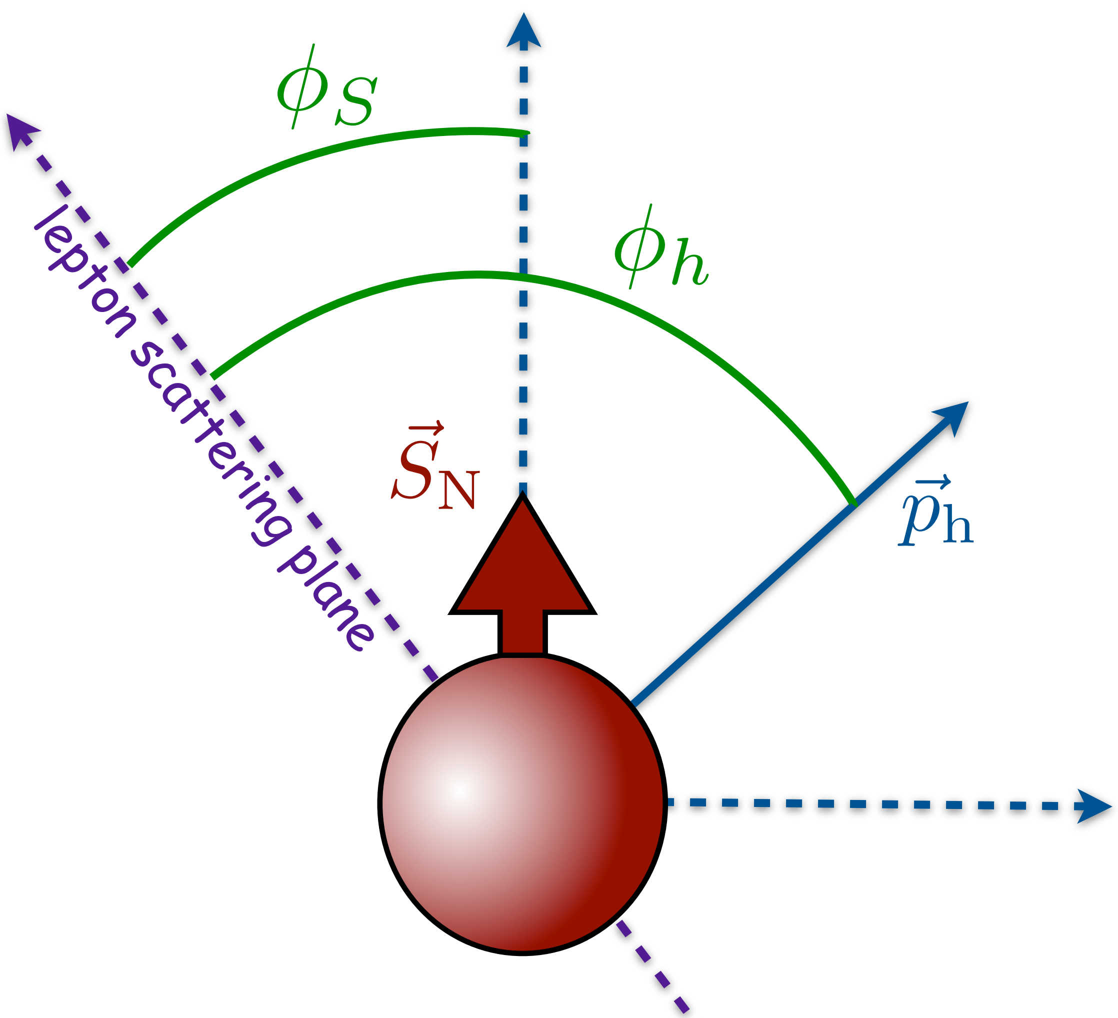
Semi-inclusive hadrons



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

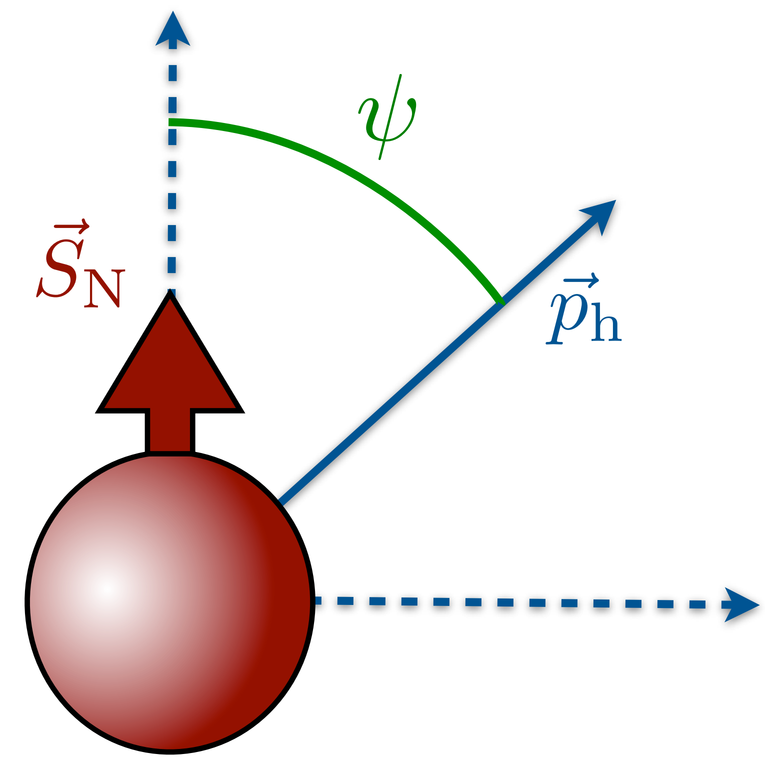
Inclusive hadron electro-production

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



virtual photon going into the page

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



lepton beam going into the page

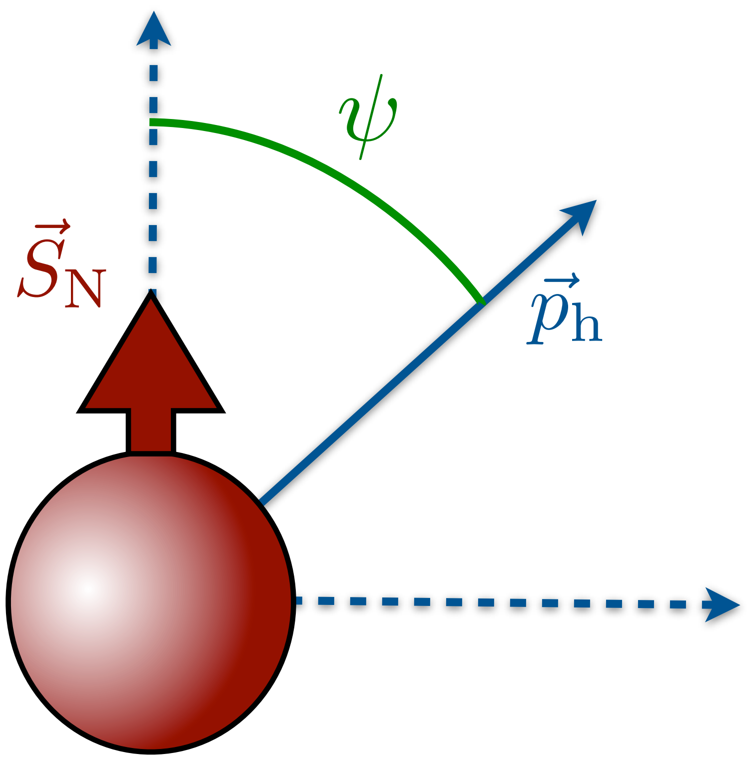
$$\psi \simeq \phi_h - \phi_S$$

➠ "Sivers angle"

Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

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

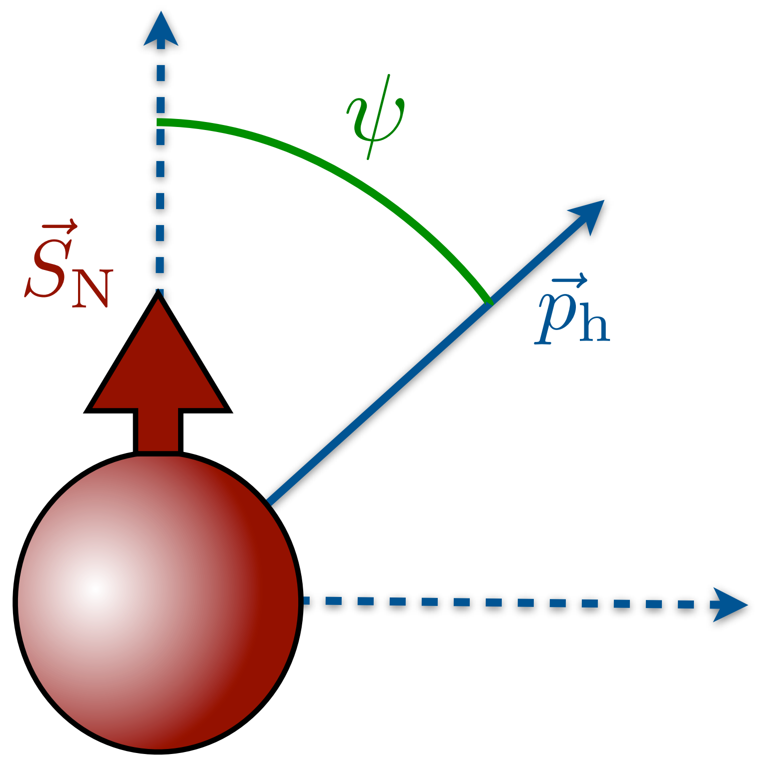


Inclusive hadron electro-production

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

- scattered lepton undetected
  ➥ lepton kinematics unknown

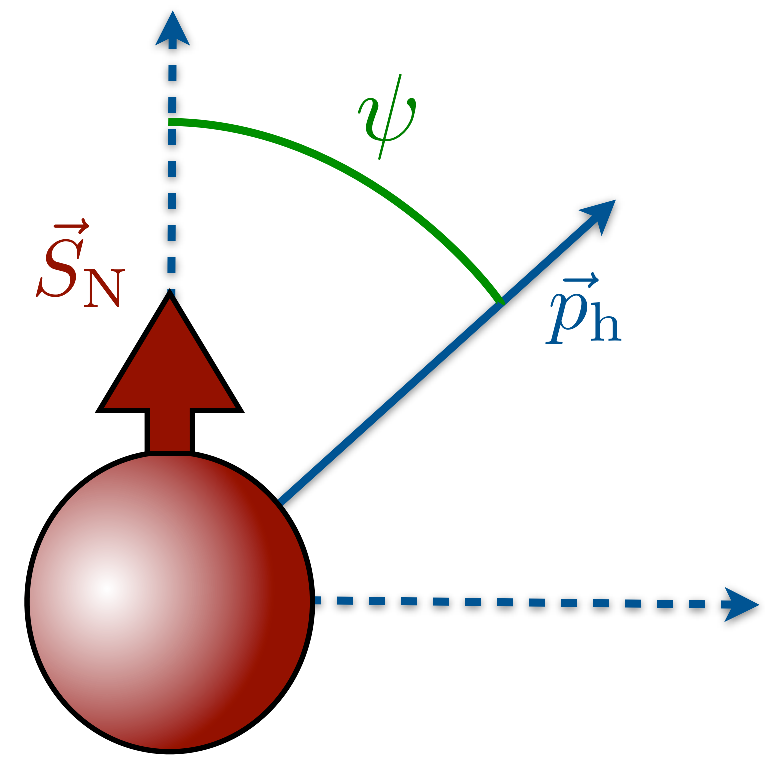
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?



Inclusive hadron electro-production

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

- scattered lepton undetected
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to S_N (k x p_h) ~ $\sin\psi$



$$A_{\mathrm{UT}}(P_T, x_F, \psi) = A_{\mathrm{UT}}^{\sin\psi}(P_T, x_F) \sin\psi$$

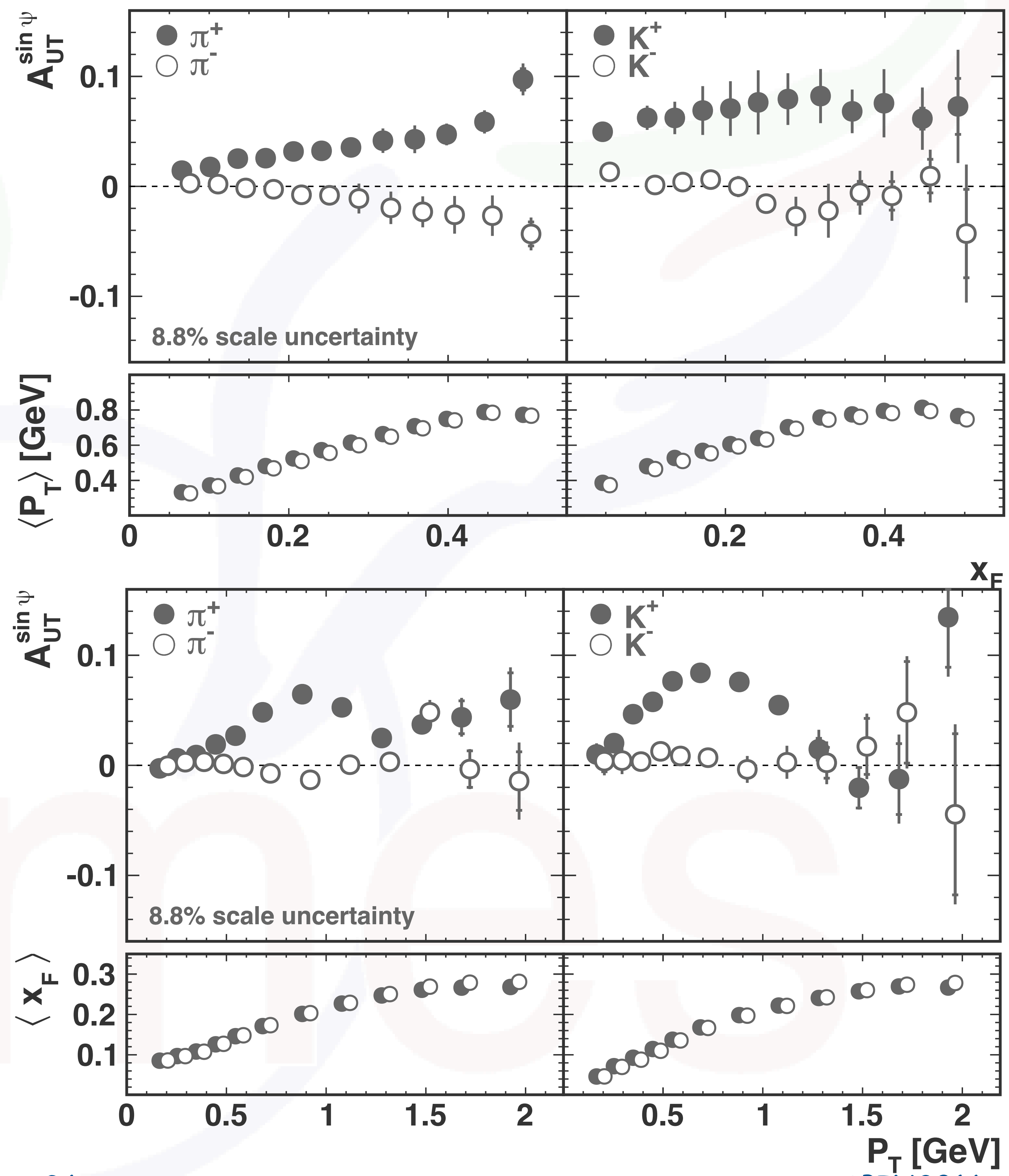
$$A_{\mathrm{N}} \equiv \frac{\int_{\pi}^{2\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UT}} \sin\psi - \int_0^{\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UT}} \sin\psi}{\int_0^{2\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UU}}}$$

$$= -\frac{2}{\pi} A_{\mathrm{UT}}^{\sin\psi}$$

1D dependences of A_{UT} sinψ amplitude

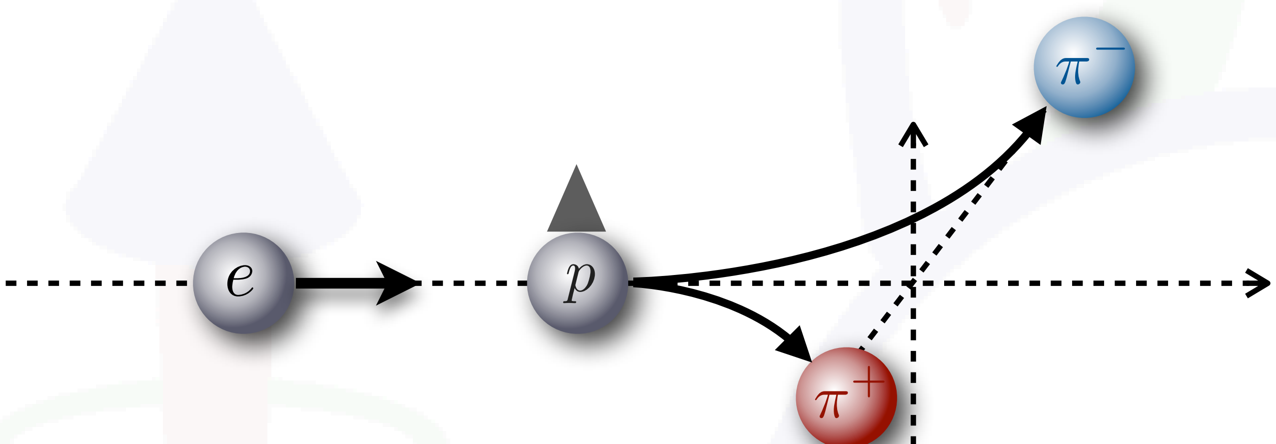
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]

- clear left-right asymmetries for pions and positive kaons
- increasing with x_F (as in pp)
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➡ look at 2D dependences



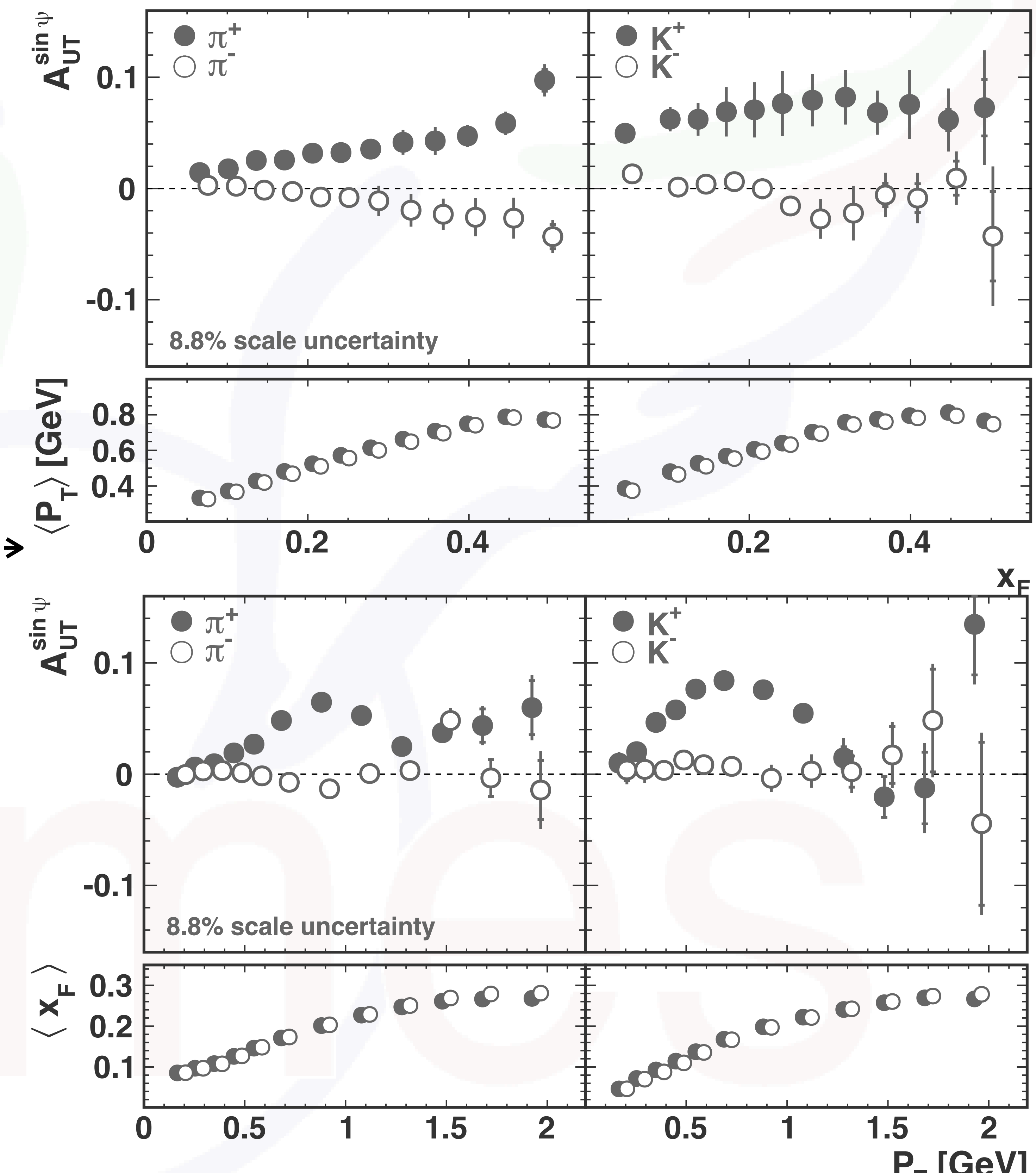
1D dependences of A_{UT} $\sin\psi$ amplitude

- clear left-right asymmetries for pions and positive kaons
- increasing with x_F (as in pp)



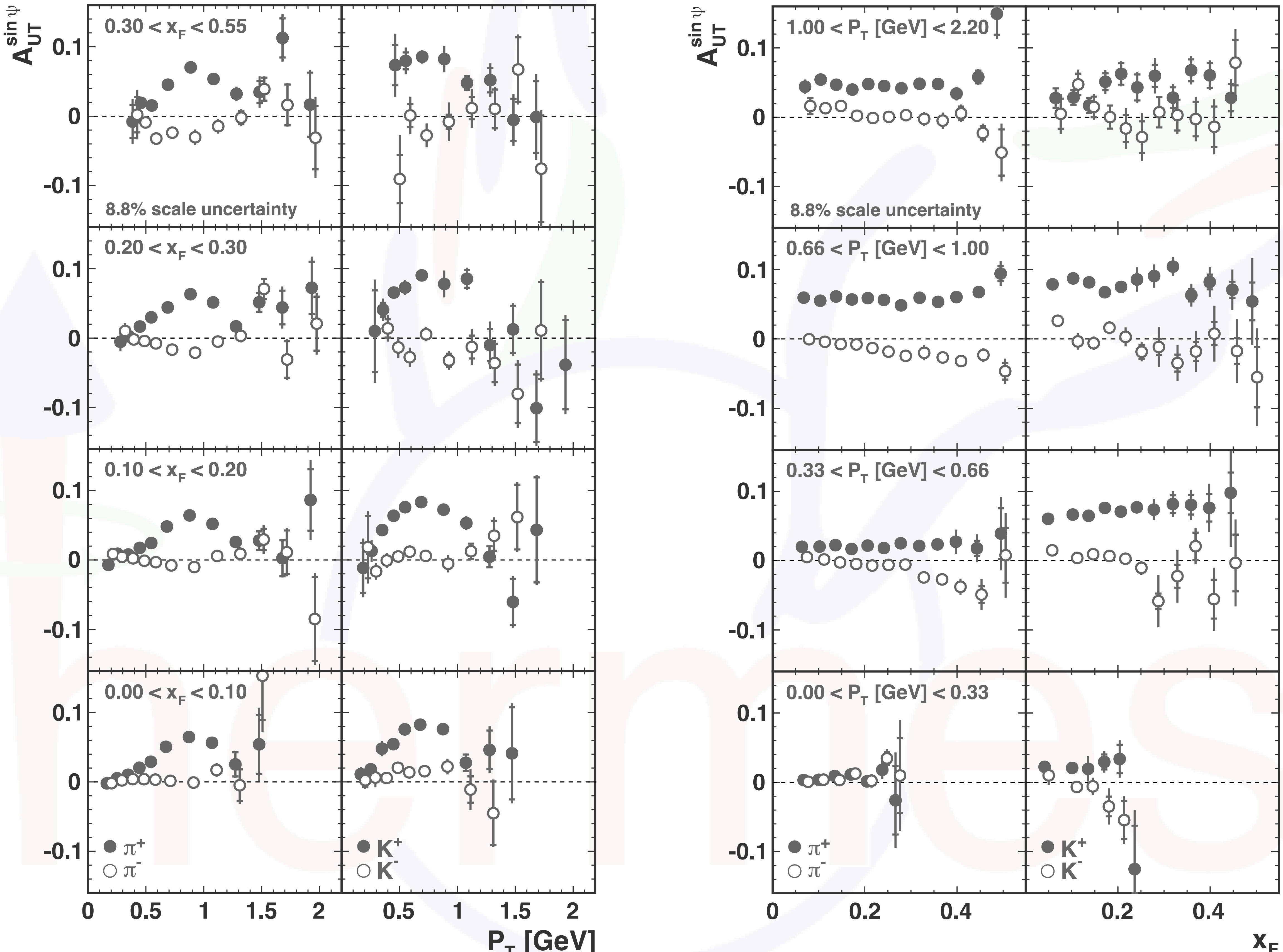
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➡ look at 2D dependences

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



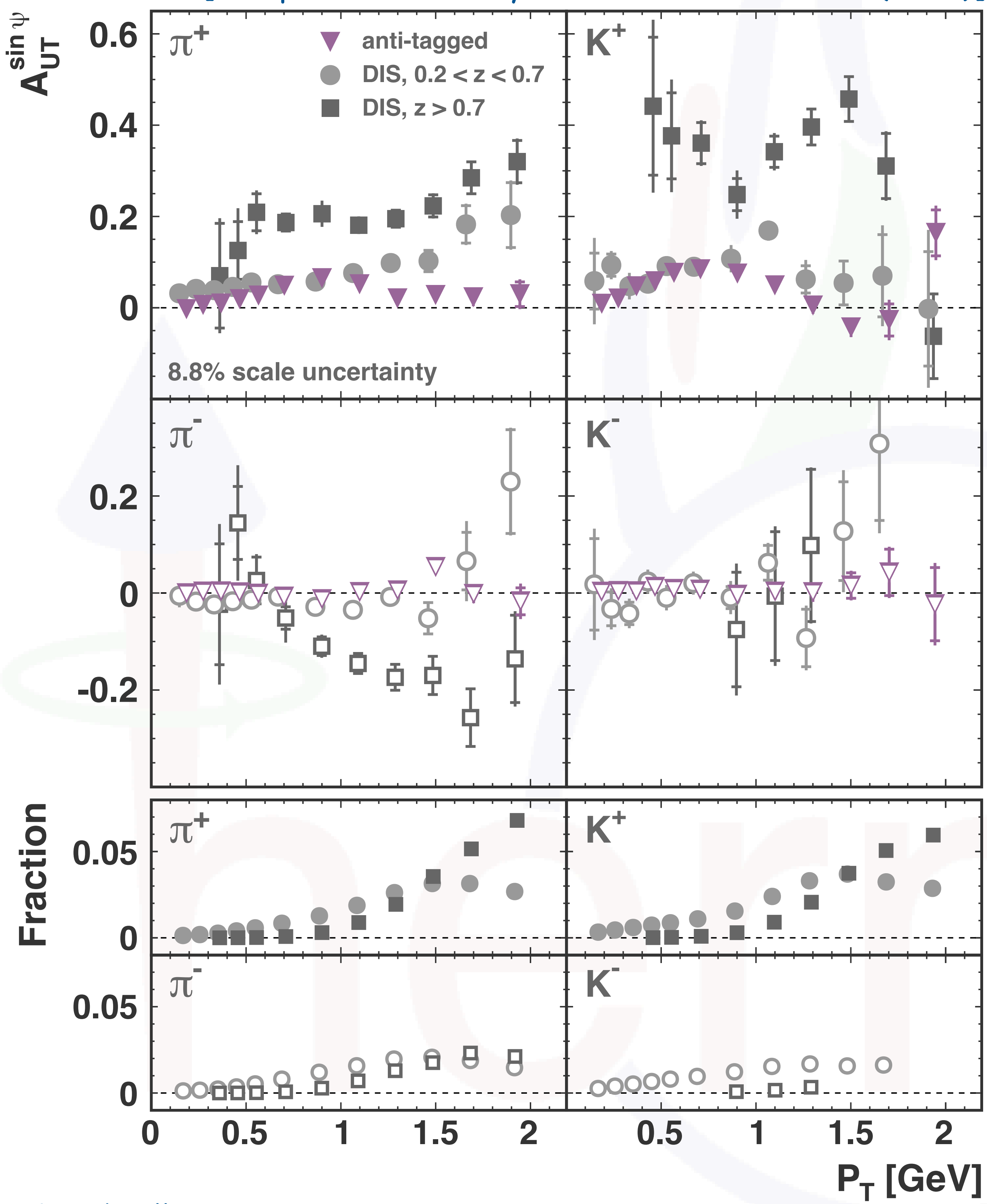
Inclusive hadrons: 2D dependences

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



Asymmetries of subprocesses

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



“anti-tagged” no lepton in acceptance

DIS 0.2<z<0.7

DIS z>0.7

- at large P_T significant contribution from DIS events (Q^2>1)
- asymmetries increase with larger z
- large asymmetries also for π^- in case of z>0.7