The Sivers and other semi-inclusive single-spin asymmetries at HERMES

Gunar.Schnell @ desy.de

Spin-Momentum Structure of the Nucleon

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + \lambda\Lambda\,g_1 + \lambda\,S^ik^i\,\frac{1}{m}\,g_{1T}\Big]$$

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^iS^ih_1 + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]$$

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}	$h_1,\ h_{1T}^{\perp}$

Twist-2 TMDs

- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

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$$+ s^i(2k^i k^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^i k^i\,\frac{1}{m}\,h_{1L}^\perp\Big]$$

quark pol.

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

Twist-2 TMDs

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- functions in black survive integration ... se momentum
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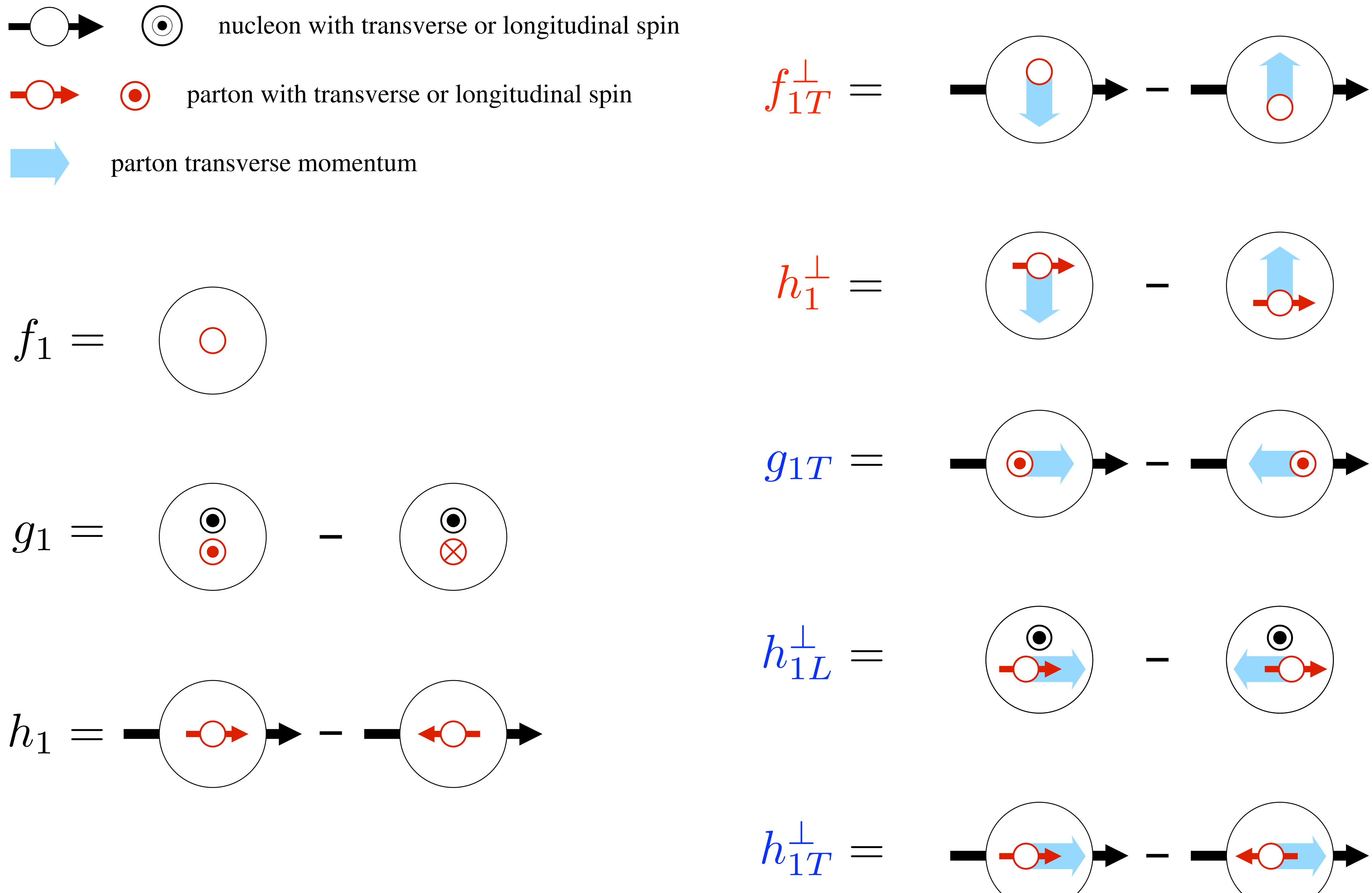
Transverse-Momentum-Dependent DF



Courtesy of A. Bacchetta

1-Hadron Production (ep→ehX)

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

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

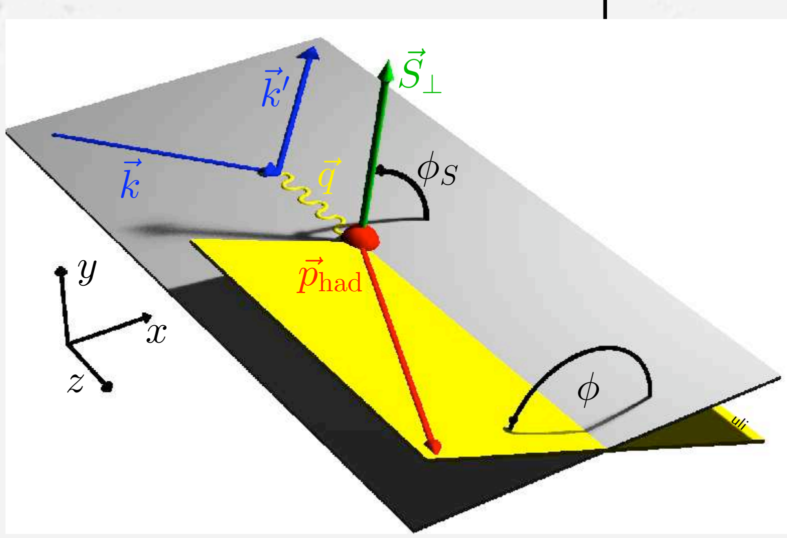
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

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

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

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

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

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$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

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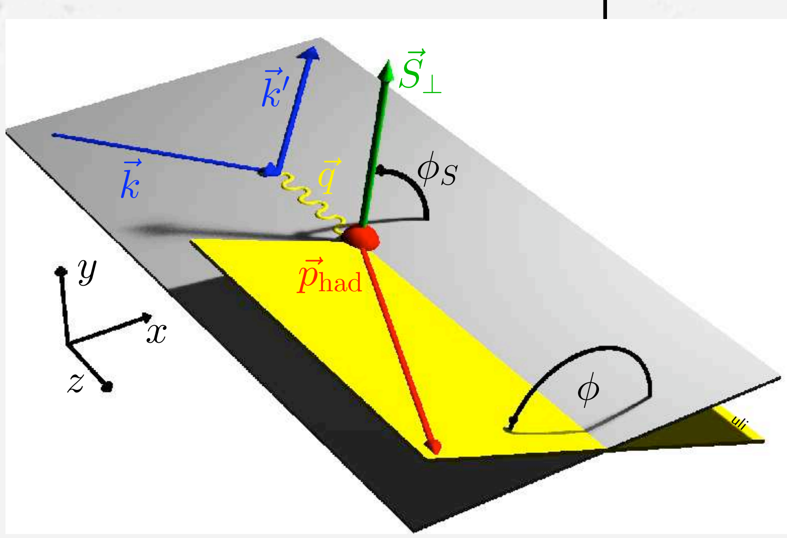
σ_{XY}: X → **Beam**, Y → **Target**

Polarization



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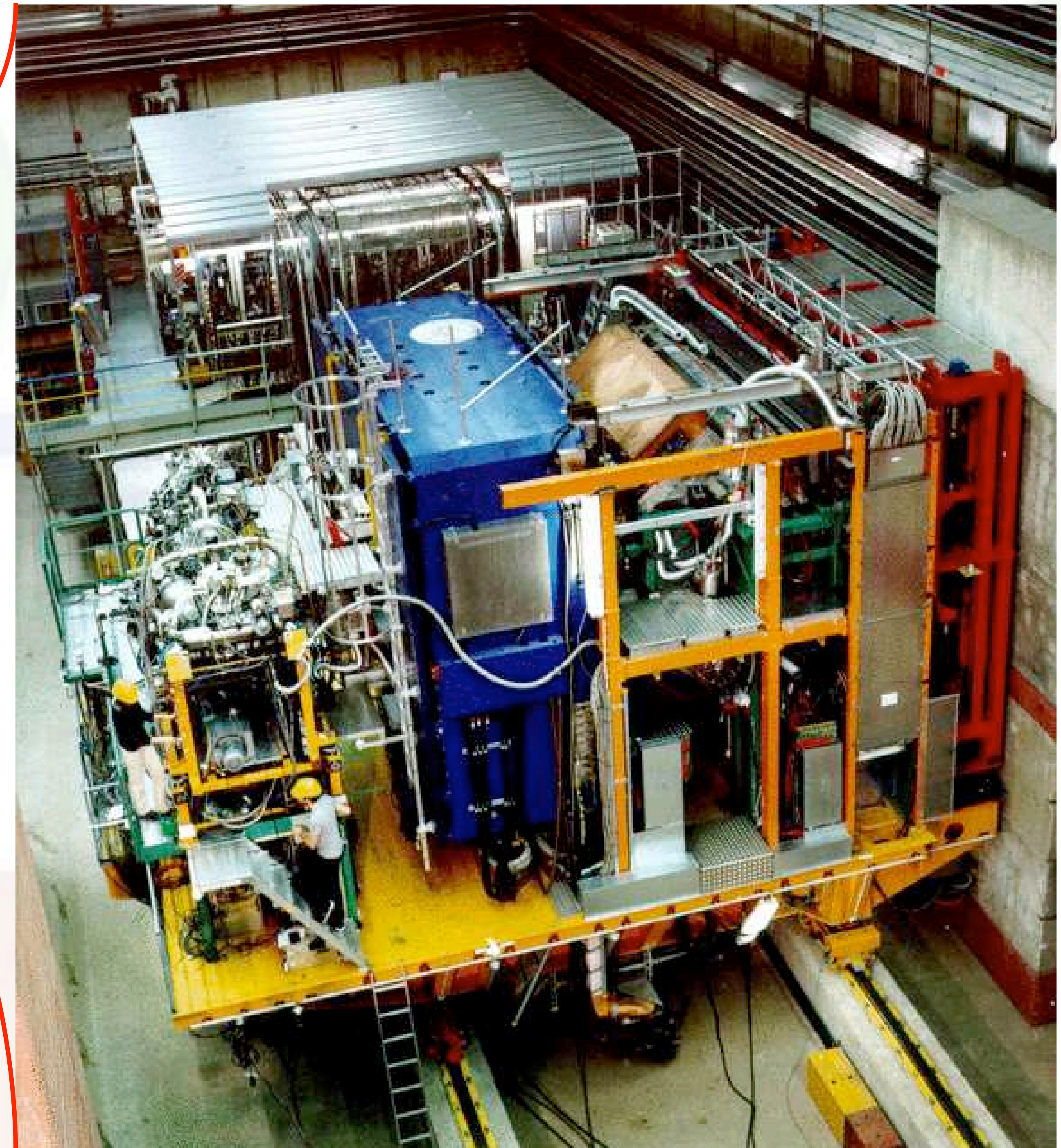
The HERMES Experiment (†2007)

27.5 GeV e^+/e^- beam of HERA



transversely polarized hydrogen target with in average 72% polarization

Extraction of amplitudes

Extraction of amplitudes

- **ideal world:**

$$\langle \sin(n\phi \pm \phi_S) \rangle_{\mathrm{UT}} \equiv \frac{\int \mathrm{d}\phi\, \mathrm{d}\phi_S \sin(n\phi \pm \phi_S) [\, \mathrm{d}\sigma(\phi, \phi_S) - \mathrm{d}\sigma(\phi, \phi_S + \pi)]}{\int \mathrm{d}\phi\, \mathrm{d}\phi_S [\, \mathrm{d}\sigma(\phi, \phi_S) + \mathrm{d}\sigma(\phi, \phi_S + \pi)]}$$

or fit experimental yield, e.g.,

$$\begin{aligned} \mathcal{N}(\phi, \phi_S) \sim\ & 1 + 2\langle \cos\phi \rangle_{\mathrm{UU}} \cos\phi + 2\langle \cos 2\phi \rangle_{\mathrm{UU}} \cos 2\phi \\ & + S_T\ [2\langle \sin(\phi - \phi_S) \rangle_{\mathrm{UT}} \sin(\phi - \phi_S) + \ldots\ ] \end{aligned}$$

Extraction of amplitudes

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or fit experimental yield, e.g.,

$$\mathcal{N}(\phi,\phi_S) \sim 1 + 2\langle\cos\phi\rangle_{\mathrm{UU}}\cos\phi + 2\langle\cos 2\phi\rangle_{\mathrm{UU}}\cos 2\phi + S_T\ [2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}\sin(\phi-\phi_S) + \ldots\ ]$$

- **real world (no perfect detection efficiency):**

$$\mathcal{N}(\phi,\phi_S) \sim \epsilon(\phi,\phi_S)\{1 + 2\langle\cos\phi\rangle_{\mathrm{UU}}\cos\phi + 2\langle\cos 2\phi\rangle_{\mathrm{UU}}\cos 2\phi + S_T\ [2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}\sin(\phi-\phi_S) + \ldots\ ]\}$$

  - ☛ **can eliminate efficiency by target-polarization balancing**
  - ☛ **if cosine modulations unknown then extract Fourier components of**

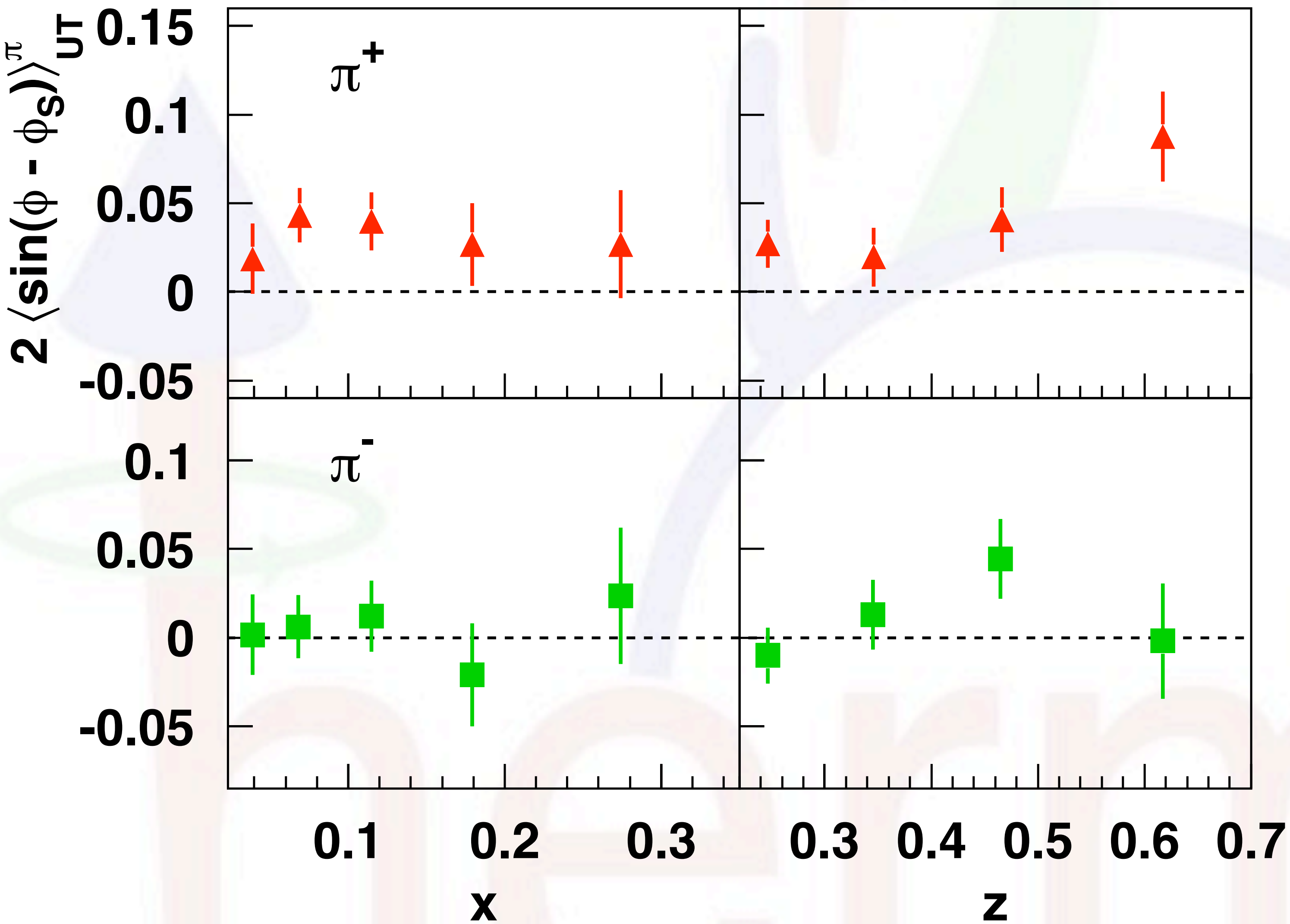
$$A_{\mathrm{UT}}(\phi,\phi_S) \equiv \frac{2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}\sin(\phi-\phi_S) + \ldots}{1 + 2\langle\cos\phi\rangle_{\mathrm{UU}}\cos\phi + 2\langle\cos 2\phi\rangle_{\mathrm{UU}}\cos 2\phi}$$

systematics of neglecting cosine terms found to be negligible

The Sivers effect - a long way since first evidence from DIS

HERMES Sivers amplitudes

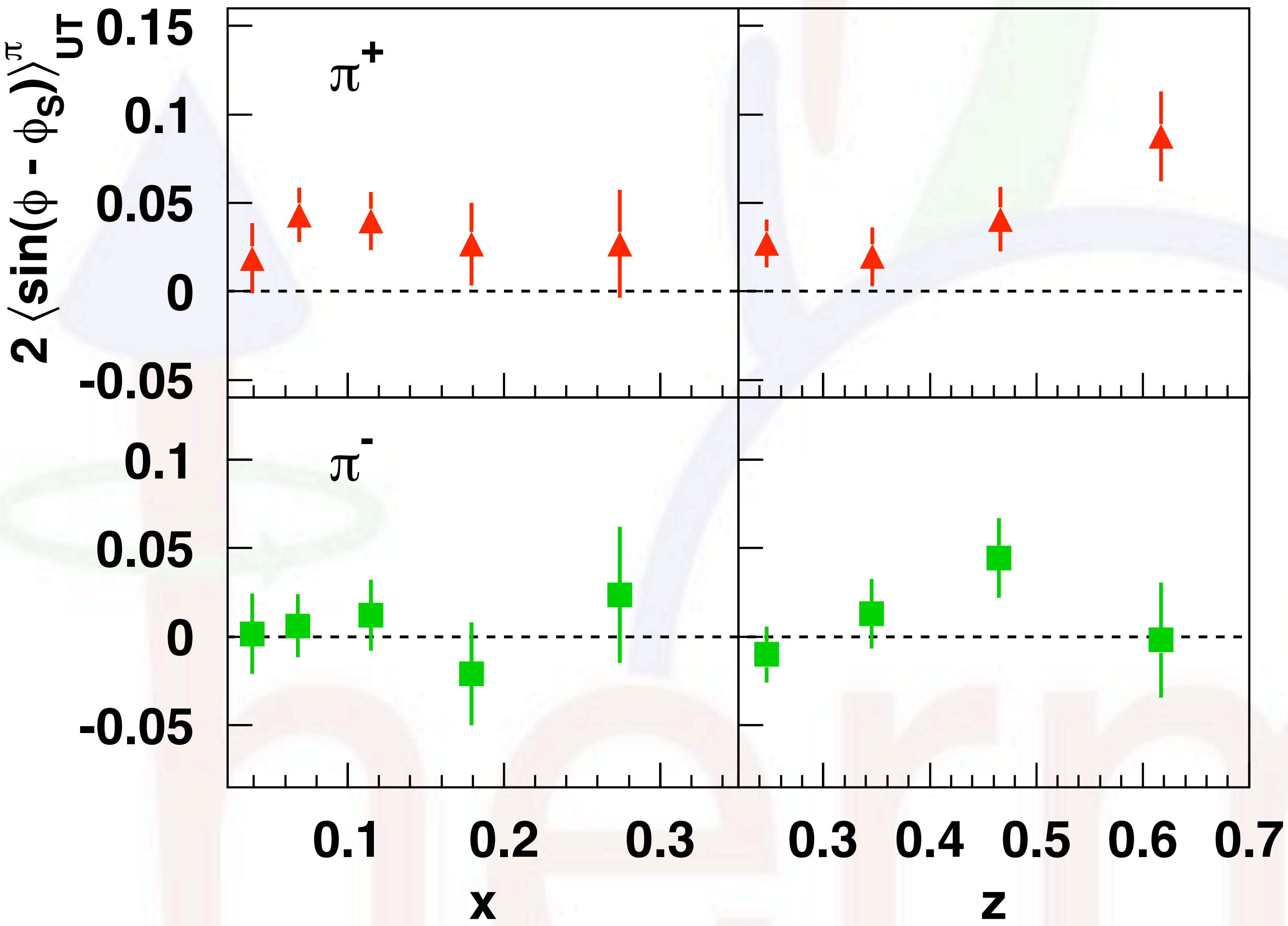
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]

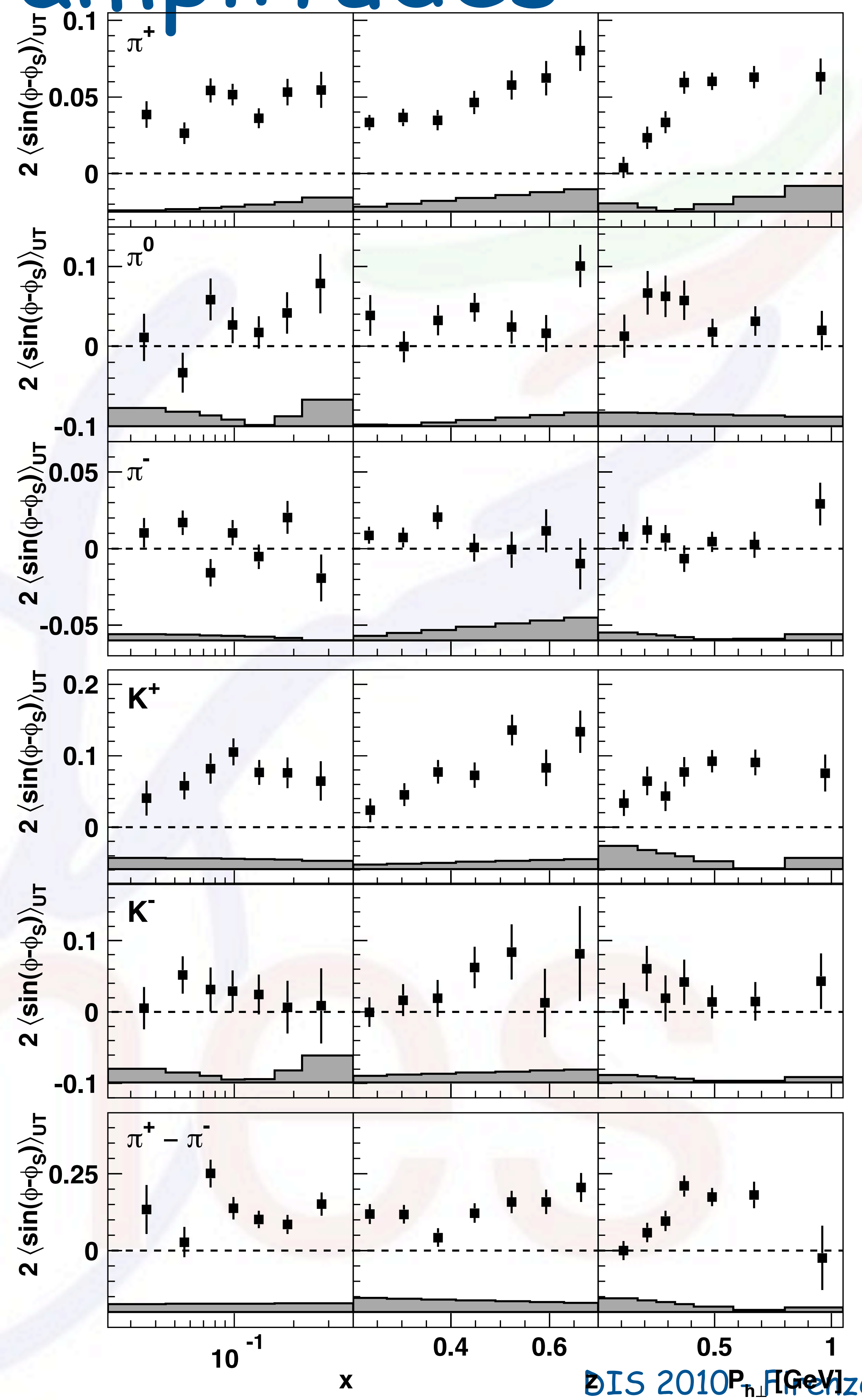


☑ first evidence for T-odd Sivers effect in SIDIS!

HERMES Sivers amplitudes

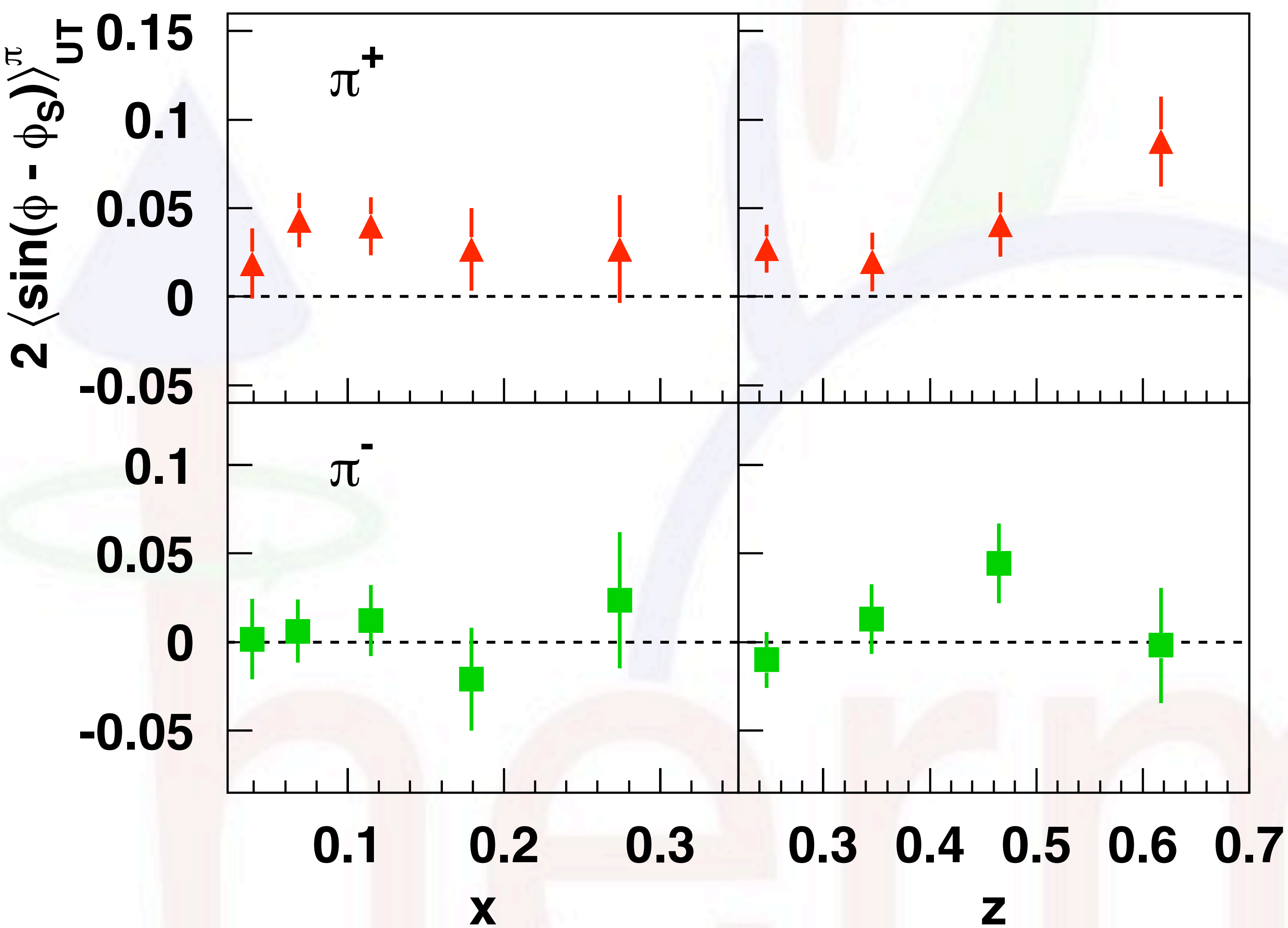
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]

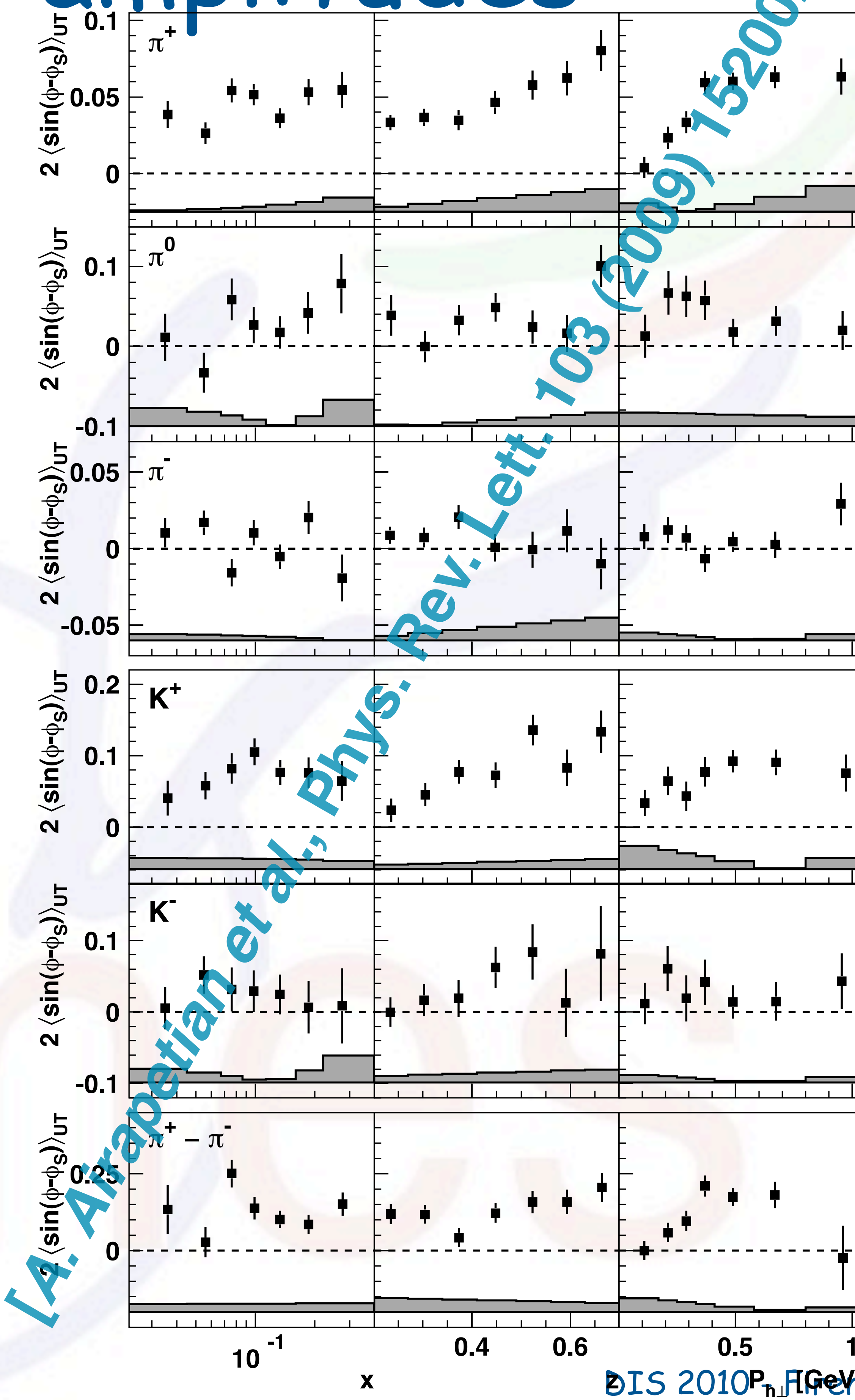




HERMES Sivers amplitudes

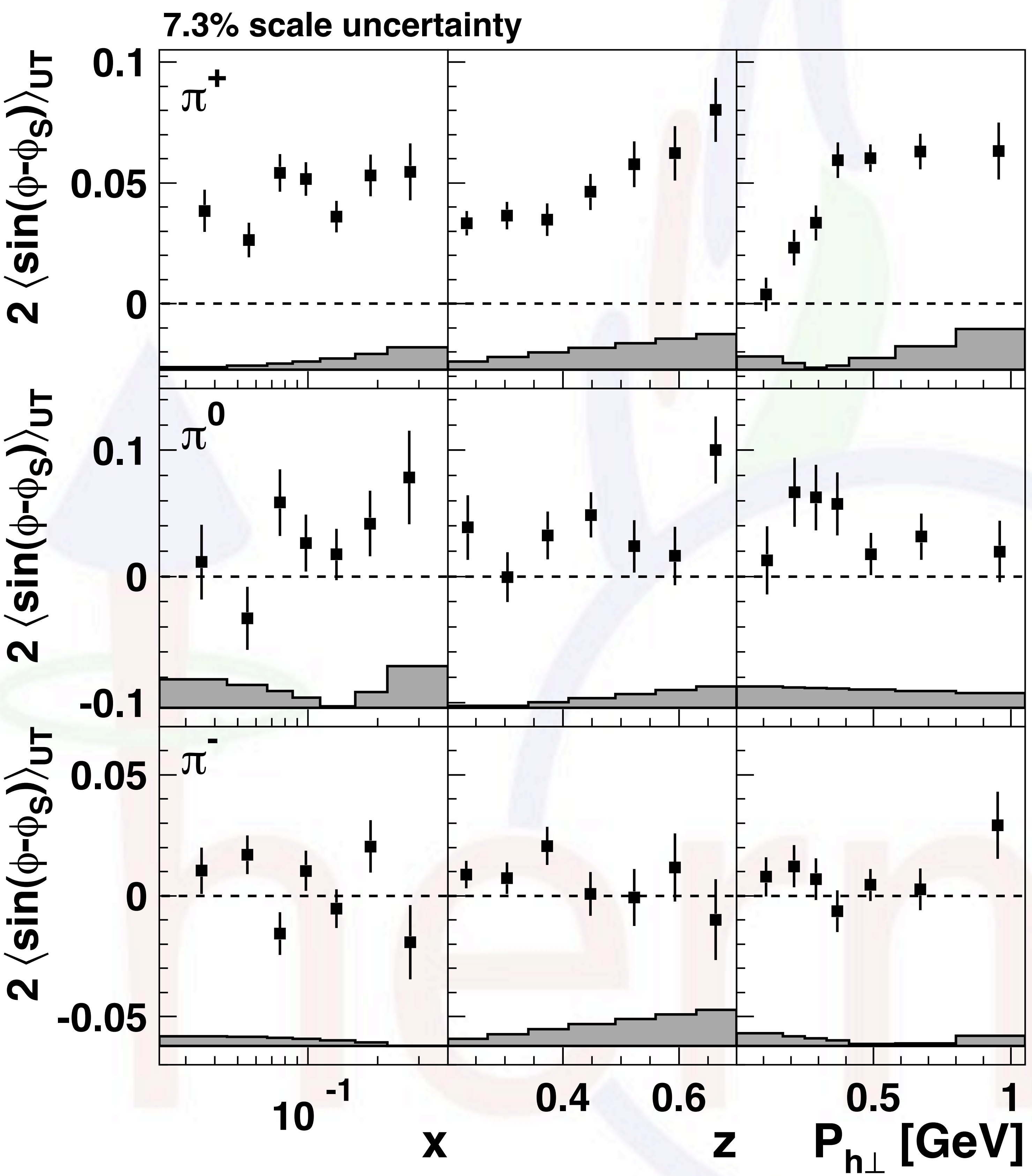
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]





[A. Airapetian et al., Phys. Rev. Lett. 103 (2009) 152002]

Sivers amplitudes for pions



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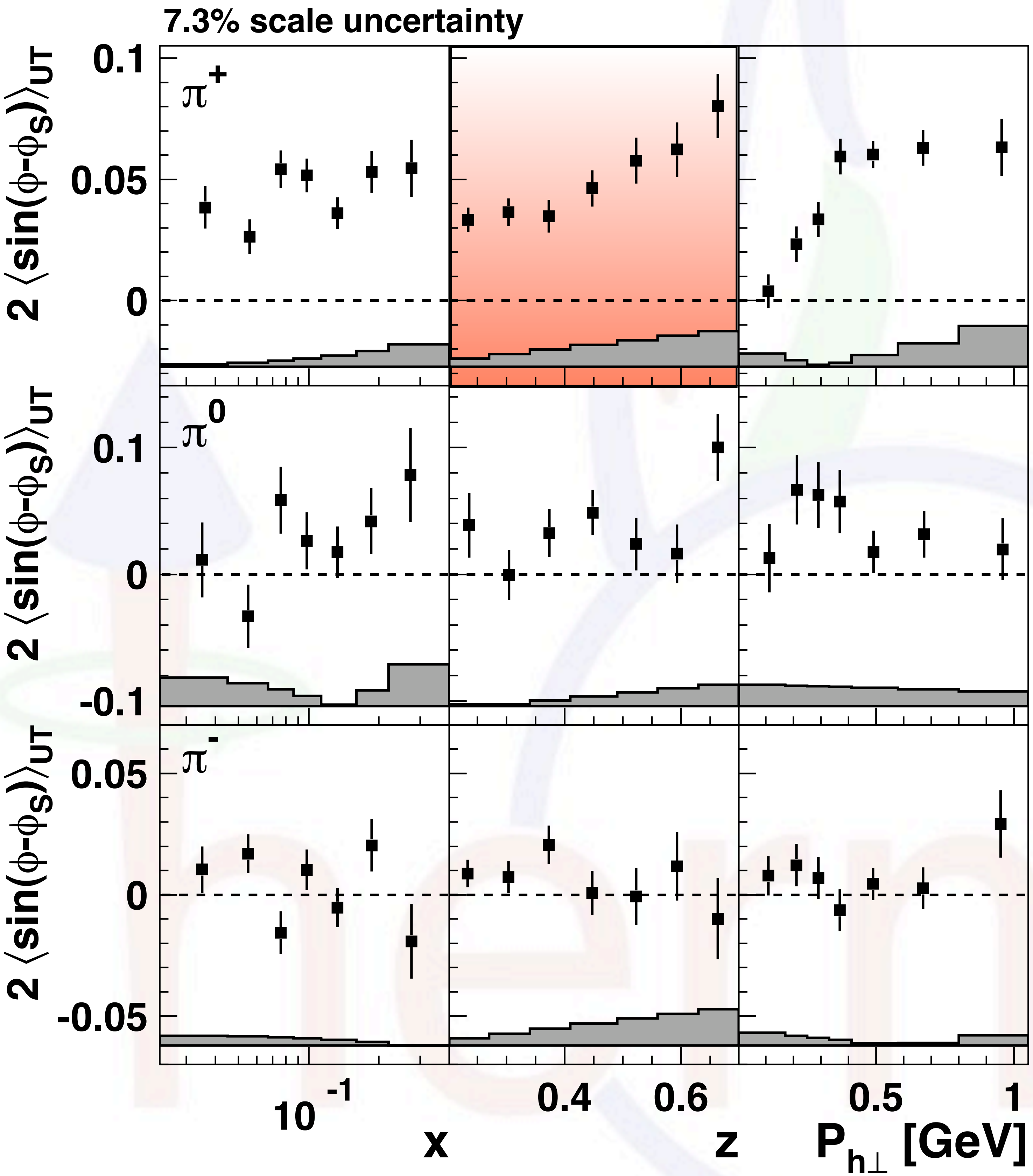
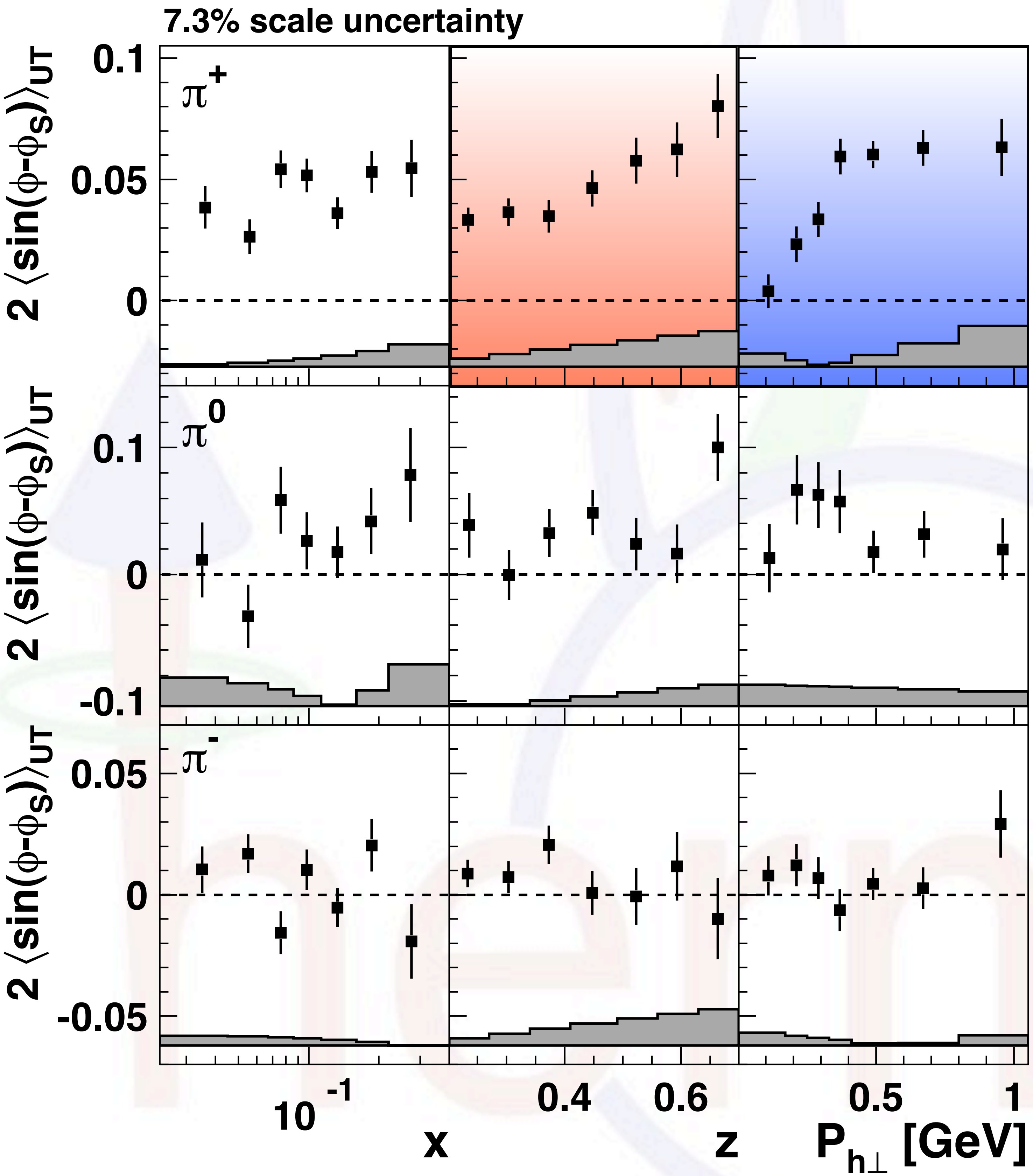


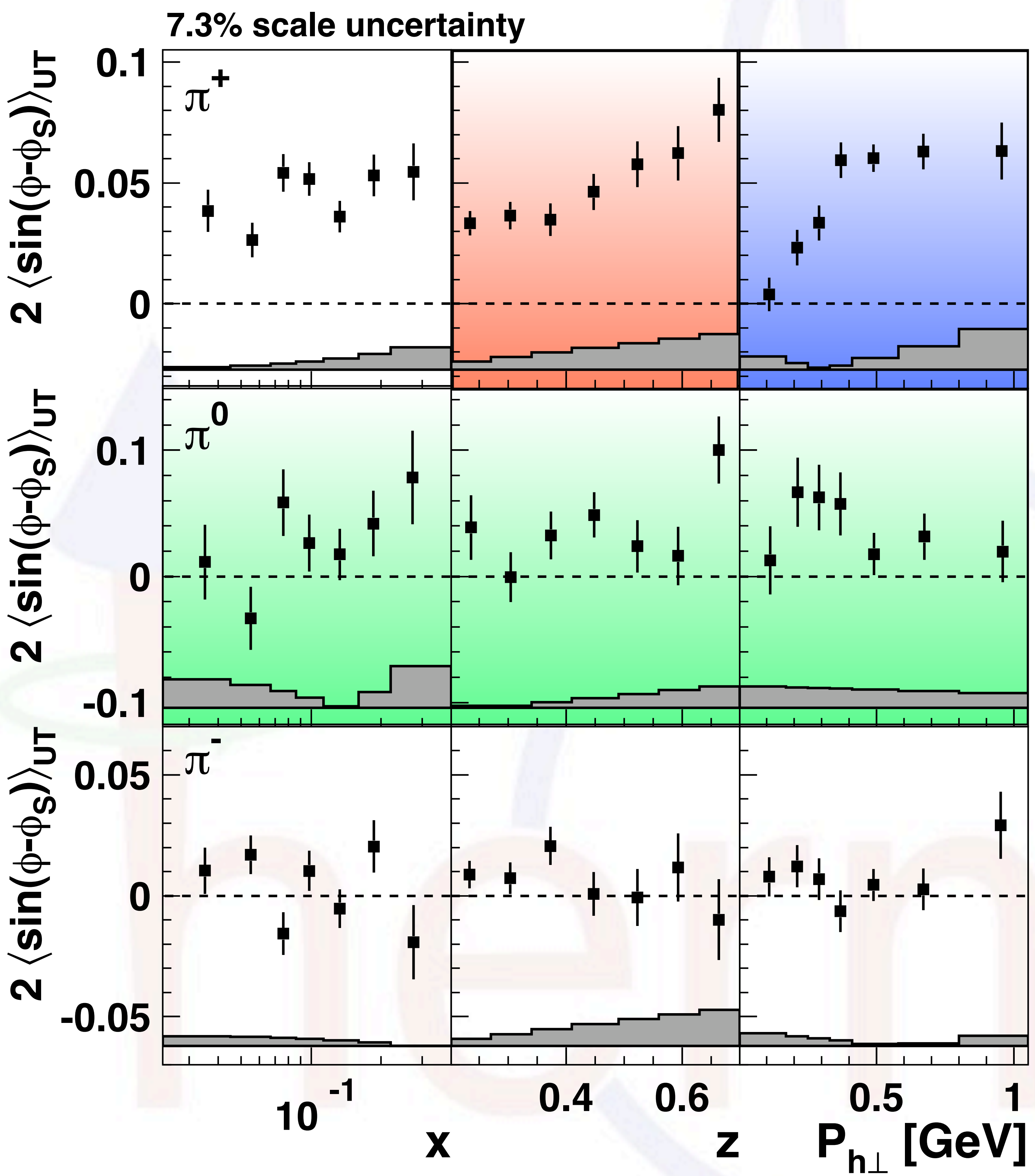
☛ clear rise with z

Sivers amplitudes for pions



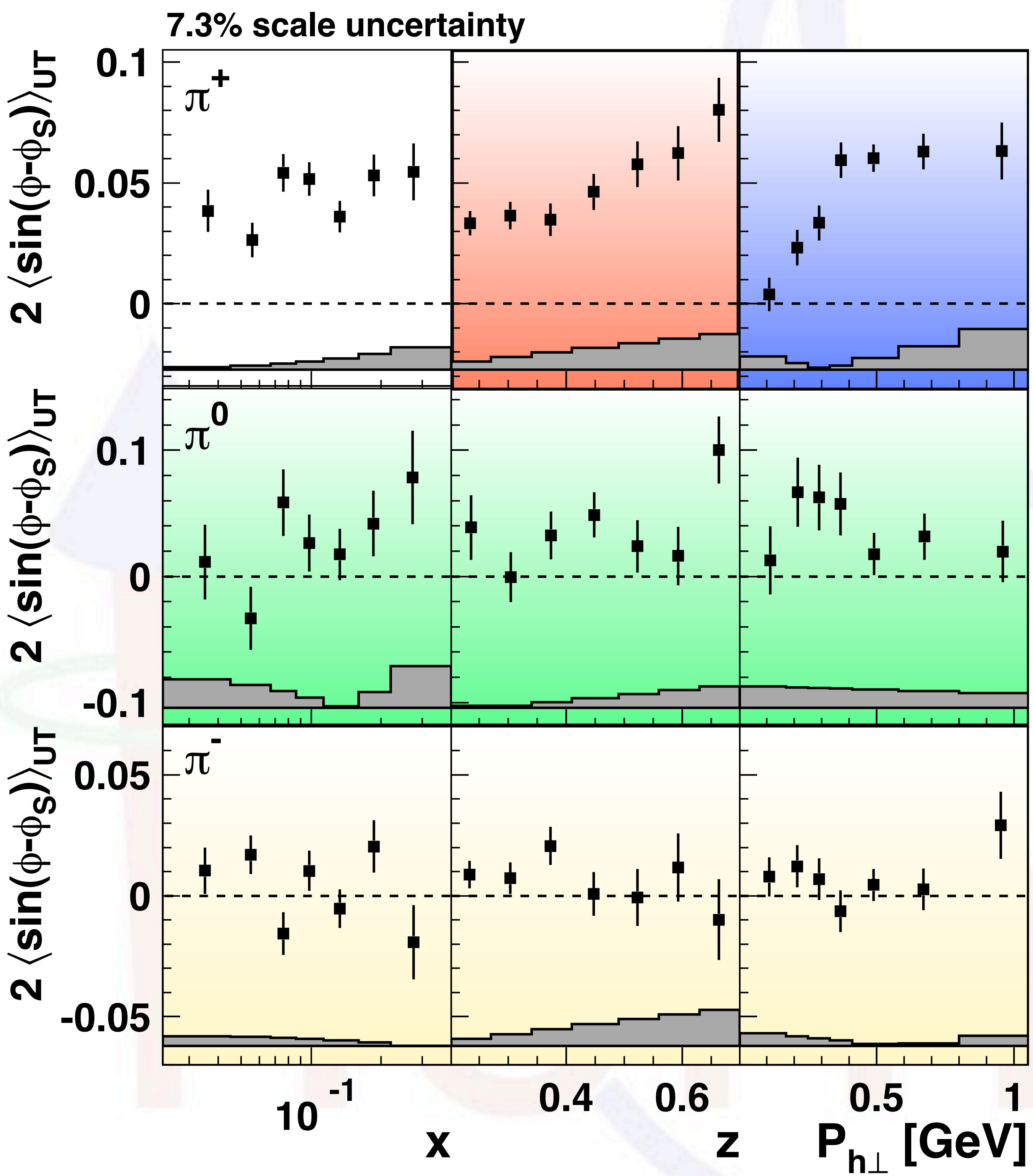
- ☛ clear rise with z
- ☛ rise at low $P_{h\perp}$
- ☛ plateau at high $P_{h\perp}$

Sivers amplitudes for pions



- ☛ clear rise with z
- ☛ rise at low $P_{h\perp}$
- ☛ plateau at high $P_{h\perp}$
- ☛ slightly positive

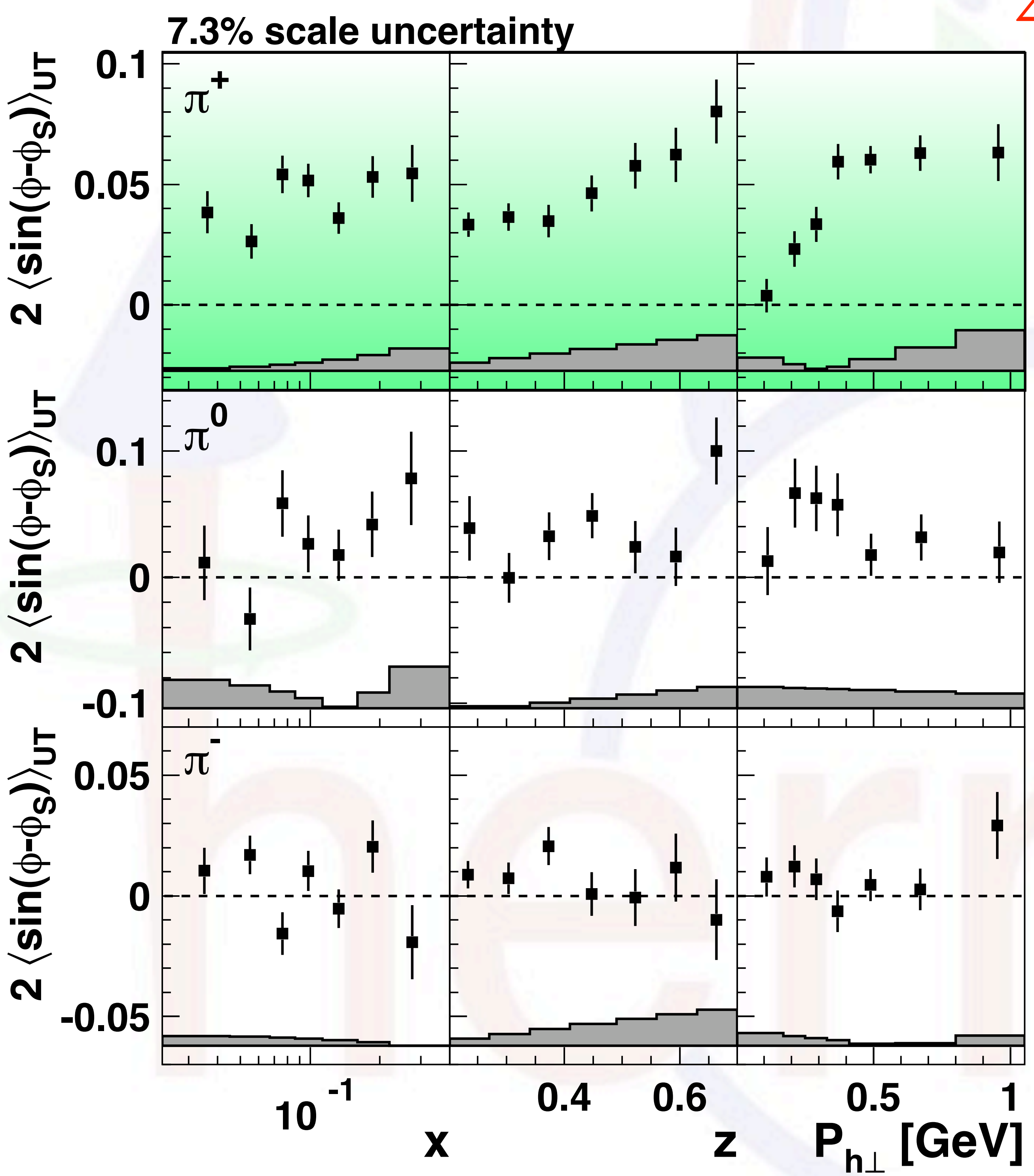
Sivers amplitudes for pions



- clear rise with z
- rise at low $P_{h\perp}$
- plateau at high $P_{h\perp}$
- slightly positive
- consistent with zero

Sivers amplitudes for pions

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



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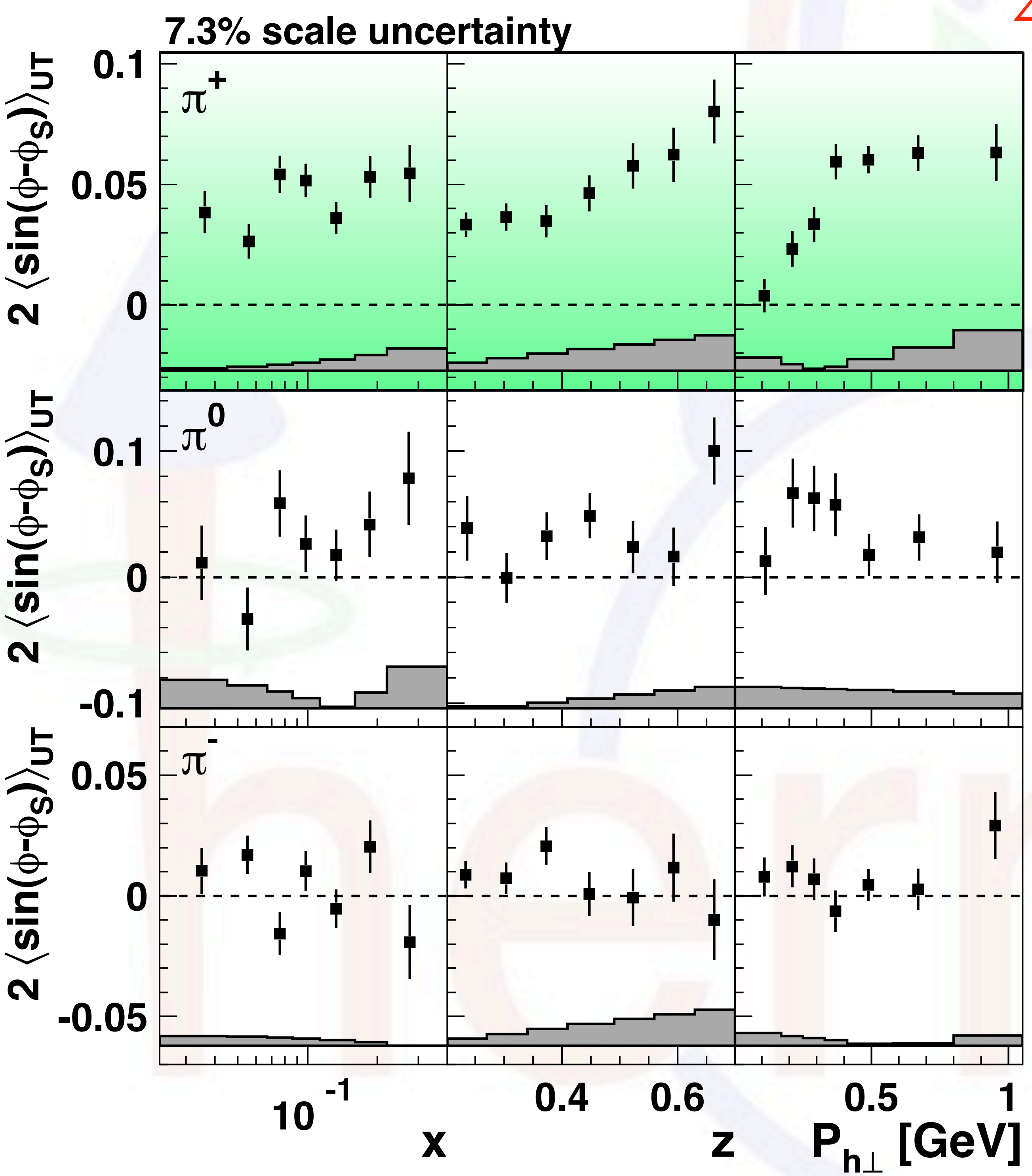

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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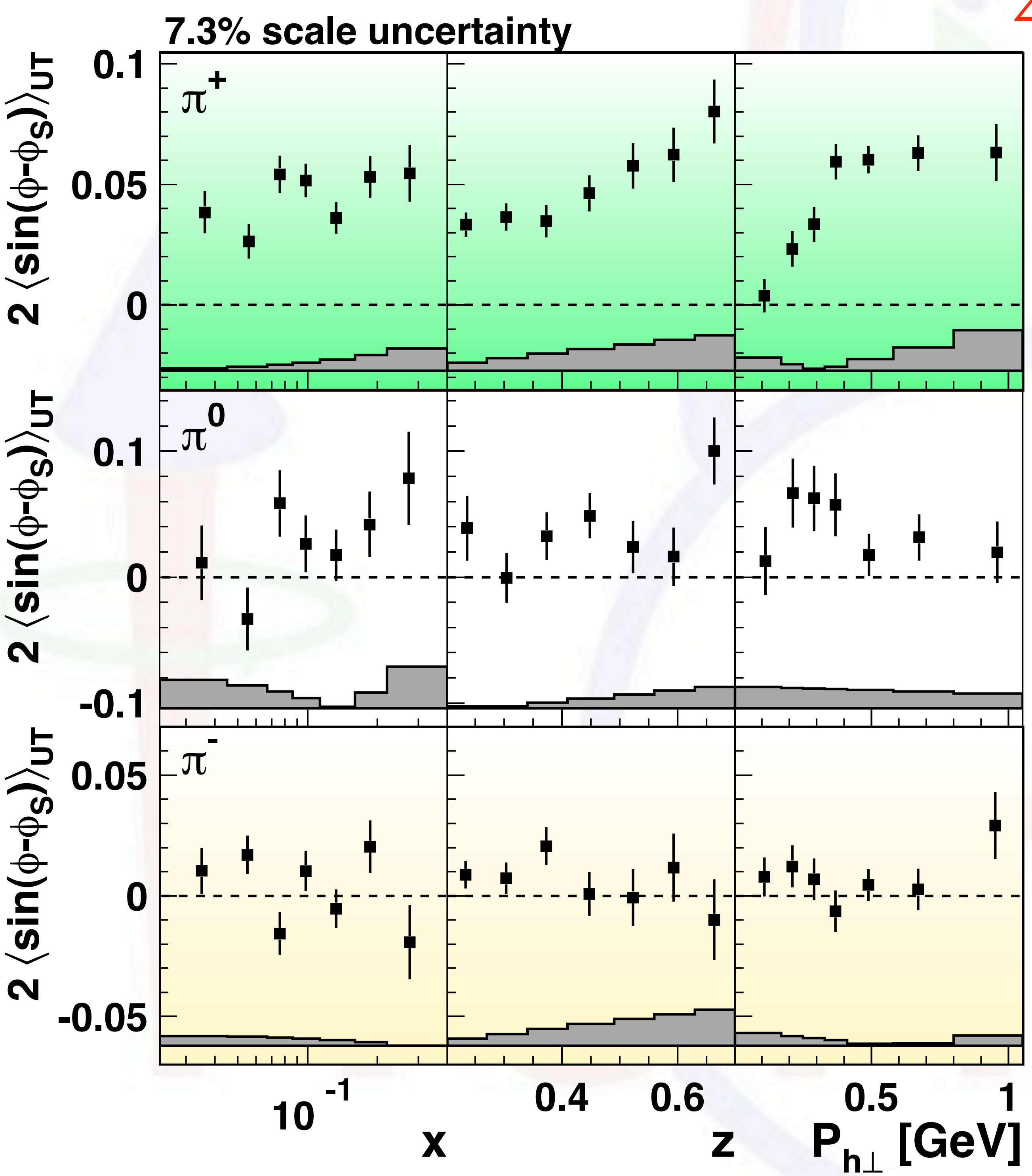

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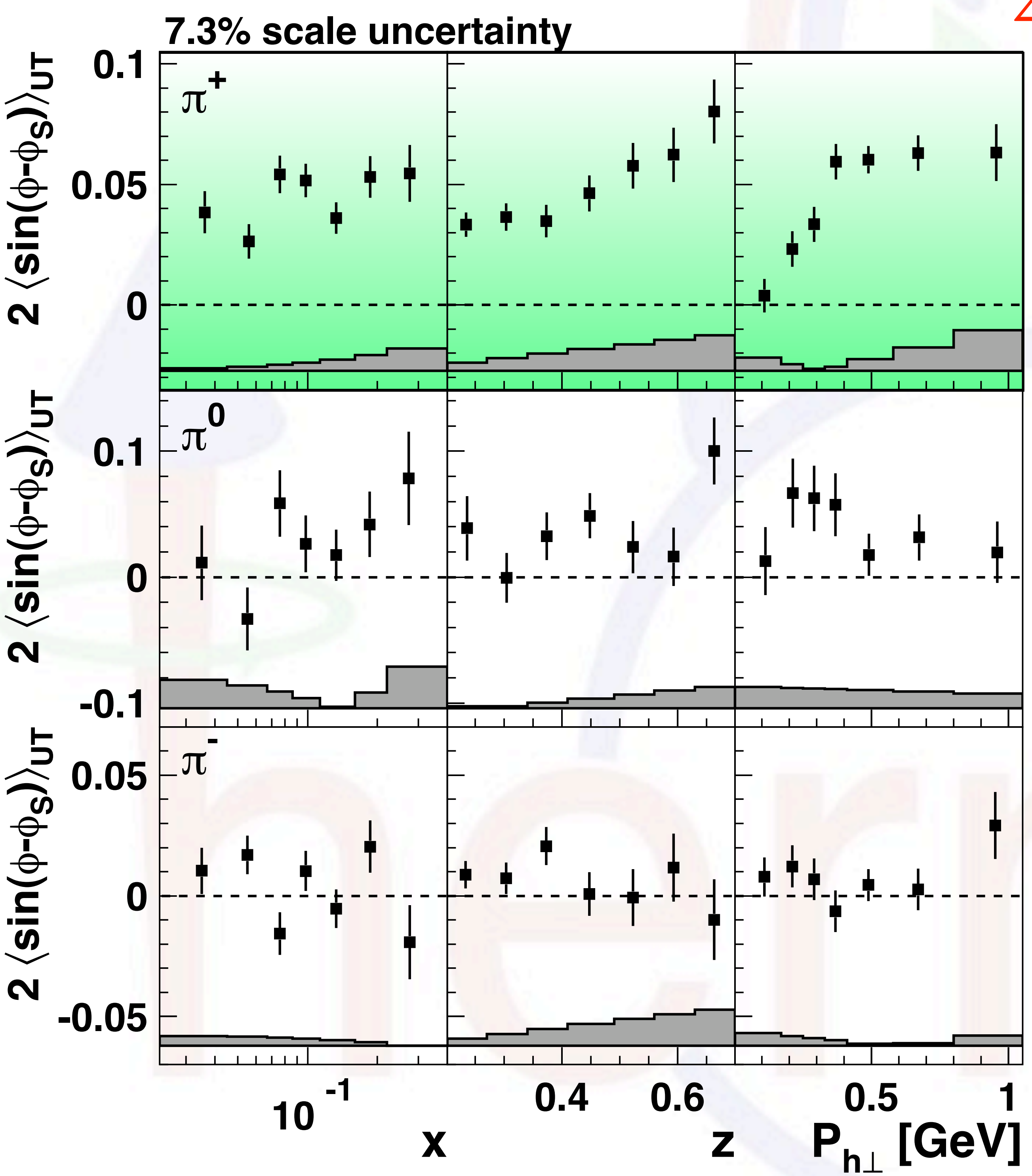
☛ u-quark Sivers DF < 0

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

Sivers amplitudes for pions

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



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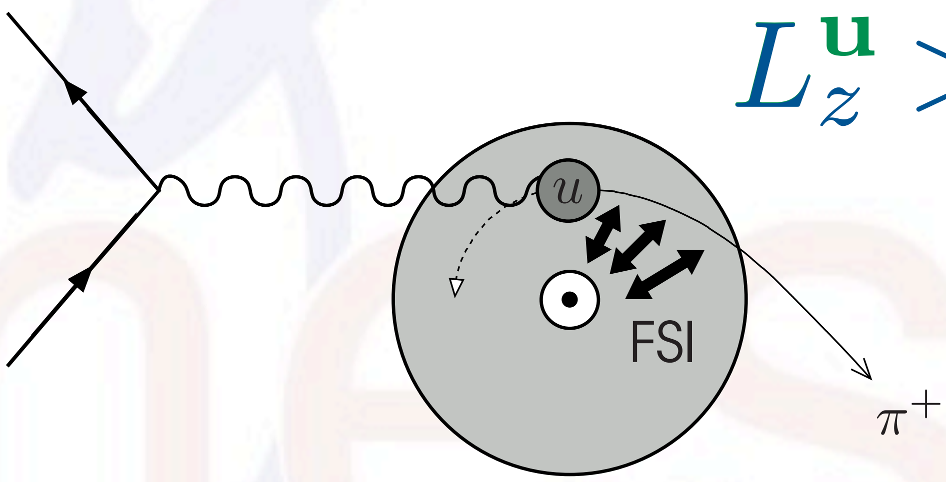
$$L_z^{\mathbf{u}} > 0$$



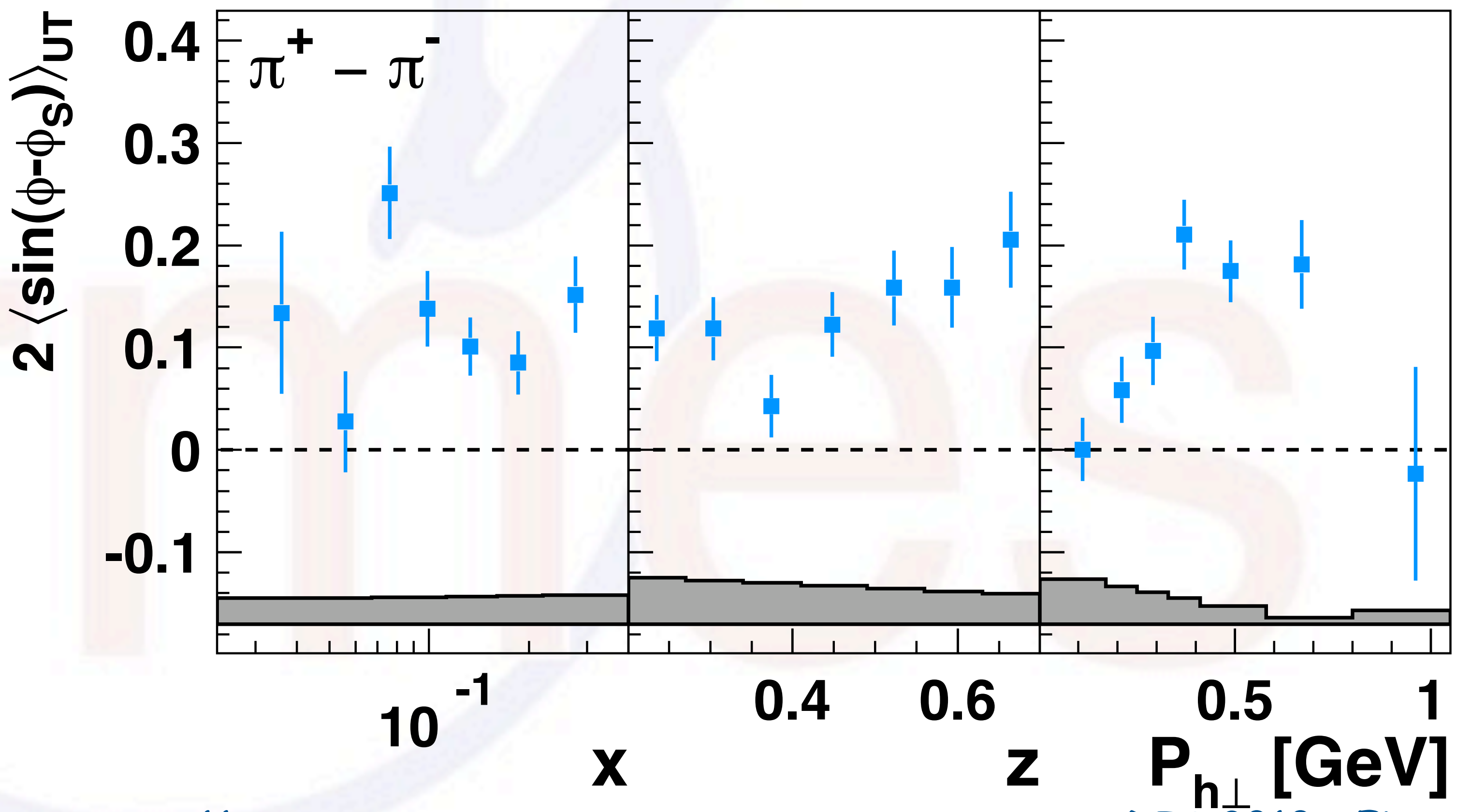
[*M. Burkardt*, Phys. Rev. D66 (2002) 014005]

Sivers "difference asymmetry"

- Transverse single-spin asymmetry of pion cross-section difference:

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{S_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

☛ $$\langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \propto -\frac{4f_{1T}^{\perp,u_v}-f_{1T}^{\perp,d_v}}{4f_1^{u_v}-f_1^{d_v}}$$



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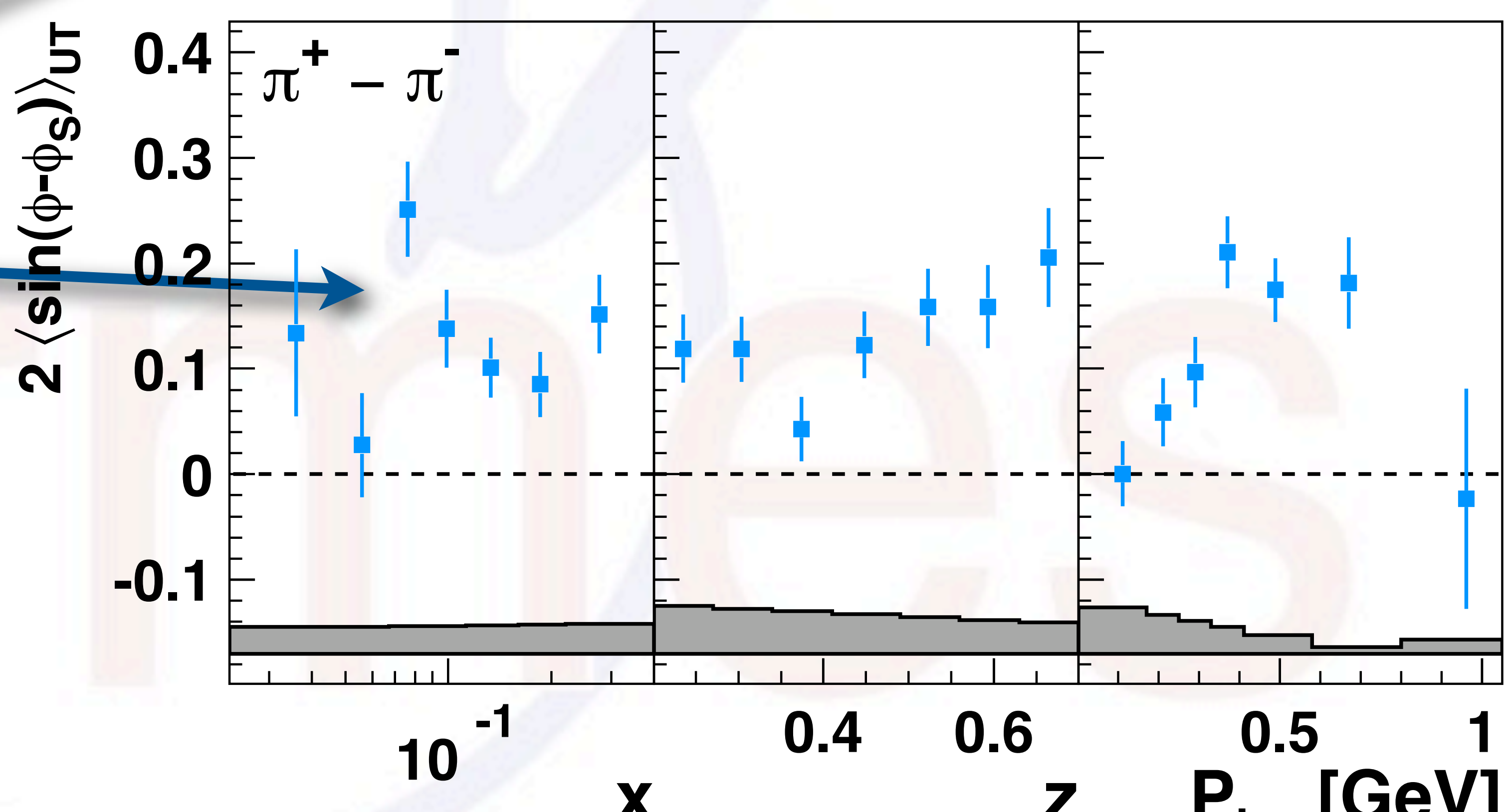
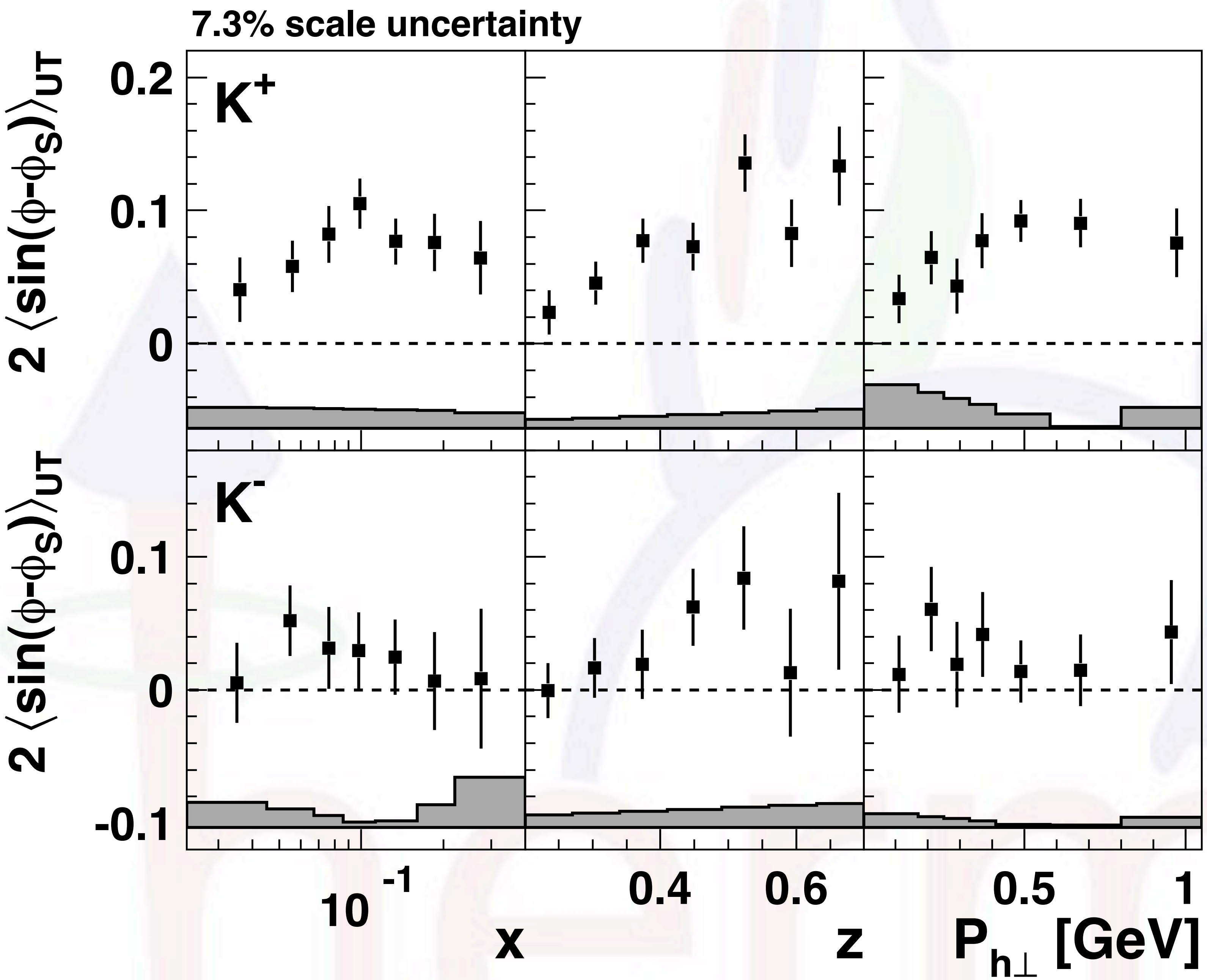
access to Sivers u-valence distribution



The kaon Sivers amplitudes



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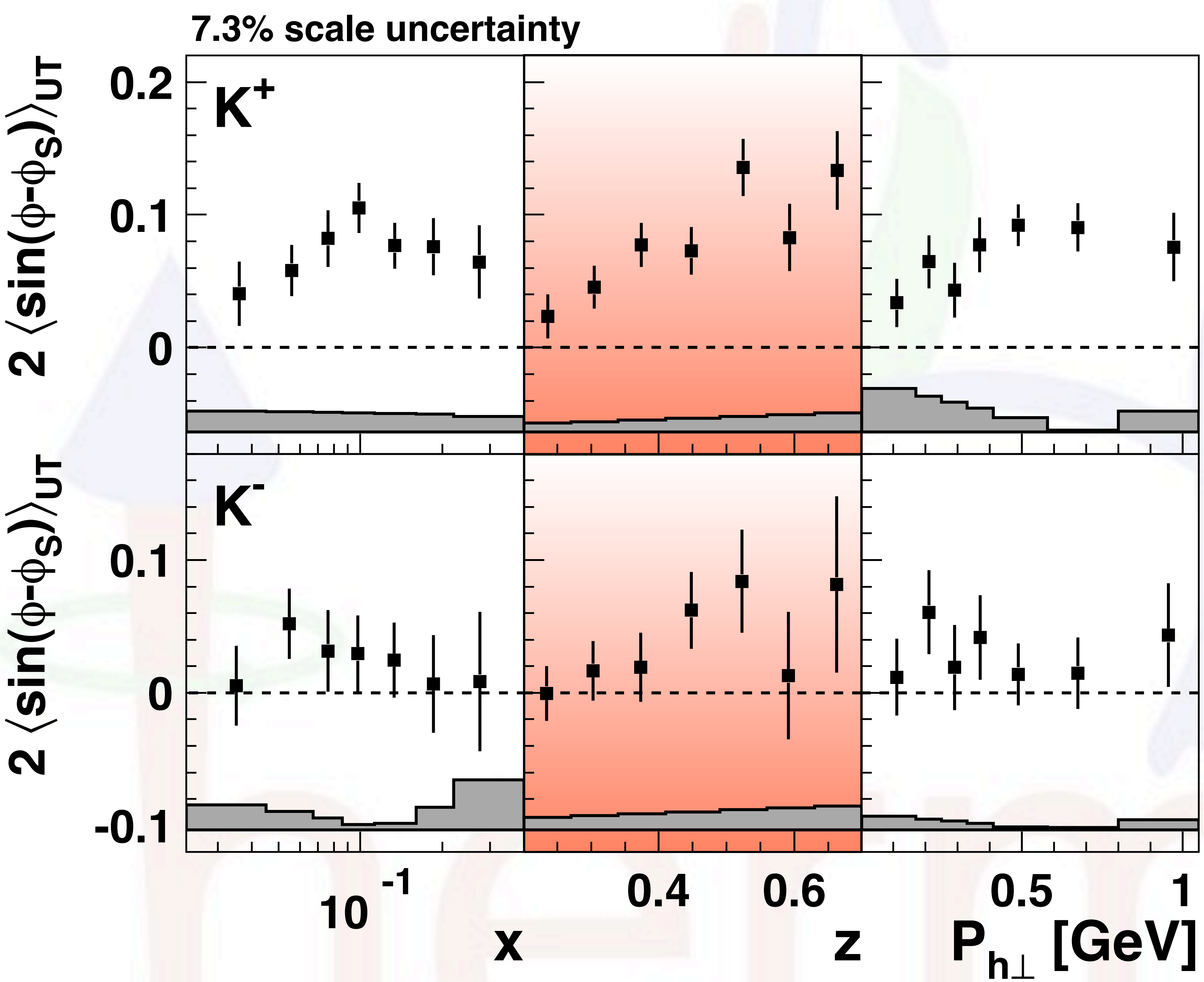

☛ clear rise with z

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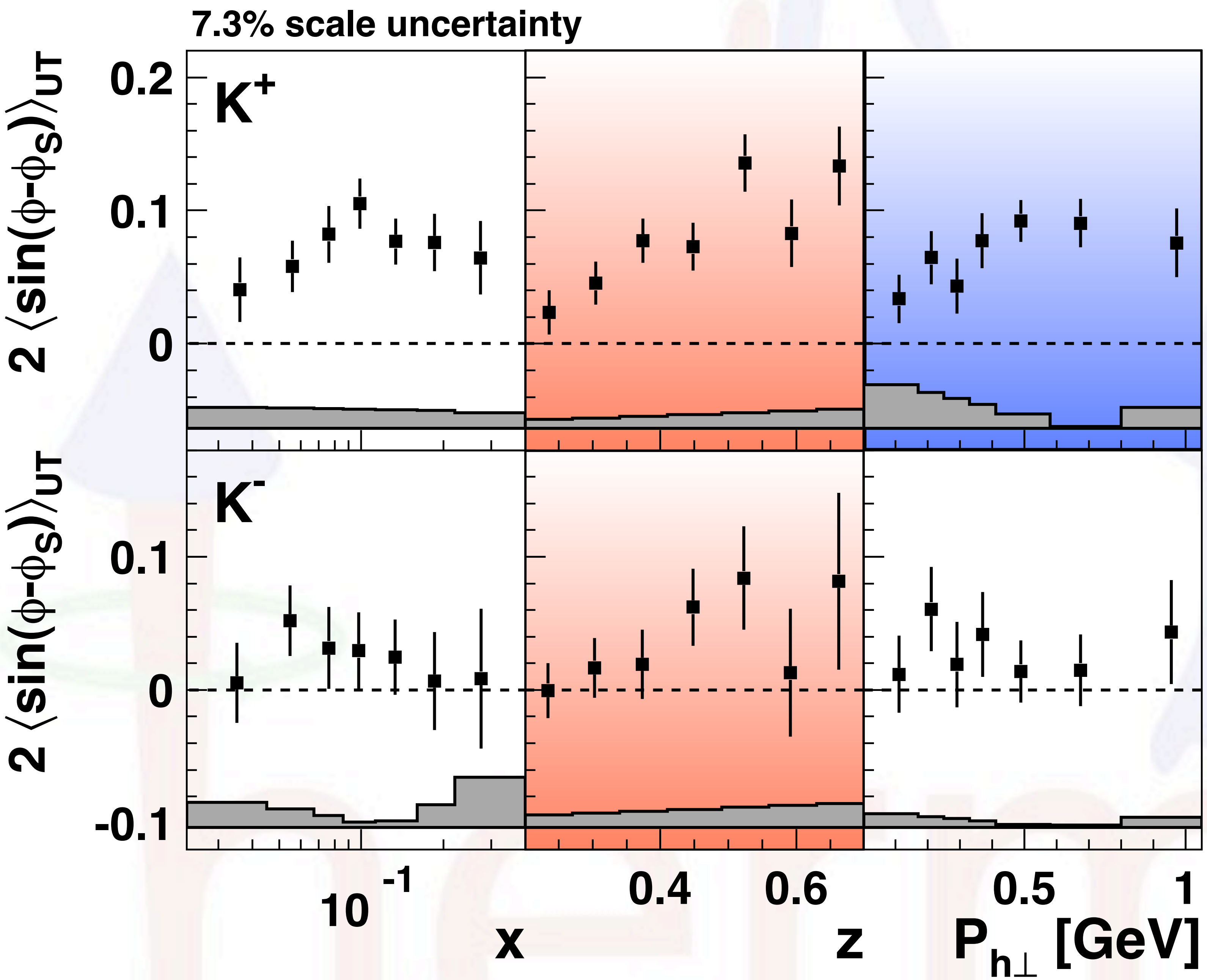

- clear rise with z
- rise at low $P_{h\perp}$
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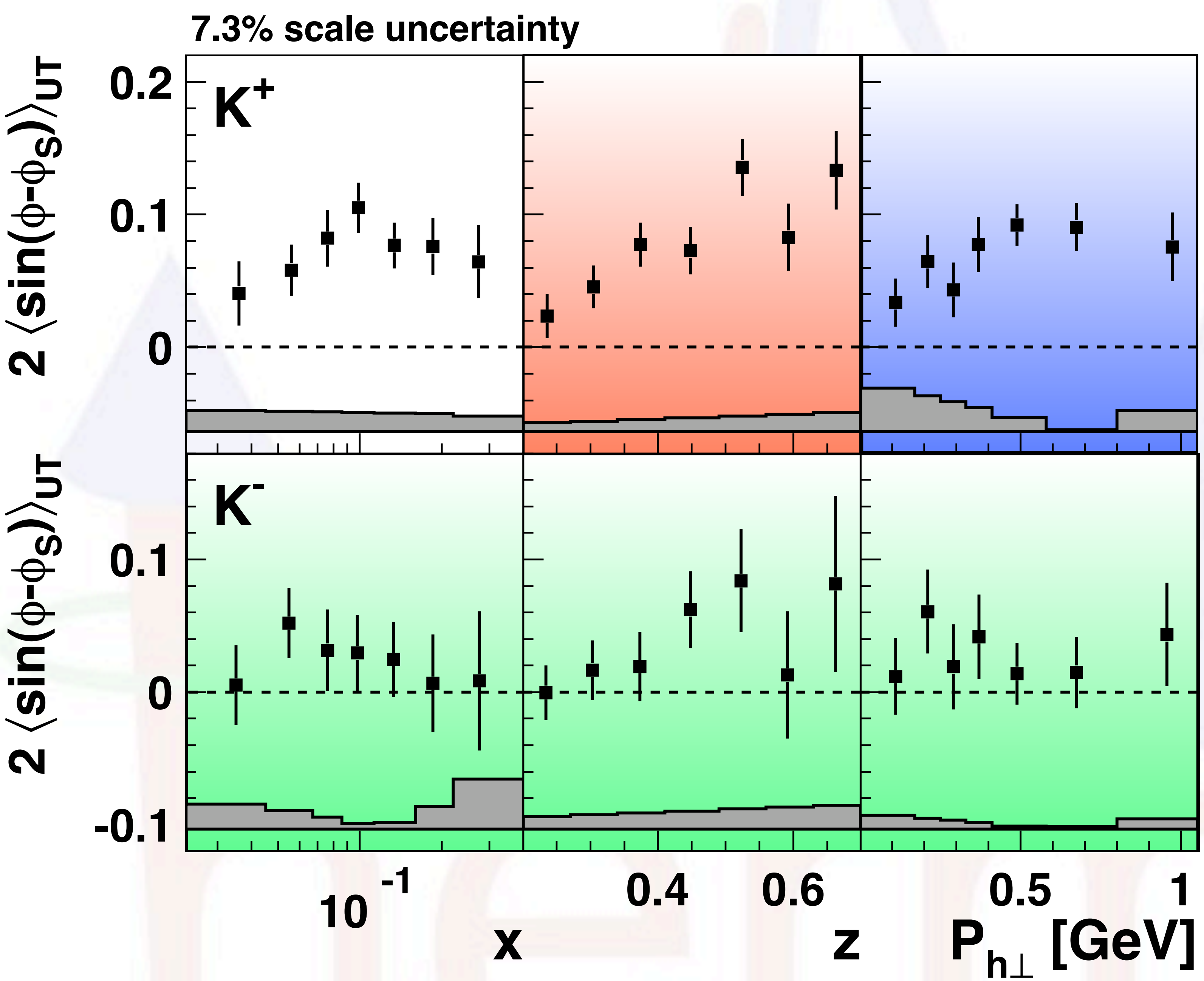

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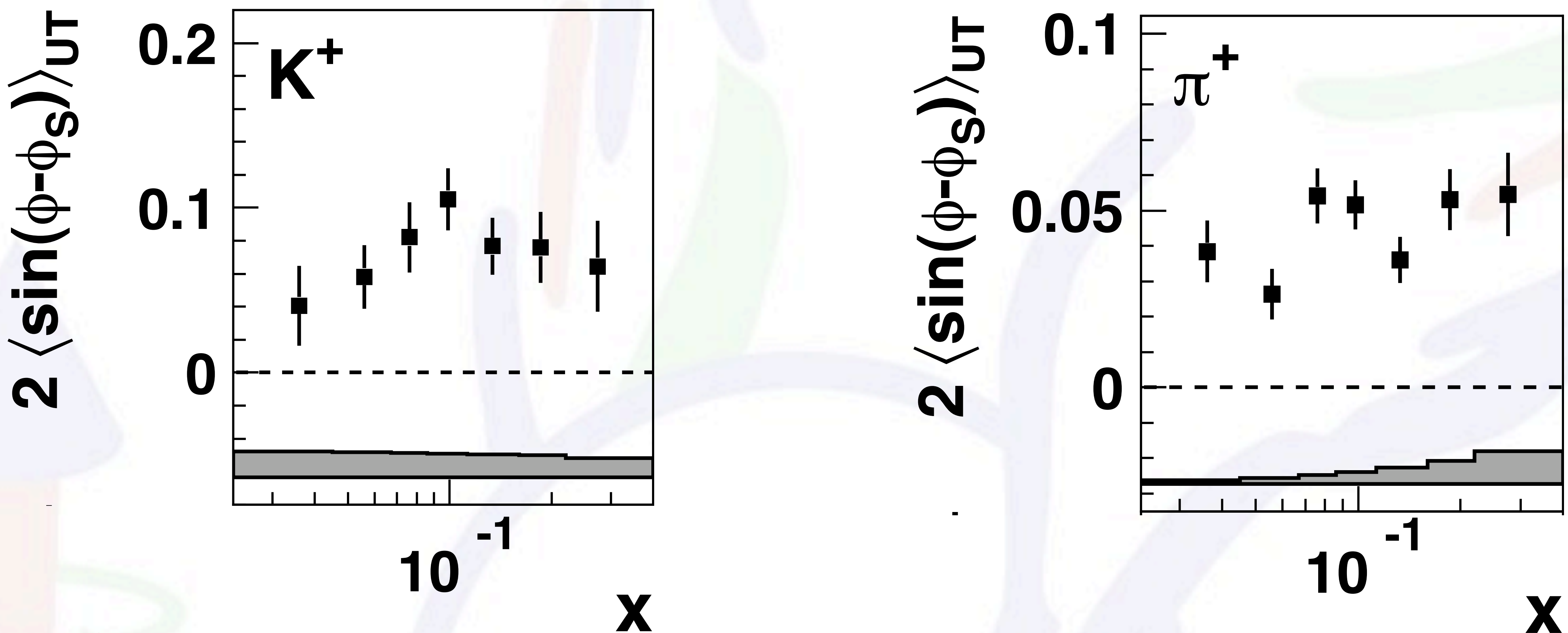
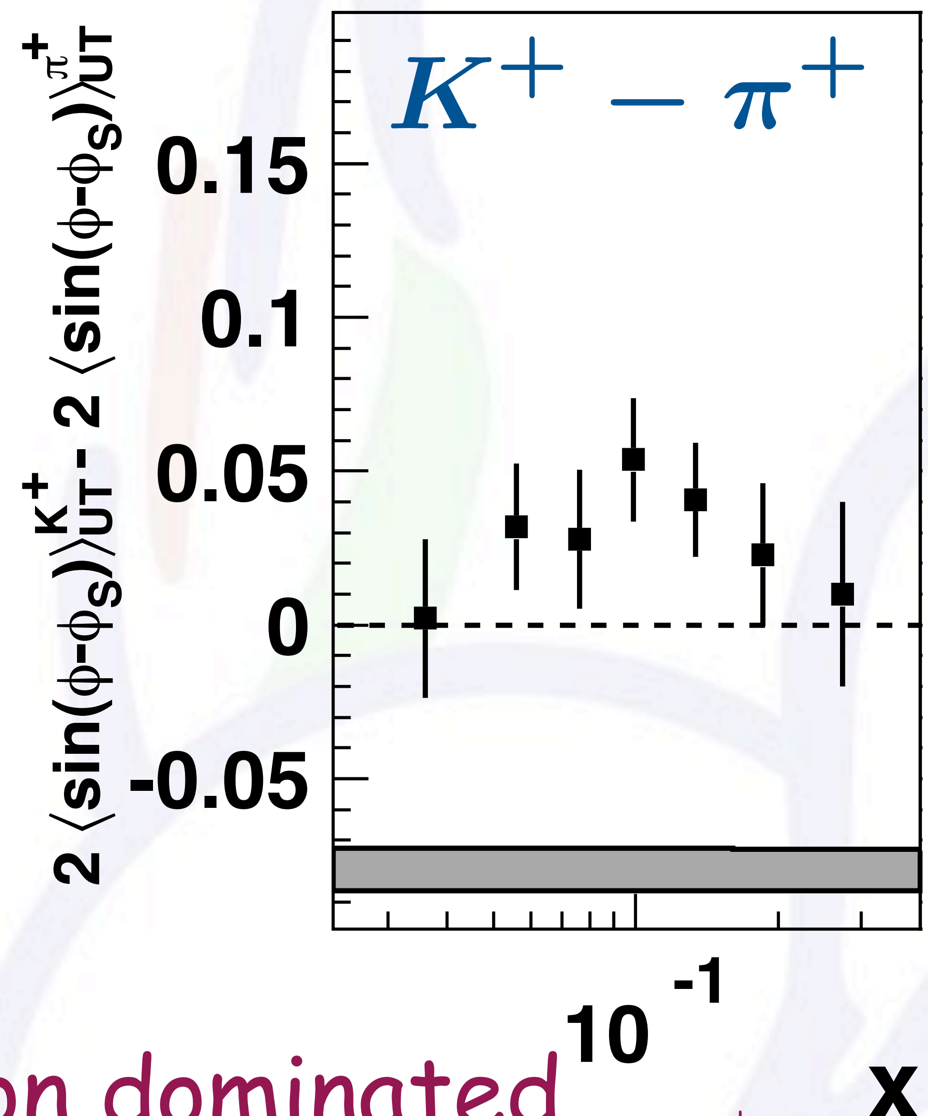
- slightly positive

The "Kaon Challenge"



π^+/K^+ production dominated by scattering off u-quarks: $\simeq - \frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes \mathcal{W}\, D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$

The "Kaon Challenge"



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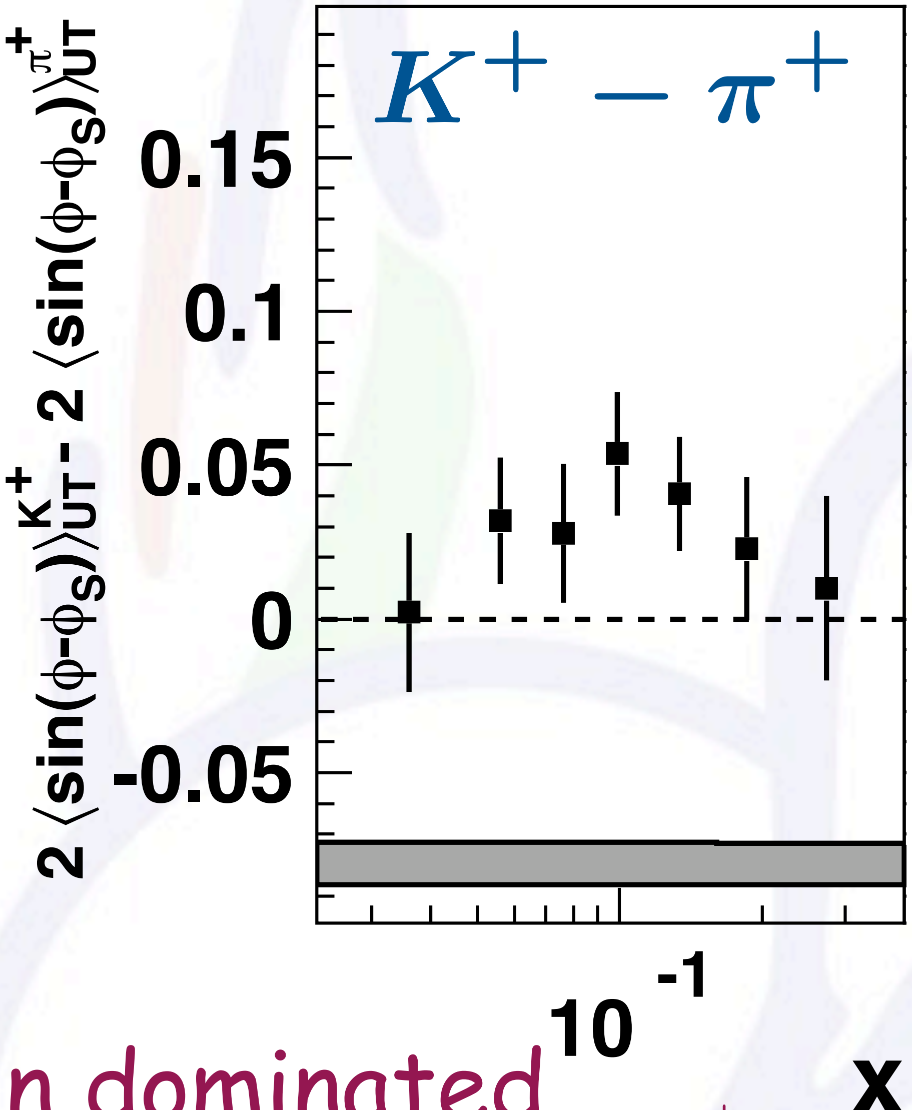

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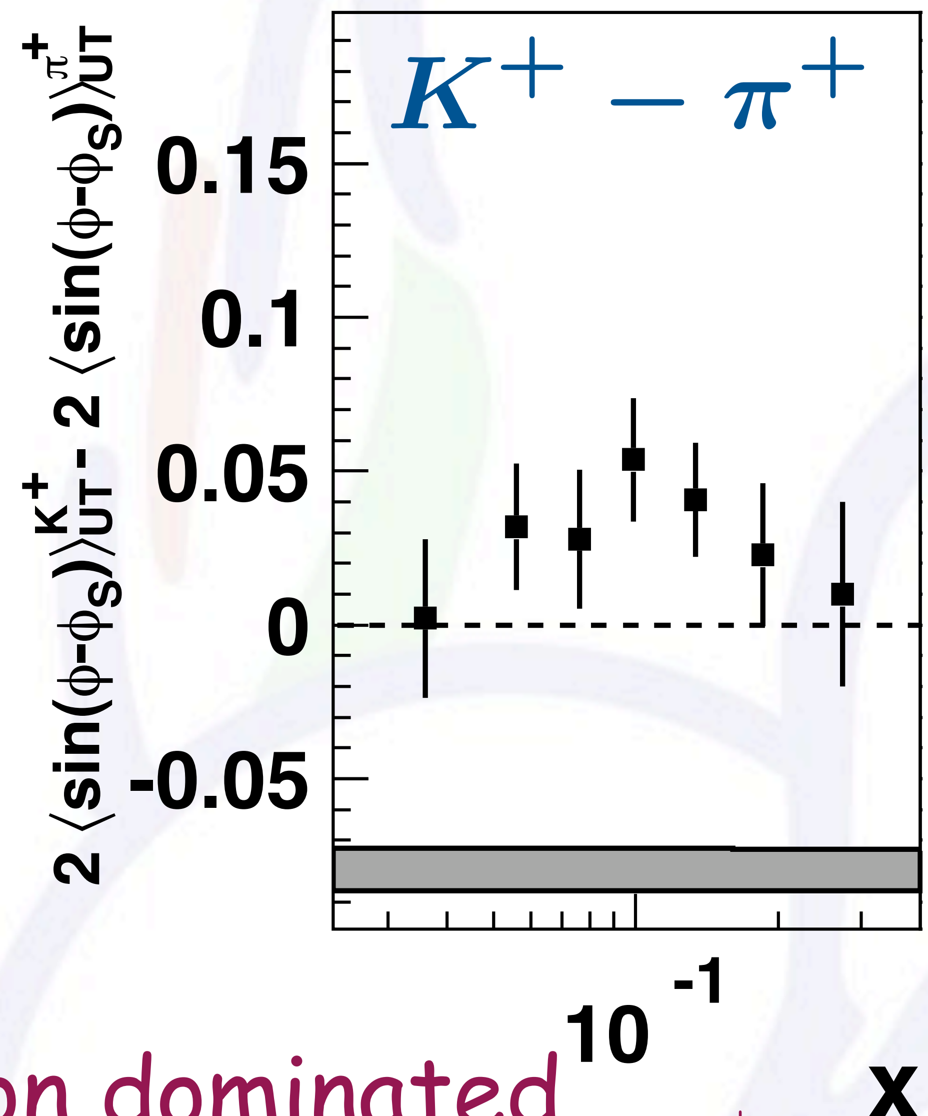
- ☐ $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks?**

The "Kaon Challenge"



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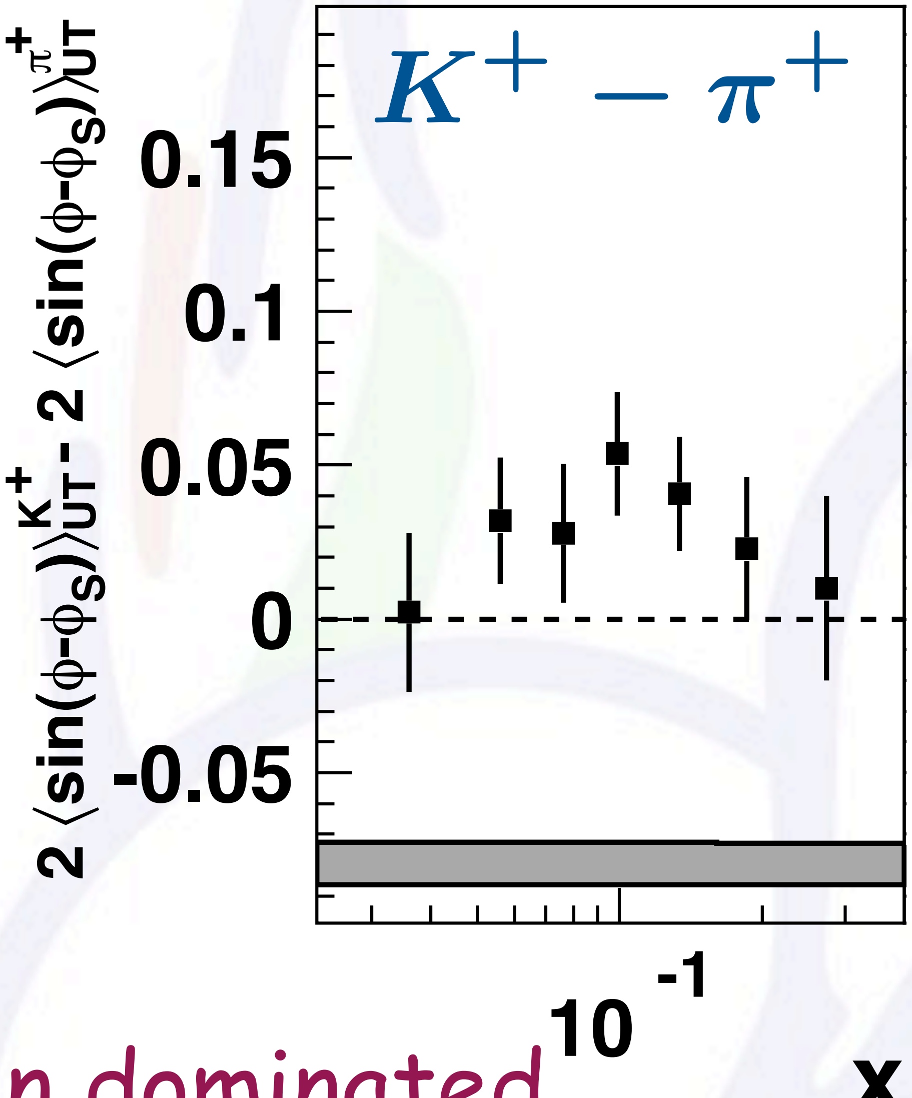
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks?**
- **convolution integrals depend on k_T dependence of fragmentation functions**

The "Kaon Challenge"

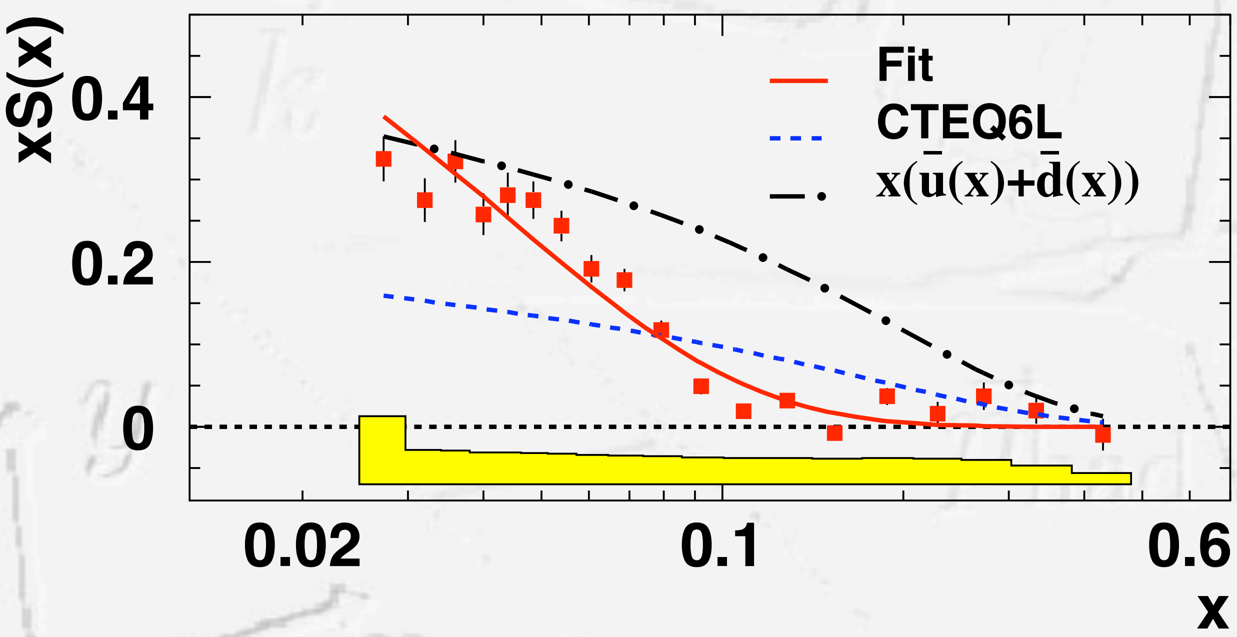


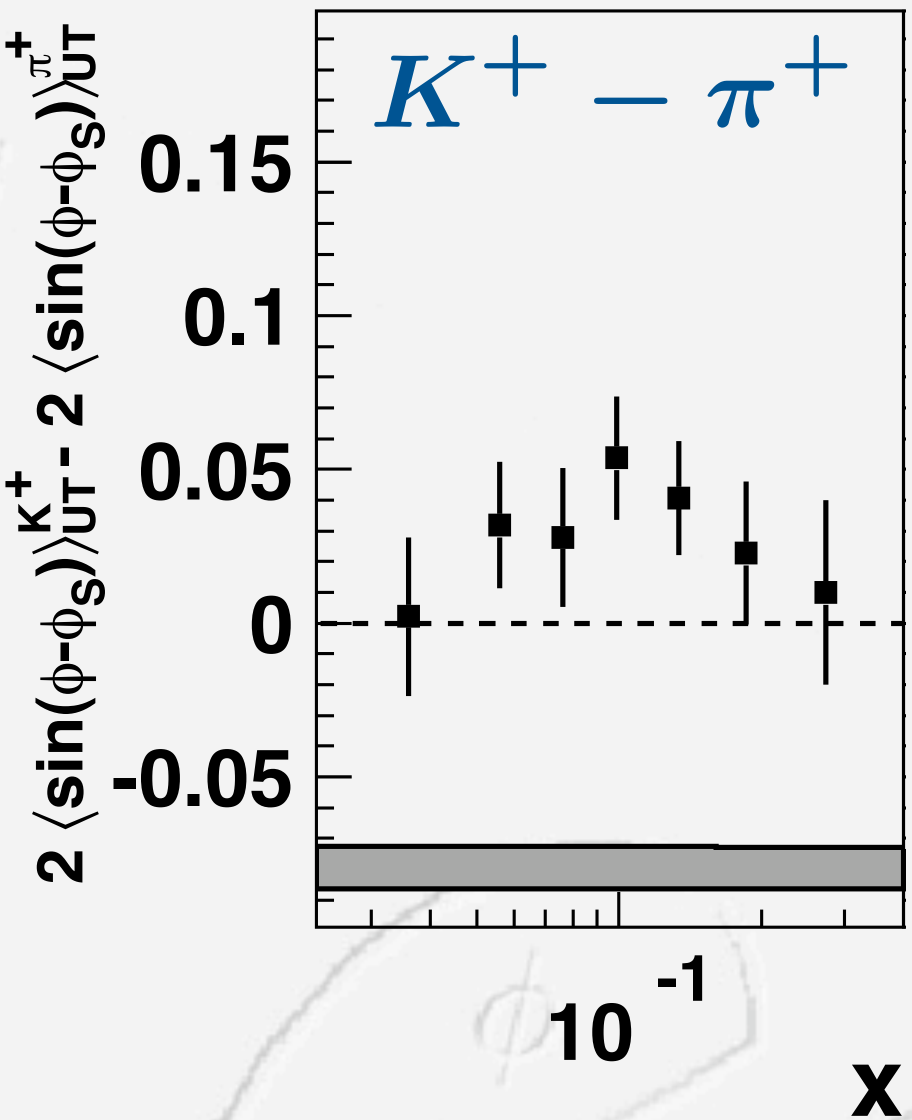
π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{\mathbf{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}}{\mathbf{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}}$

- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on k_T dependence of fragmentation functions
- possible difference in dependences on the kinematics integrated over

Role of sea quarks

[A. Airapetian et al., PLB 666, 446 (2008)]





Role of sea quarks

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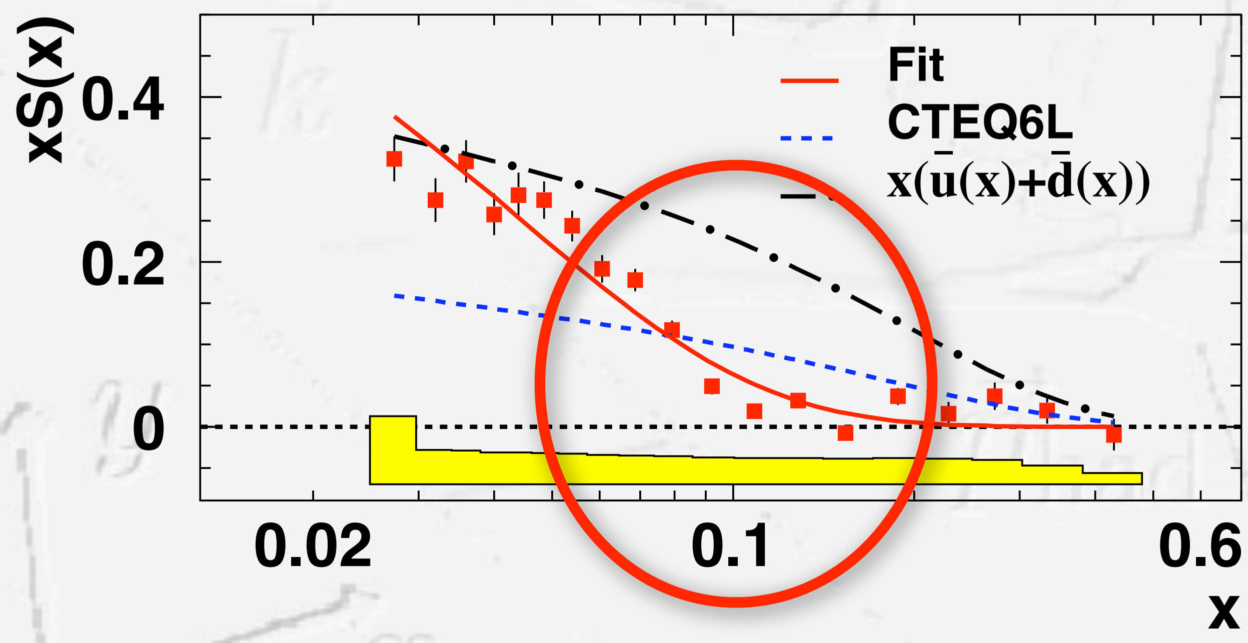
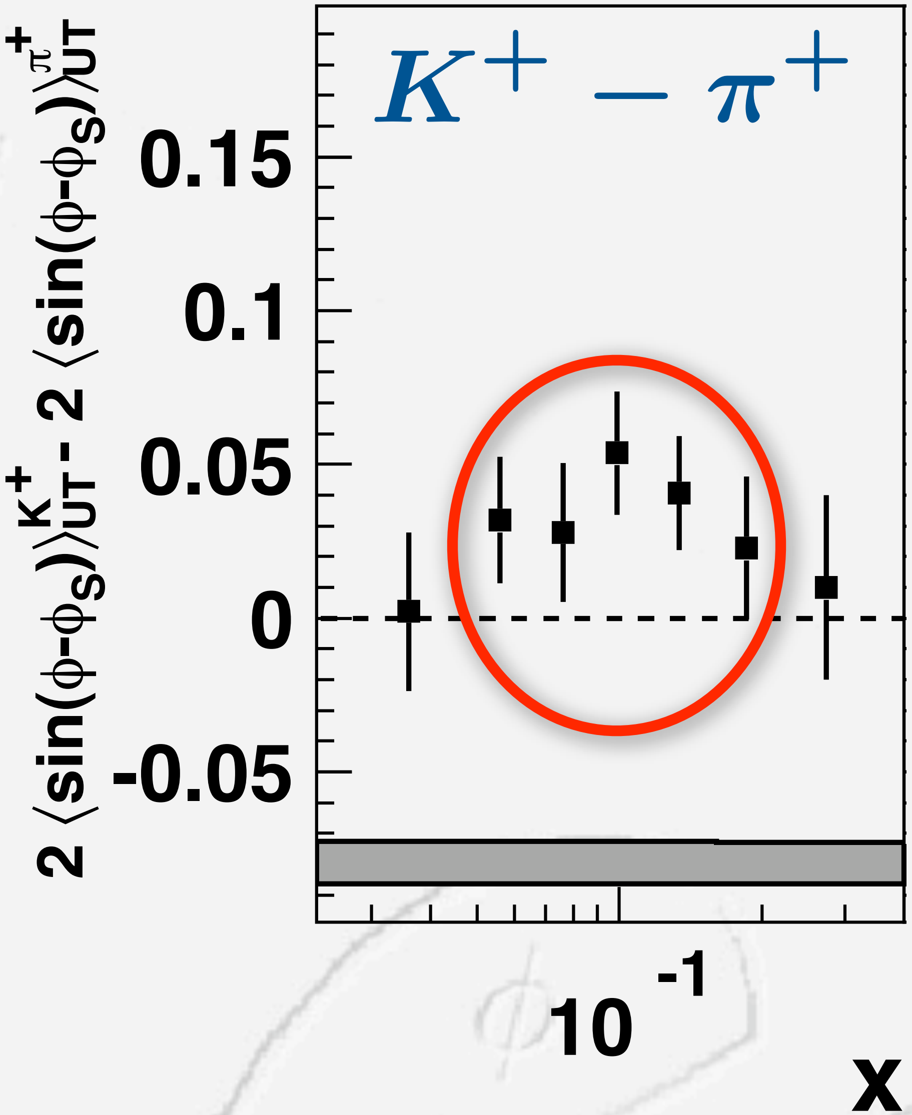
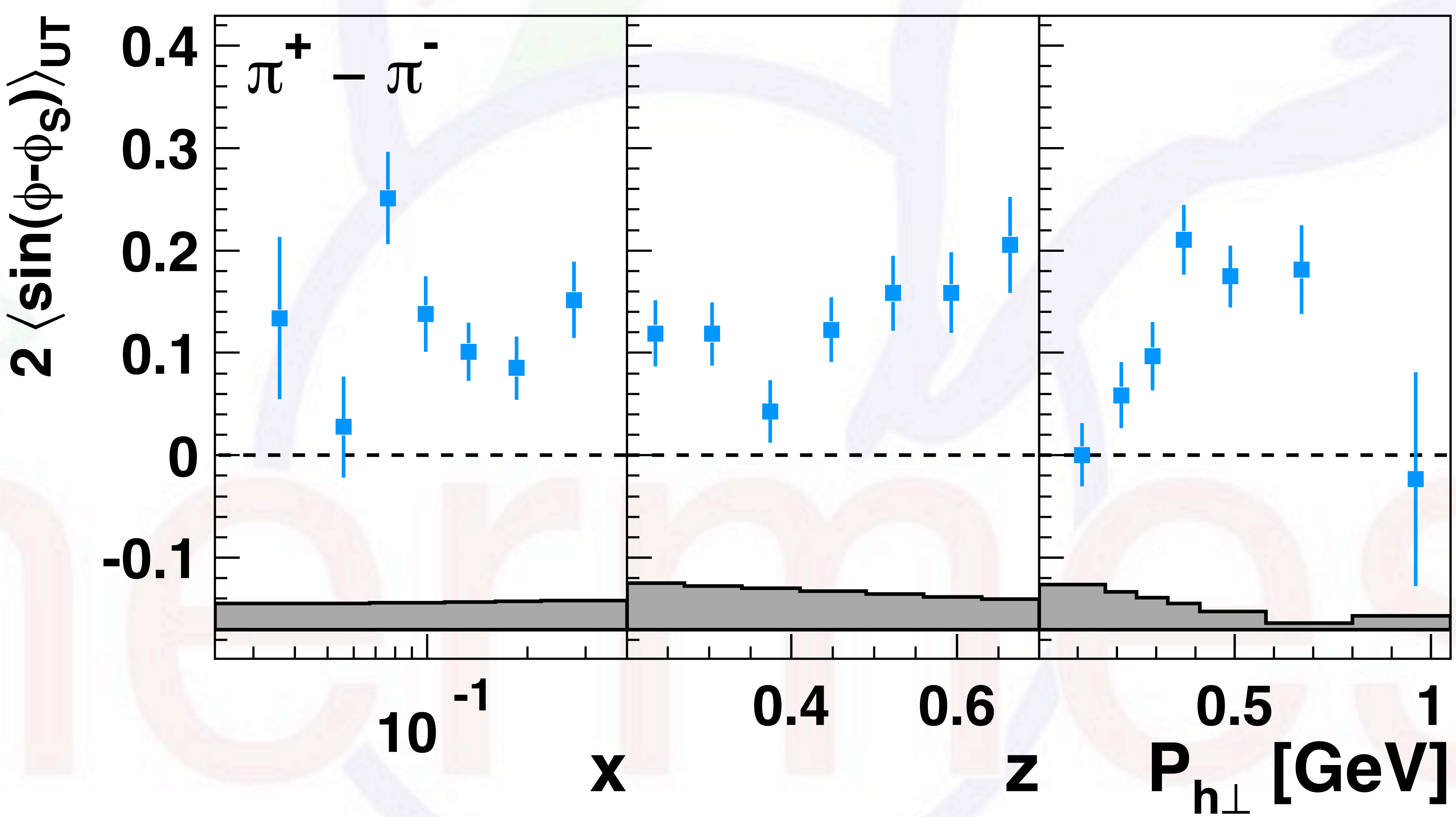




differences biggest in region where strange sea is most different from light sea

Cancelation of fragmentation function

$$\langle \sin(\phi - \phi_S)\rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \propto -\frac{4 f_{1T}^{\perp, u_v} - f_{1T}^{\perp, d_v}}{4 f_1^{u_v} - f_1^{d_v}}$$



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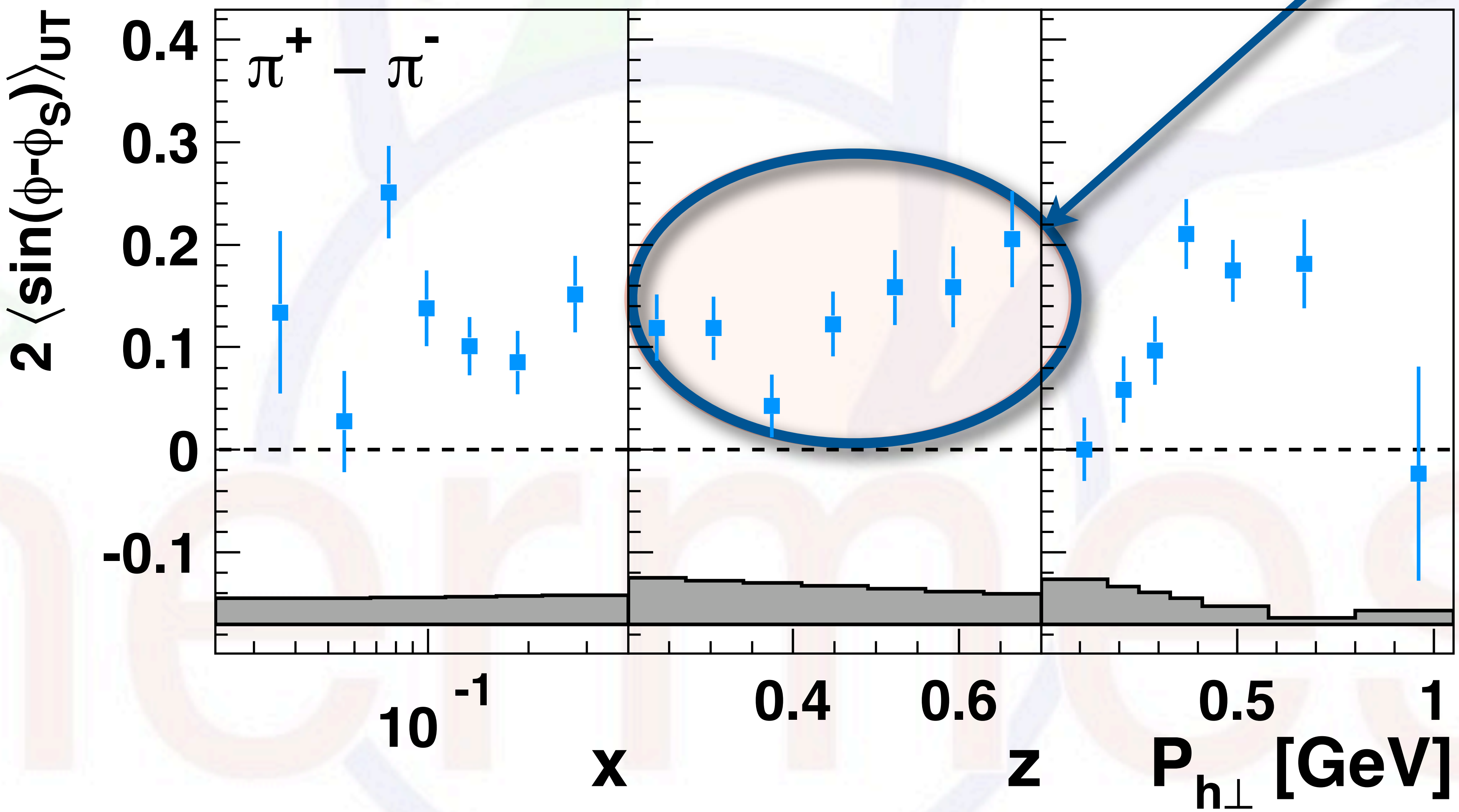
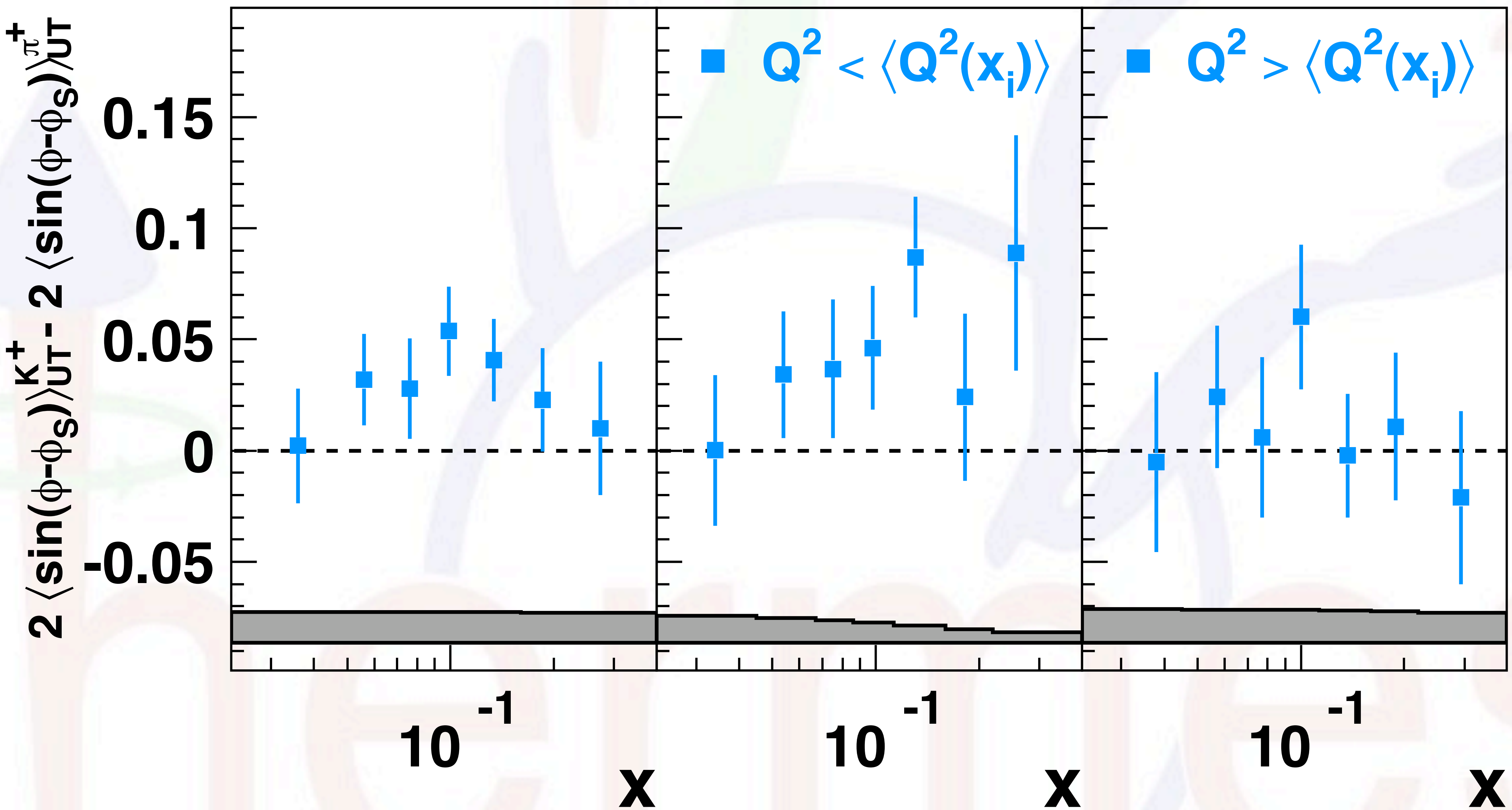
should be flat



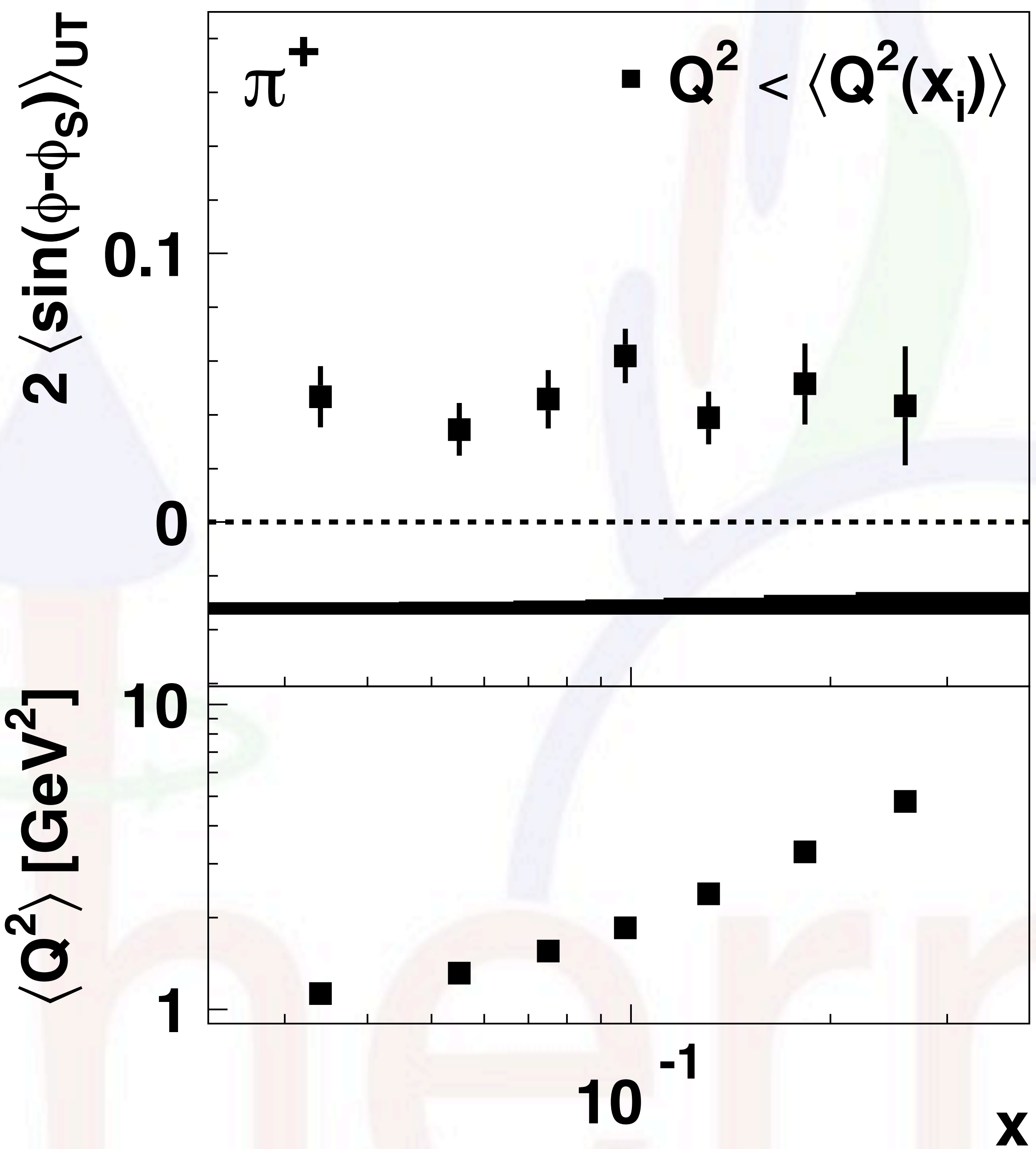
Q^2 dependence of amplitudes

- separate each x-bin into two Q^2 bins:

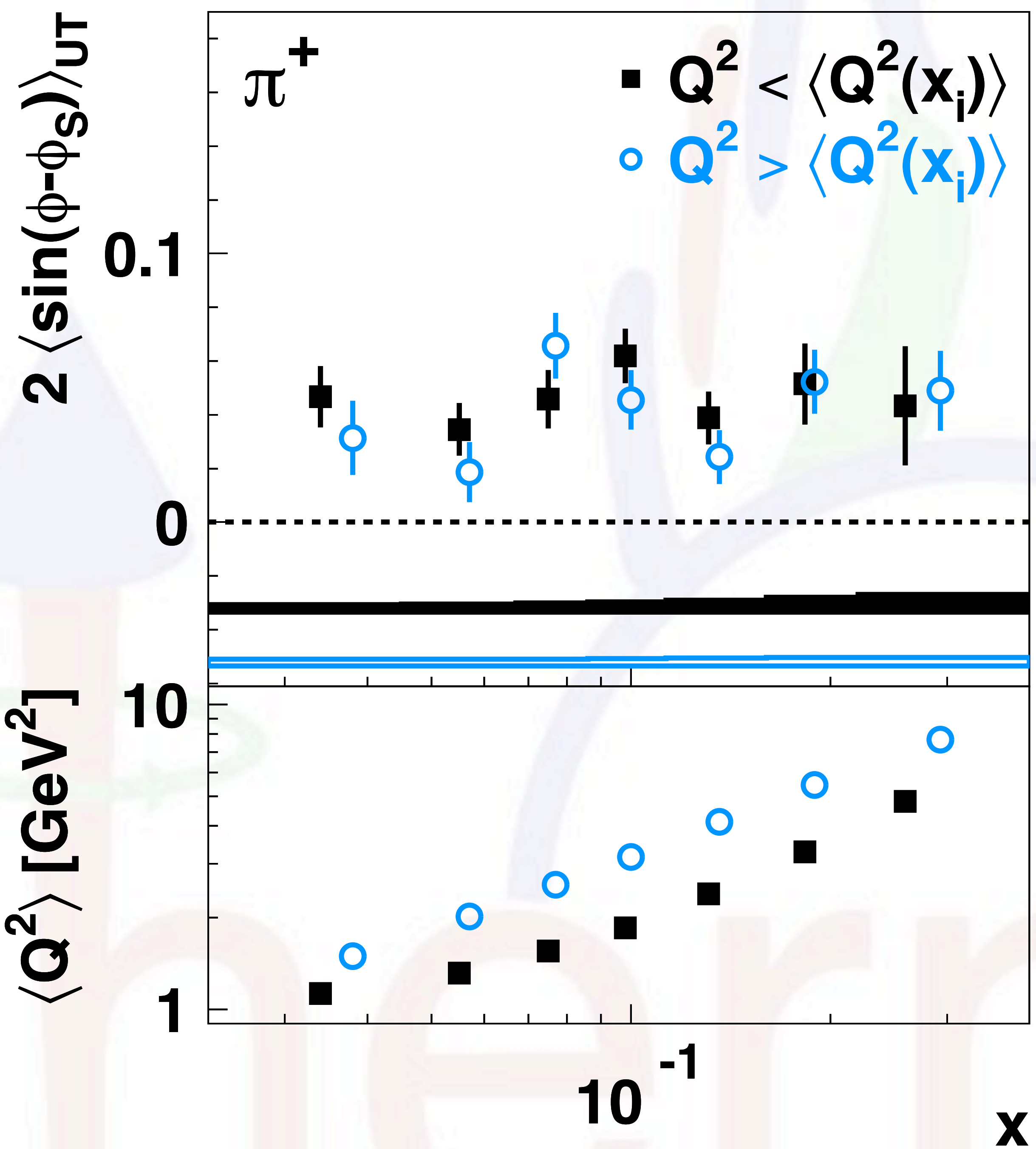


- only in low-Q^2 region significant (>90% c.l.) deviation

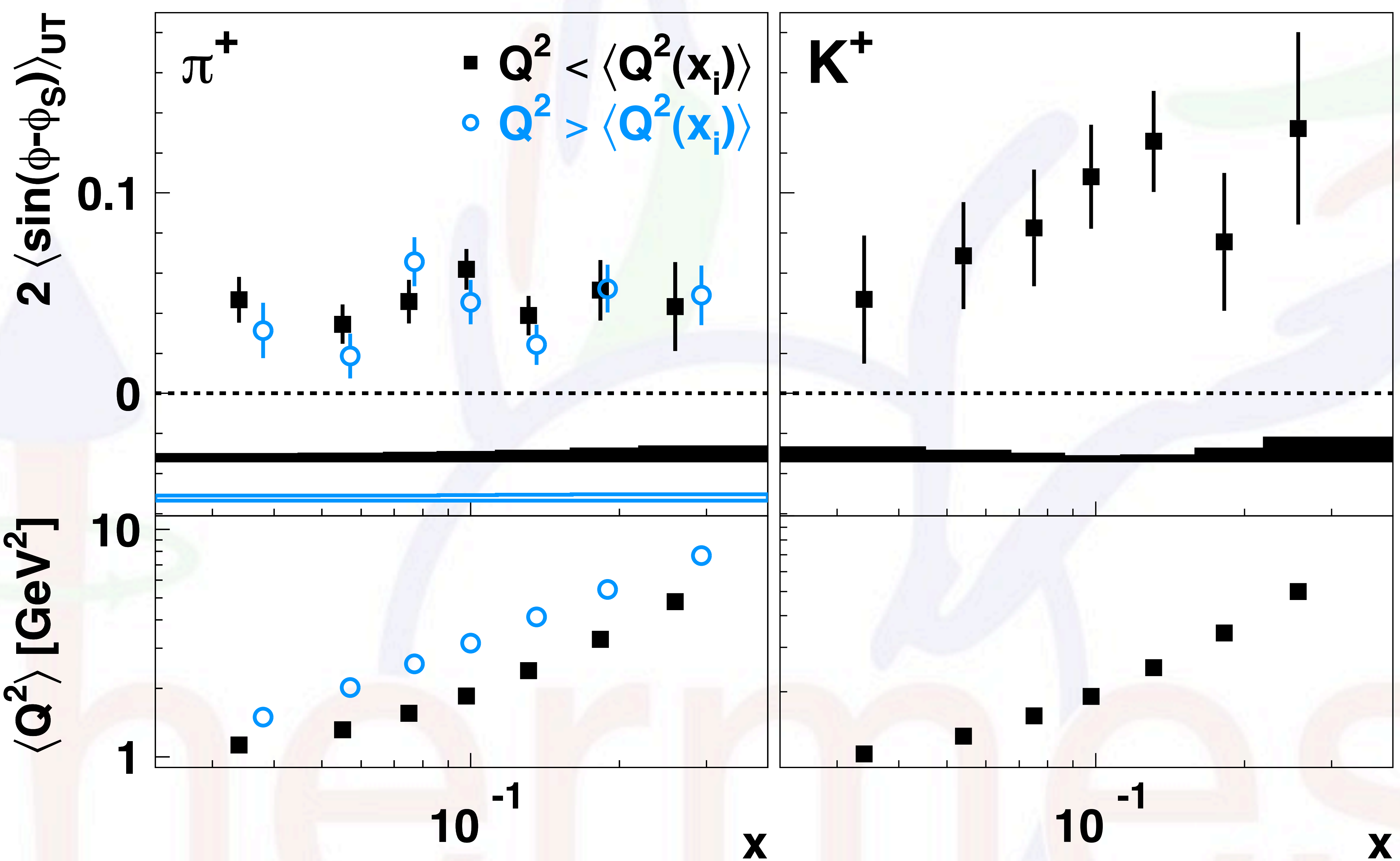
Q^2 dependence of amplitudes



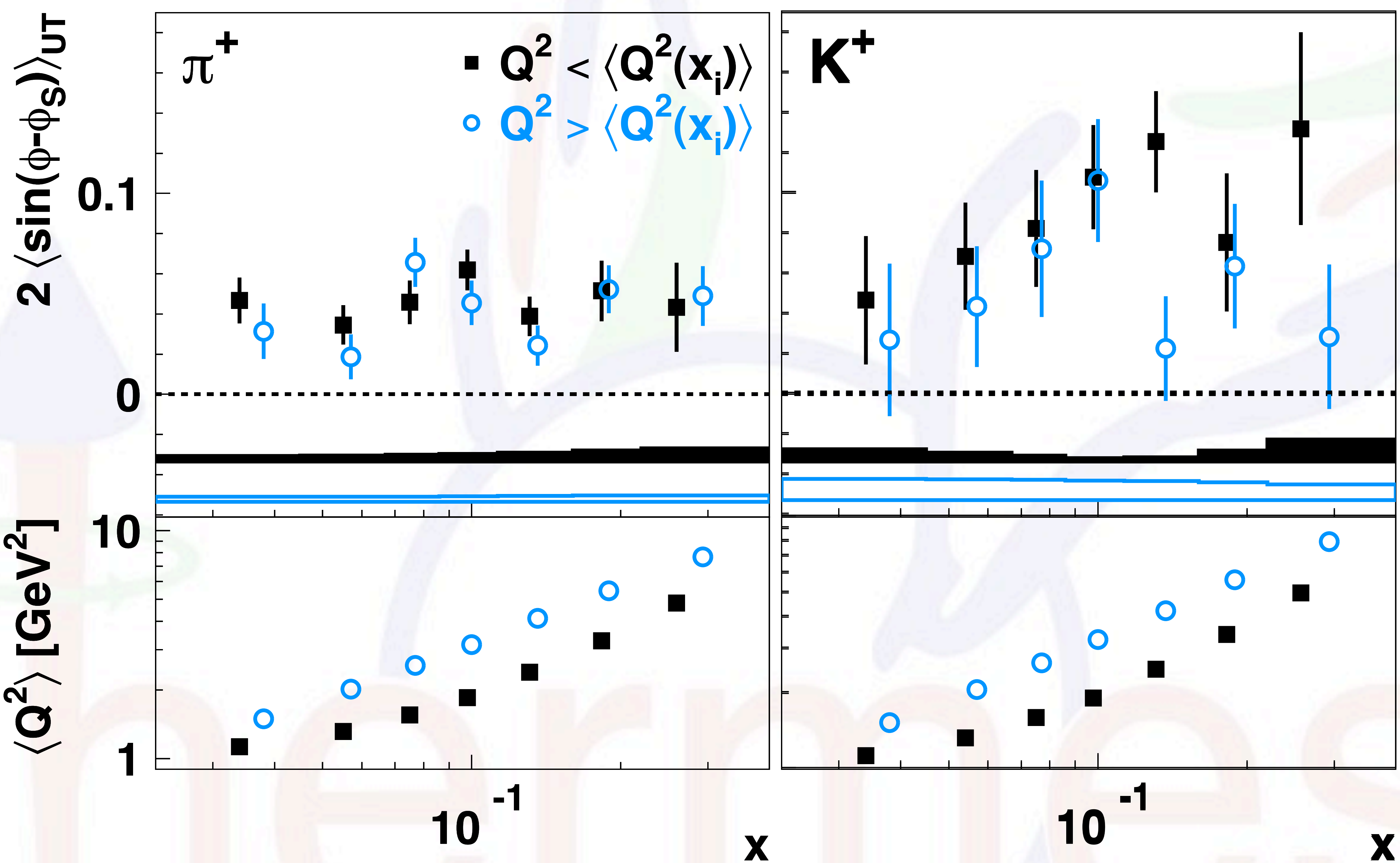
Q^2 dependence of amplitudes



Q^2 dependence of amplitudes



Q^2 dependence of amplitudes

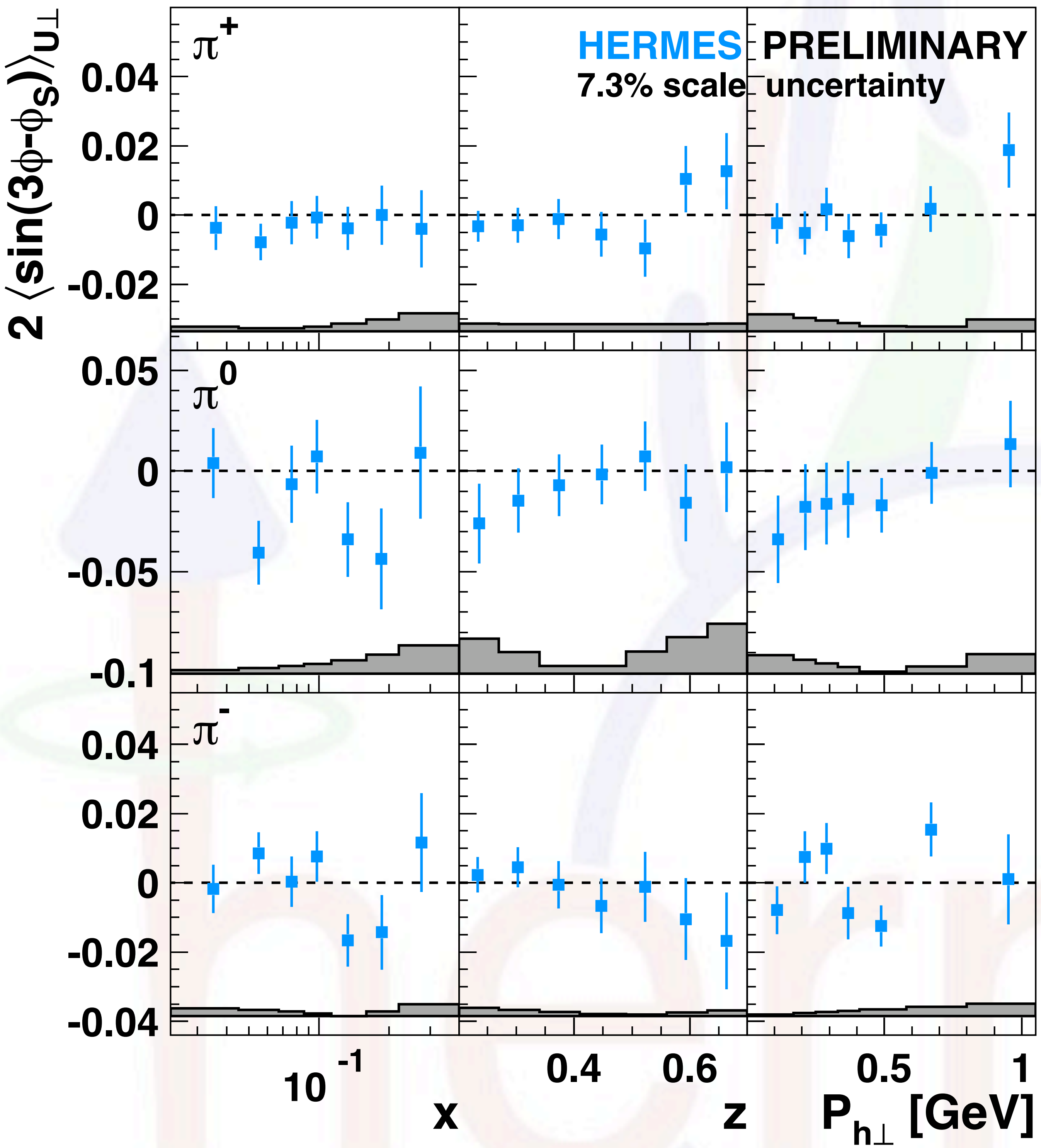


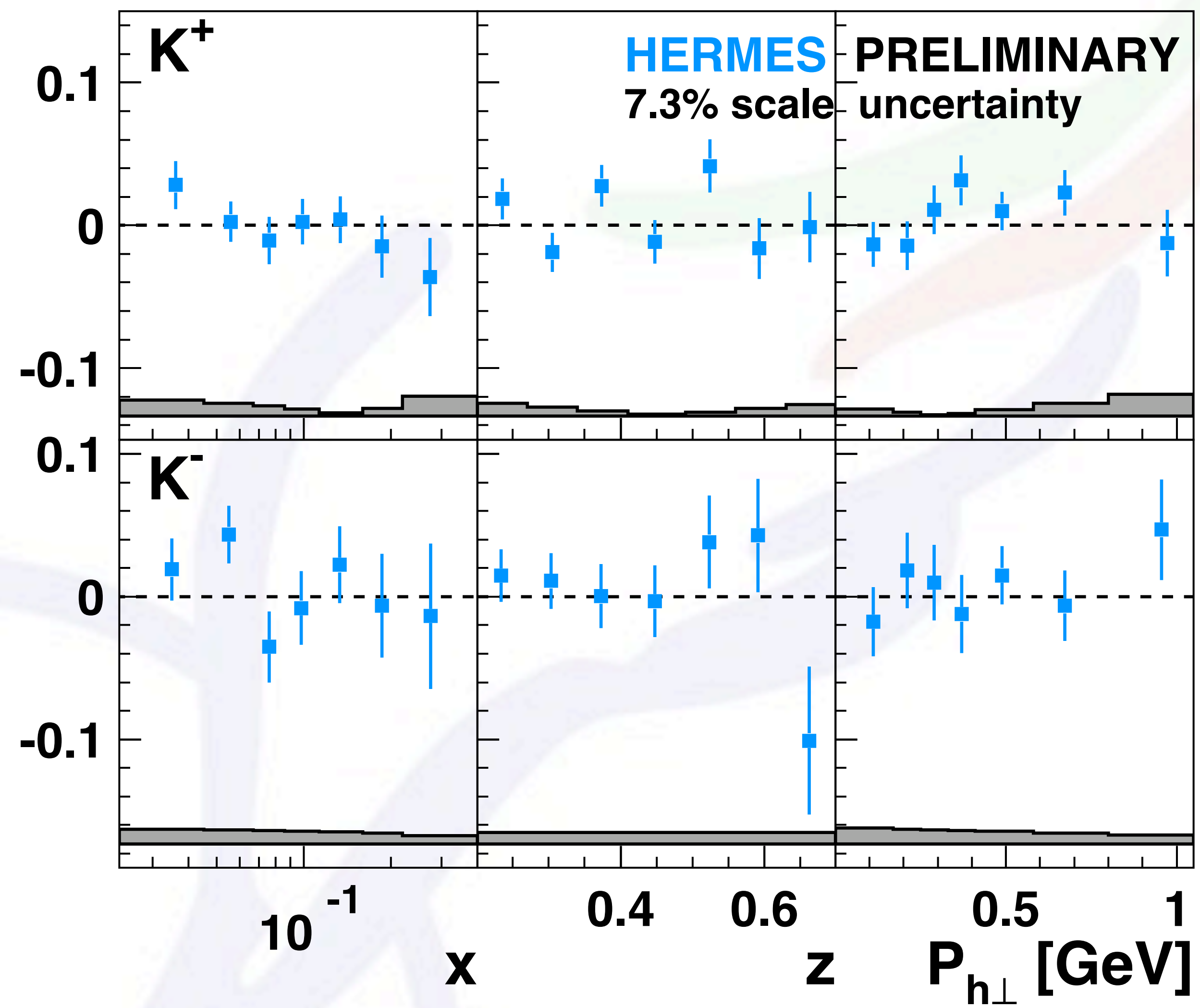
☛ hint of Q^2 dependence of kaon amplitude

The others *)

*) excluding Collins amplitudes

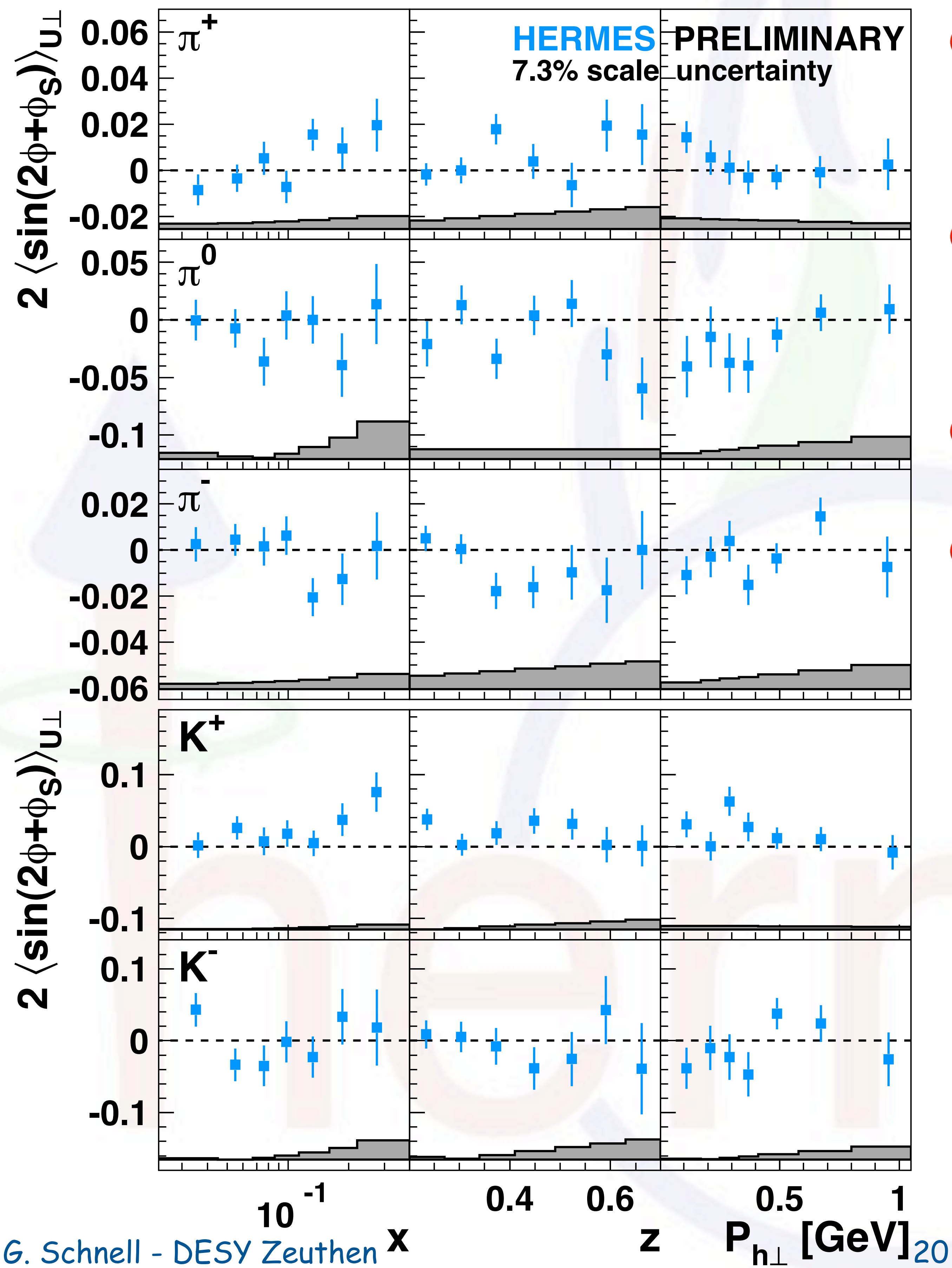
Pretzelosity - $\sin(3\phi-\phi_S)$



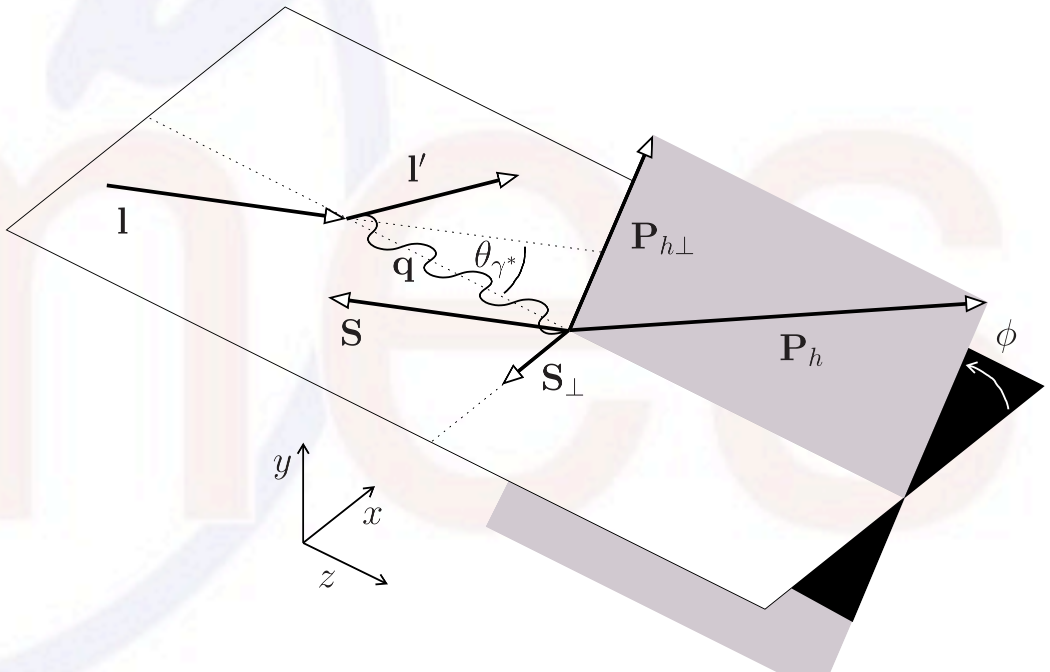


- no significant non-zero signal observed
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

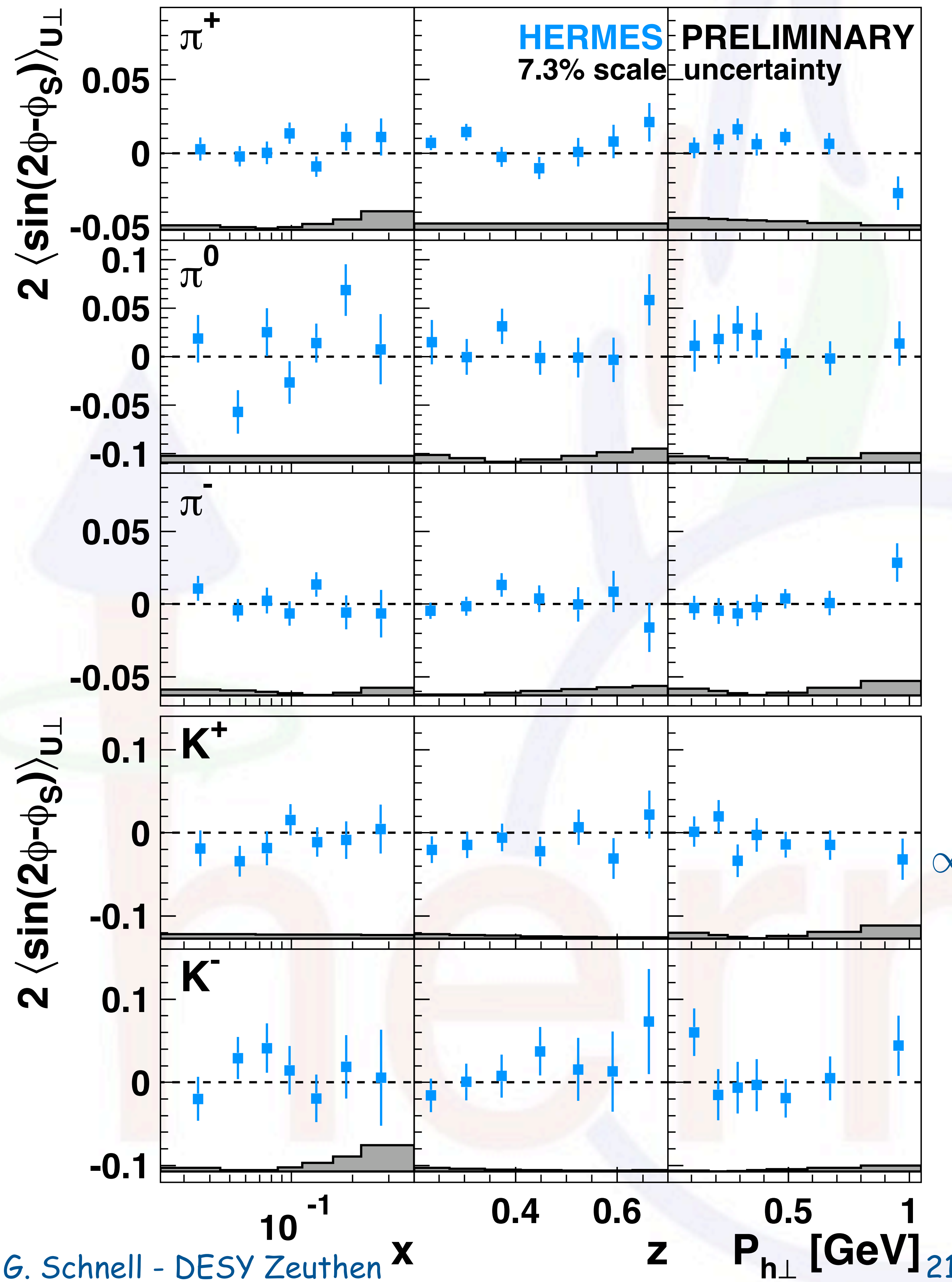
Subleading twist III - sin(2φ+φ$_s$)



- no significant non-zero signal observed except maybe K$^+$
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- related to worm-gear $h_{1L}^{\perp}$
- arises solely from longitudinal component of target-spin (≲15%)



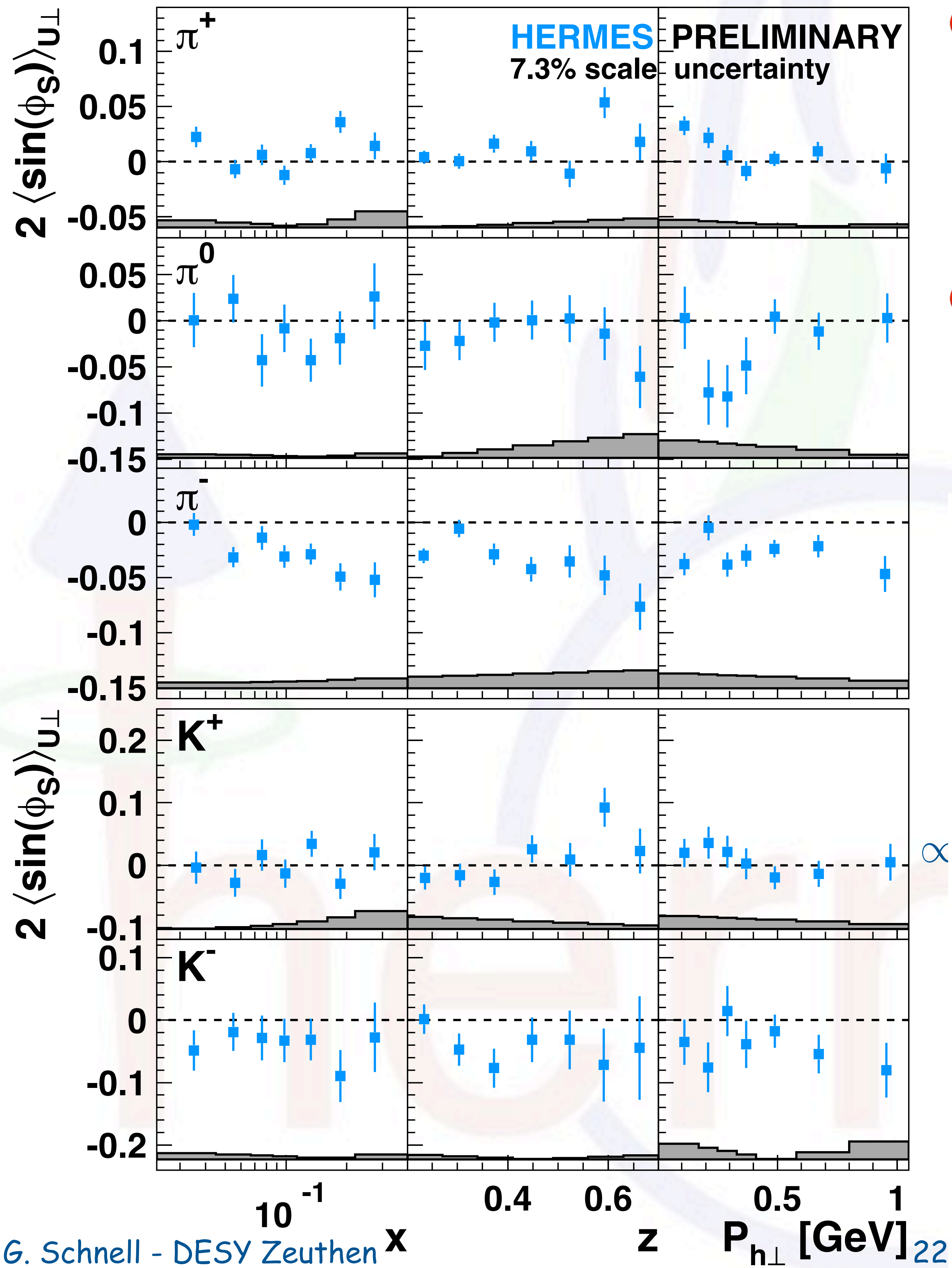
Subleading twist III - $\sin(2\phi-\phi_S)$



- no significant non-zero signal observed
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- various terms related to pretzelosity, worm-gear, Sivers etc.:

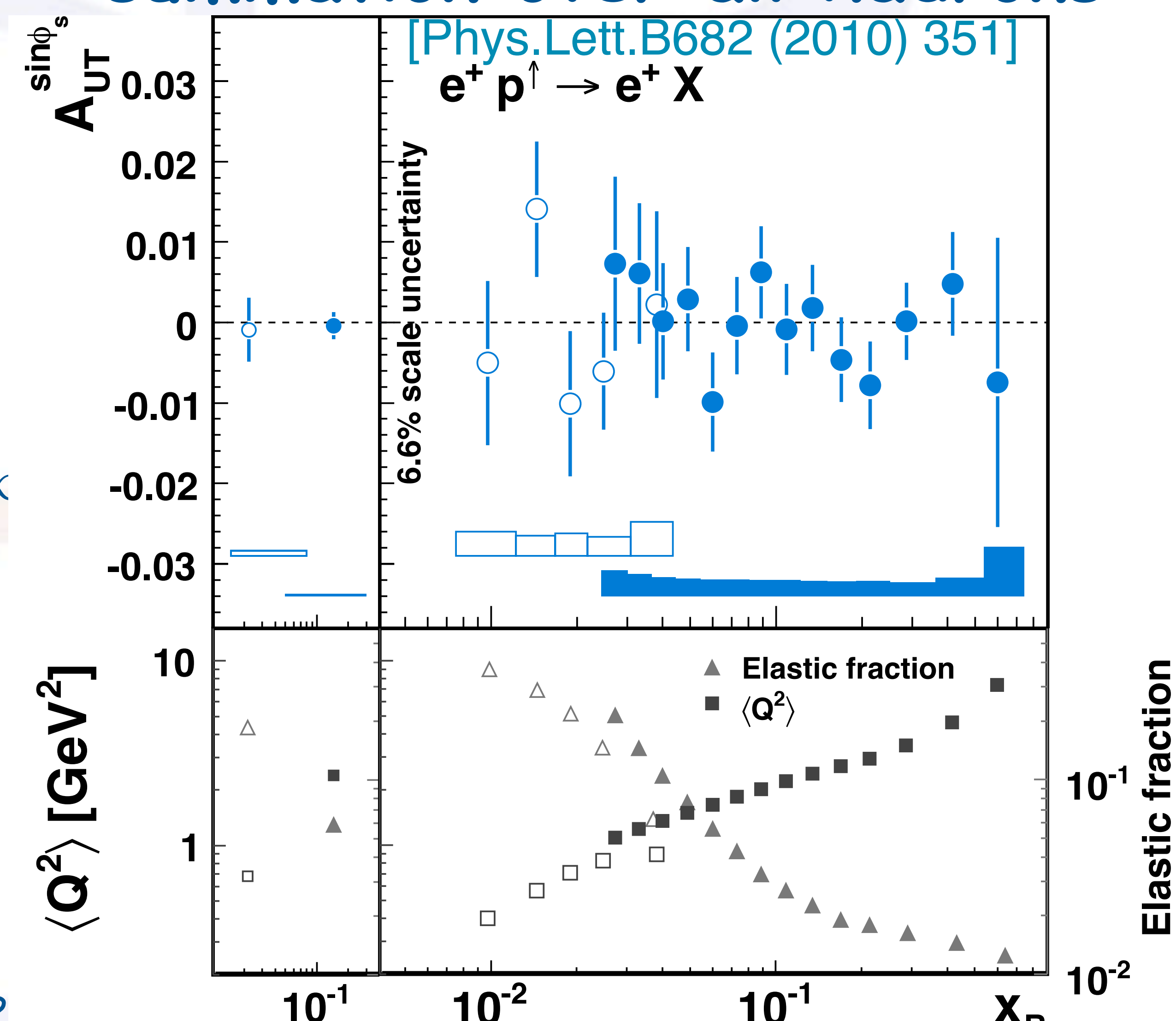
$$\propto \mathcal{W}_1(p_T, k_T, P_{h\perp}) \left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp} \frac{\tilde{H}}{z} \right) - \mathcal{W}_2(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) + \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{D}^{\perp}}{z} \right) \right]$$

Subleading twist III - $\sin(\phi_s)$

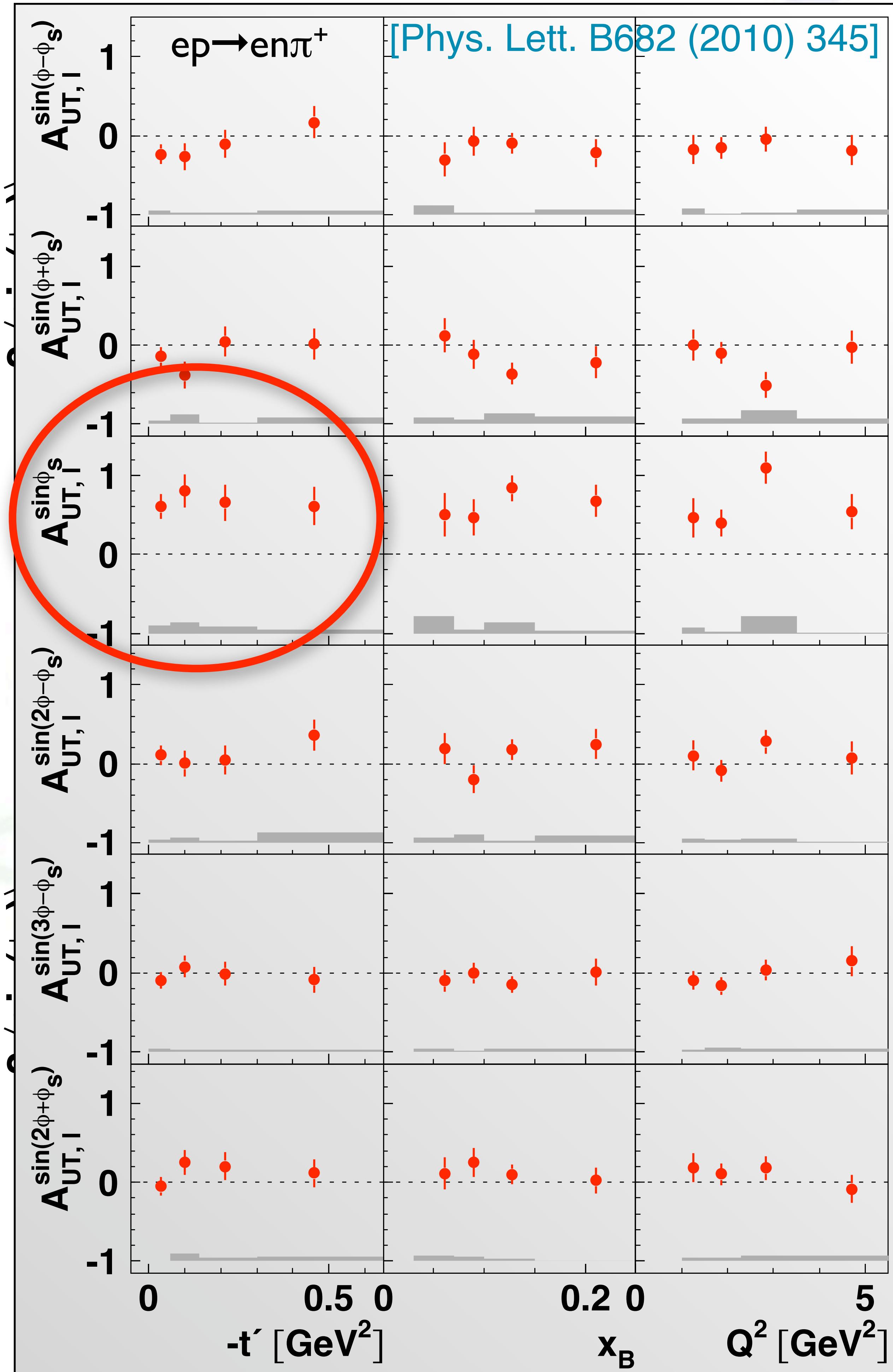


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons

$\propto$



...ist III - sin(ϕ_s)



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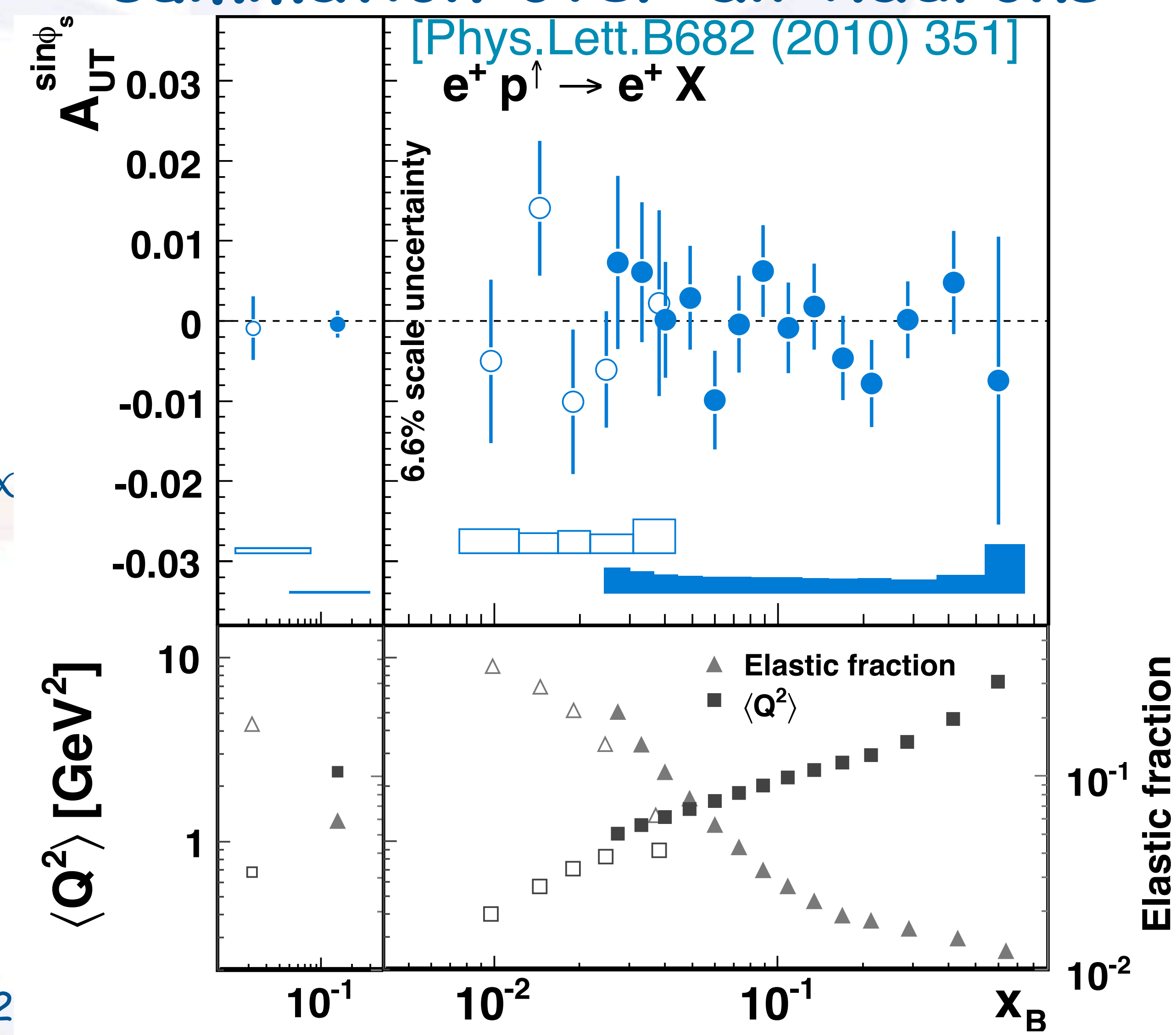
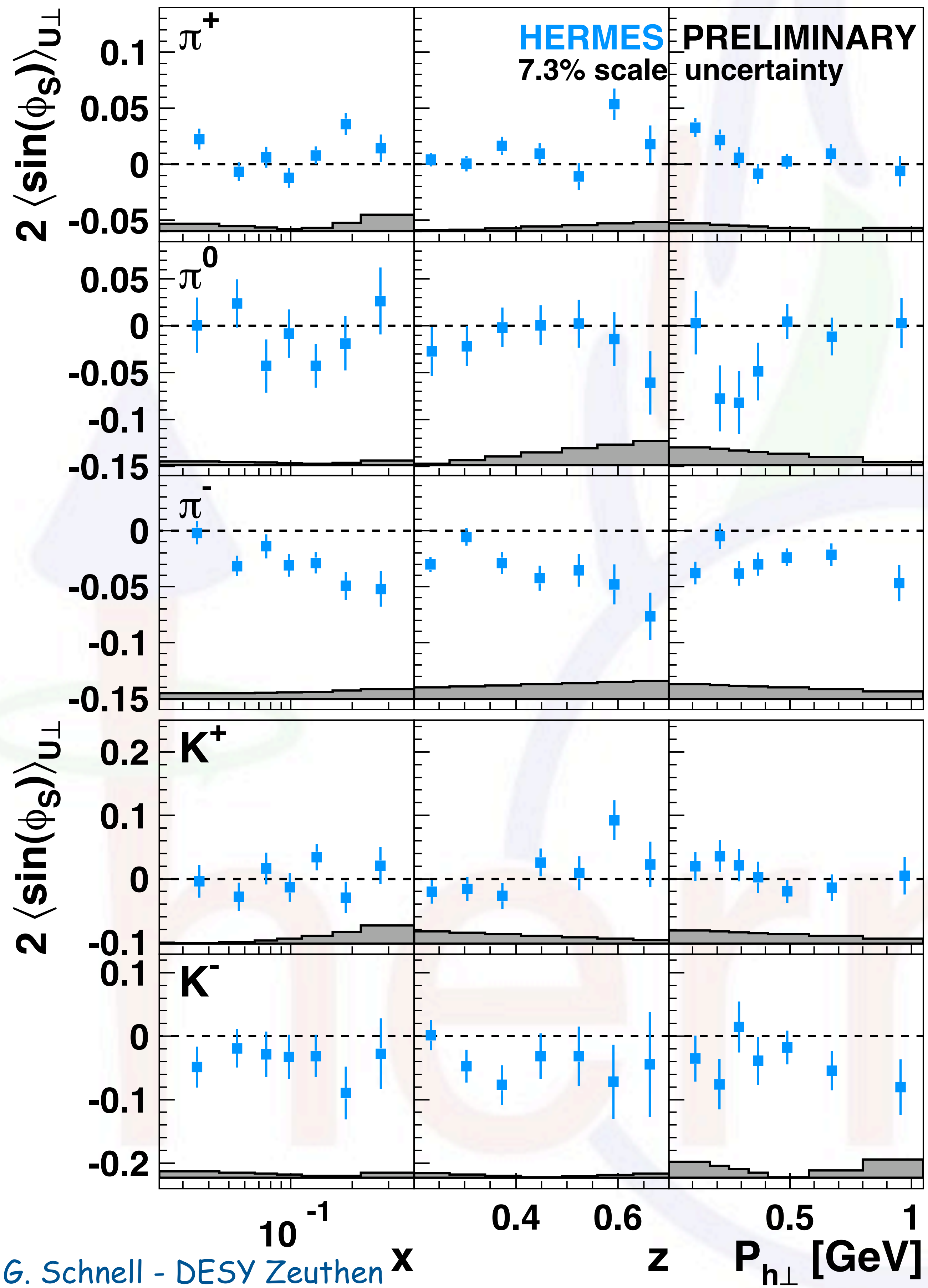


Subleading twist III - sin(ϕ_S)



- significant non-zero signal observed for negatively charged mesons
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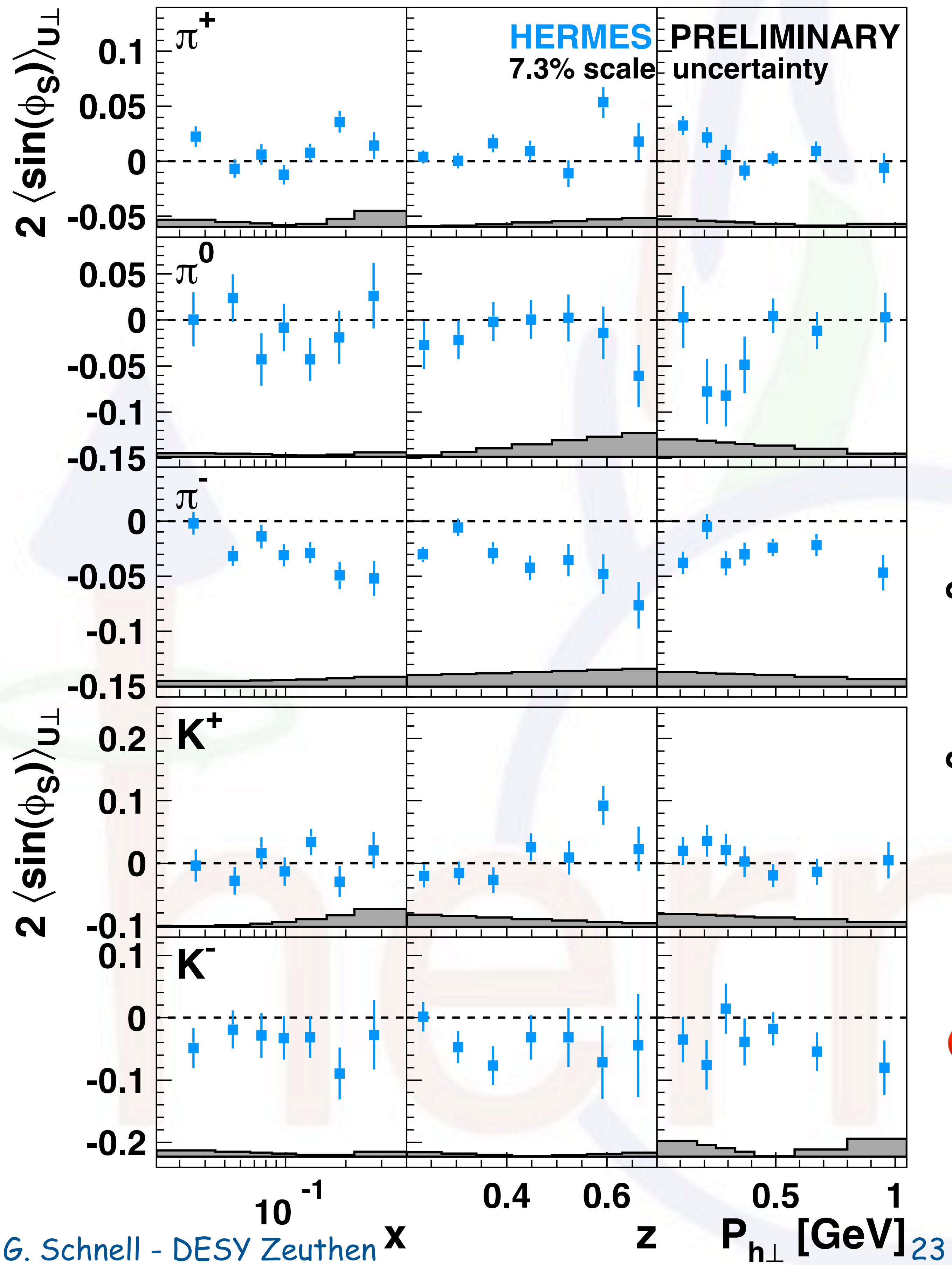
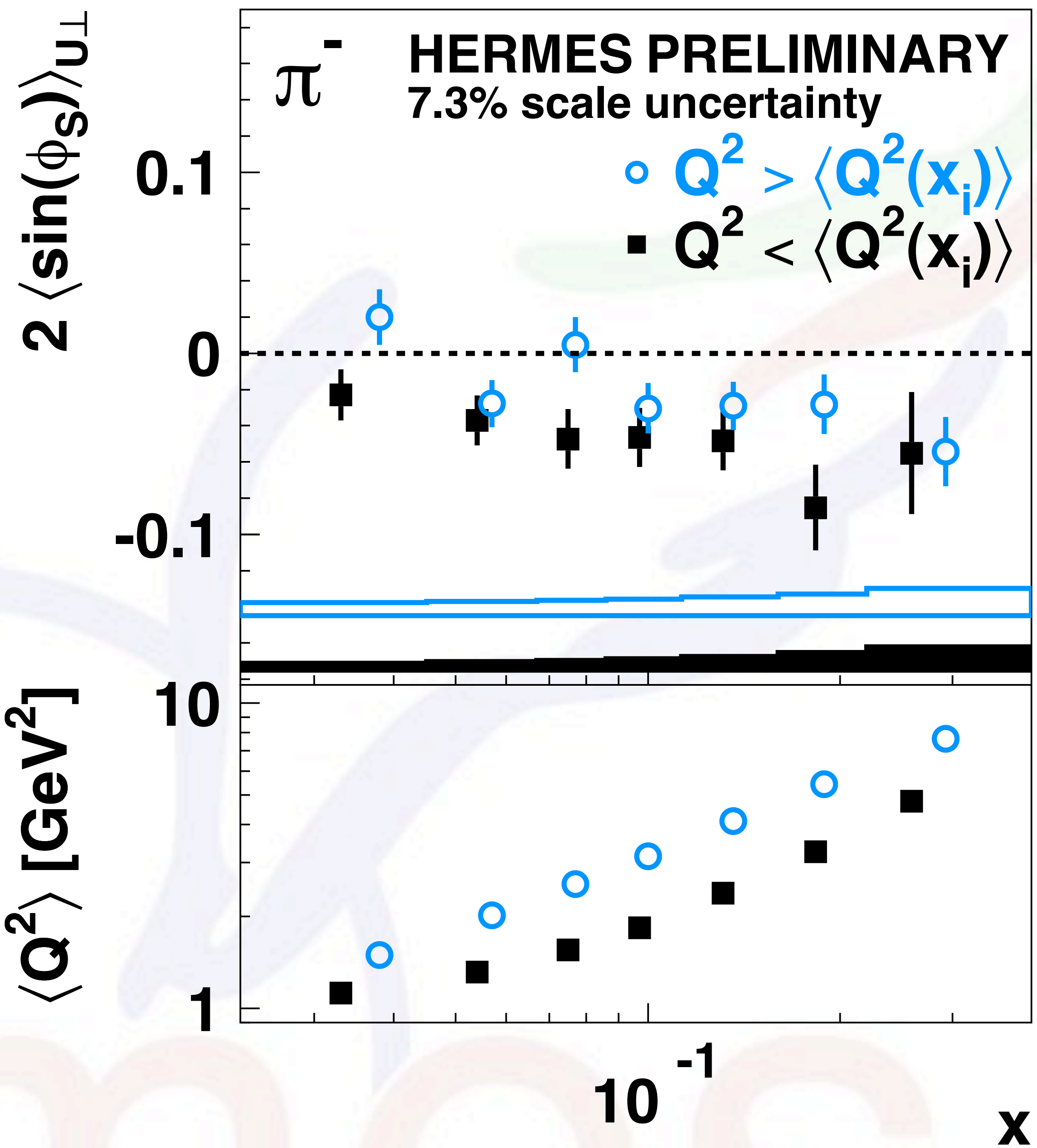
- various terms related to transversity, worm-gear, Sivers etc.:

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

Subleading twist III - $\sin(\phi_s)$





- Q^2 dependence seen in signal for negative pions

Summary & Outlook

- clear signals for Sivers function observed
- indication of positive (negative) u-quark (d-quark) orbital angular momentum
- pretzelosity either too small or its contribution to semi-inclusive DIS too much suppressed
- no sizable $\sin(\phi \pm \phi_S)$ modulation seen
- significant (and surprising?) non-zero $\sin(\phi_S)$ modulation for π^-
- double-spin asymmetry A_{LT} analysis ongoing
- final Collins amplitude results coming out soon