XVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Firenze, 19th-23rd April 2010

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

Gunar.Schnell @ desy.de

Spin-Momentum Structure of the Nucleon

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

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

		quark pol.		
		U	L	T
nucleon pol.	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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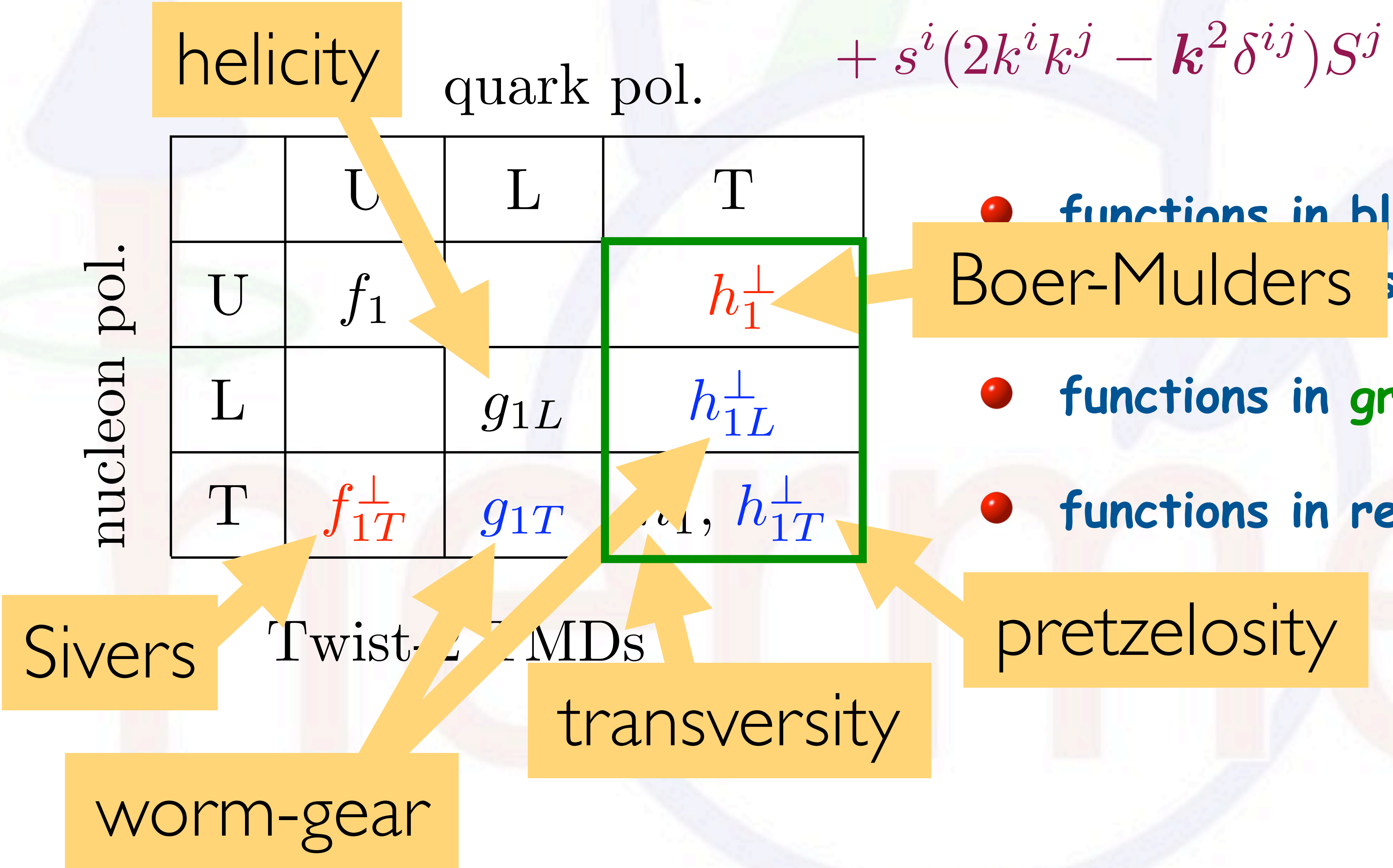

quark pol.

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

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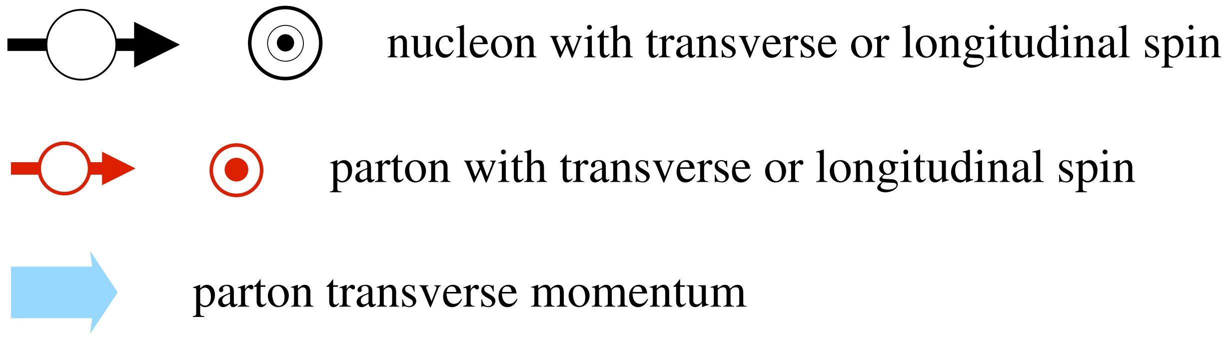
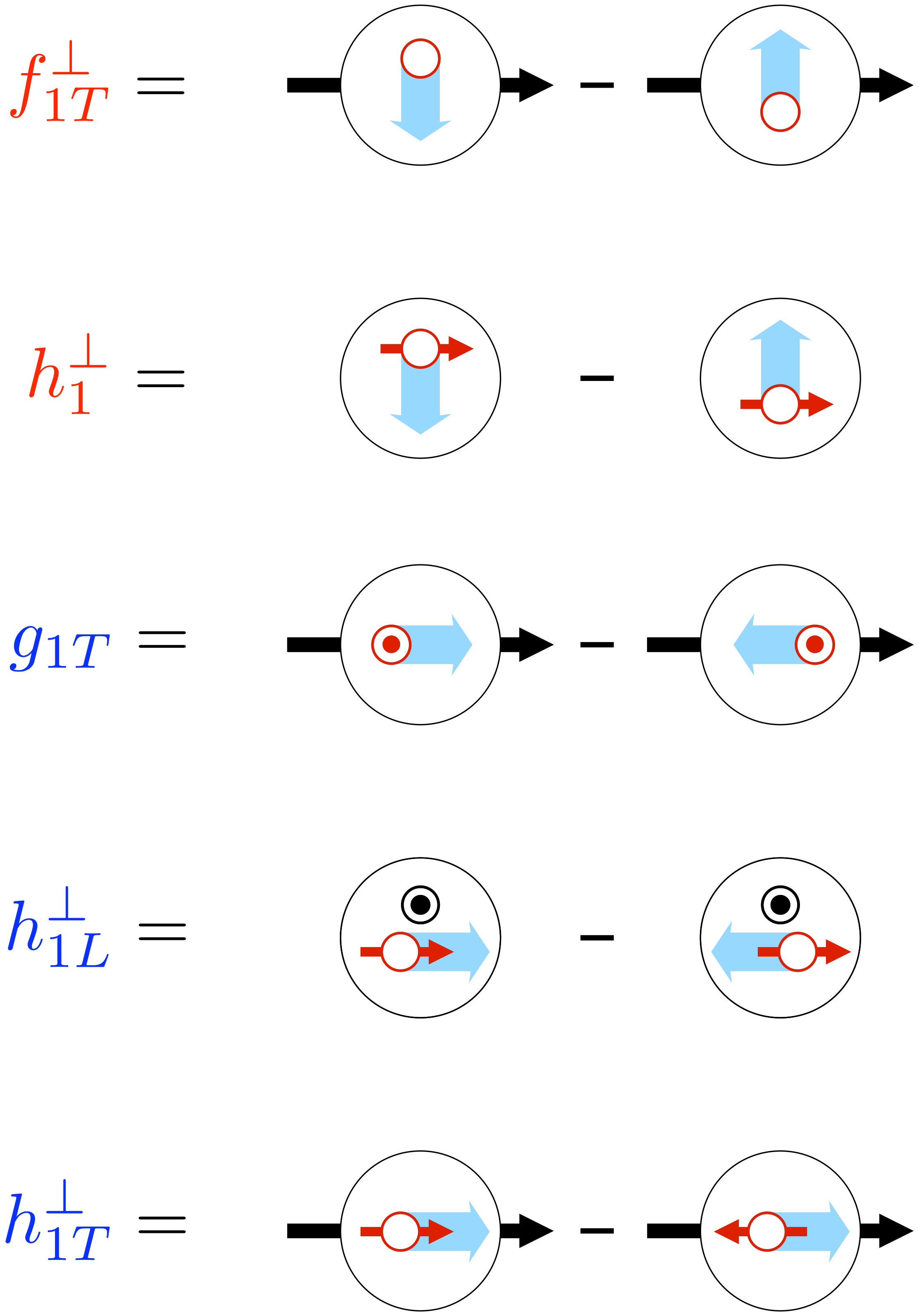
Transverse-Momentum-Dependent DF



nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum



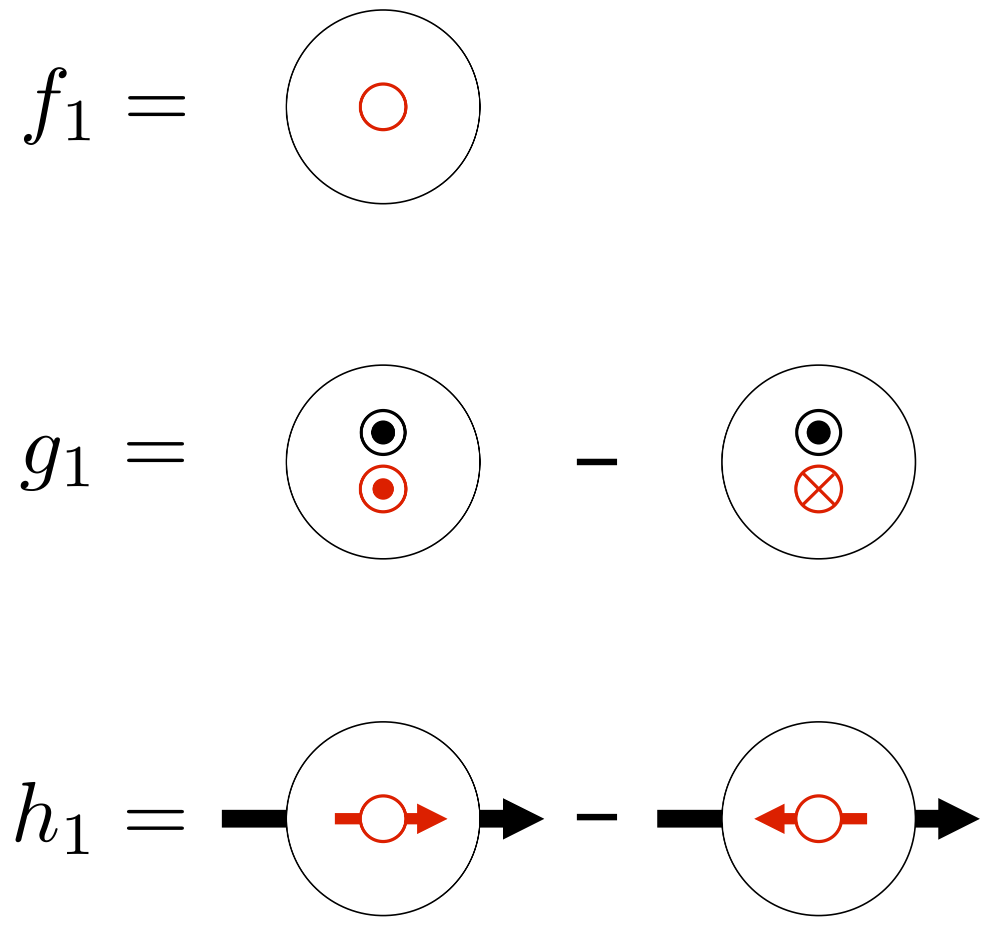
$f_{1T}^{\perp} =$

$h_1^{\perp} =$

$g_{1T} =$

$h_{1L}^{\perp} =$

$h_{1T}^{\perp} =$



$f_1 =$

$g_1 =$

$h_1 =$

Courtesy of A. Bacchetta

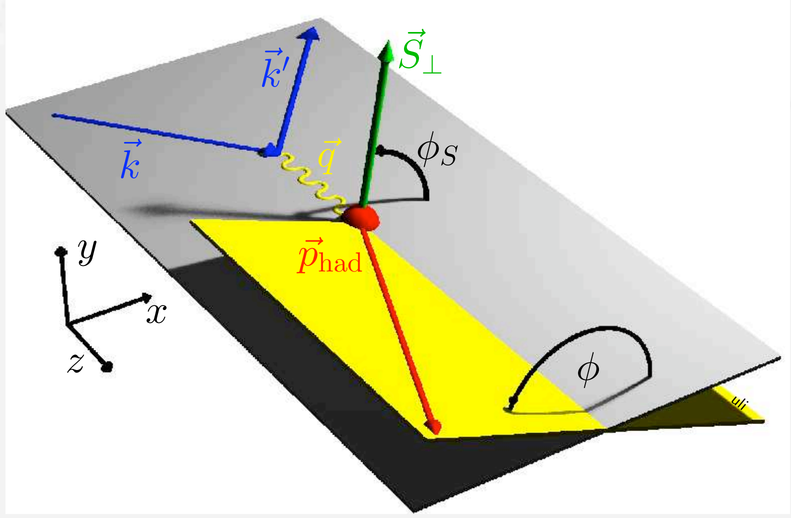
1-Hadron Production (ep→ehX)

$$
\begin{aligned}
d\sigma = \; & d\sigma^{0}_{UU} + \cos 2\phi \, d\sigma^{1}_{UU} + \frac{1}{Q} \cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^{3}_{LU} \\
& + S_L \left\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q} \sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q} \cos\phi \, d\sigma^{7}_{LL} \right] \right\} \\
& + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right. \\
& \qquad + \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \qquad \left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q} \left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

$$\sigma_{XY}$$

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

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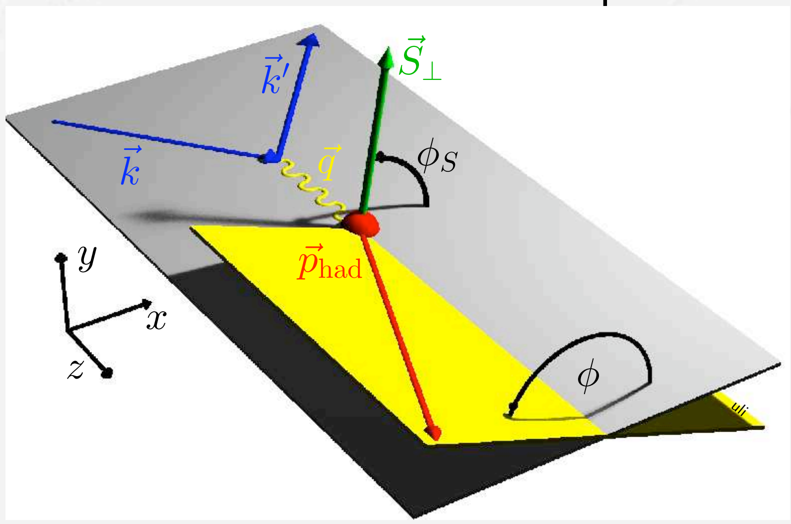
& + S_T \left\{ \boxed{\sin(\phi-\phi_S)\, d\sigma^8_{UT}} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \boxed{\sin(3\phi-\phi_S)\, d\sigma^{10}_{UT}} \frac{1}{Q} \right. \\
& \quad + \boxed{\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)} \\
& \quad \left. + \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\}
\end{aligned}
$$

σ_{XY}

Beam **Target**

Polarization



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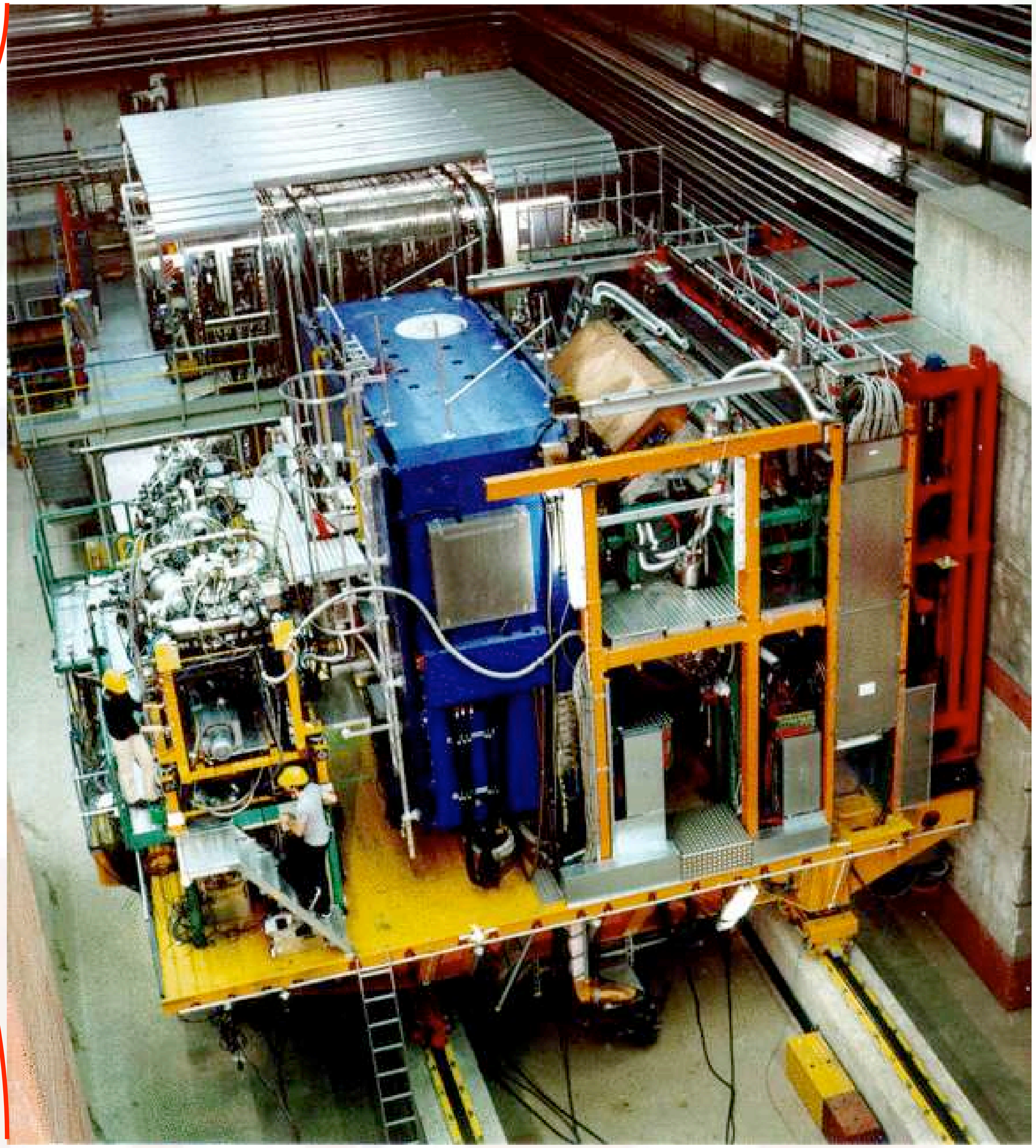
The HERMES Experiment (†2007)

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.,

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

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

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

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

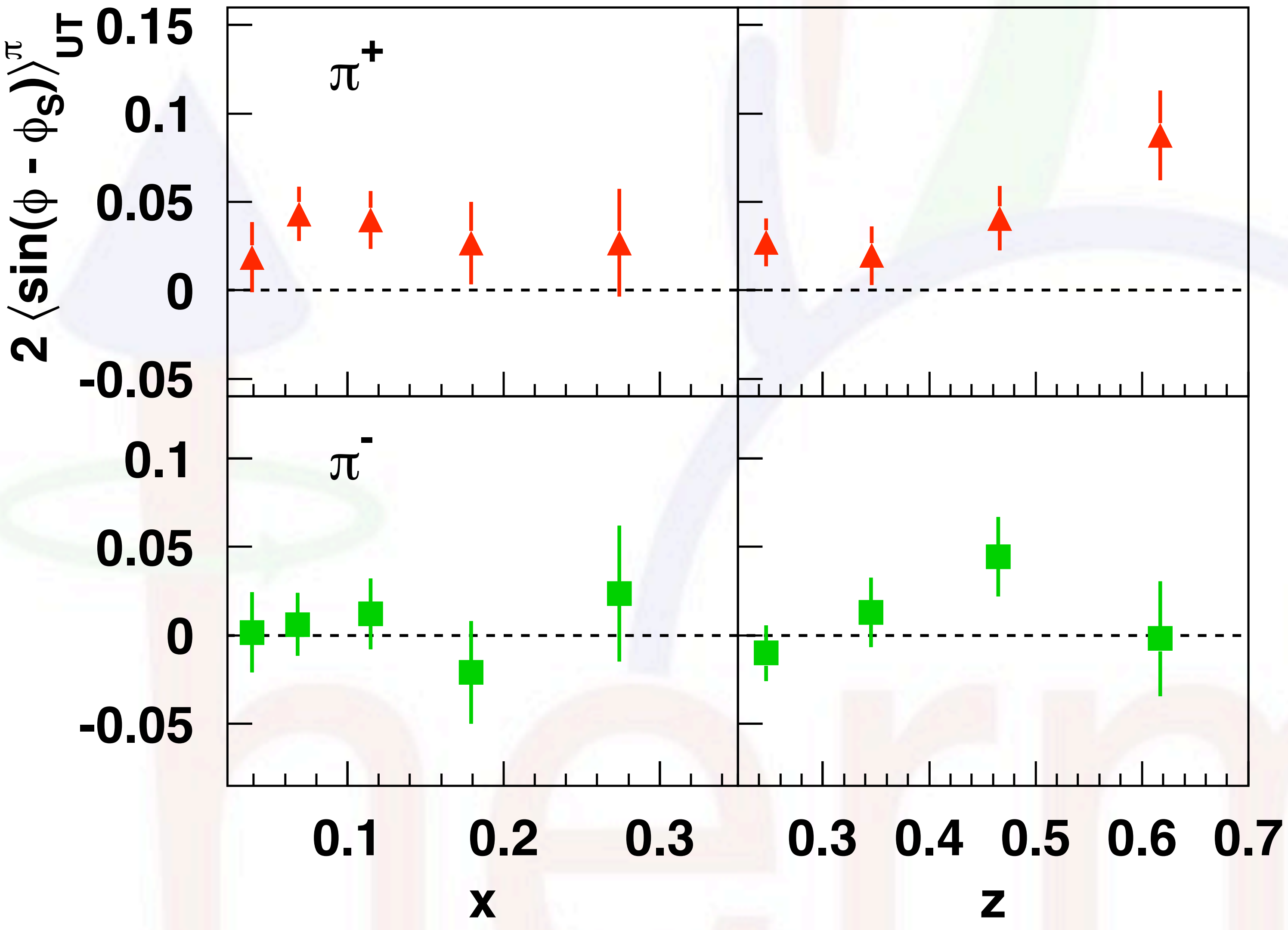
$$A_{\mathrm{UT}}(\phi,\phi_S) \equiv \frac{2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}}\sin(\phi-\phi_S) + \ldots}{1 \ + \ 2\langle\cos\phi\rangle_{\mathrm{UU}}\cos\phi + 2\langle\cos 2\phi\rangle_{\mathrm{UU}}\cos 2\phi}$$

systematics of neglecting cosine terms found to be negligible

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

HERMES Sivers amplitudes

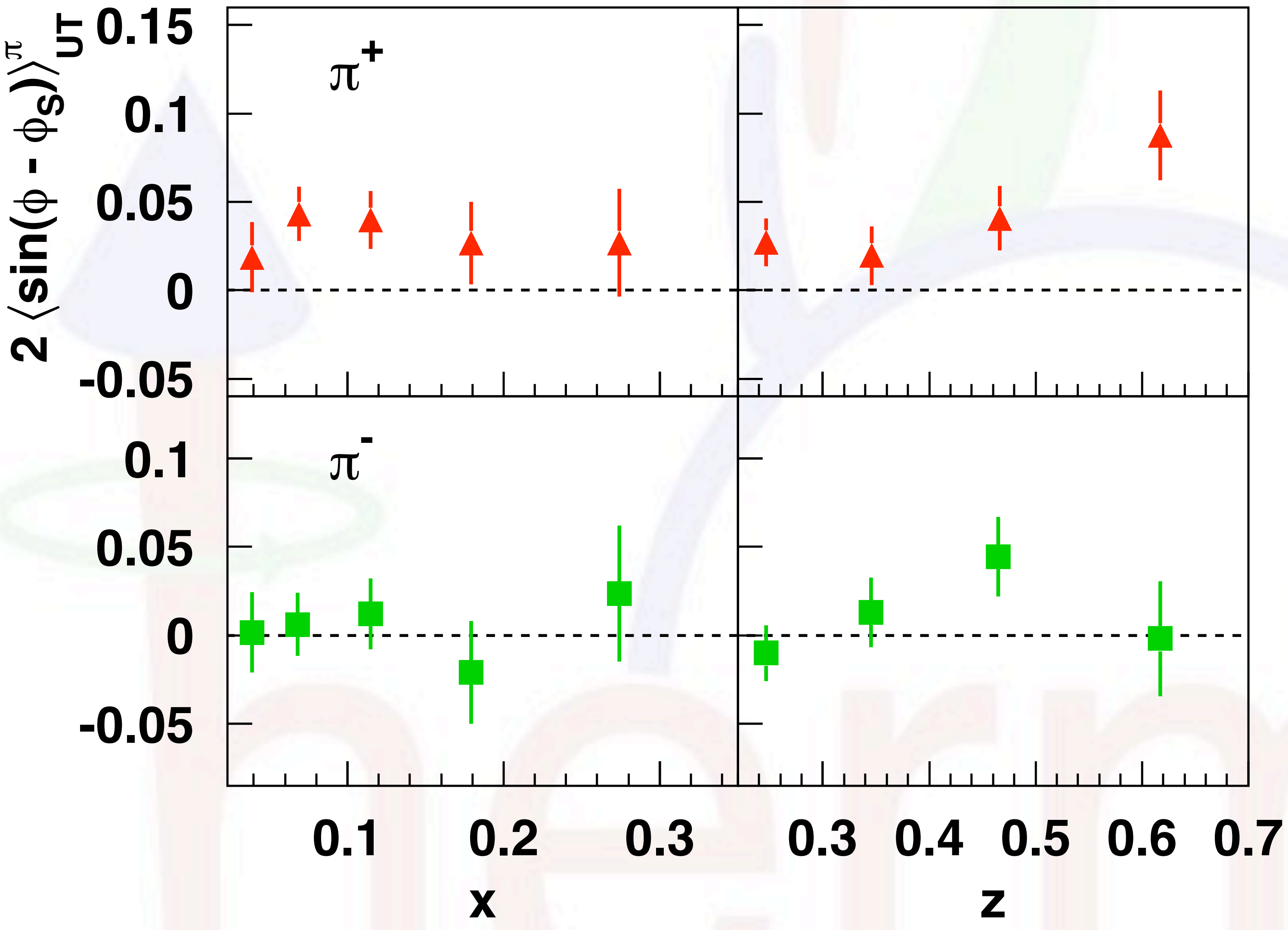
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]

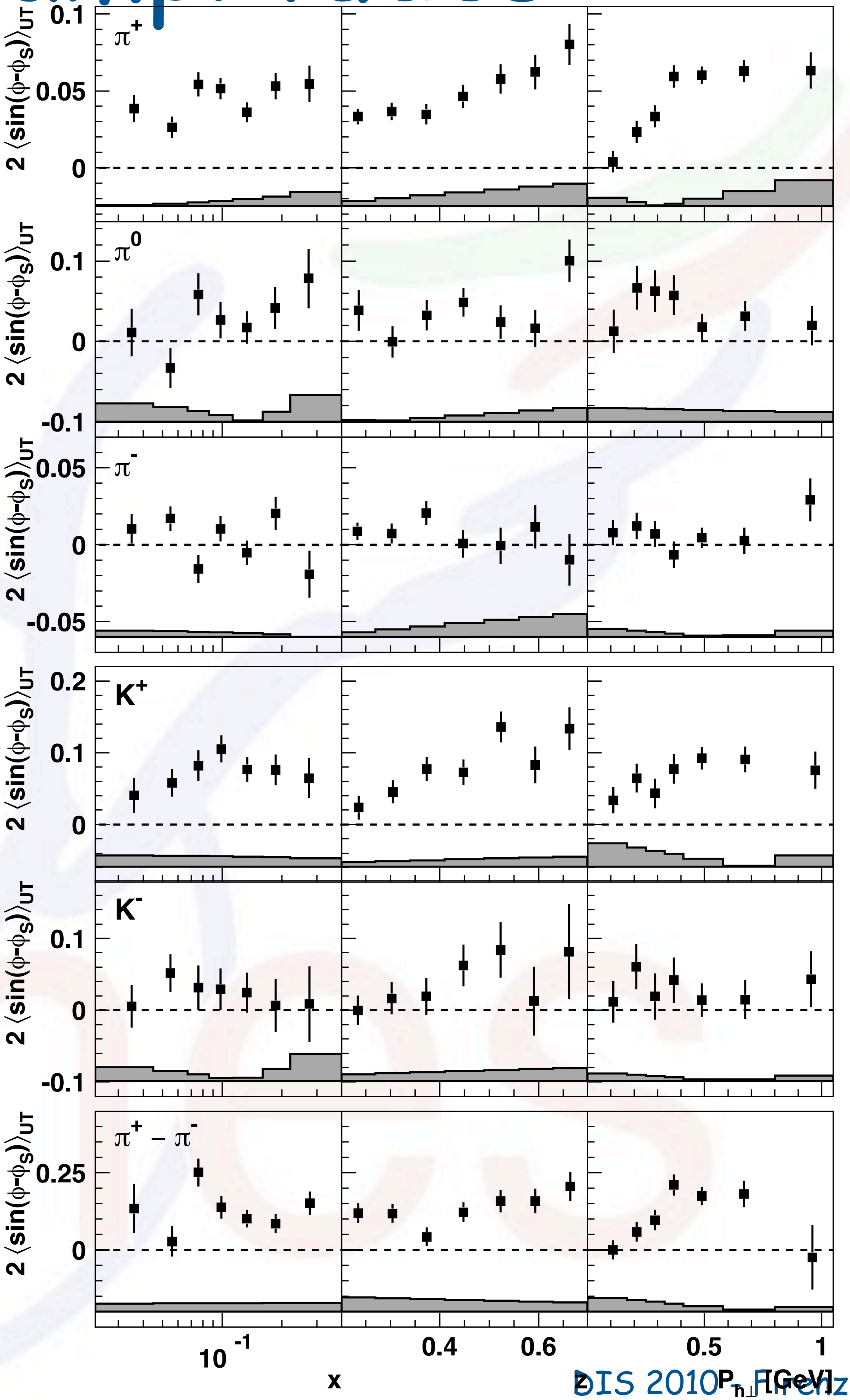


☑ first evidence for T-odd Sivers effect in SIDIS!

HERMES Sivers amplitudes

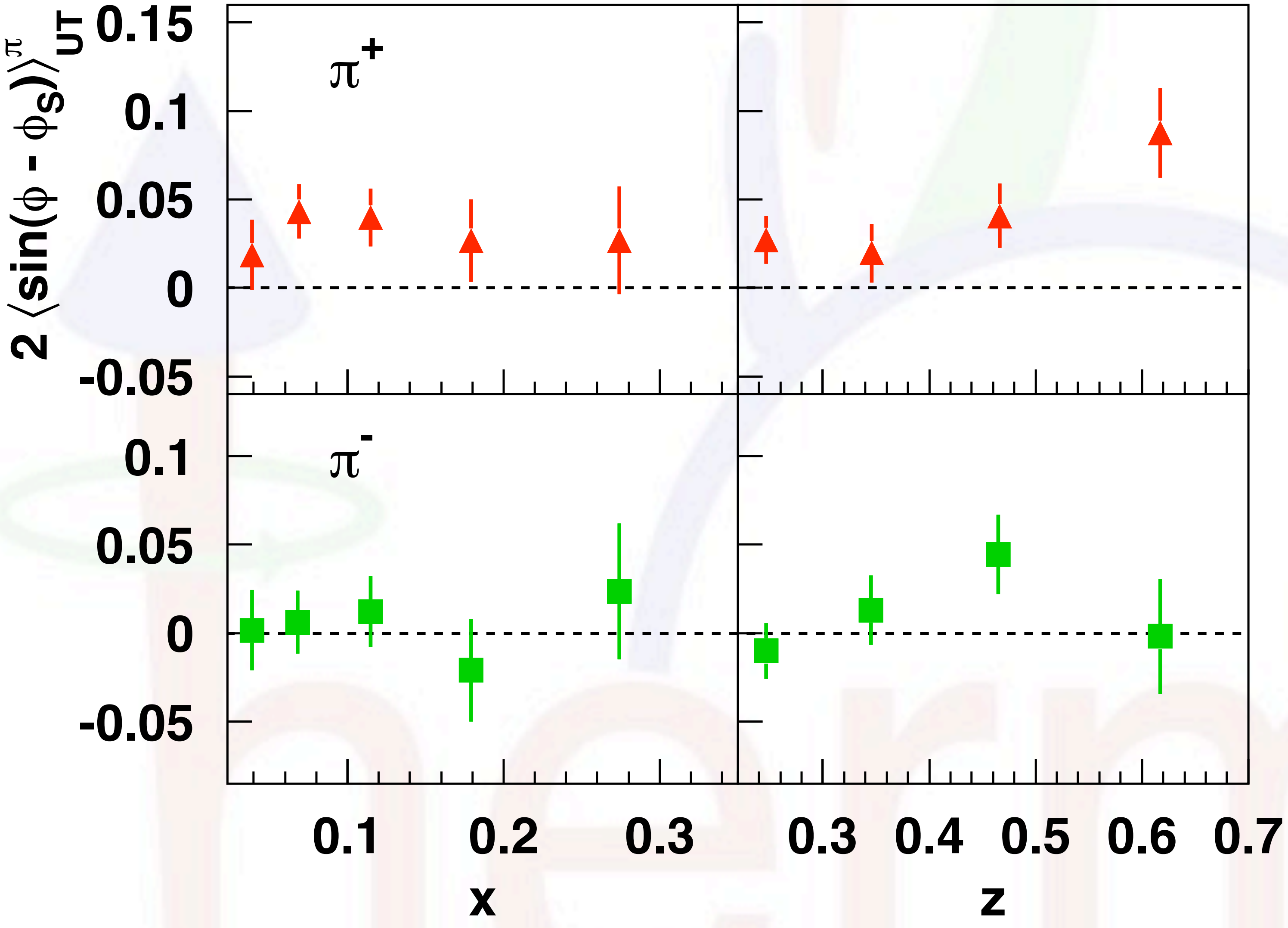
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]

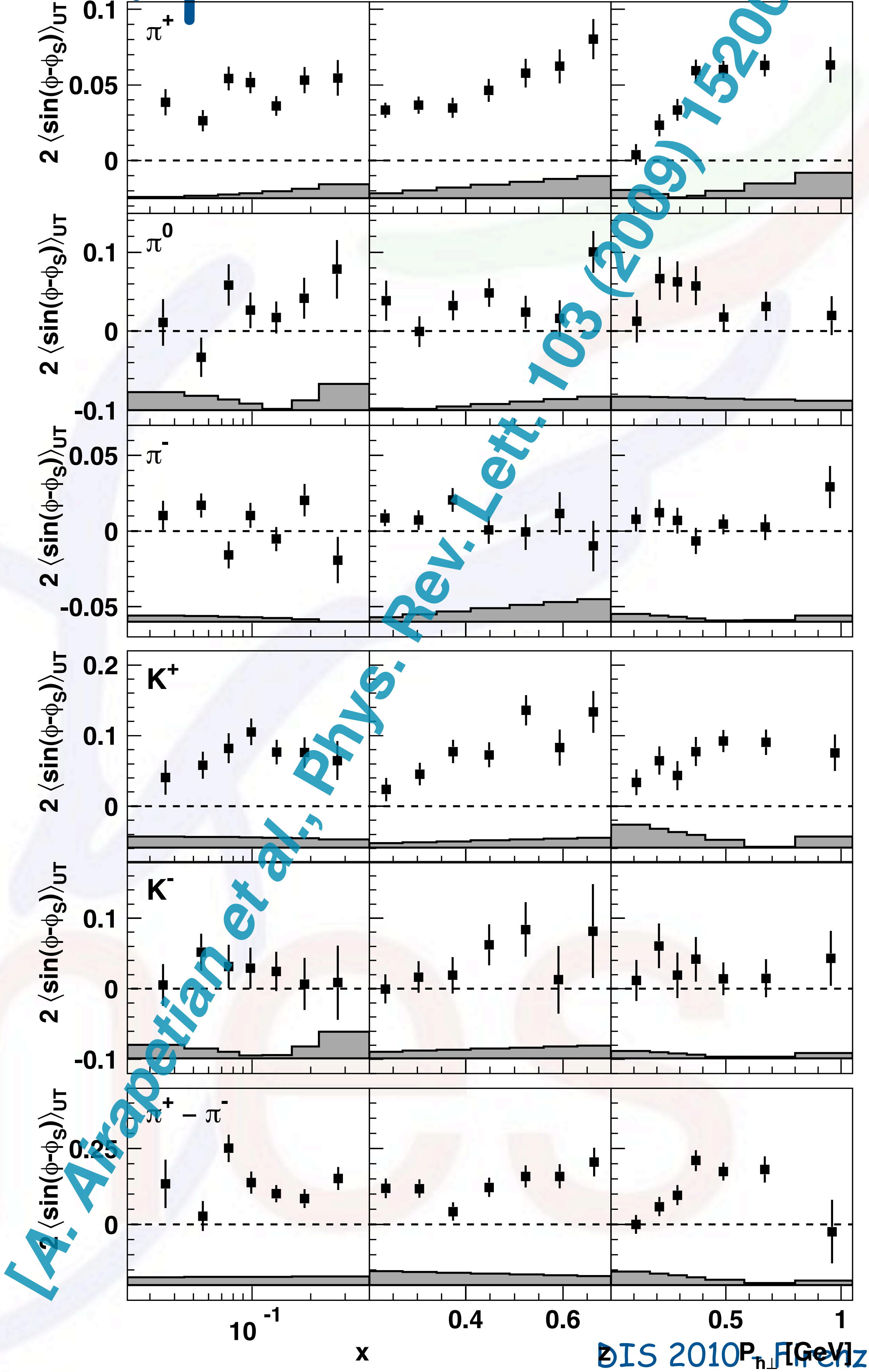




HERMES Sivers amplitudes

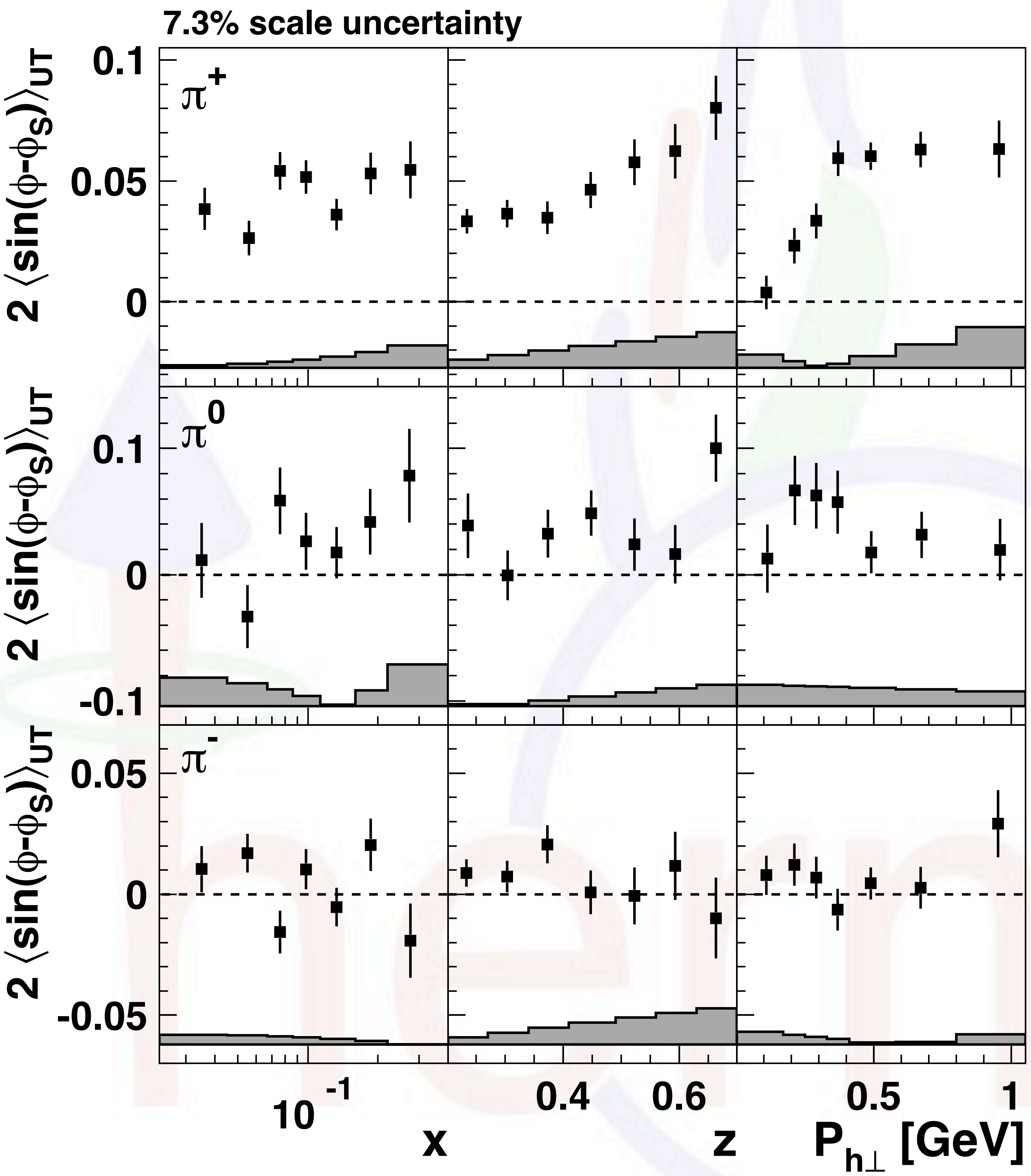
[*A. Airapetian et al.*, Phys. Rev. Lett. 94 (2005) 012002]



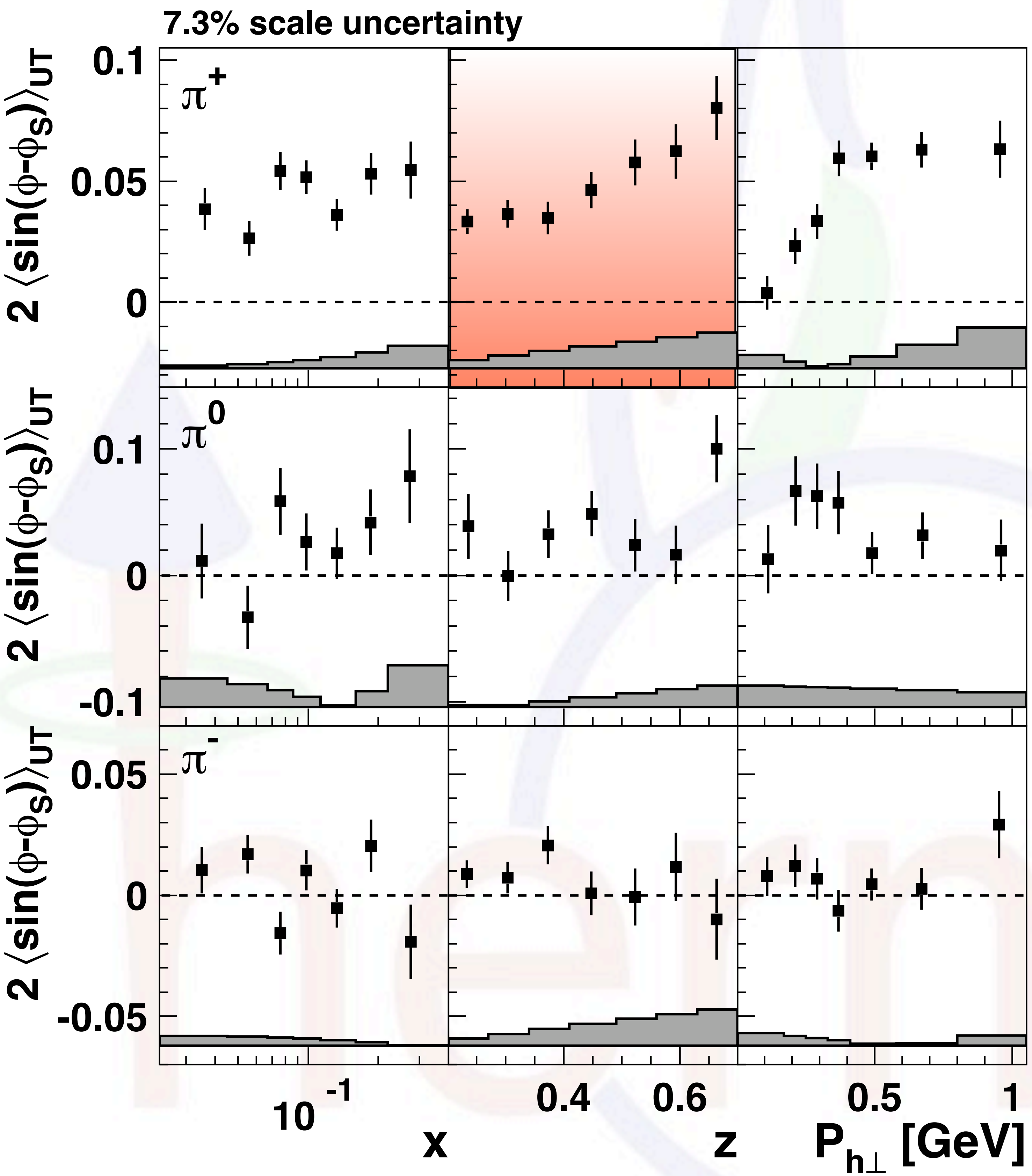


[A. Airapetian et al., Phys. Rev. Lett. 103 (2009) 152002]

Sivers amplitudes for pions

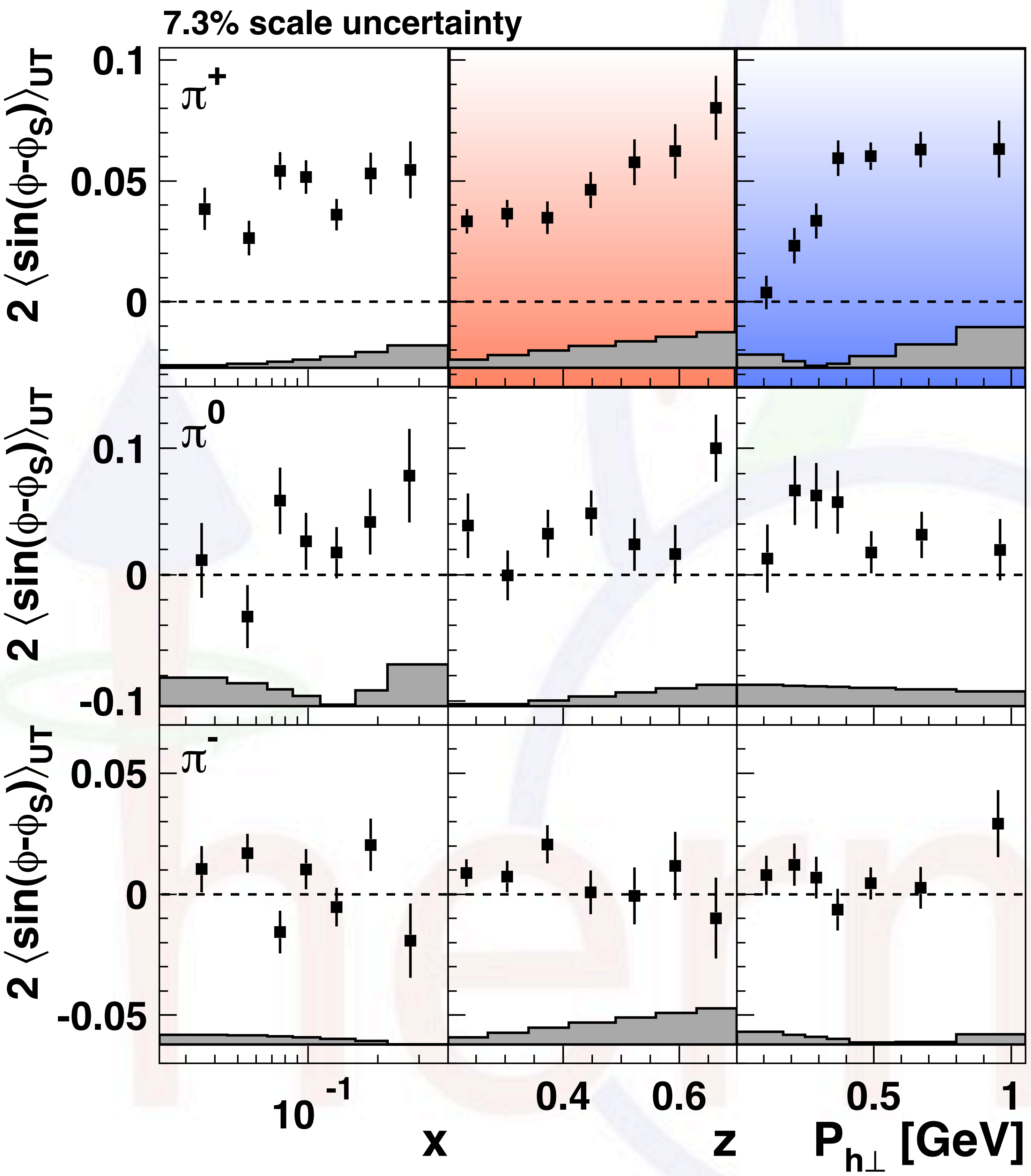


Sivers amplitudes for pions



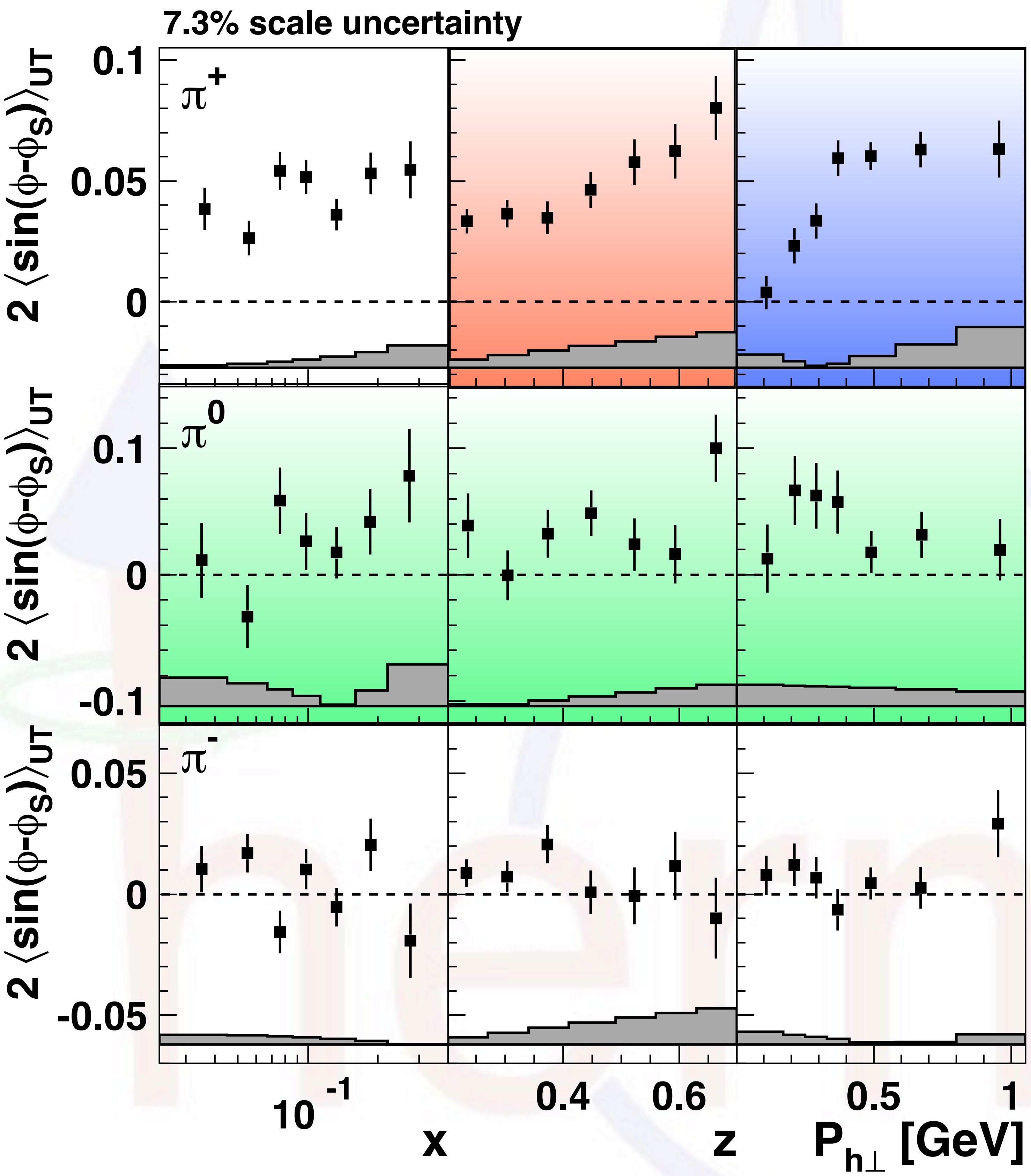
- ☛ clear rise with z

Sivers amplitudes for pions



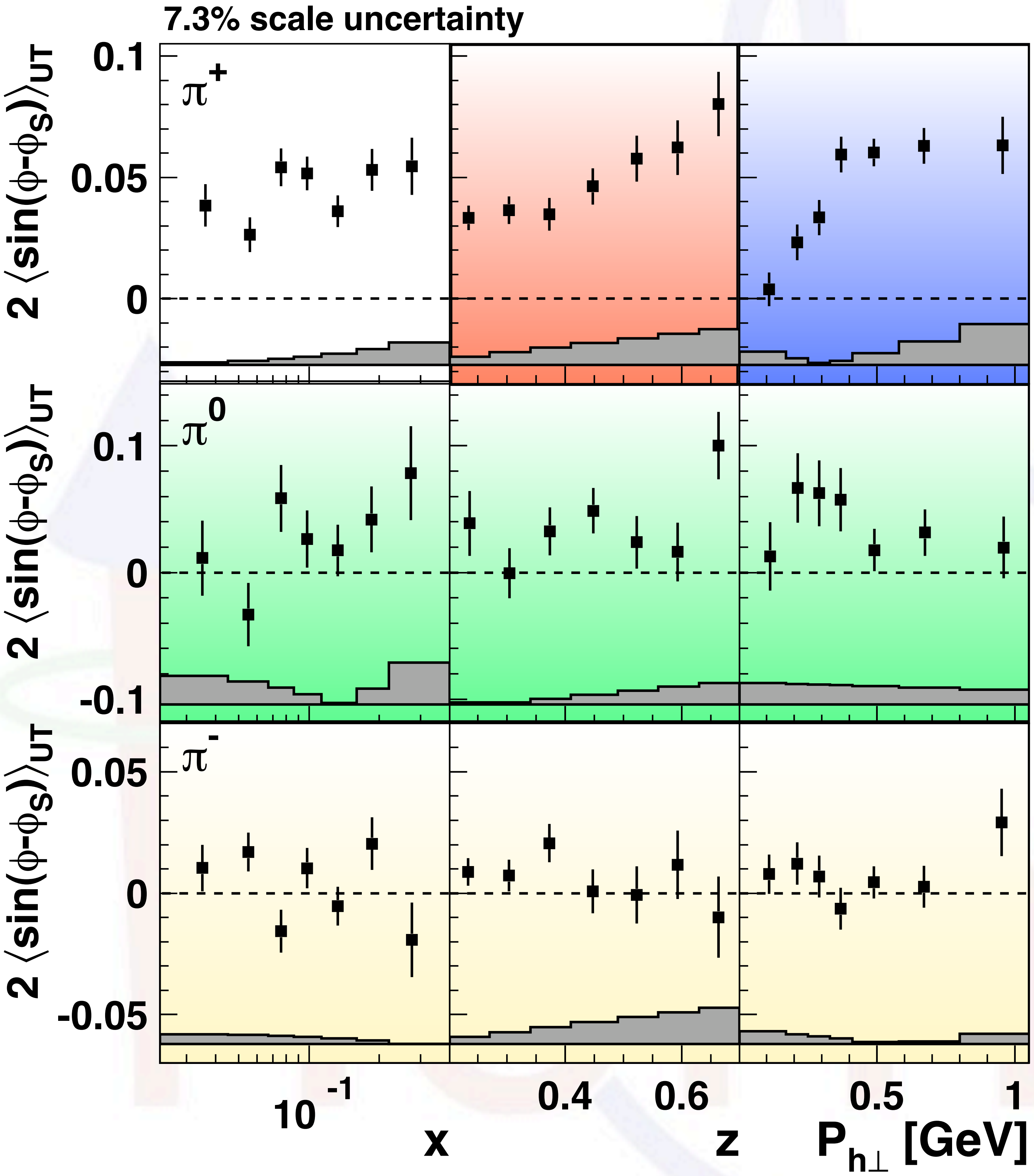
- ☛ clear rise with z
- ☛ rise at low $P_{h\perp}$
- ☛ plateau at high $P_{h\perp}$

Sivers amplitudes for pions



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

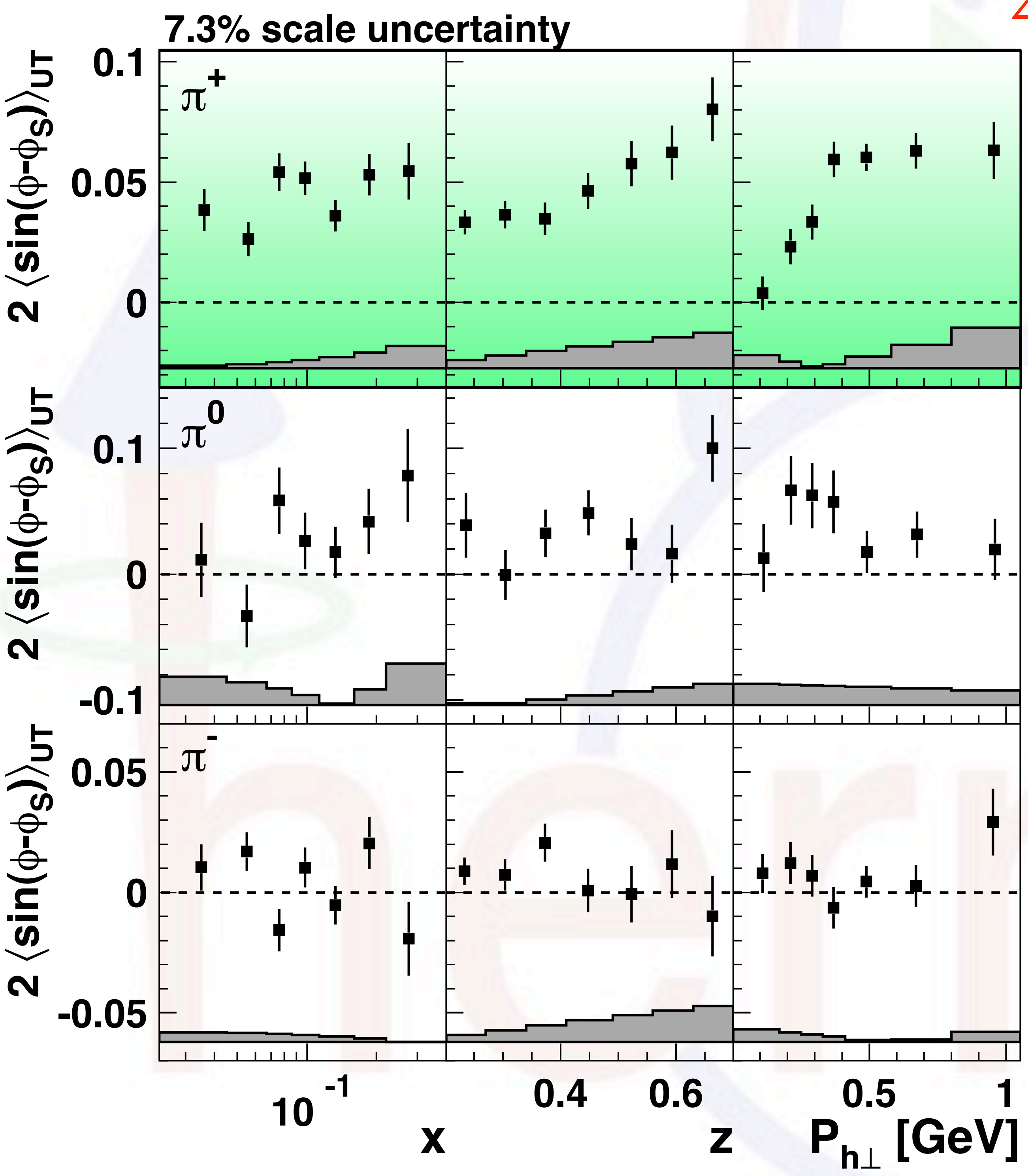
Sivers amplitudes for pions



- ☛ 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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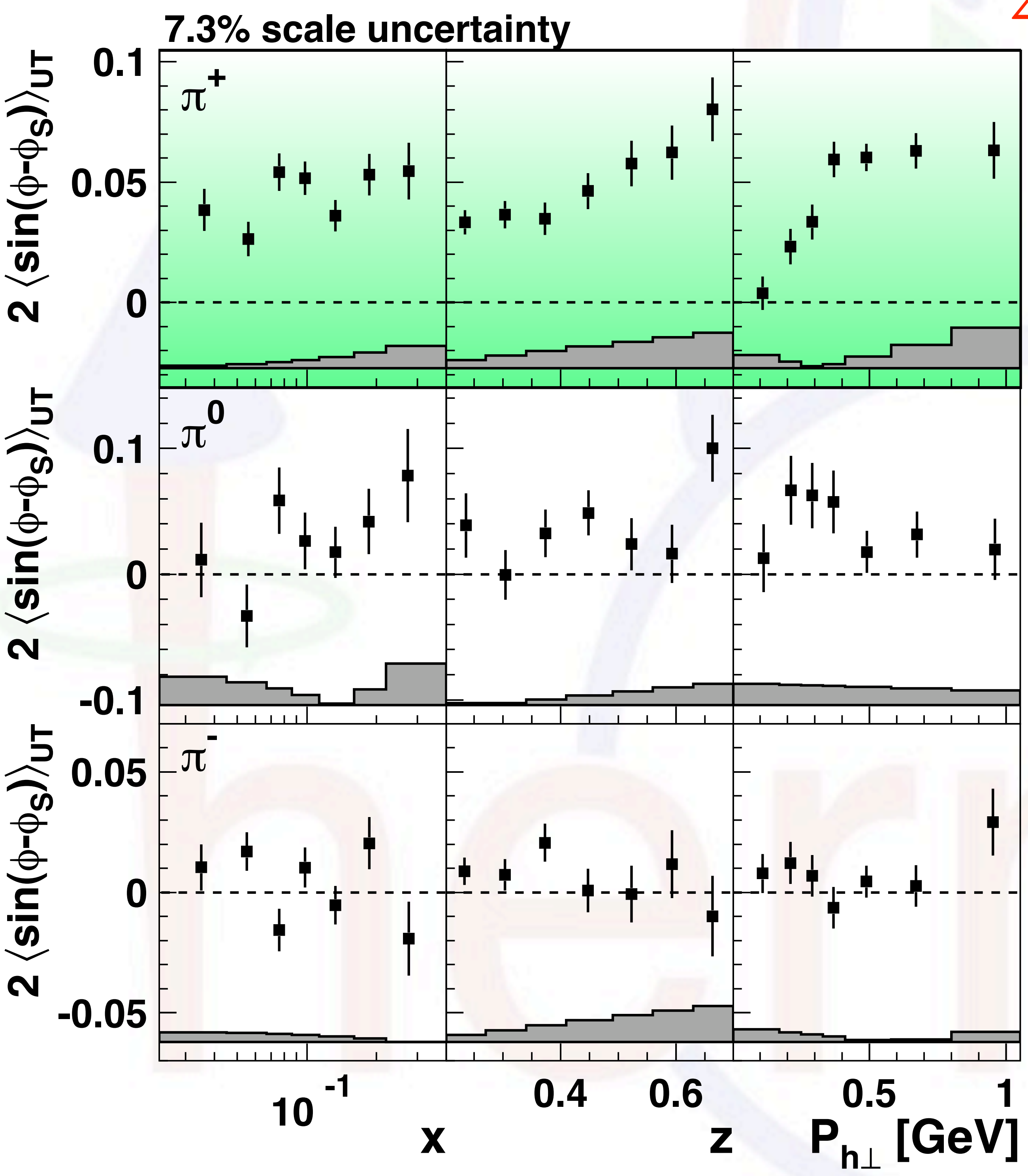

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

Sivers amplitudes for pions

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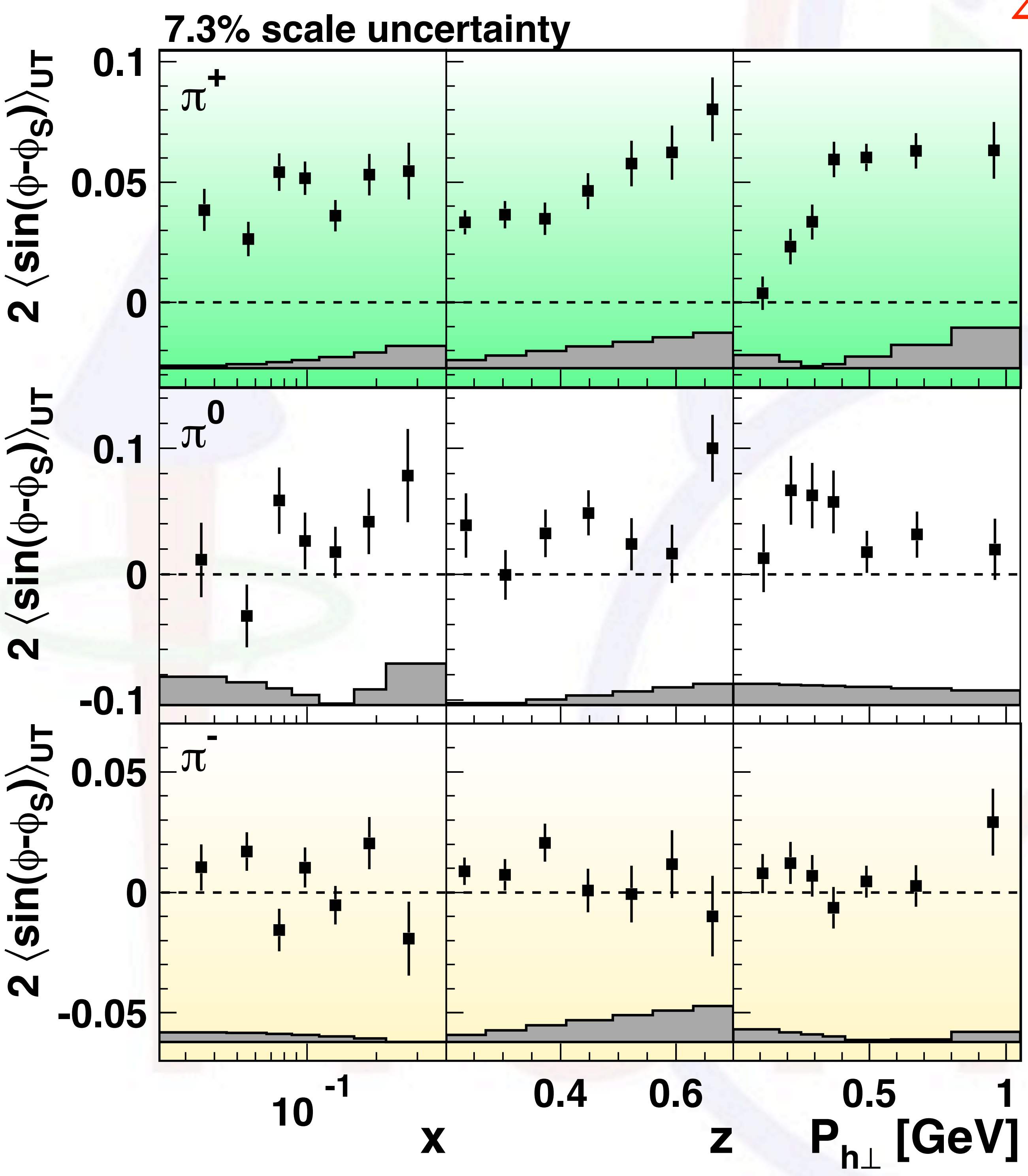

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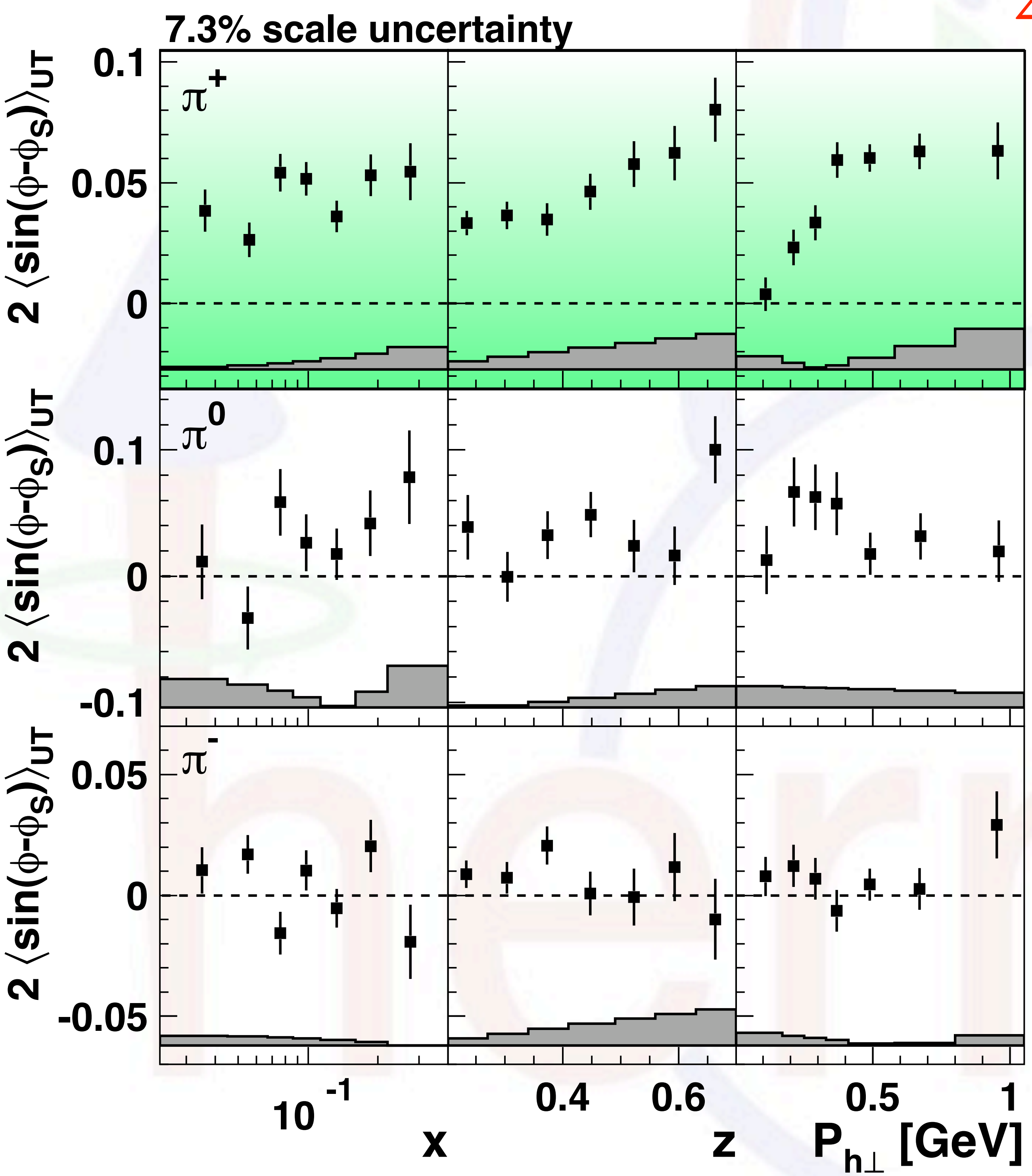
- ☛ u-quark Sivers DF < 0
- ☛ d-quark Sivers DF > 0 (cancelation for π^-)

Sivers amplitudes for pions

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



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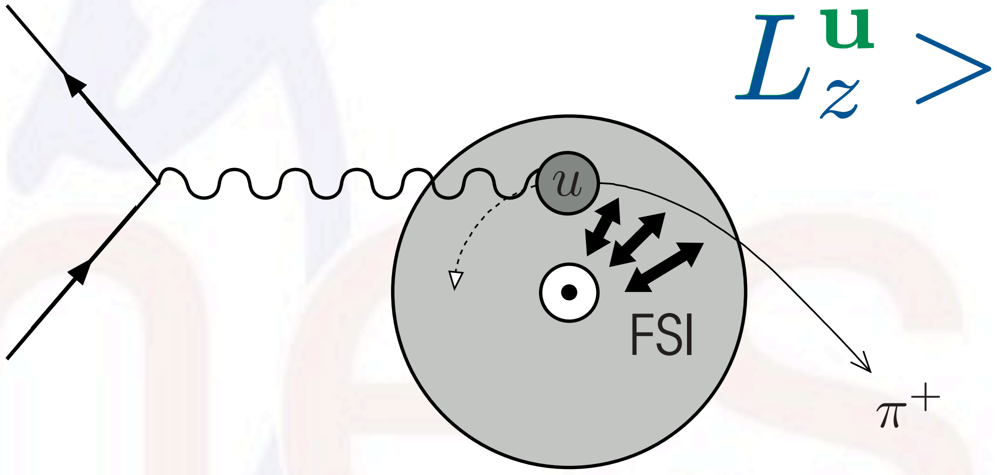
$$L_z^{\mathbf{u}} > 0$$



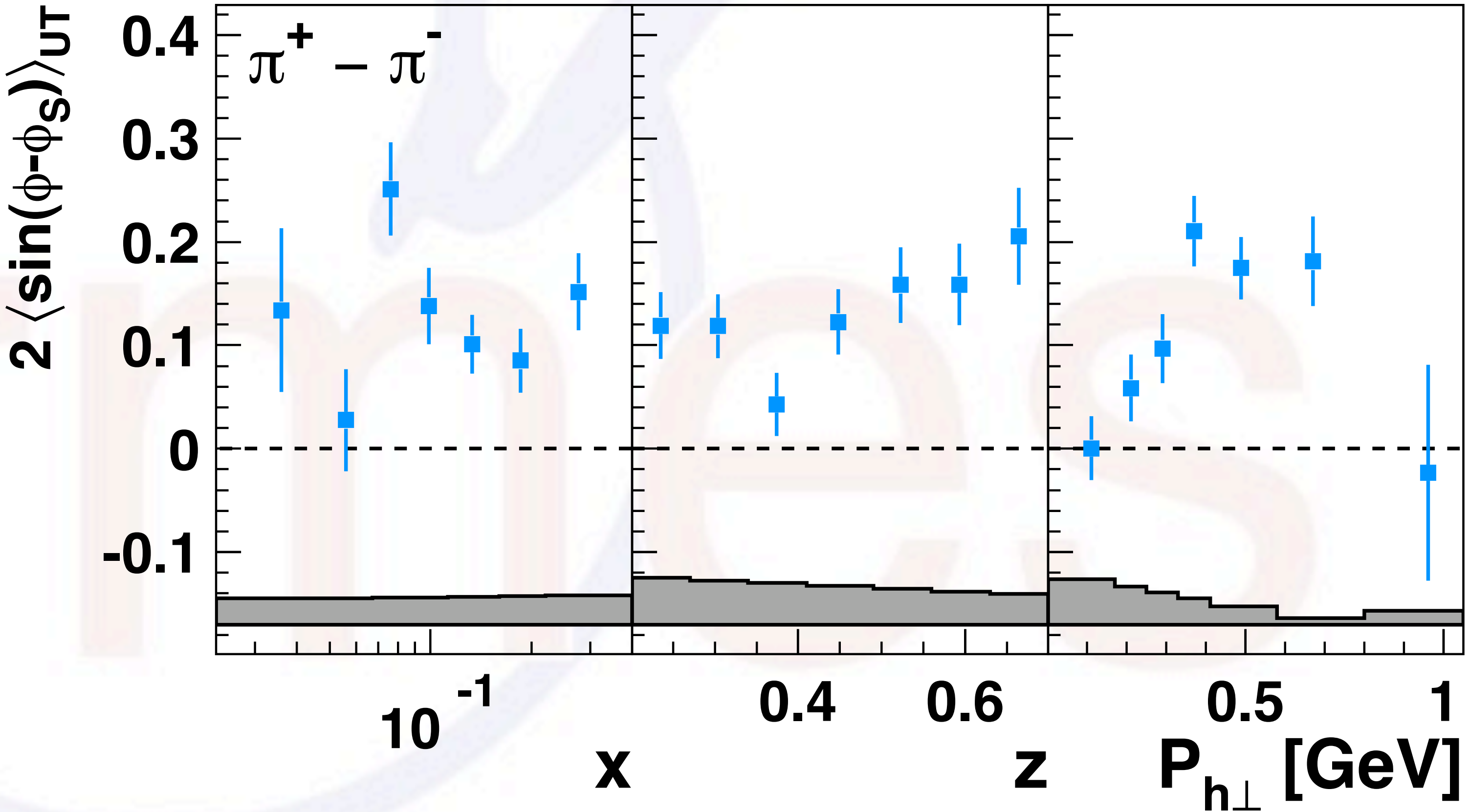
[*M. Burkardt*, Phys. Rev. D66 (2002) 014005]

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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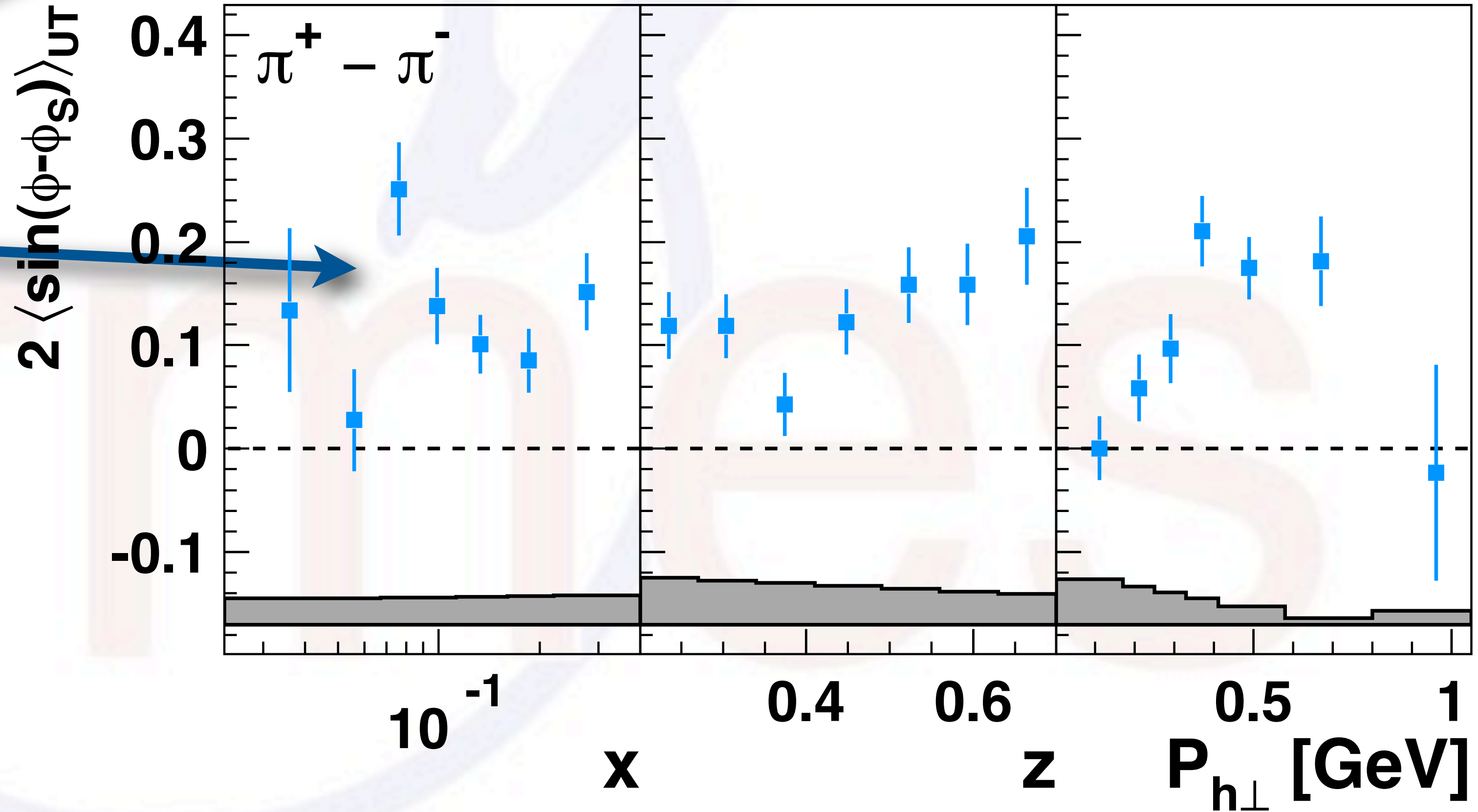
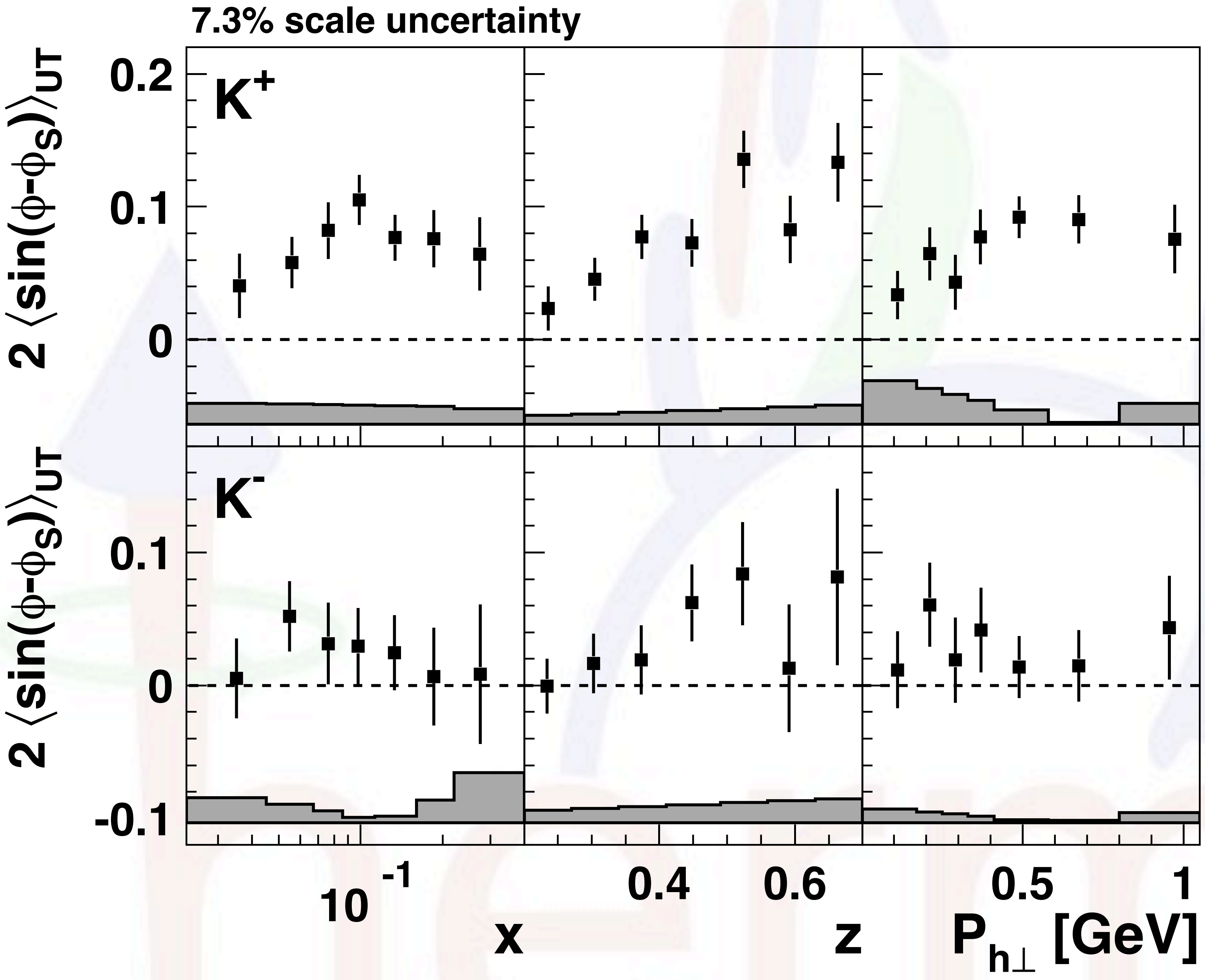
access to Sivers

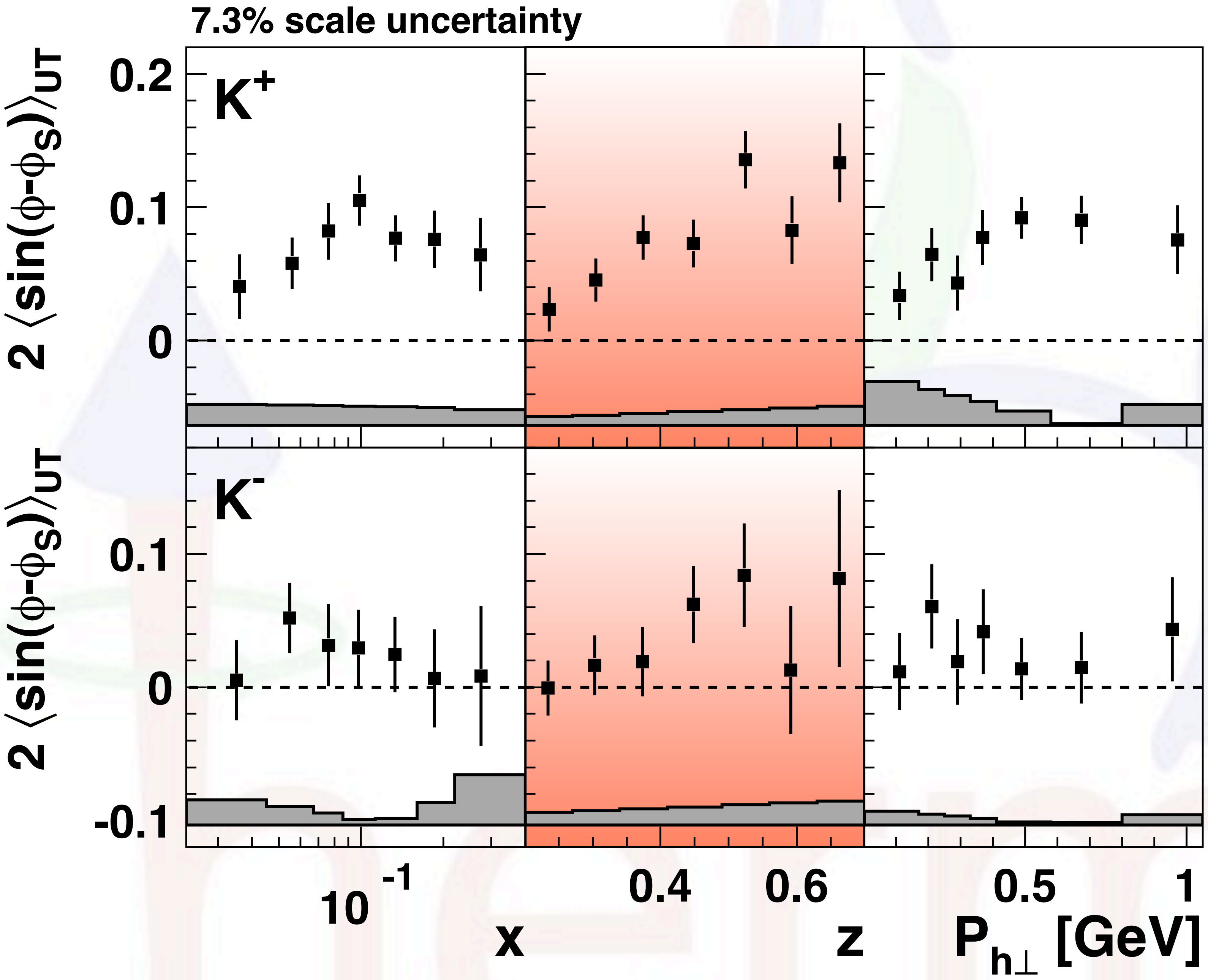
u-valence distribution



The kaon Sivers amplitudes

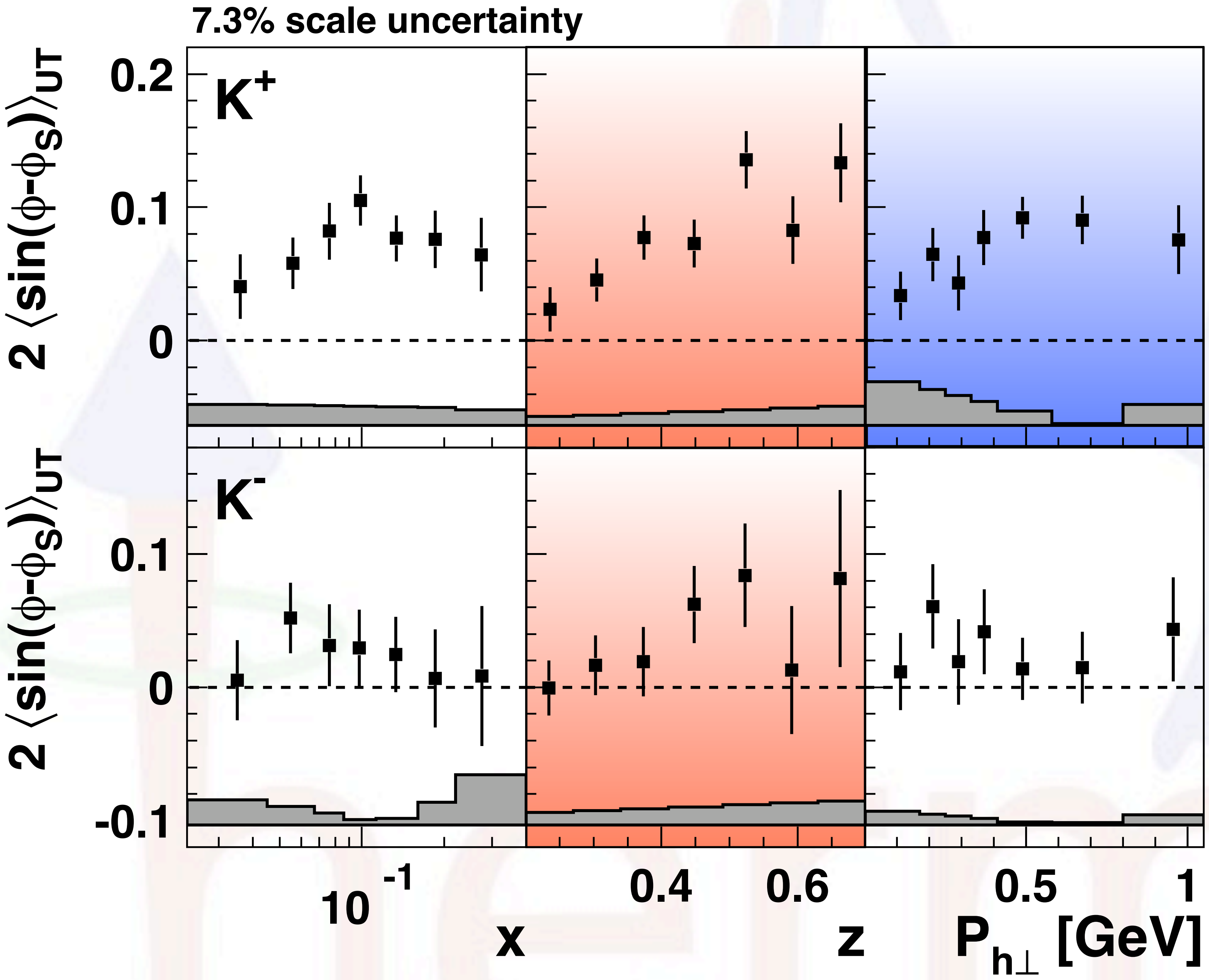


The kaon Sivers amplitudes



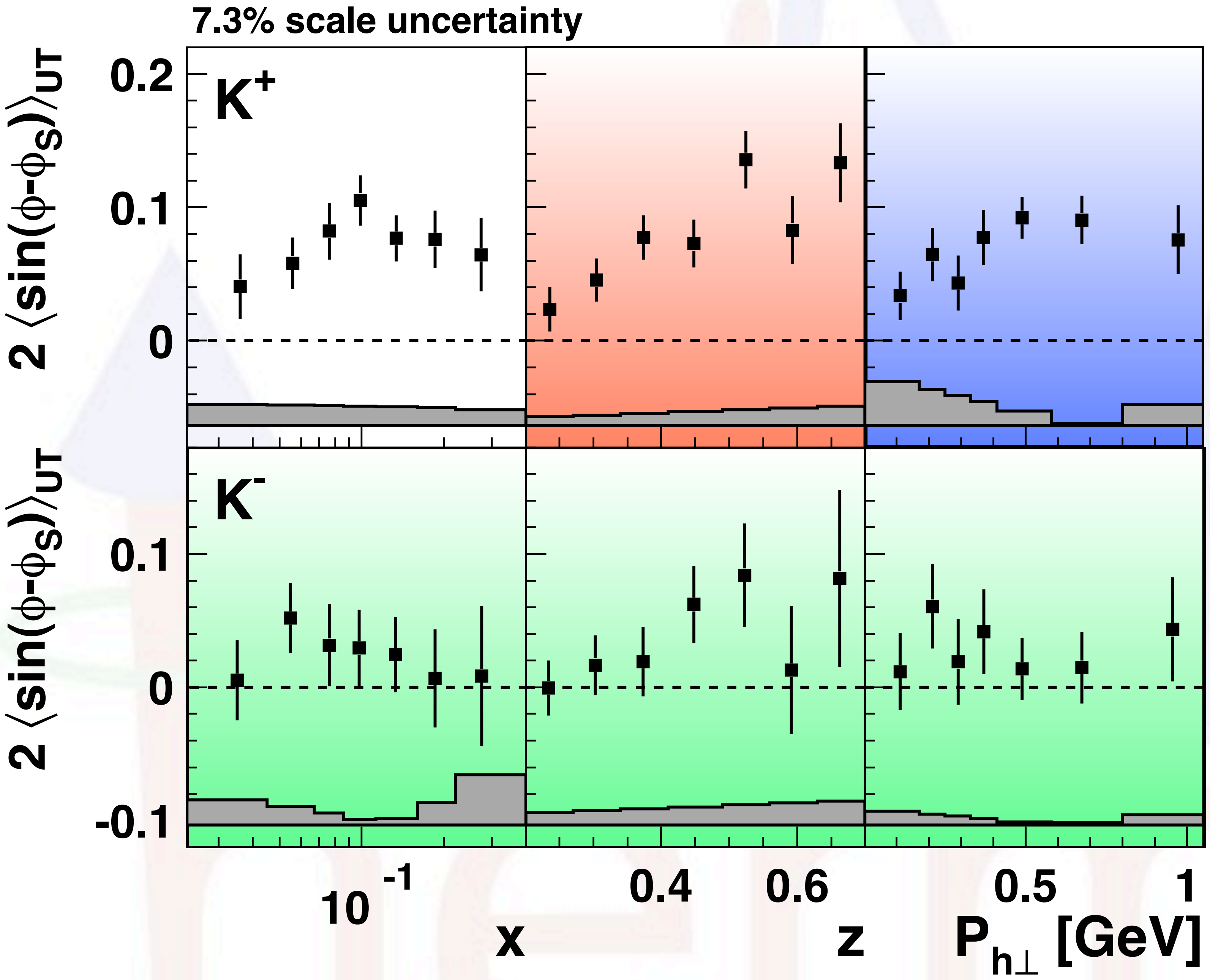
☛ clear rise with z

The kaon Sivers amplitudes



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

The kaon Sivers amplitudes



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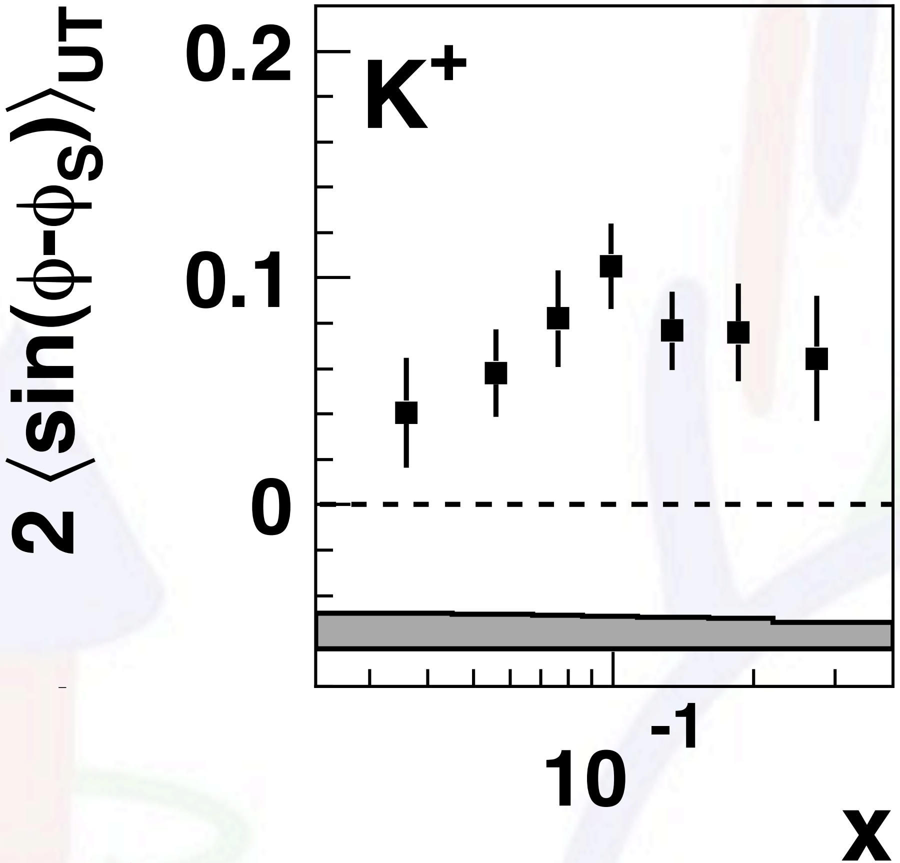
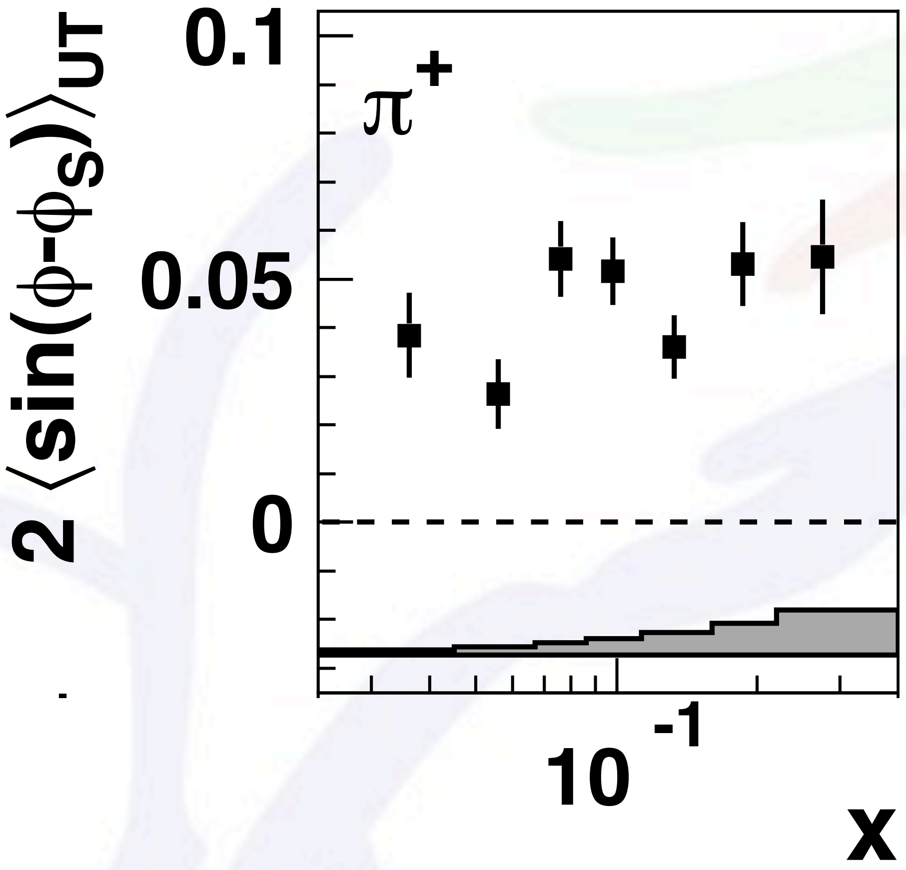
- ☛ plateau at high $P_{h\perp}$
- ☛ slightly positive

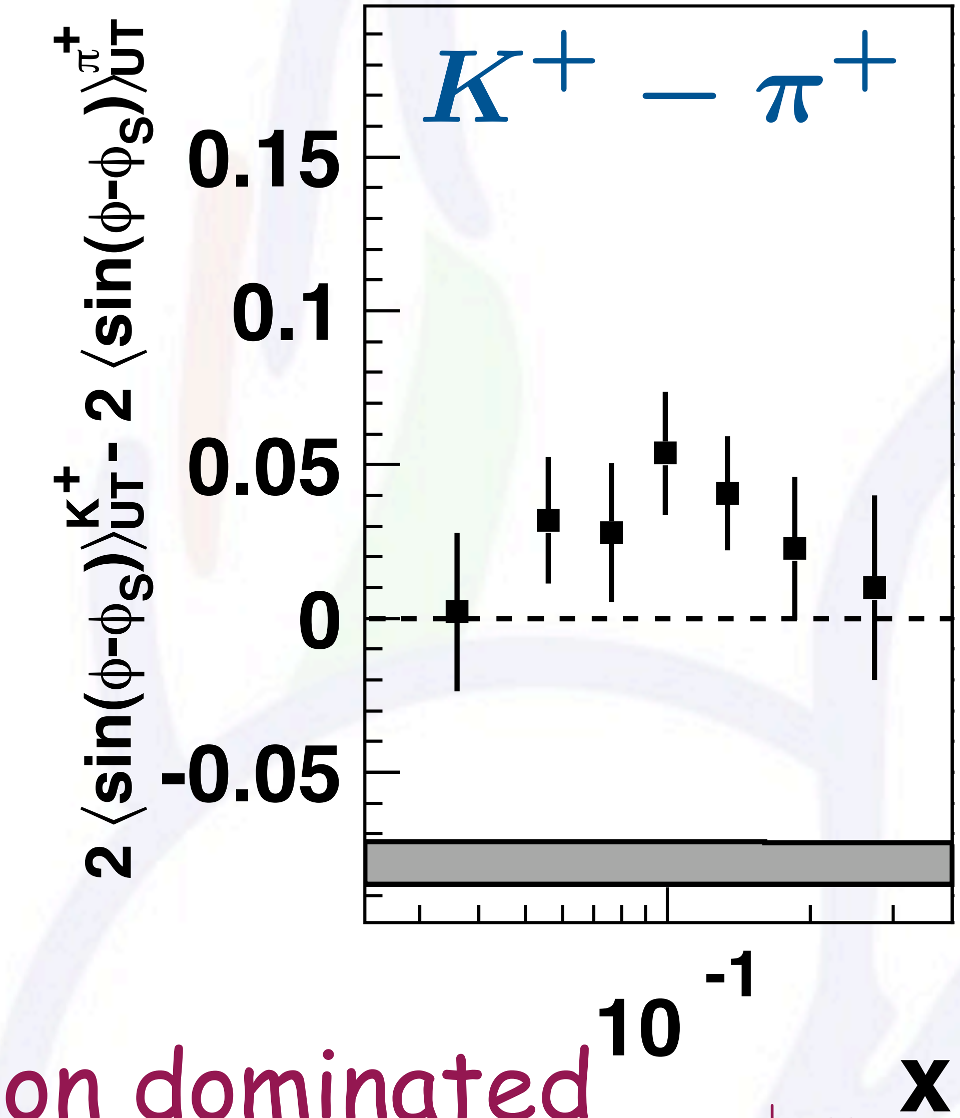
The "Kaon Challenge"





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

The "Kaon Challenge"



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

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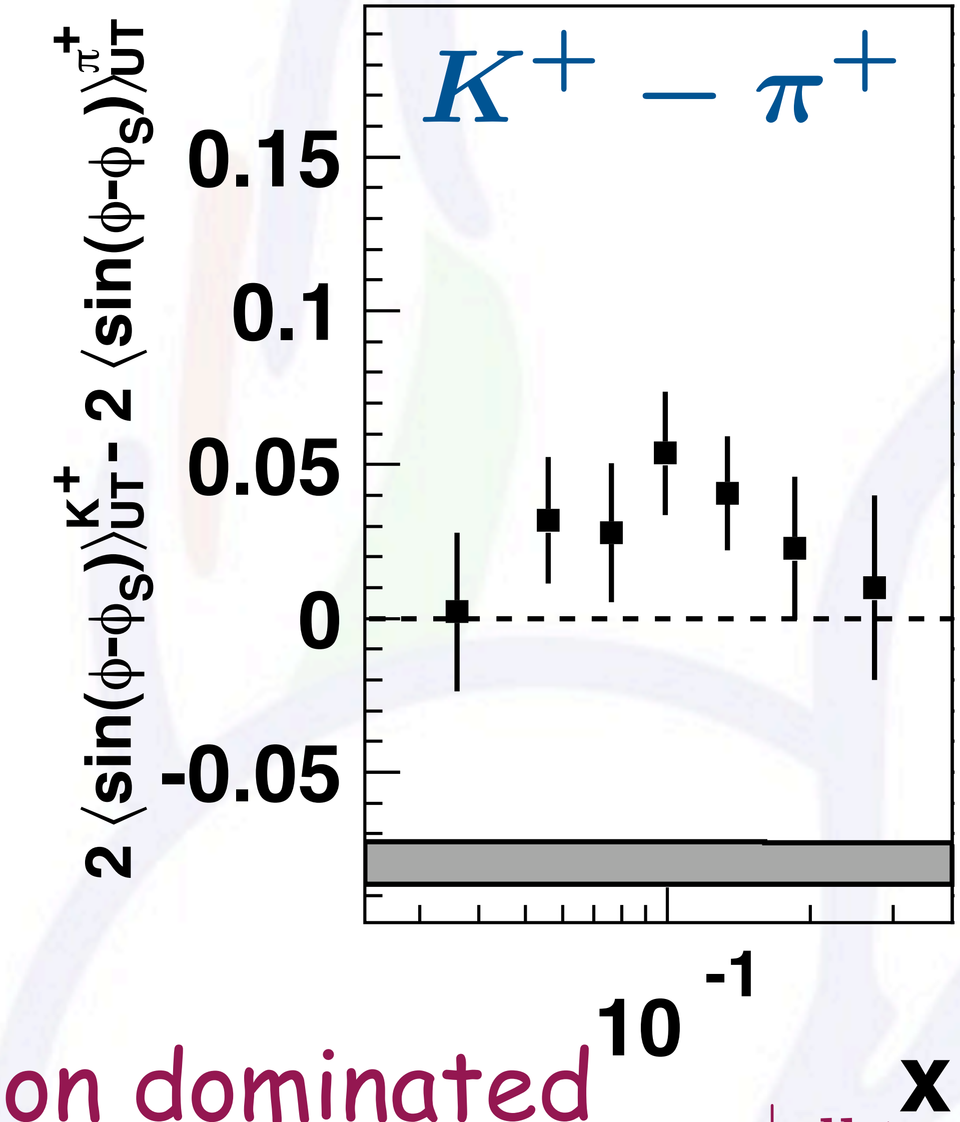

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☐ $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

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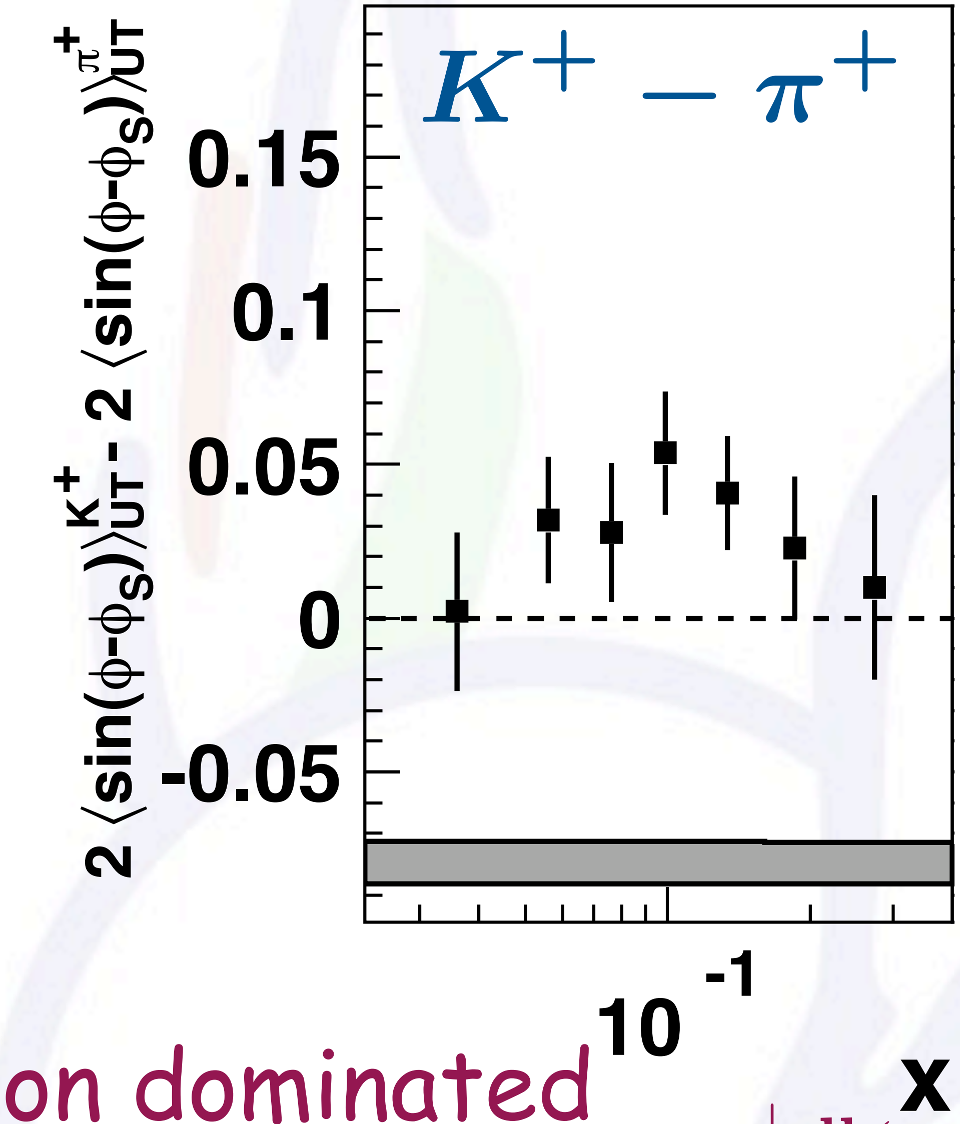

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
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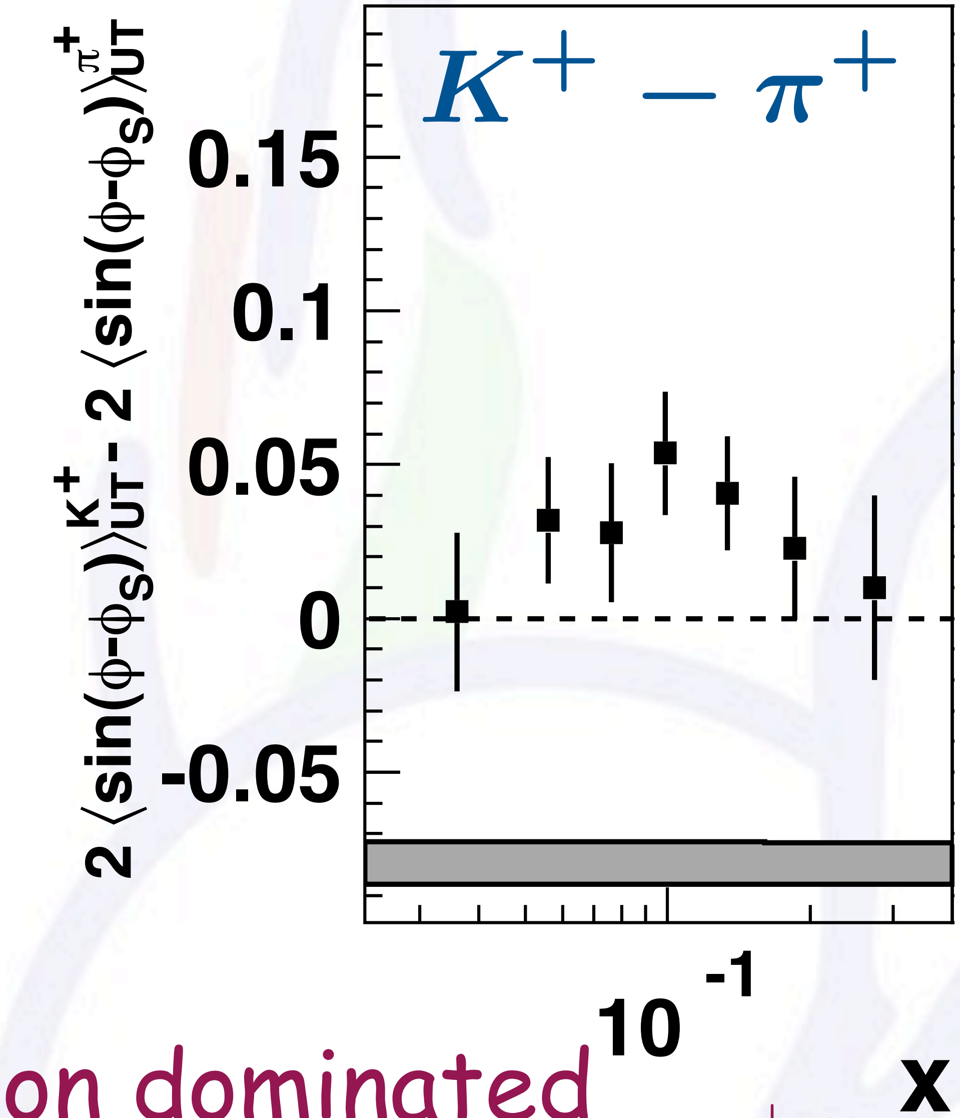

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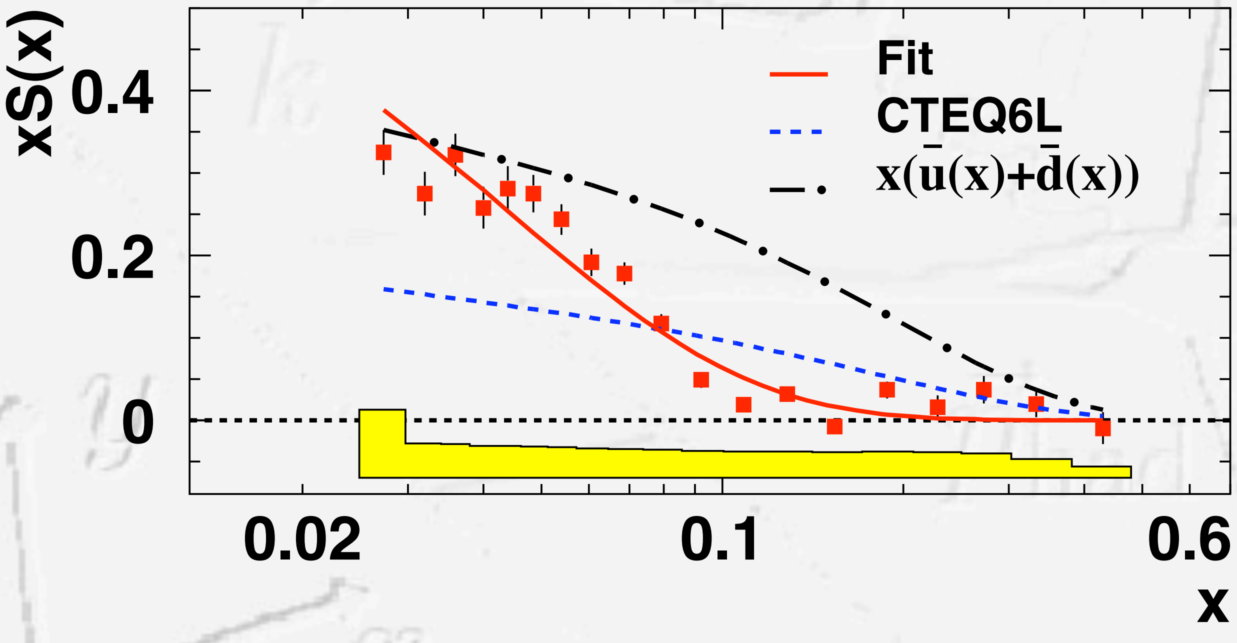
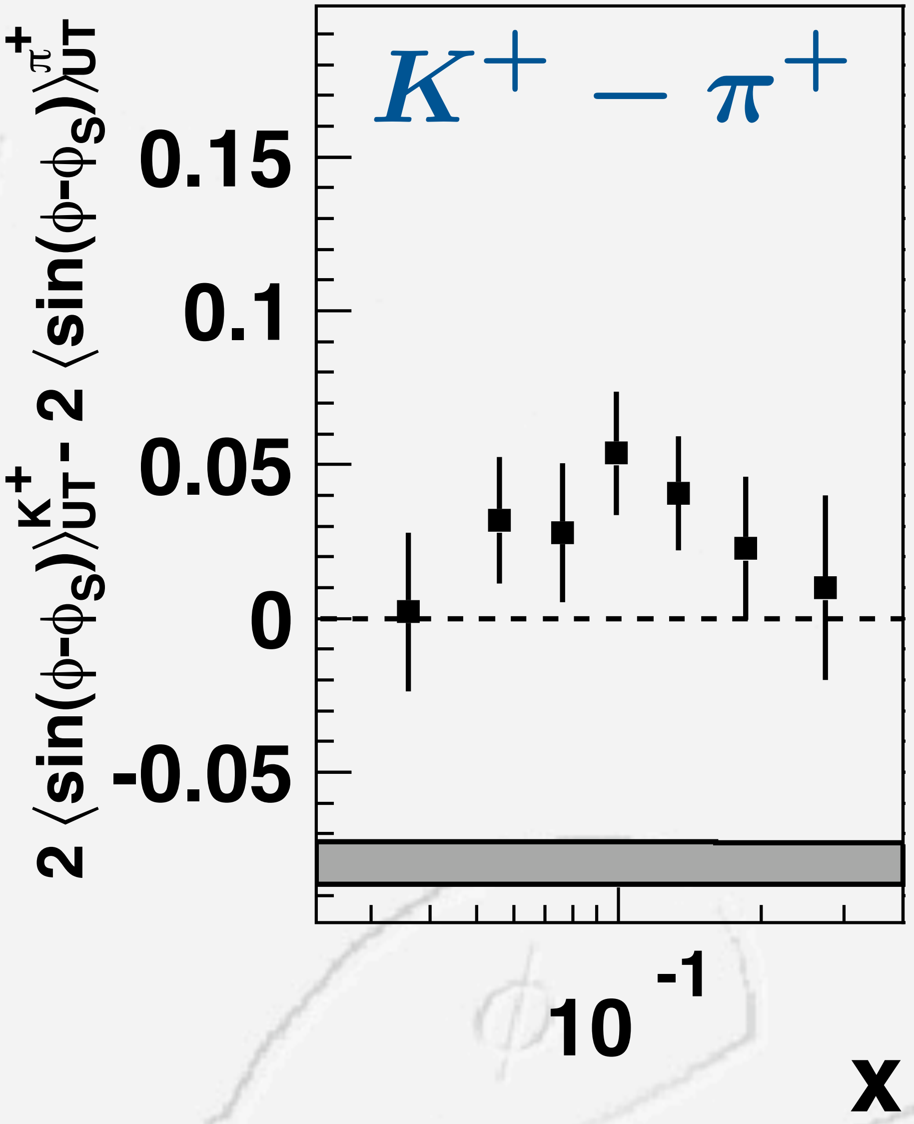
- ☐ $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➡ non-trivial role of sea quarks?
- ☐ convolution integrals depend on k_T dependence of fragmentation functions
- ☐ possible difference in dependences on the kinematics integrated over

Role of sea quarks

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





Role of sea quarks

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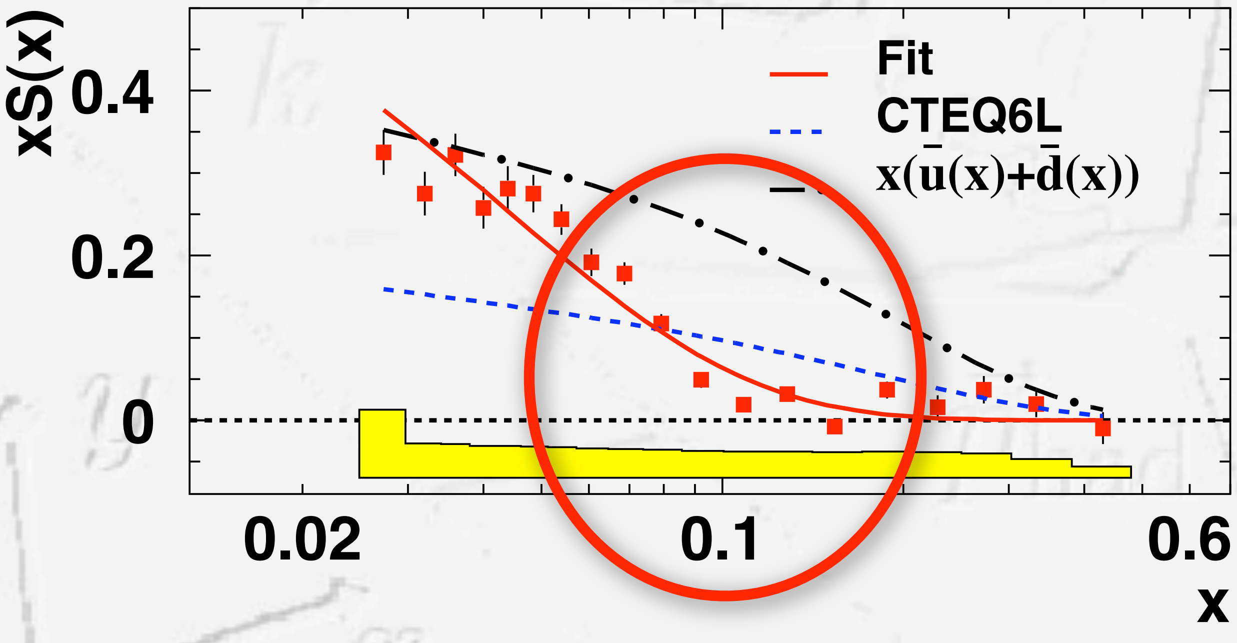
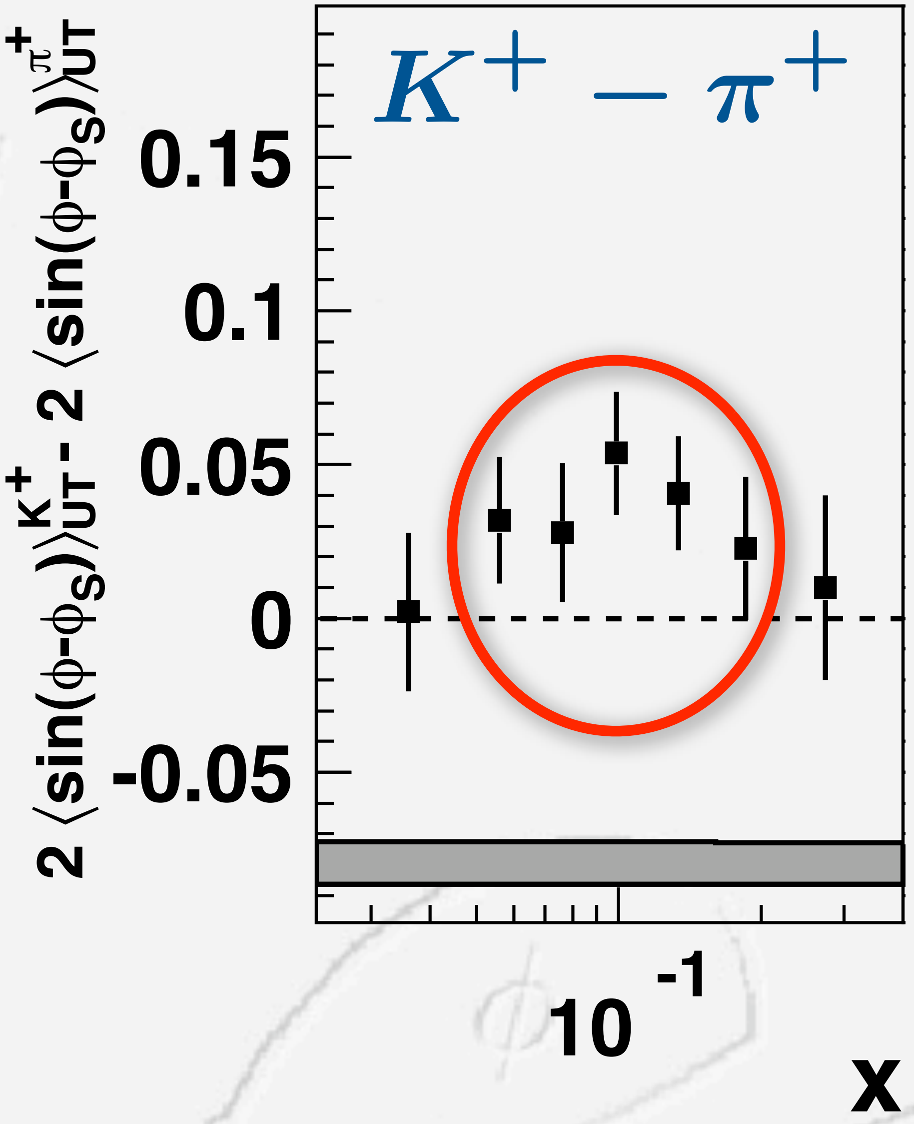
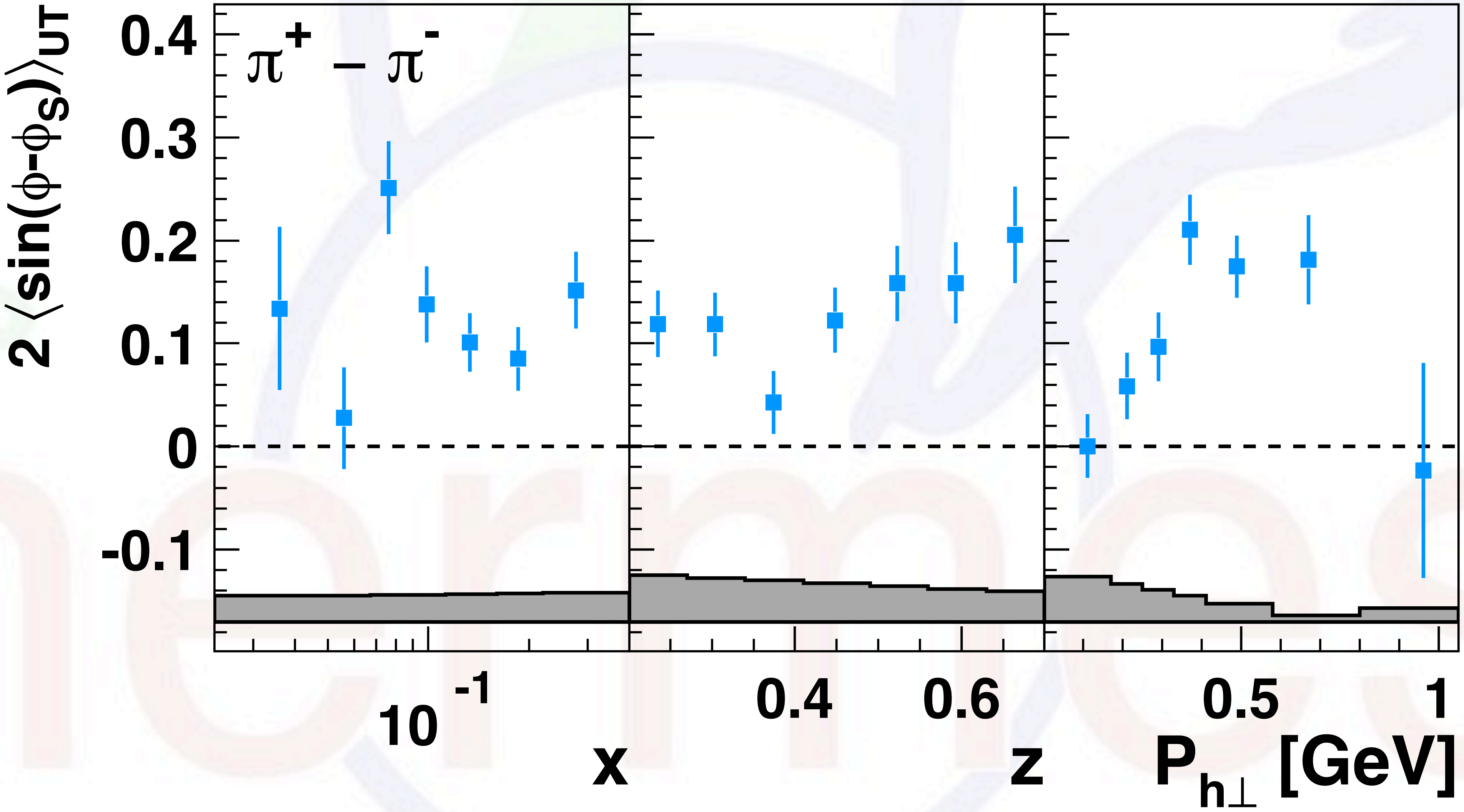




differences biggest in region where strange sea is most different from light sea

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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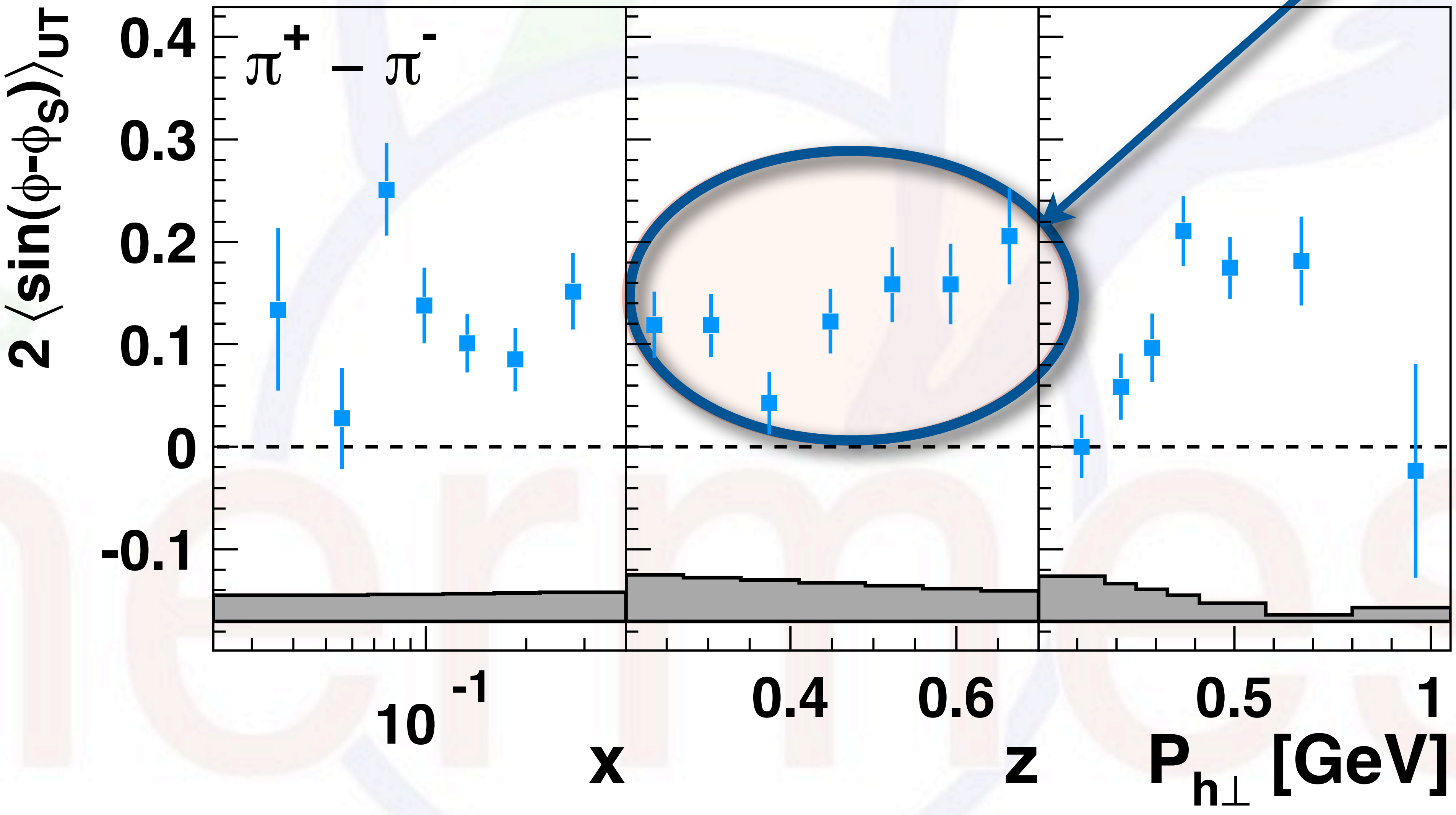
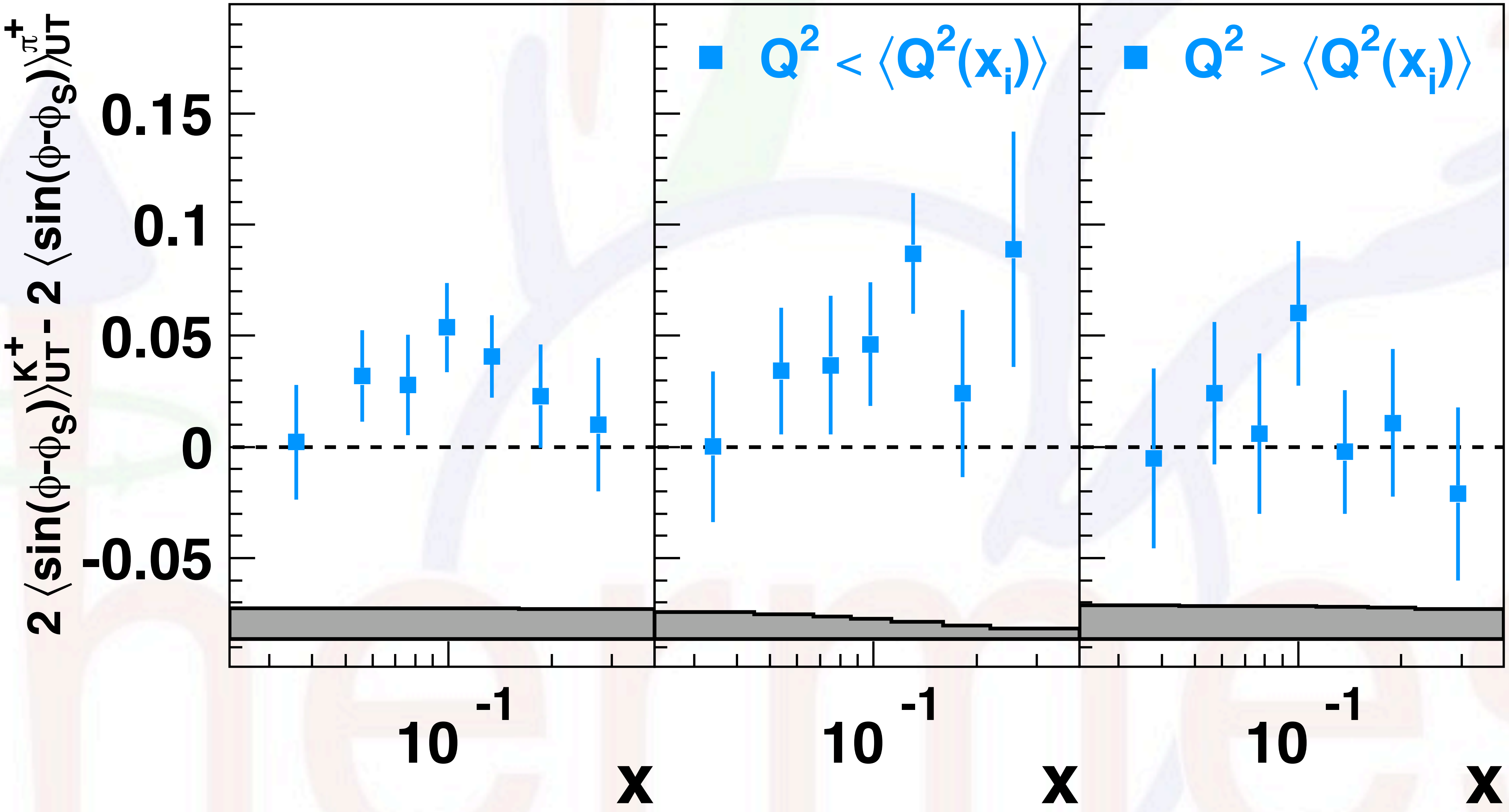
should be flat



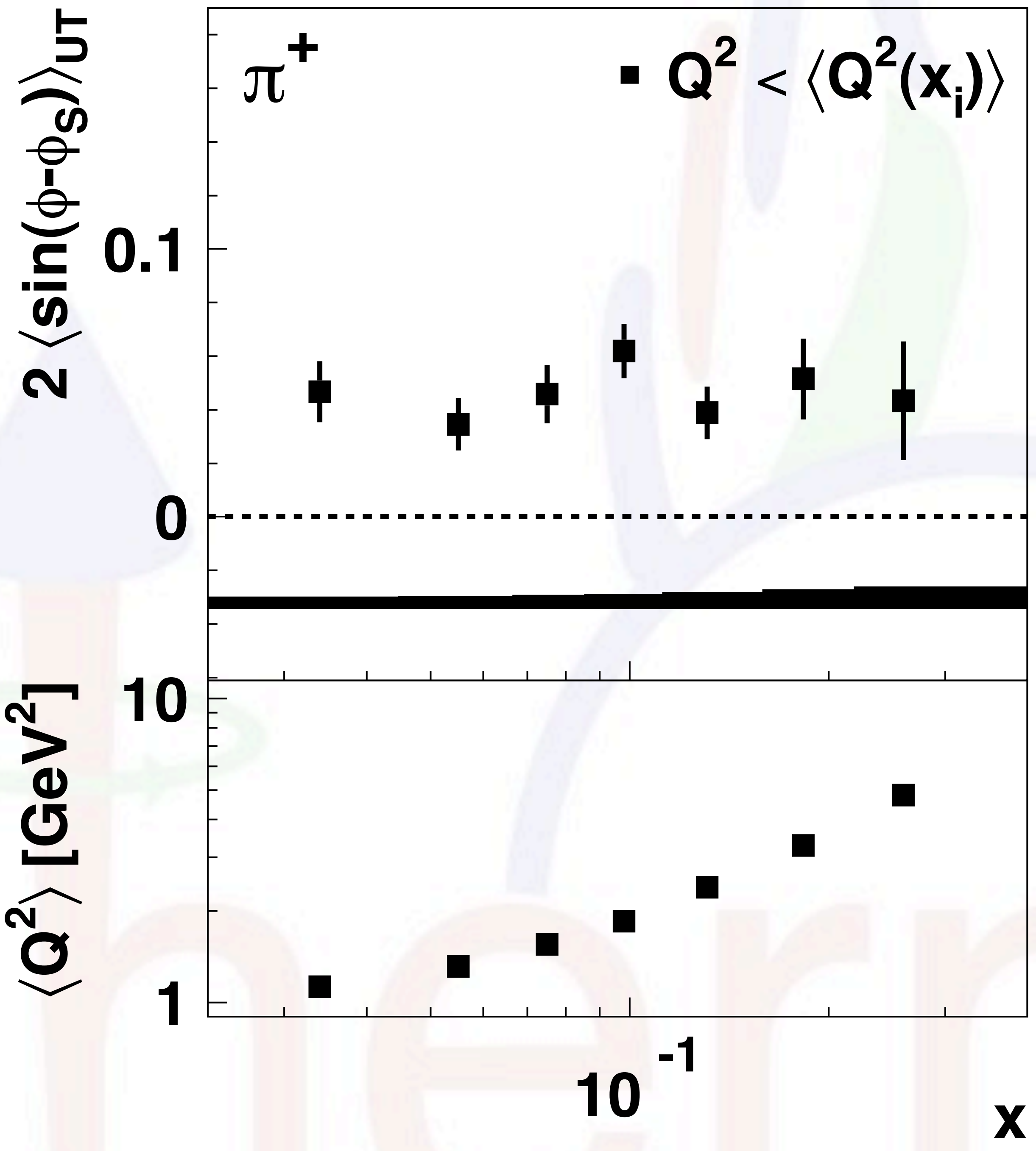
Q^2 dependence of amplitudes

- **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



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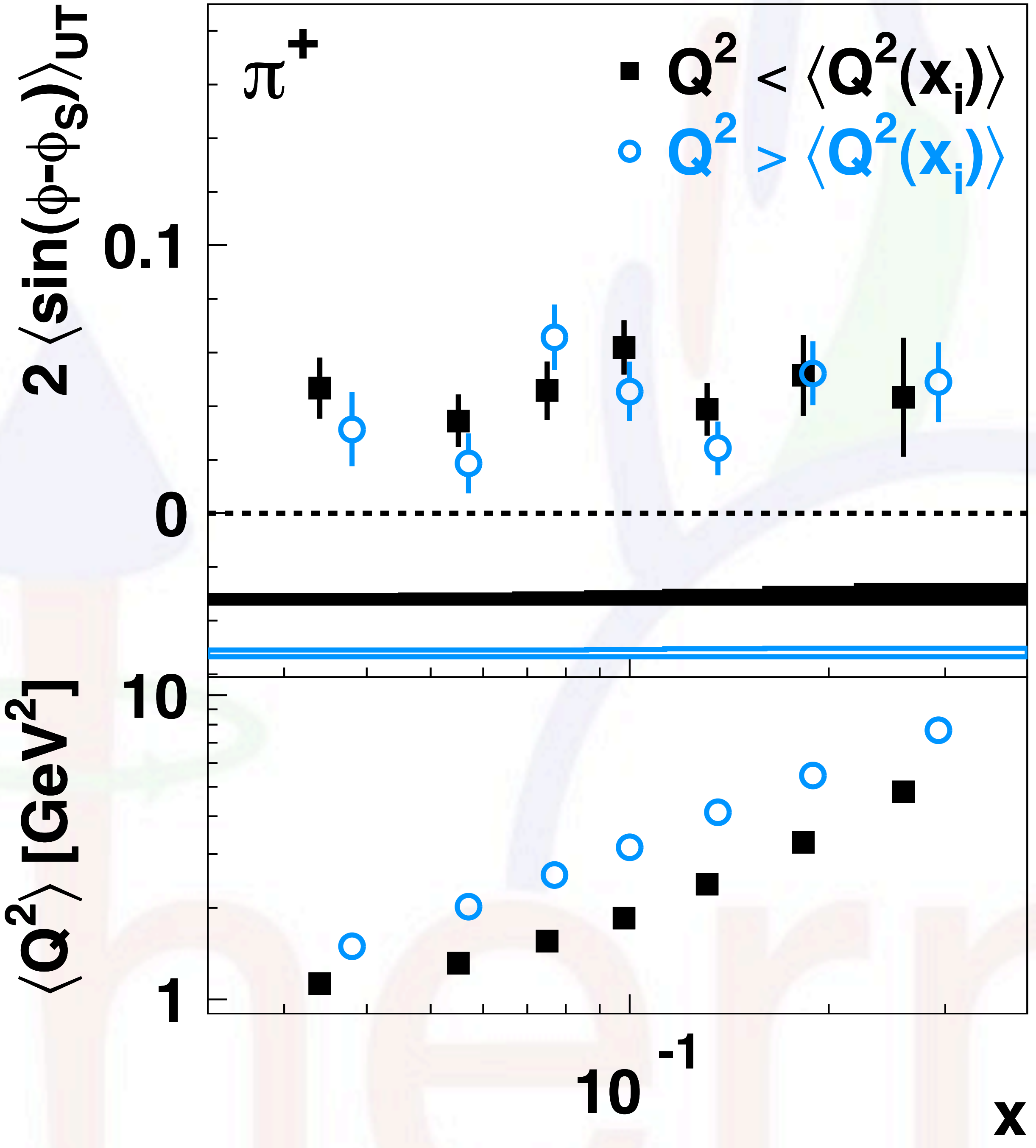

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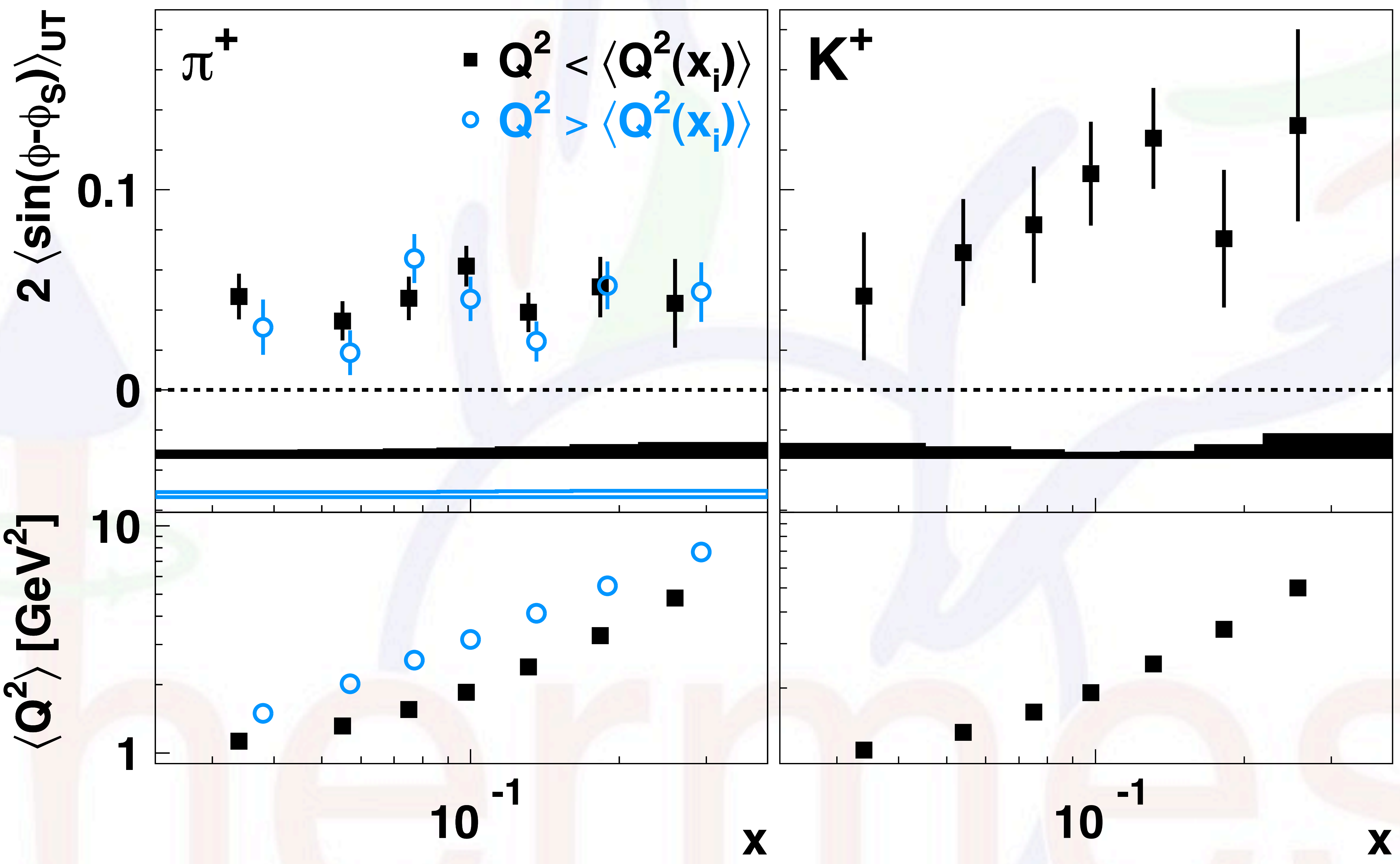
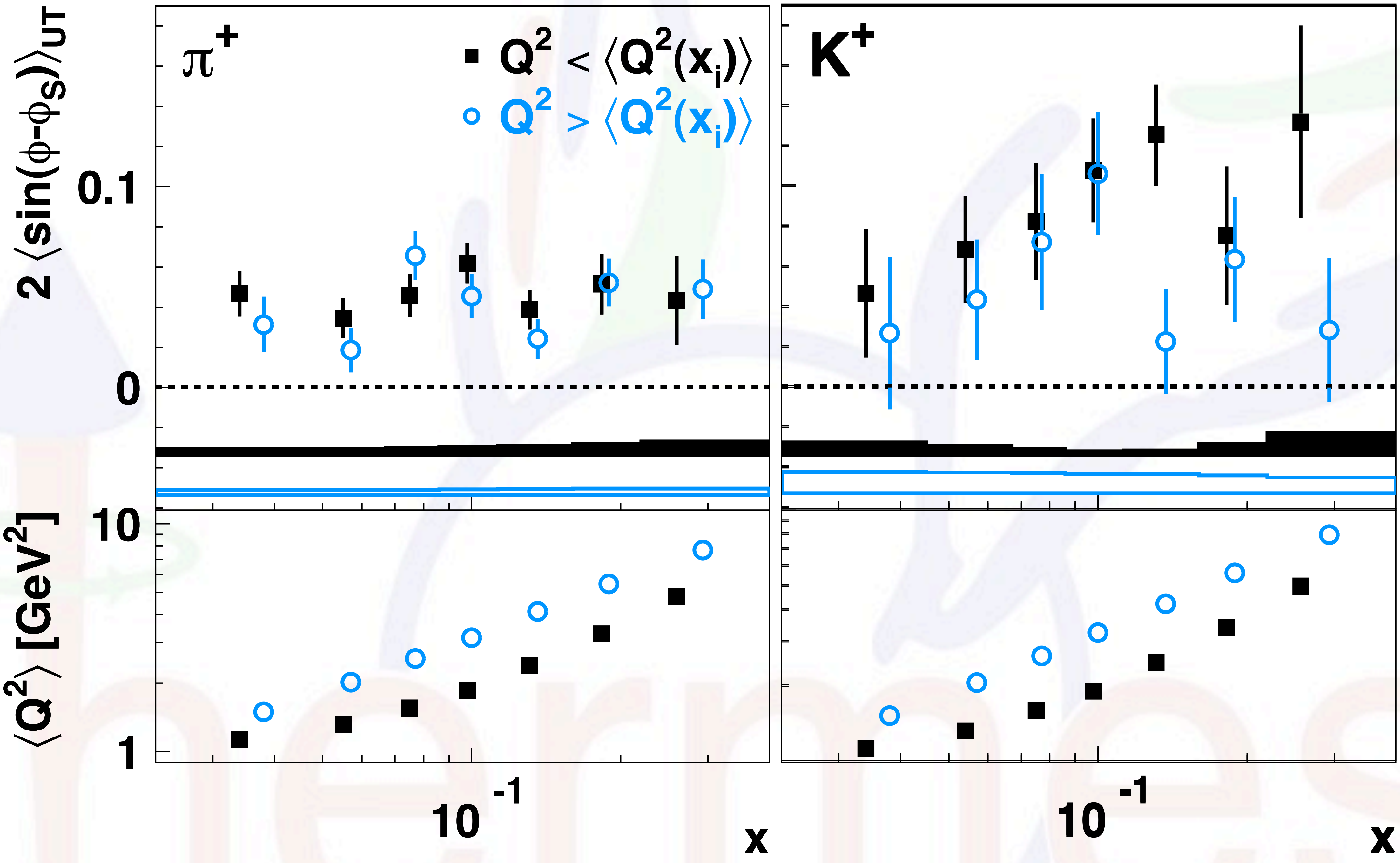


Q^2 dependence of amplitudes

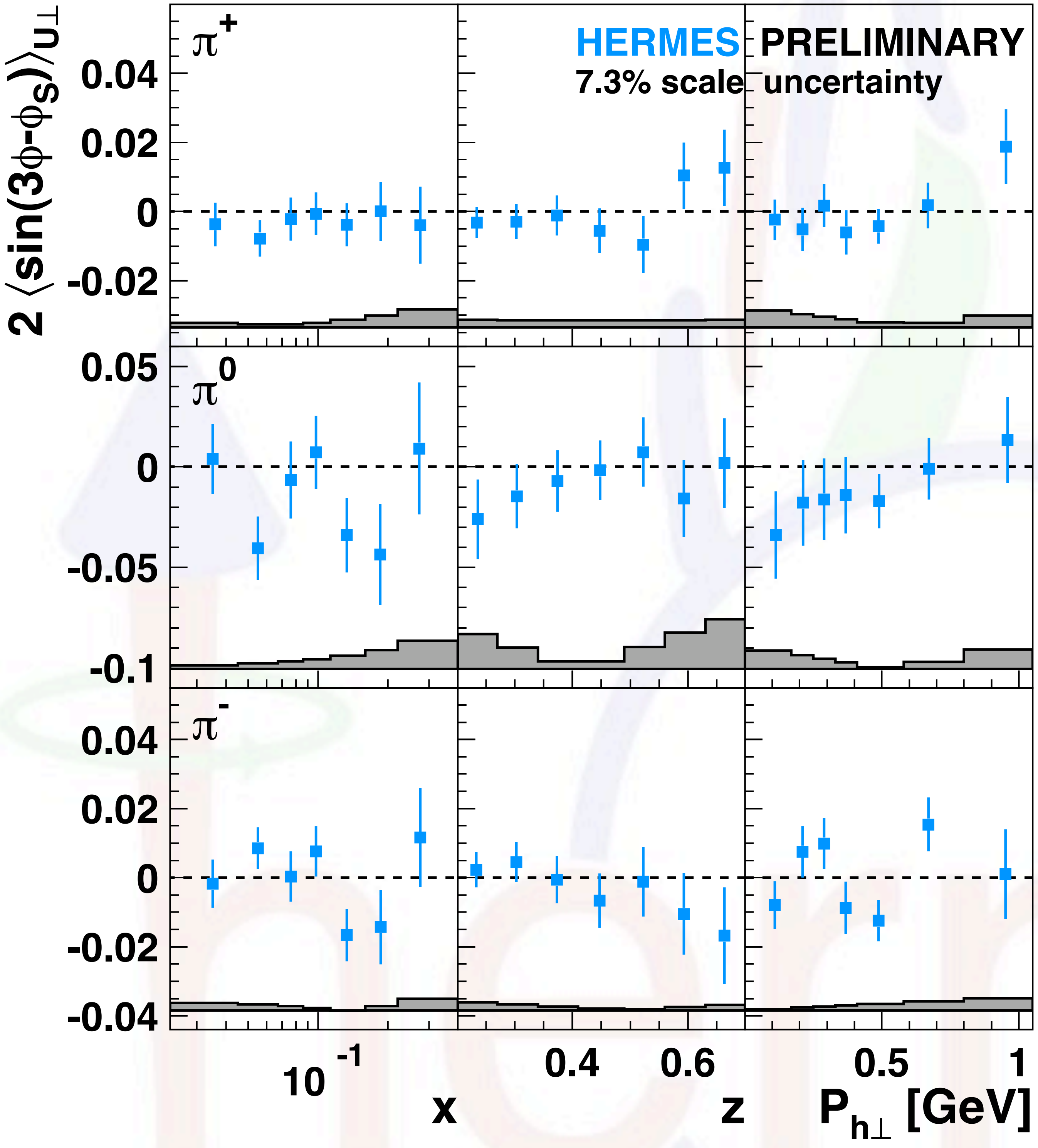


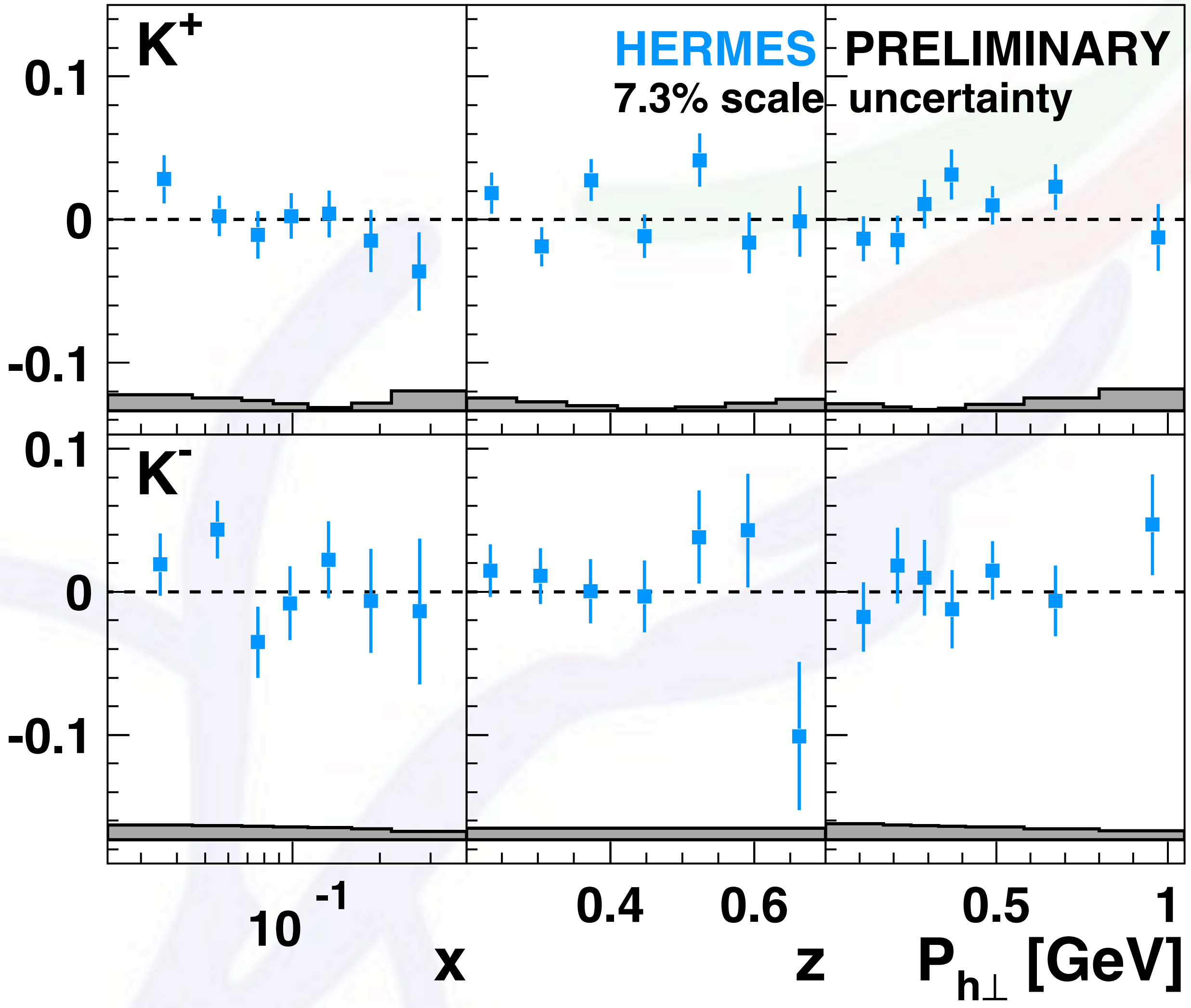
☛ **hint of Q^2 dependence of kaon amplitude**

The others *)

*) excluding Collins amplitudes

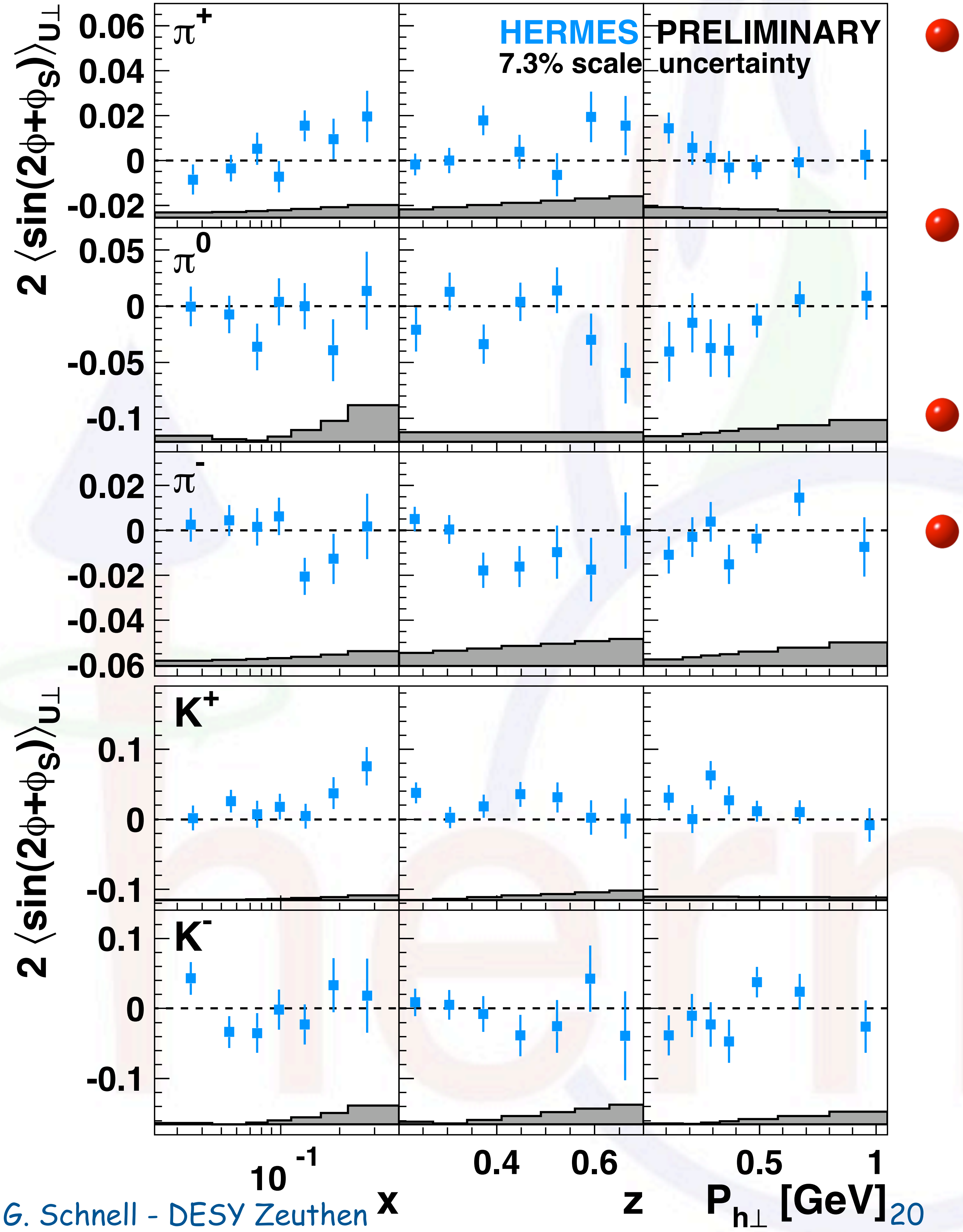
Pretzelosity - $\sin(3\phi-\phi_s)$



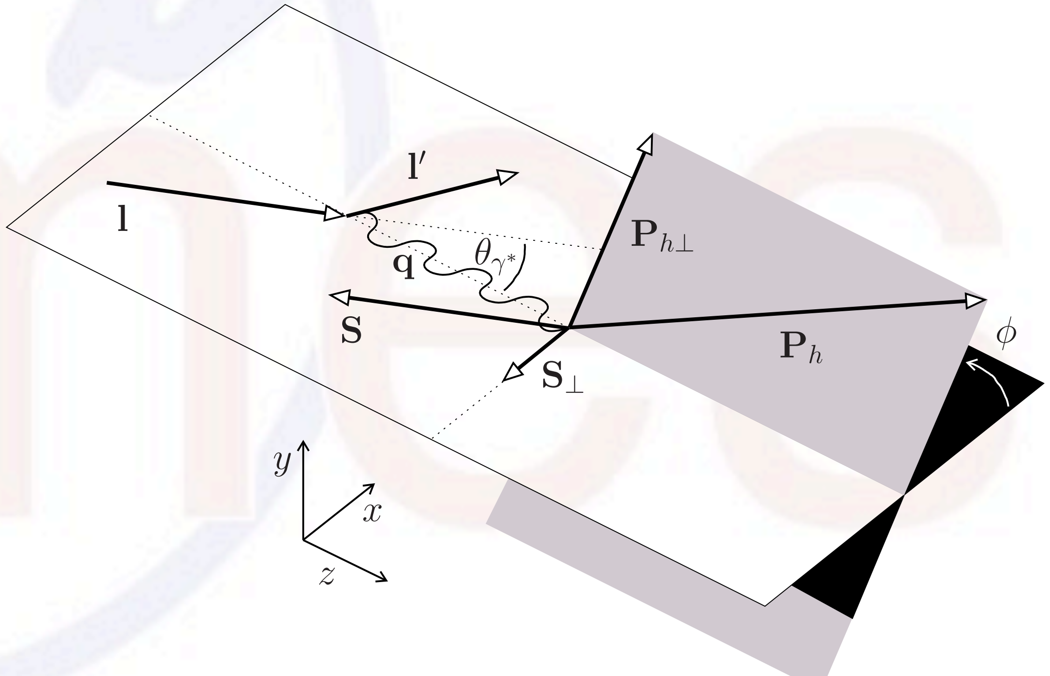


- no significant non-zero signal observed
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

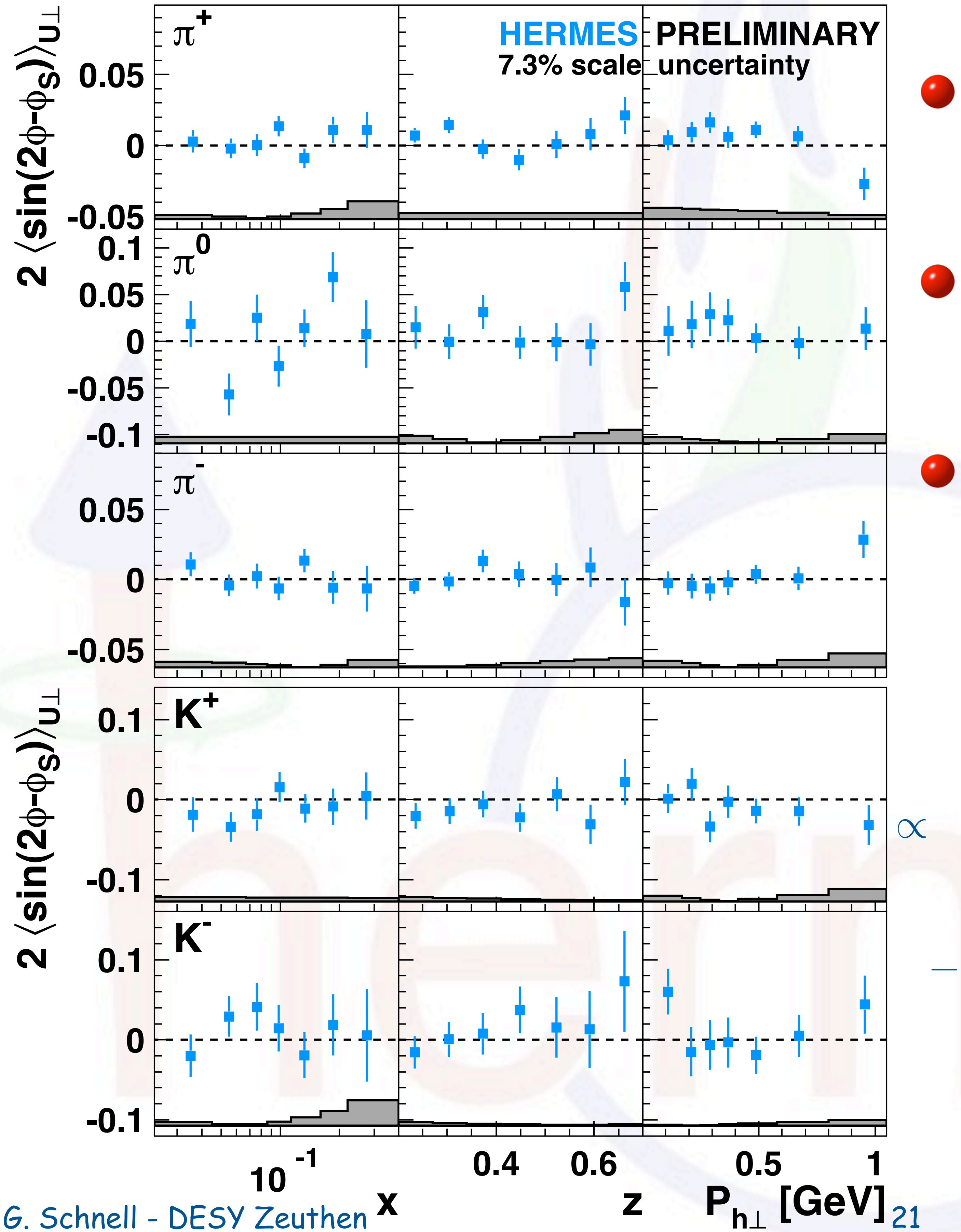
Subleading twist III - $\sin(2\phi+\phi_s)$



- 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(2ϕ−ϕ$_s$)

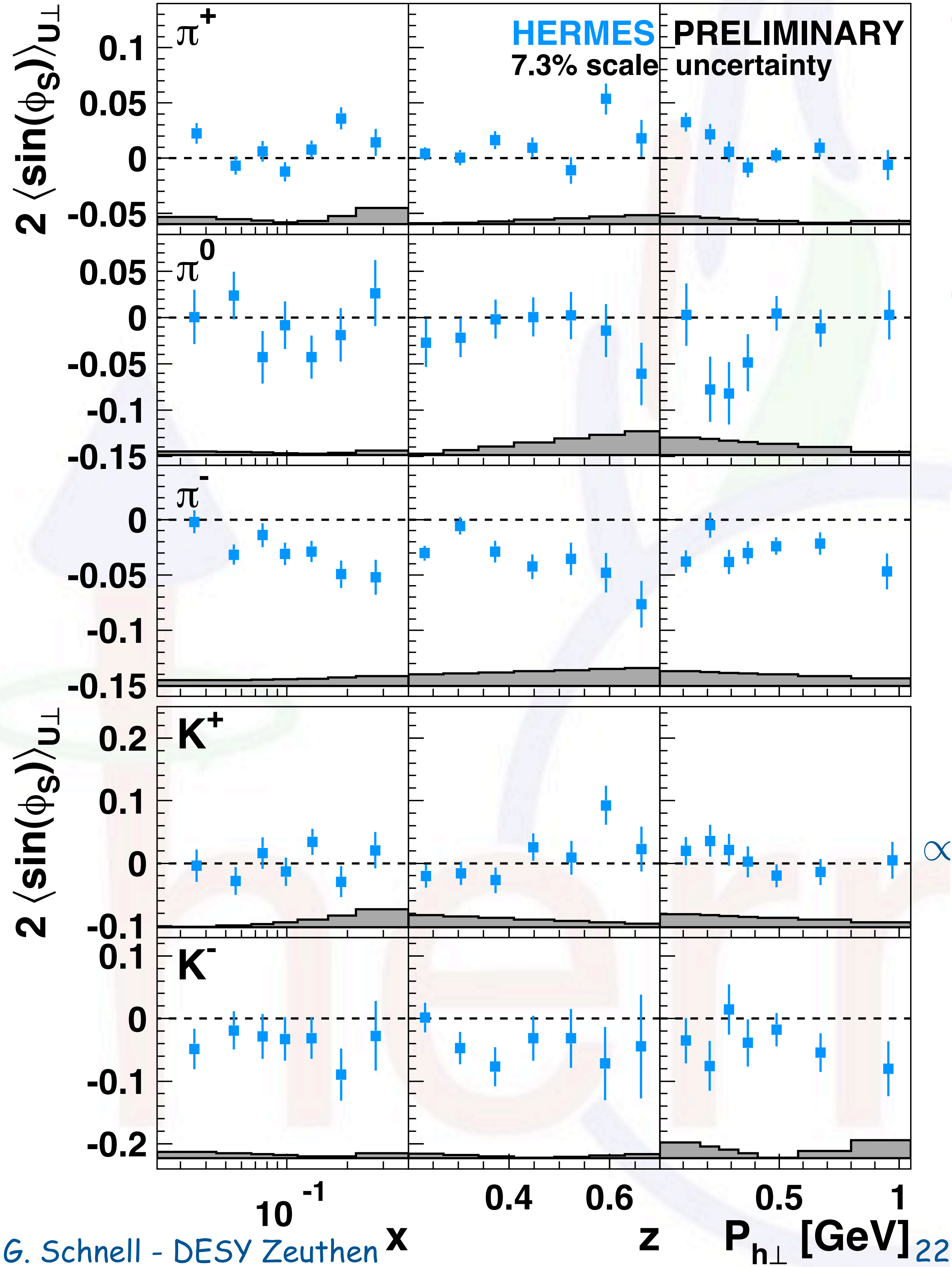


- no significant non-zero signal observed
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- various terms related to pretzelosity, worm-gear, Sivers etc.:

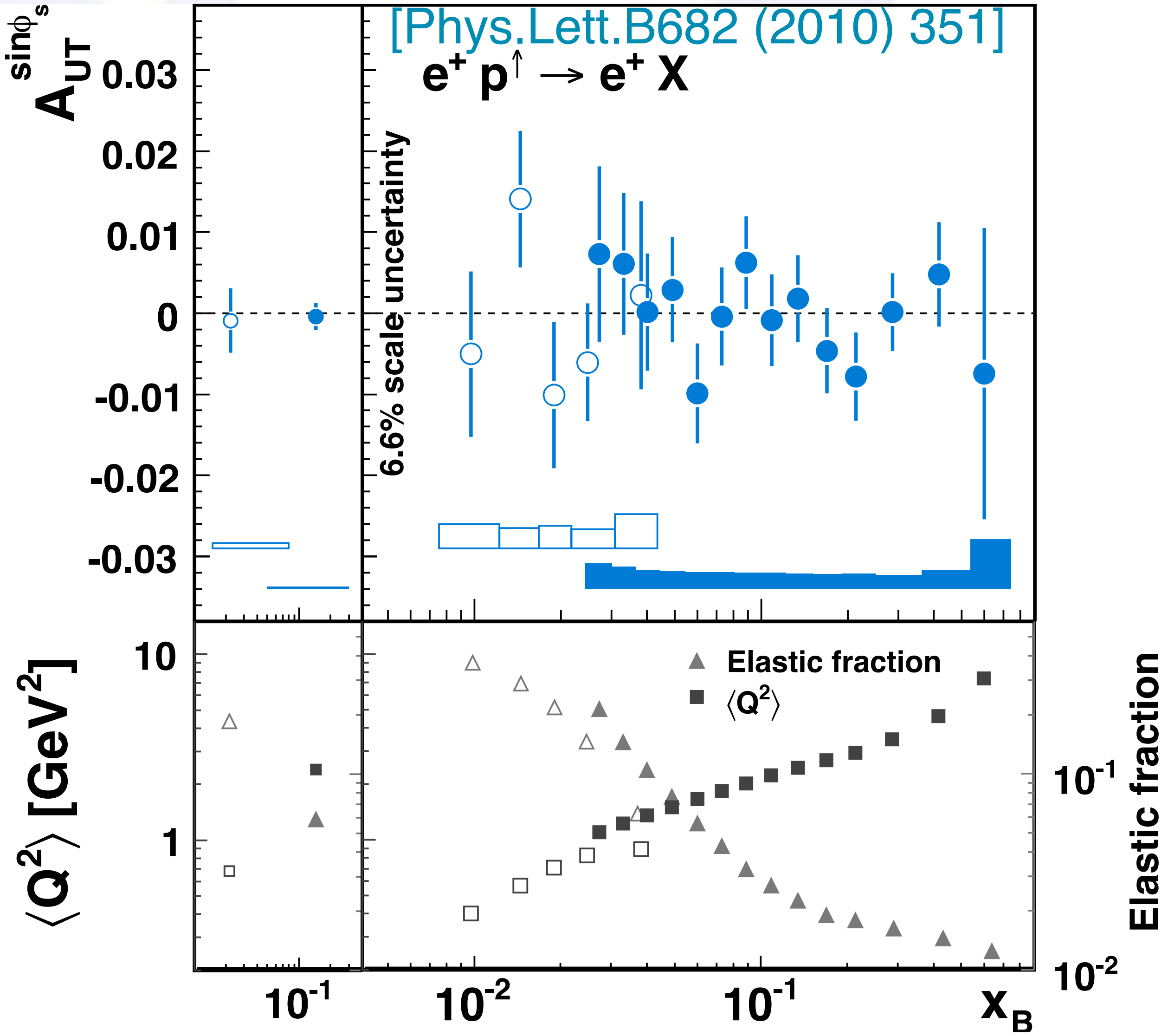
$$\propto \mathcal{W}_1(\mathbf{p_T},\mathbf{k_T},\mathbf{P_{h\perp}})\left(\mathbf{x f_T^\perp D_1} - \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{h_{1T}^\perp}\frac{\tilde{\mathbf{H}}}{\mathbf{z}}\right) - \mathcal{W}_2(\mathbf{p_T},\mathbf{k_T},\mathbf{P_{h\perp}})\left[\left(\mathbf{x h_T H_1^\perp} +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

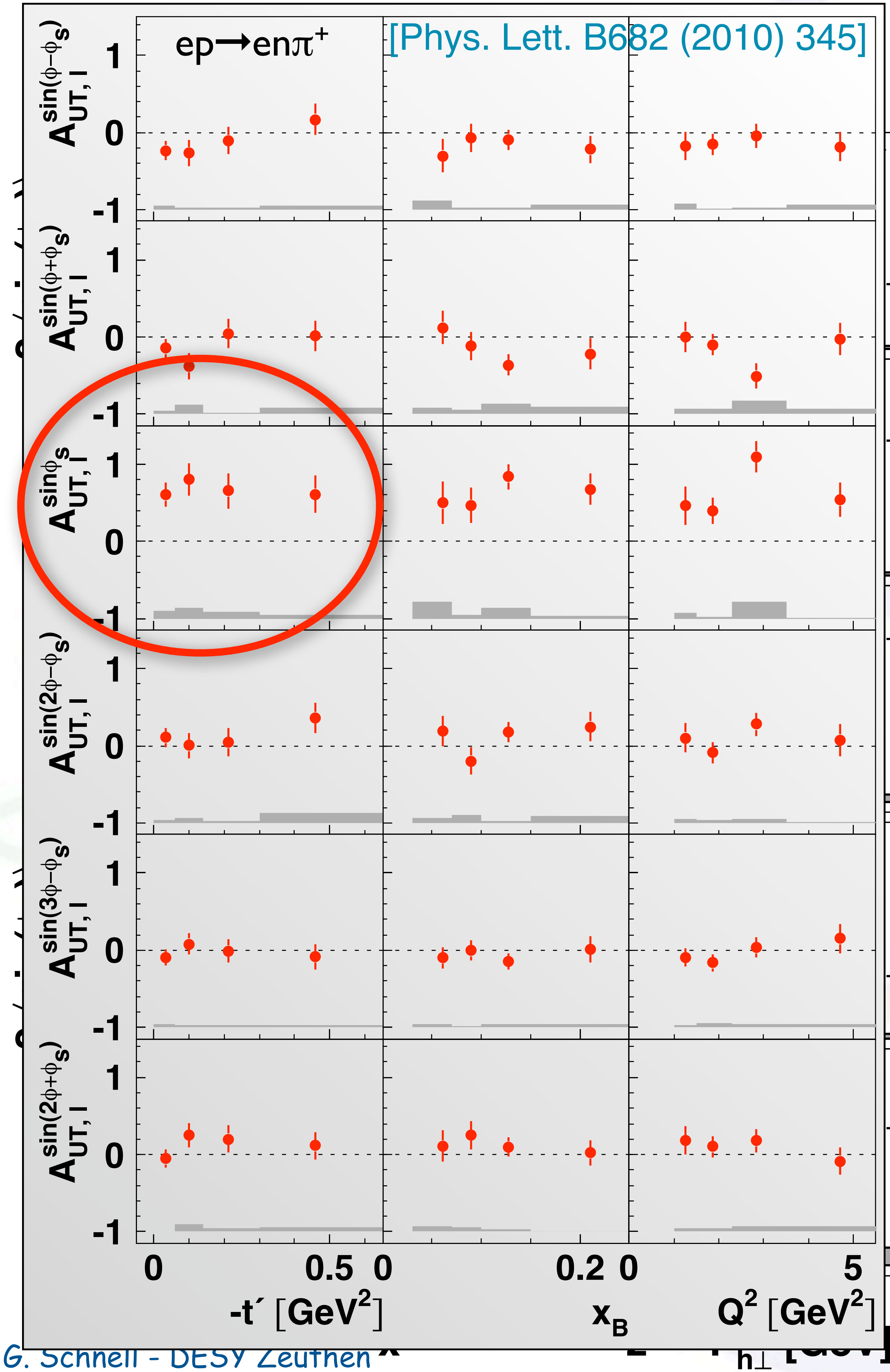
Subleading twist III - $\sin(\phi_s)$

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



$\propto$





[Phys. Lett. B682 (2010) 345]

ist III - sin(ϕ_S)

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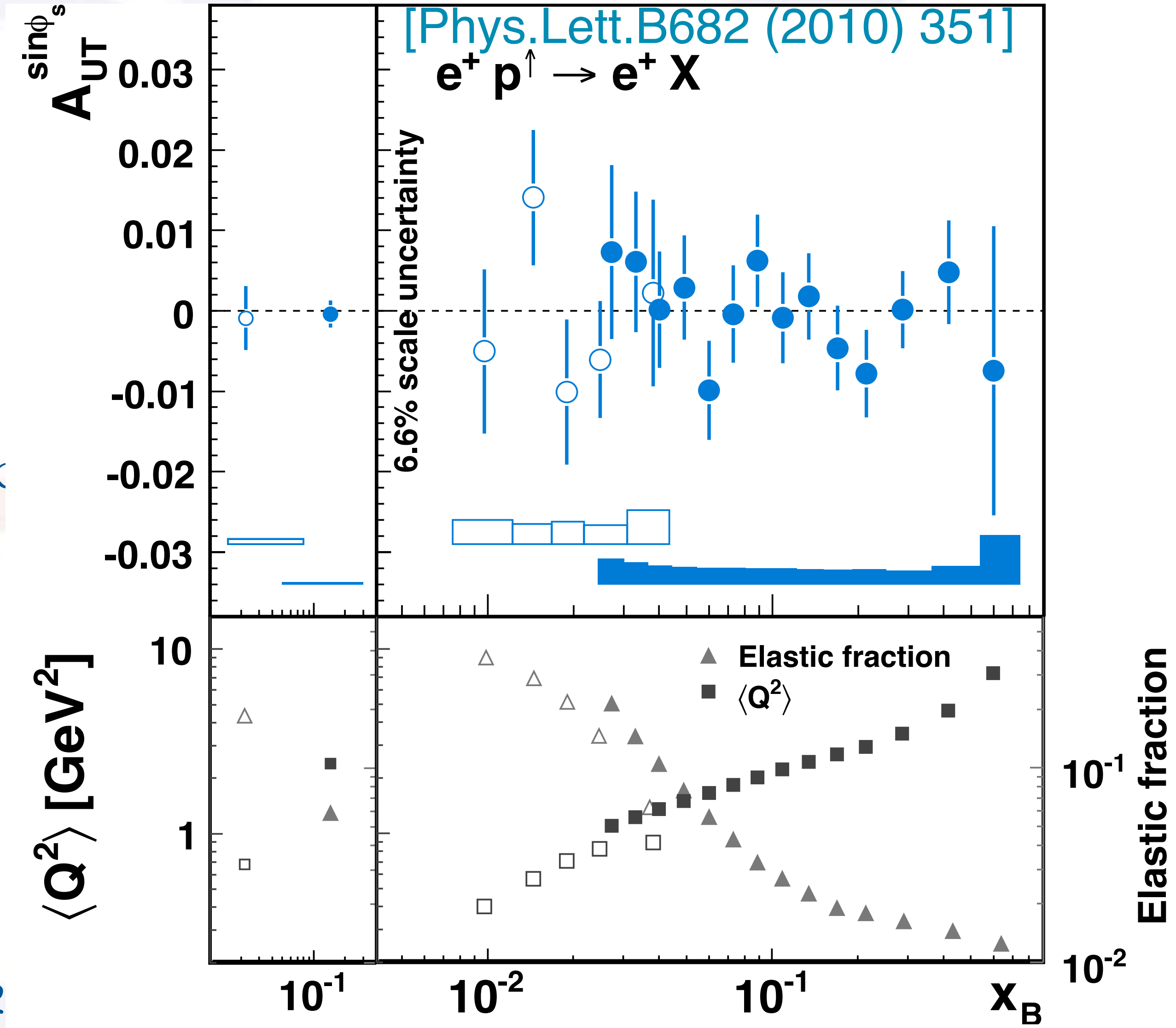
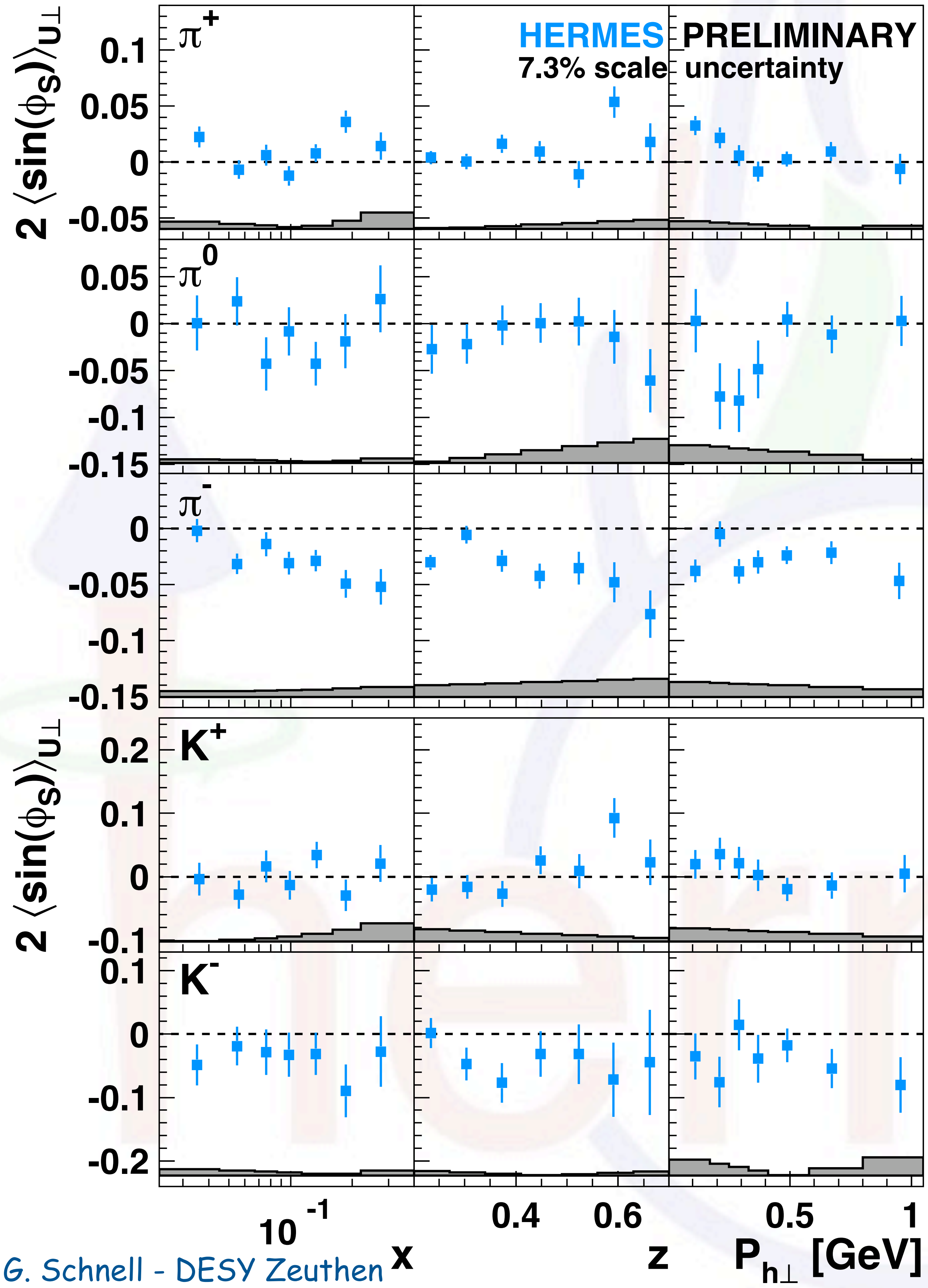


[Phys.Lett.B682 (2010) 351]

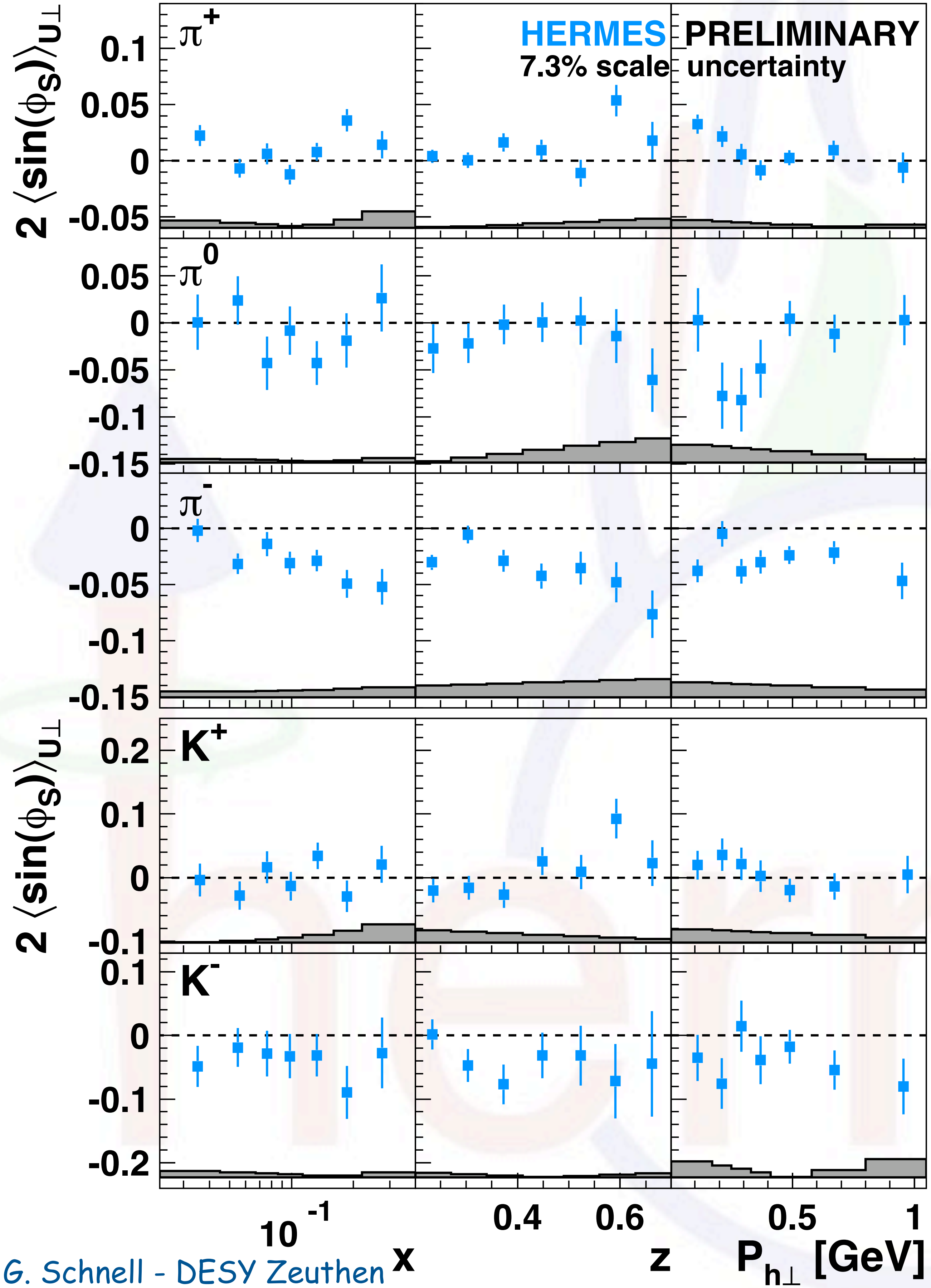
Subleading twist III - sin(ϕ_s)

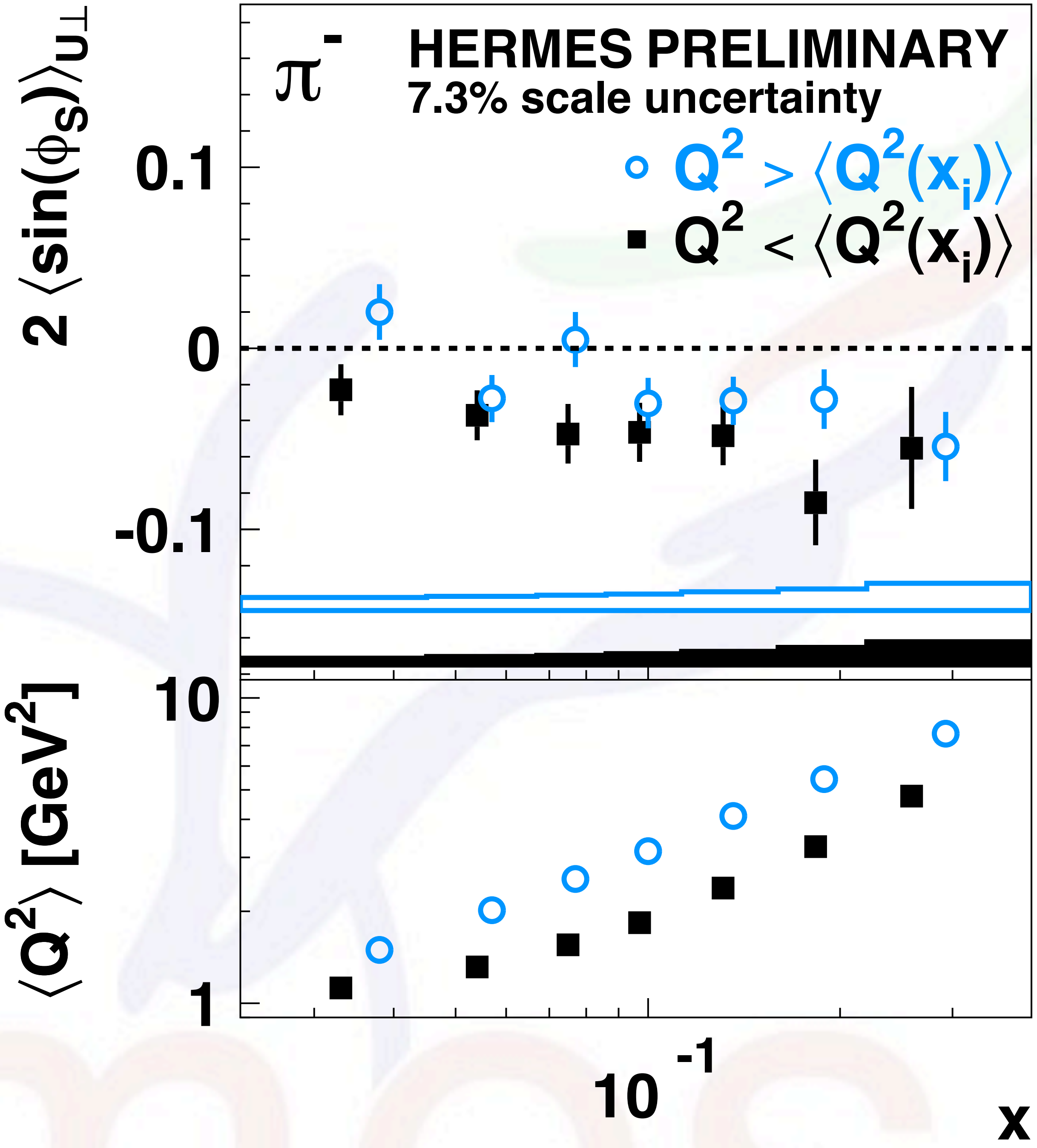


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to **transversity**, **worm-gear**, **Sivers** etc.:

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

Subleading twist III - sin(ϕ_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**