Transverse Partonic Structure of Hadrons

Yerevan, Armenia
June 21-26 / 2009

TMDs in Single-Spin Asymmetries at HERMES

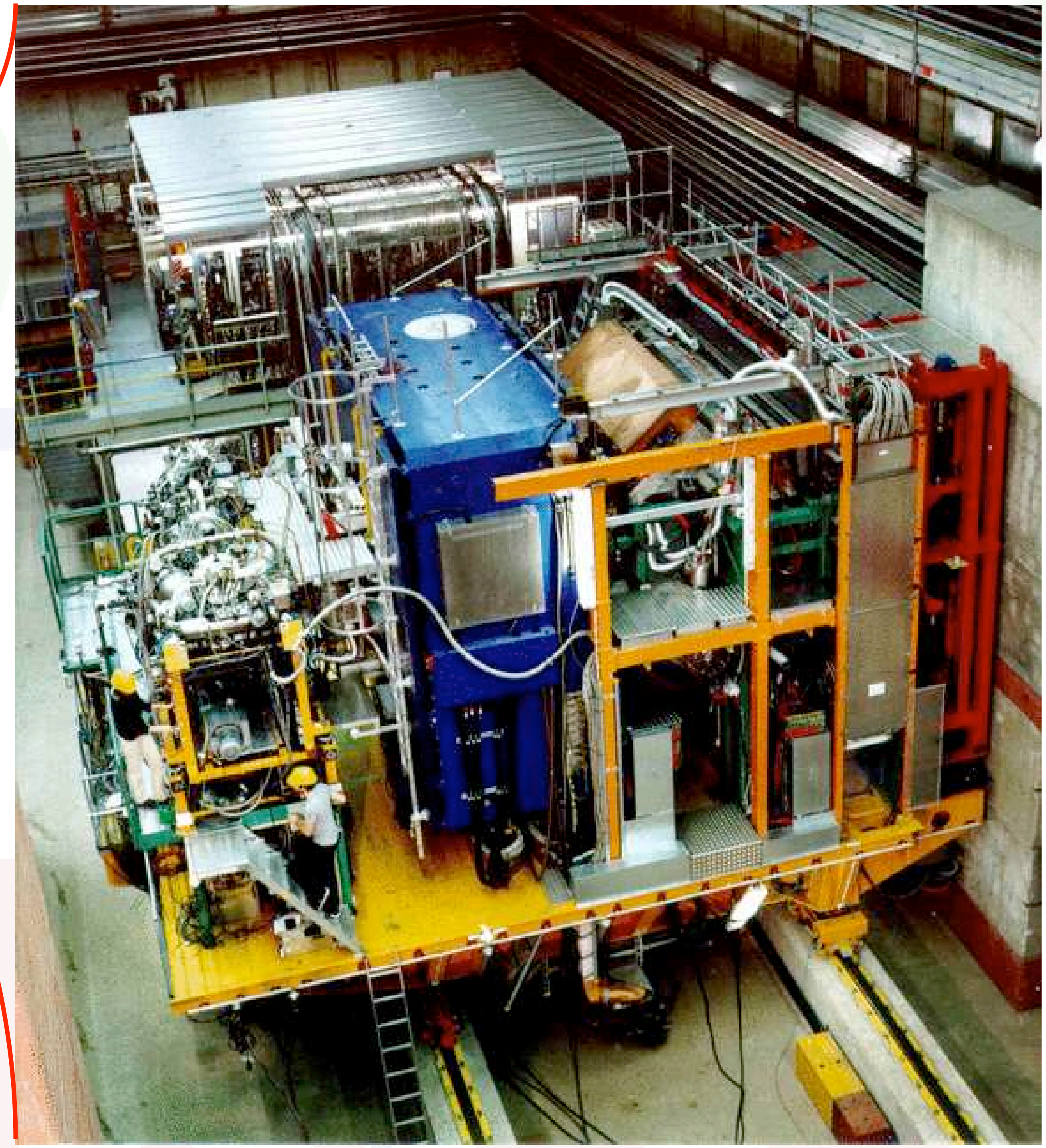
Gunar.Schnell @ desy.de
DESY Zeuthen

DESY

hermes

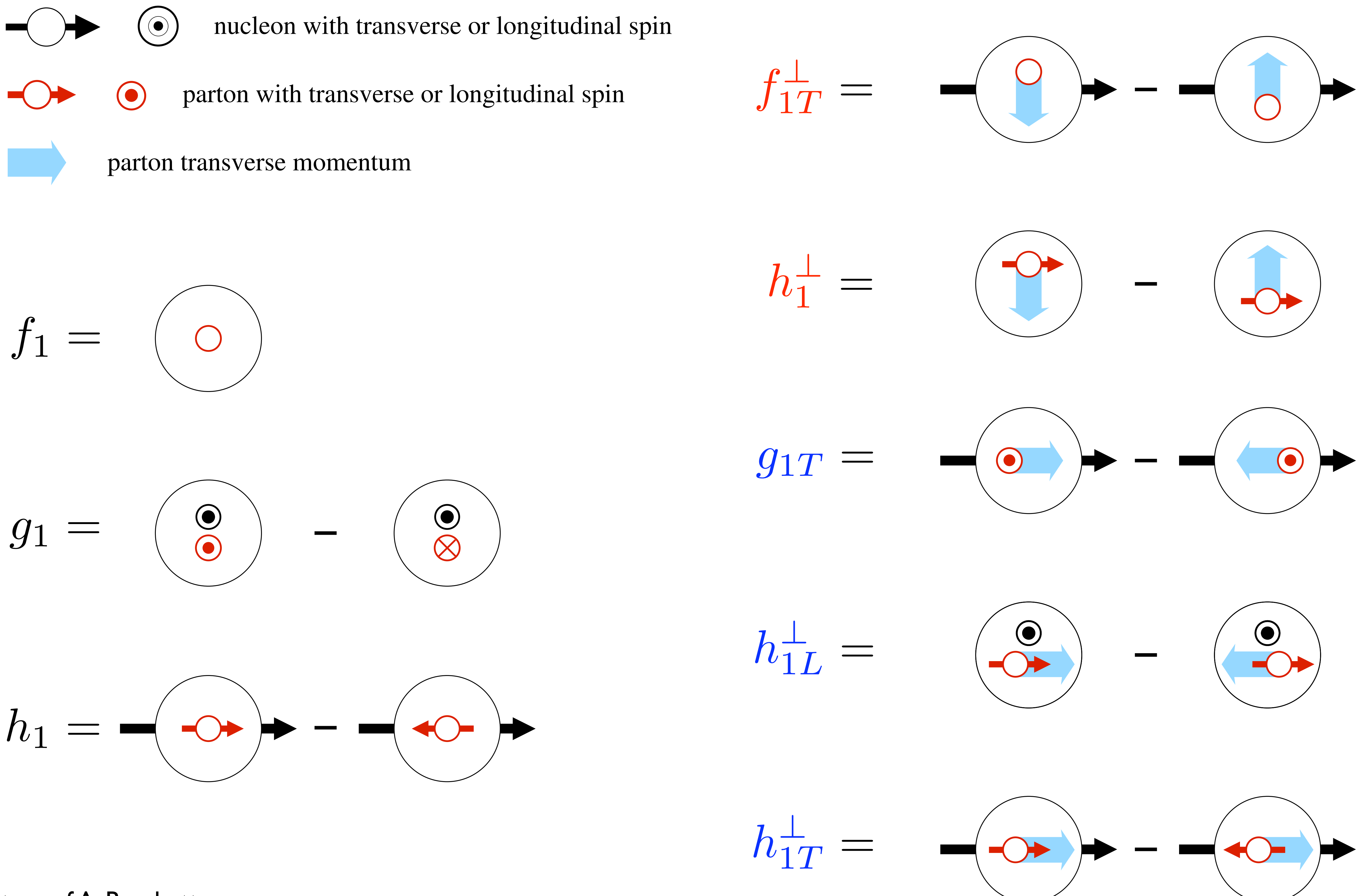
The HERMES Experiment

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



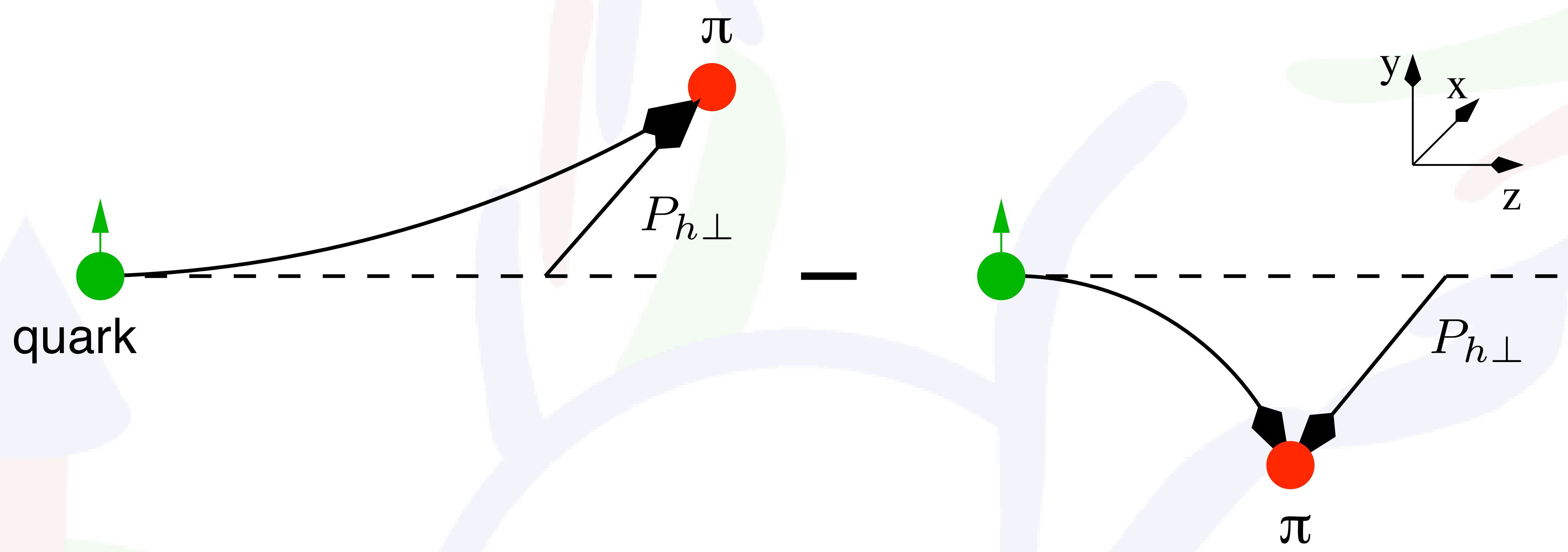
this talk: unpolarized and transversely/longitudinally polarized internal H targets

Transverse-Momentum-Dependent DF



Courtesy of A. Bacchetta

Collins fragmentation function



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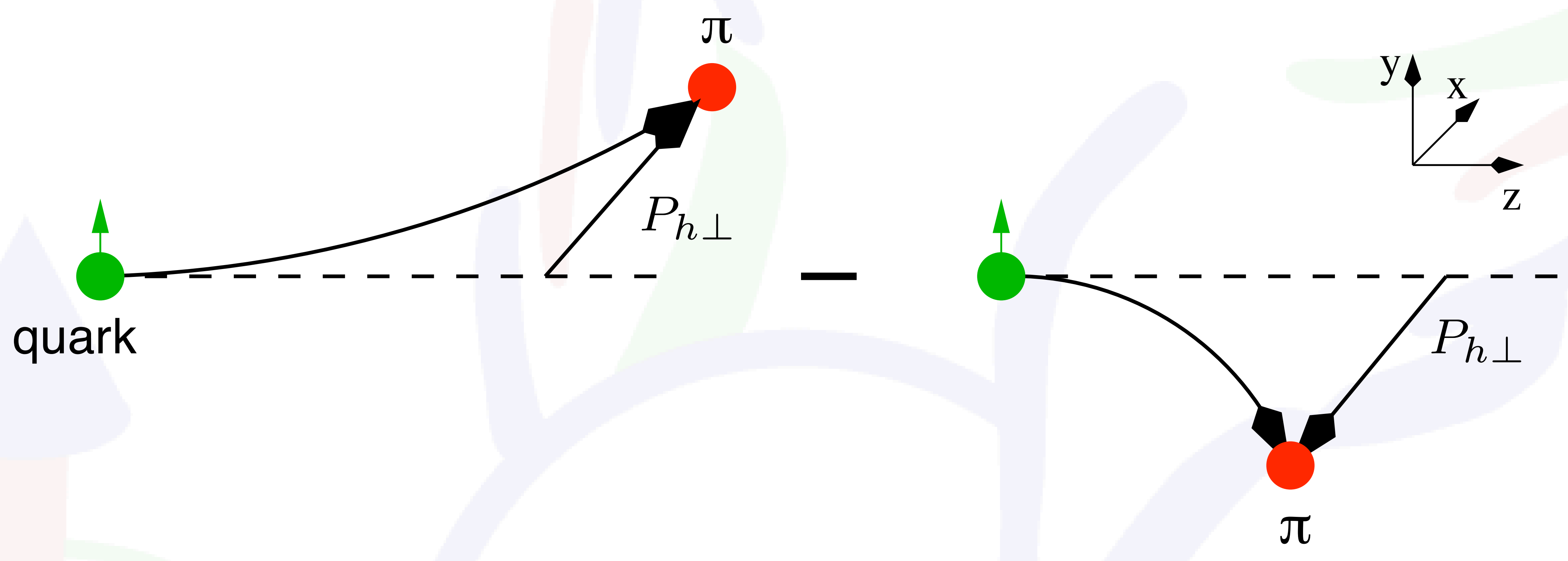


- provides a correlation between spin of quark and transverse momentum of produced hadron

1-Hadron Production (ep→ehX)

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

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

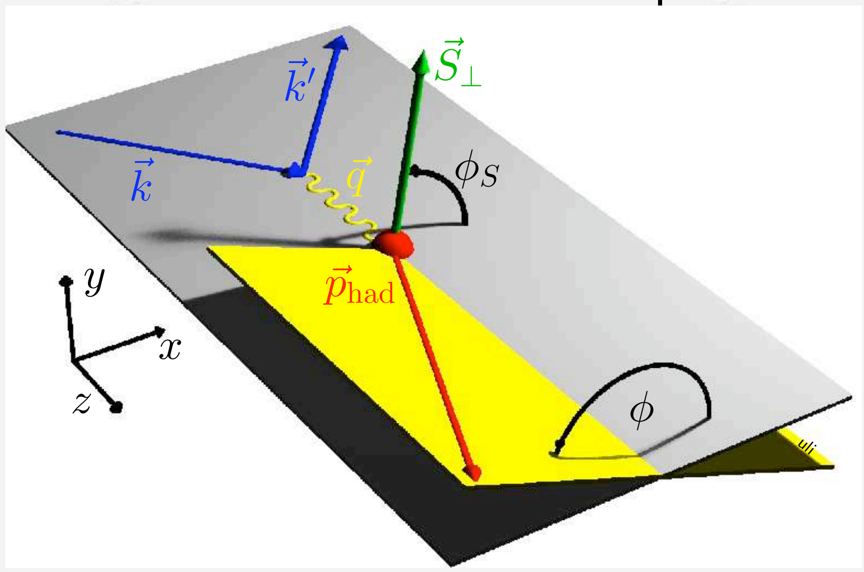
$$+S_T\left\{\sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT}\, \frac{1}{Q}\right.$$

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

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

σ_{XY}

Beam Target
Polarization



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

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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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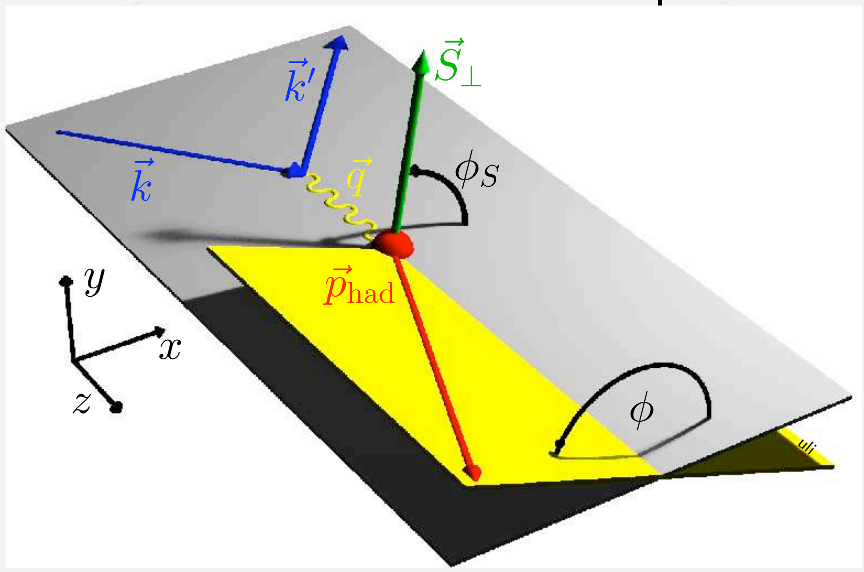
$$+\frac{1}{Q}$$

$$+\lambda_e \left[\cos(\phi - \right.$$

σ_{XY}

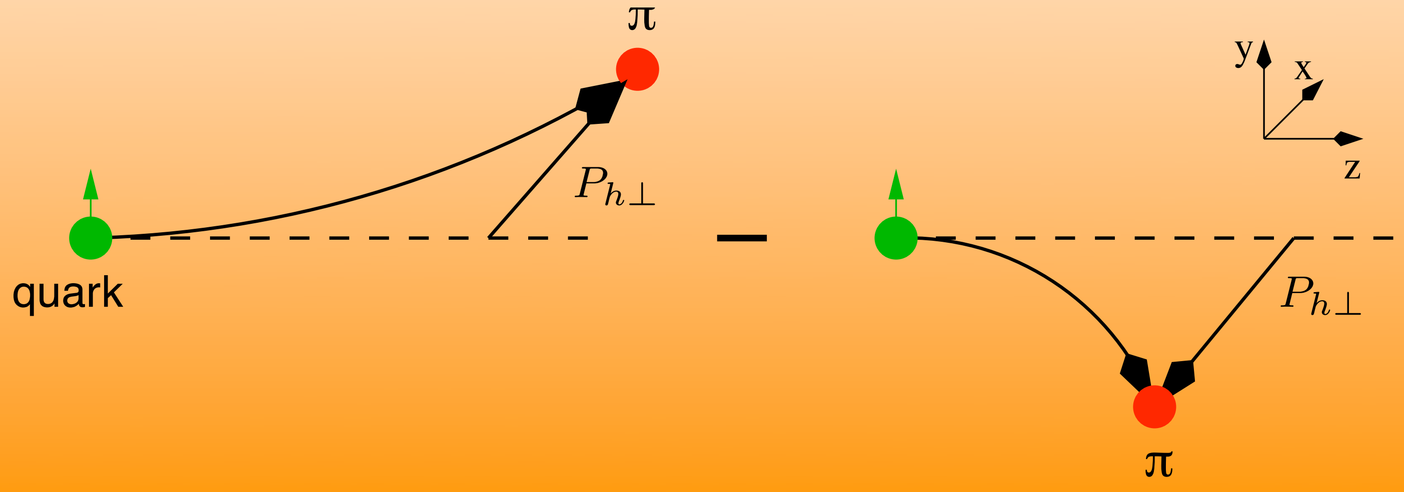
Beam Target

Polarization



Collins Effect:

sensitive to quark transverse spin



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$$\frac{1}{\ldots} \ldots d\sigma^{12}_{UT})$$

$$\ldots + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT}) \Big] \Big\}$$

Sivers Effect:

- correlates hadron's transverse momentum with nucleon spin
- requires orbital angular momentum

. Phys. B 461 (1996) 197

) 57 (1998) 5780

95 (2004) 309

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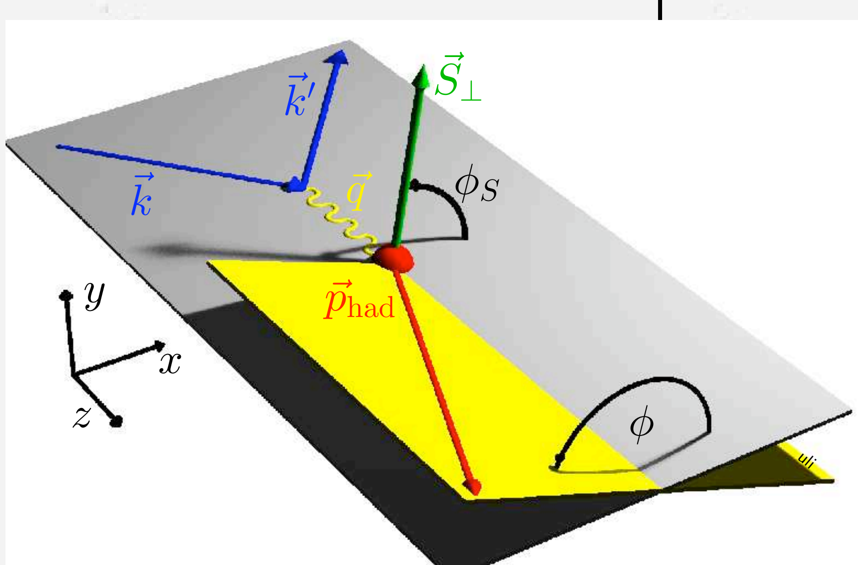
$$+S_T \; \ldots \;) \, d\sigma^{10}_{UT} \; \frac{1}{Q}$$

Twist-3 Effects
involving longitudinal beam or target polarization

σ_{XY}

Beam Target
Polarization

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



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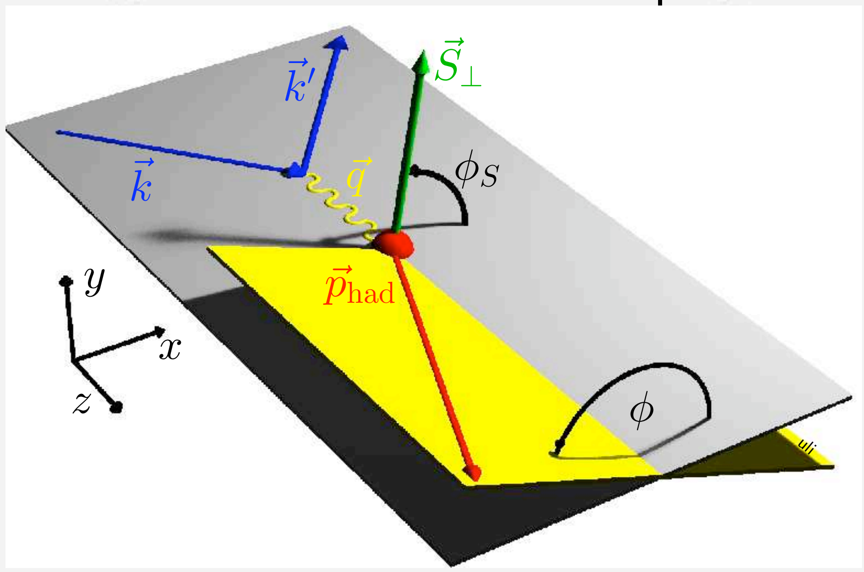
σ_{XY}

Beam Target Polarization



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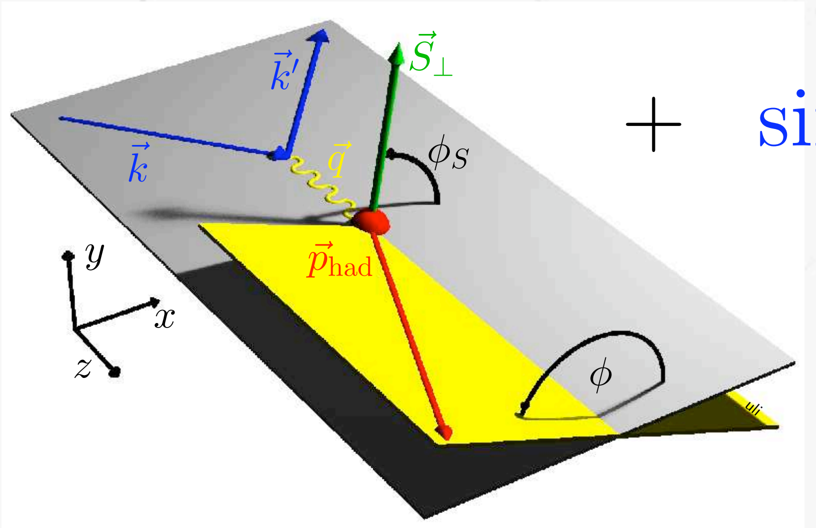
Measuring azimuthal SSA

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^{\uparrow}(\phi,\phi_S)-N_h^{\downarrow}(\phi,\phi_S)}{N_h^{\uparrow}(\phi,\phi_S)+N_h^{\downarrow}(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M_h}h_1^q(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{p_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M}f_{1T}^{\perp,q}(x,p_T^2)D_1^q(z,k_T^2)\right]$$

$$+ \quad \cdots$$

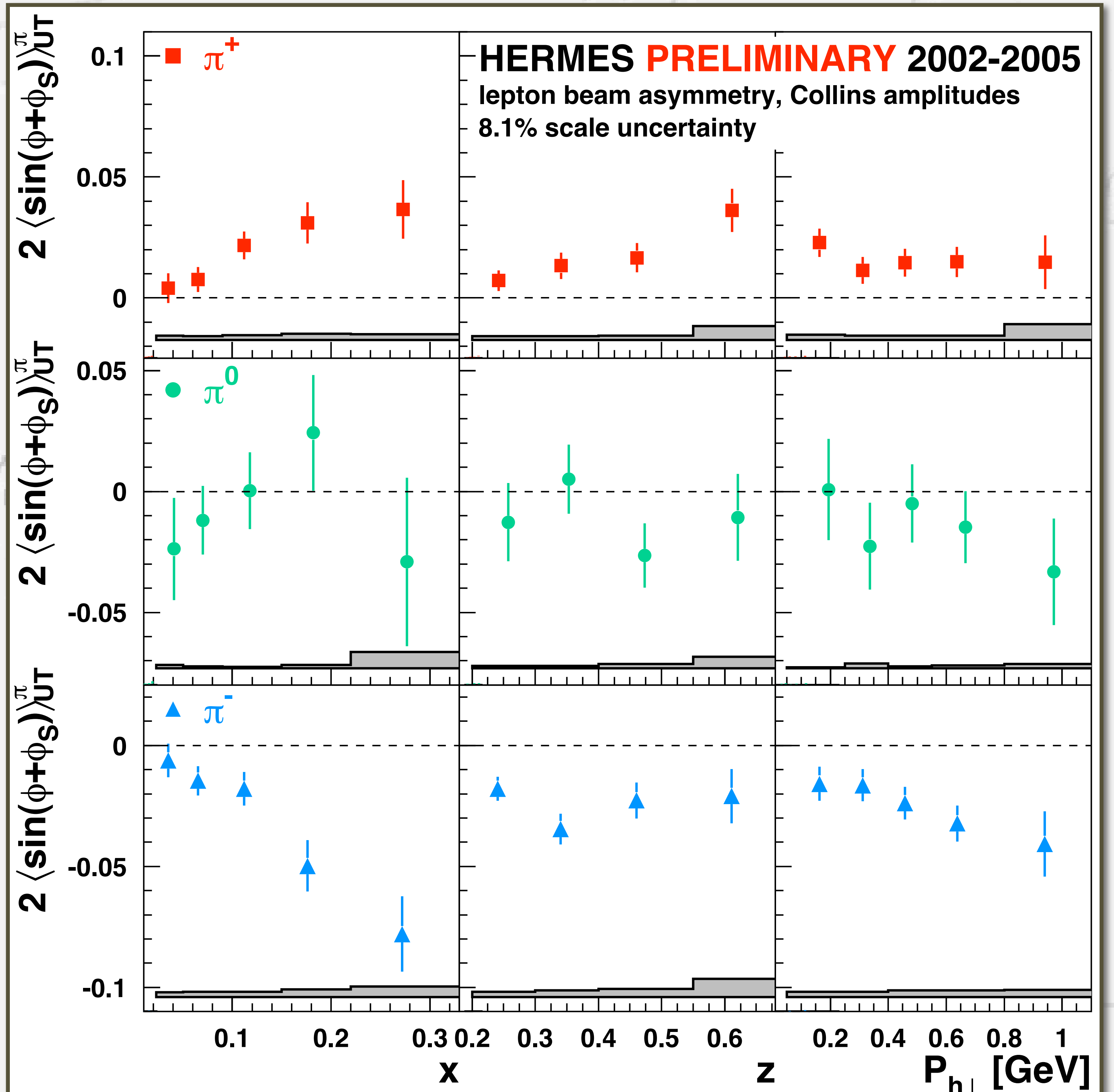


$\mathcal{I}[\ldots]$: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

$\Rightarrow$ 2D Max.Likelihd. fit of to get Collins and Sivers amplitudes:

$$PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\,\sin(\phi\pm\phi_s)+\ldots)\}$$

The HERMES Collins amplitudes



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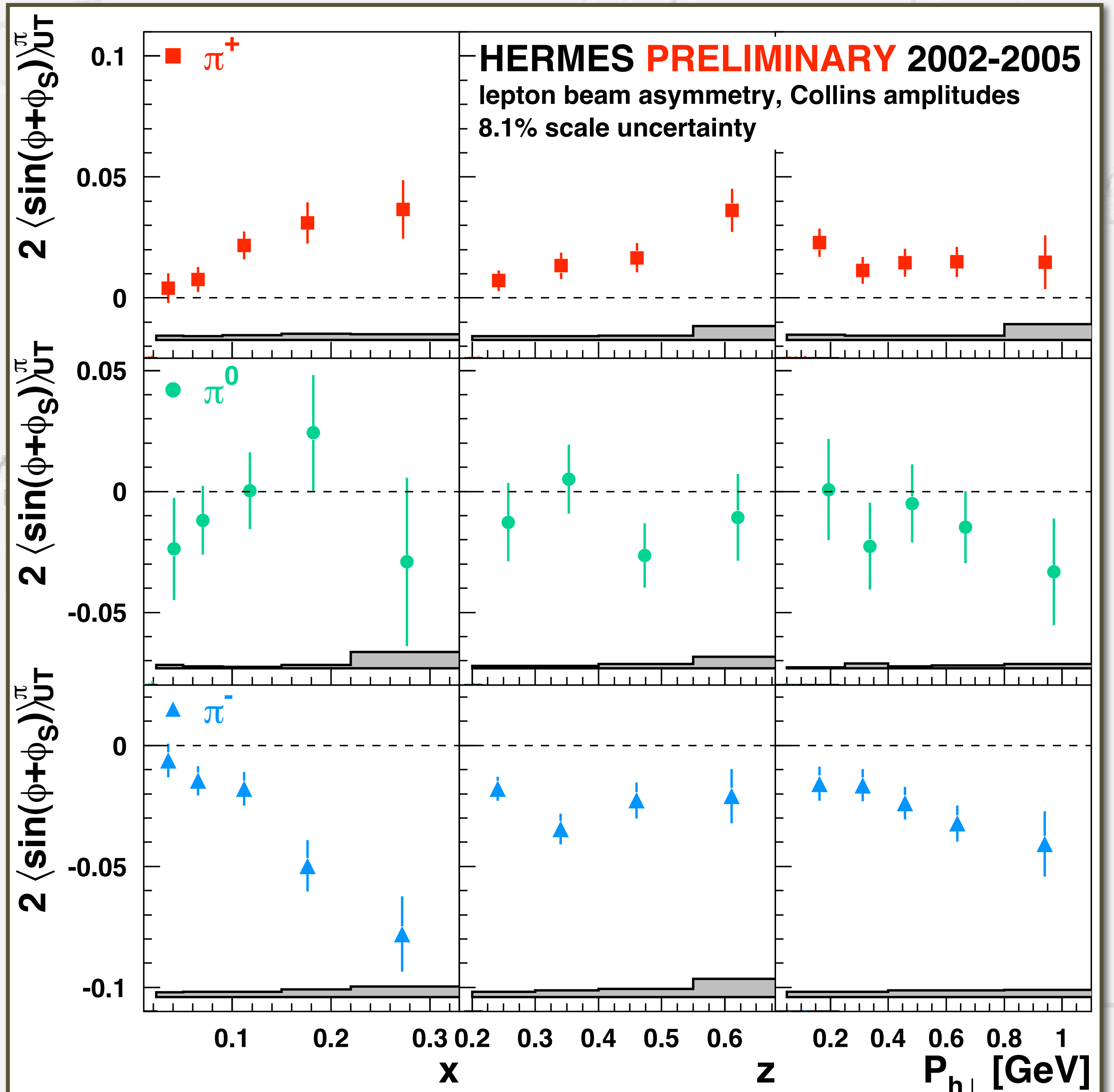

☑ non-zero Collins effect observed!

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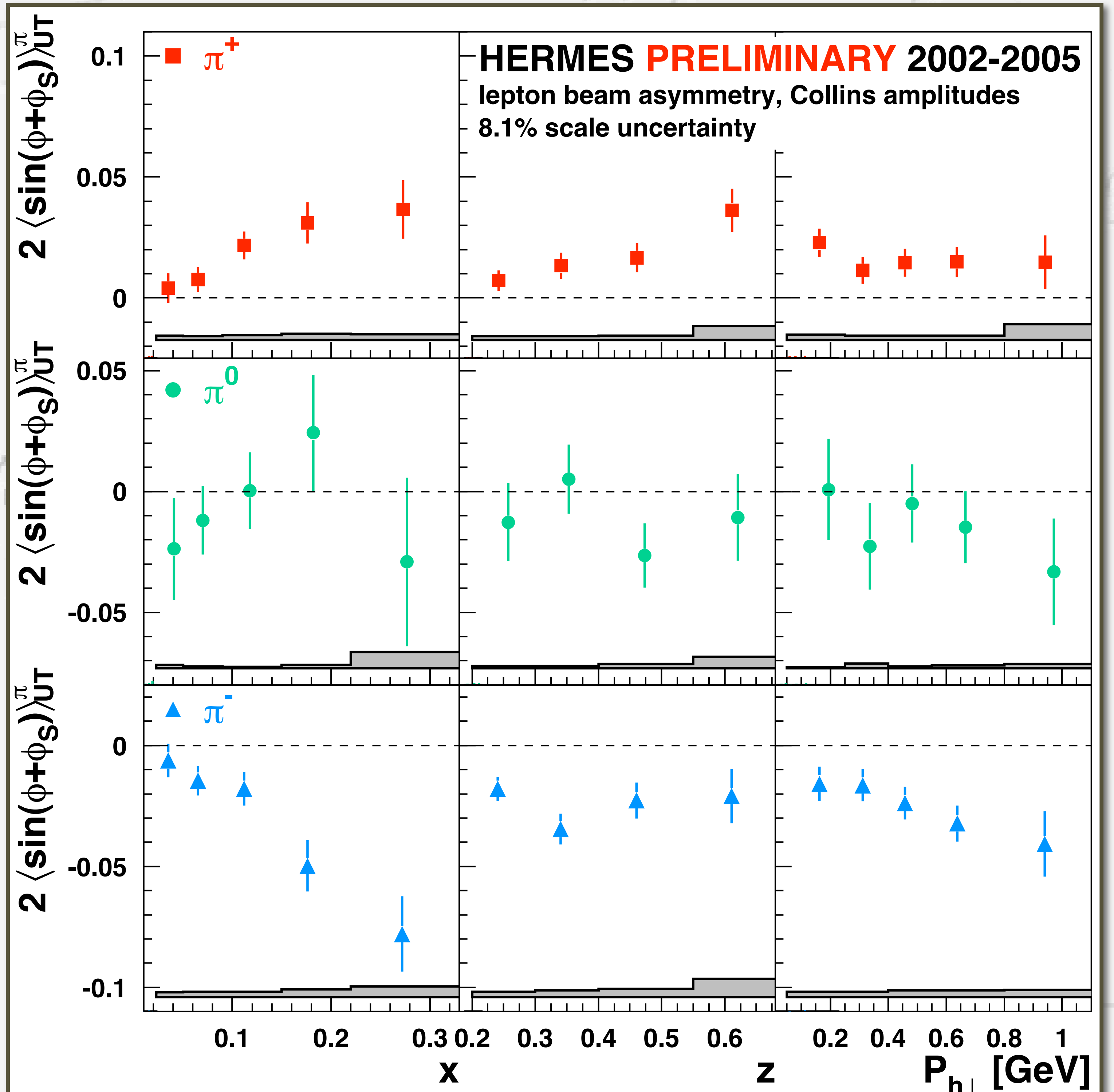
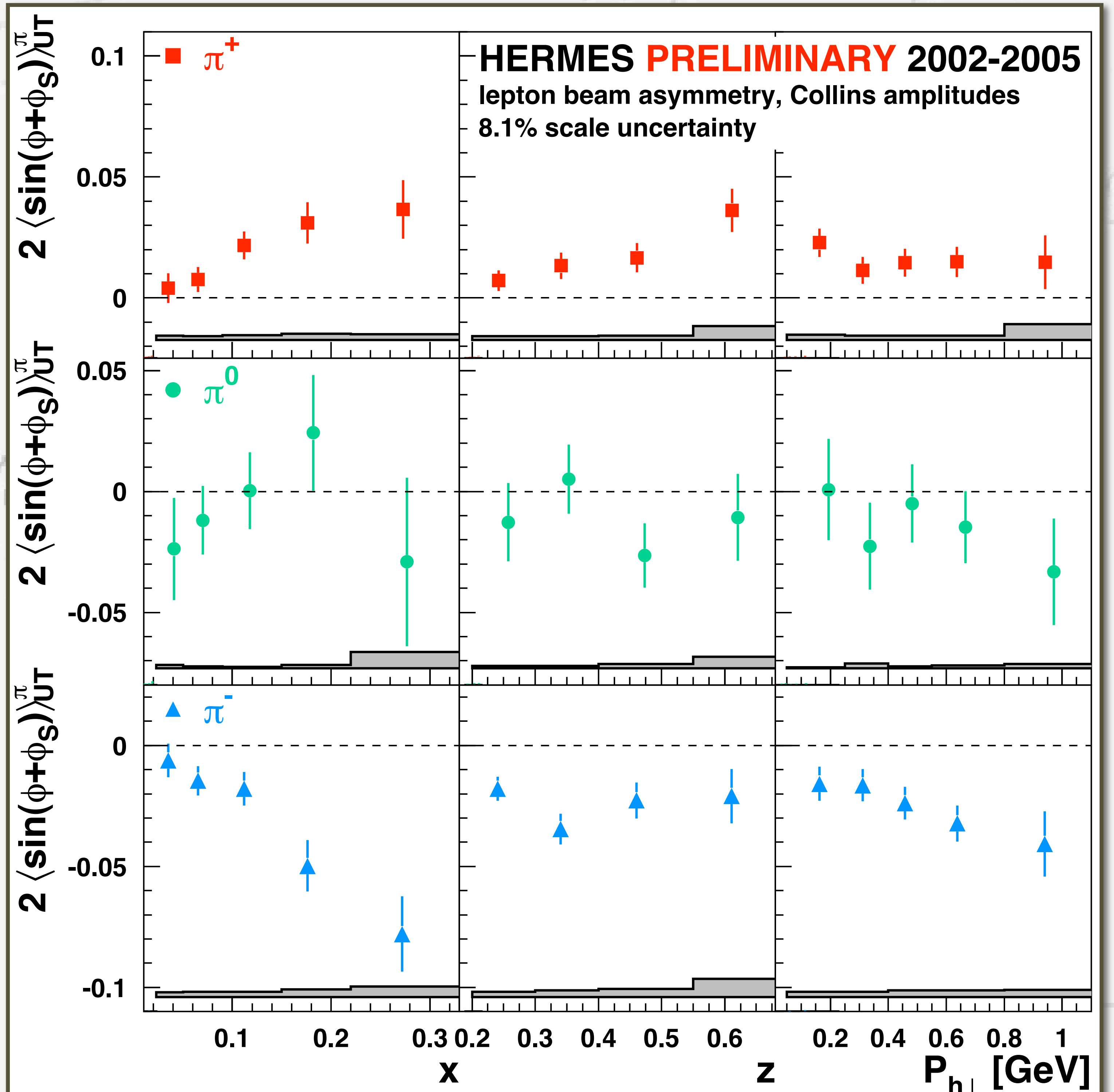


- ☑ non-zero Collins effect observed!
- ☑ both Collins FF and transversity sizeable

The HERMES Collins amplitudes

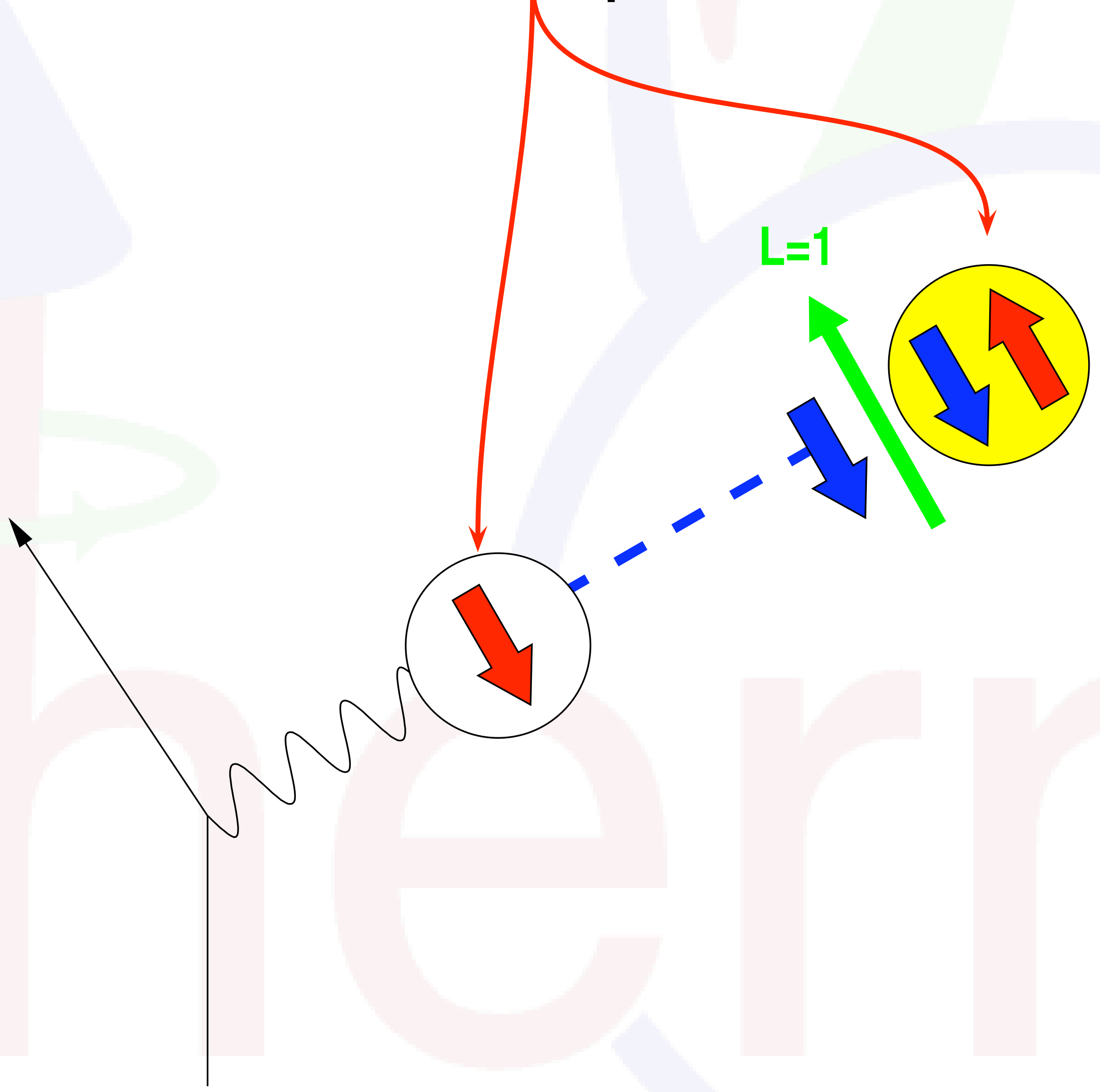


- published† results confirmed with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$)
  maybe expected ($\delta d \equiv h_1^d < 0$)
- unexpected large π^- asymmetry
  $\Rightarrow$ role of disfavored Collins FF
  most likely: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- isospin symmetry among charged and neutral pions fulfilled

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

Collins Fragmentation Function String Model Interpretation (Artru)

transverse spin of struck quark (polarization component in lepton scattering plane reversed by photoabsorption)



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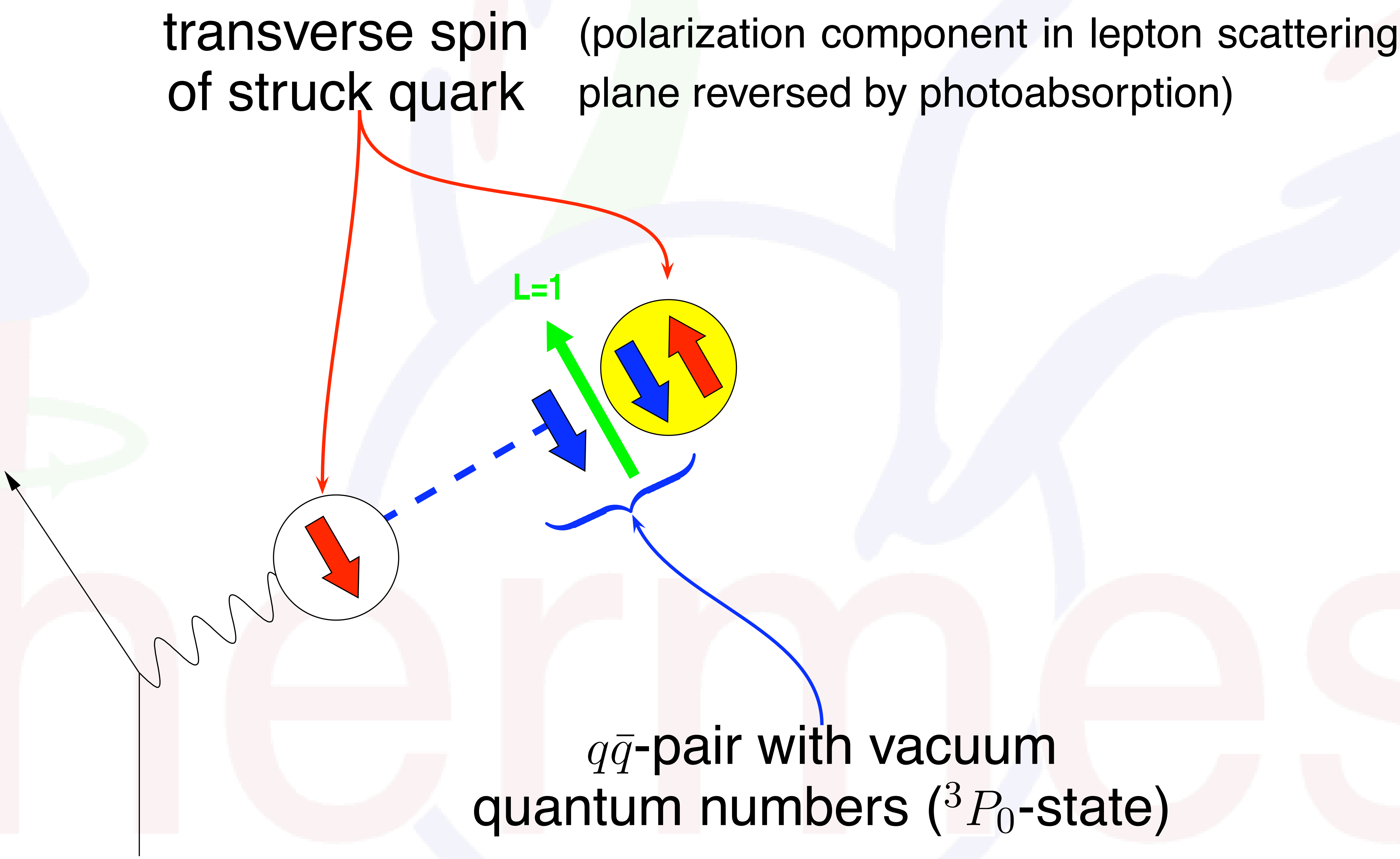

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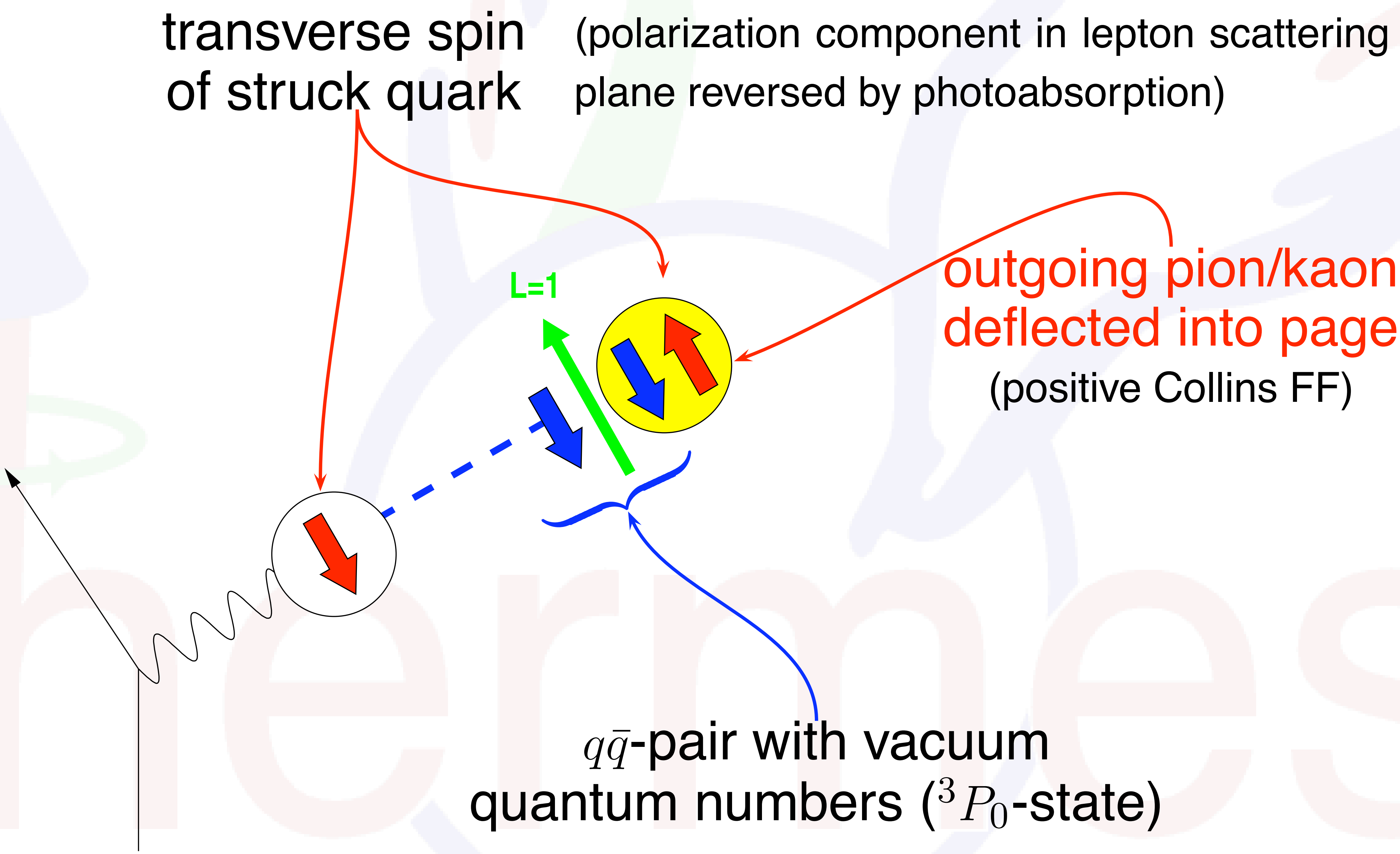

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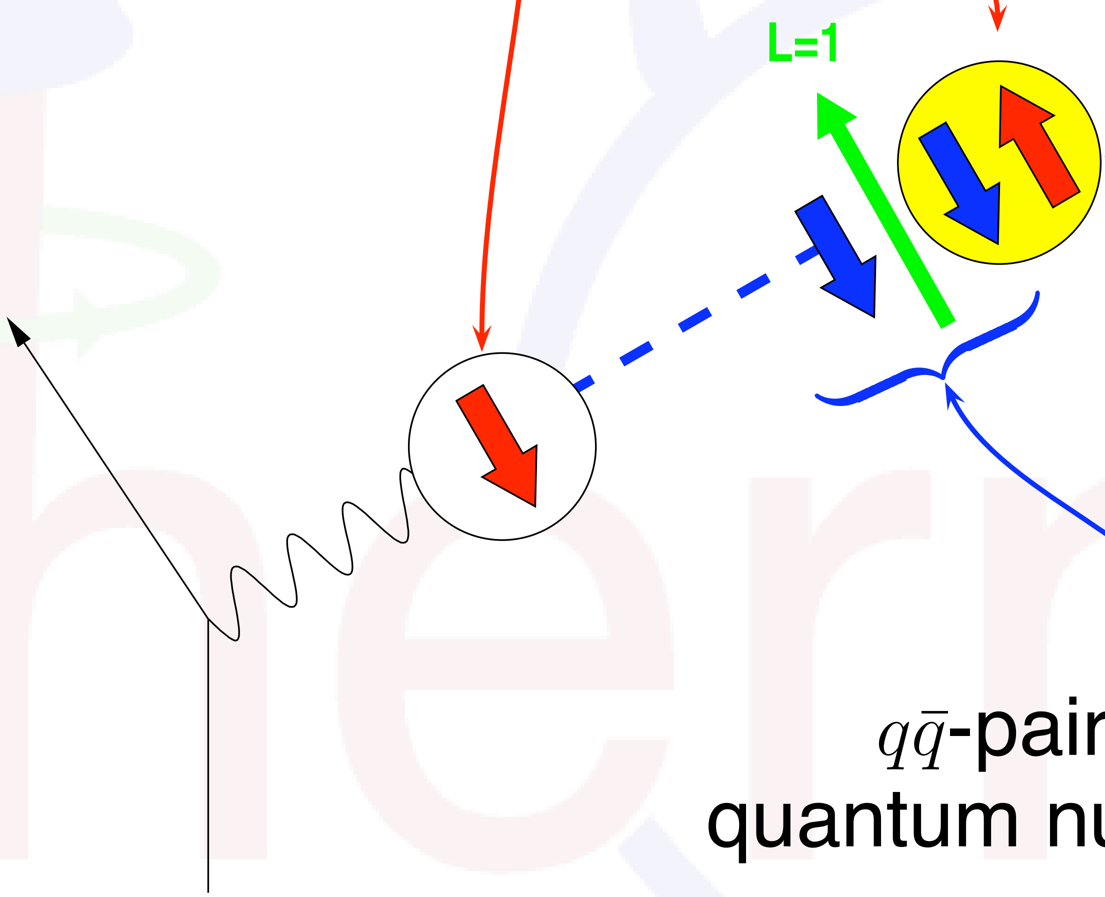


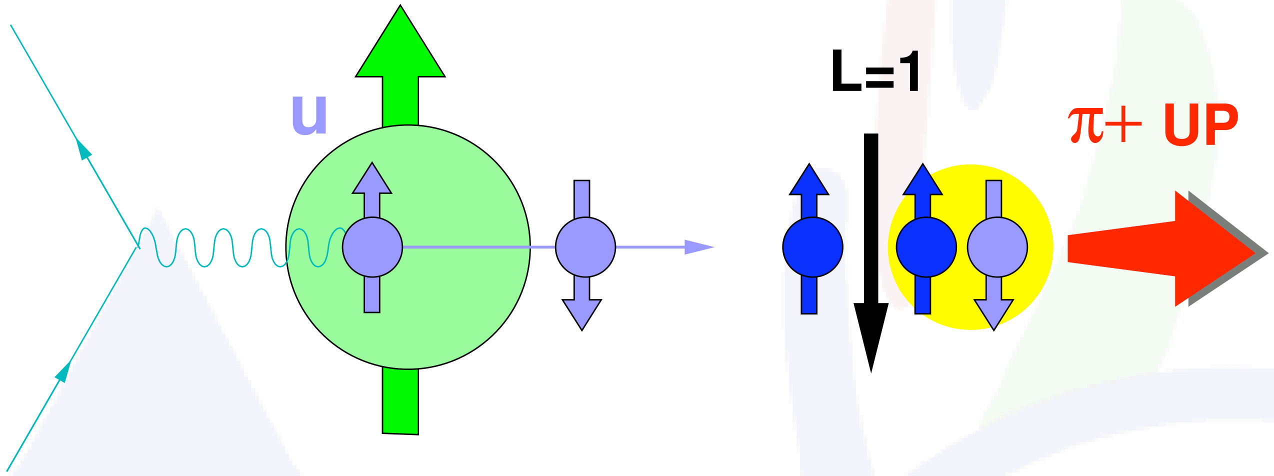
outgoing pion/kaon deflected into page
(positive Collins FF)

pion from next string break deflected out of page
(negative Collins FF)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

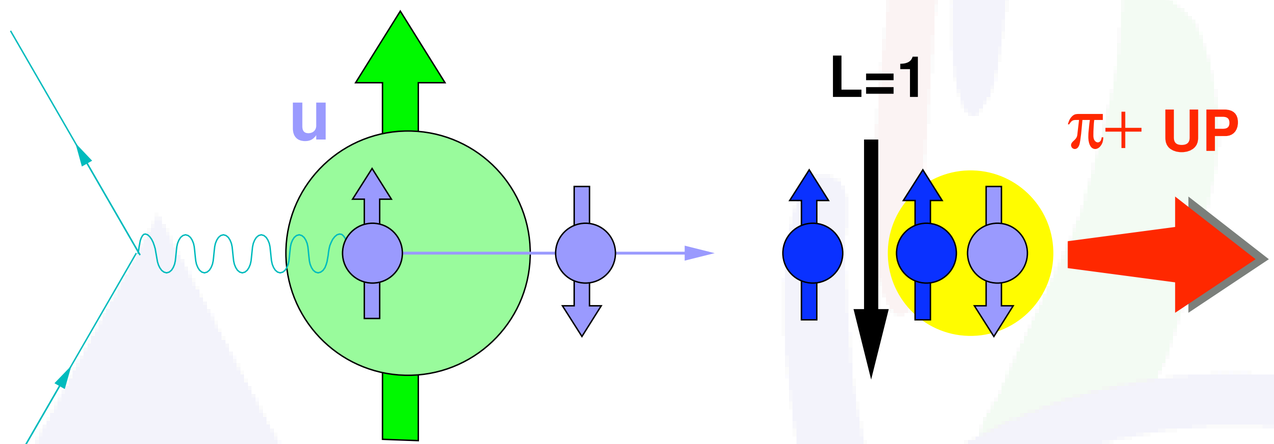
Artru model vs. HERMES

Artru model vs. HERMES



$$\left.\begin{array}{l}\phi_S = \;\; 0 \\ \phi \;\; = \pi/2\end{array}\right\} \sin(\phi + \phi_S) > 0$$

Artru model vs. HERMES



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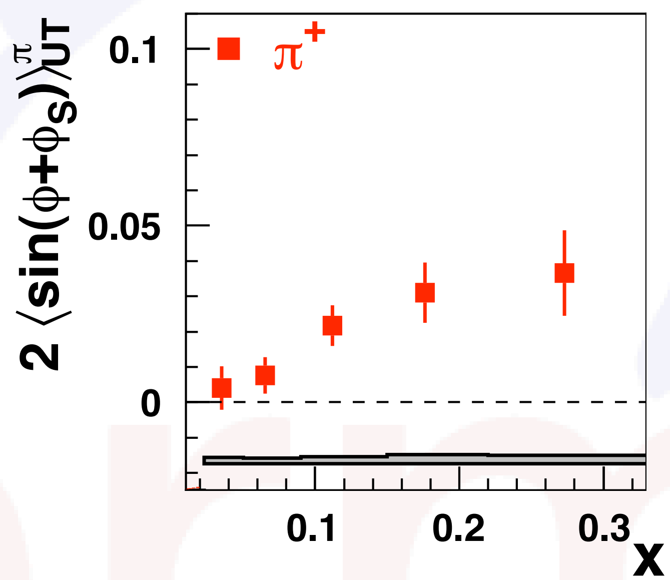
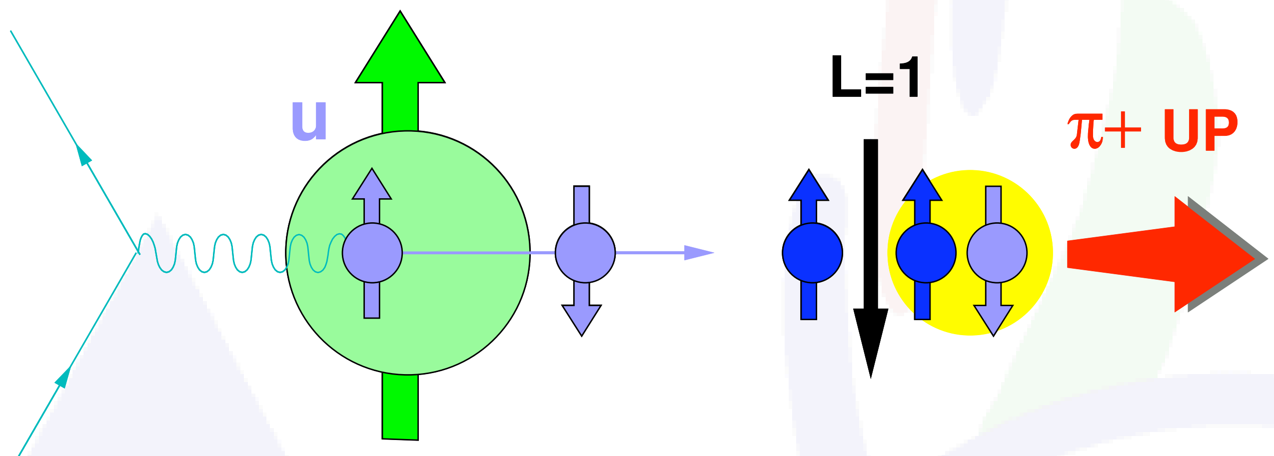


Artru model vs. HERMES



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✓

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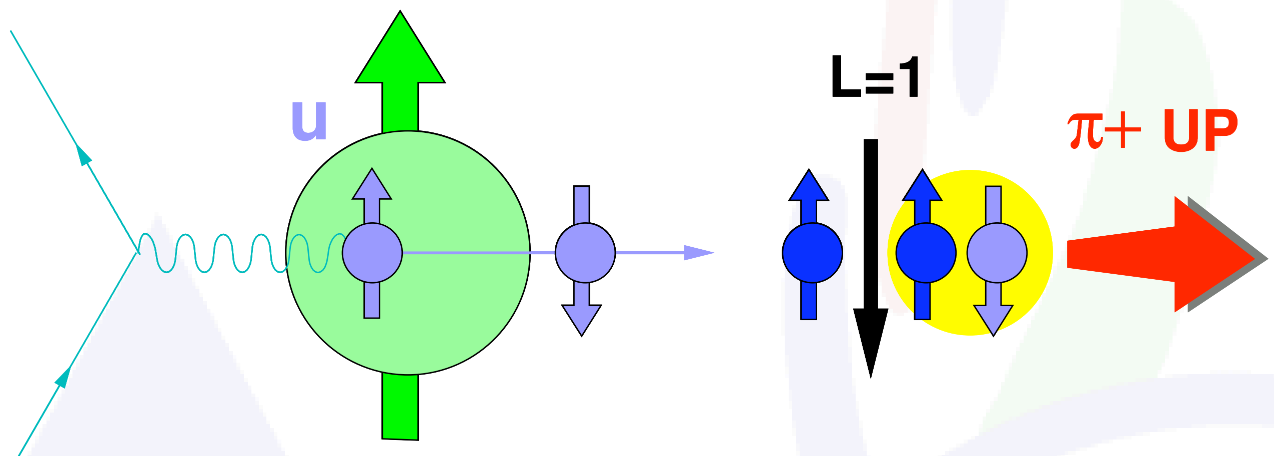

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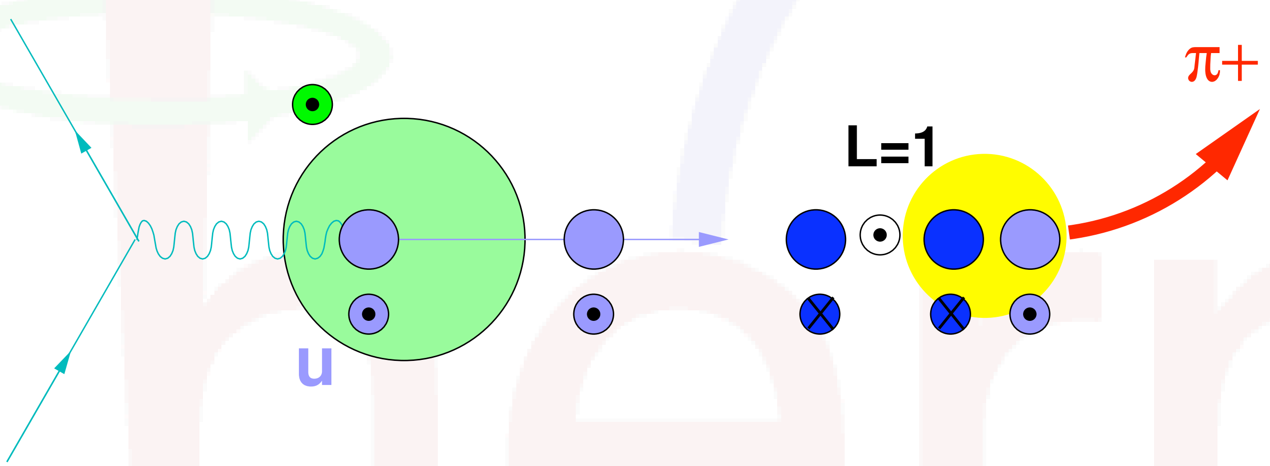

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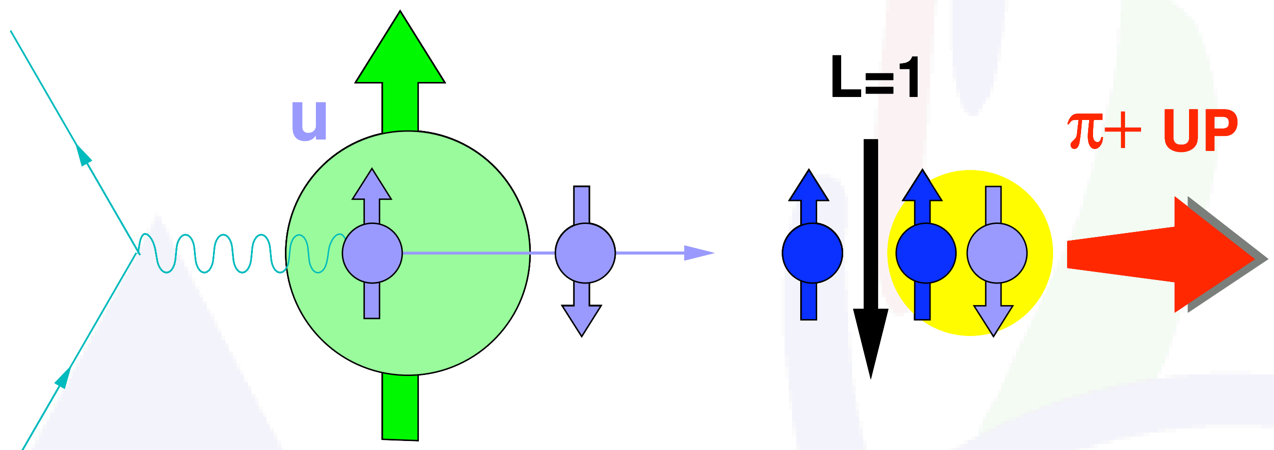

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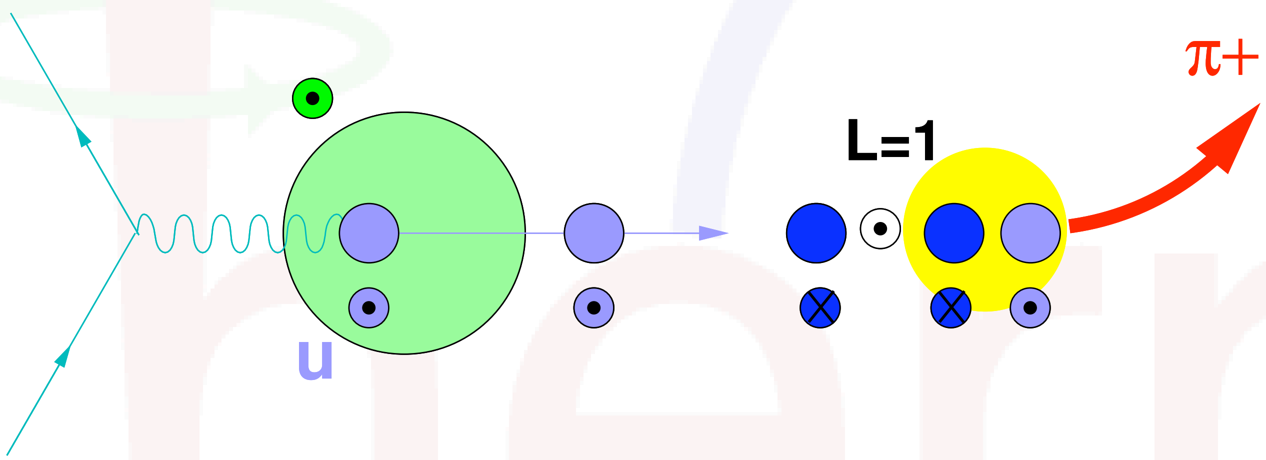

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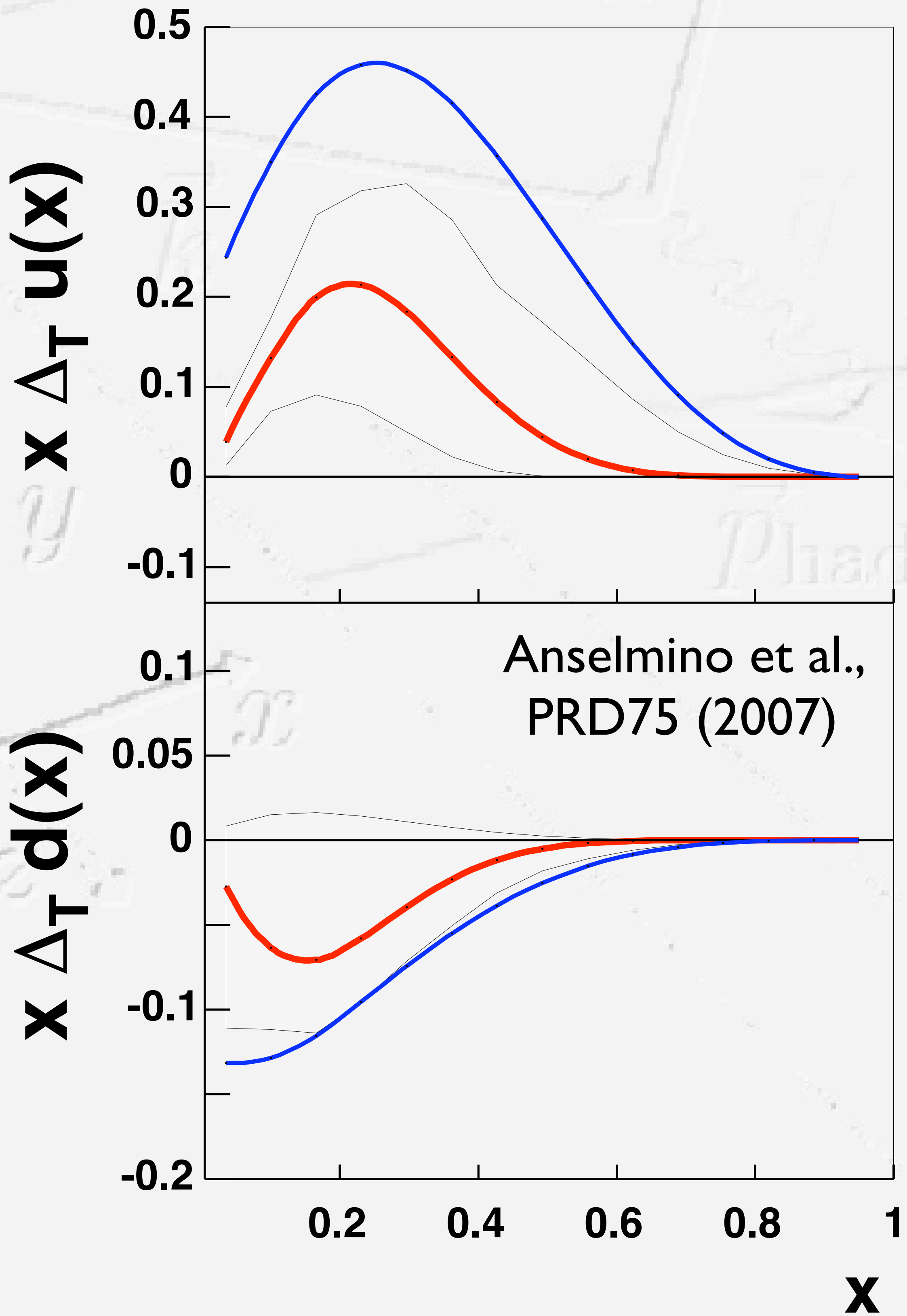
Artru model and HERMES results in agreement!

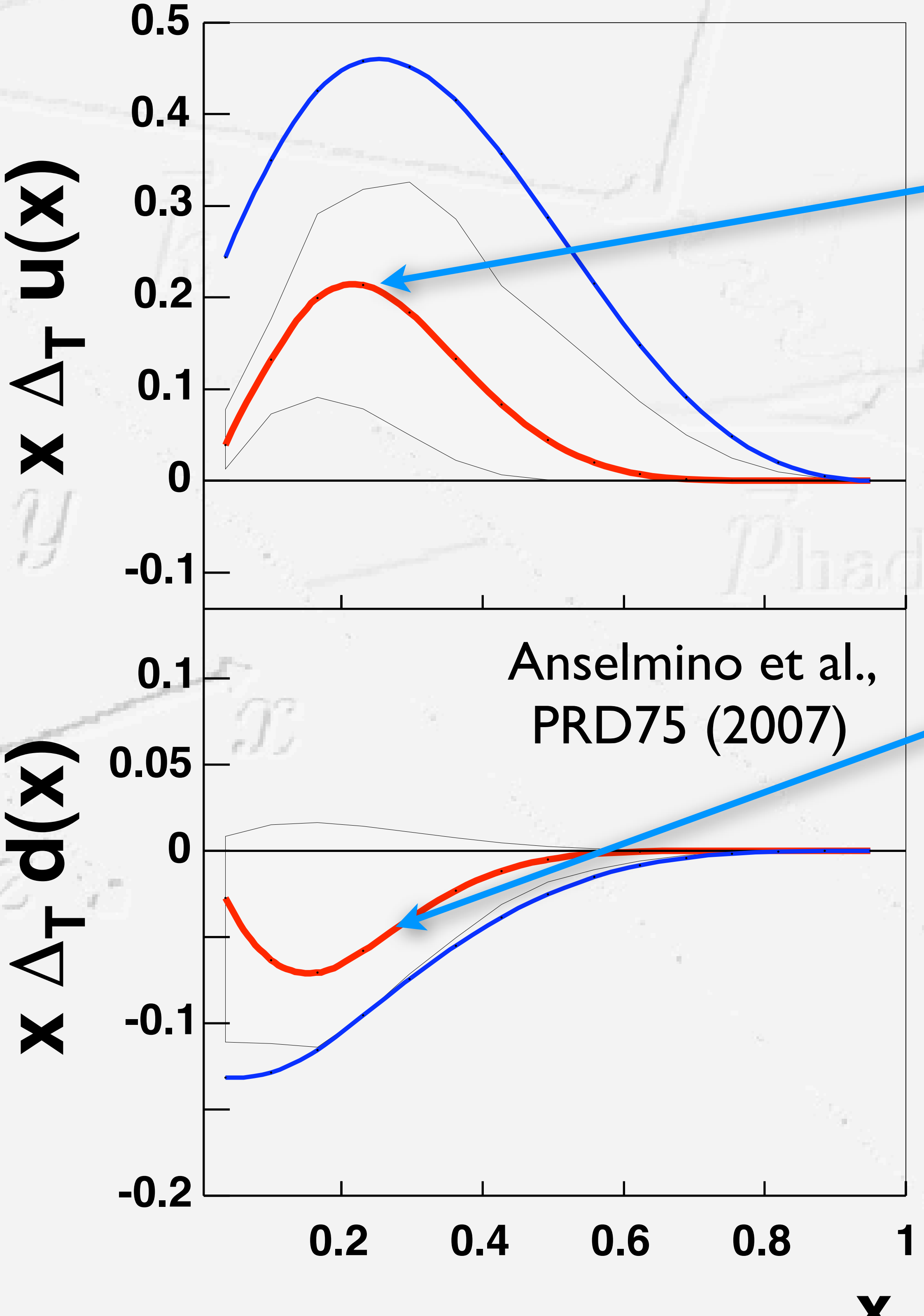
First glimpse at transversity

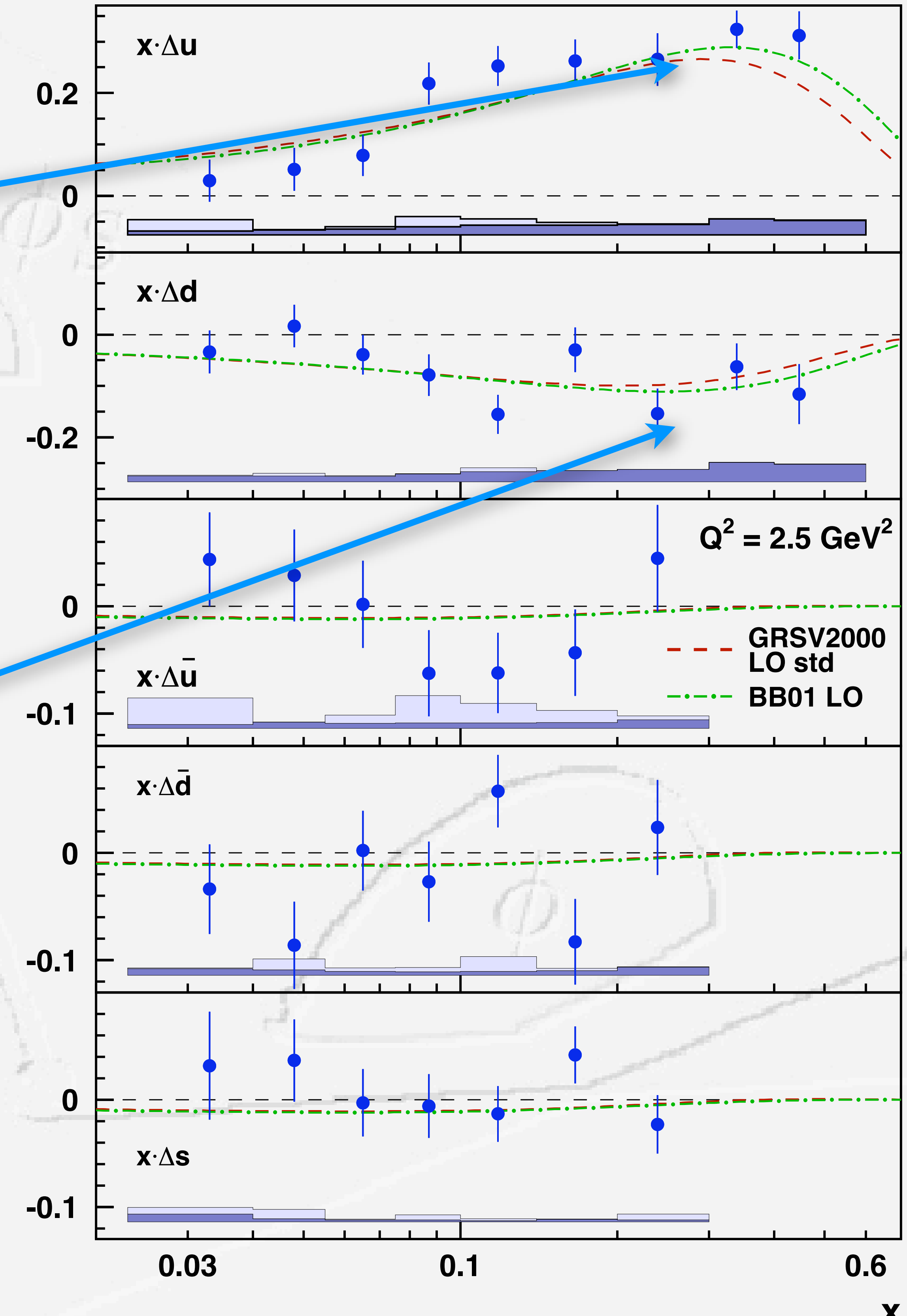


Combined analysis of data from:

- **HERMES**
- **COMPASS**
- **BELLE**

First glimpse at transversity

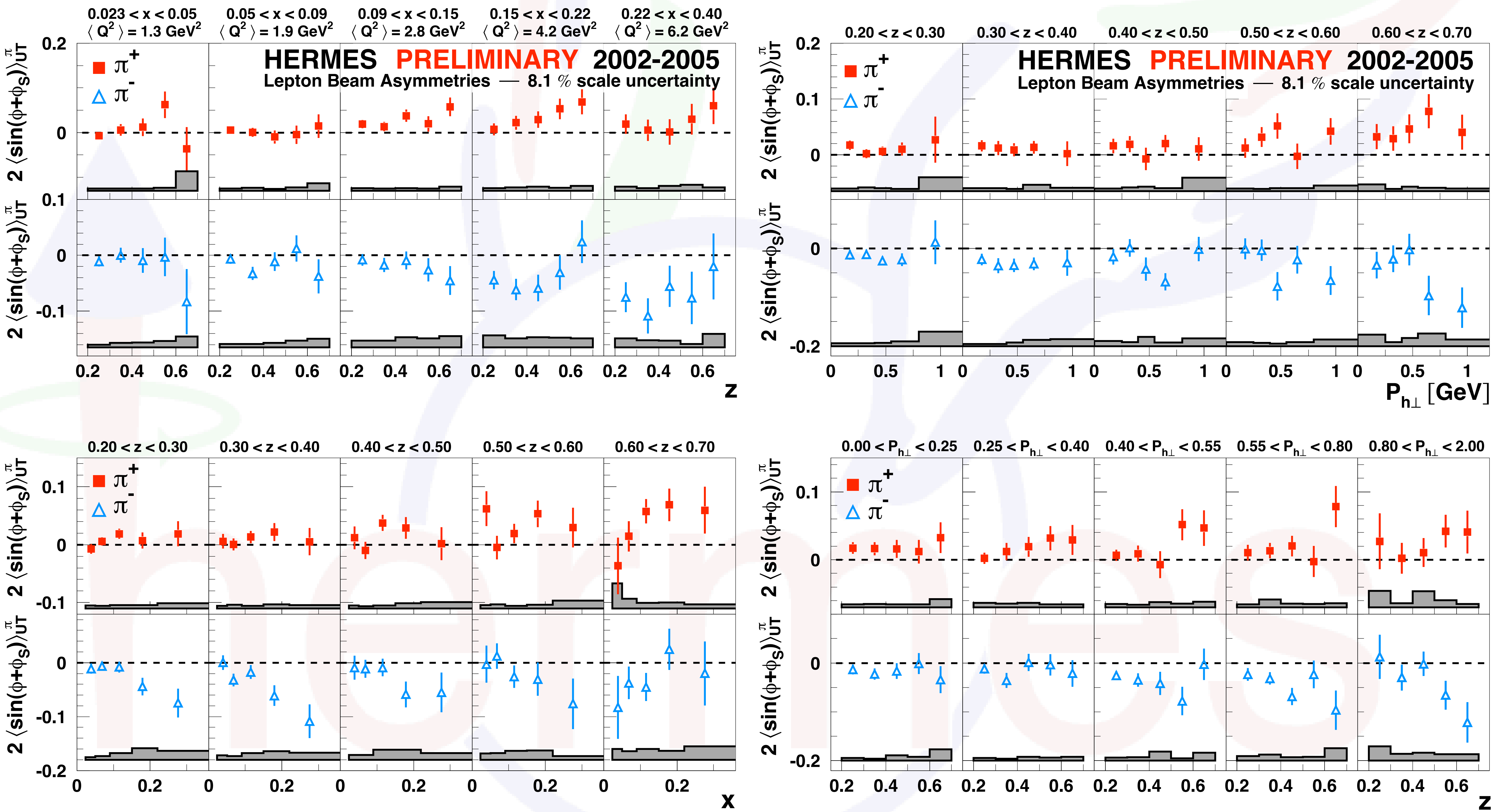




2D Binning of Collins amplitudes

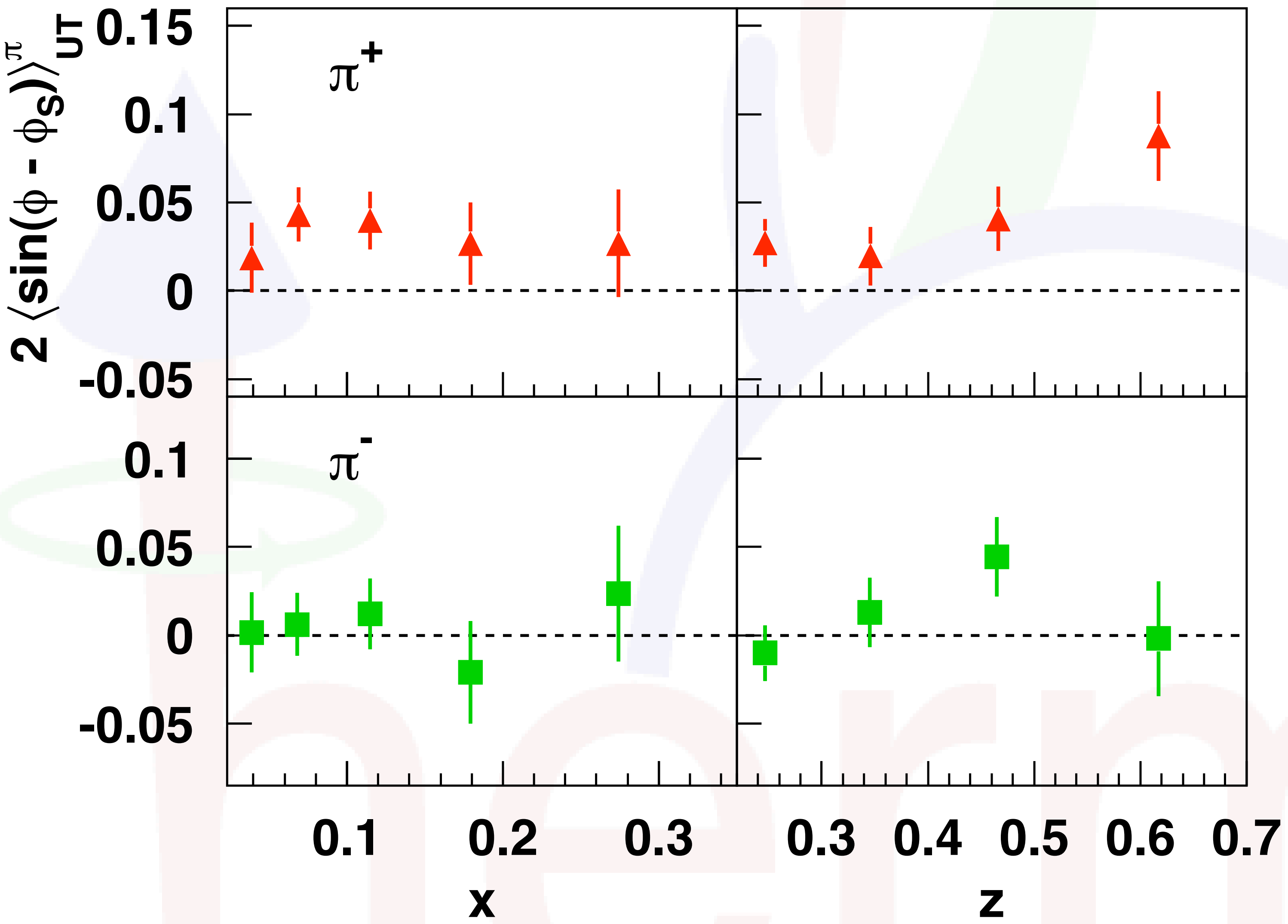
- kinematic dependences often don't factorize

  bin in as many independent variables as possible:



HERMES Sivers amplitudes

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



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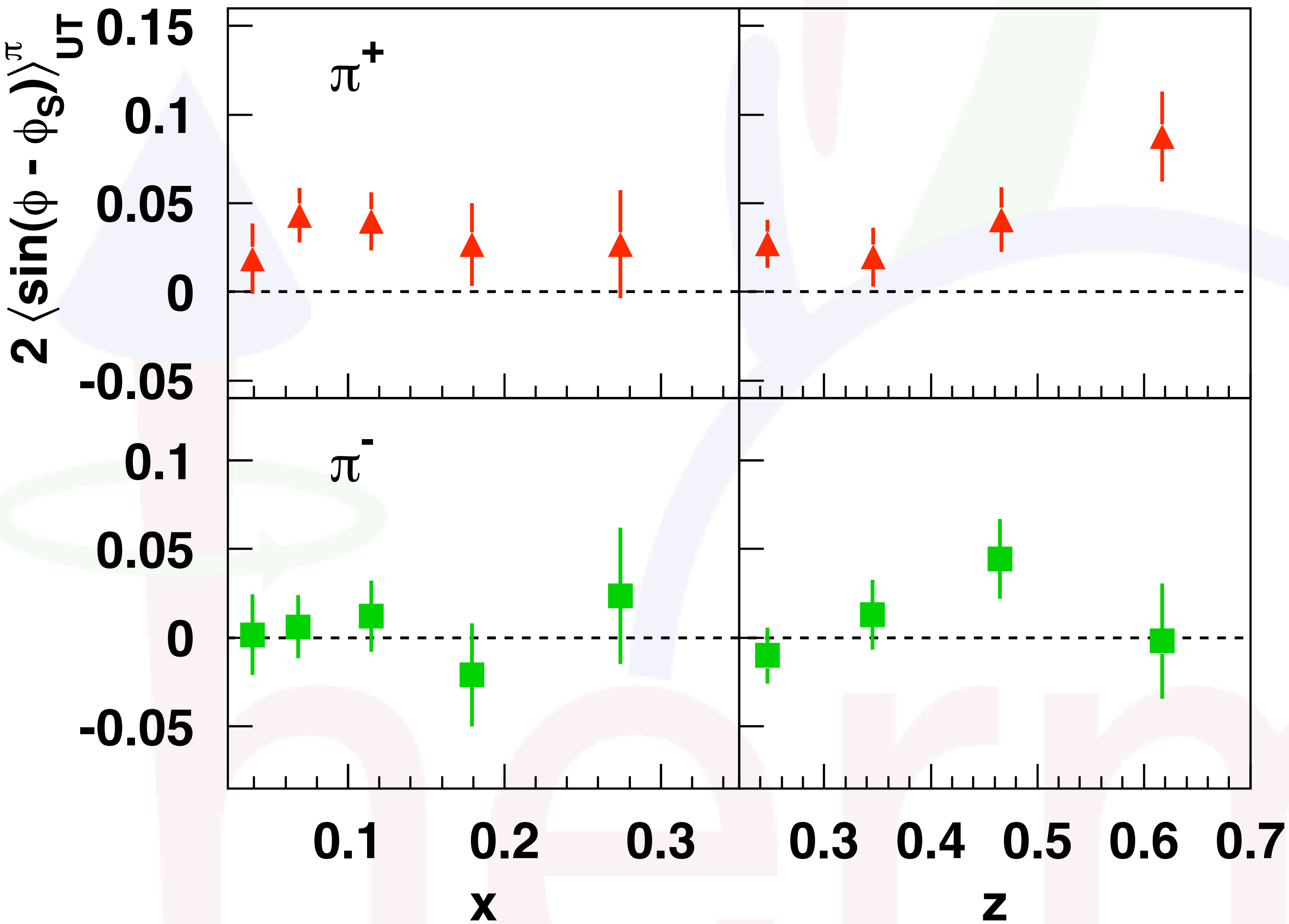

☑ first observation of T-odd Sivers effect in SIDIS!

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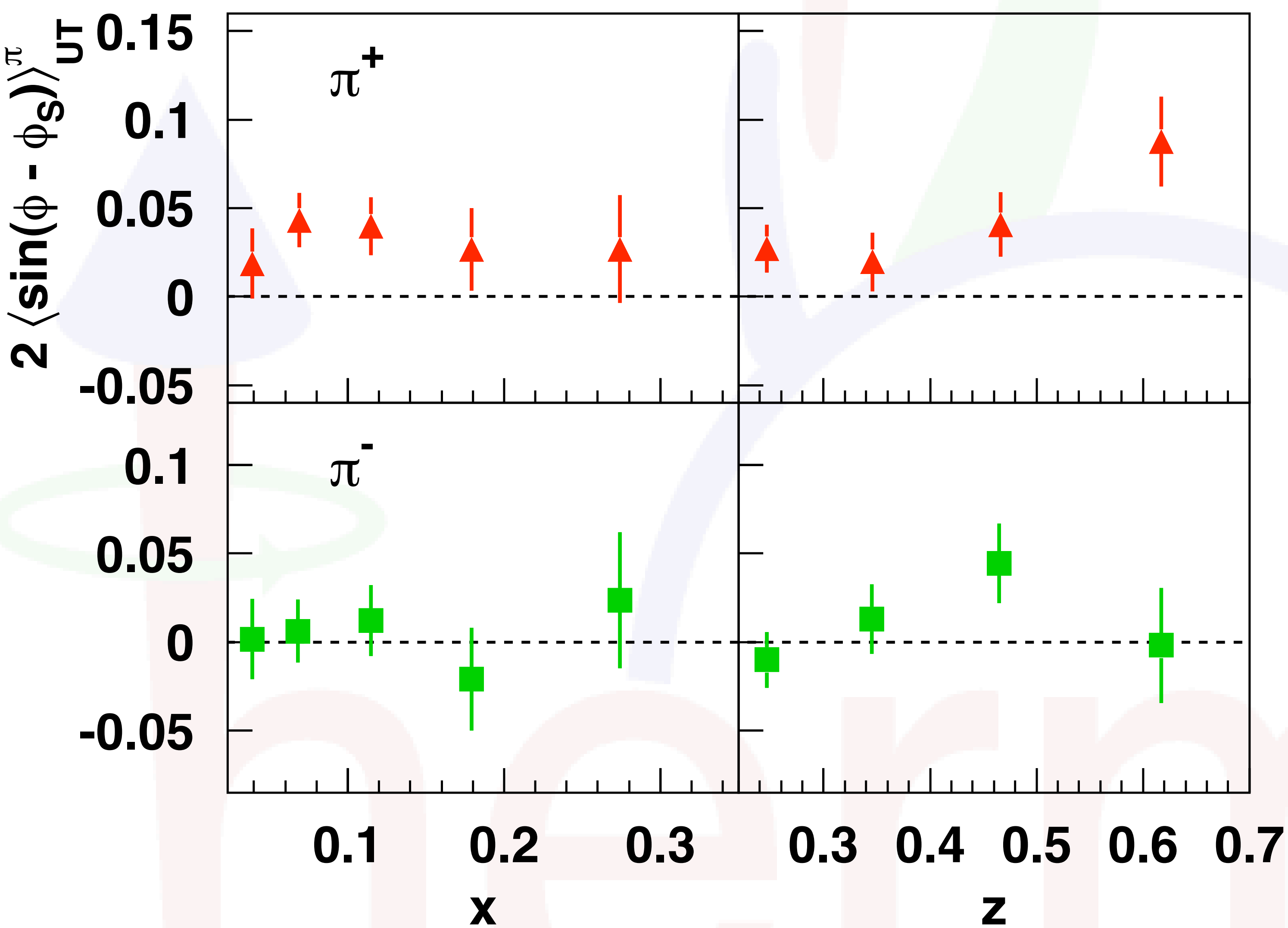

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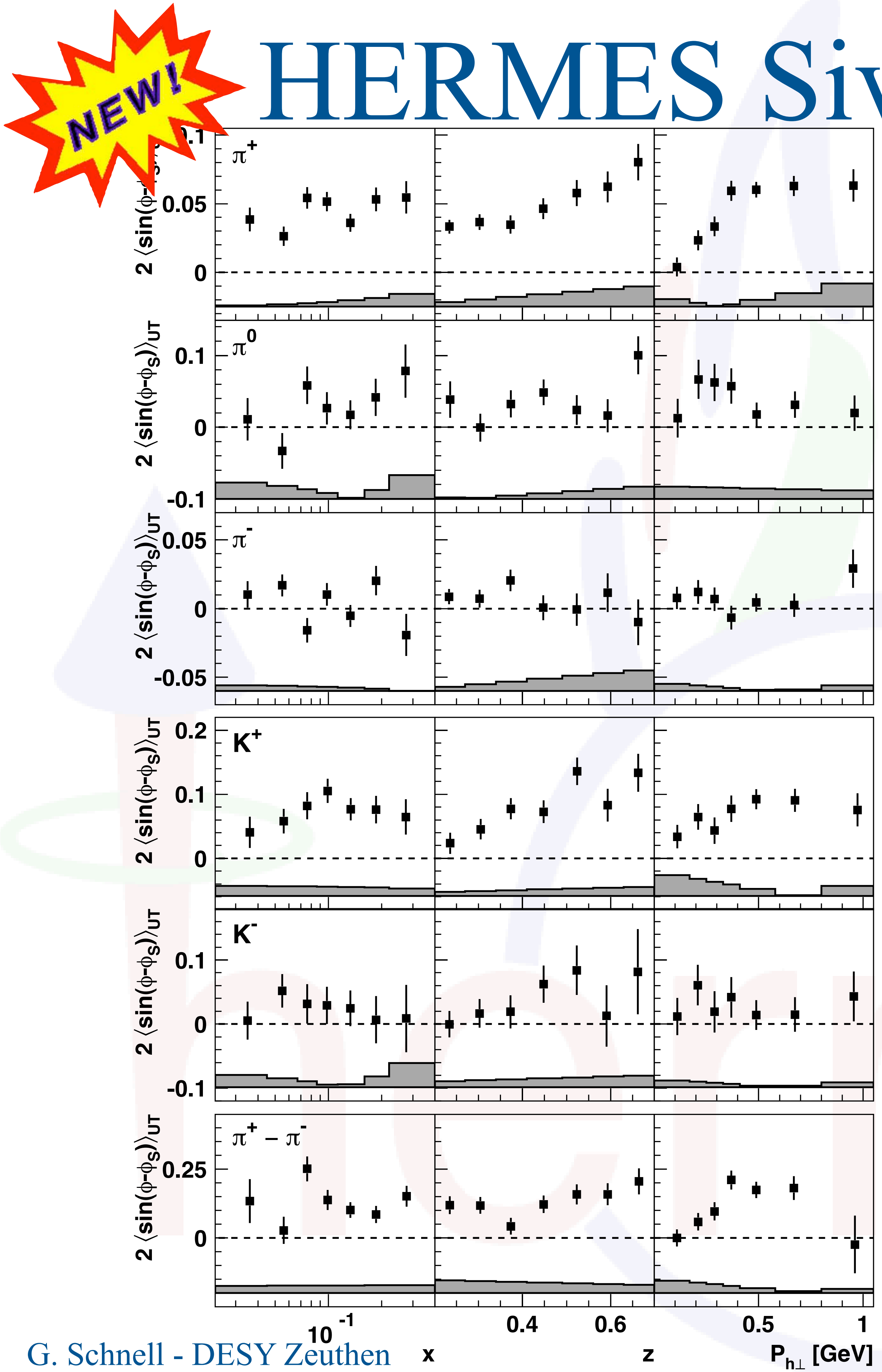
- ☑ u-quark dominance suggests sizeable u-quark orbital motion

HERMES Sivers amplitudes



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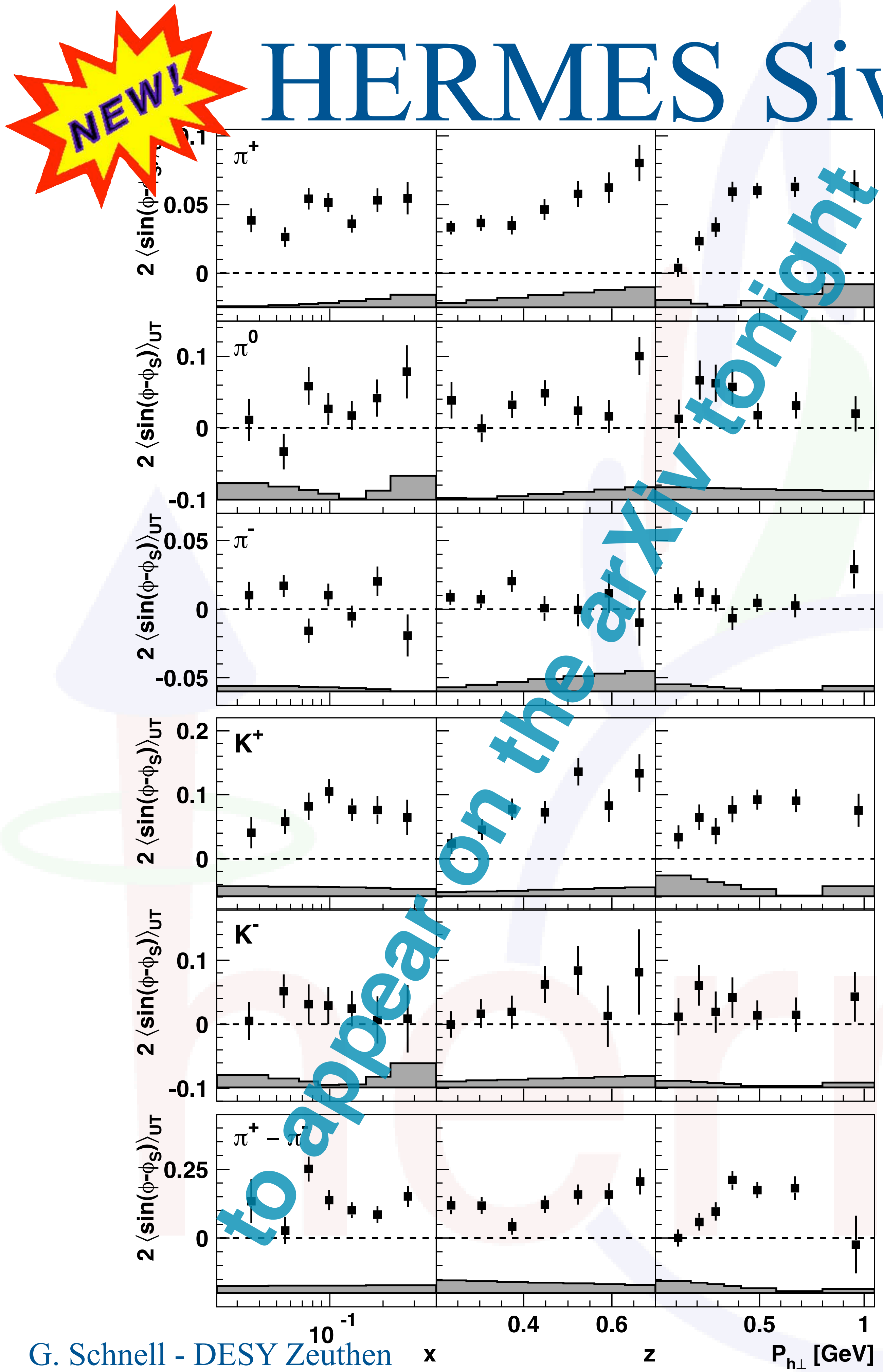

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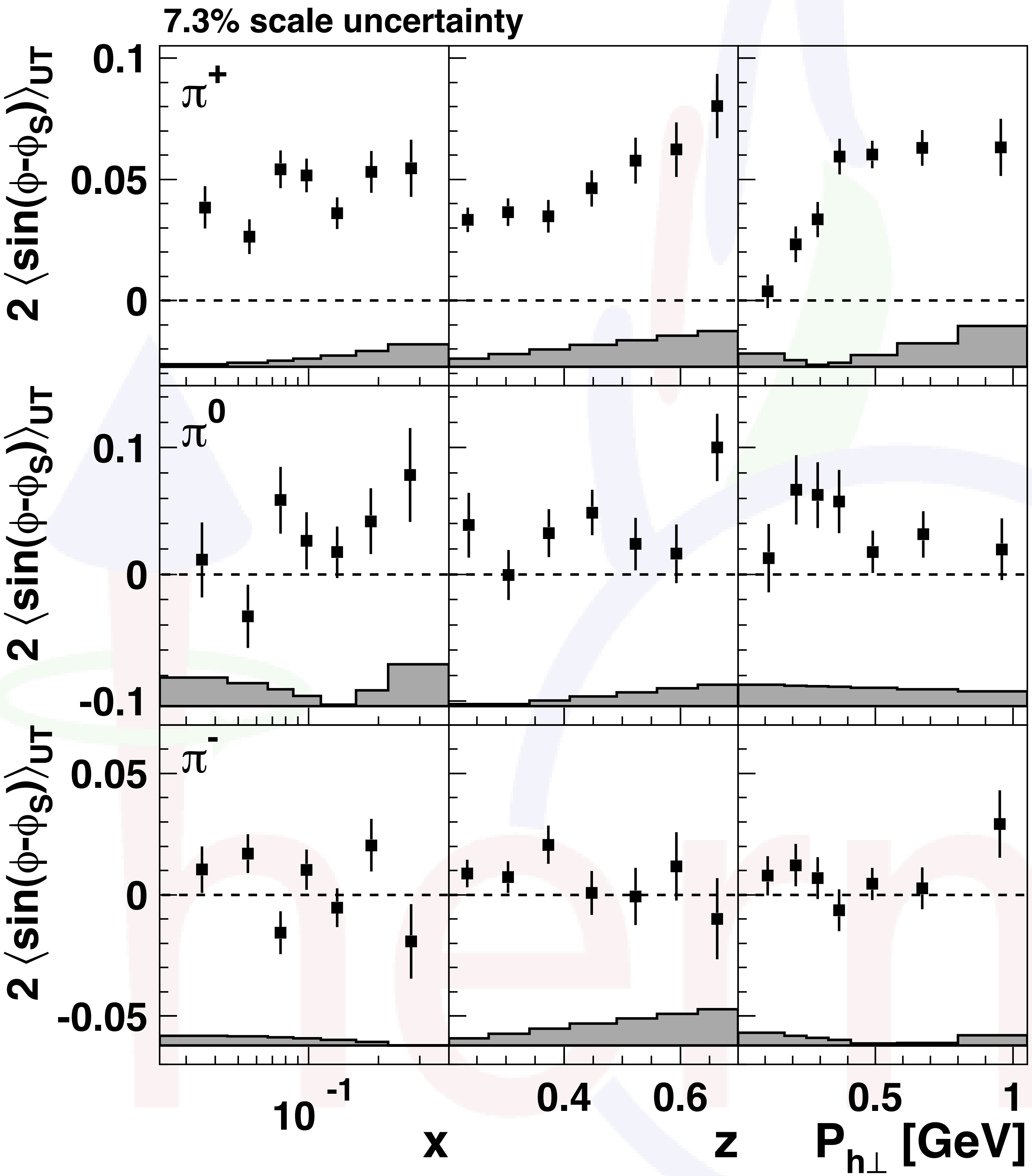
Sivers amplitudes for pions



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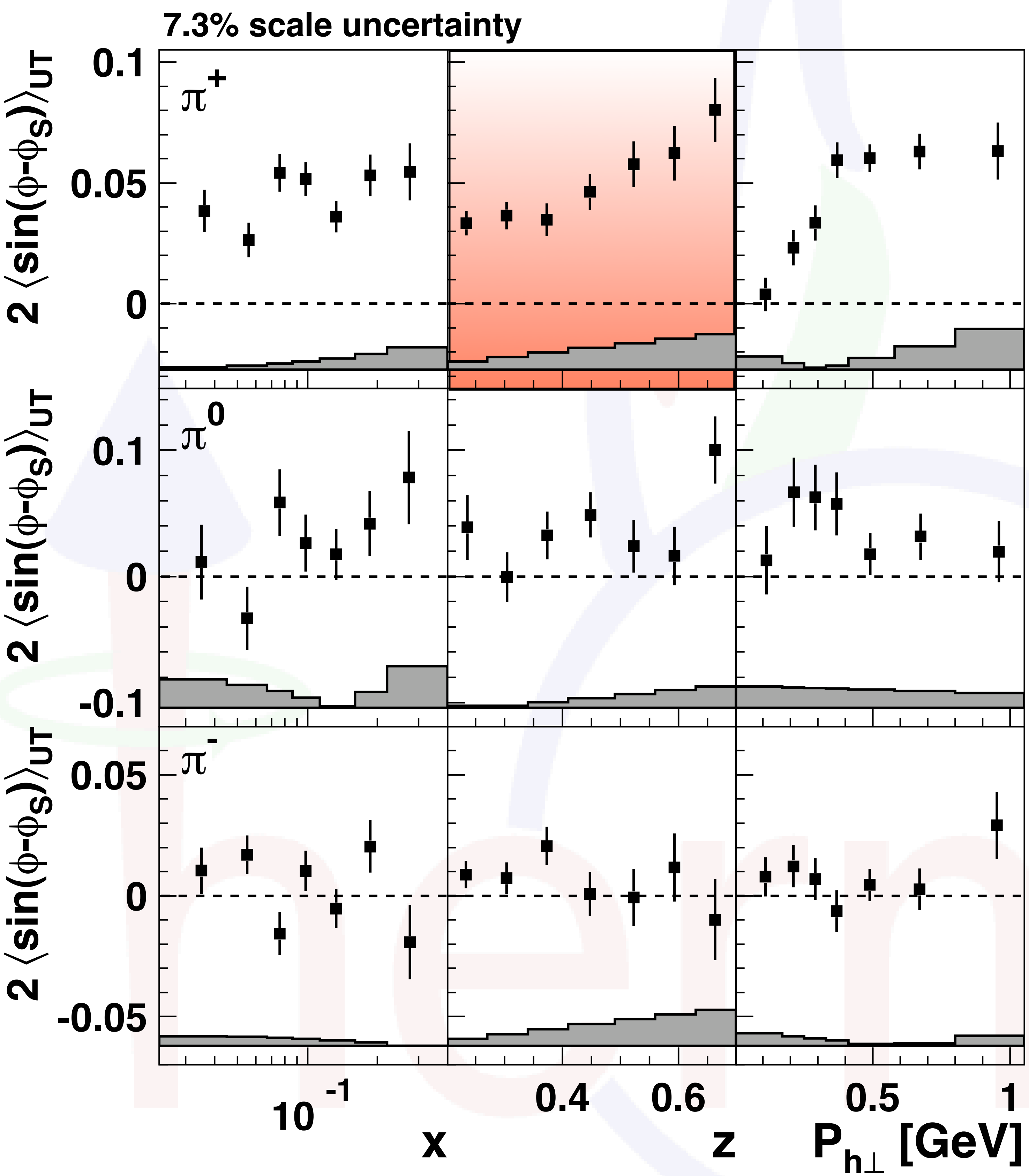
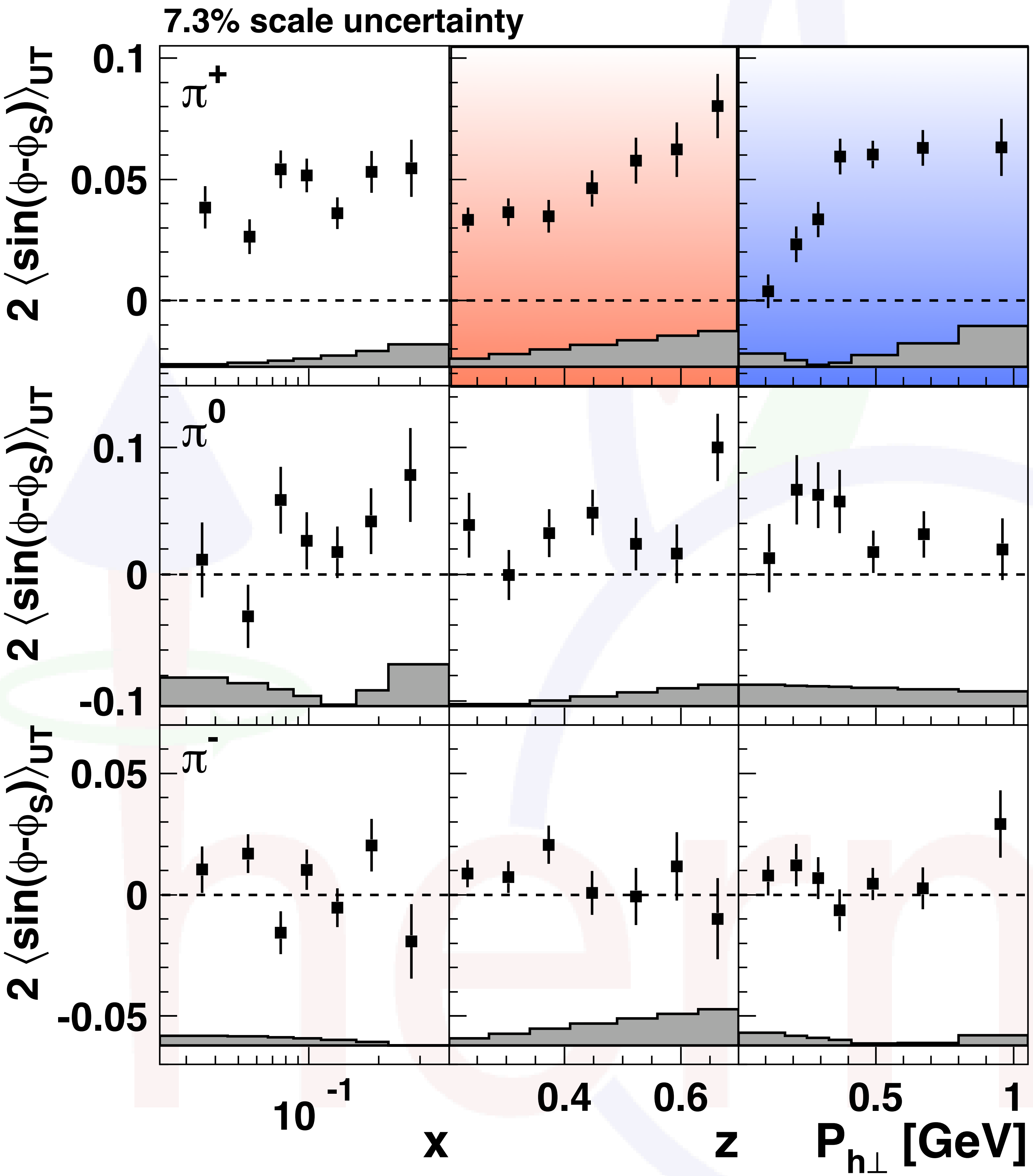


☛ **clear rise with z**

Sivers amplitudes for pions

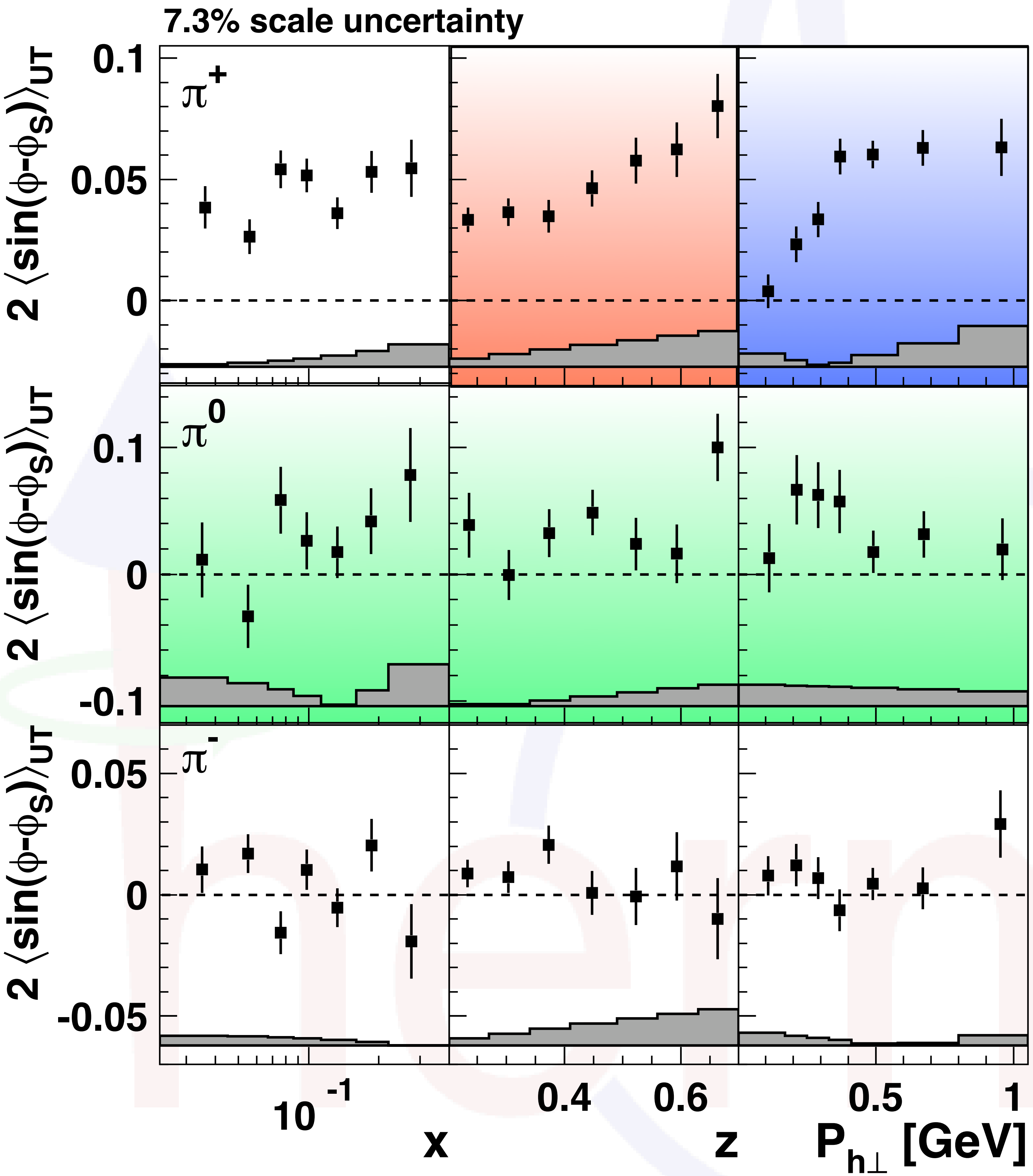


☛ **clear rise with z**

☛ **rise at low $P_{h\perp}$**

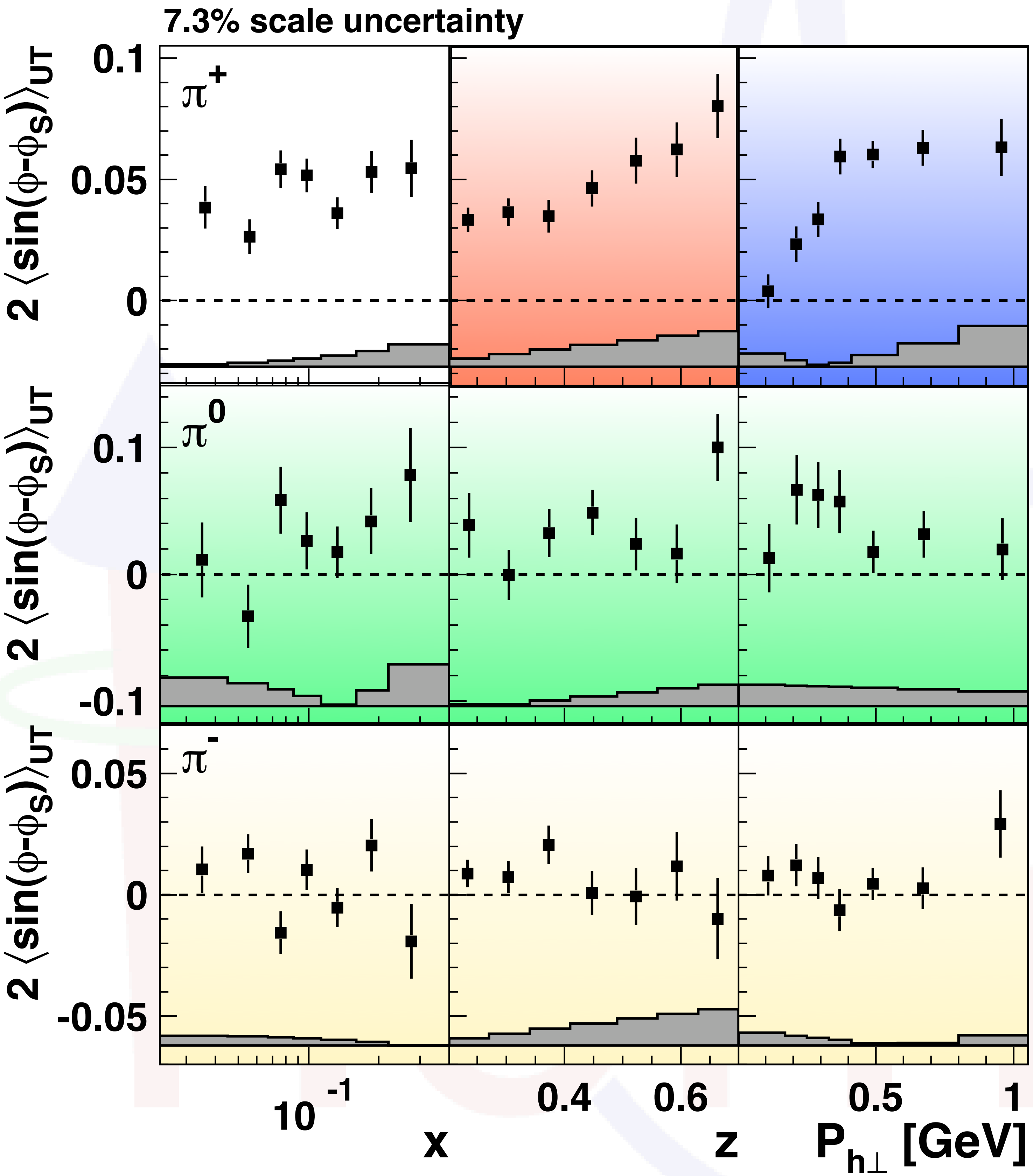
☛ **plateau at high $P_{h\perp}$**

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

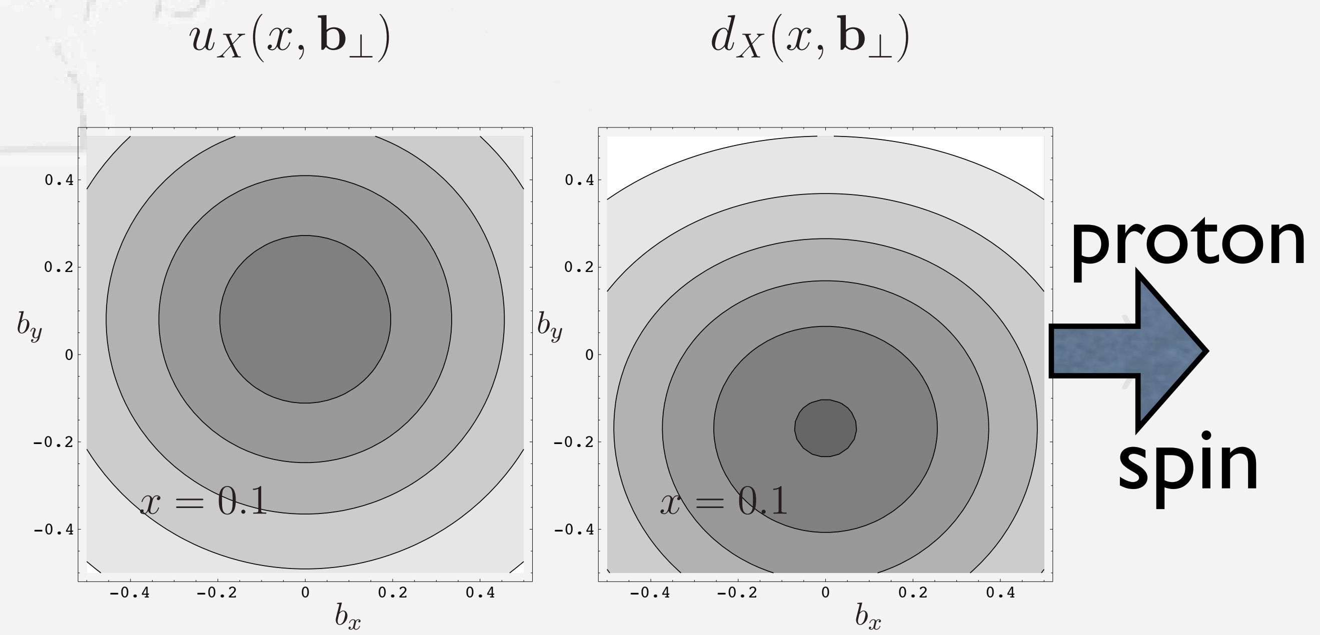
"Chromodynamic Lensing"

approach by M. Burkardt:

[hep-ph/0309269]

spatial distortion of q-distribution

(obtained using anom. magn. moments & impact parameter dependent PDFs)



“Chromodynamic Lensing”

approach by M. Burkardt:

[hep-ph/0309269]

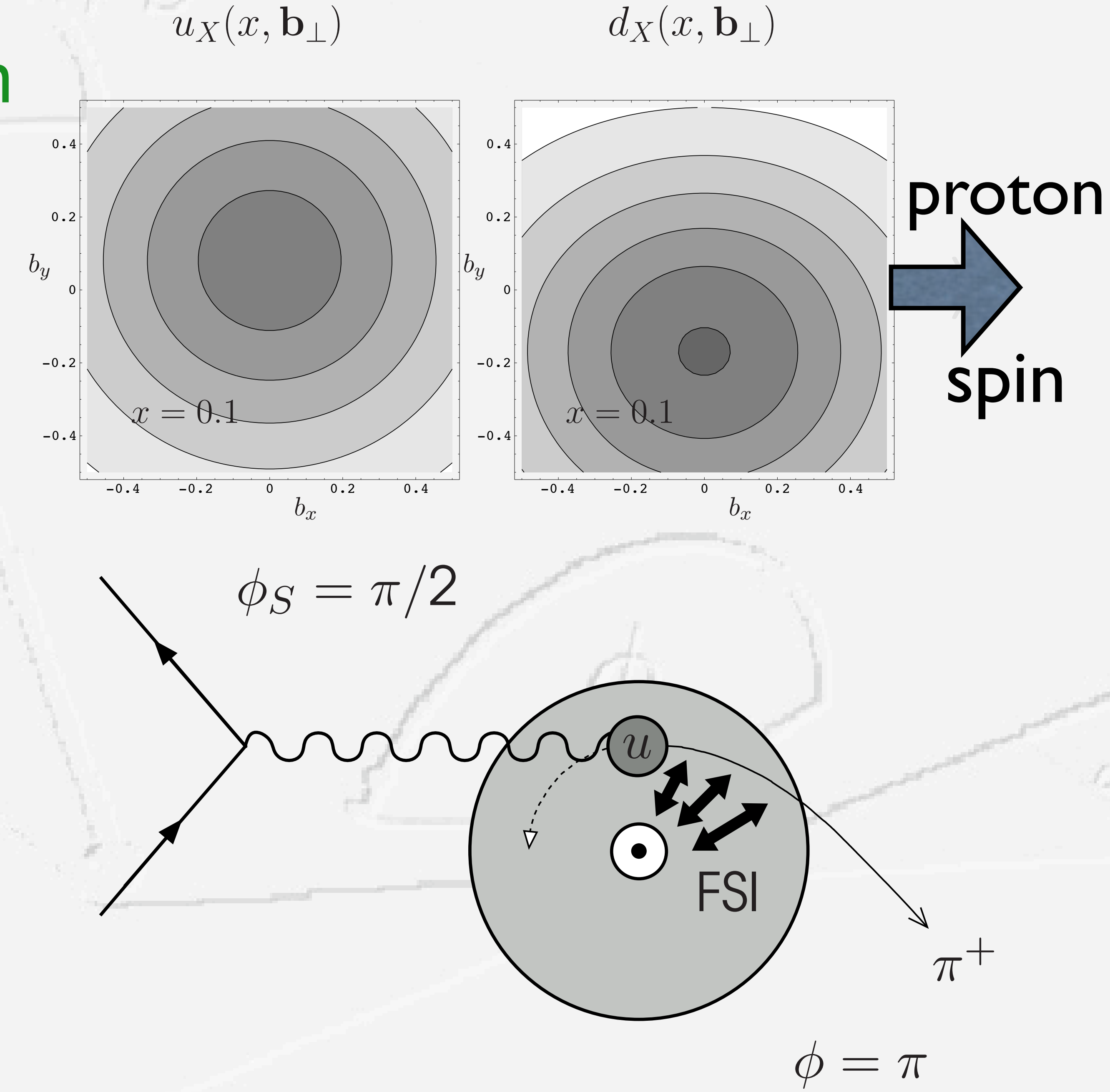
spatial distortion of q-distribution

(obtained using anom. magn. moments & impact parameter dependent PDFs)

+ attractive QCD potential

(gluon exchange)

$\Rightarrow$ transverse asymmetries



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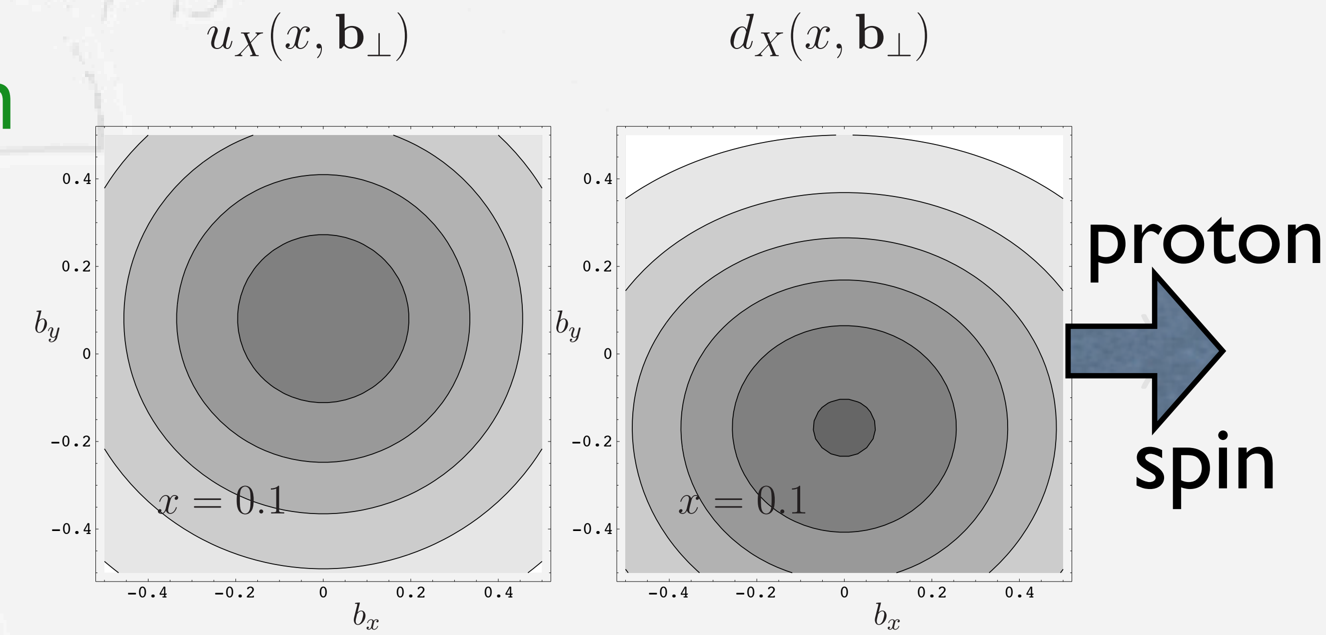

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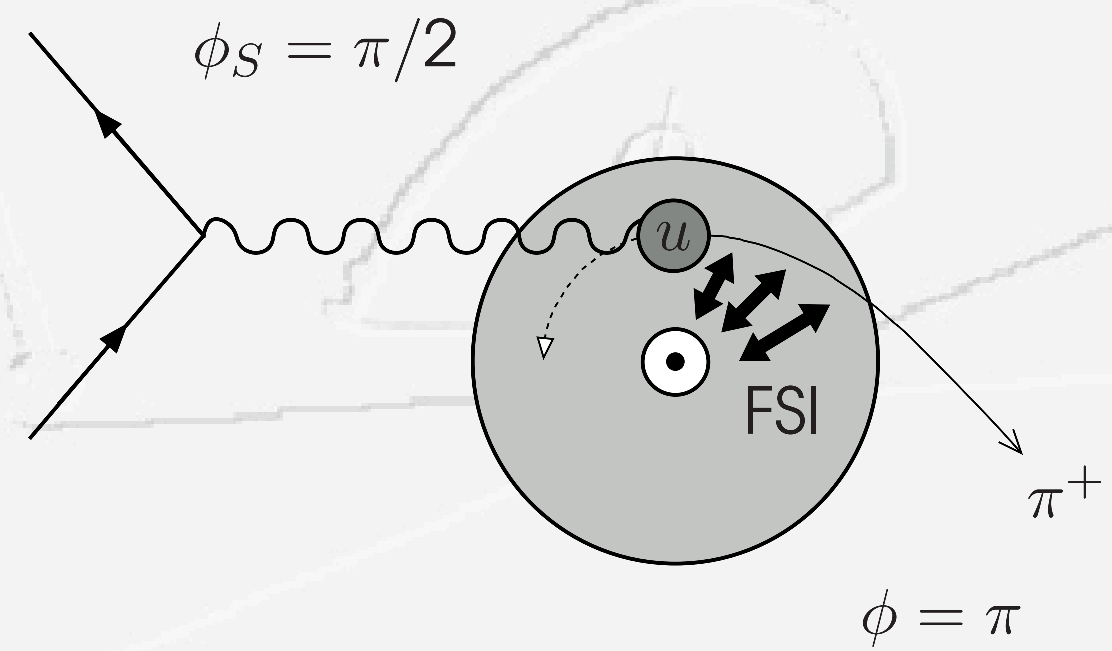
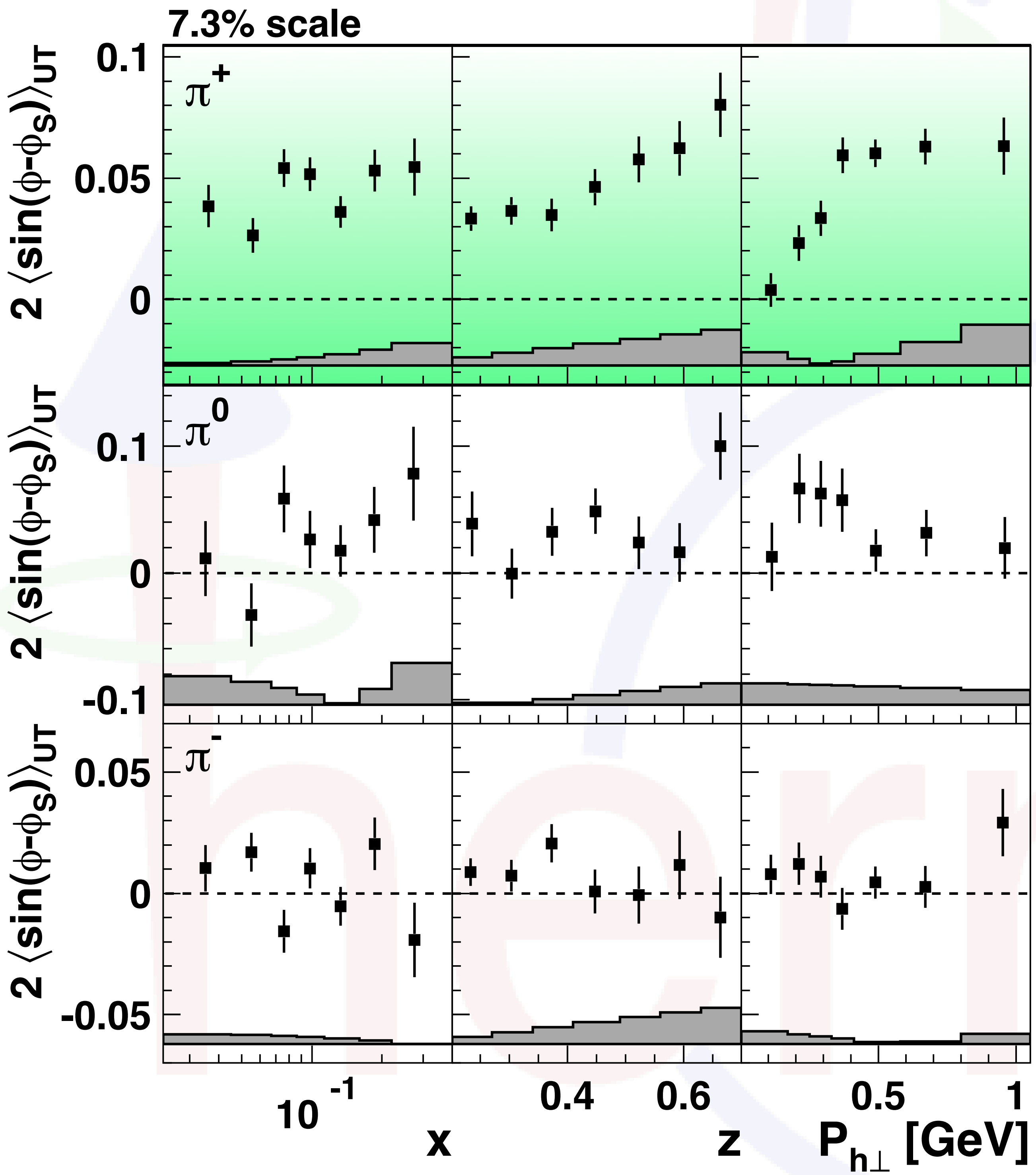


$$L_z^u > 0$$

Sivers amplitudes for pions

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



$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\rightarrow\pi^+}(z,K_T^2)}{f_1^u(x)\ D_1^{u\rightarrow\pi^+}(z)}$$

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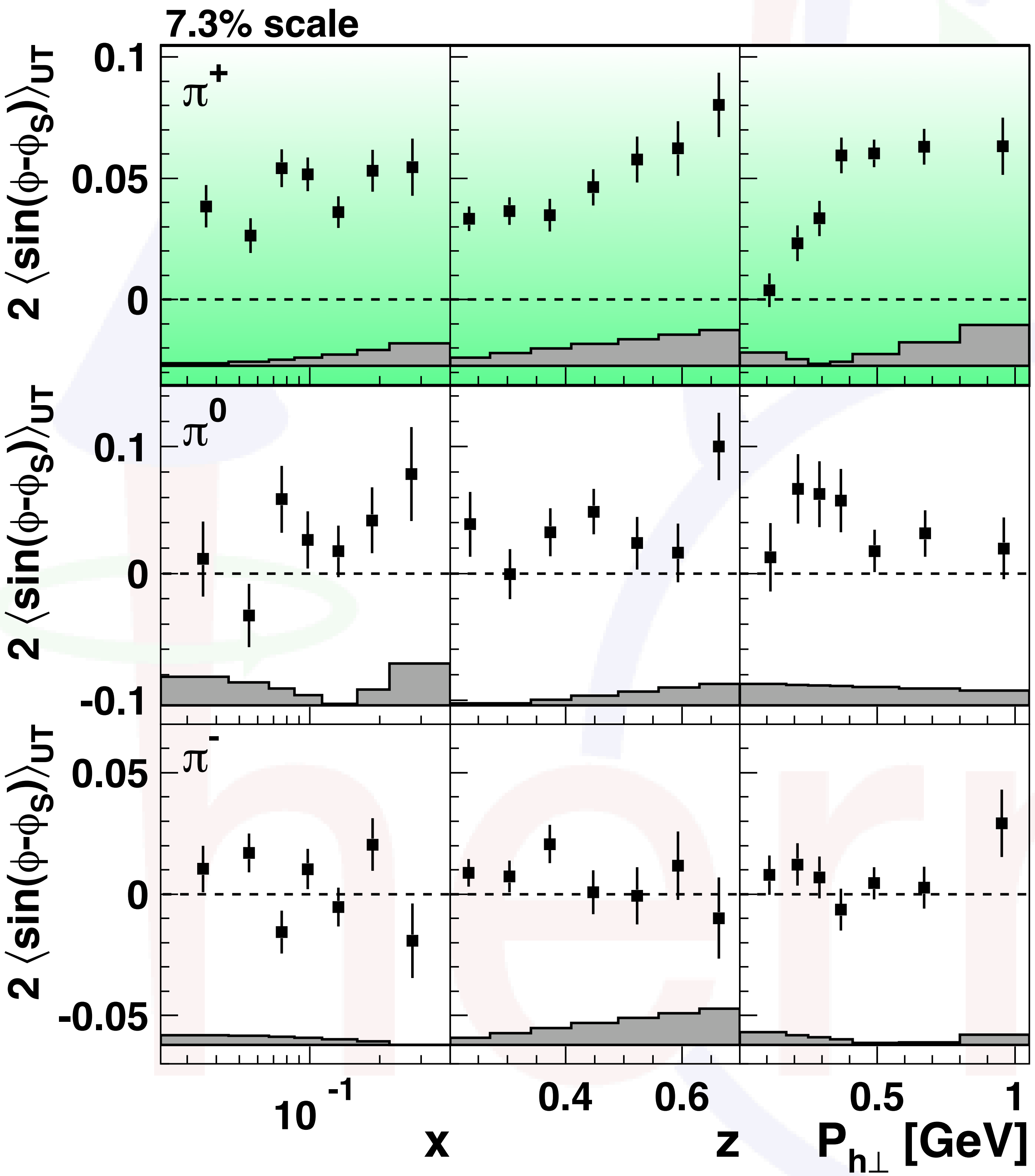

π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\; D_1^{u\to\pi^+}(z)}$$

☛ **u-quark Sivers DF < 0**

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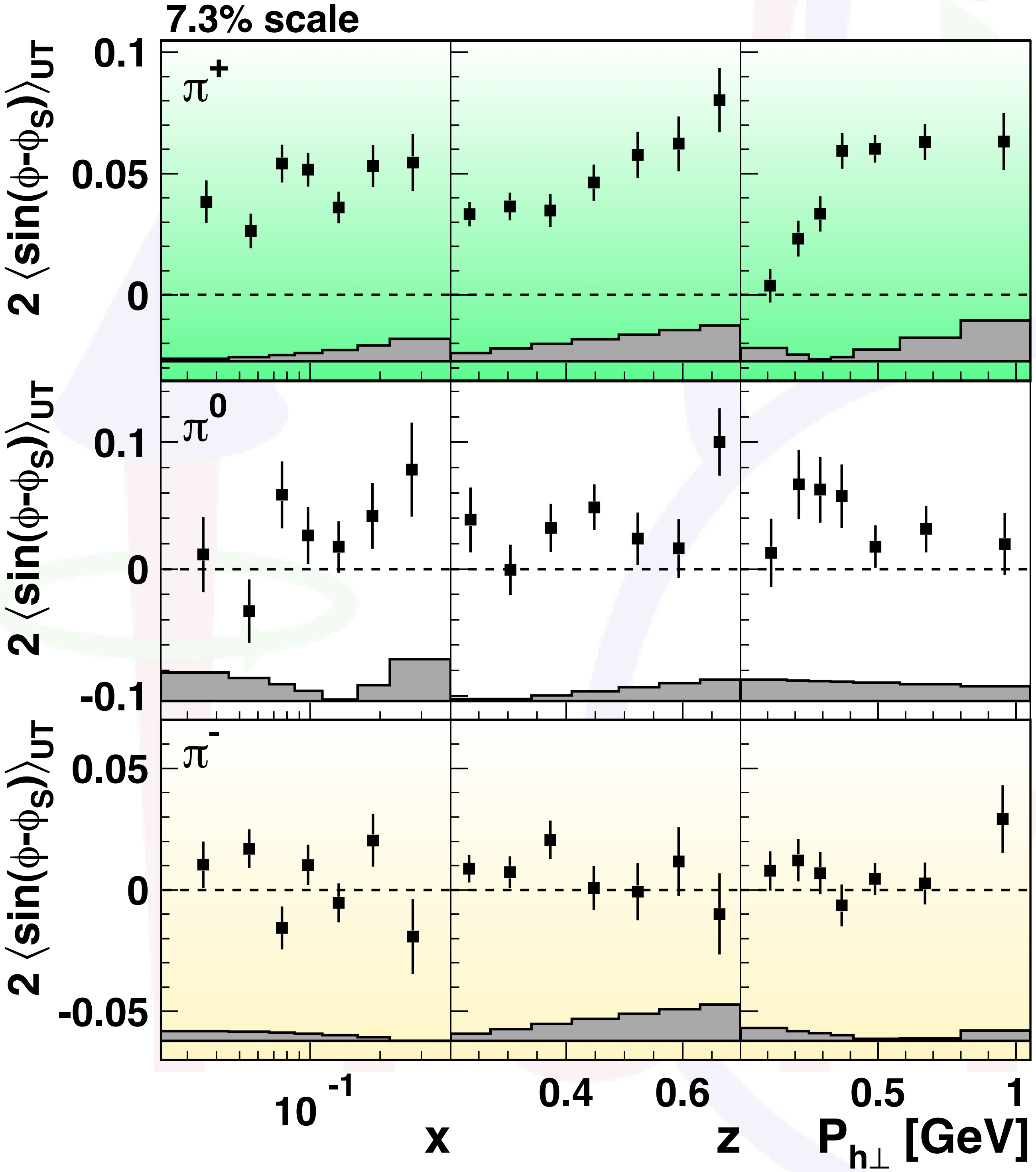

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☛ u-quark Sivers DF < 0

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

Sivers "Difference Asymmetry"

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

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

Sivers "Difference Asymmetry"

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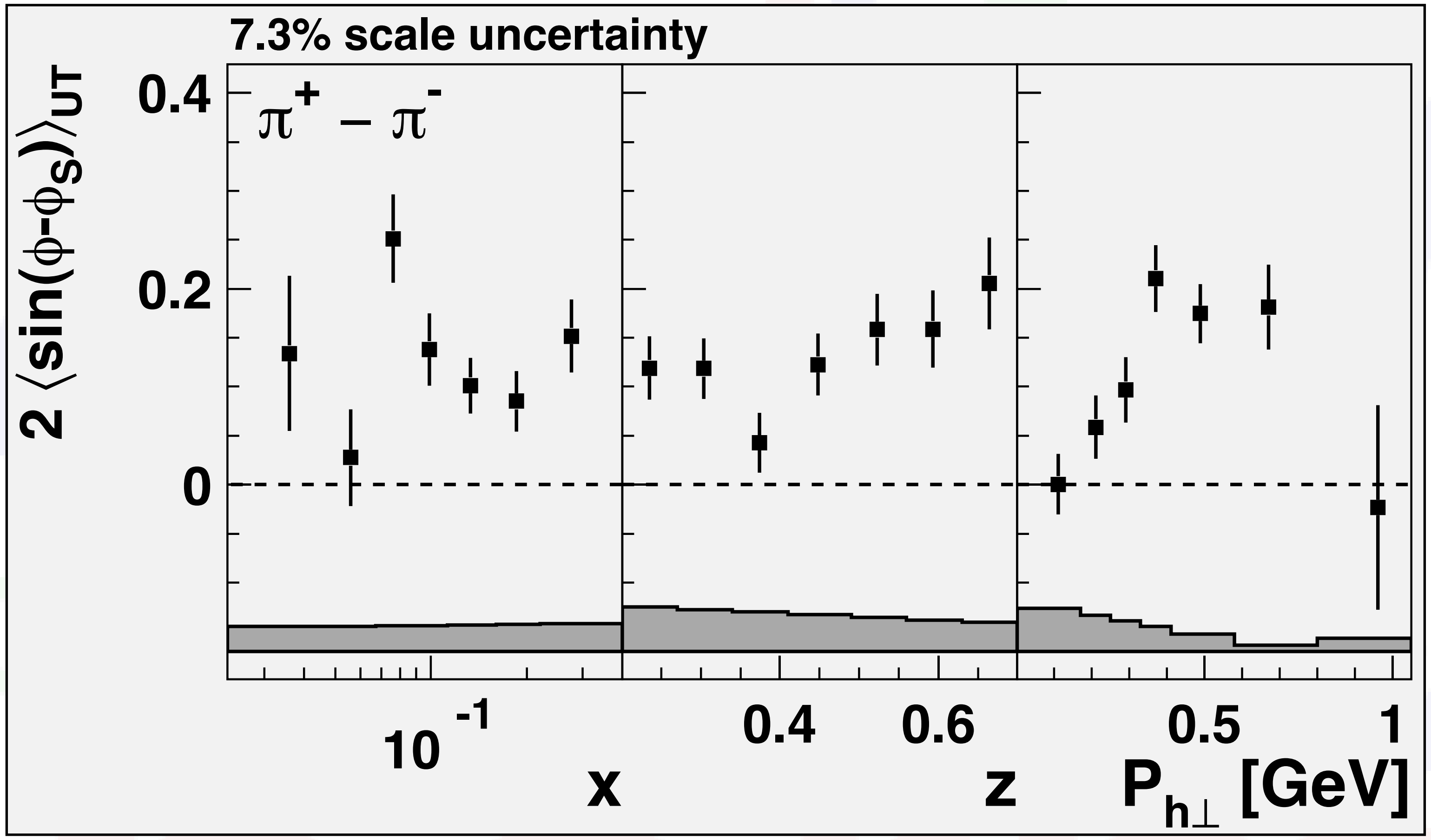

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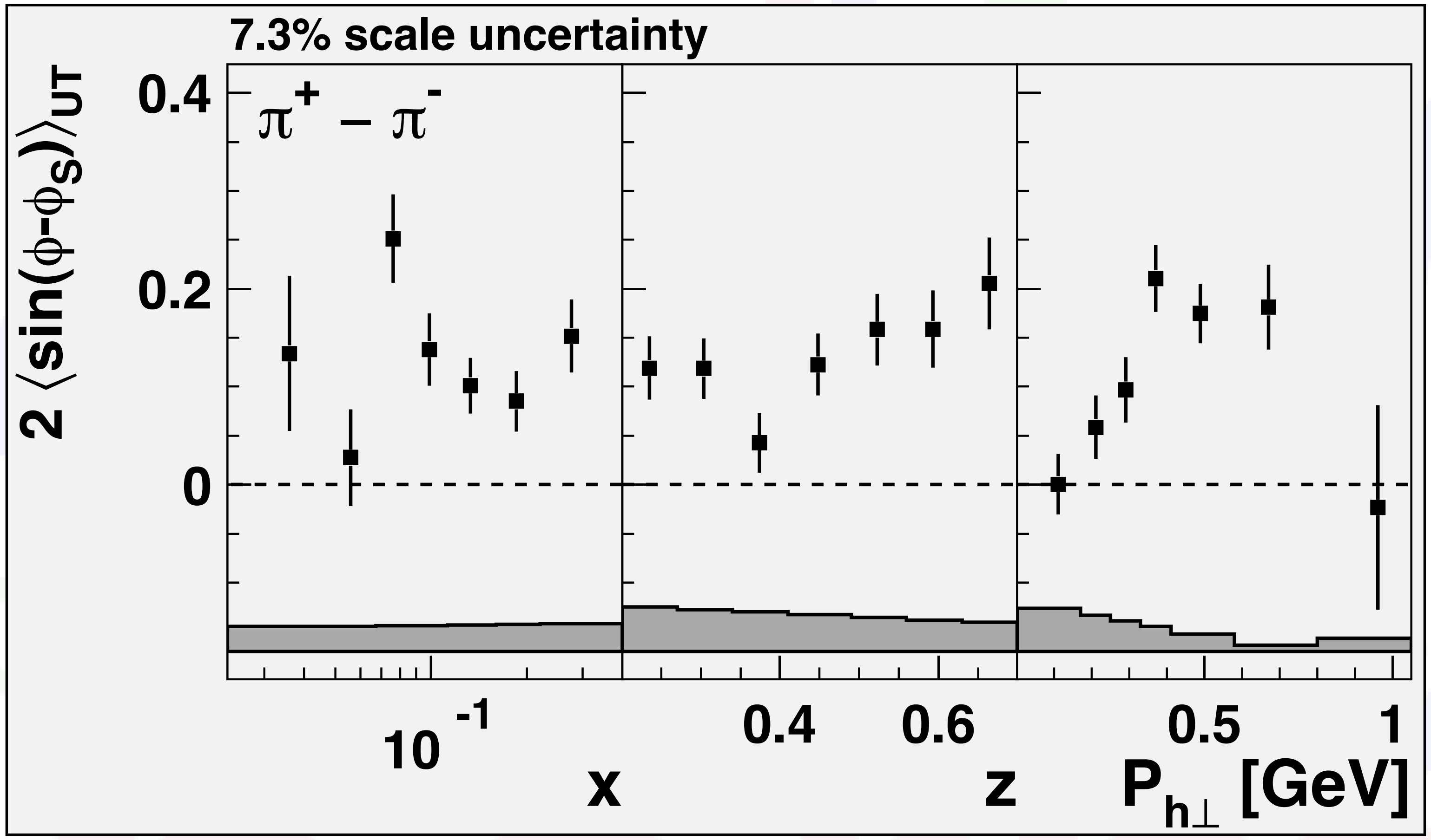

access to Sivers valence distribution

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

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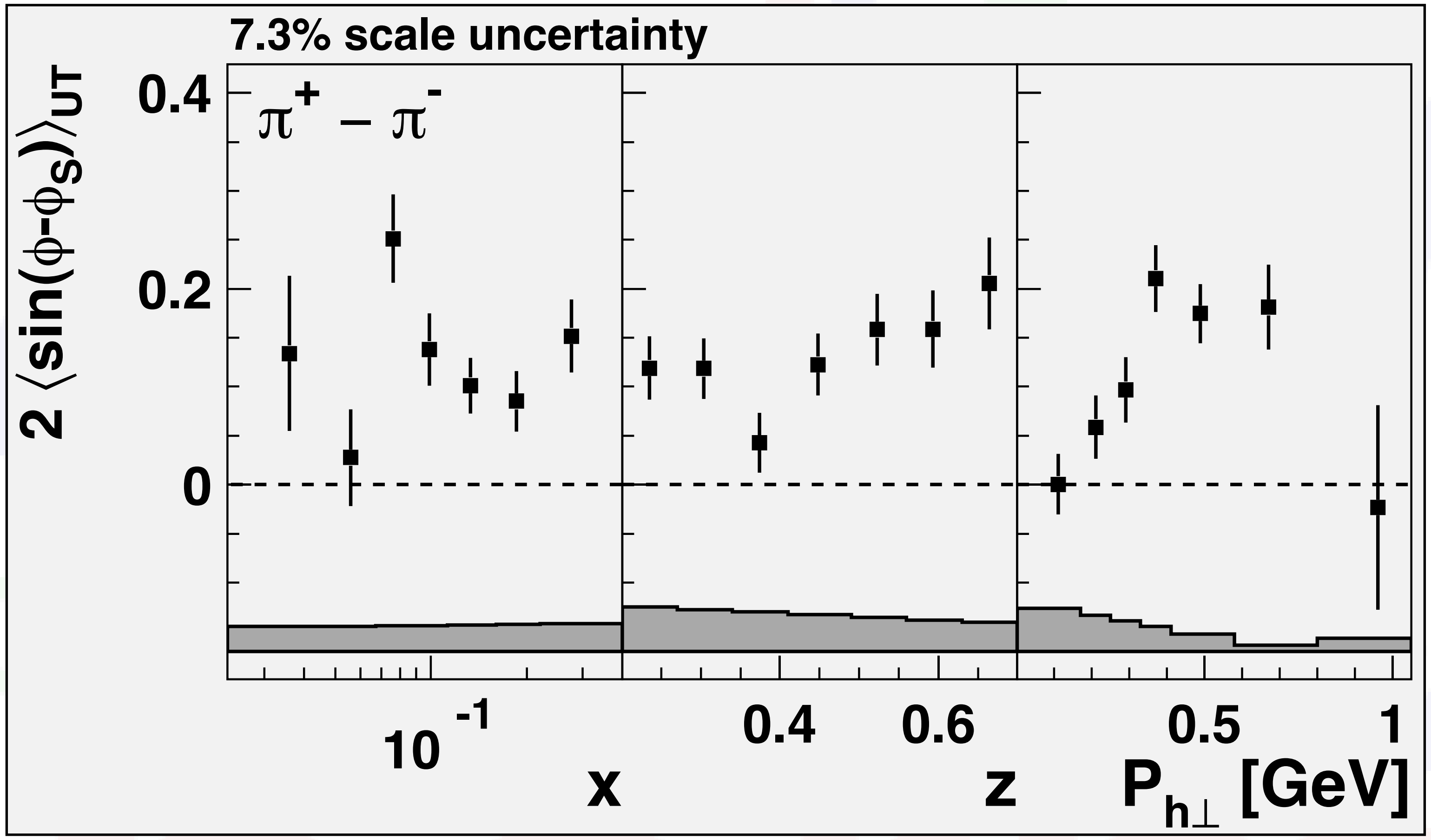

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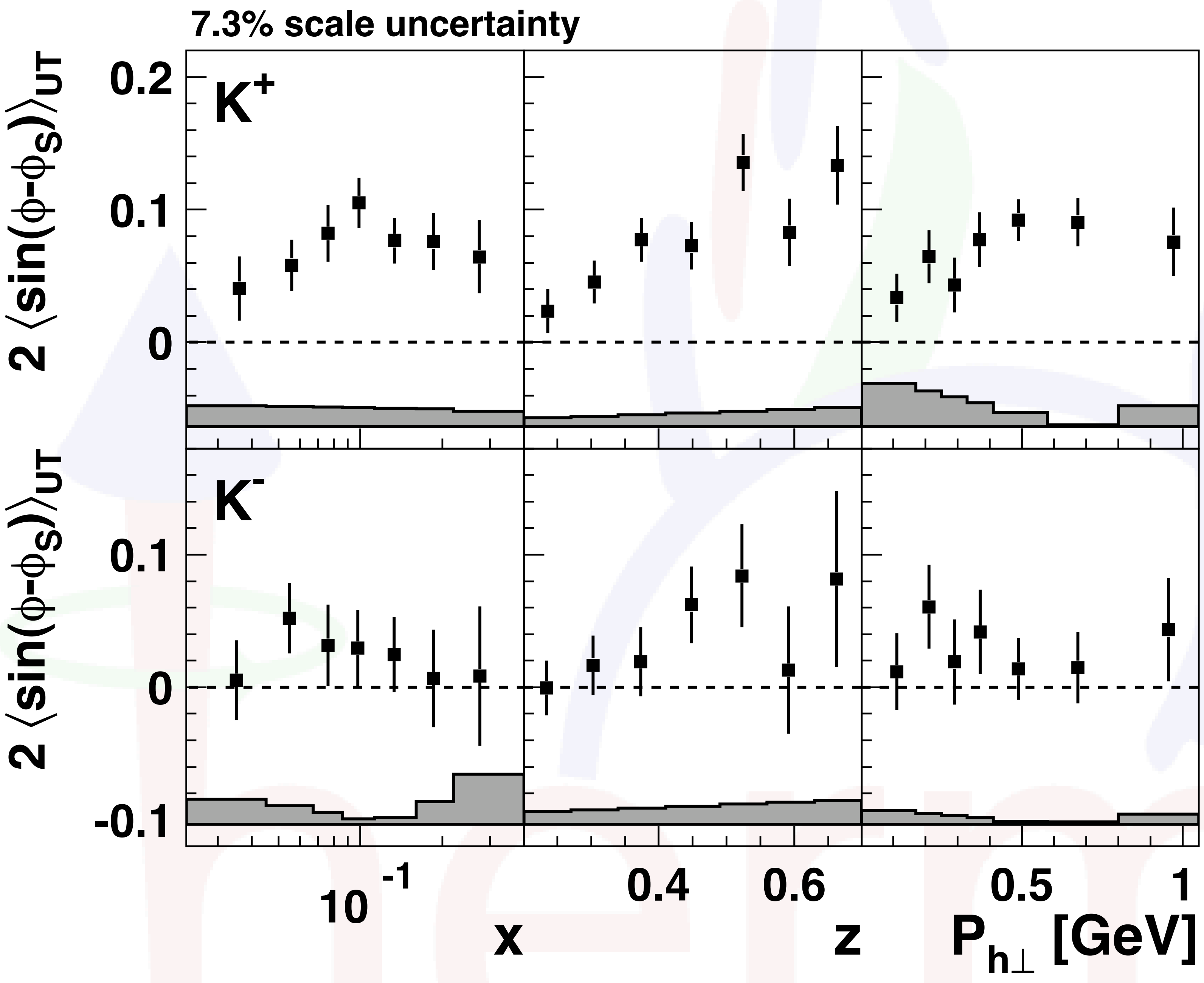
The kaon Sivers amplitudes



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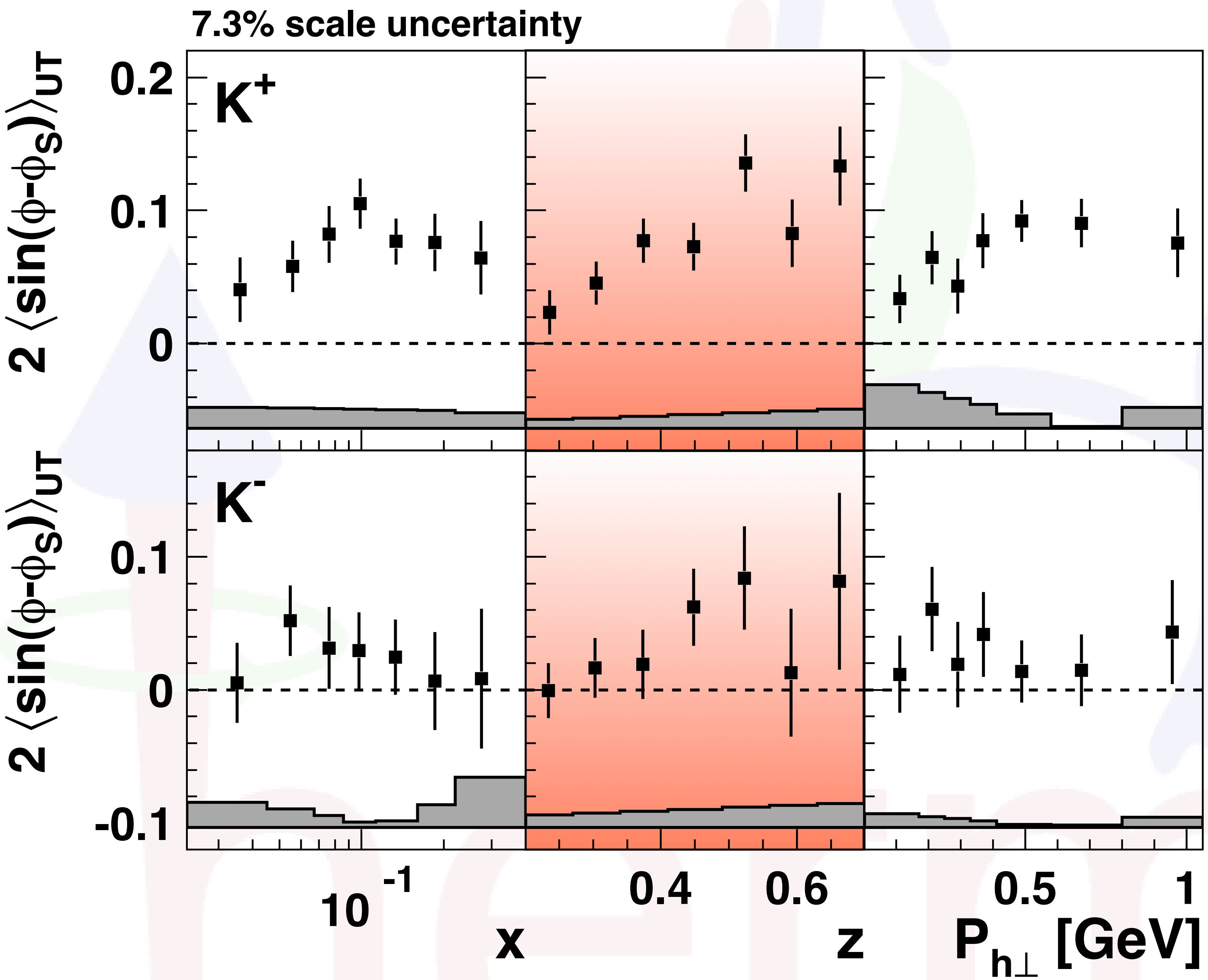
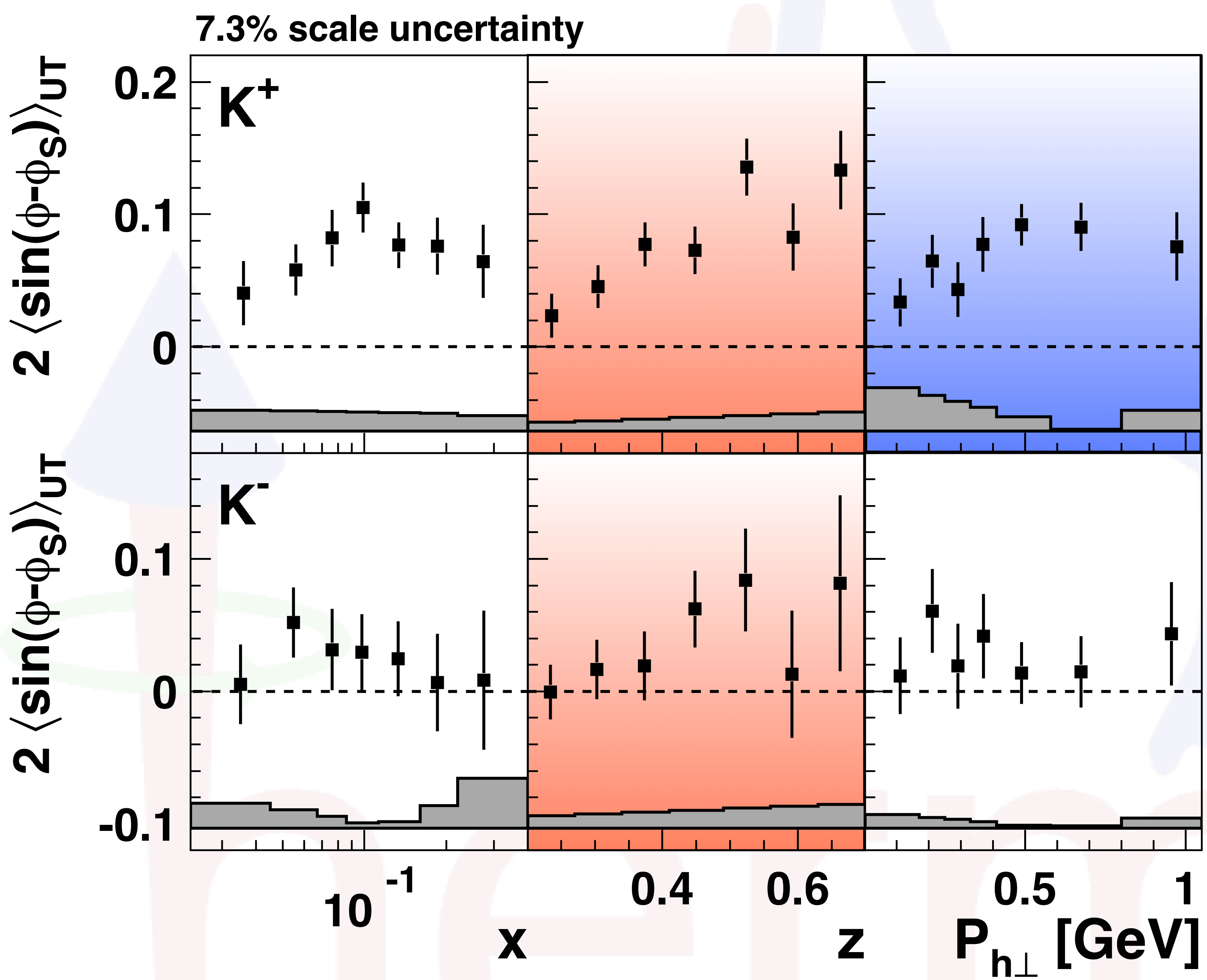


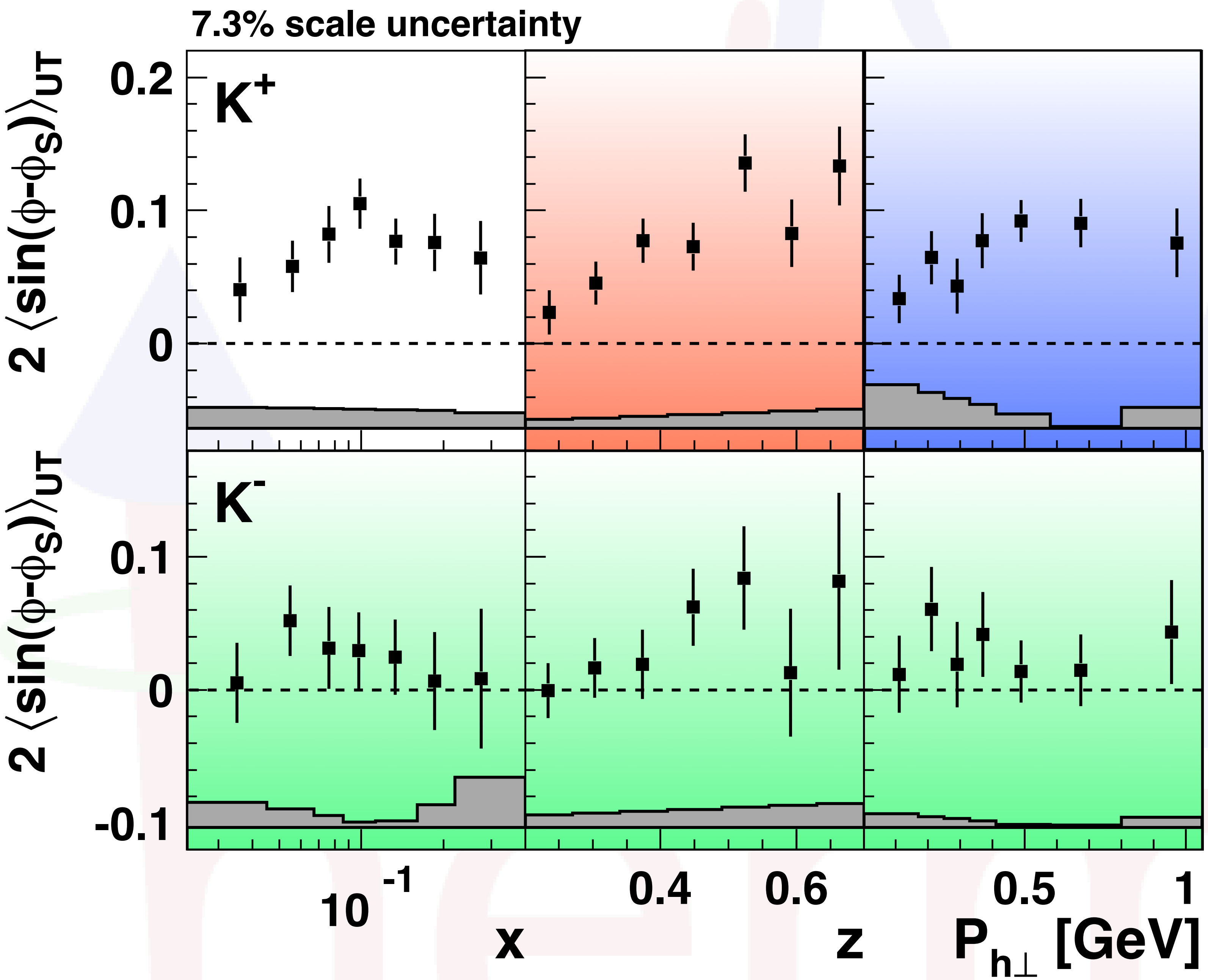
☛ clear rise with z

The kaon Sivers amplitudes



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

The kaon Sivers amplitudes



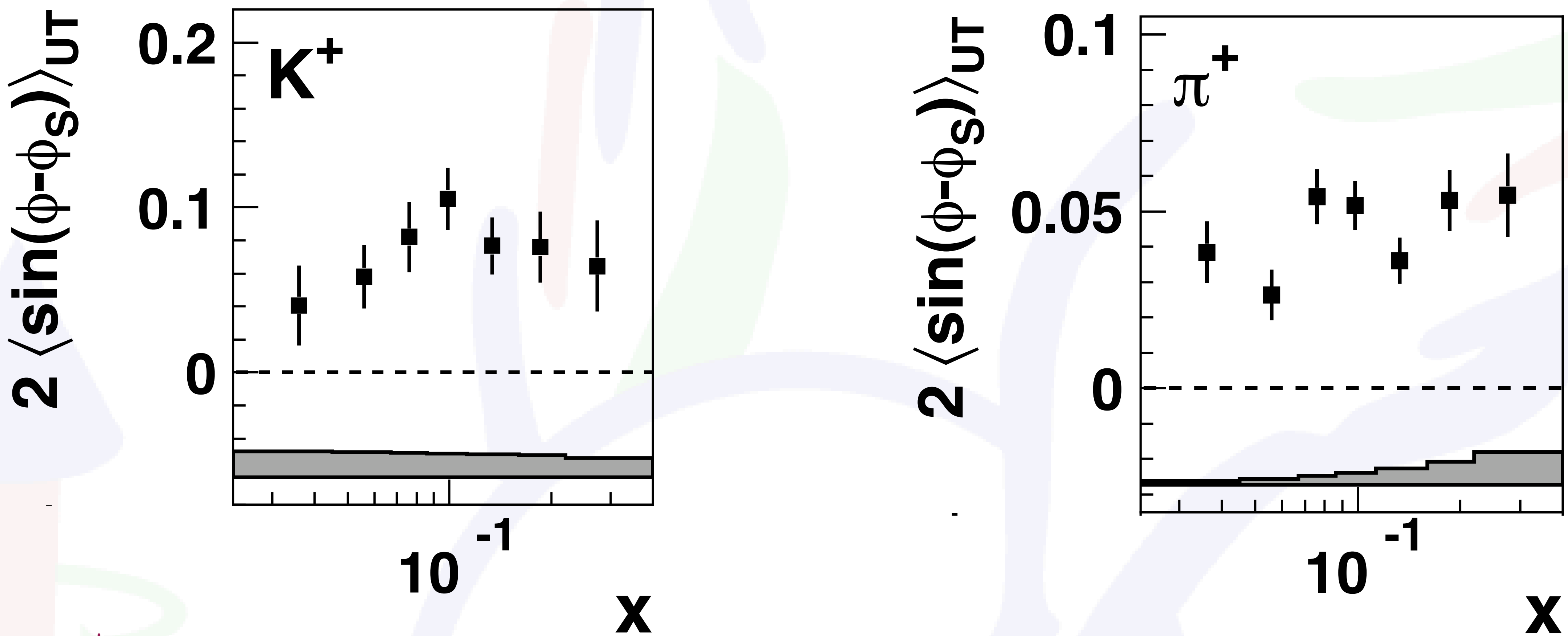
☛ clear rise with z

☛ rise at low $P_{h\perp}$

☛ plateau at high $P_{h\perp}$

☛ slightly positive

The “Kaon Challenge”



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

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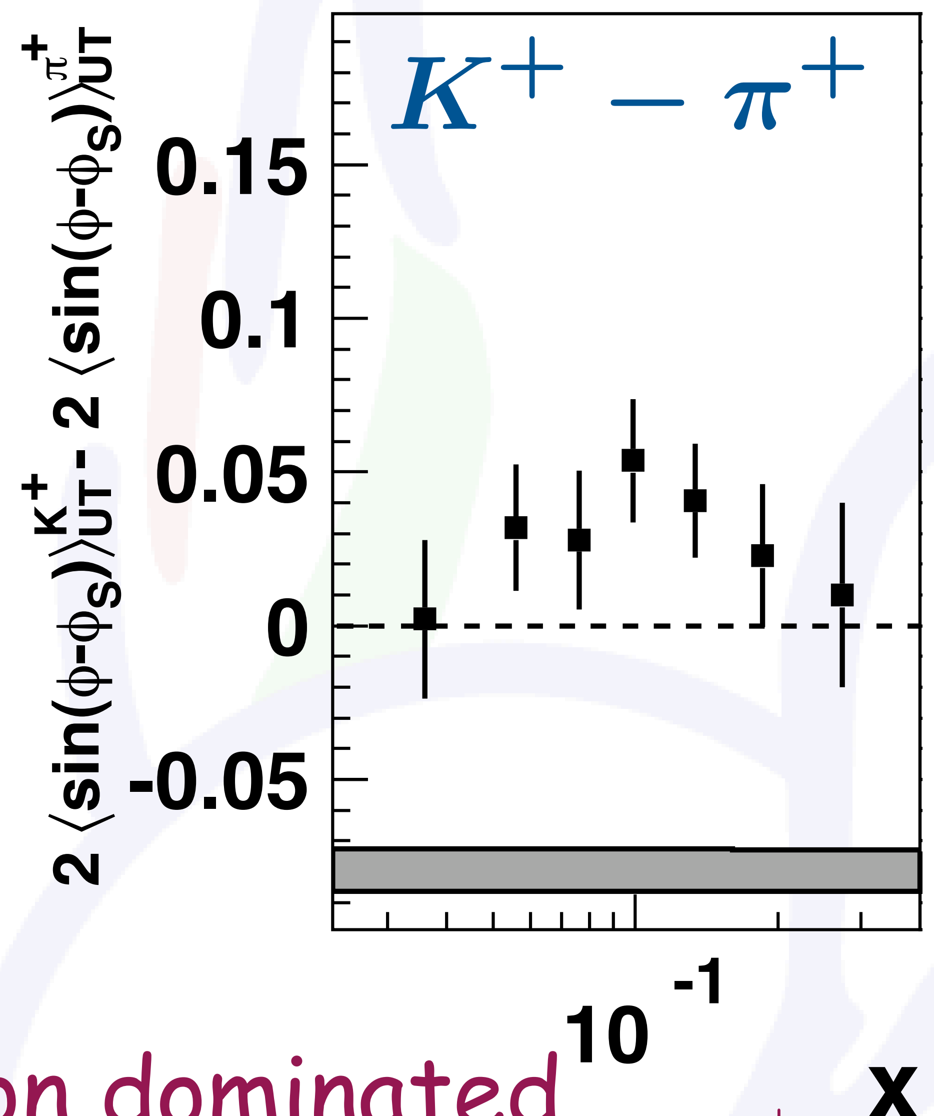

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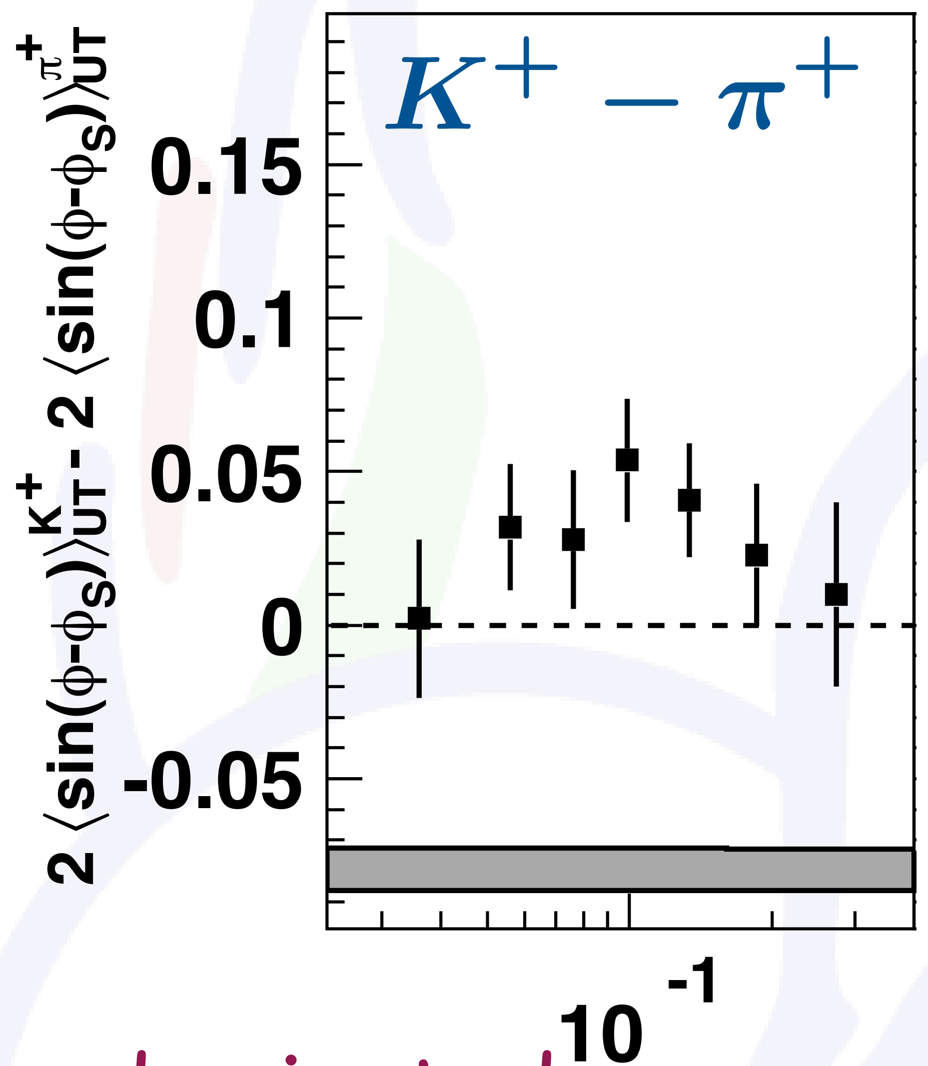

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks**

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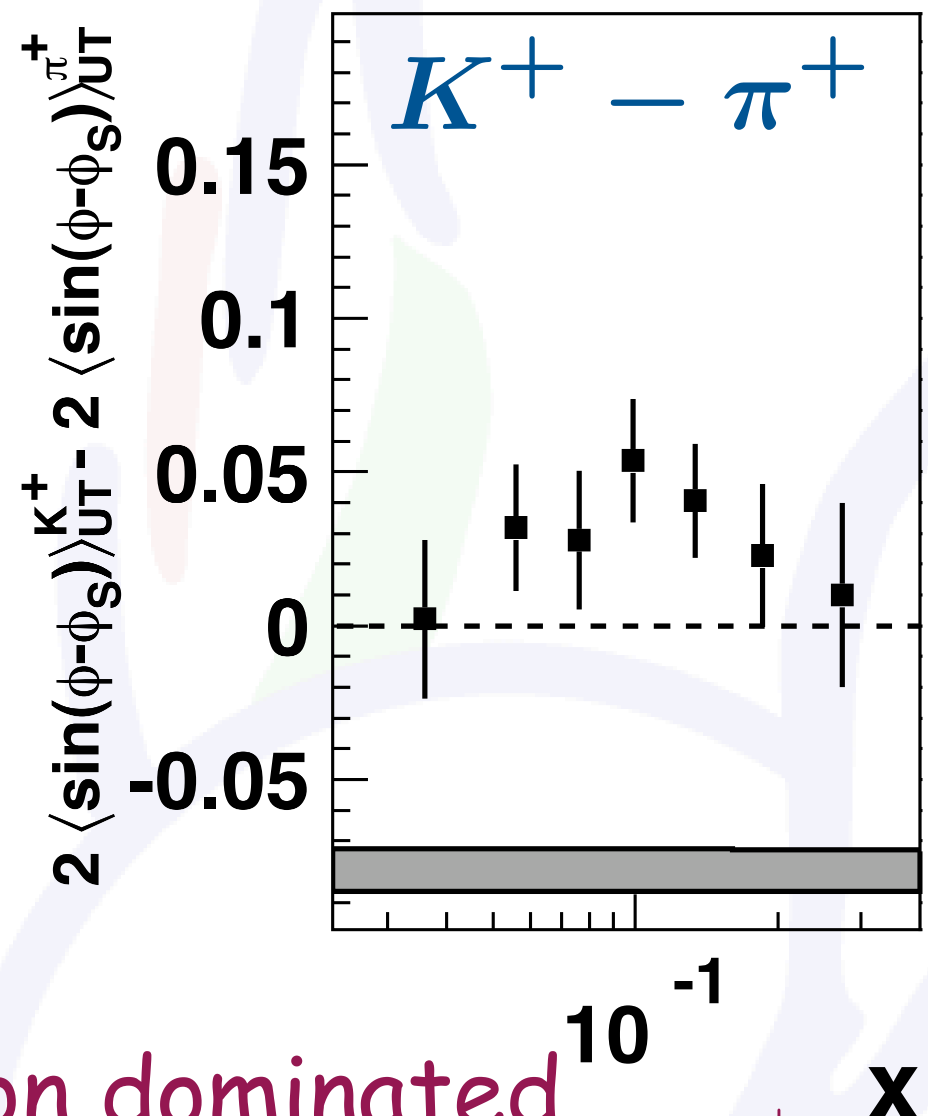

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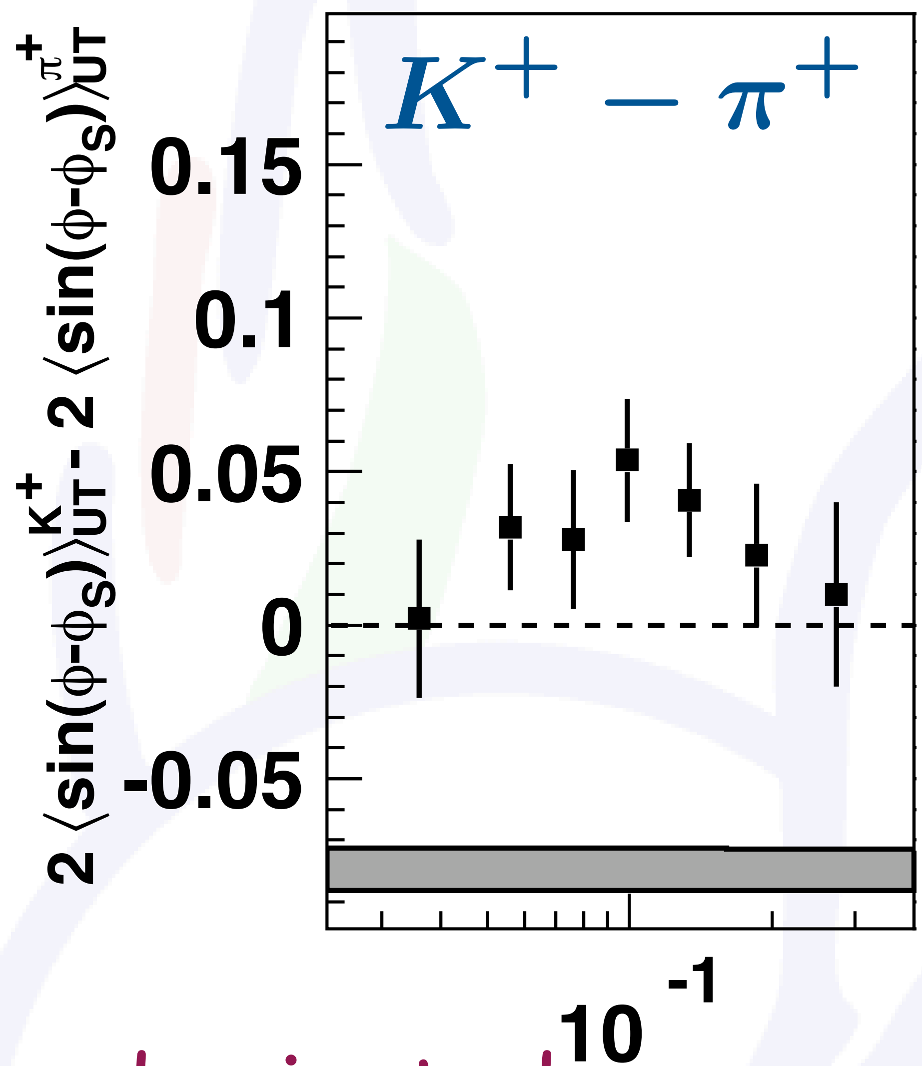

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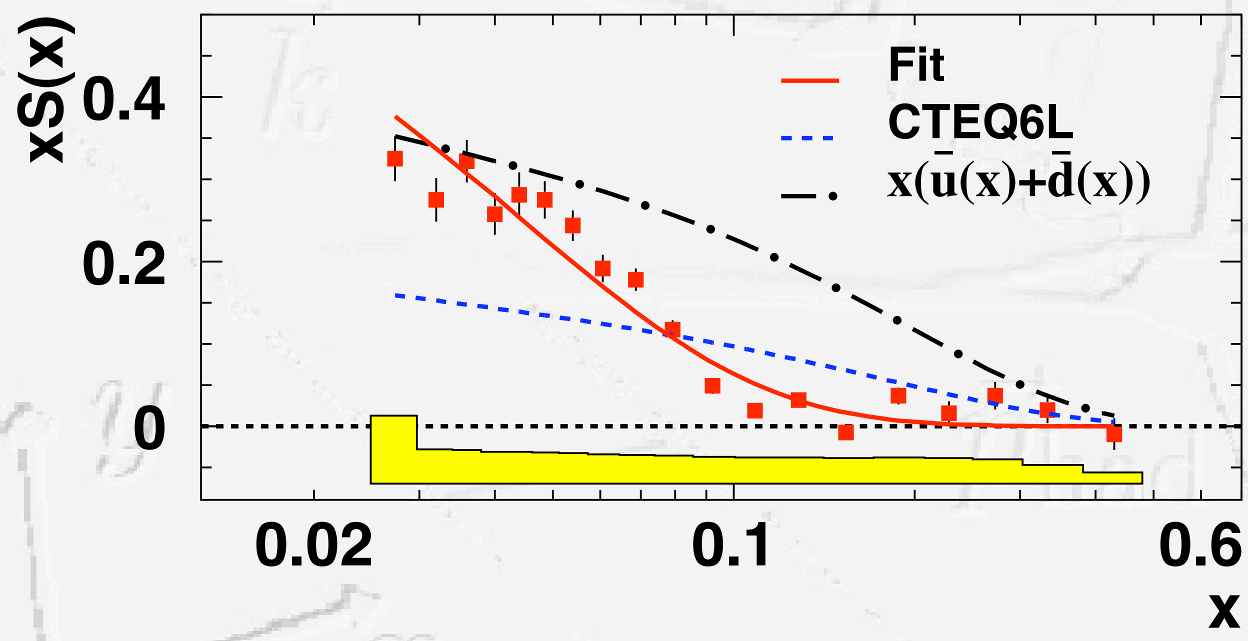
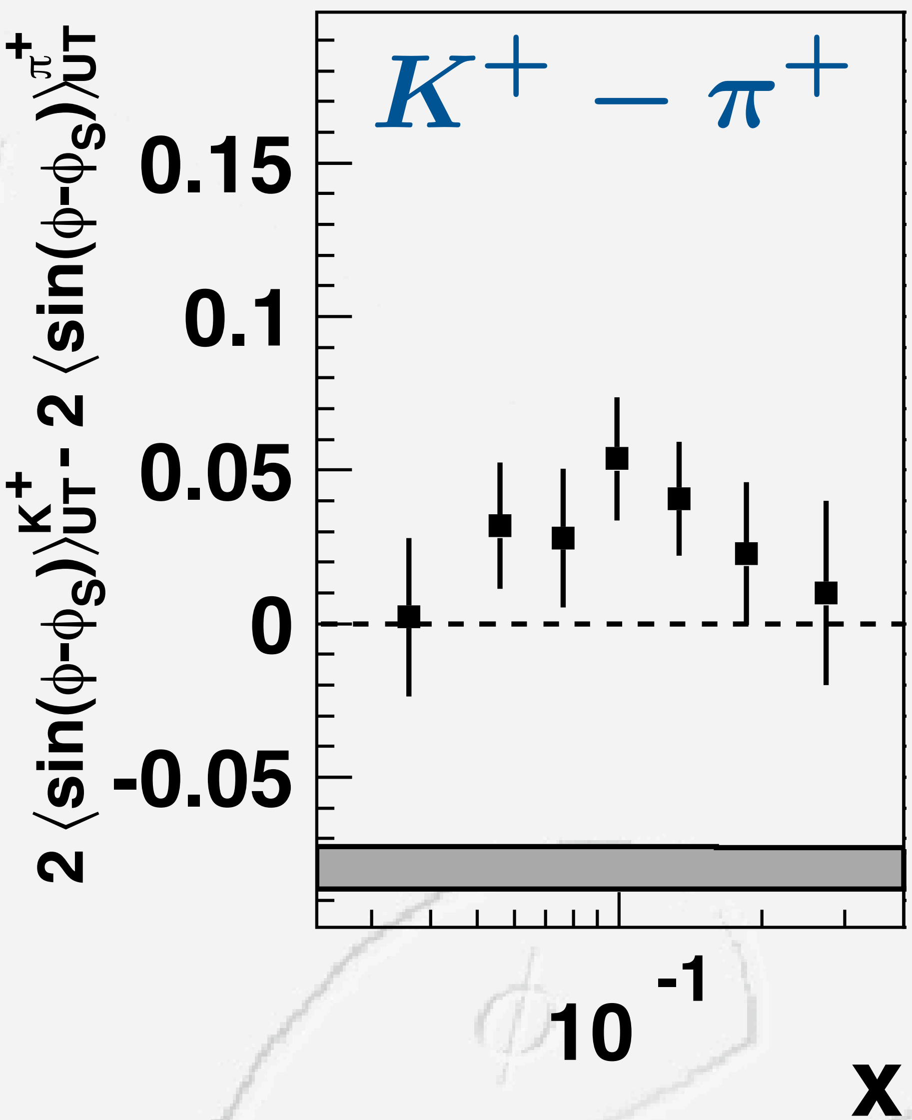
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➡ non-trivial role of sea quarks
- convolution integral in numerator depends on K_T dependence of FFs
- difference in dependences on kinematics integrated over

Role of sea quarks

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





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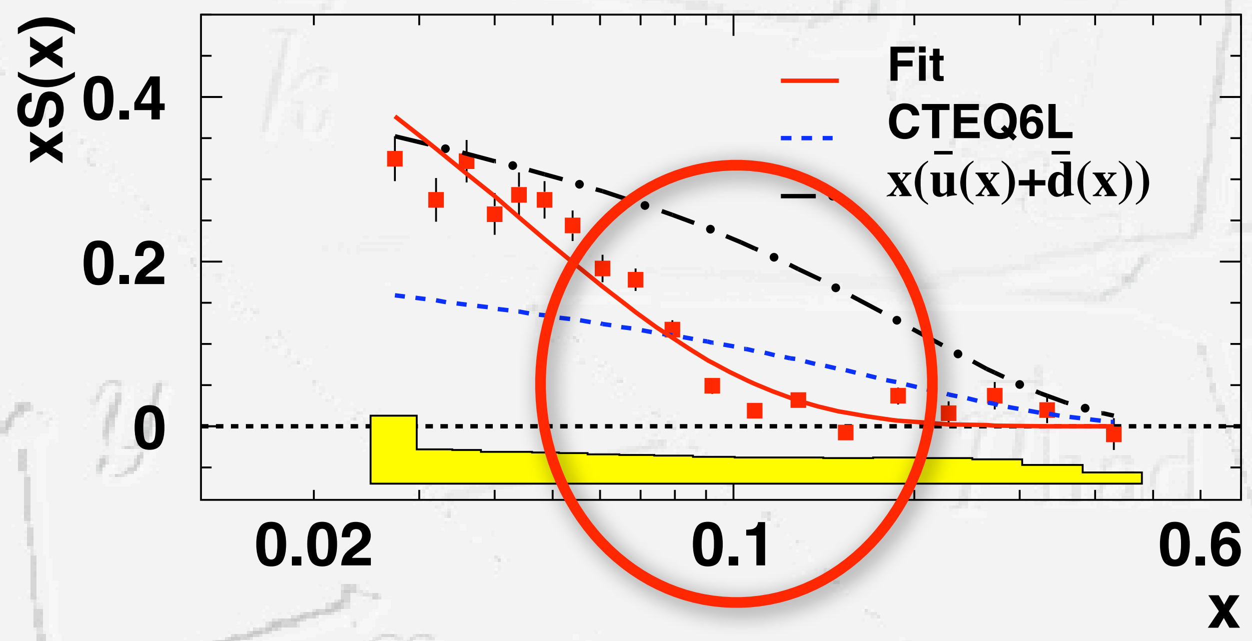
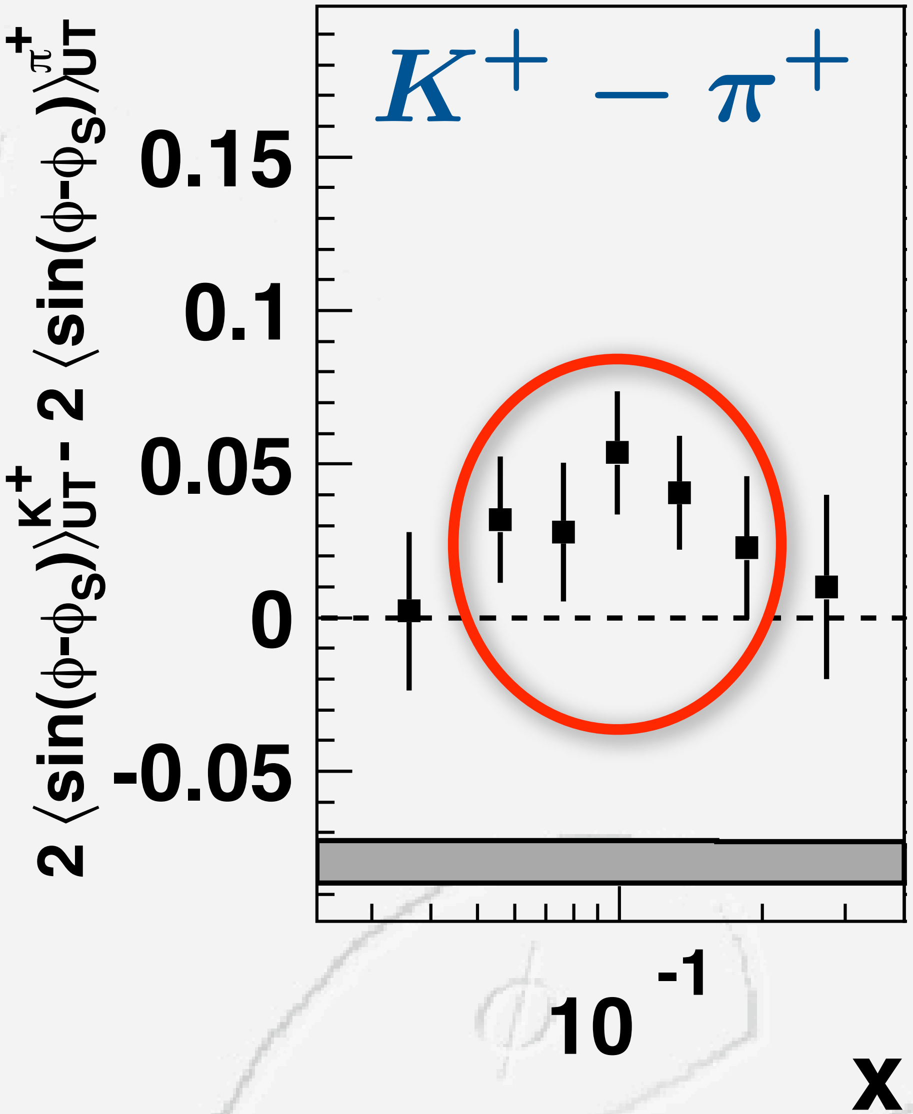
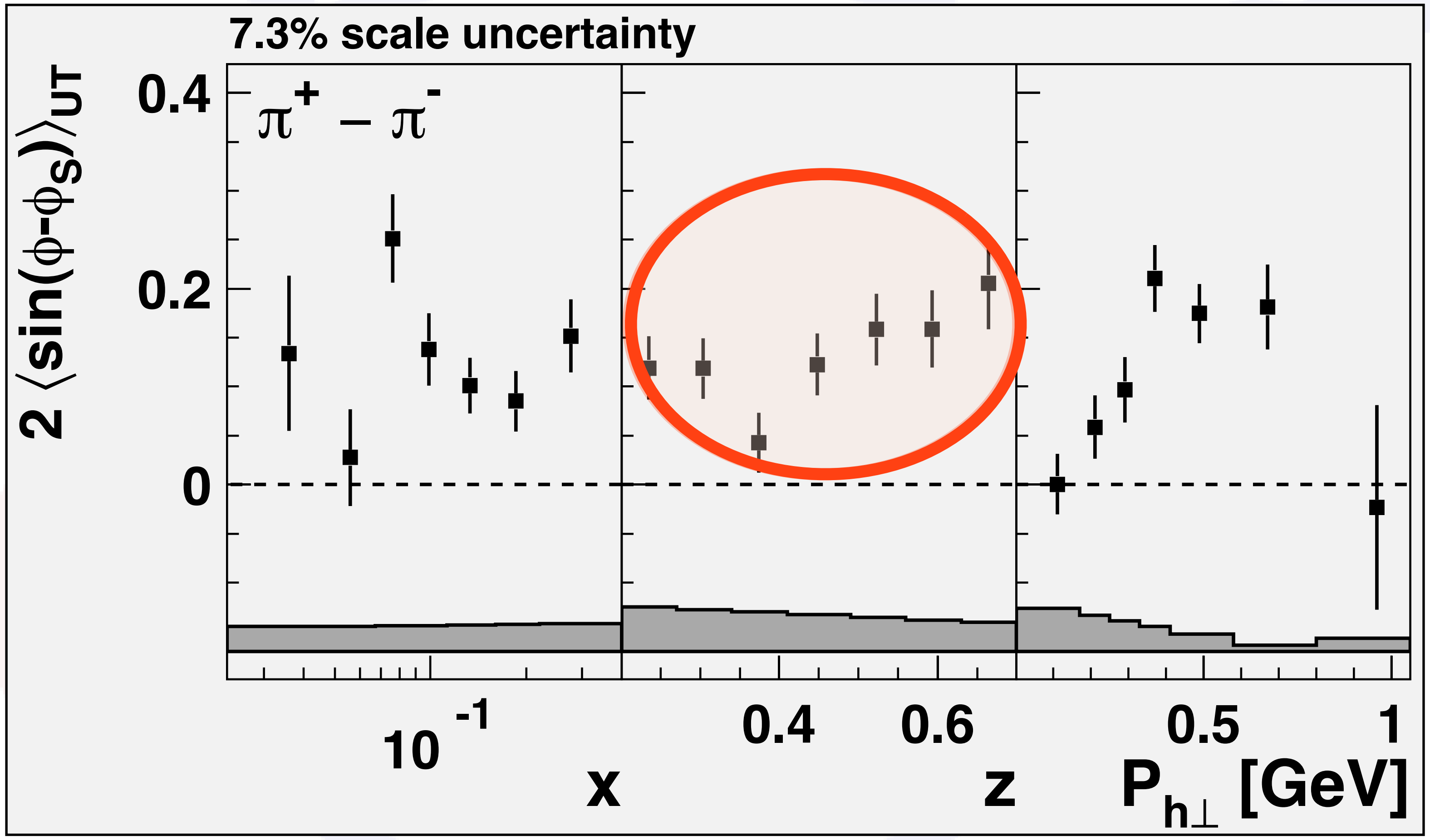




differences biggest in region where strange sea is most different from light sea

Cancelation of fragmentation function

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



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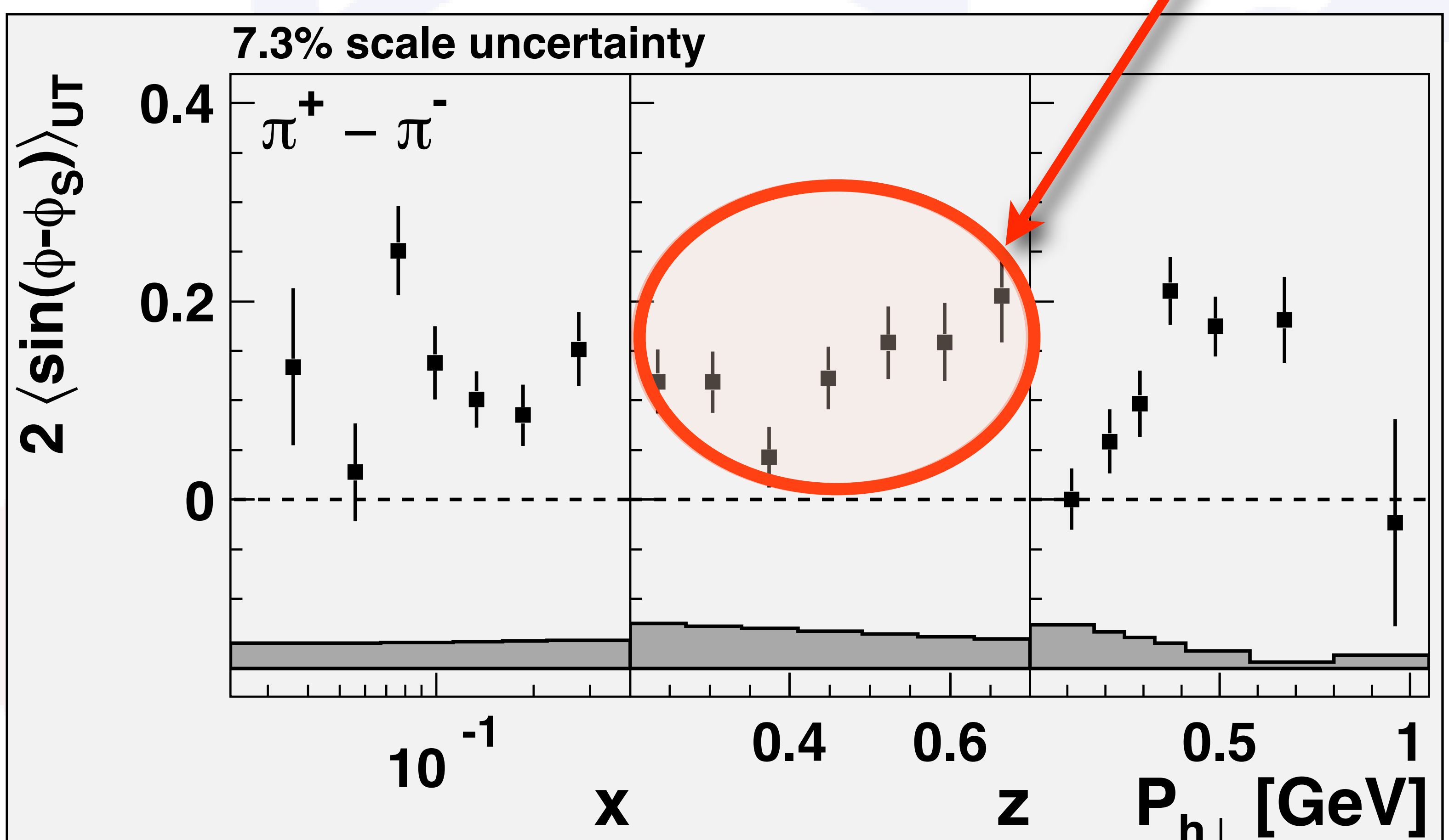
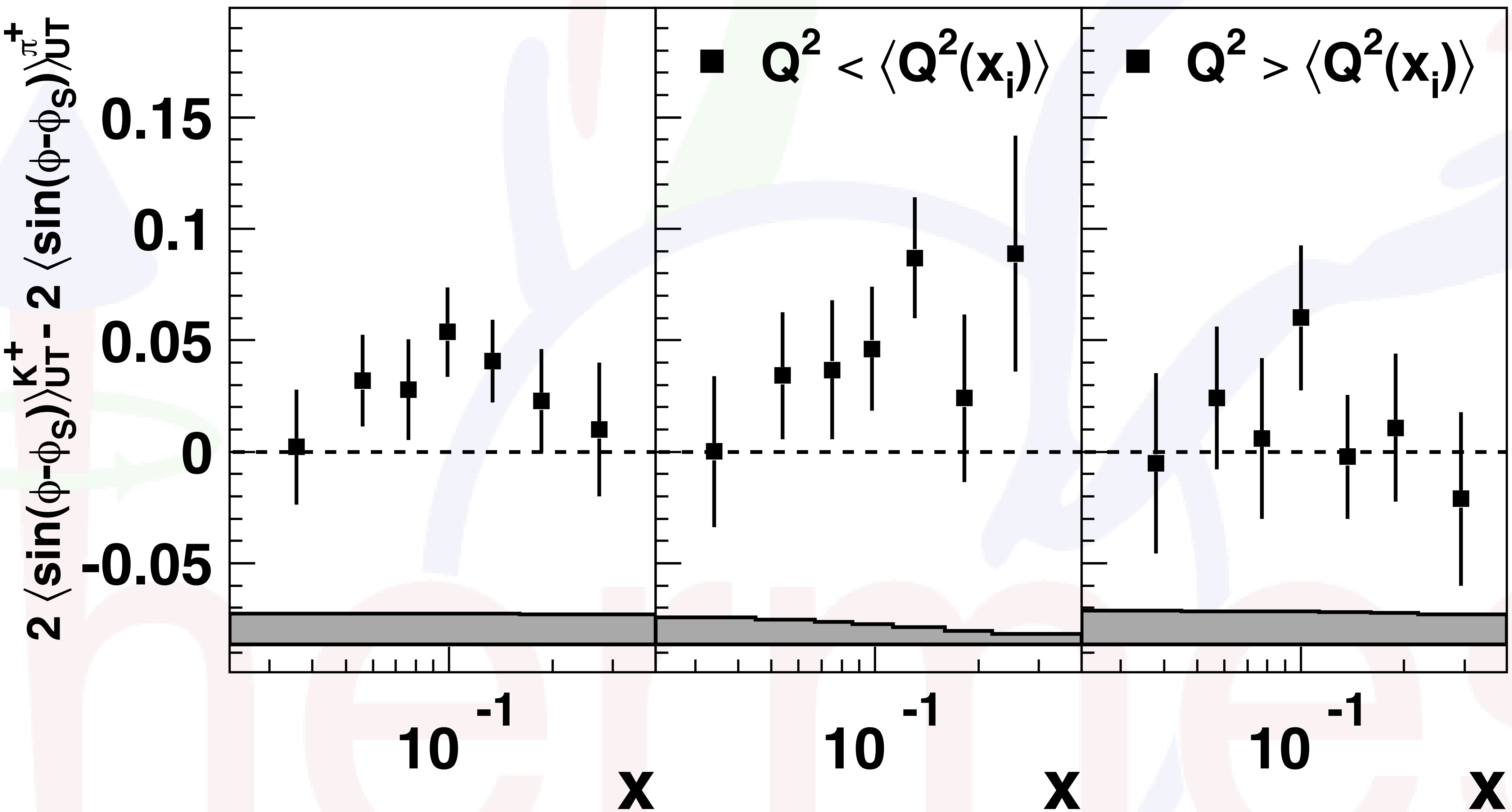
should be flat

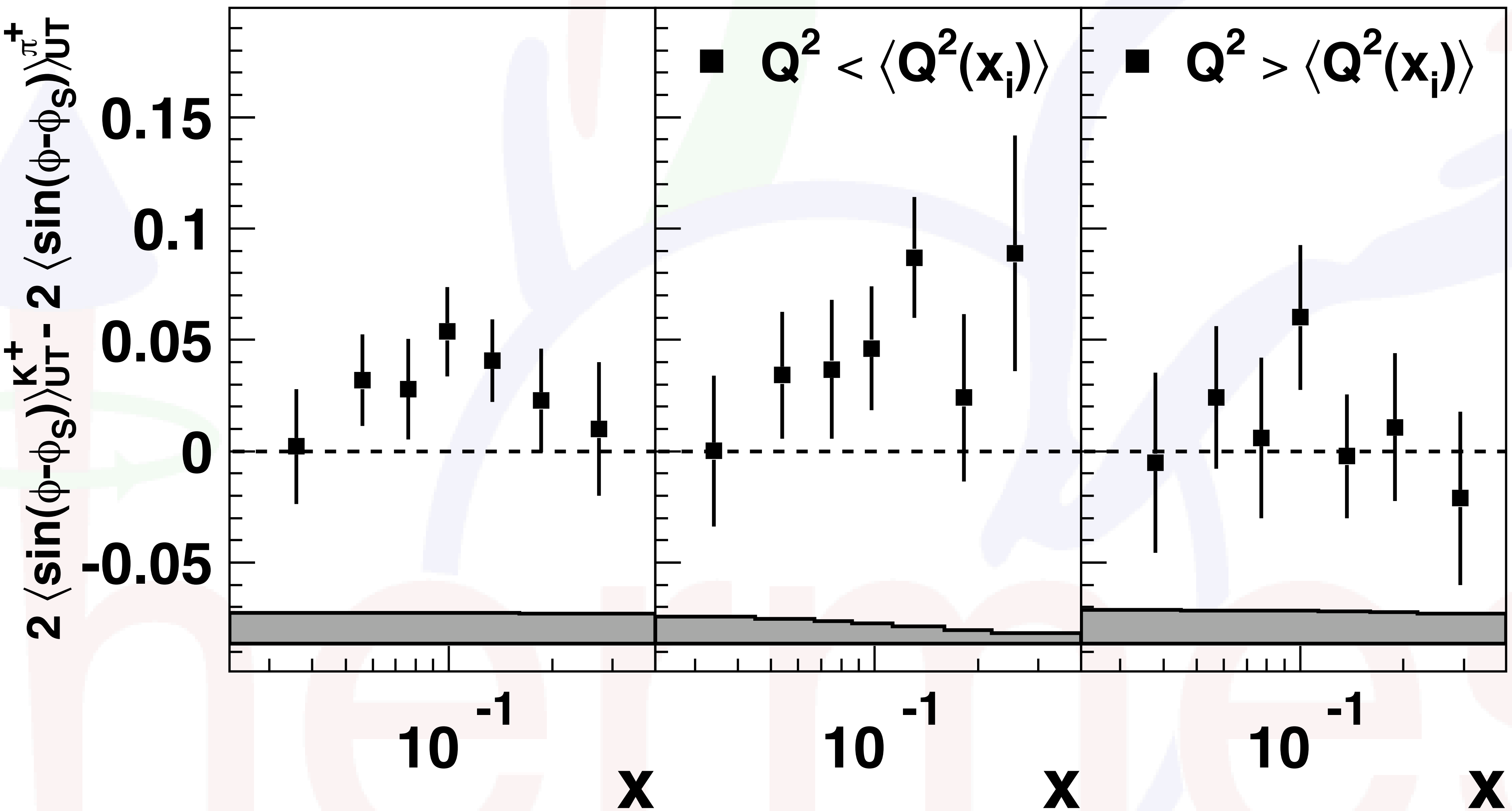


Q^2 dependence of amplitudes



Q^2 dependence of amplitudes

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



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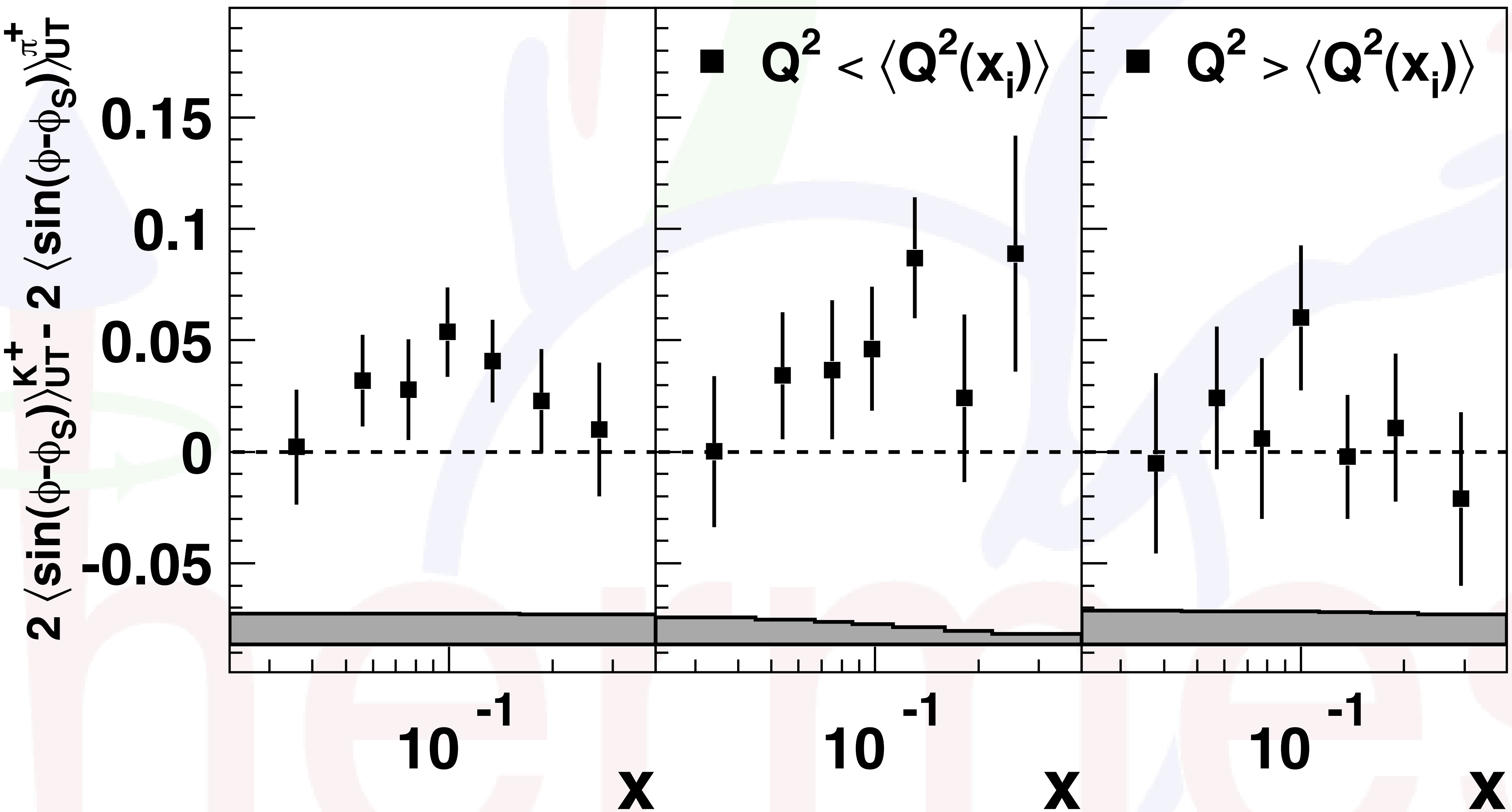
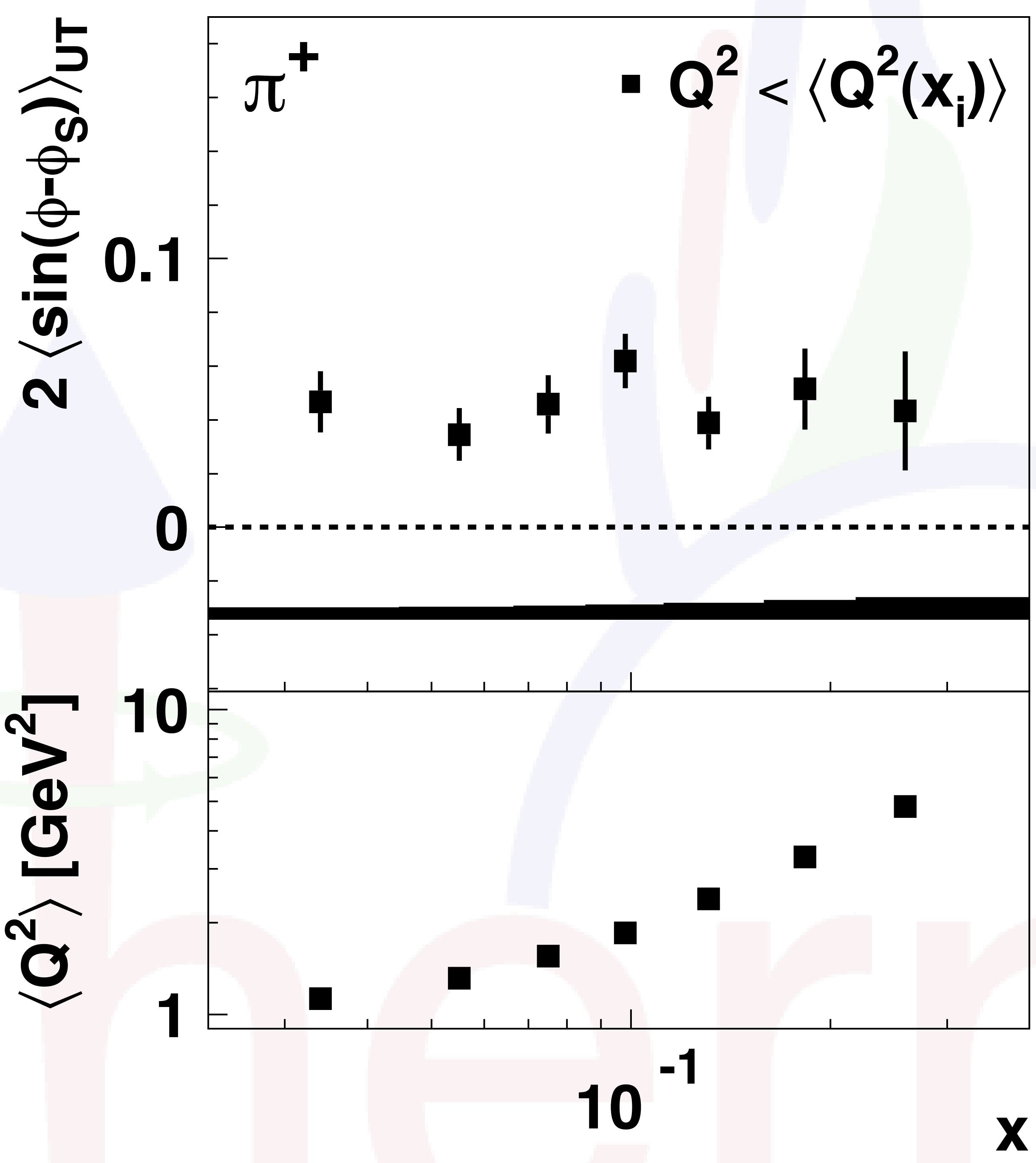


- **only in low-Q^2 region significant (>90% c.l.) deviation**

Q^2 dependence of amplitudes



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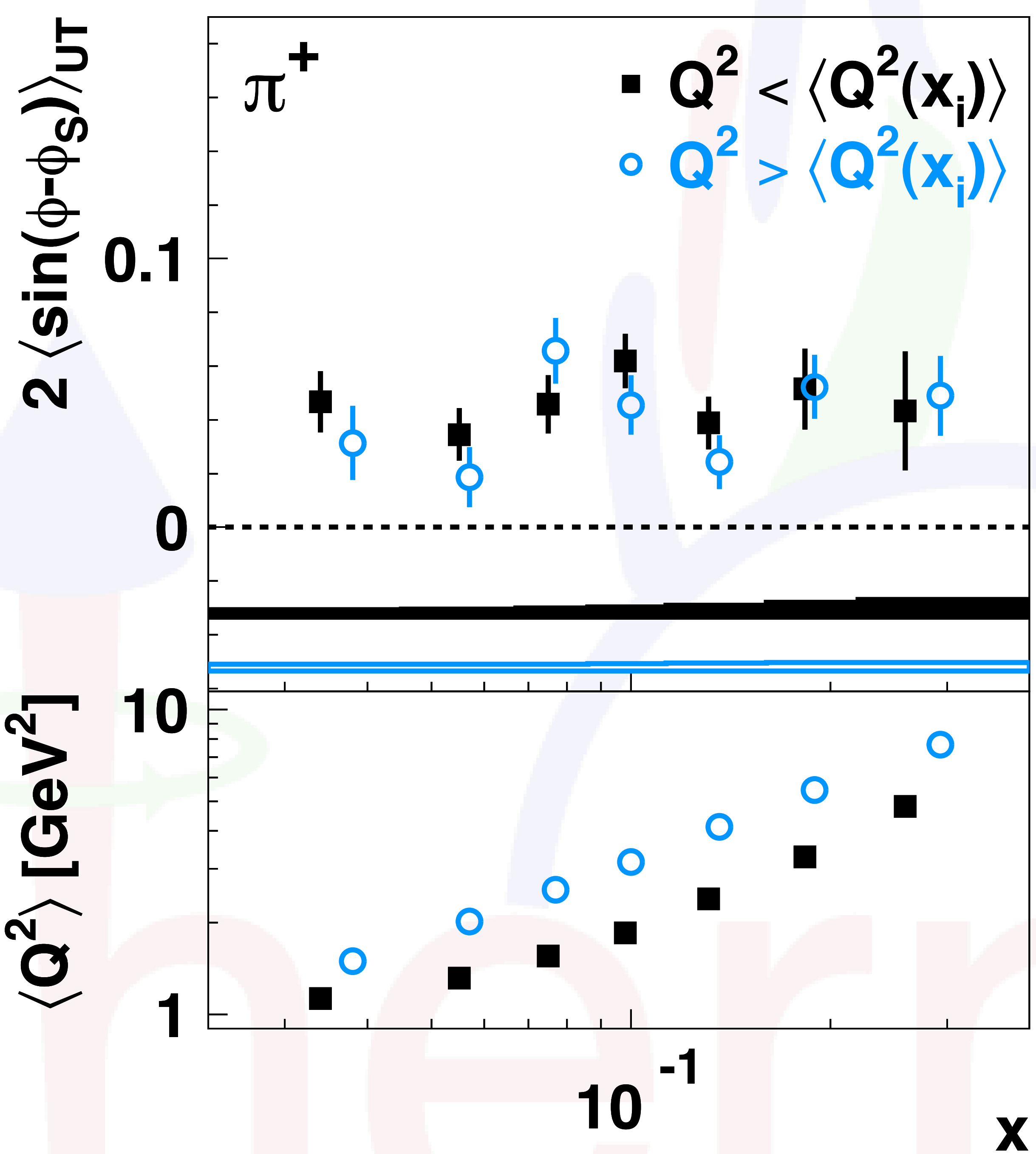

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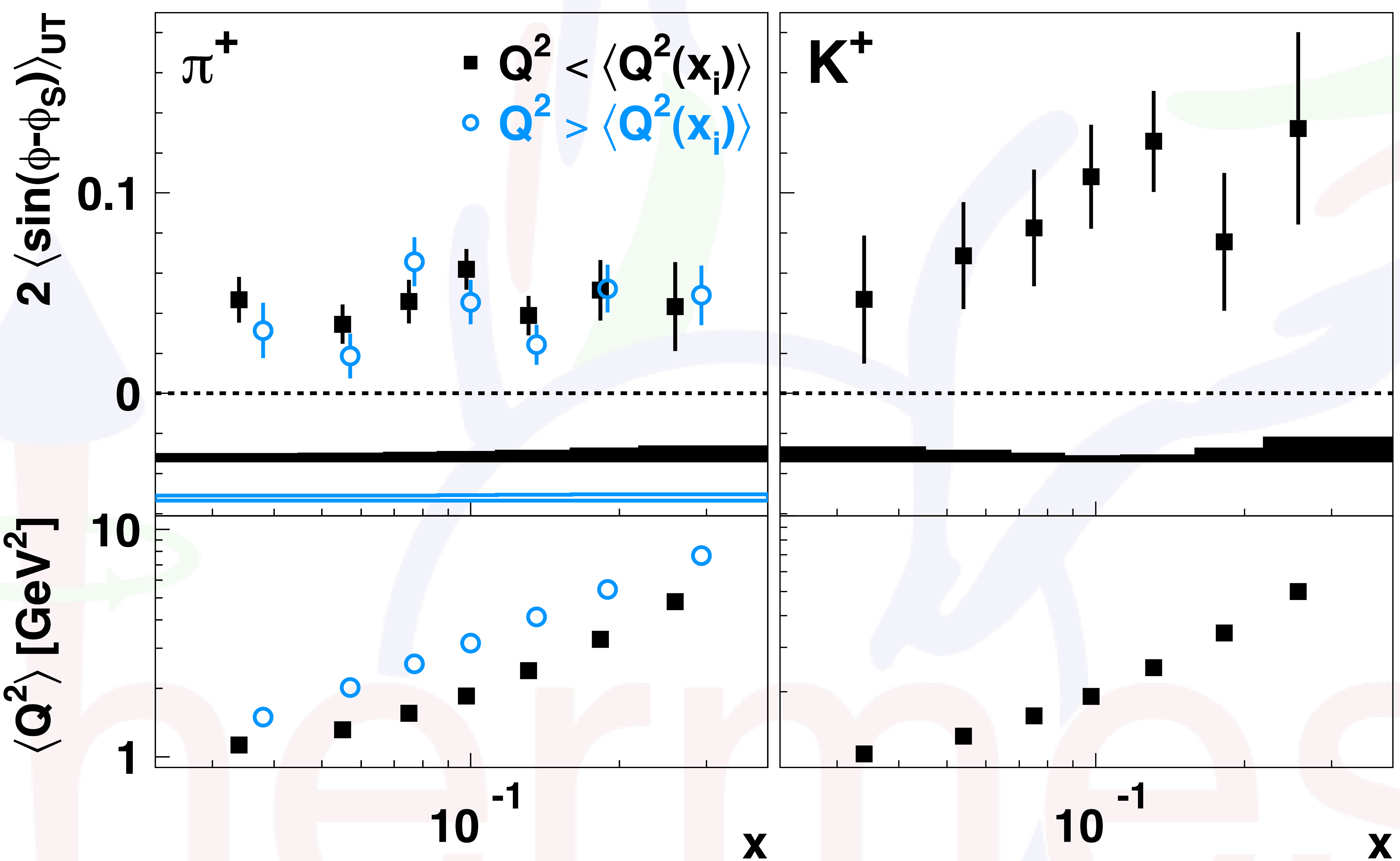

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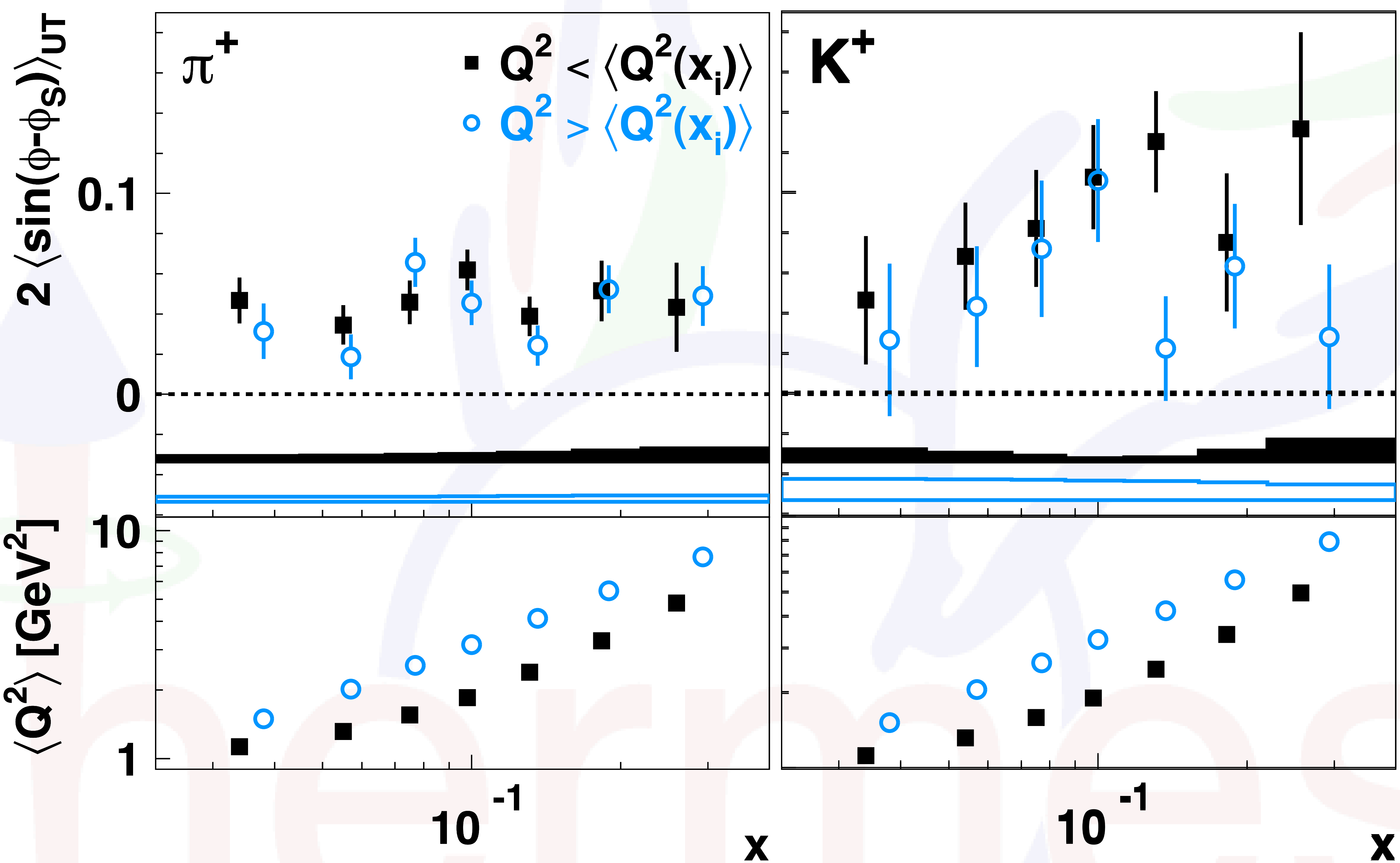
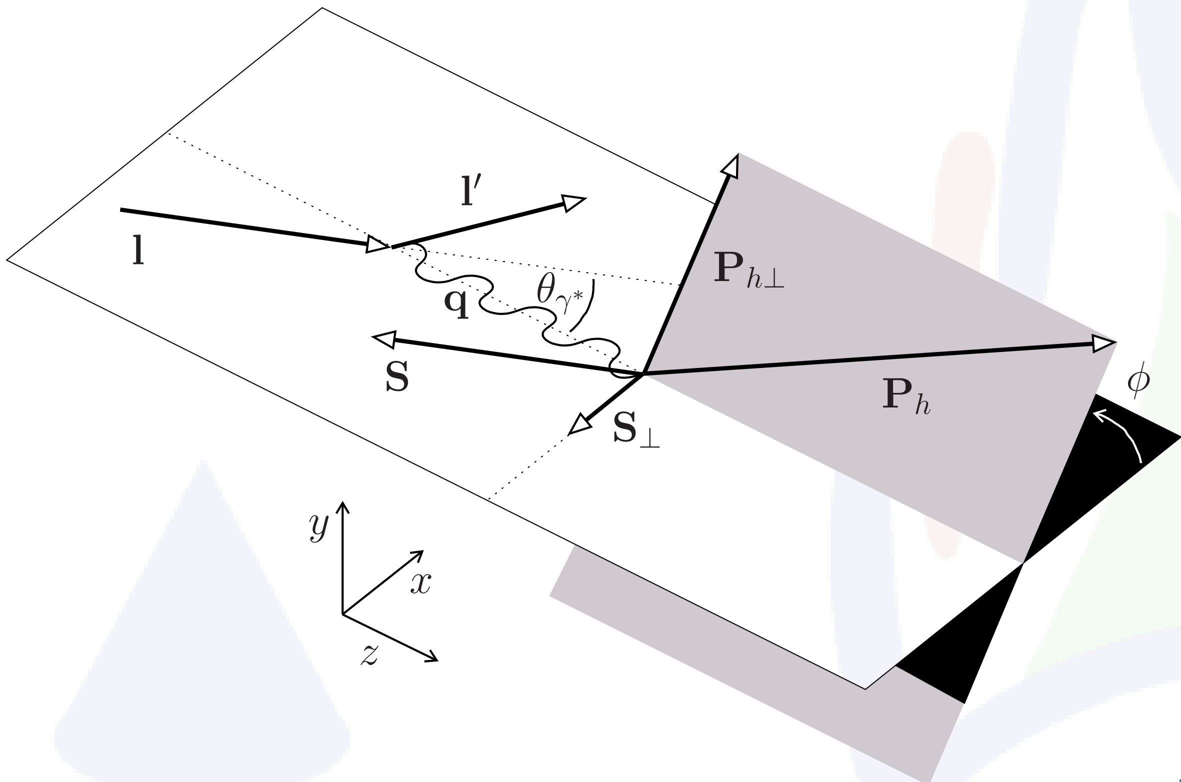


☛ hint of Q2 dependence of kaon amplitude

Longitudinal SSA

Mixing of azimuthal moments



Experiment: Target polarization w.r.t. beam direction "l"

Theory: Target polarization w.r.t. virtual-γ direction "q"

☛ Mixing of various amplitudes via

[Diehl and Sapeta, Eur. Phys. J. C41 (2005)]

$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{l} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{q} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT} \end{pmatrix}$$

($\cos\theta_{\gamma^*} \simeq 1$, $\sin\theta_{\gamma^*}$ **up to 15% at HERMES energies)**

Mixing of azimuthal moments

$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{l} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{q} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{q} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{q} \end{pmatrix}$$

solve for photon-axis moments:

$$\left\langle \sin\phi \right\rangle_{UL}^{q} \simeq \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$

$$\left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{q} \simeq \left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{l} - \frac{1}{2}\sin\theta_{\gamma^*} \left(\left\langle \sin\phi \right\rangle_{UL}^{l} + \tan\theta_{\gamma^*} \left\langle \sin(\phi\mp\phi_S) \right\rangle_{UT}^{l} \right)$$

Longitudinal Target-Spin Asymmetry

$$\left\langle \sin\phi \right\rangle_{UL}^{\text{q}} = \left\langle \sin\phi \right\rangle_{UL}^{\text{l}} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\text{l}} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\text{l}} \right)$$

$$\left\langle \sin\phi \right\rangle_{UL}^{\text{q}} \propto \frac{M}{Q}\,\mathcal{I}\left[\frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{k_T}}{M_h} \left(\frac{M_h}{zM} g_1 G^{\perp} + x h_L H_1^{\perp} \right) + \frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{p_T}}{M} \left(\frac{M_h}{zM} h_{1L}^{\perp} \tilde{H} - x f_L^{\perp} D_1 \right) \right]$$

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

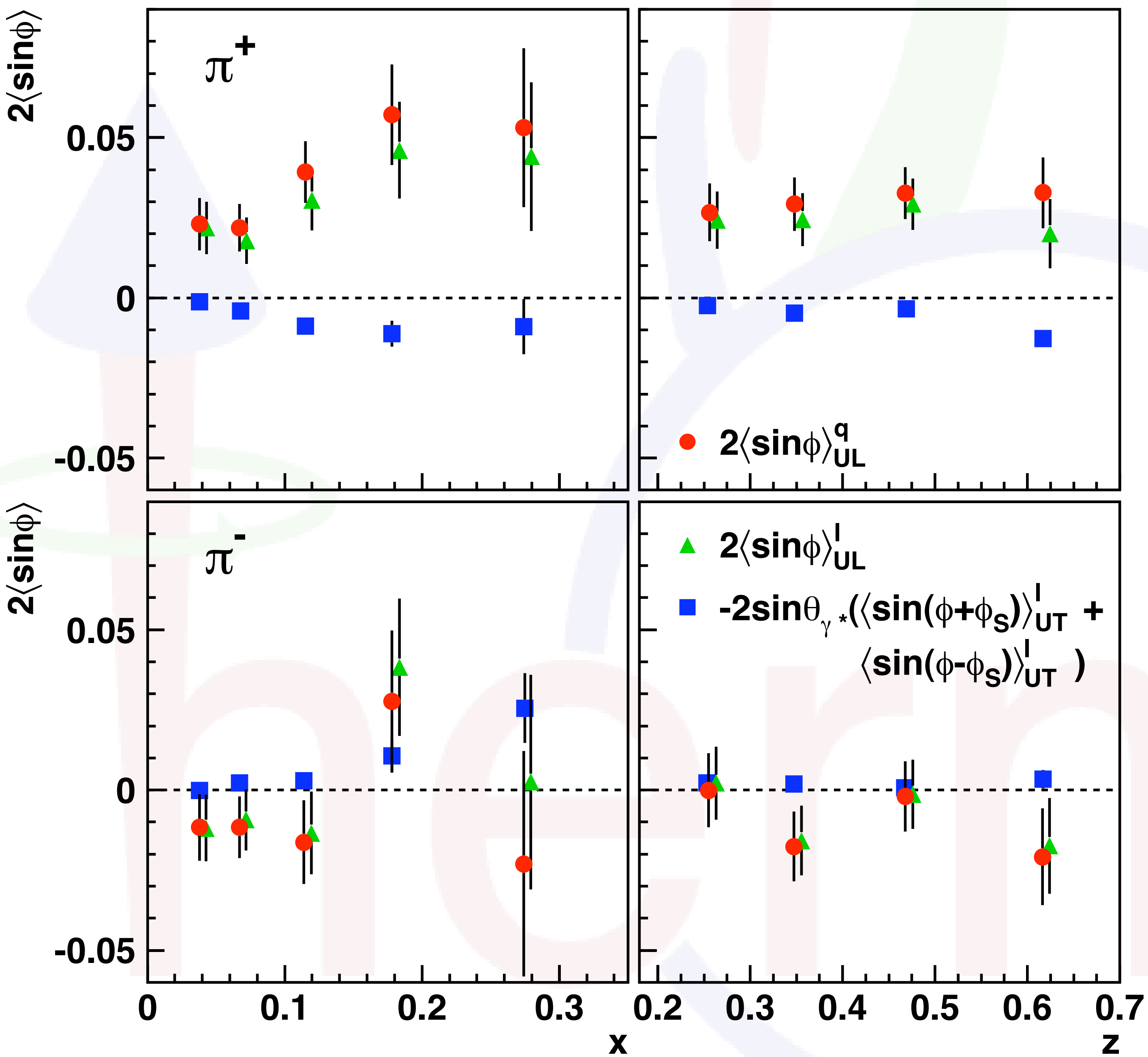
$\Rightarrow$ they are all subleading-twist expressions!

$\left\langle \sin\phi \right\rangle_{UL}^{\text{l}}$ . . . **Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047**

$\left\langle \sin(\phi\pm\phi_S) \right\rangle_{UT}^{\text{l}}$ . . . **Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002**

Longitudinal Target-Spin Asymmetry

$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$



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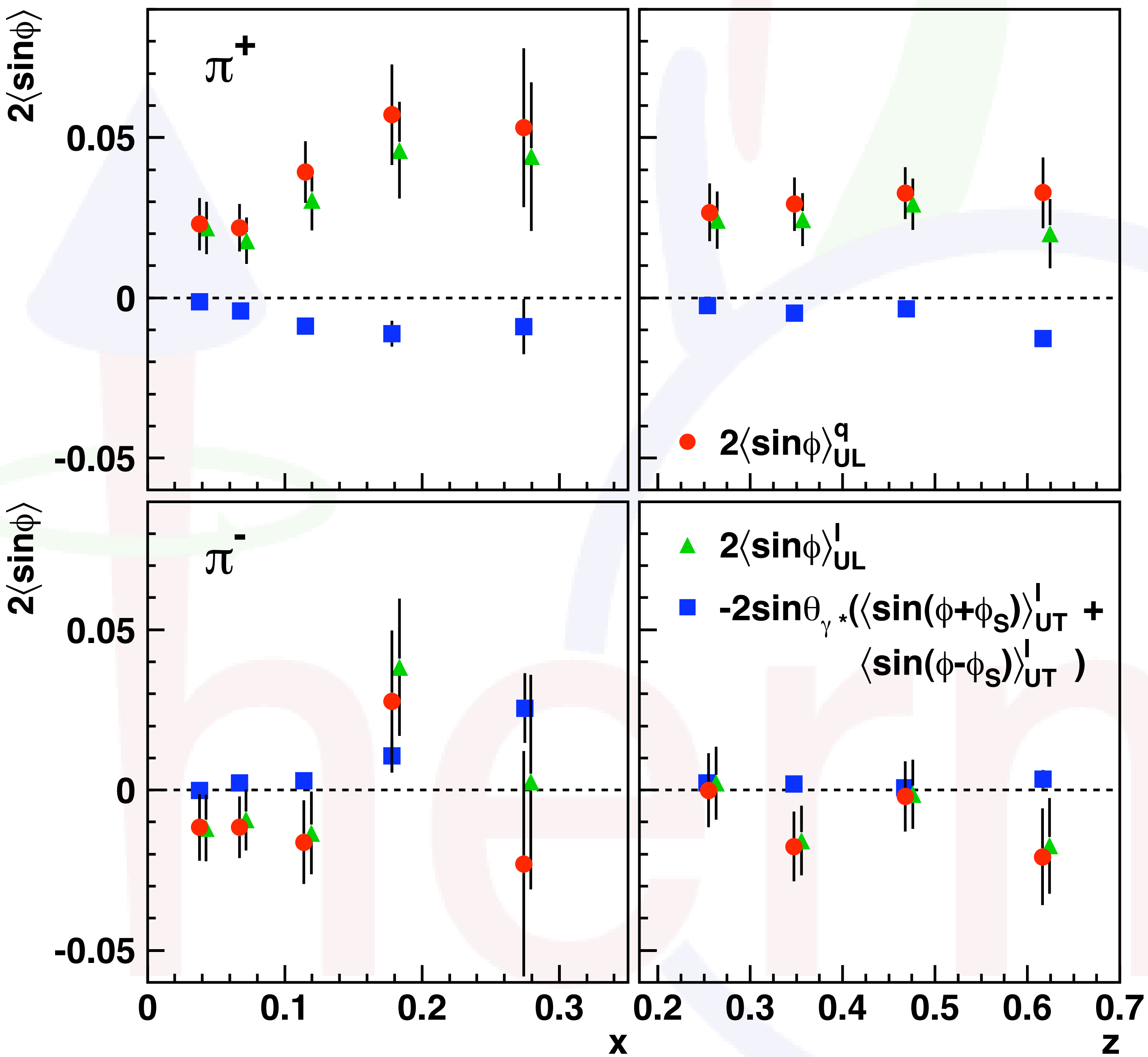

☑ clear evidence for twist-3 asymmetry

Longitudinal Target-Spin Asymmetry

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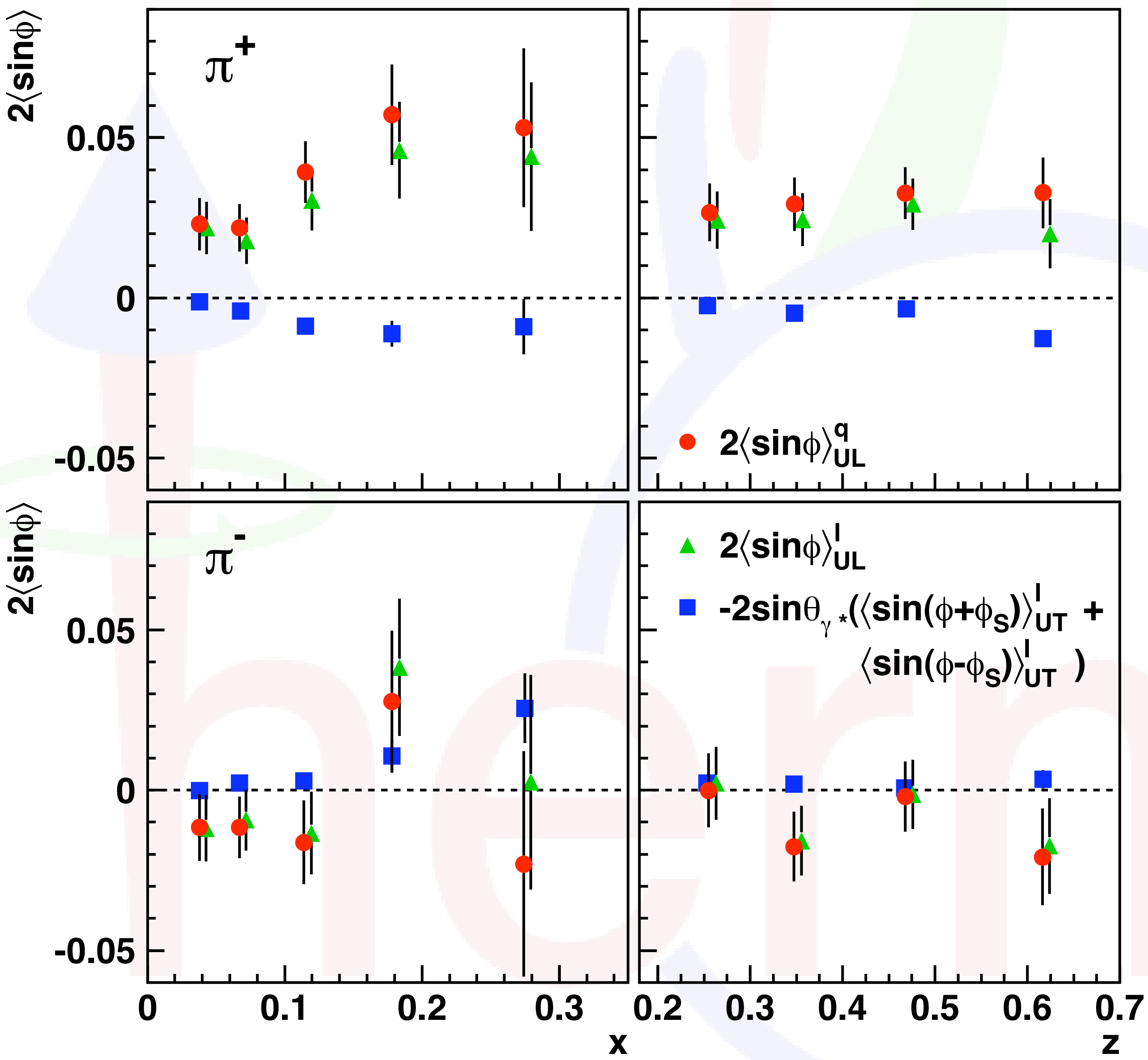

- ☑ clear evidence for twist-3 asymmetry
- ☑ A_{UL} significantly positive for π^+

Longitudinal Target-Spin Asymmetry

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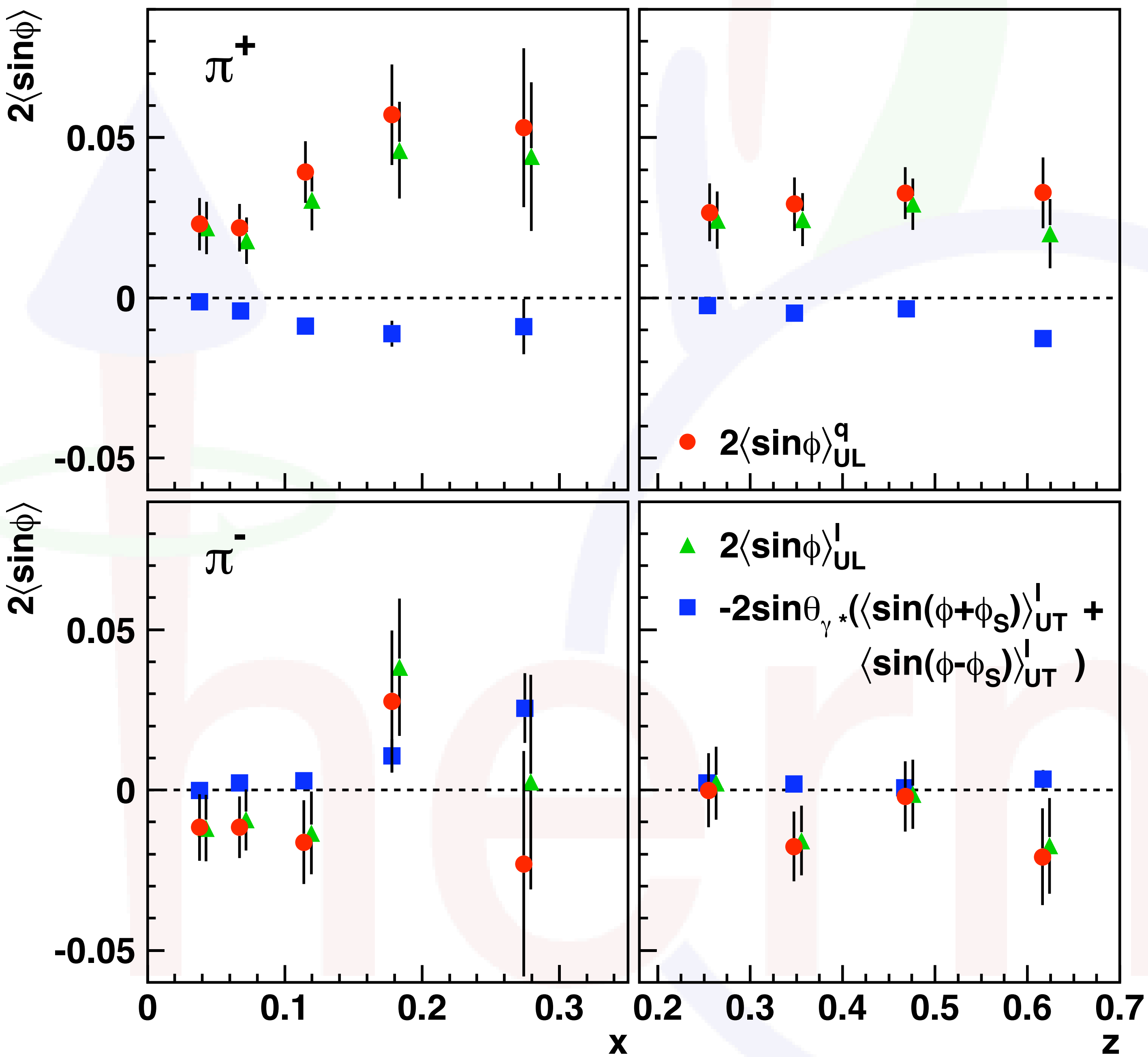


- ☑ clear evidence for twist-3 asymmetry
- ☑ A_{UL} significantly positive for π^+
- ☑ consistent with zero for π^-

The other longitudinal SSA

- longitudinally polarized beam & unpolarized target ⇒ subleading-twist

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

$$
\begin{aligned}
\langle \sin\phi \rangle_{LU} \propto\ & \lambda_e \frac{M}{Q}\, \mathcal{I}\left[x e(x) H_1^{\perp}(z) - \frac{M_h}{zM} h_1^{\perp}(x) E(z) \right. \\
& + \frac{M_h}{zM} f_1(x) G^{\perp}(z) - x g^{\perp}(x) D_1(z) \\
& \left. + \frac{m_q}{M} h_1^{\perp}(x) D_1(z) - \frac{m_q}{M} f_1(x) H_1^{\perp}(z) \right]
\end{aligned}
$$

quark-mass suppressed ☞ (last line)

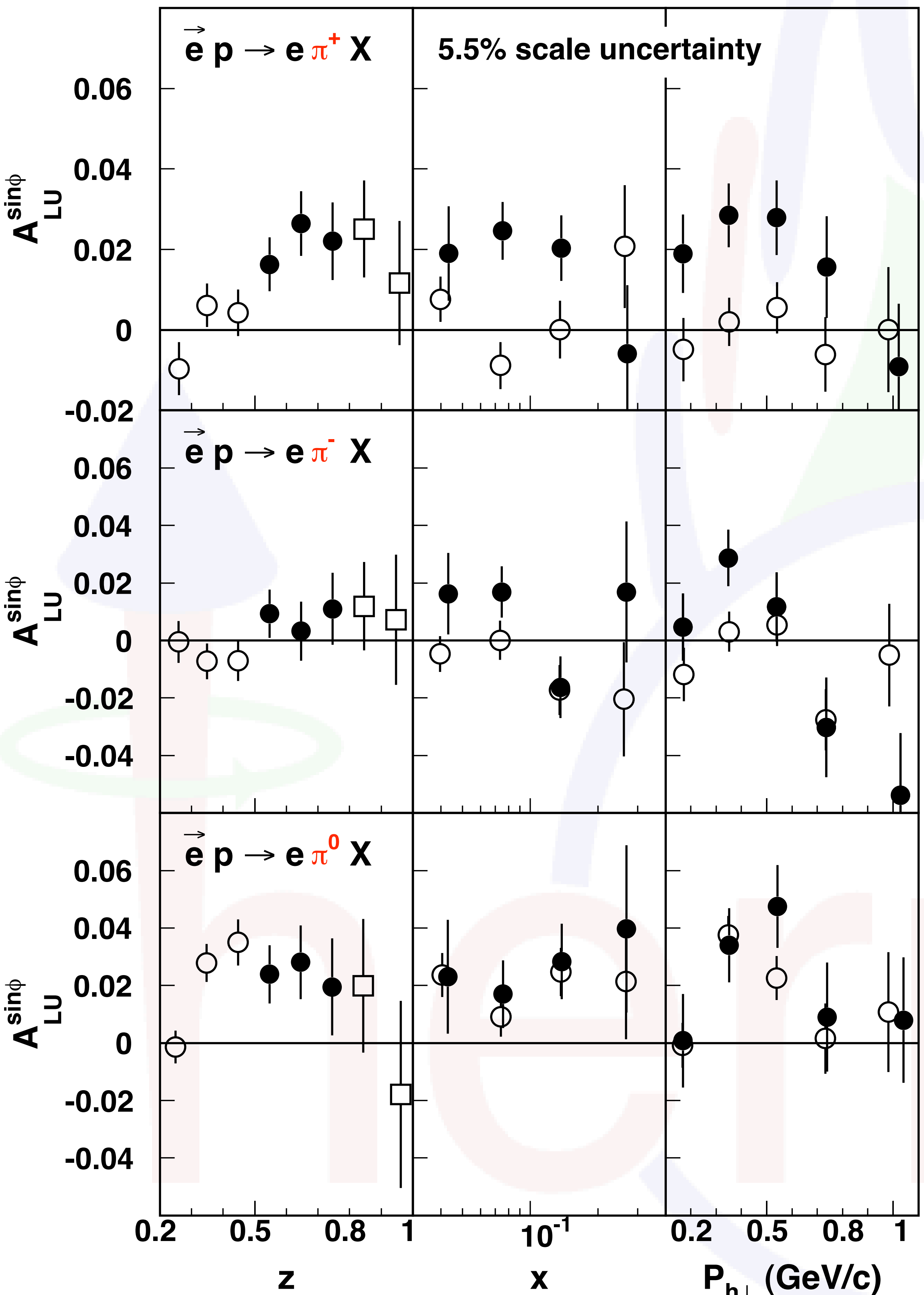
The other longitudinal SSA

- longitudinally polarized beam & unpolarized target ⇒ subleading-twist
  [Bacchetta et al., Phys. Lett. B 595 (2004) 309]

$$\langle \sin\phi \rangle_{LU} \propto \lambda_e \frac{M}{Q}\, \mathcal{I}\Big[x e(x) H_1^{\perp}(z) - \frac{M_h}{zM} h_1^{\perp}(x) E(z) + \frac{M_h}{zM} f_1(x) G^{\perp}(z) - x g^{\perp}(x) D_1(z) \Big]$$

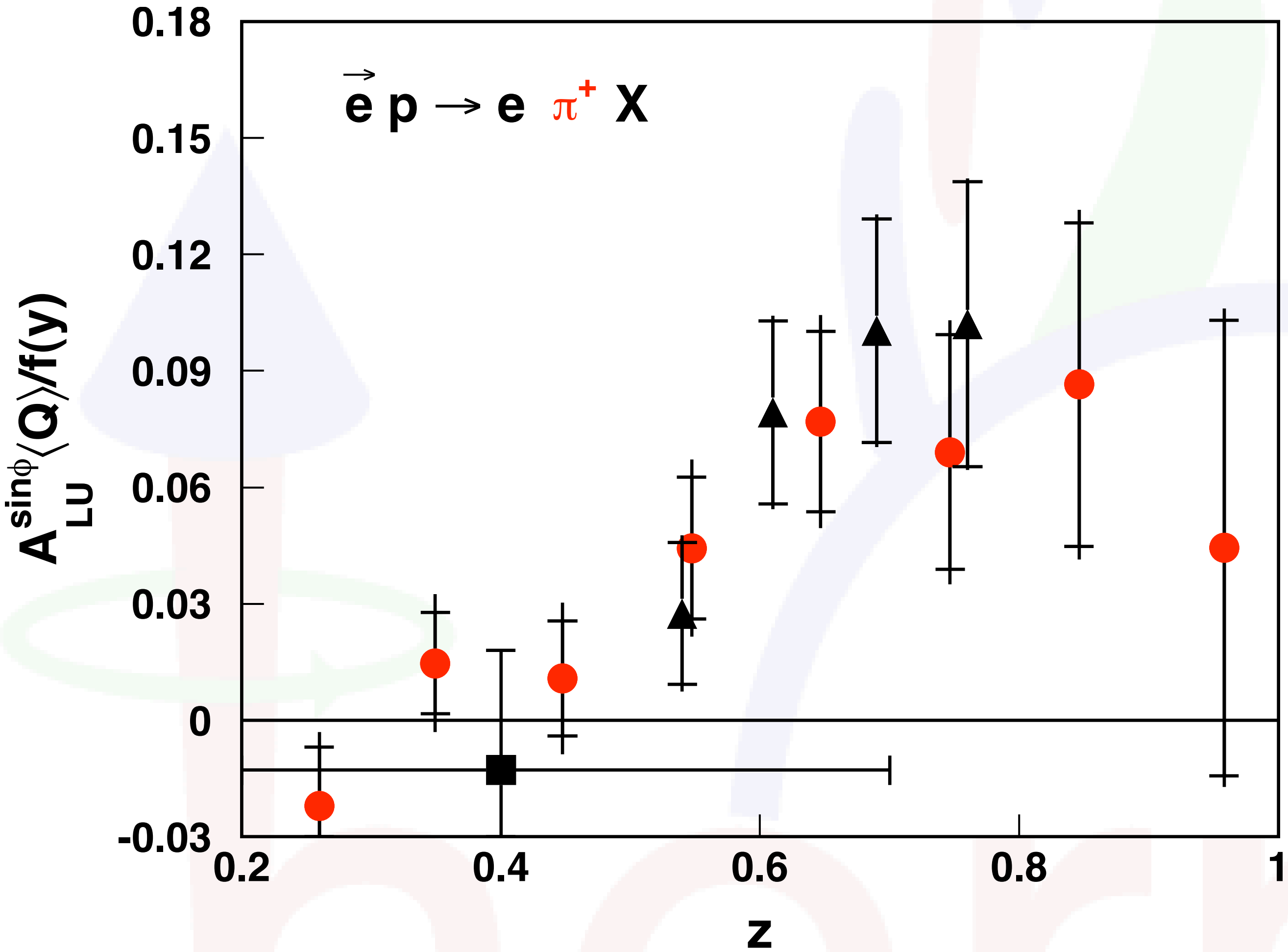
many terms contributing - difficult to separate

Longitudinal-beam-spin asymmetry



- lepton-beam asymmetries, i.e., include kinematic prefactors
- BSA studied in three distinct z ranges
- significantly positive for π^+ and π^0
- consistent with zero for π^-

Longitudinal-beam-spin asymmetry

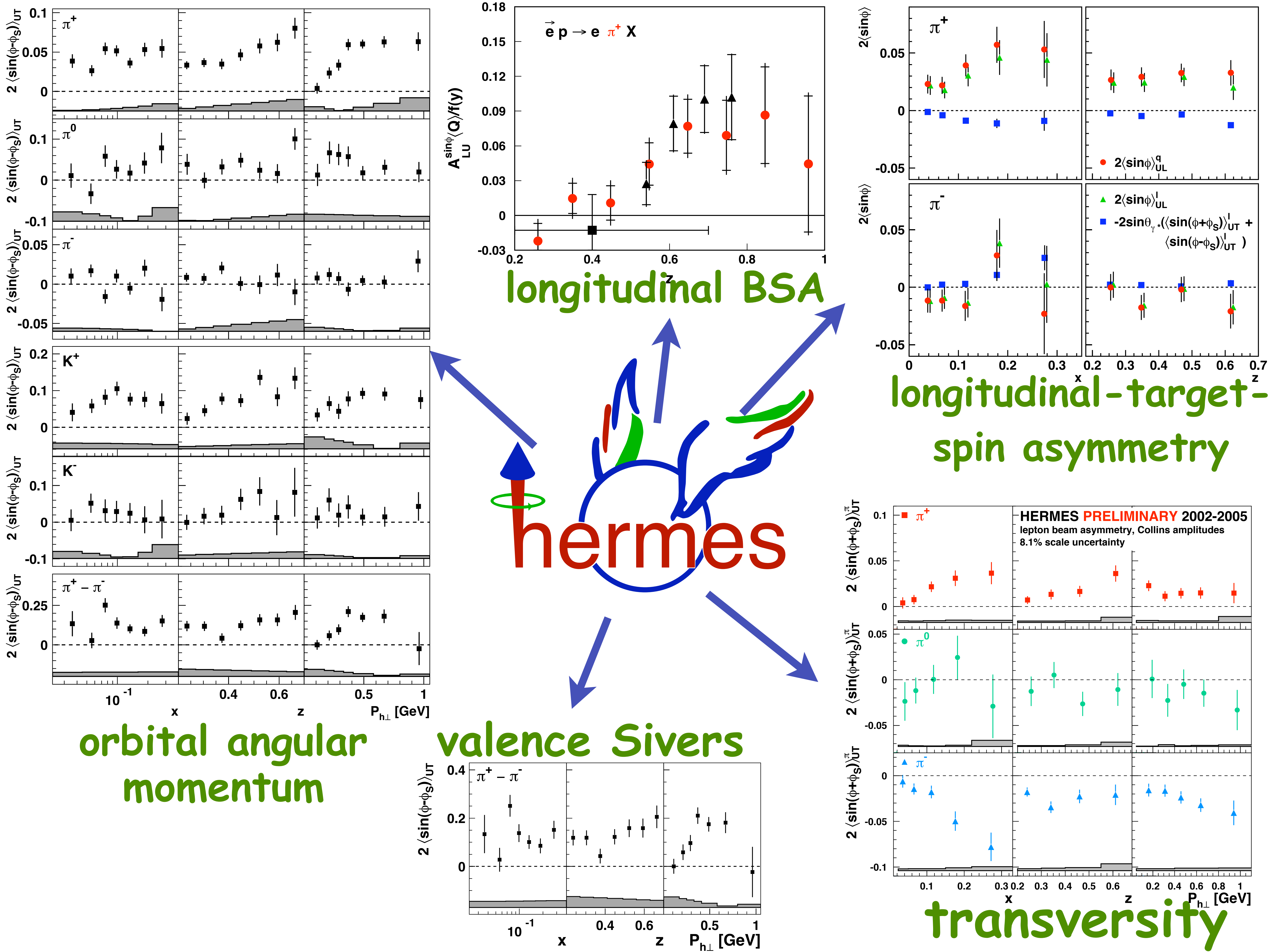


- comparison with CLAS results needs "rescaling" to virtual-photon asymmetries
- take out common prefactor:

$$\frac{1}{Q}\frac{2y\sqrt{1-y}}{1-y+y^2/2}$$

- good agreement with CLAS

hermes



longitudinal BSA
$\vec{e}\,p \rightarrow e\,\pi^+\,X$
$A_{LU}^{\sin\phi}\langle Q\rangle/f(y)$
longitudinal-target-spin asymmetry
$2\langle\sin\phi\rangle^q_{UL}$
$2\langle\sin\phi\rangle^l_{UL}$
$-2\sin\theta_{\gamma^*}(\langle\sin(\phi+\phi_S)\rangle^l_{UT} + \langle\sin(\phi-\phi_S)\rangle^l_{UT})$
orbital angular momentum
hermes
valence Sivers
HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Collins amplitudes
8.1% scale uncertainty
transversity
$2\langle\sin(\phi-\phi_S)\rangle_{UT}$
$2\langle\sin(\phi+\phi_S)\rangle^{\pi}_{UT}$
x
z
$P_{h\perp}$ [GeV]