LightCone 2010 - Valencia, Spain
June 14^{th} - 18^{th}, 2010

The HERMES view on the nucleon's TMD partonic structure

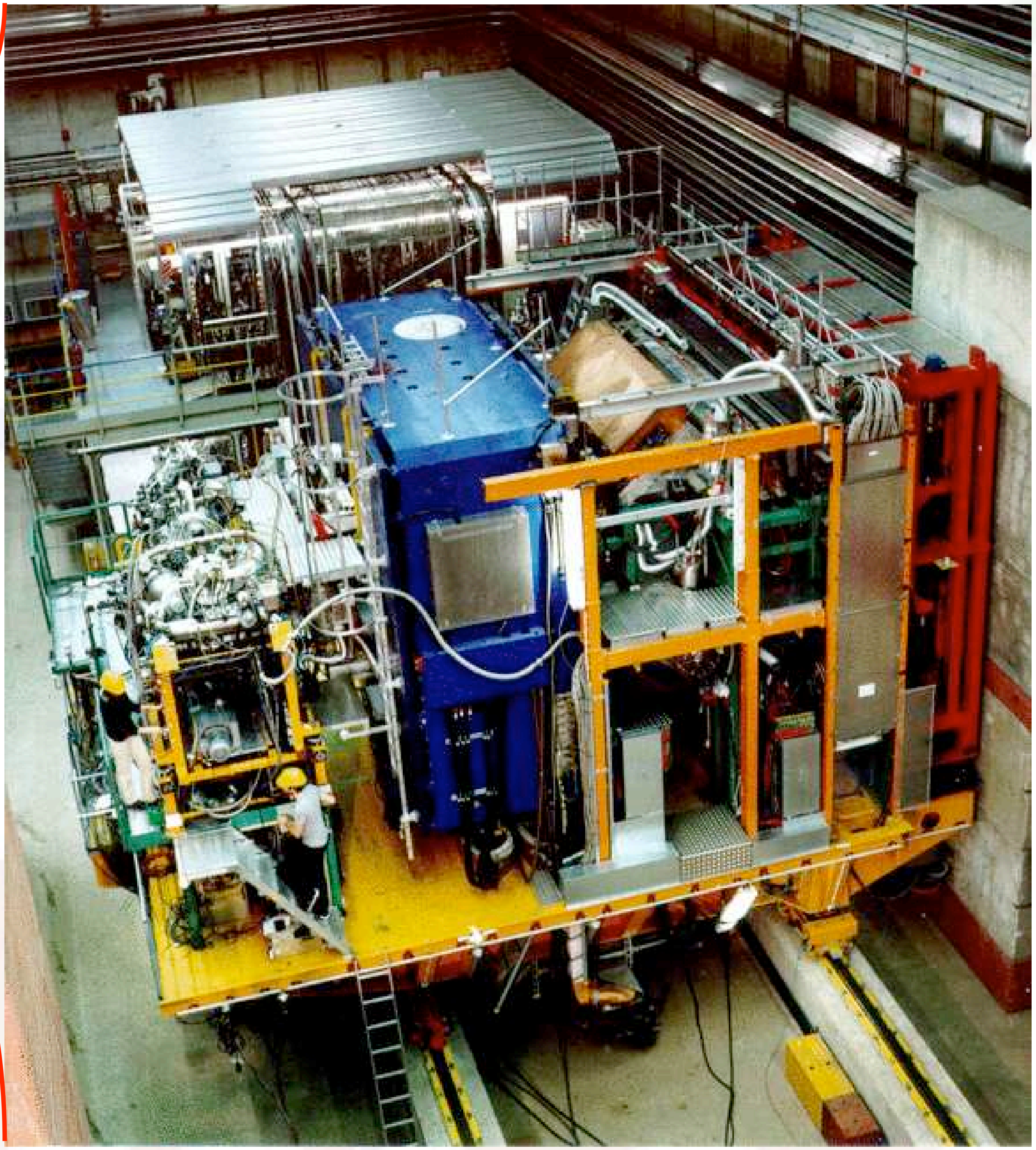
- a small selection from many results -

Gunar.Schnell @ desy.de
[on behalf of the HERMES collaboration]

Photo: Emilio García

The HERMES Experiment (†2007)

27.6 GeV polarized e^+/e^-
beam scattered off ...



unpolarized (H, D, He,..., Xe)
as well as **transversely (H)**
and longitudinally (H, D)
polarized (pure) gas targets

Last* time at LightCone ...

* HERMES' previous appearance: August 6th, 2002

First glimpse of transversity?

HERMES 1996/97: longitudinal polarized proton target

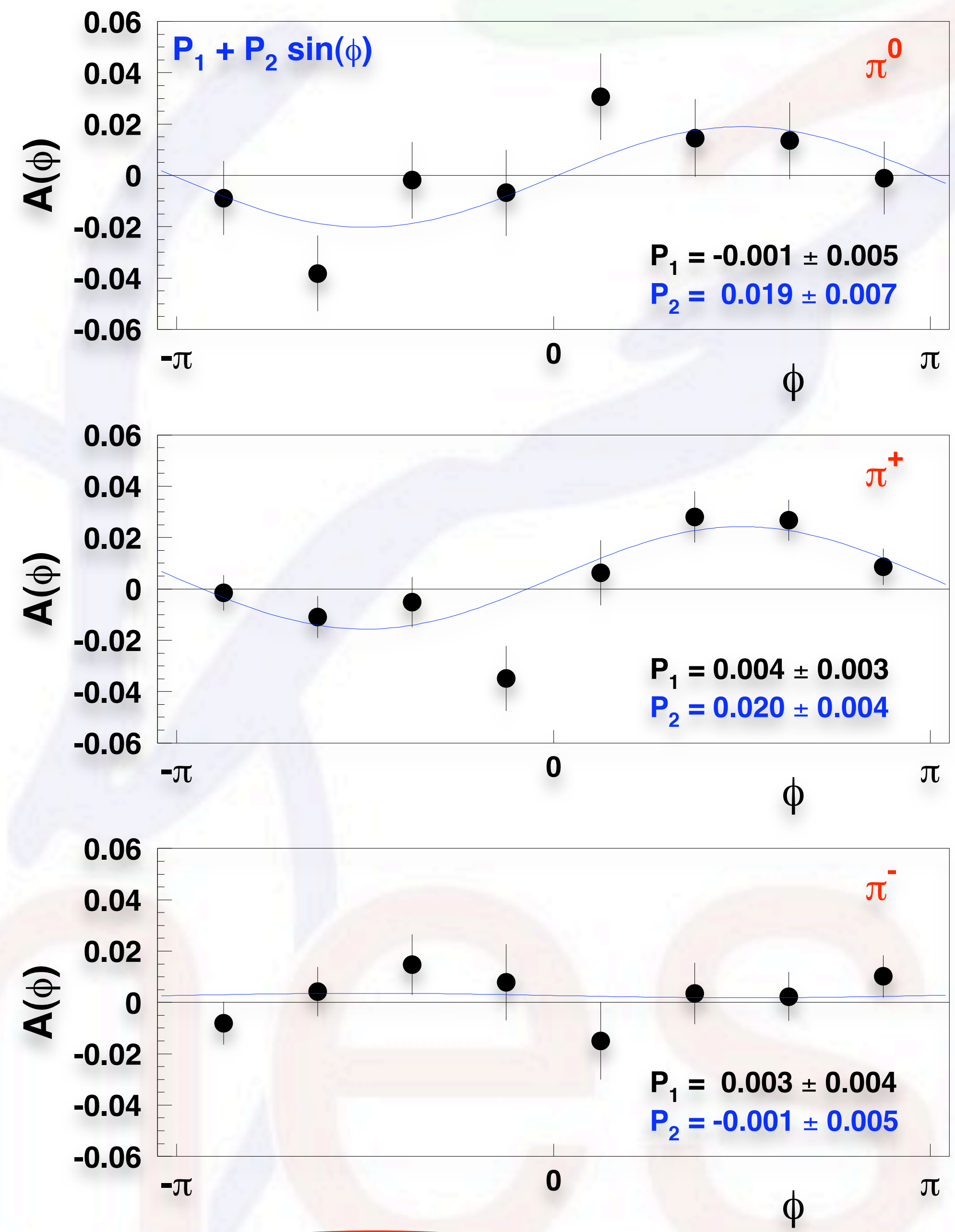
transverse component S_T of target spin (w.r.t. virtual photon):

$$S_T \propto \sin\Theta_\gamma \simeq \frac{2Mx}{Q}\sqrt{1-y} \sim \mathbf{0.15}$$

$\Rightarrow$ glimpse on transversity?!

Longitudinal target SSA:

$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



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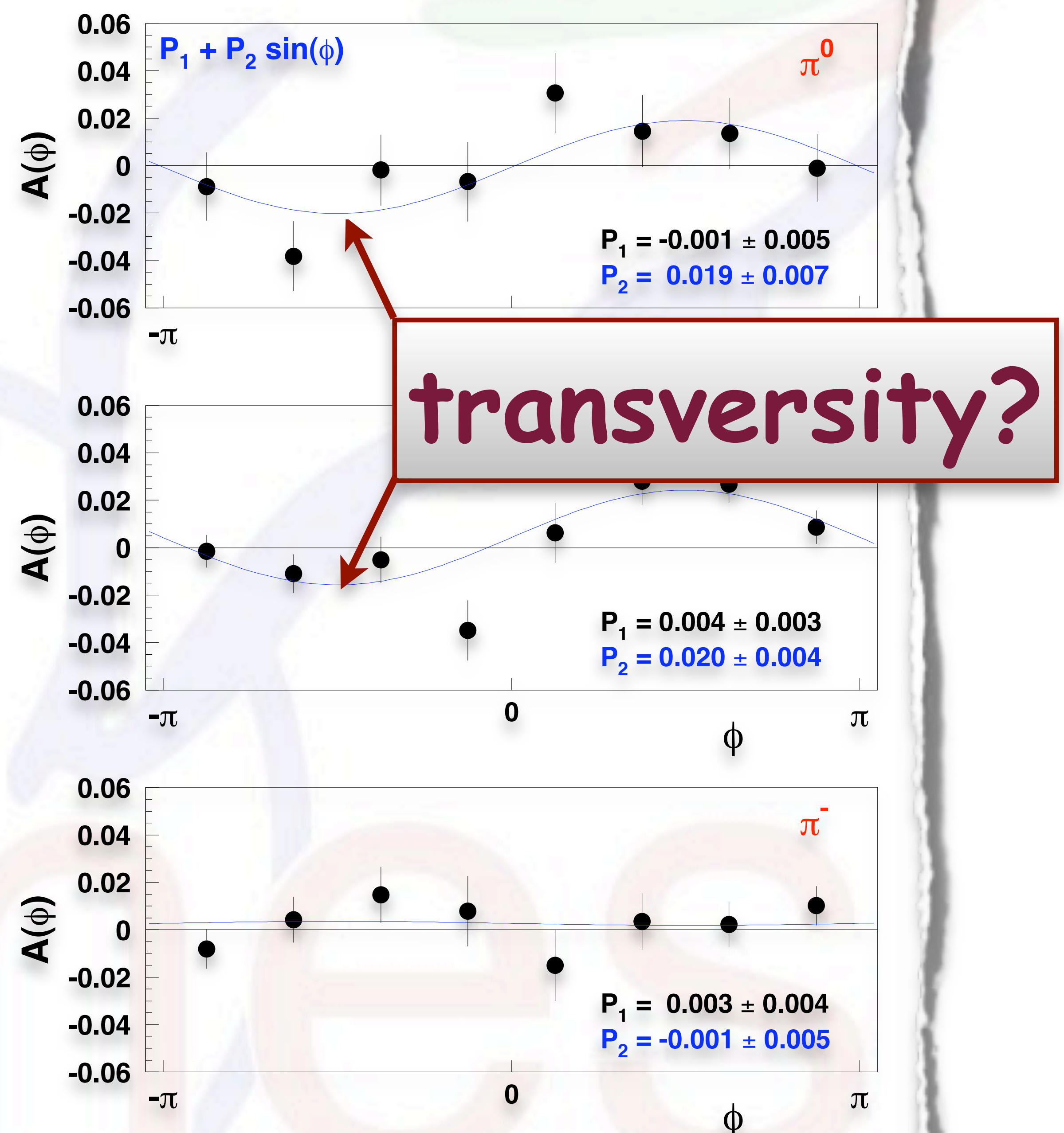

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Gunar Schnell (DESY), HERMES Collaboration   LightCone 2002 – Los Alamos, August 6th, 2002   – p. 13

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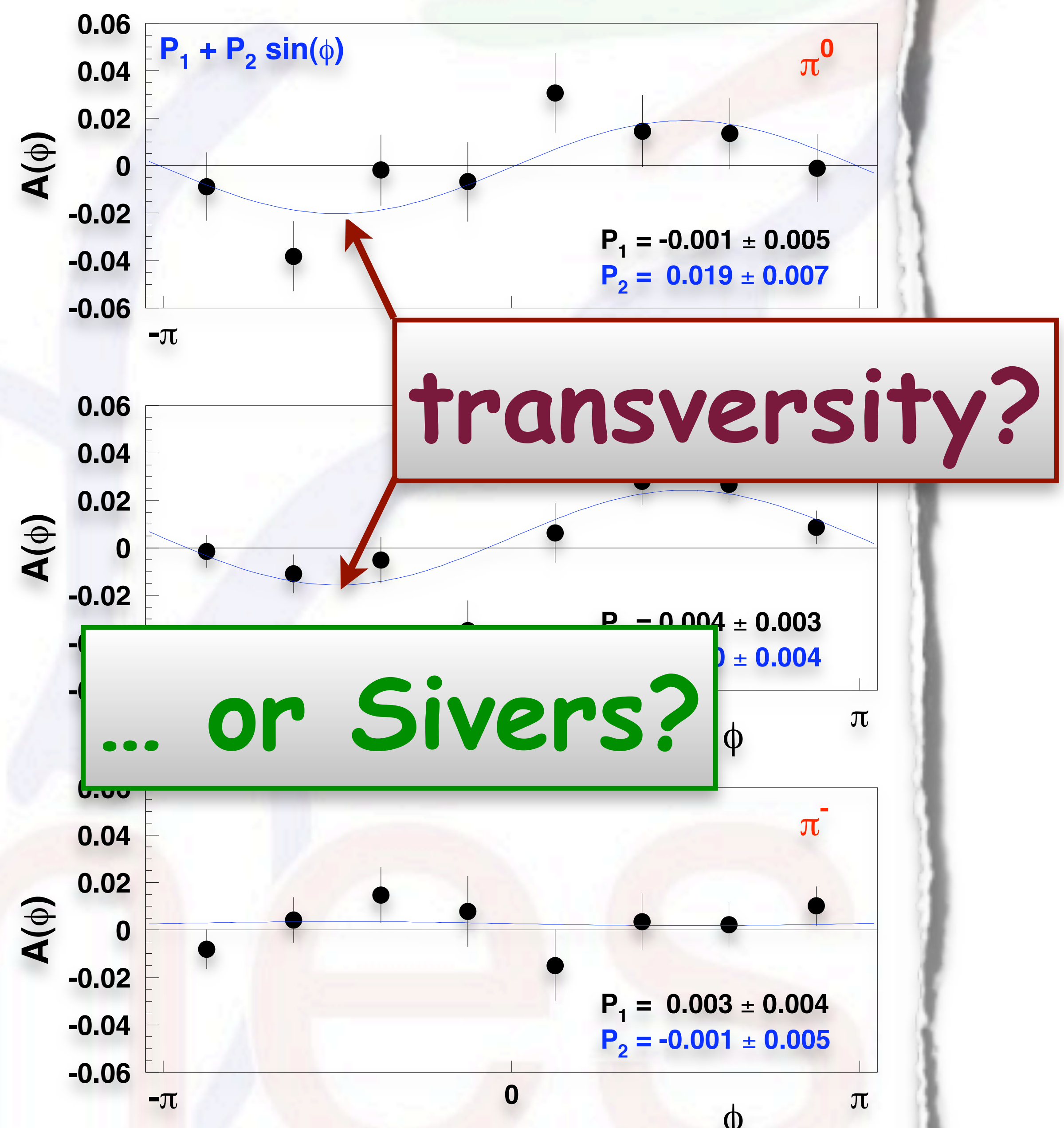

Gunar Schnell (DESY), HERMES Collaboration

LightCone 2002 – Los Alamos, August 6th, 2002

– p. 13

First glimpse of transversity?

HERMES 1996/97

transverse compor

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⇒ glimpse on trans

Longitudinal targe

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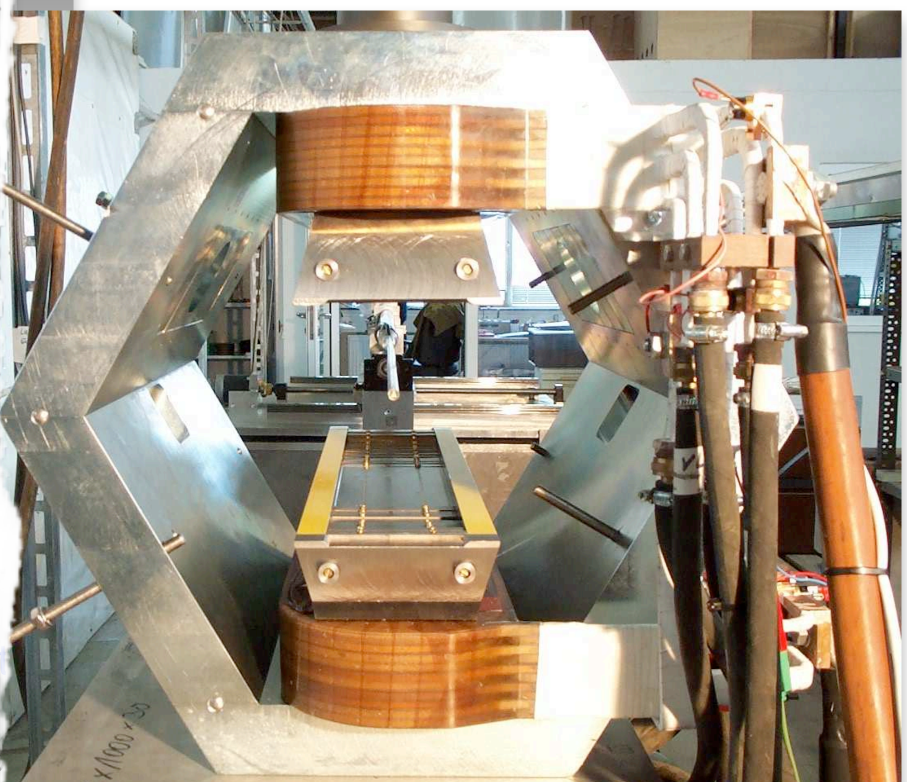
Outlook



New Target Magnet for HERMES

- **Transverse target ($B = 0.295T$)**
- **High uniformity along beam direction:** $\Delta B \leq 4.5 \cdot 10^{-5} T$
- **Transversely polarized hydrogen**
- **Target polarization above 80%**

- $\langle \sin\phi \rangle_{UT}$ becomes dominant
- Sivers and Collins distinguishable
  $\hookrightarrow h_1$ and $H_1^\perp$ as well as $f_{1T}^\perp$ accessible

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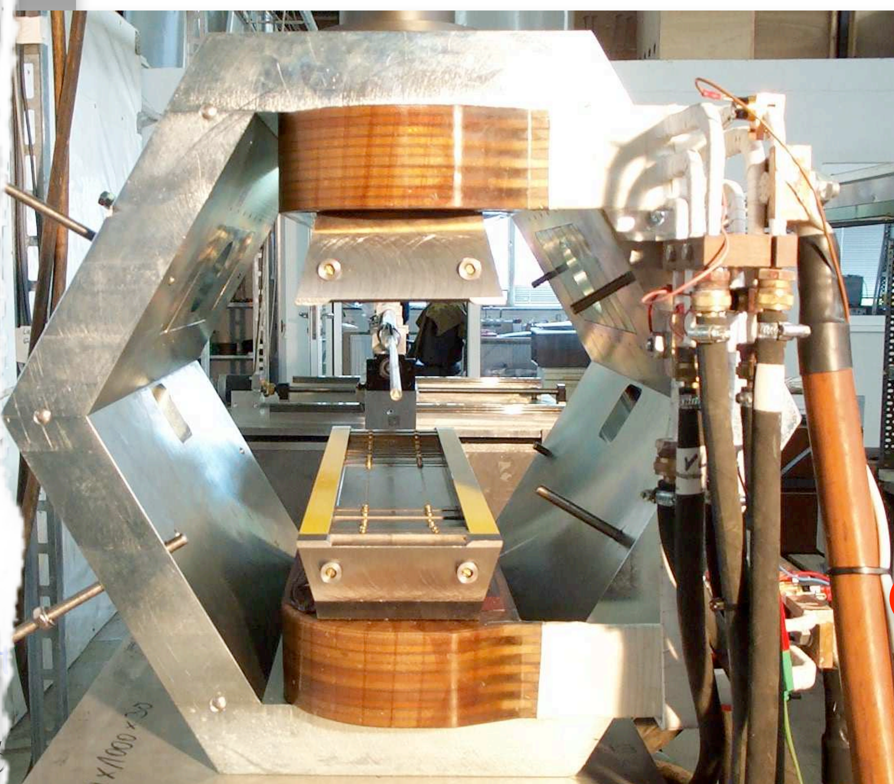

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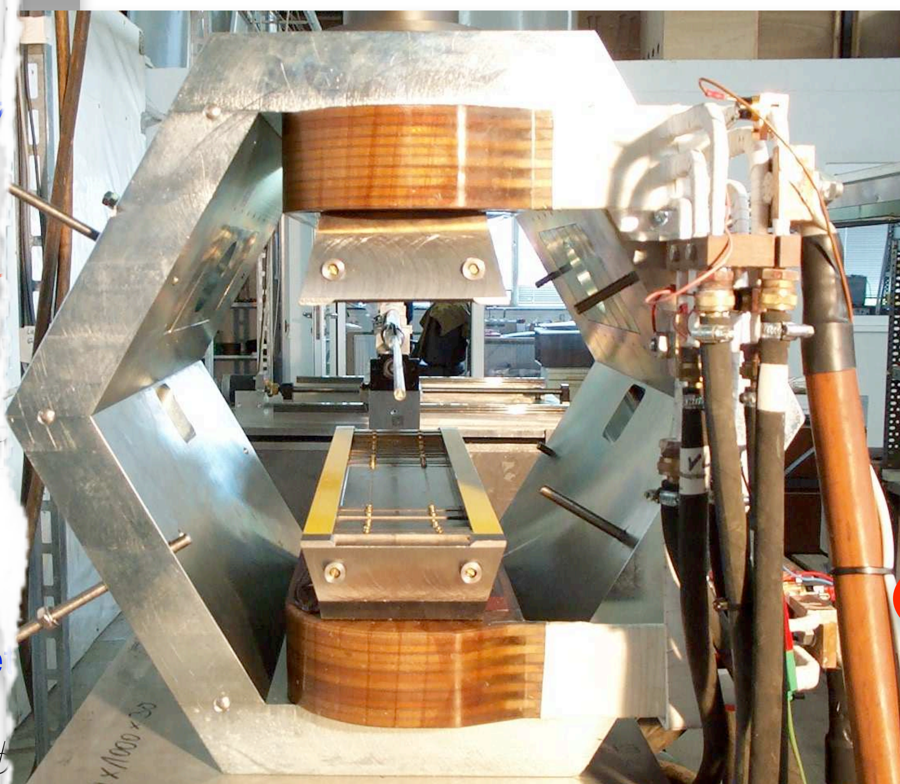

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… and now the conclusion

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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helicity

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

Twist-2 TMDs

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

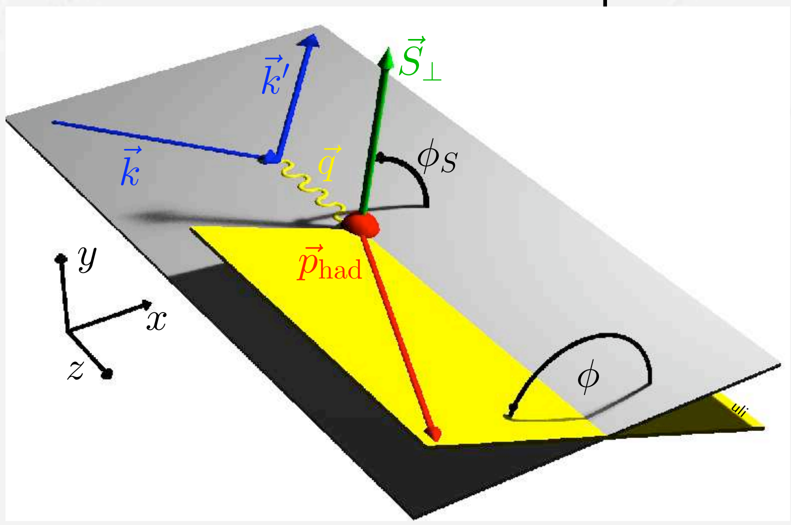
- functions in black survive integration ... se momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

1-Hadron Production (ep→ehX)

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

σ_{XY}

Beam **Target**
Polarization



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

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

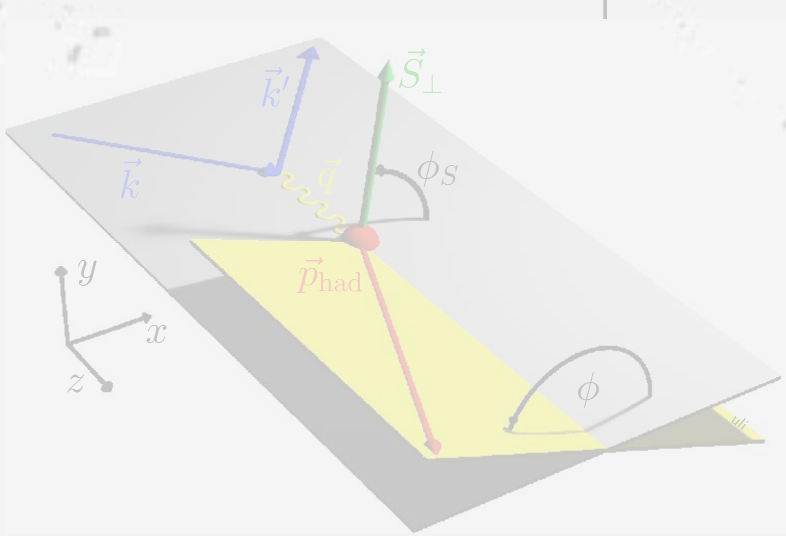
$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)$$

σ_{XY}

Beam Target

Polarization

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



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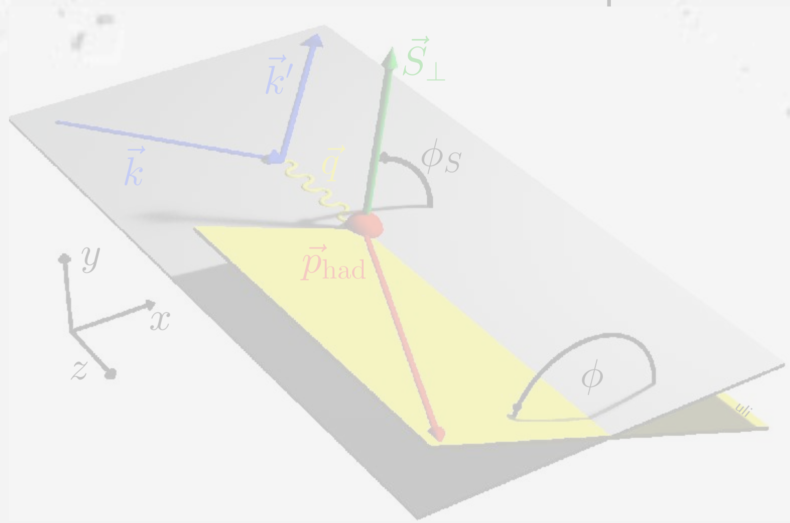
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^{8} + \boxed{\sin(\phi + \phi_S) \, d\sigma_{UT}^{9}} + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right.$$

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

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

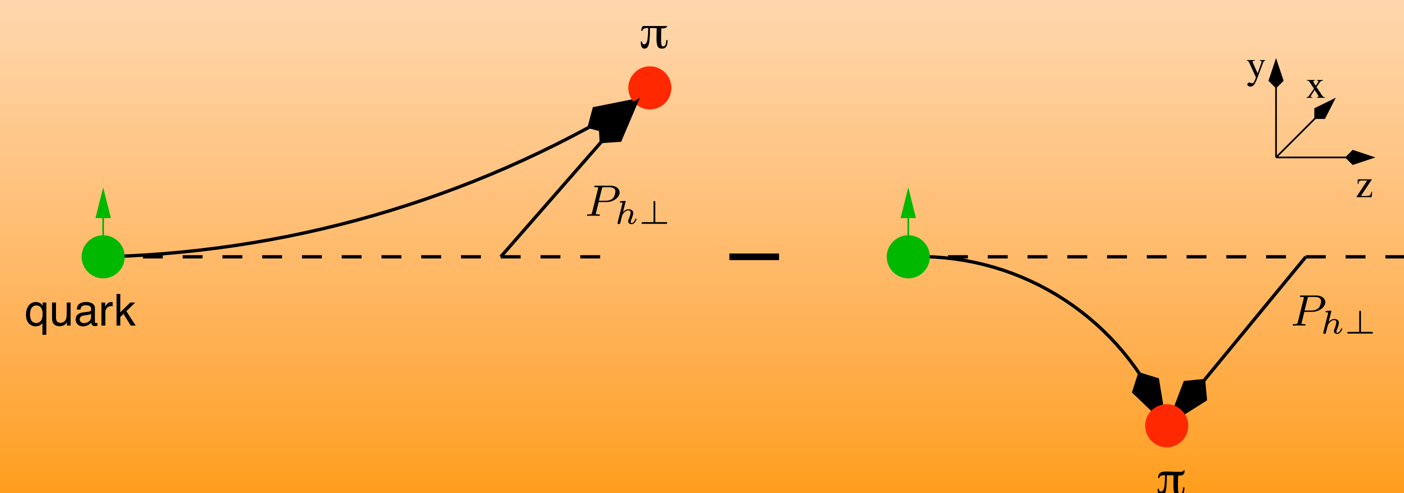
σ_{XY}

Beam Target
Polarization



Collins Effect:

sensitive to quark transverse spin



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

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

Sivers Effect:

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

Phys. B 461 (1996) 197

7 (1998) 5780

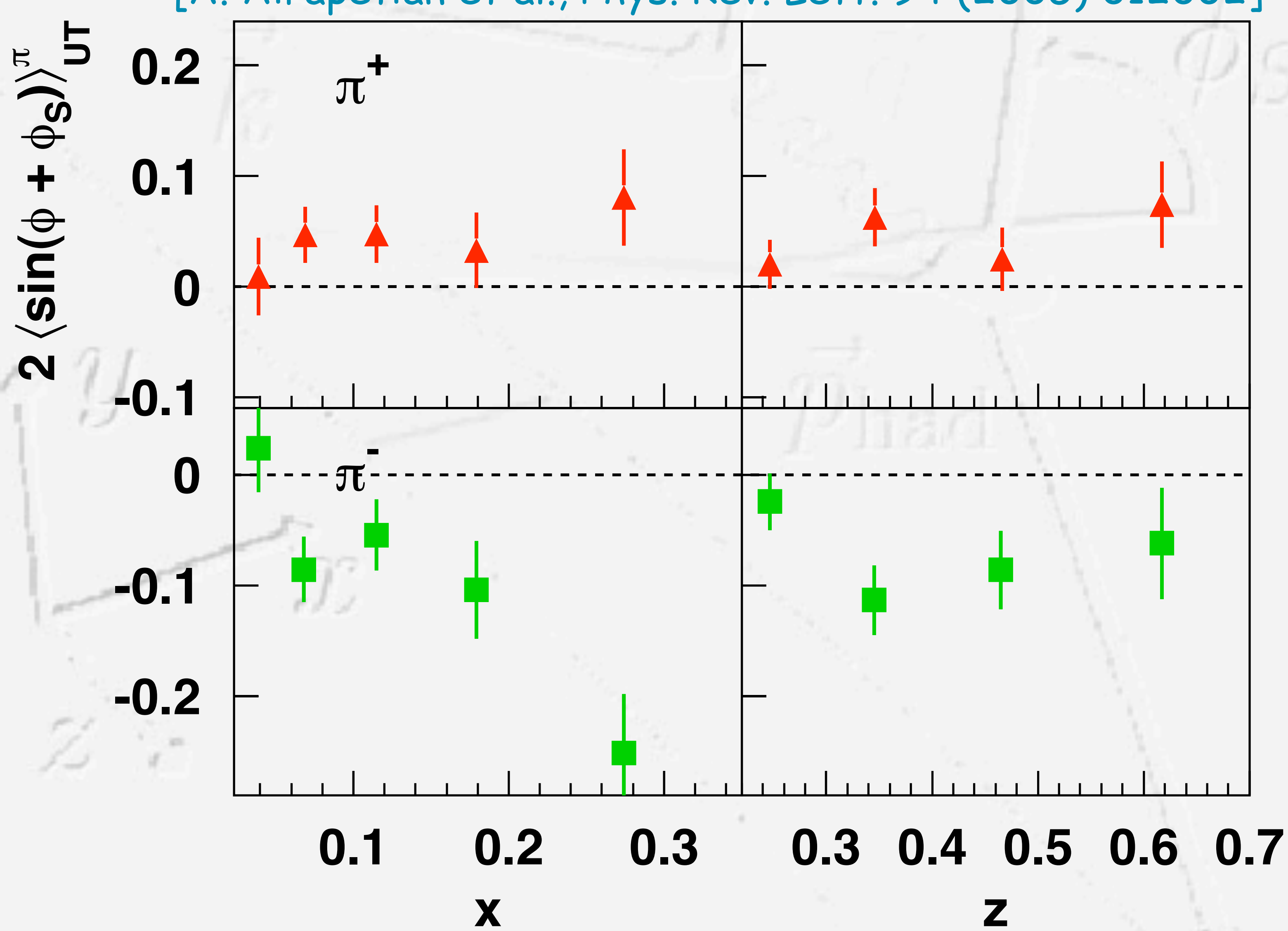
5 (2004) 309

) 093

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

The HERMES Collins amplitudes

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



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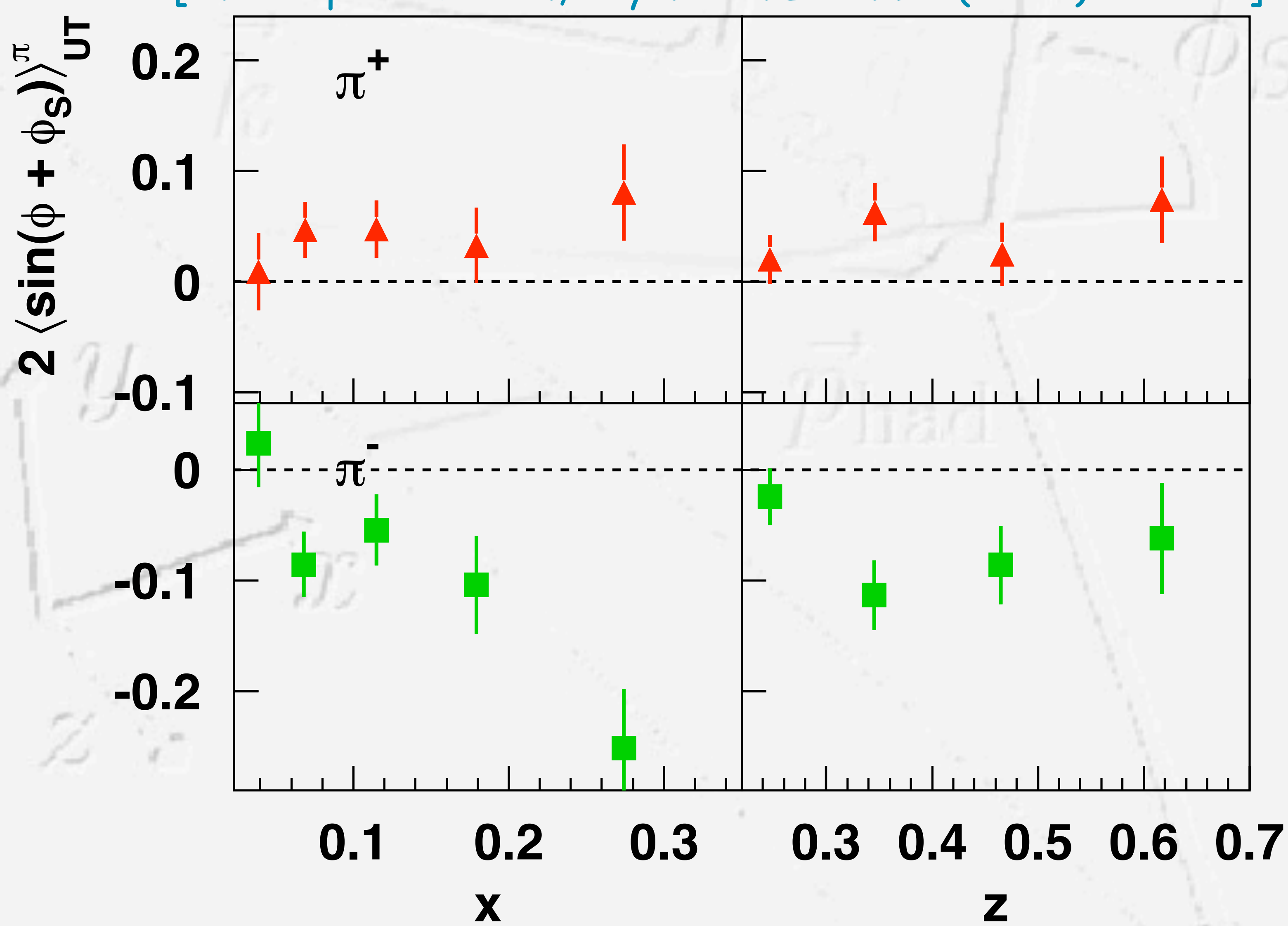

☑ non-zero Collins effect observed!

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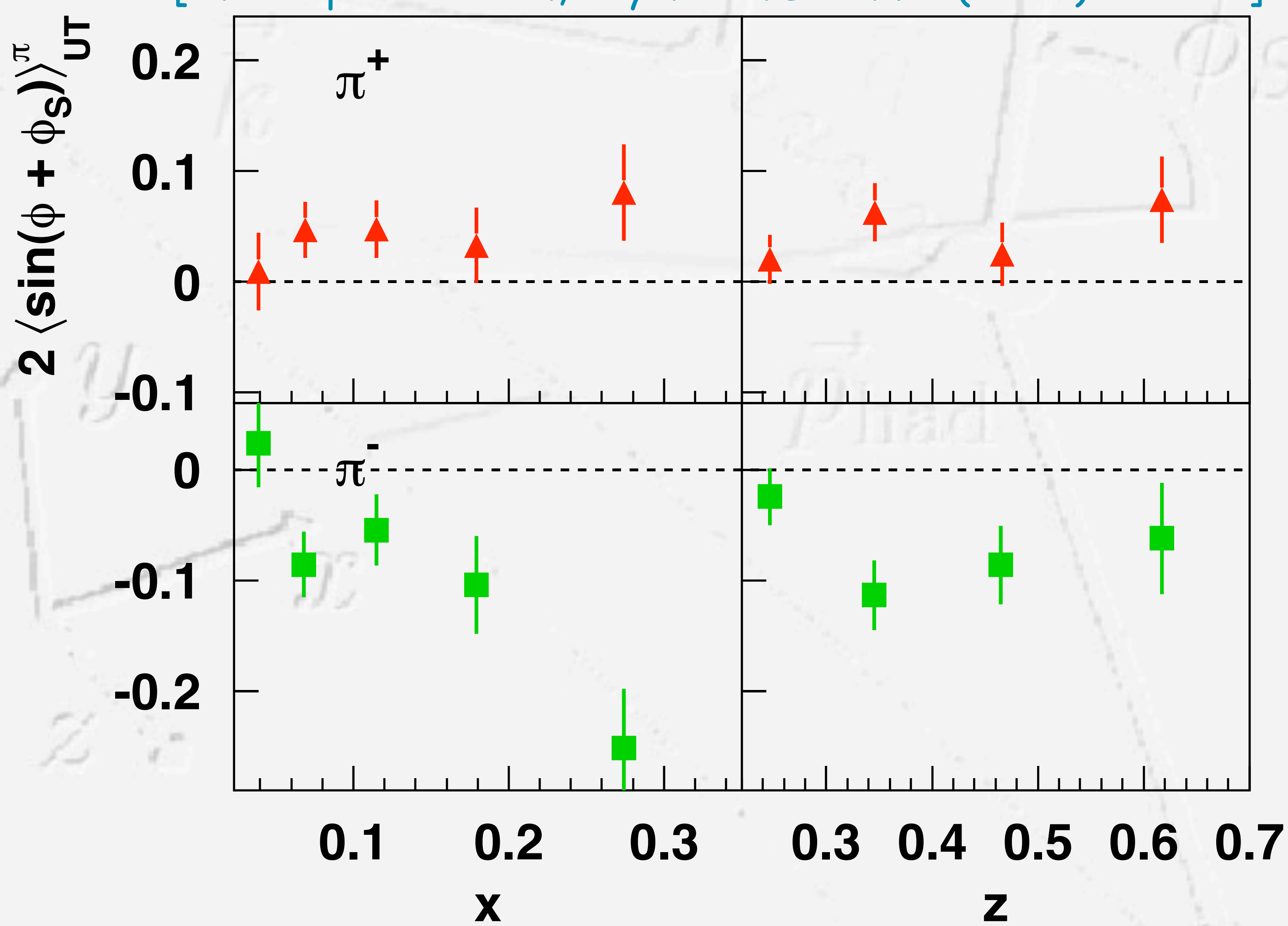
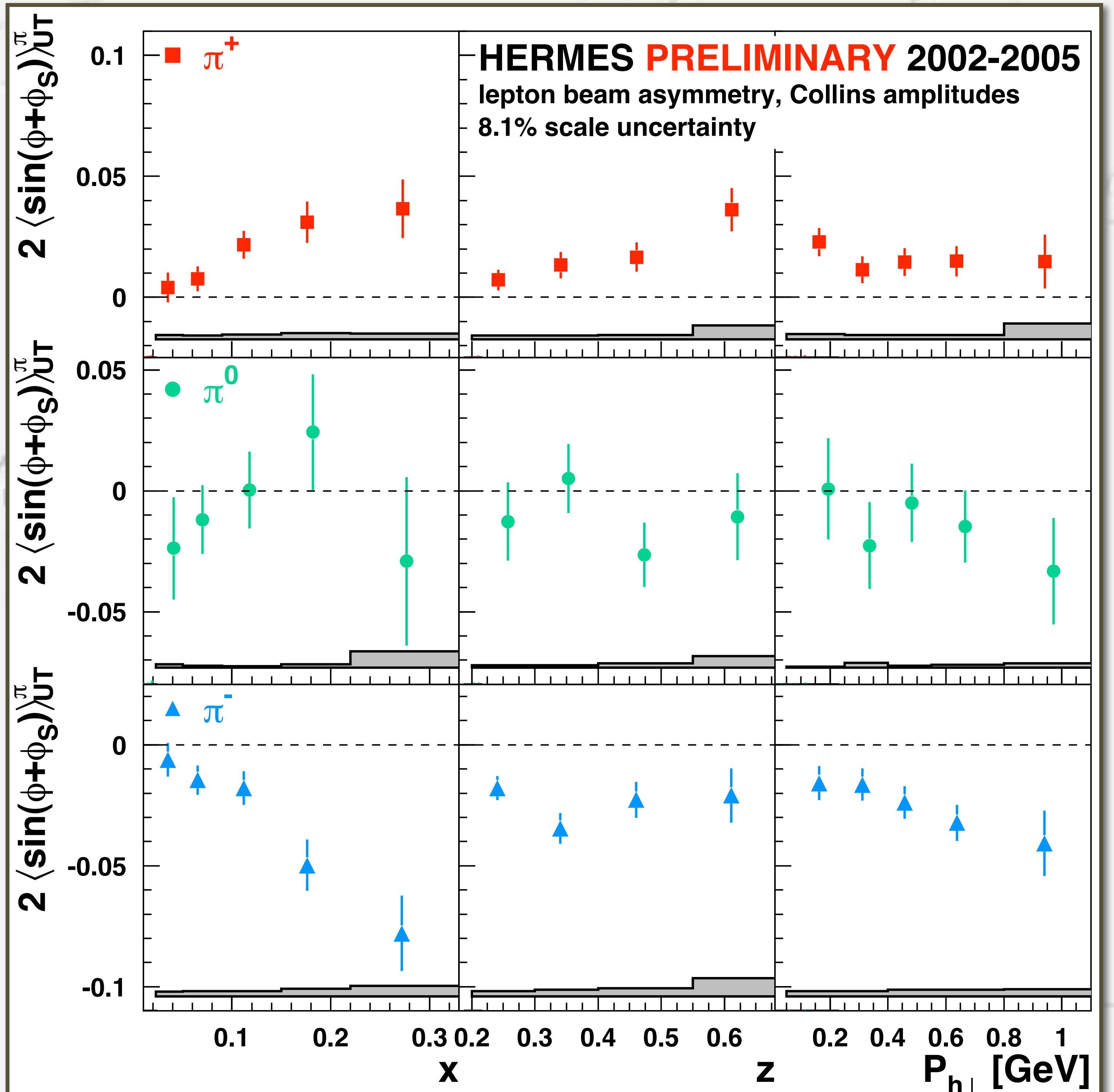


- non-zero Collins effect observed!
- both Collins FF and transversity sizeable

The HERMES Collins amplitudes

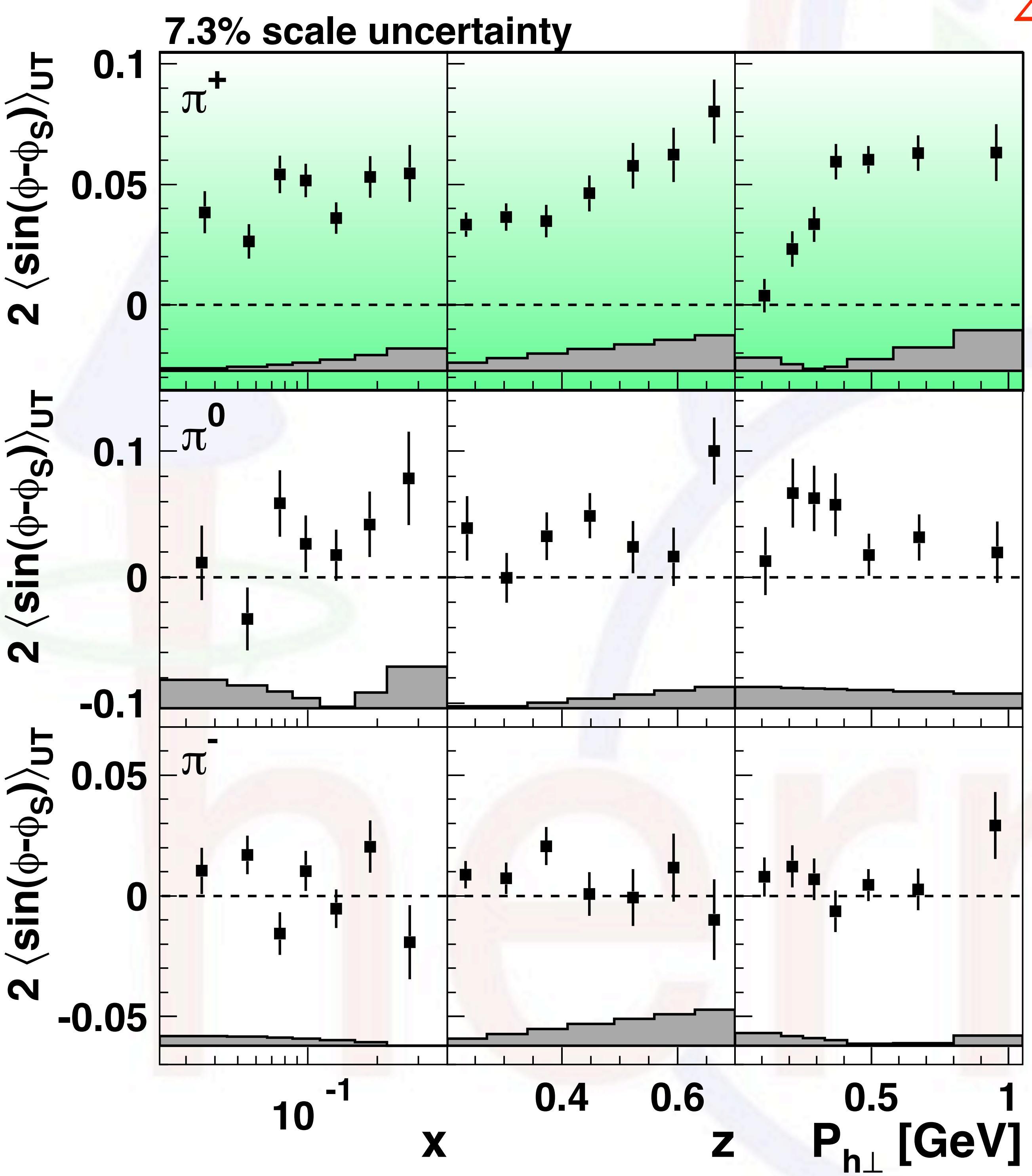


- published† results confirmed with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$
  maybe expected ($\delta d \equiv h_1^d < 0$)
- unexpected large π^- asymmetry
  $\Rightarrow$ role of disfavored 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]

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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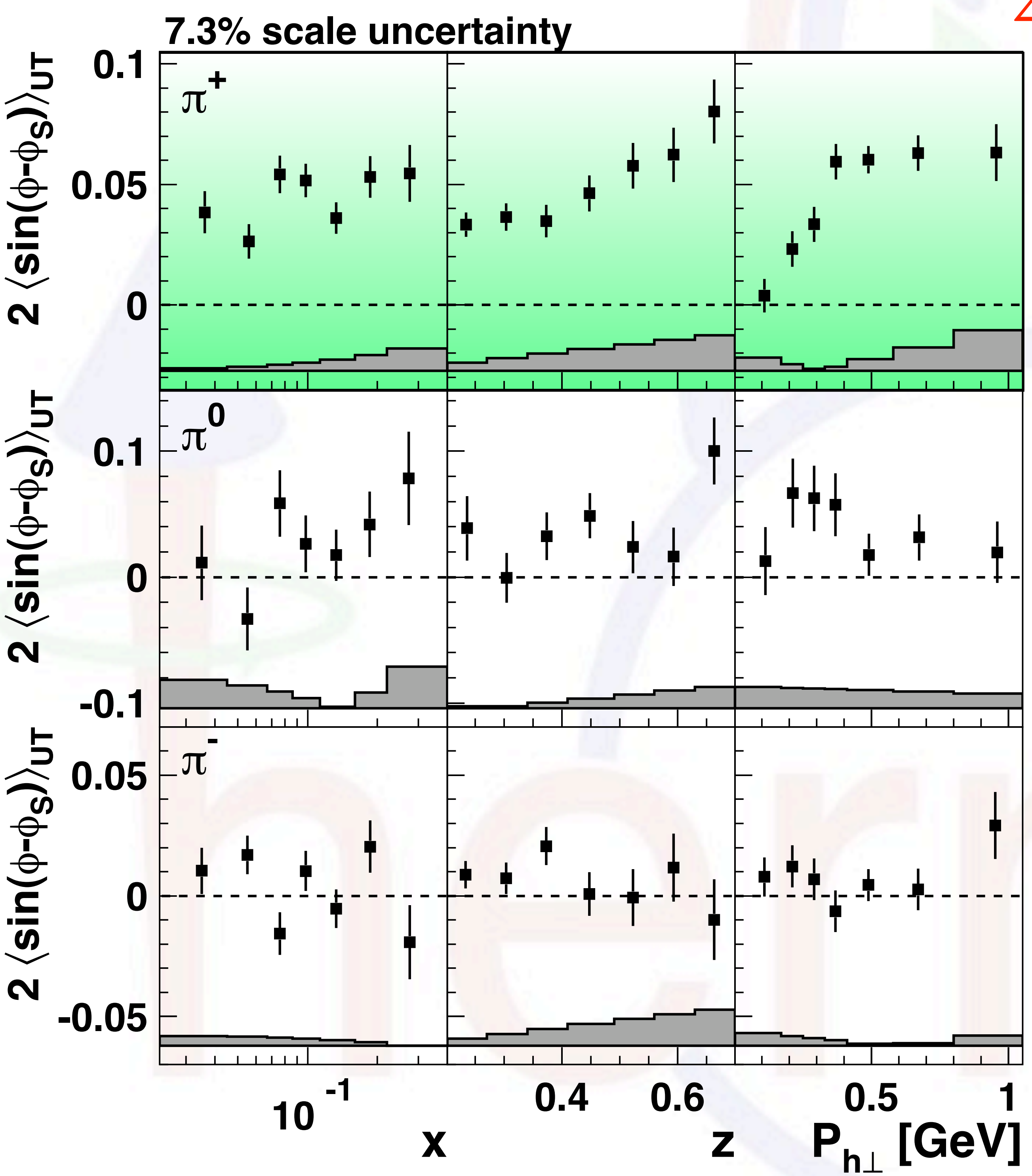

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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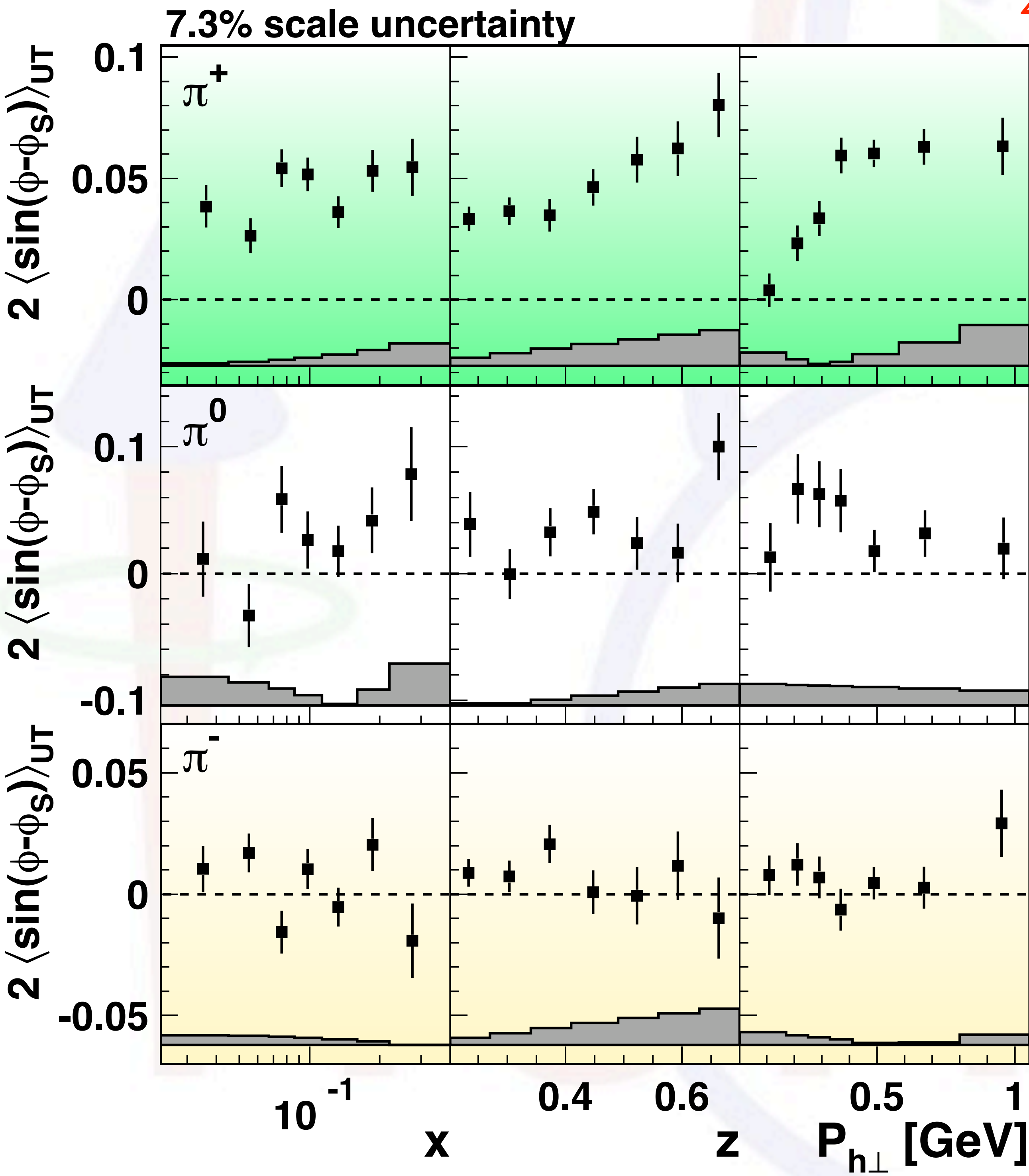

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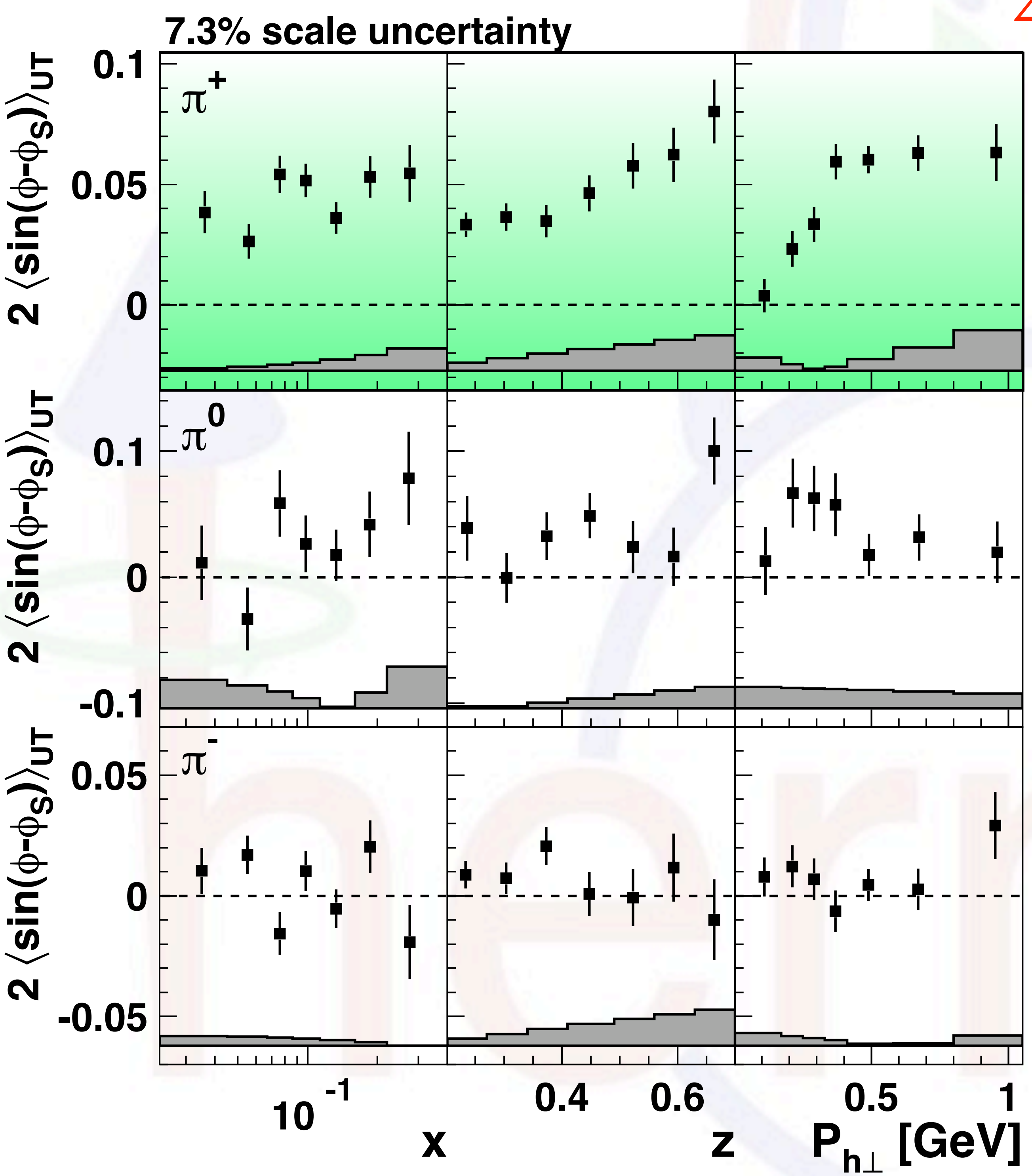
☛ u-quark Sivers DF < 0

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

Sivers amplitudes for pions

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



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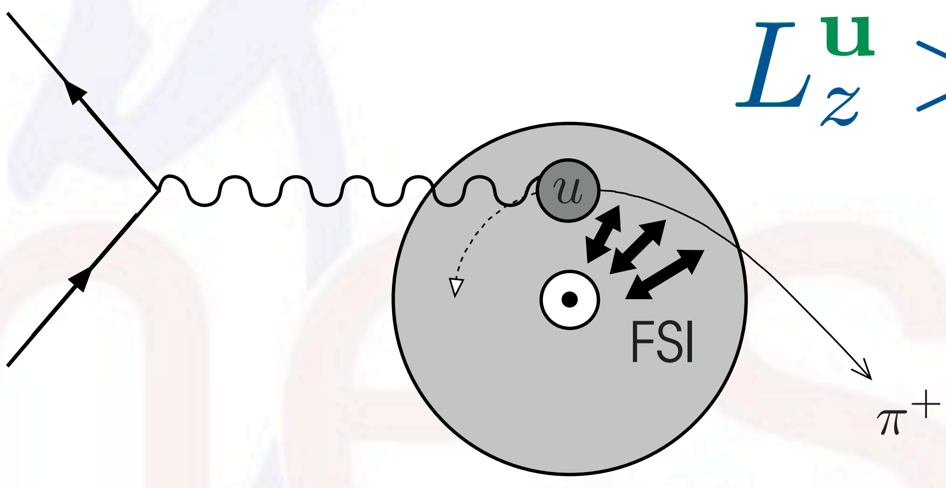
$$L_z^{\mathbf{u}} > 0$$



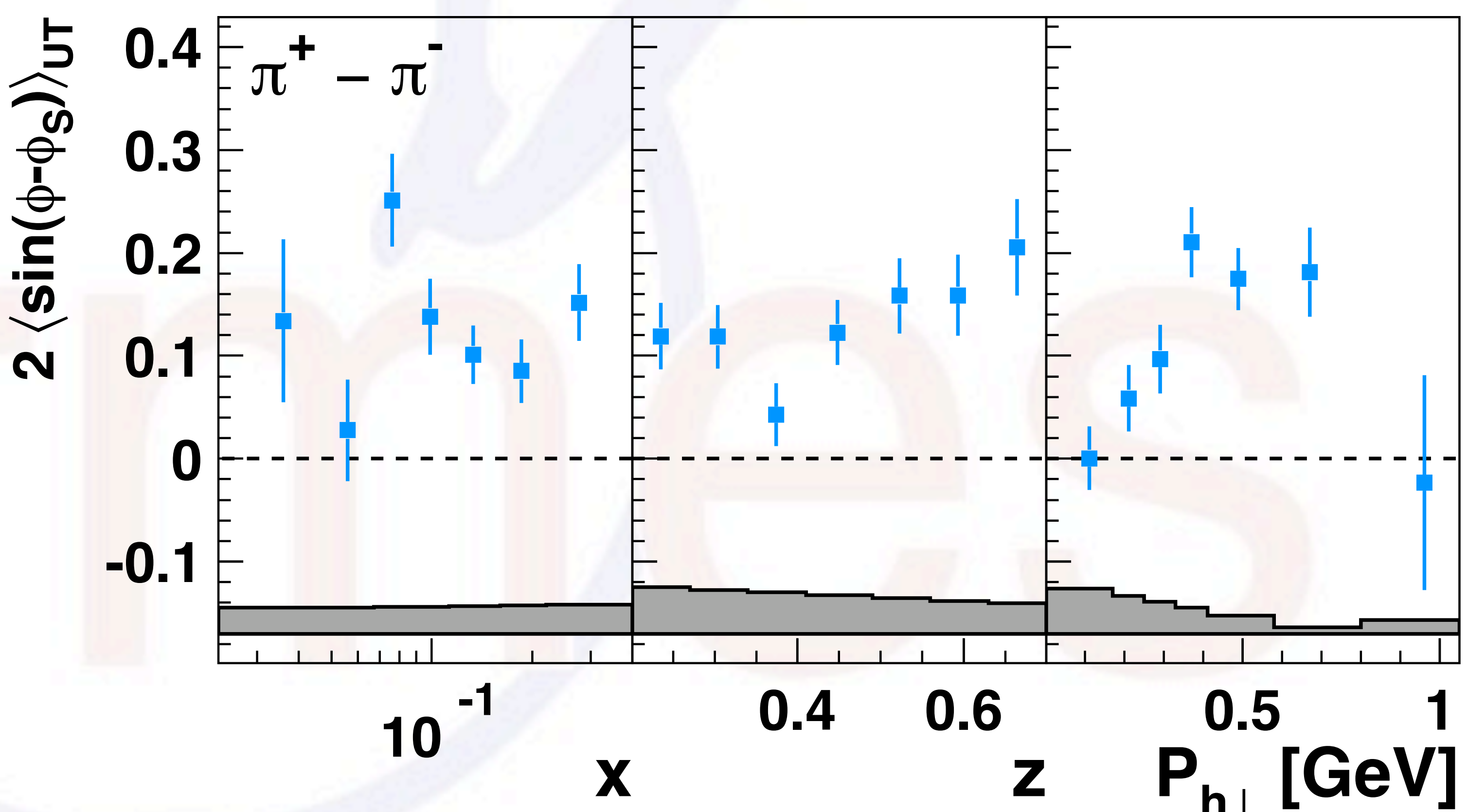
[*M. Burkardt*, Phys. Rev. D66 (2002) 014005]

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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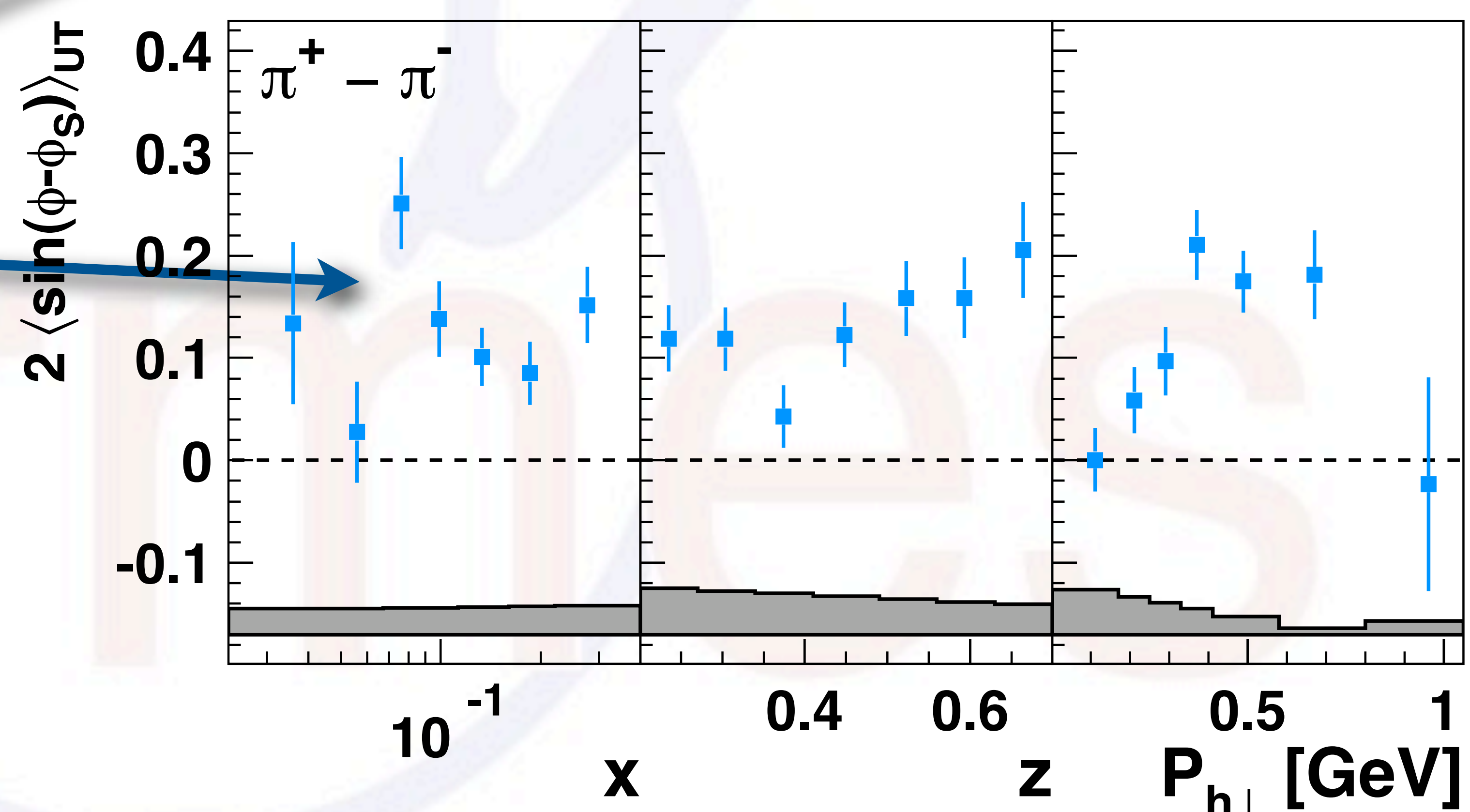
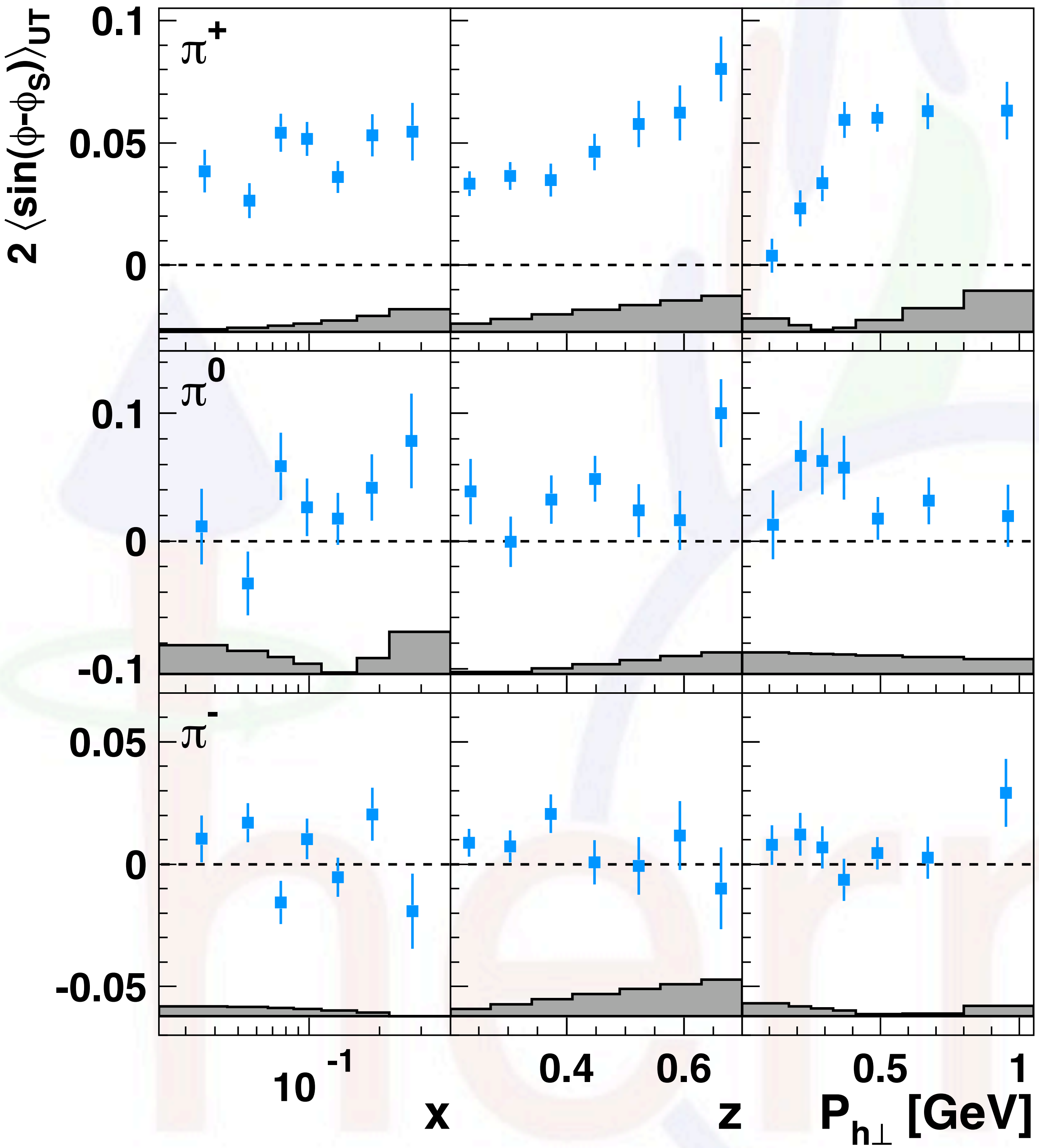
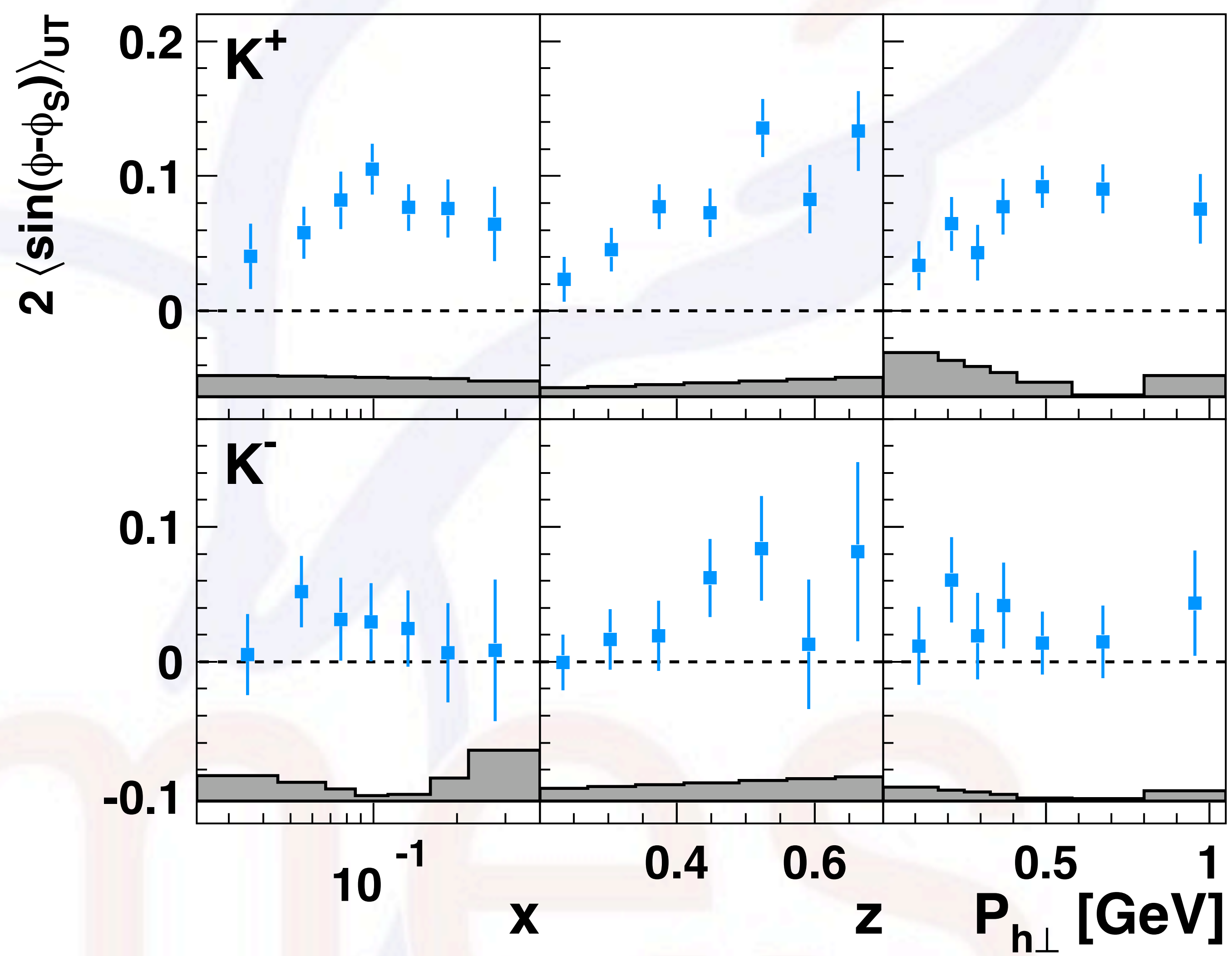
access to Sivers

u-valence distribution

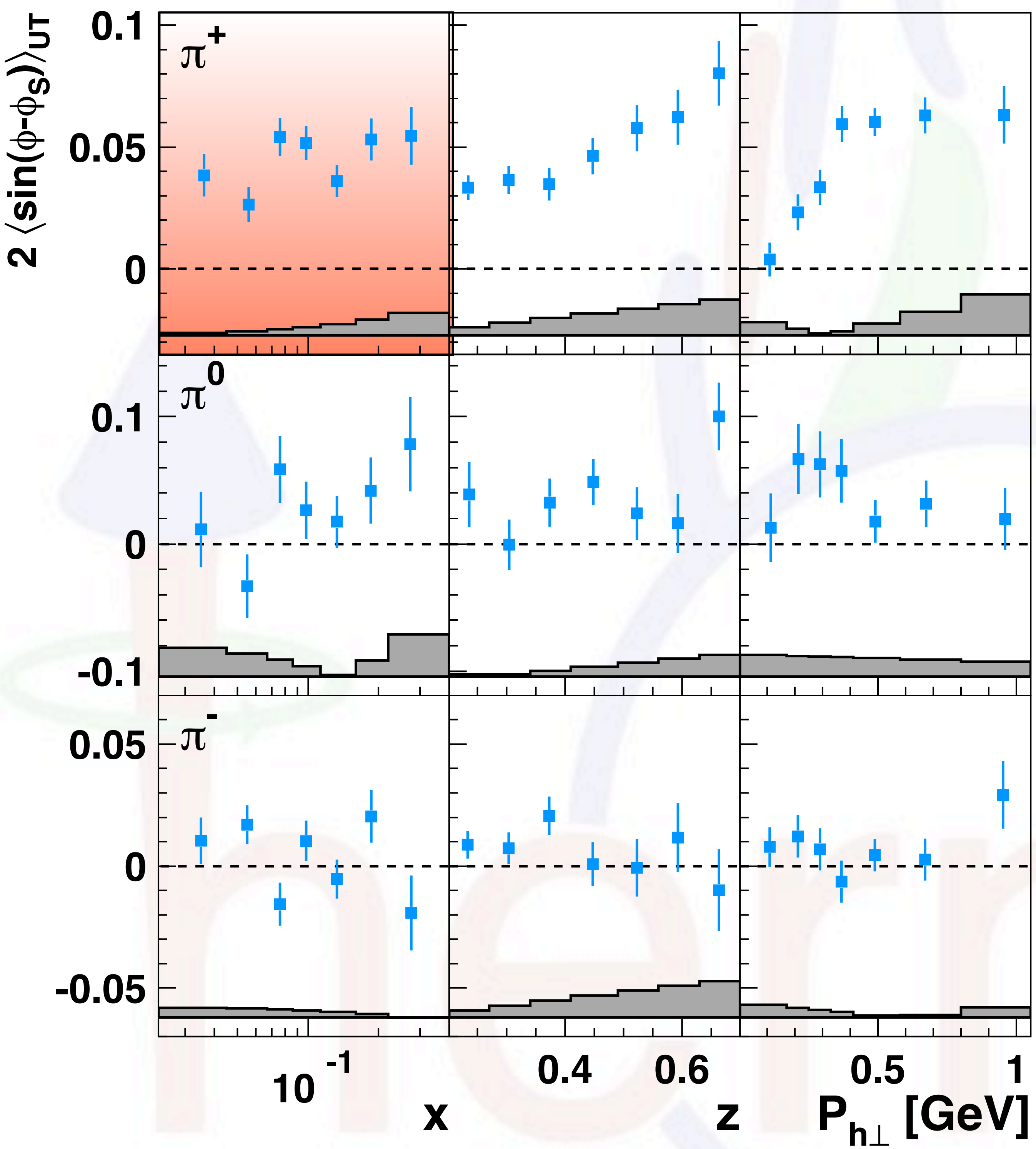


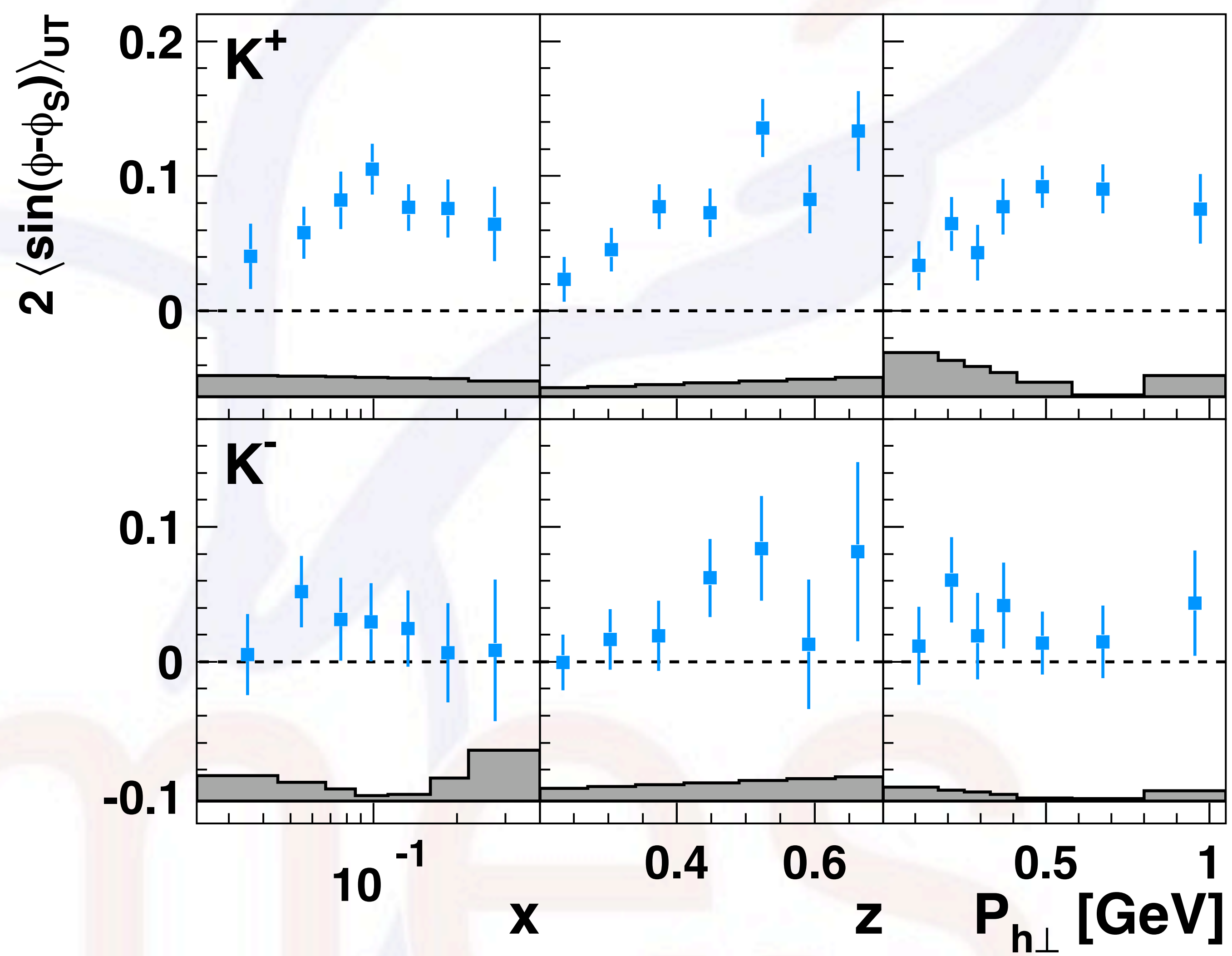
The kaon Sivers amplitudes





The kaon Sivers amplitudes





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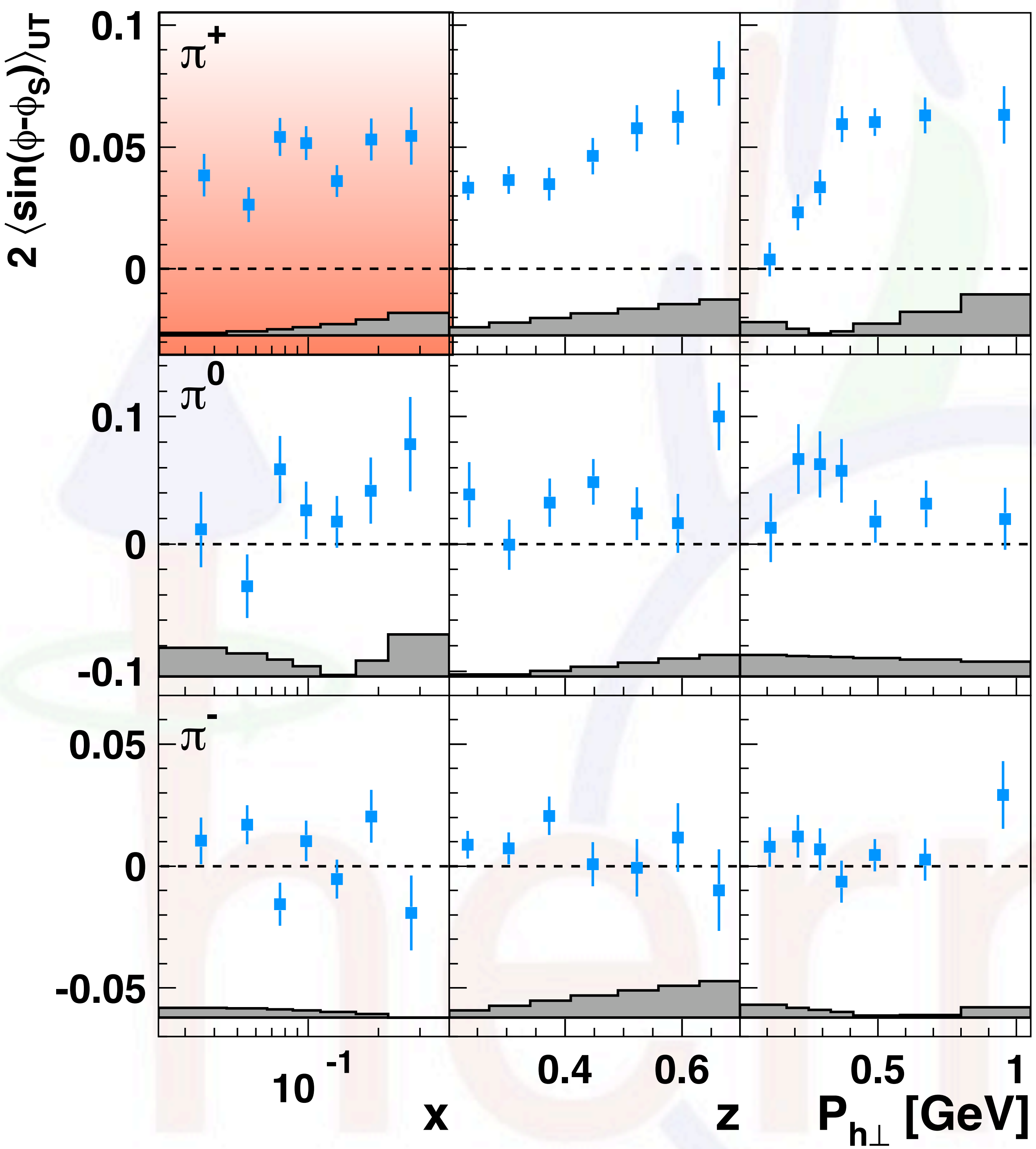
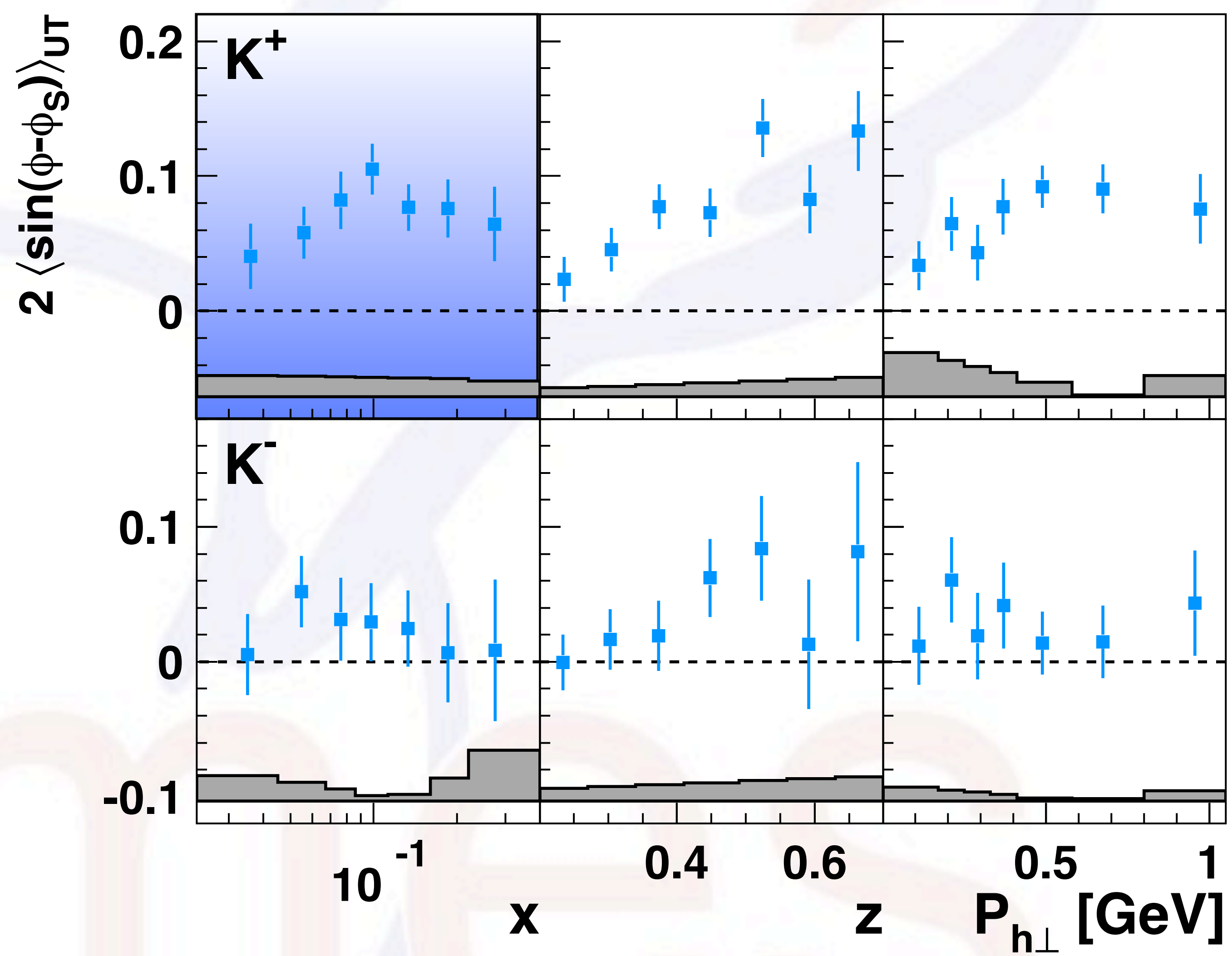
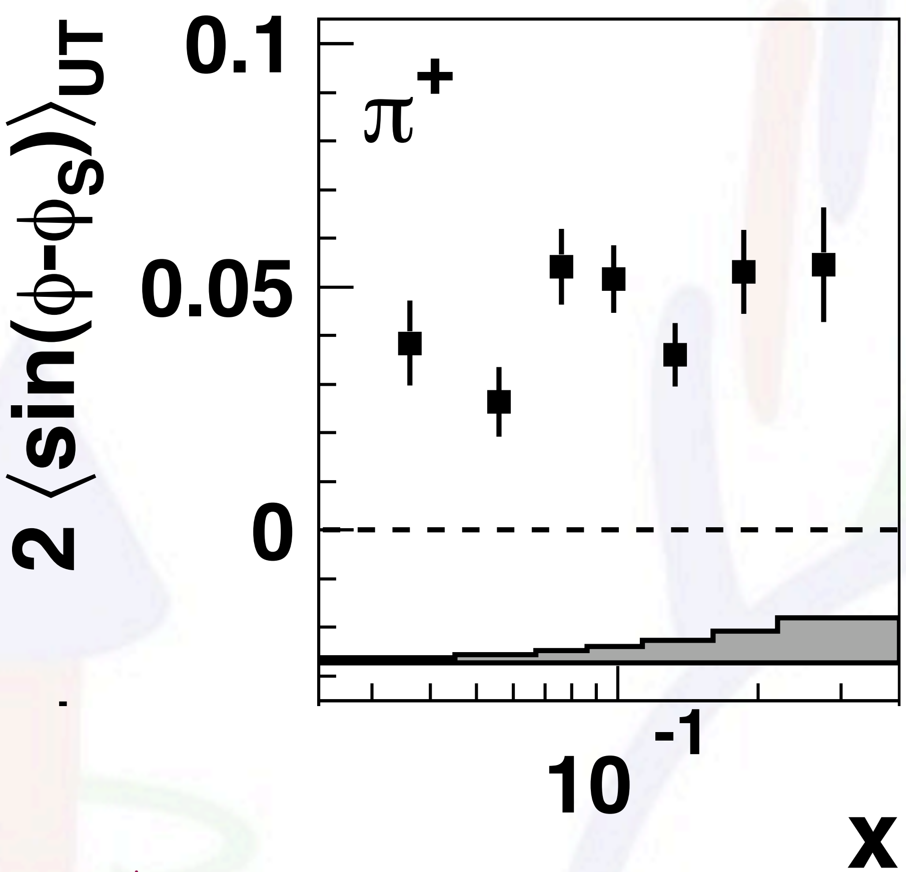
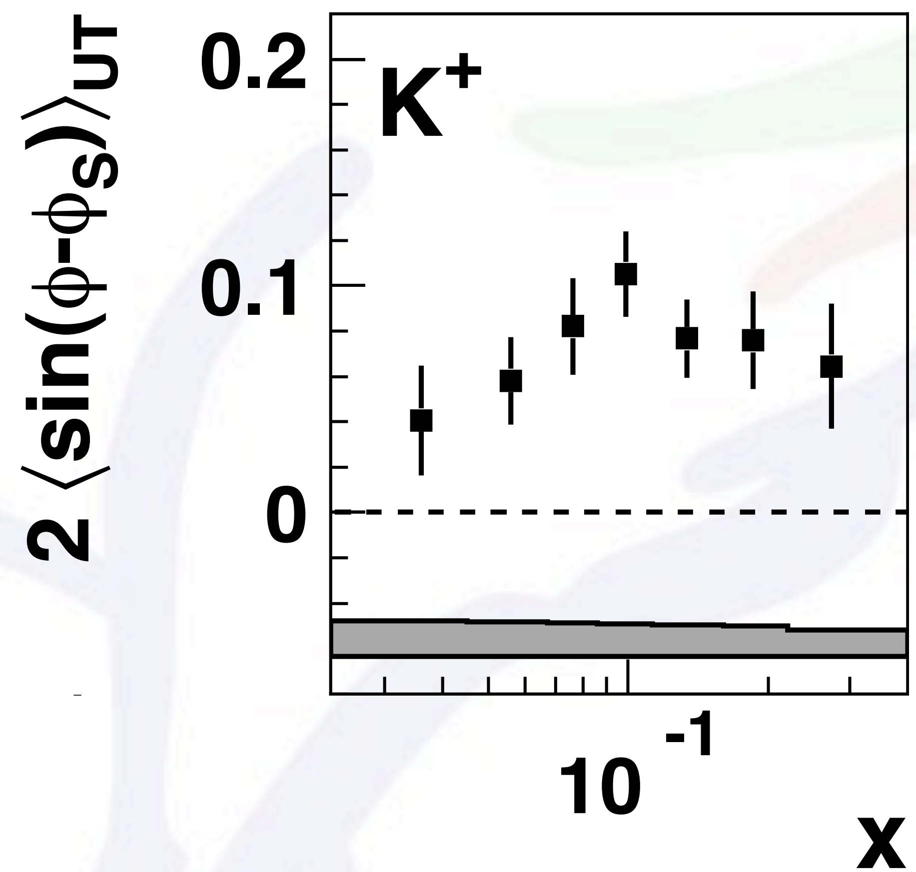




The "Kaon Challenge"





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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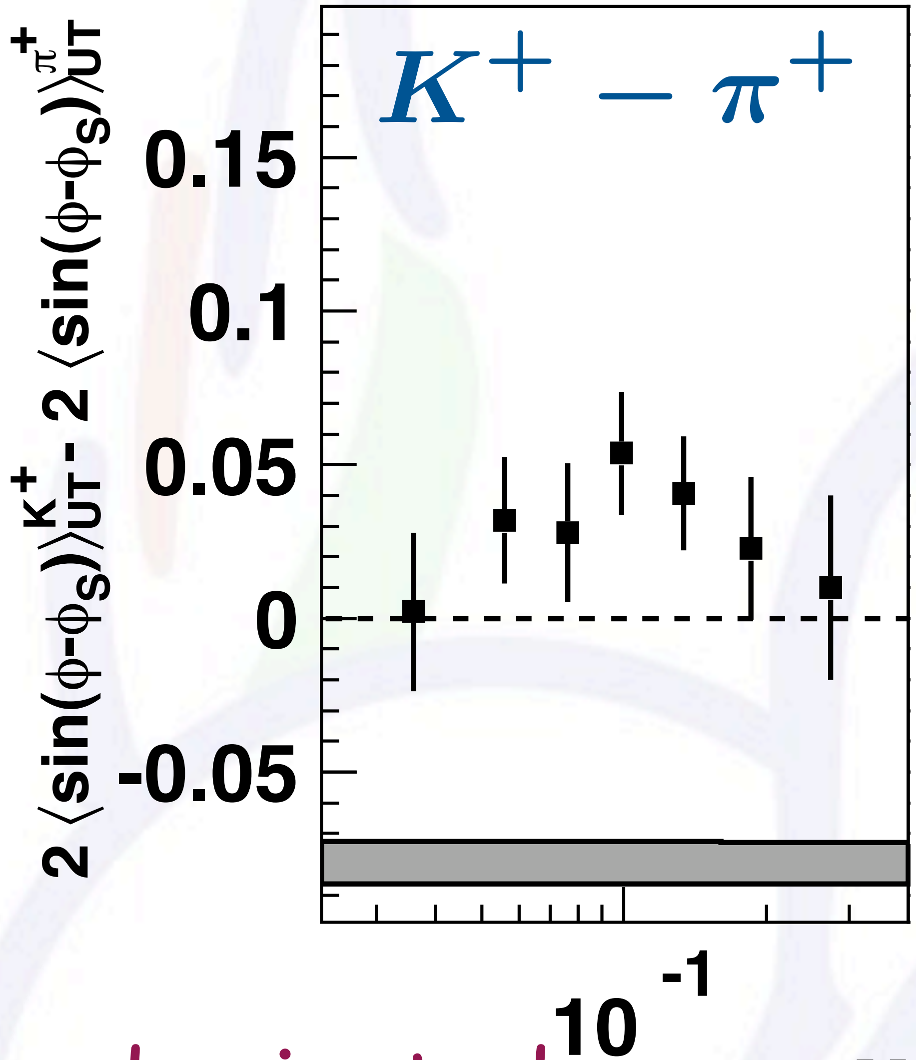

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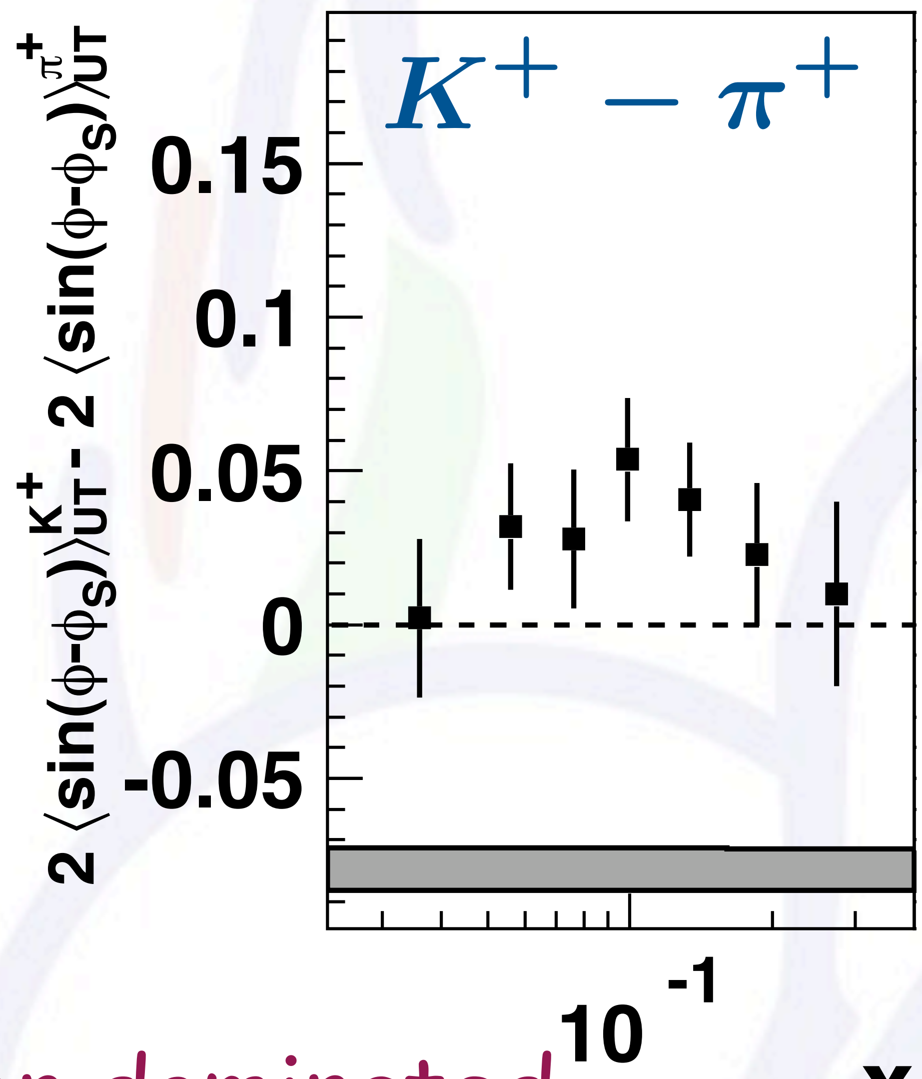

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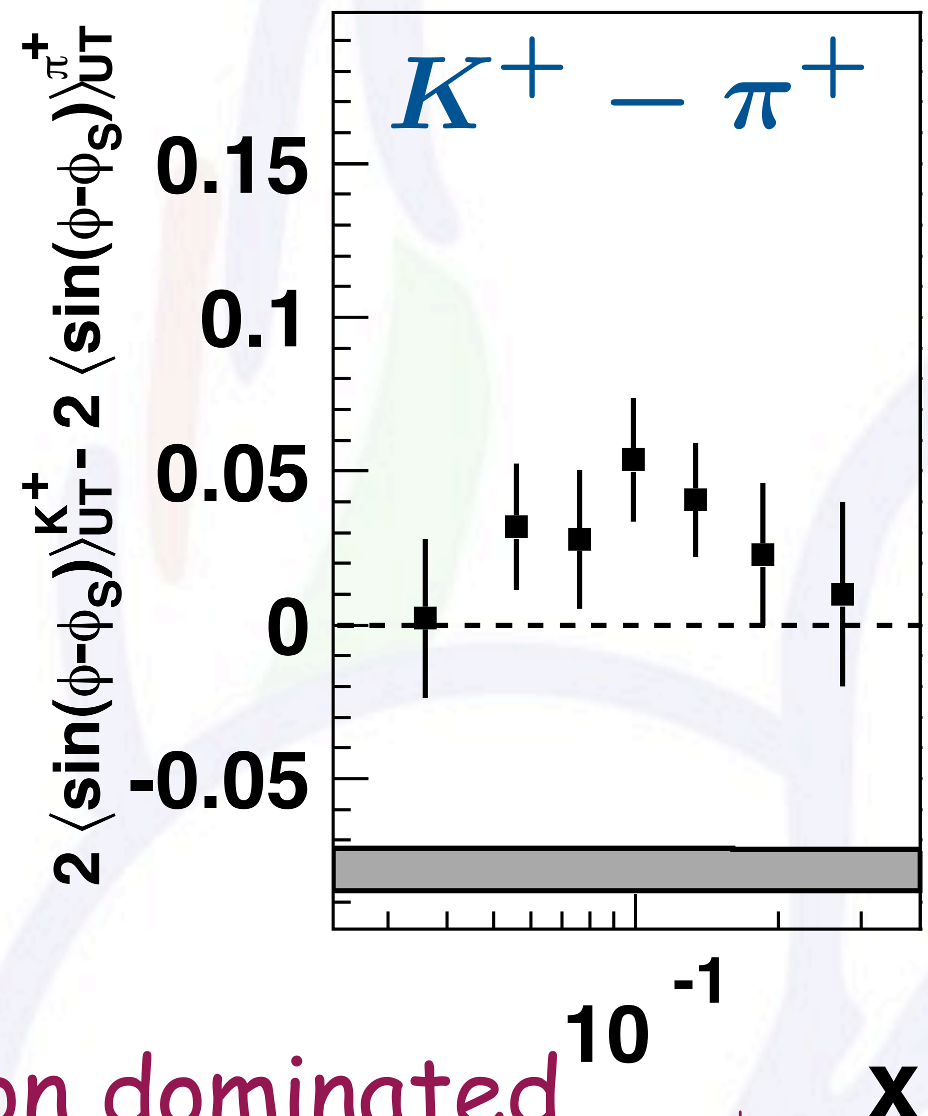
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

The "Kaon Challenge"



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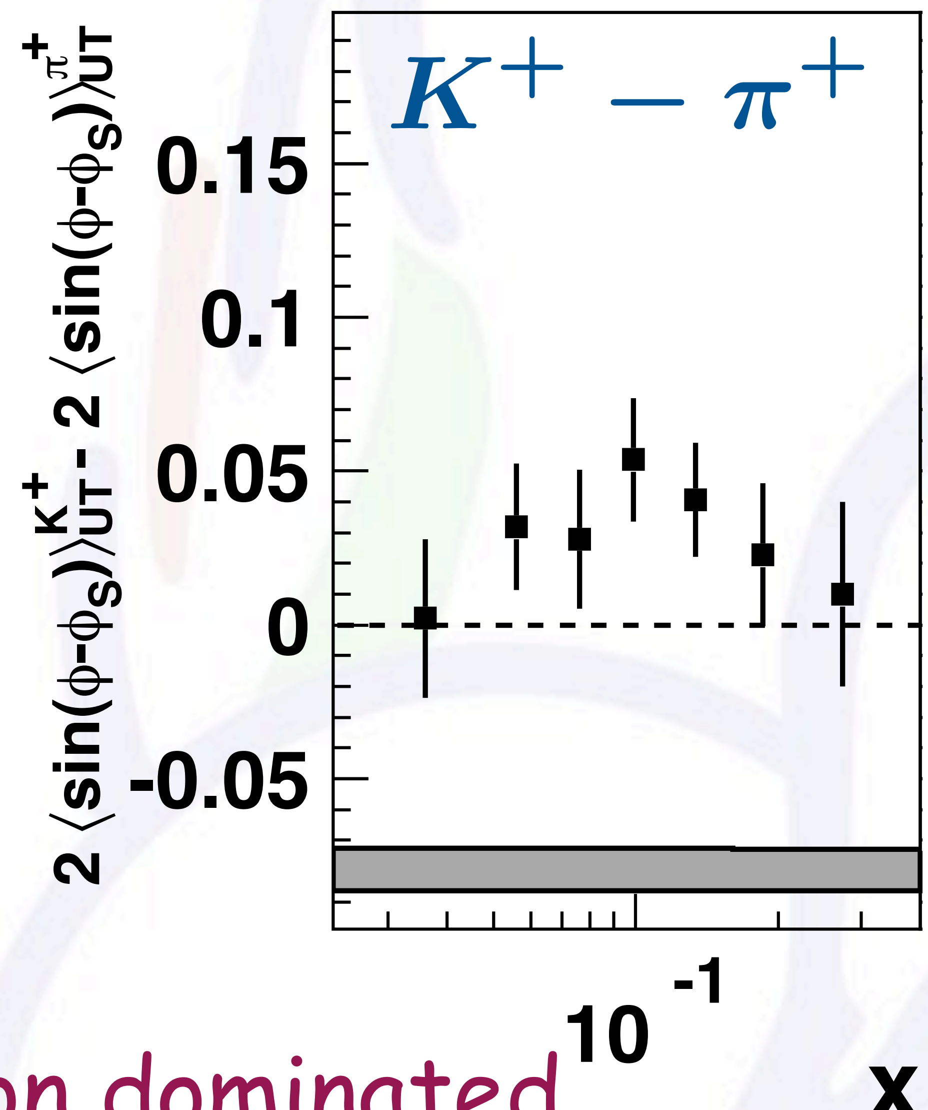
- convolution integrals depend on k_T dependence of fragmentation functions

The "Kaon Challenge"



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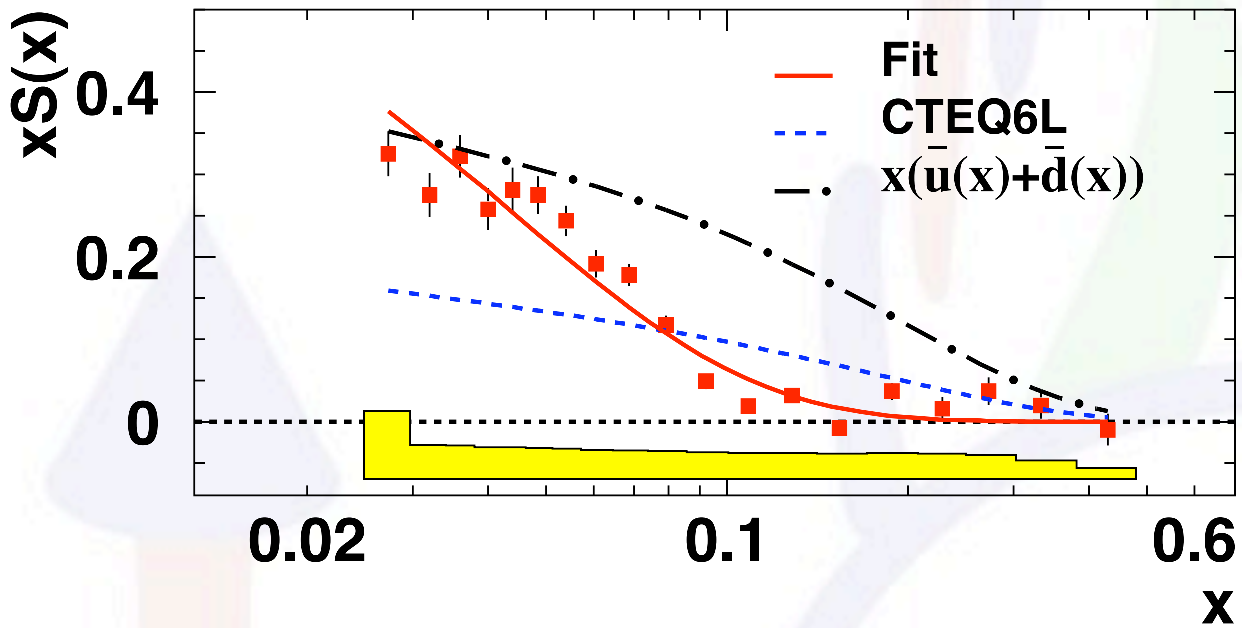
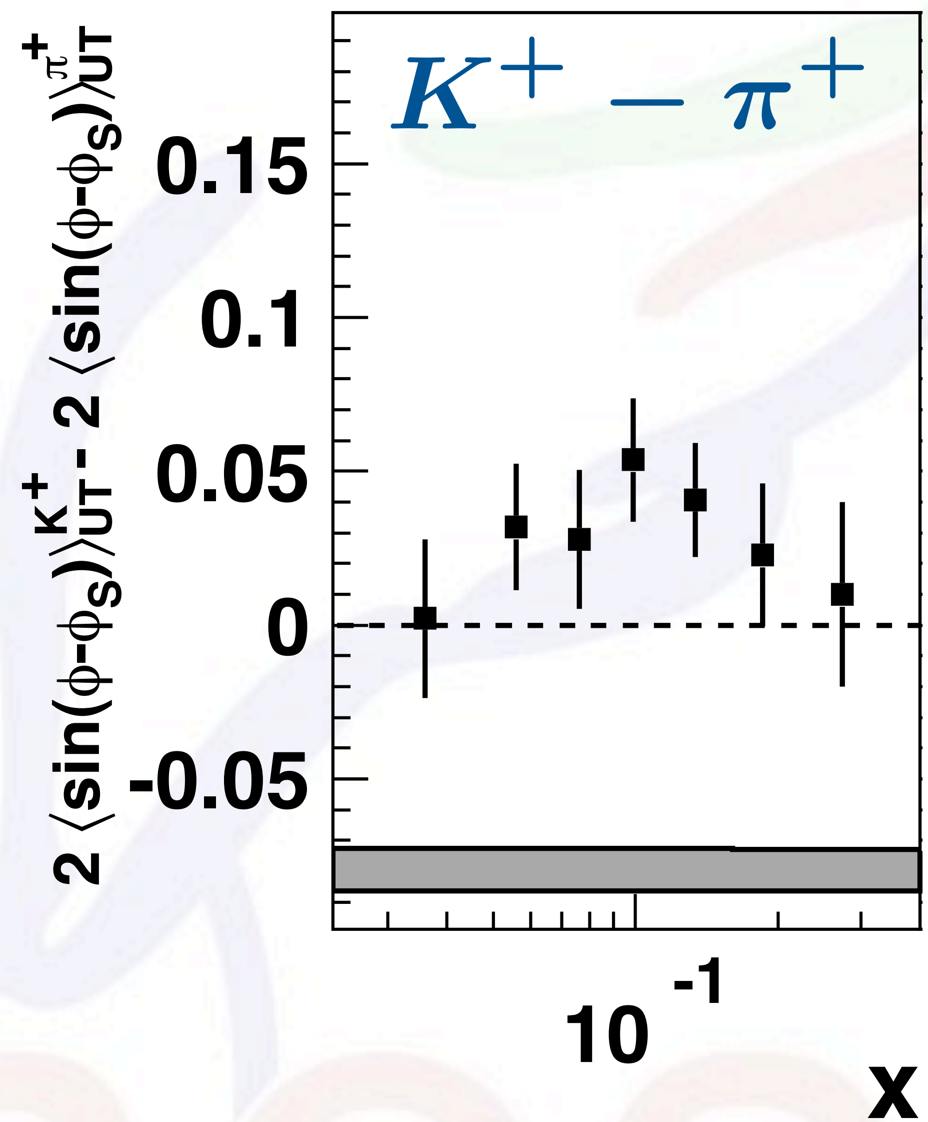
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on k_T dependence of fragmentation functions
- possible difference in dependences on the kinematics integrated over

Role of sea quarks

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





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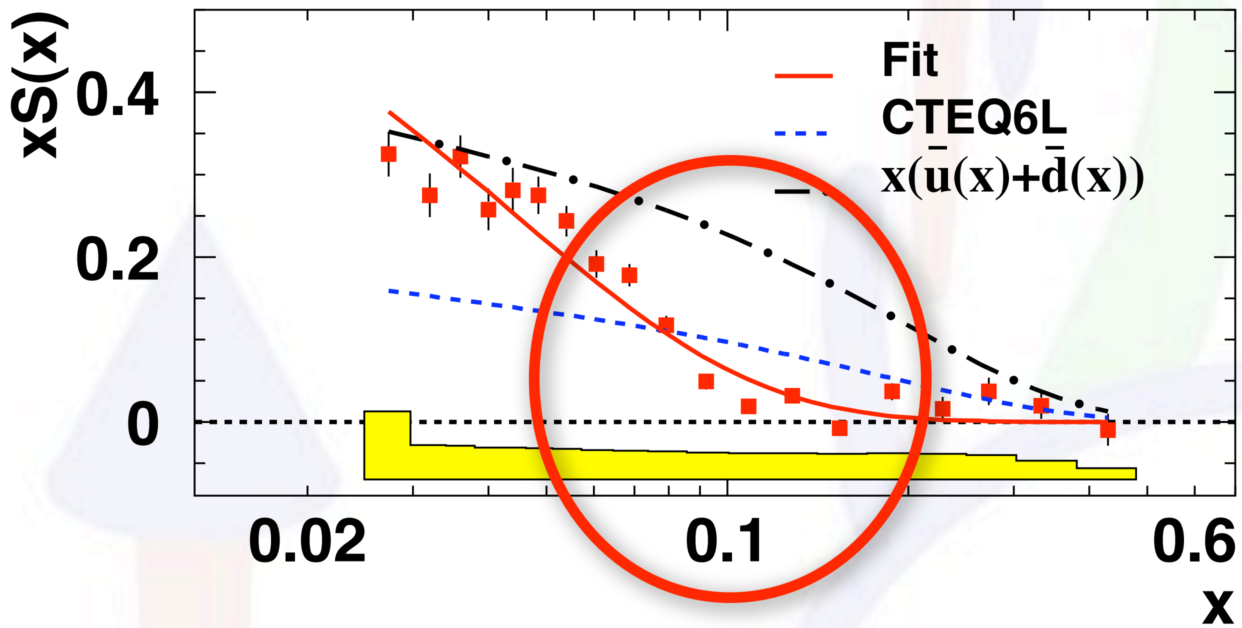
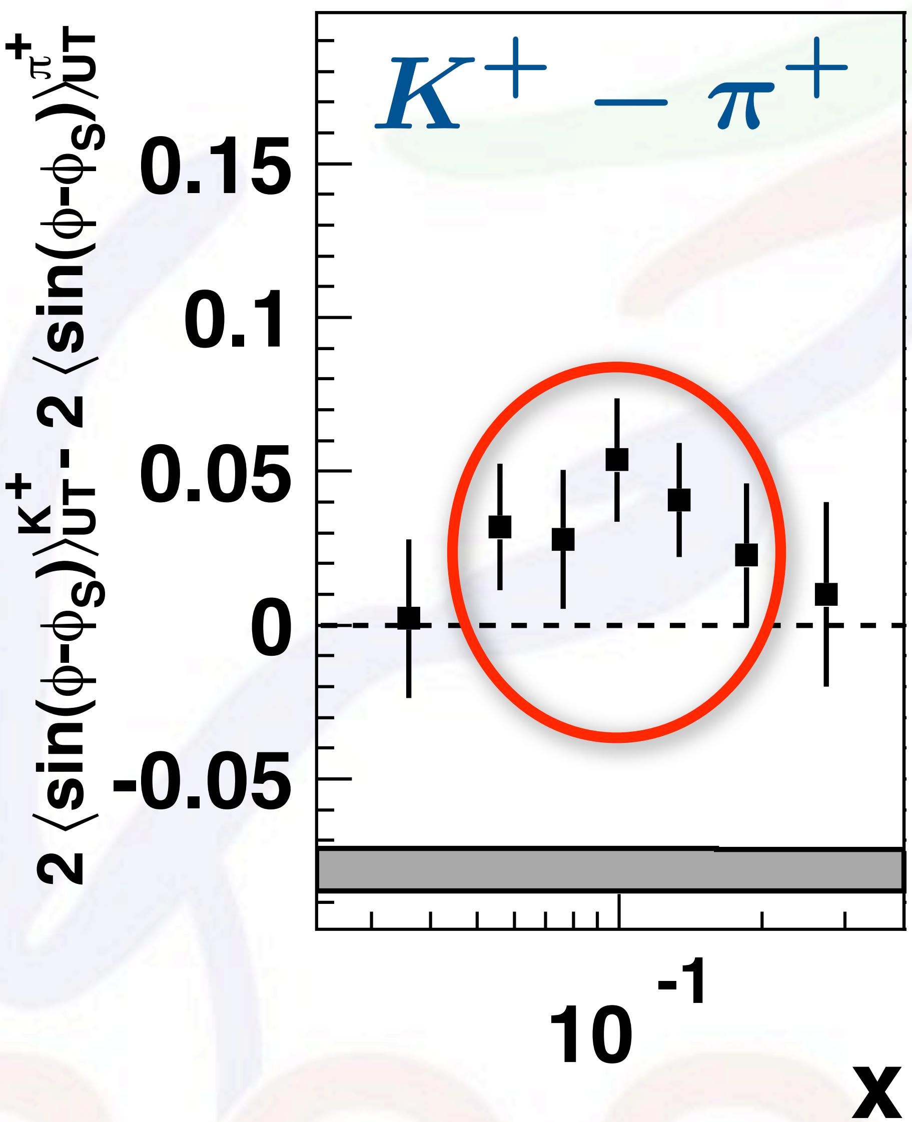
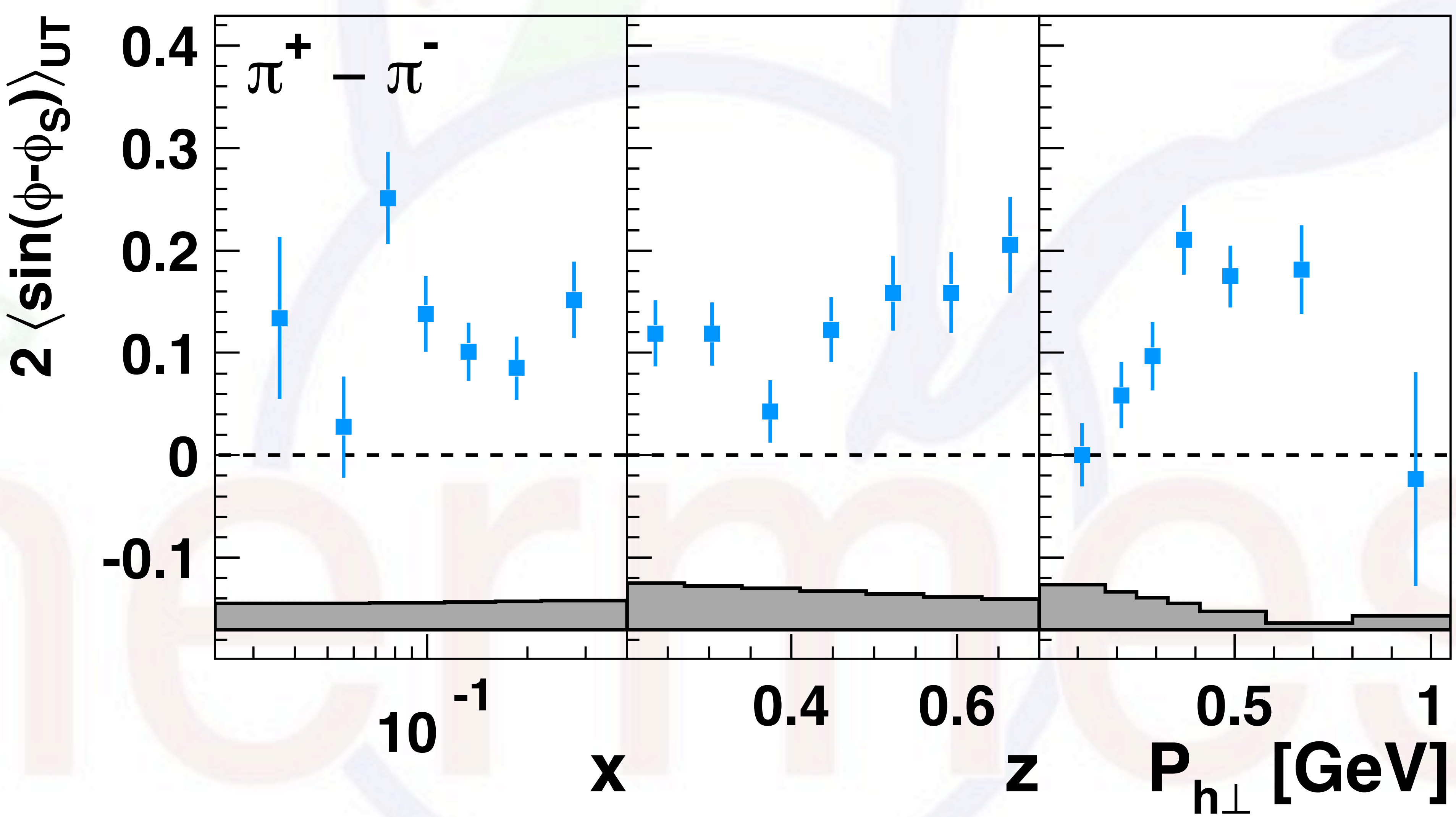




differences biggest in region where strange sea is most different from light sea

Cancelation of fragmentation function

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



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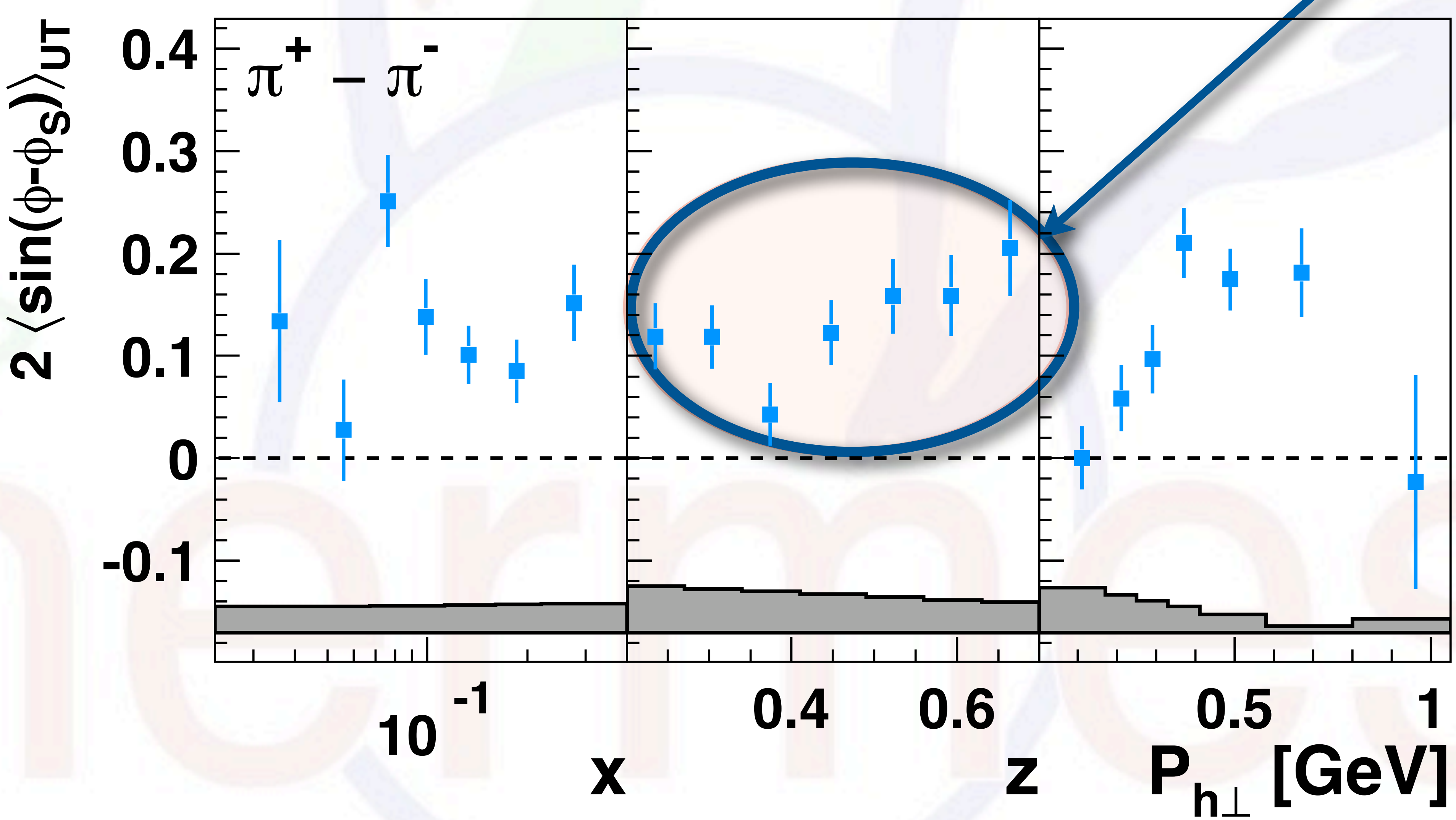
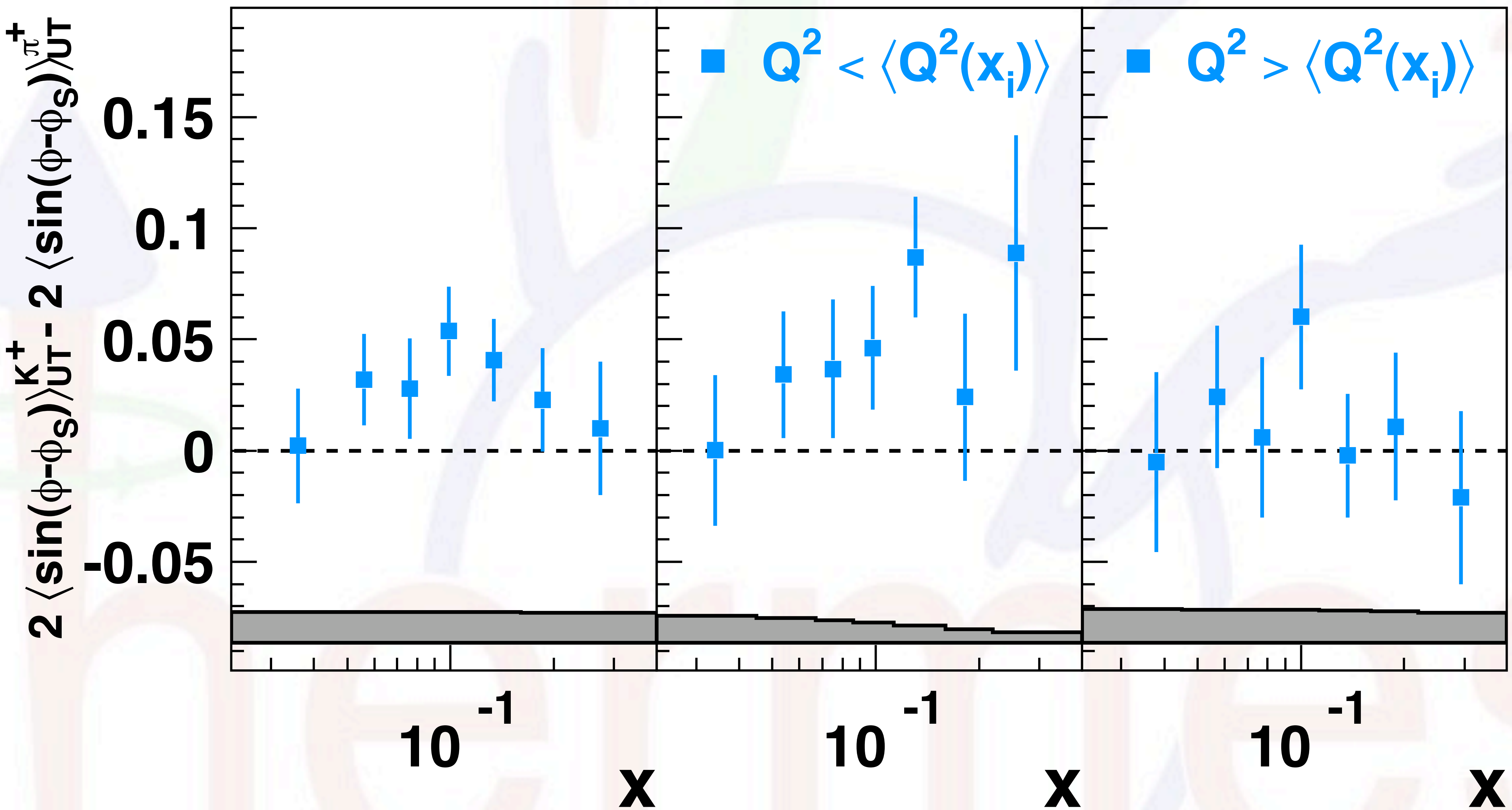
should be flat



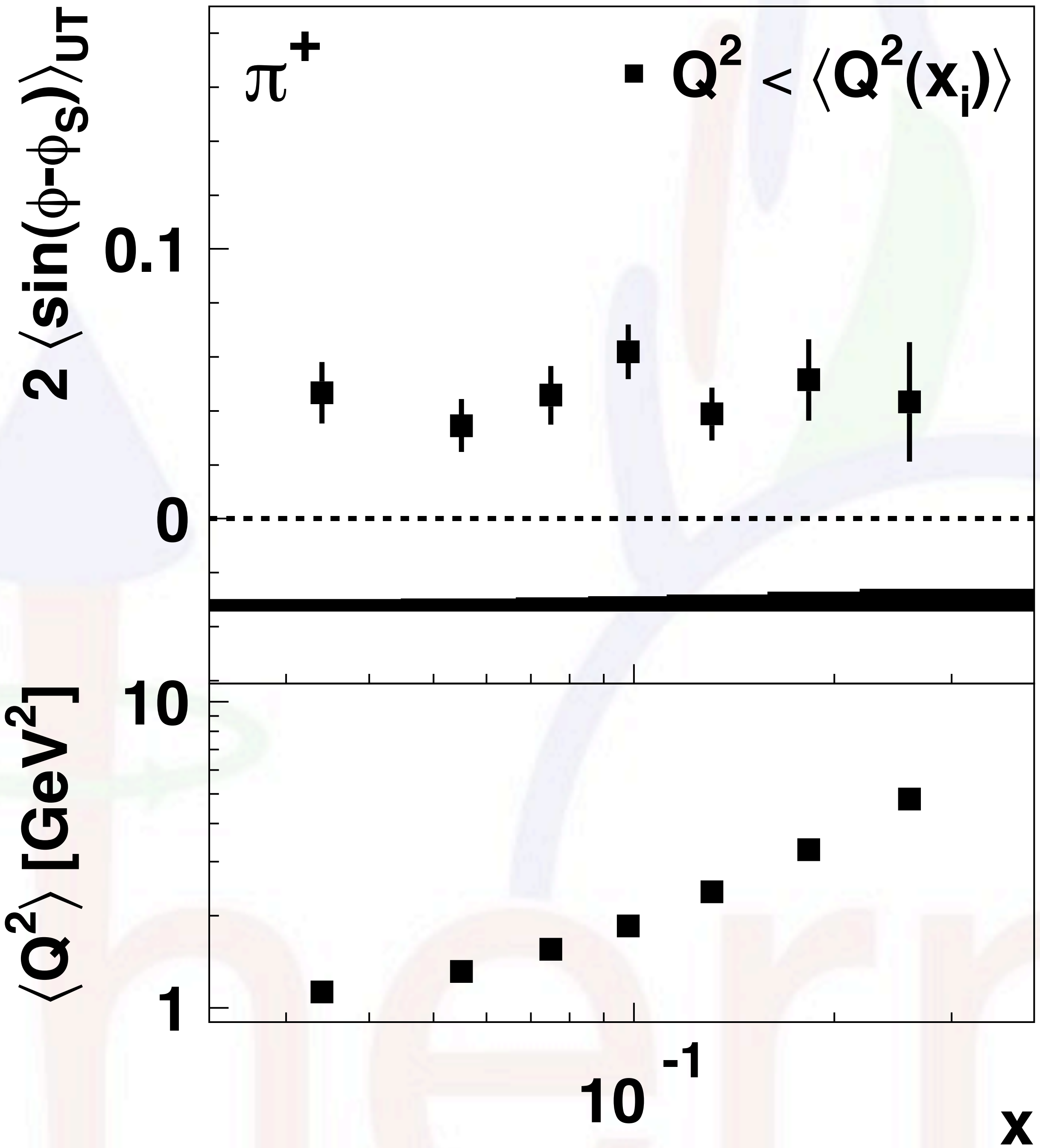
Q^2 dependence of amplitudes

- 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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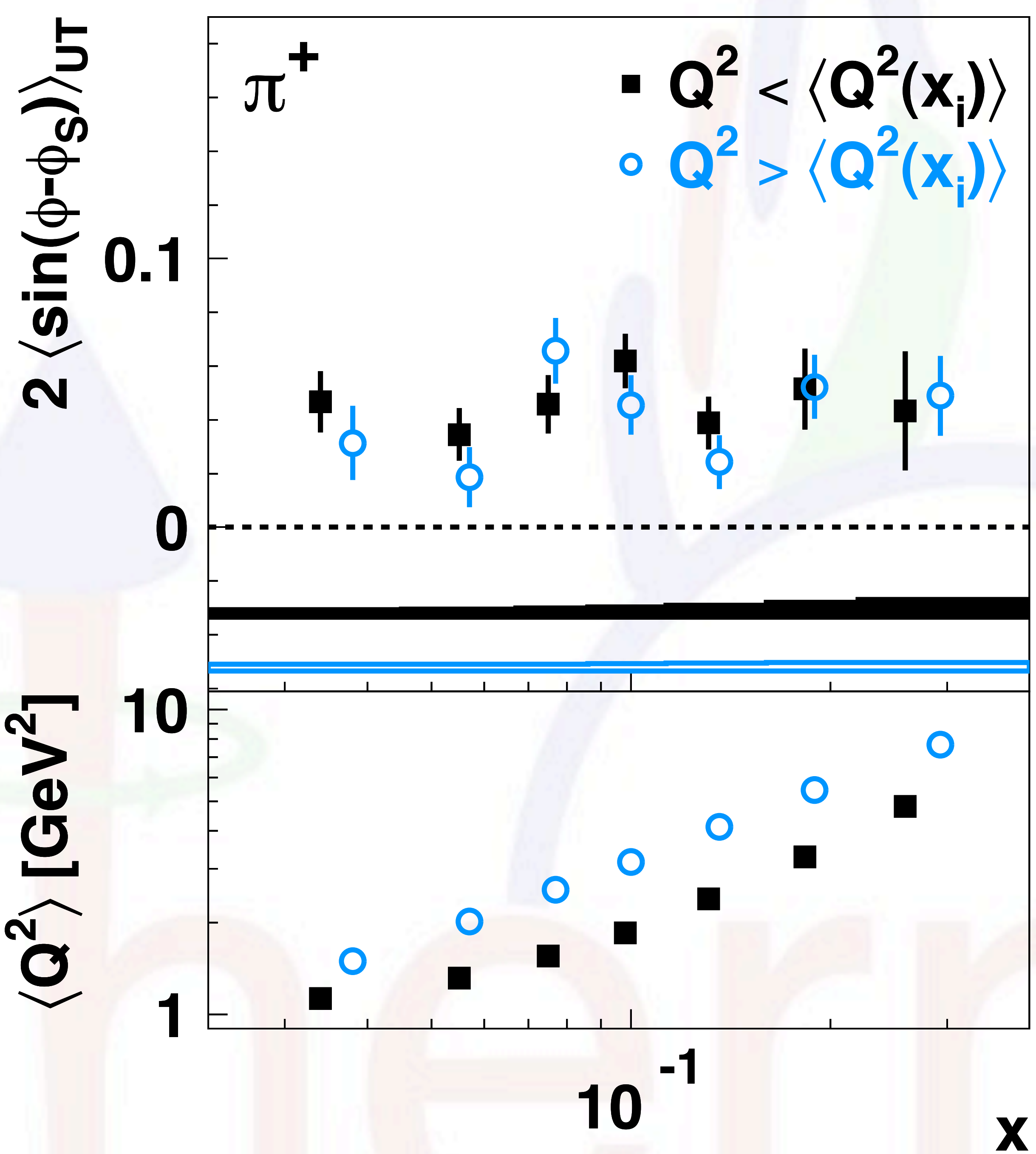
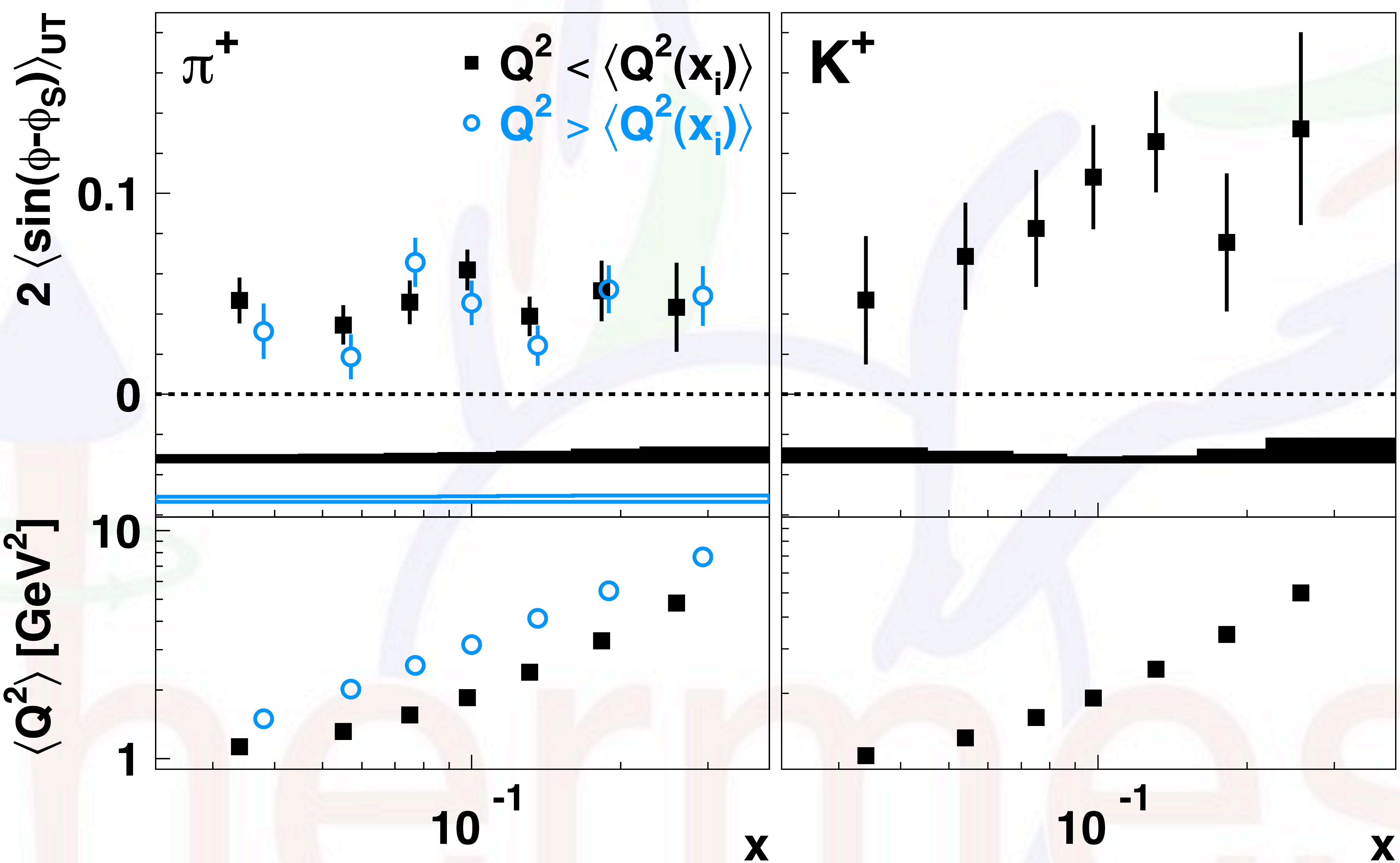
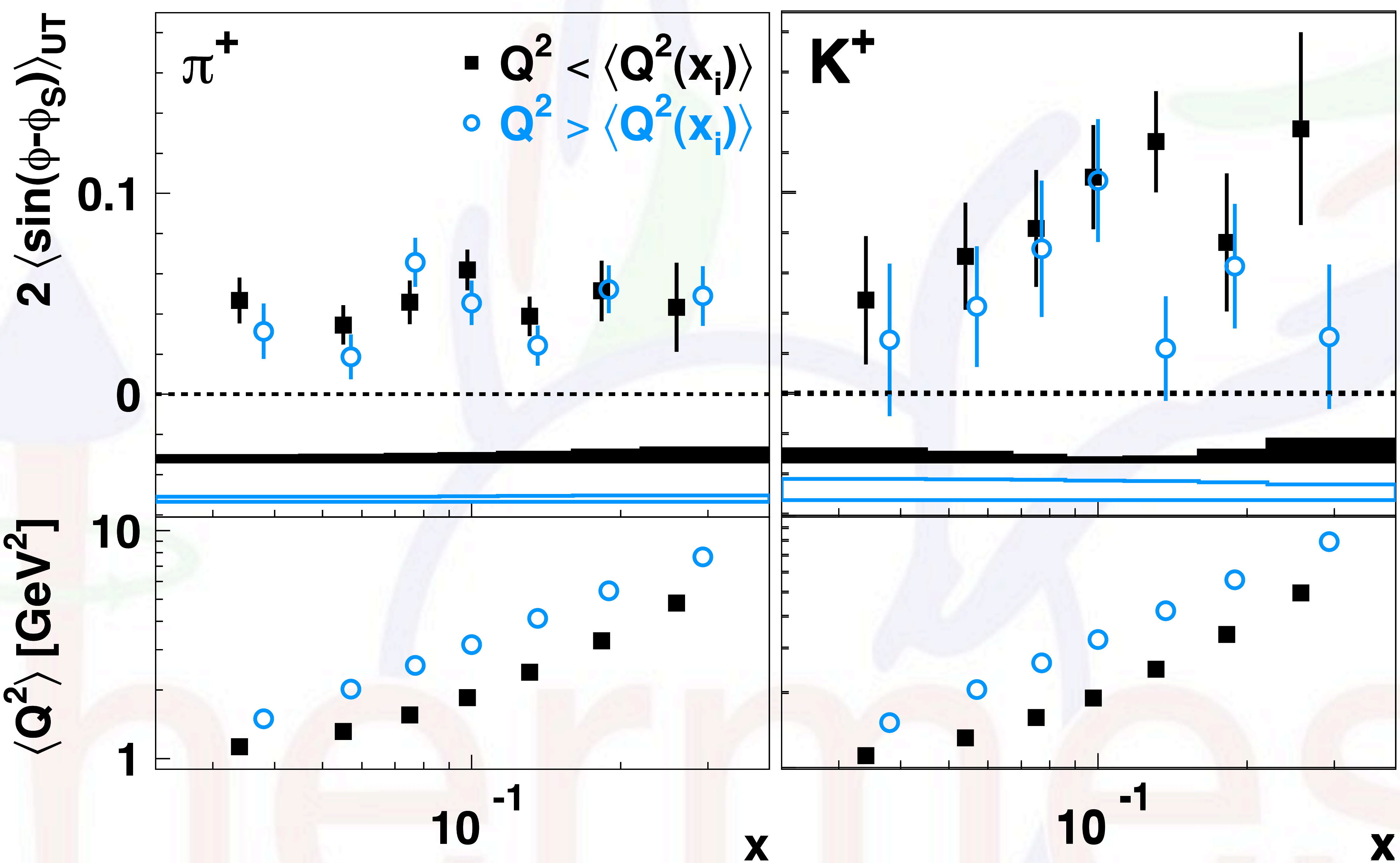


Q^2 dependence of amplitudes



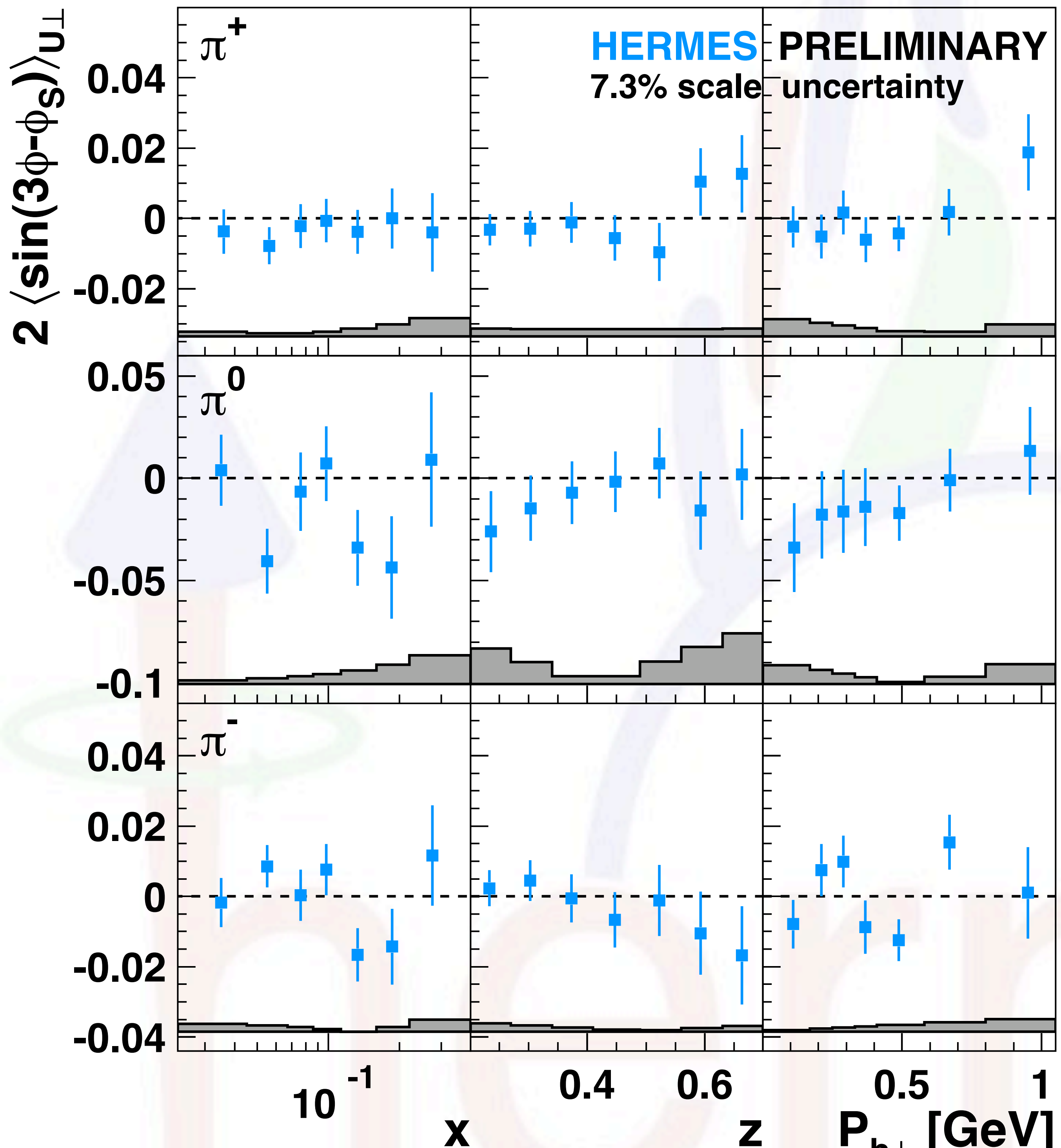
Q^2 dependence of amplitudes

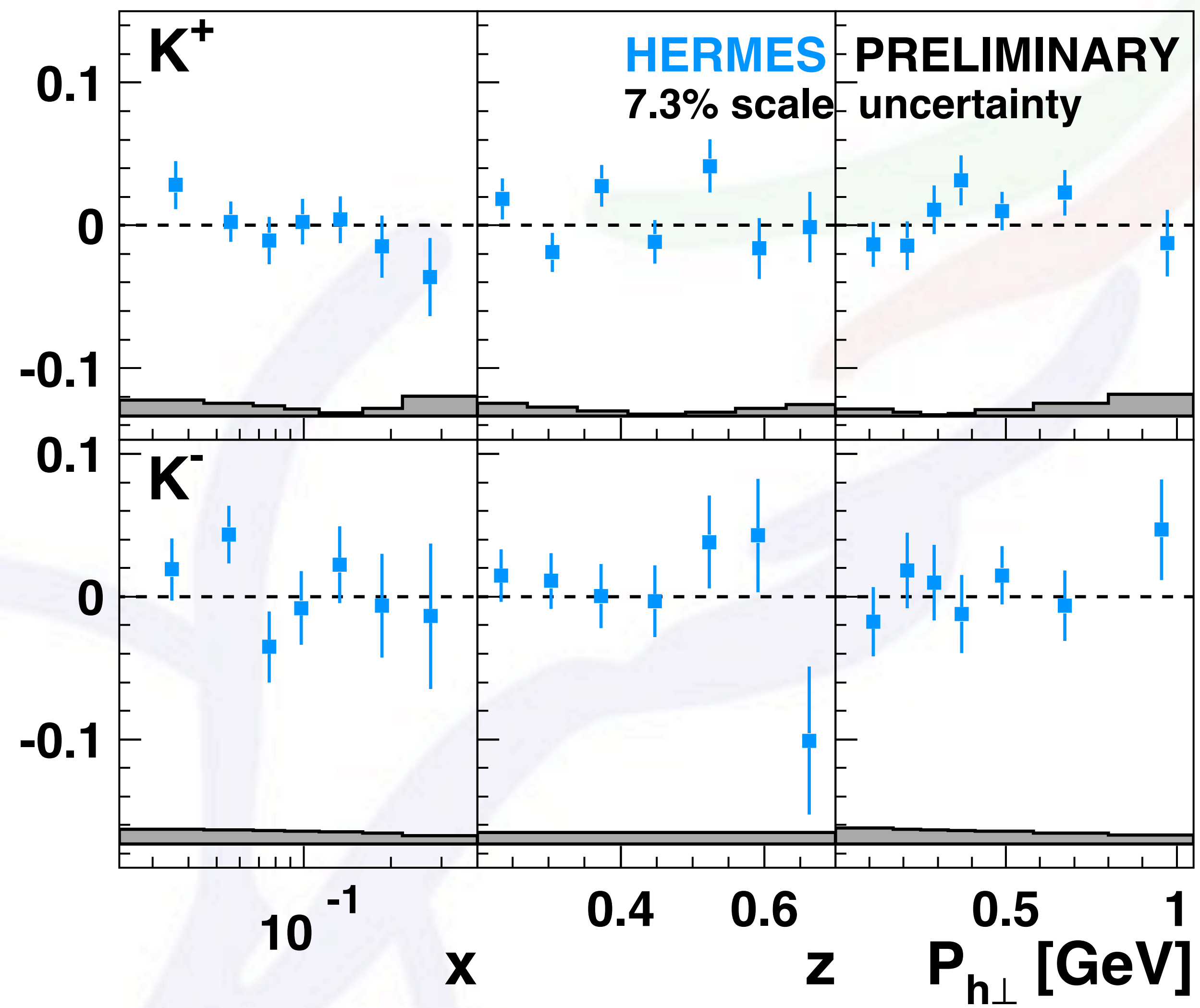


☛ hint of Q^2 dependence of kaon amplitude

The “others”

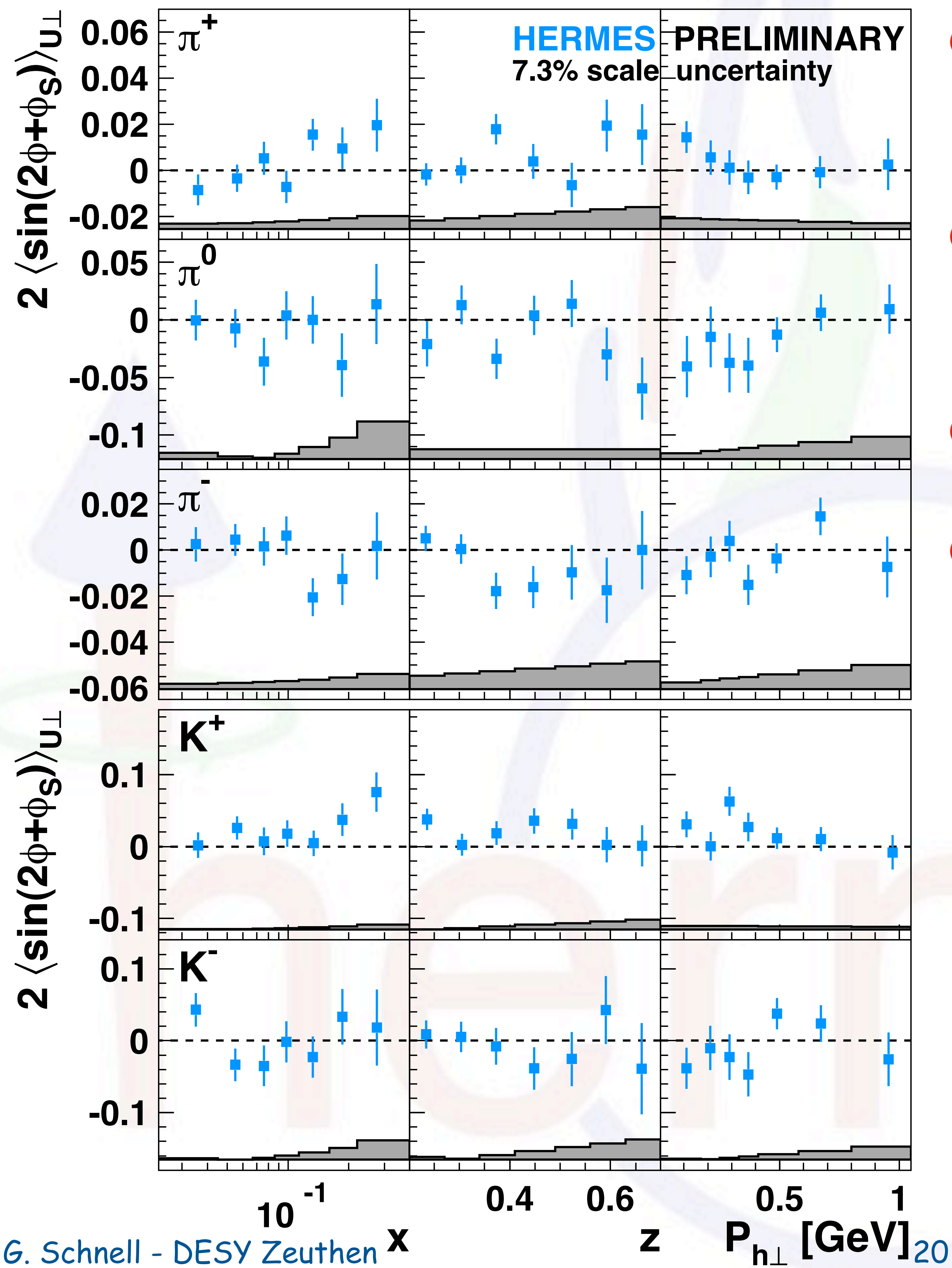
Pretzelosity - $\sin(3\phi-\phi_S)$



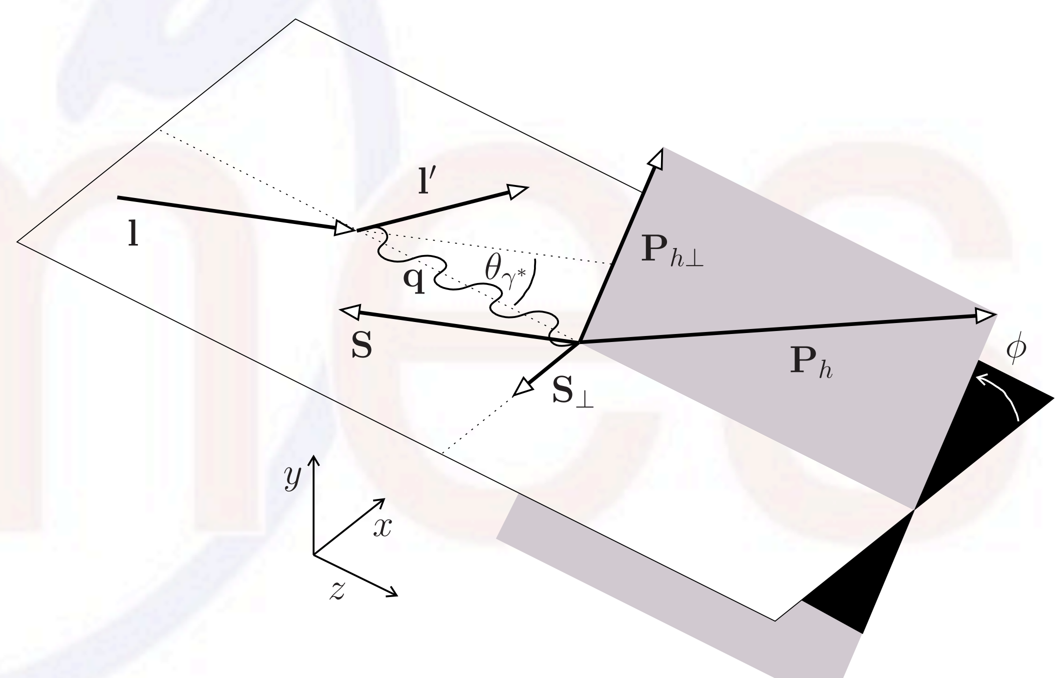


- no significant non-zero signal observed
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

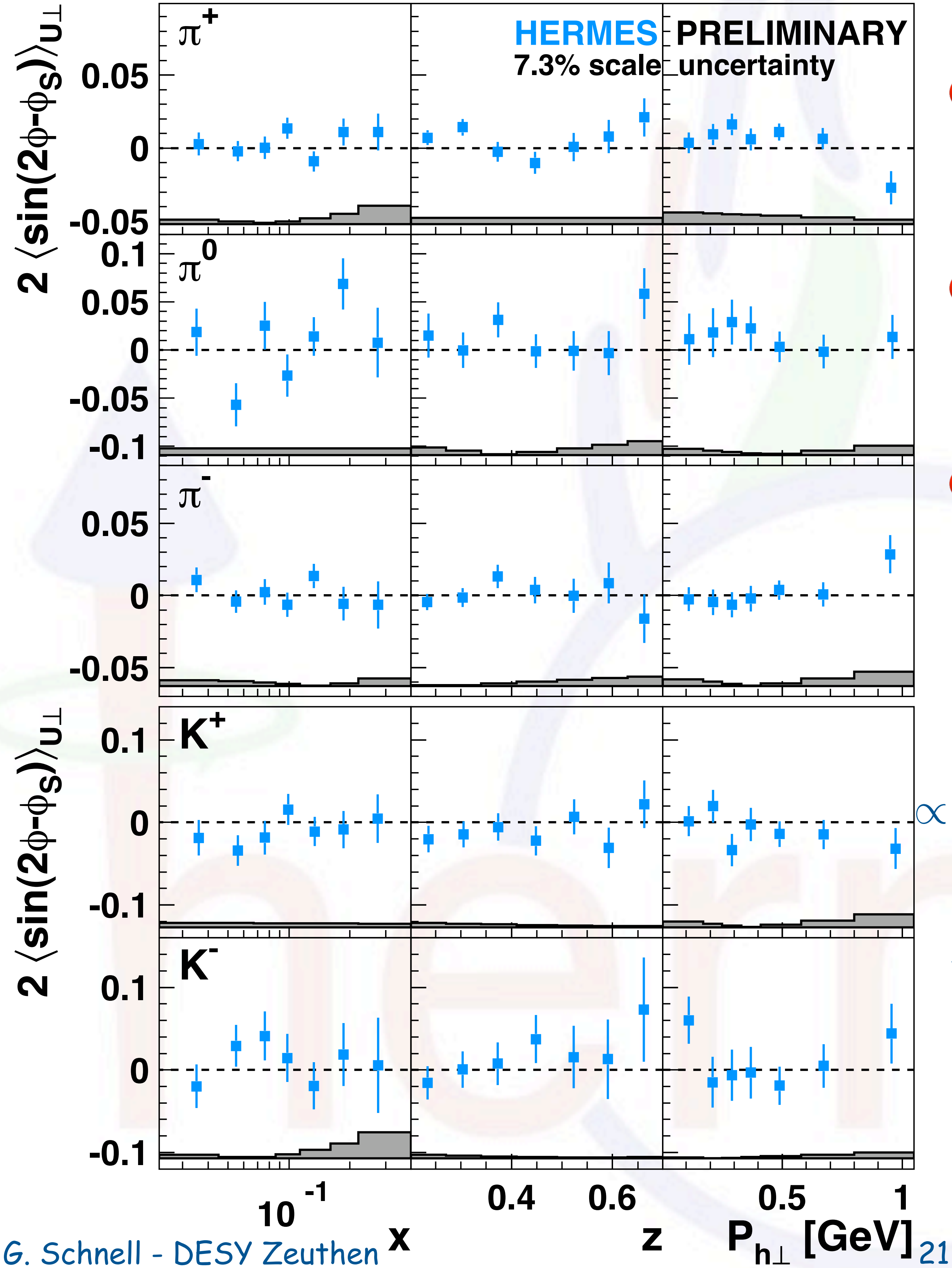
Subleading twist I - sin(2ϕ+ϕ$_S$)



- 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%)



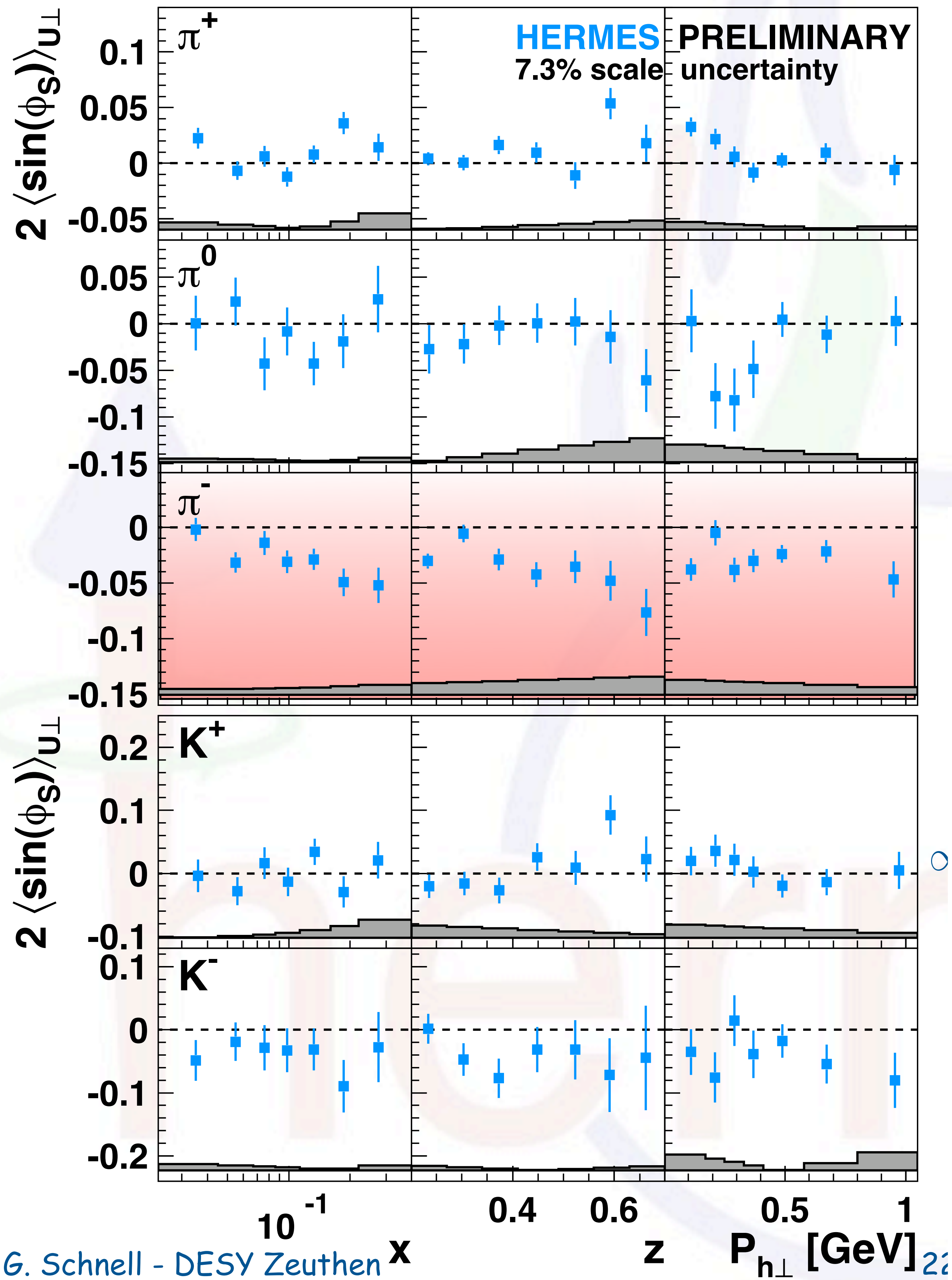
Subleading twist II - $\sin(2\phi-\phi_s)$



- 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.:

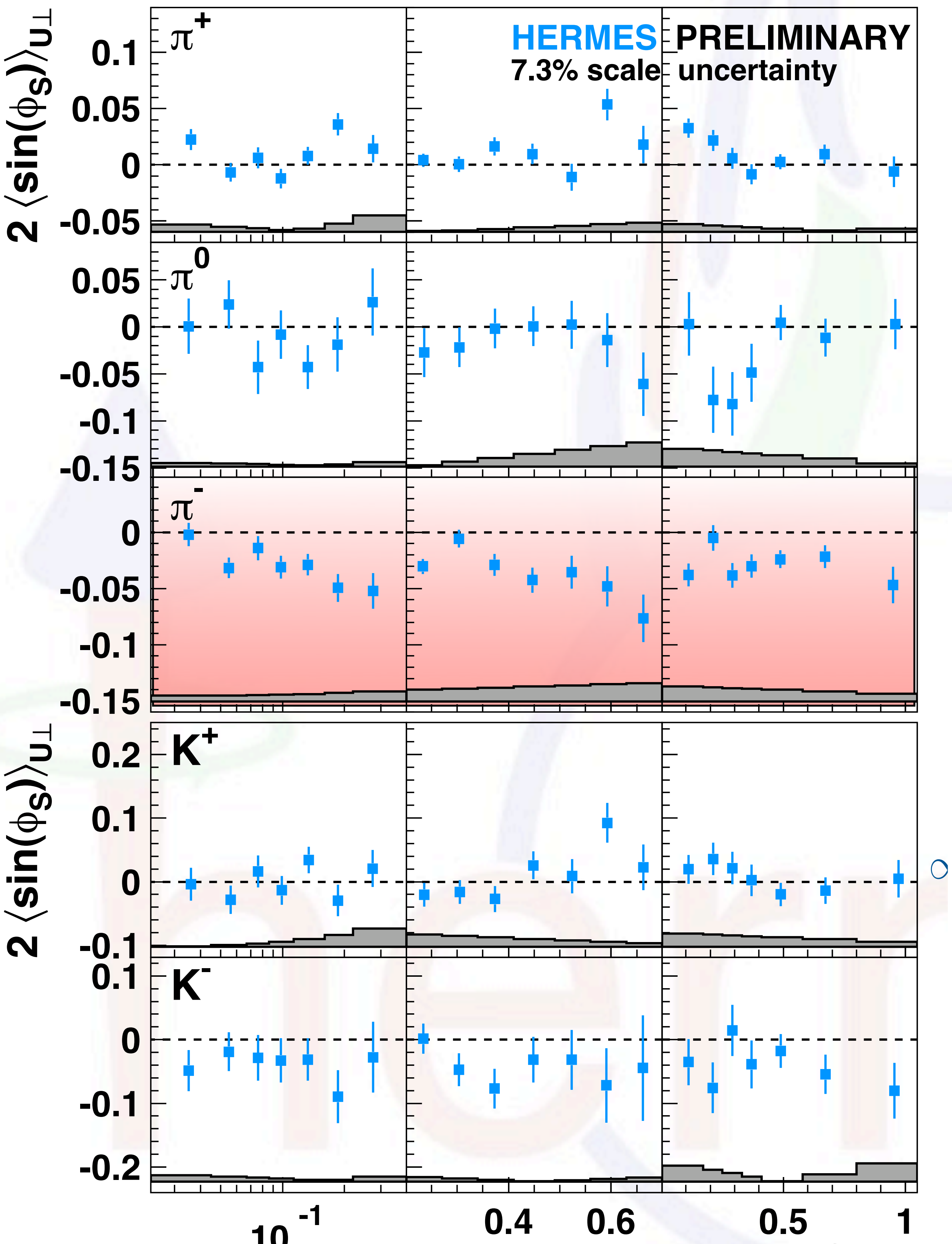
$$\propto \mathcal{W}_1(p_T,k_T,P_{h\perp})\left(xf_T^\perp D_1-\frac{M_h}{M}h_{1T}^\perp\frac{\tilde{H}}{z}\right)$$
$$-\mathcal{W}_2(p_T,k_T,P_{h\perp})\left[\left(xh_T H_1^\perp+\frac{M_h}{M}g_{1T}\frac{\tilde{G}^\perp}{z}\right)+\left(xh_T^\perp H_1^\perp-\frac{M_h}{M}f_{1T}^\perp\frac{\tilde{D}^\perp}{z}\right)\right]$$

Subleading twist III - sin(ϕ_S)



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

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



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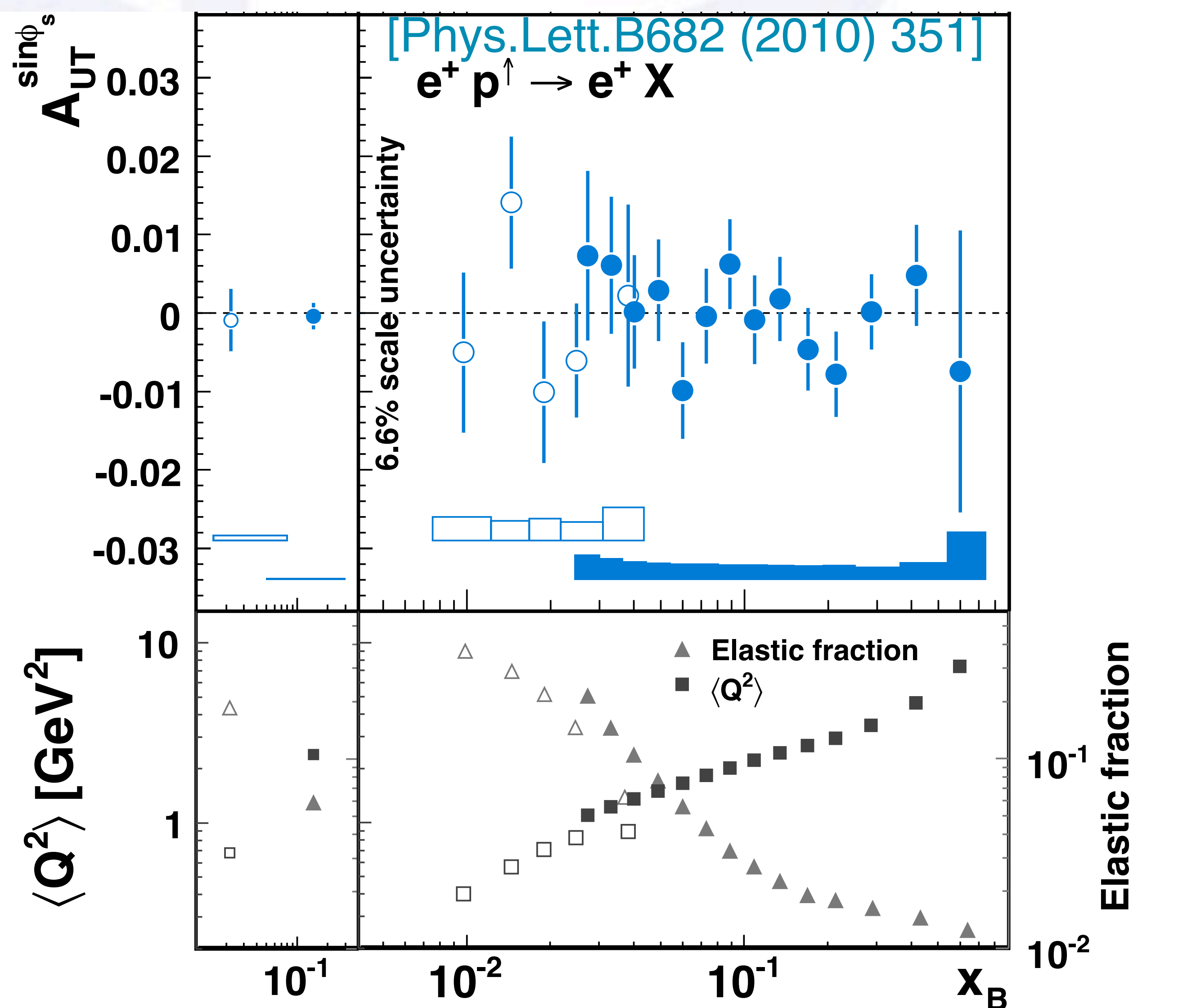
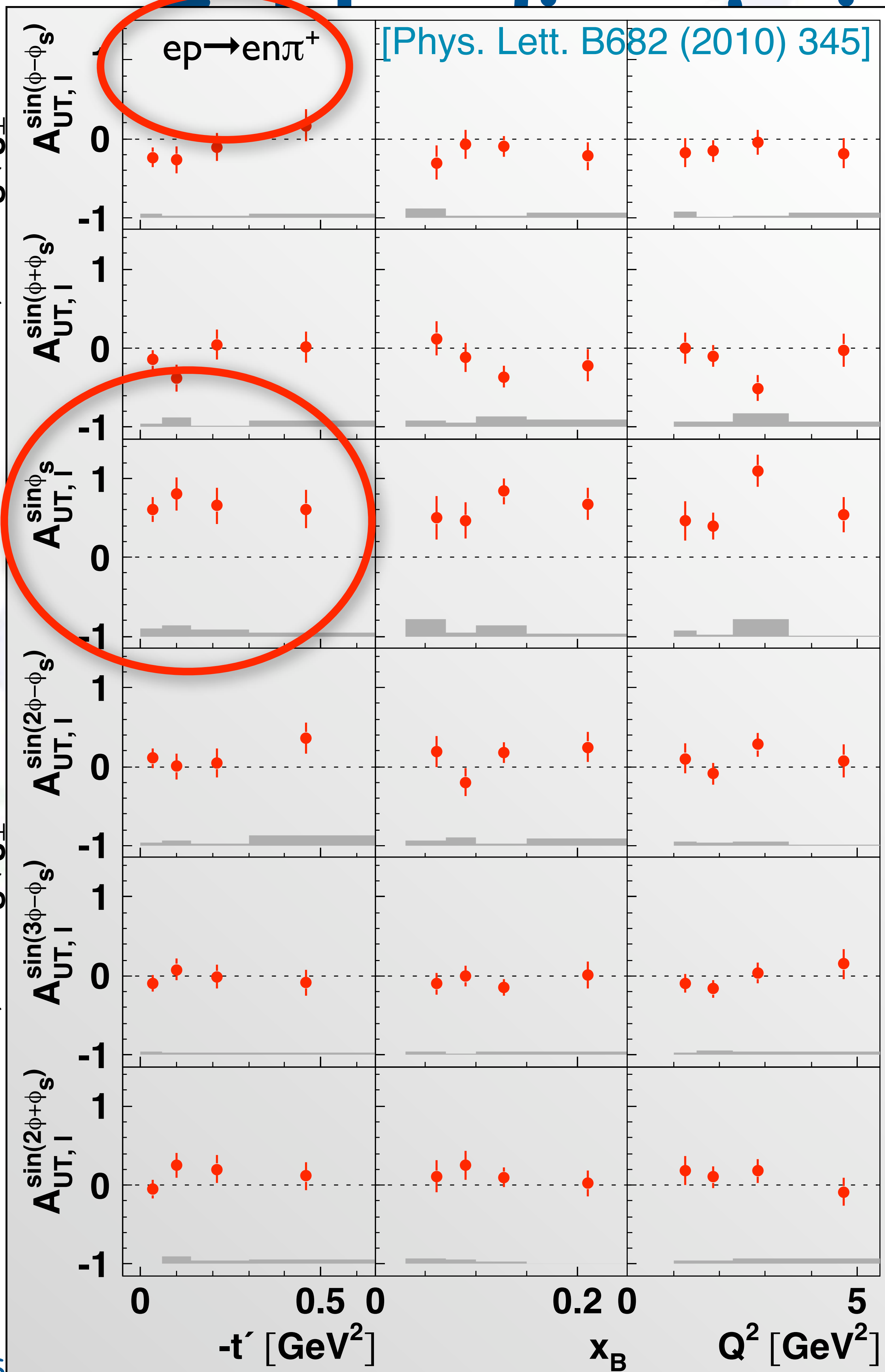


...st III - $\sin(\phi_S)$



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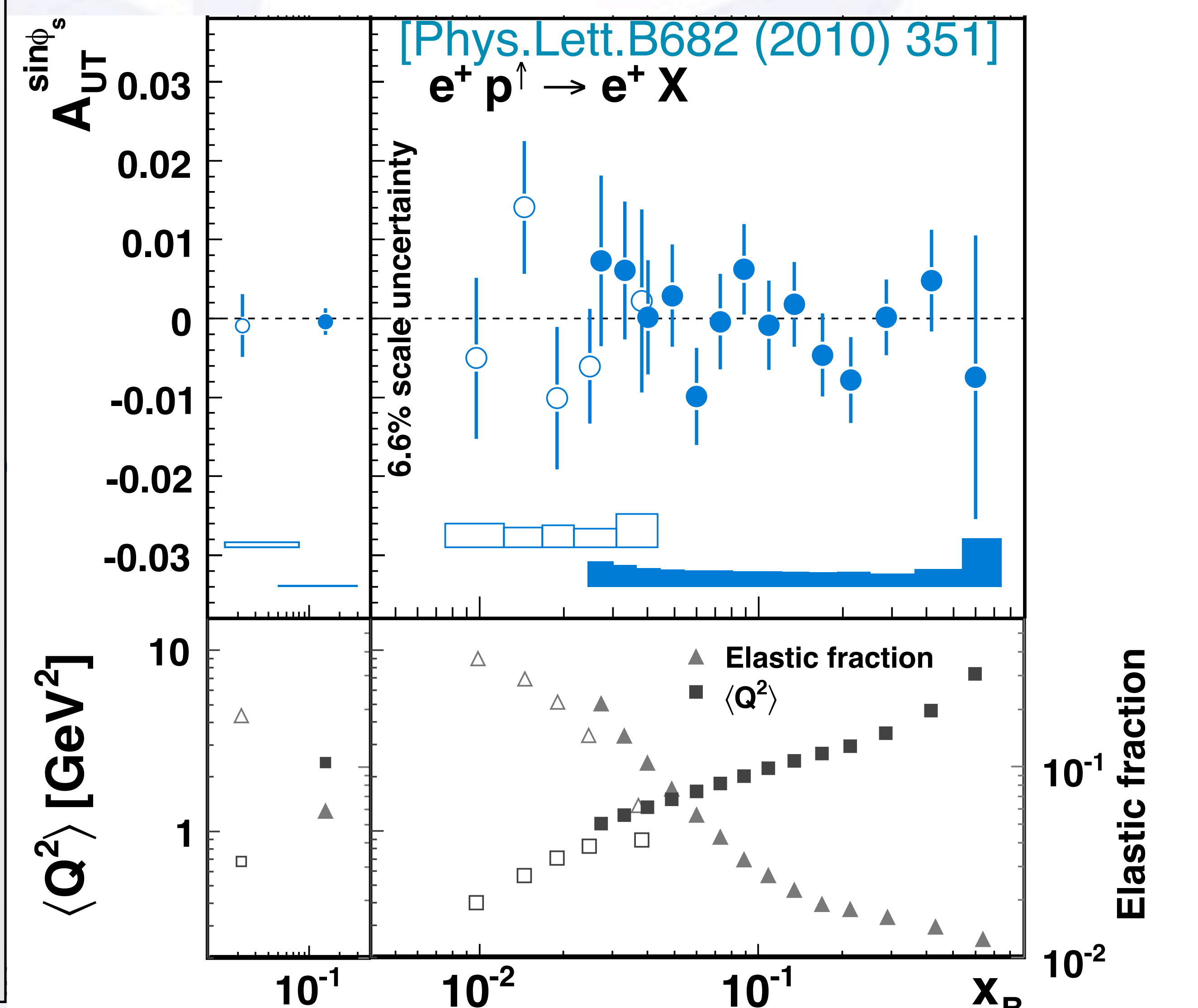

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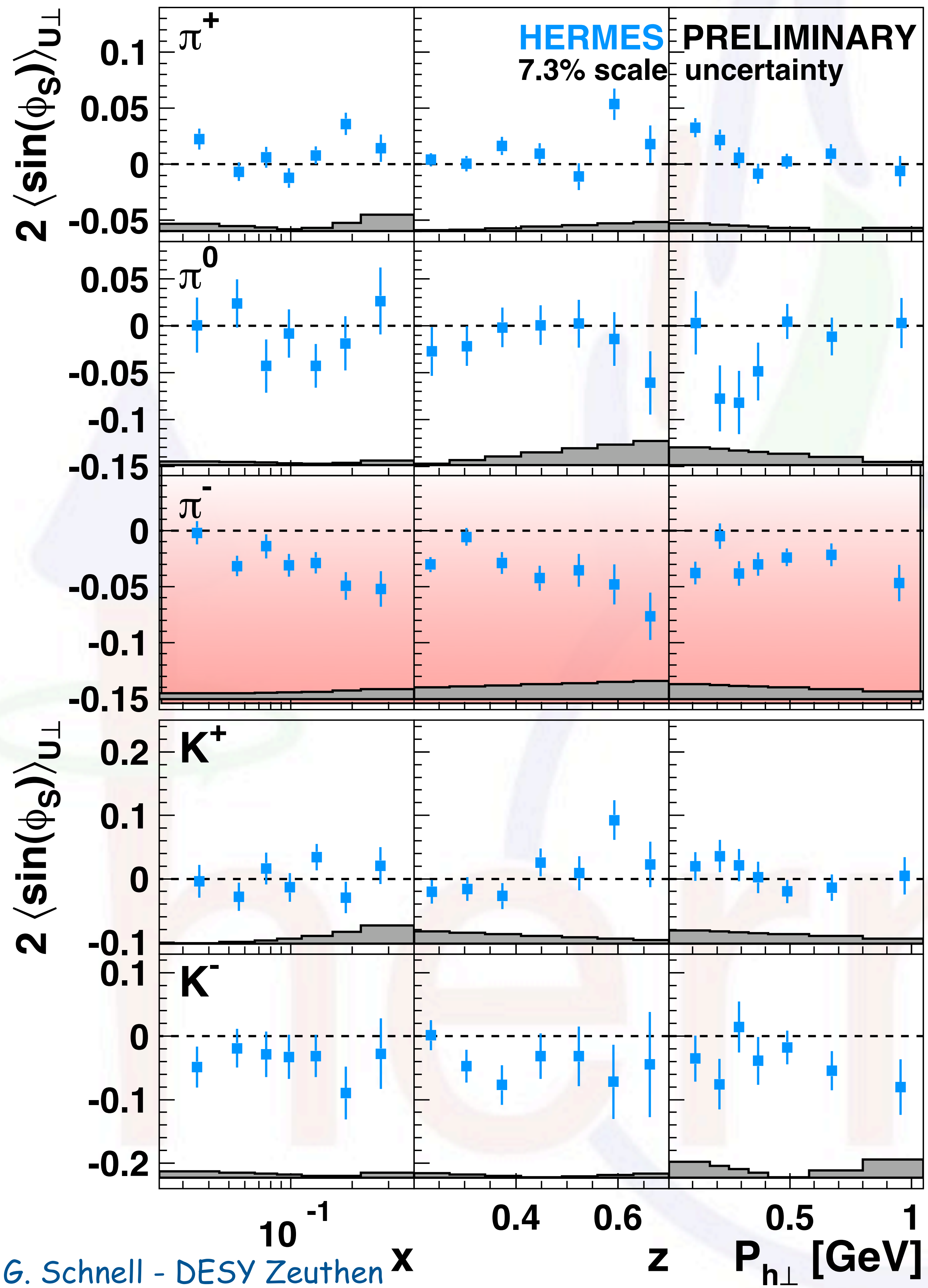
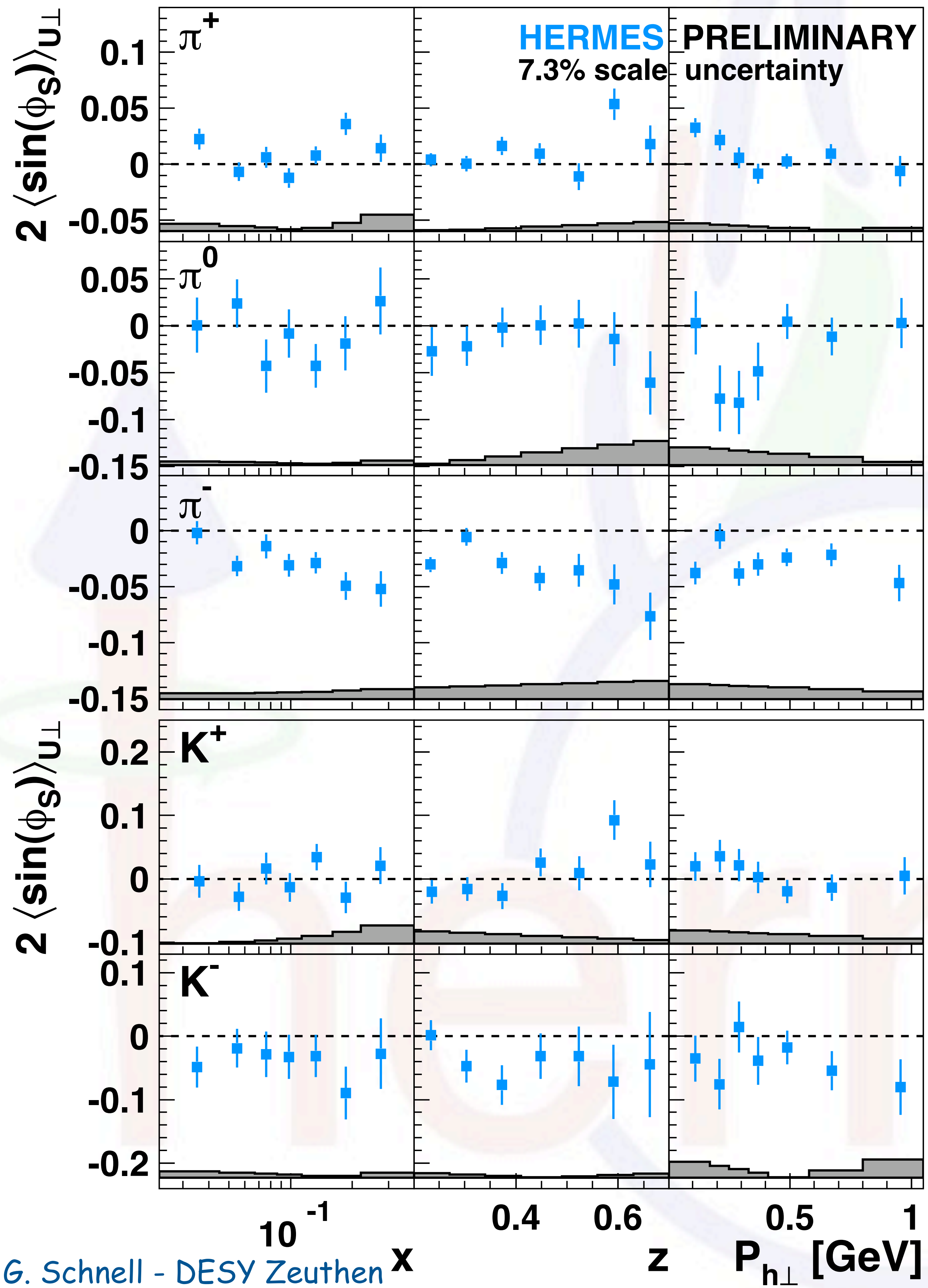
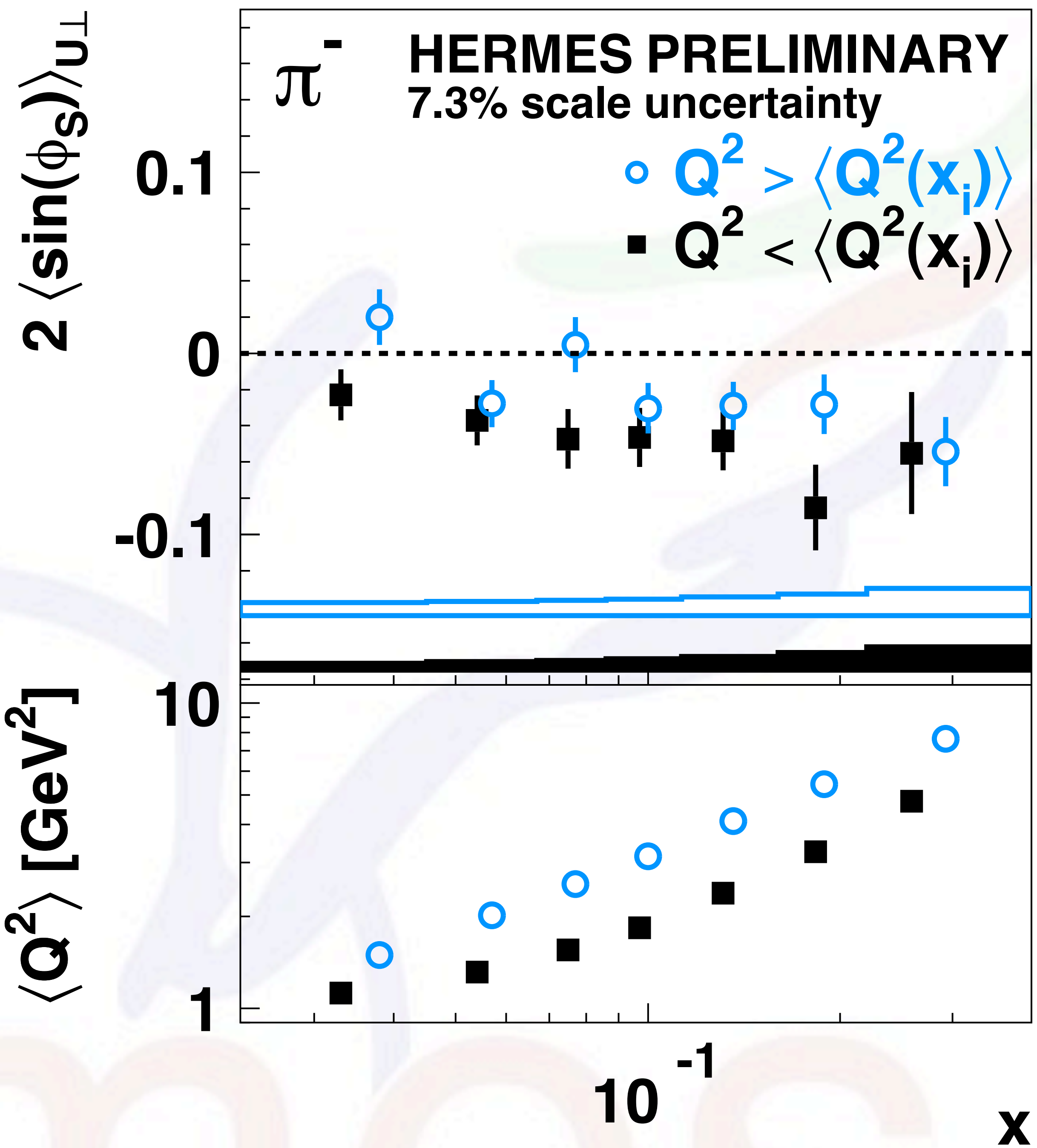


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

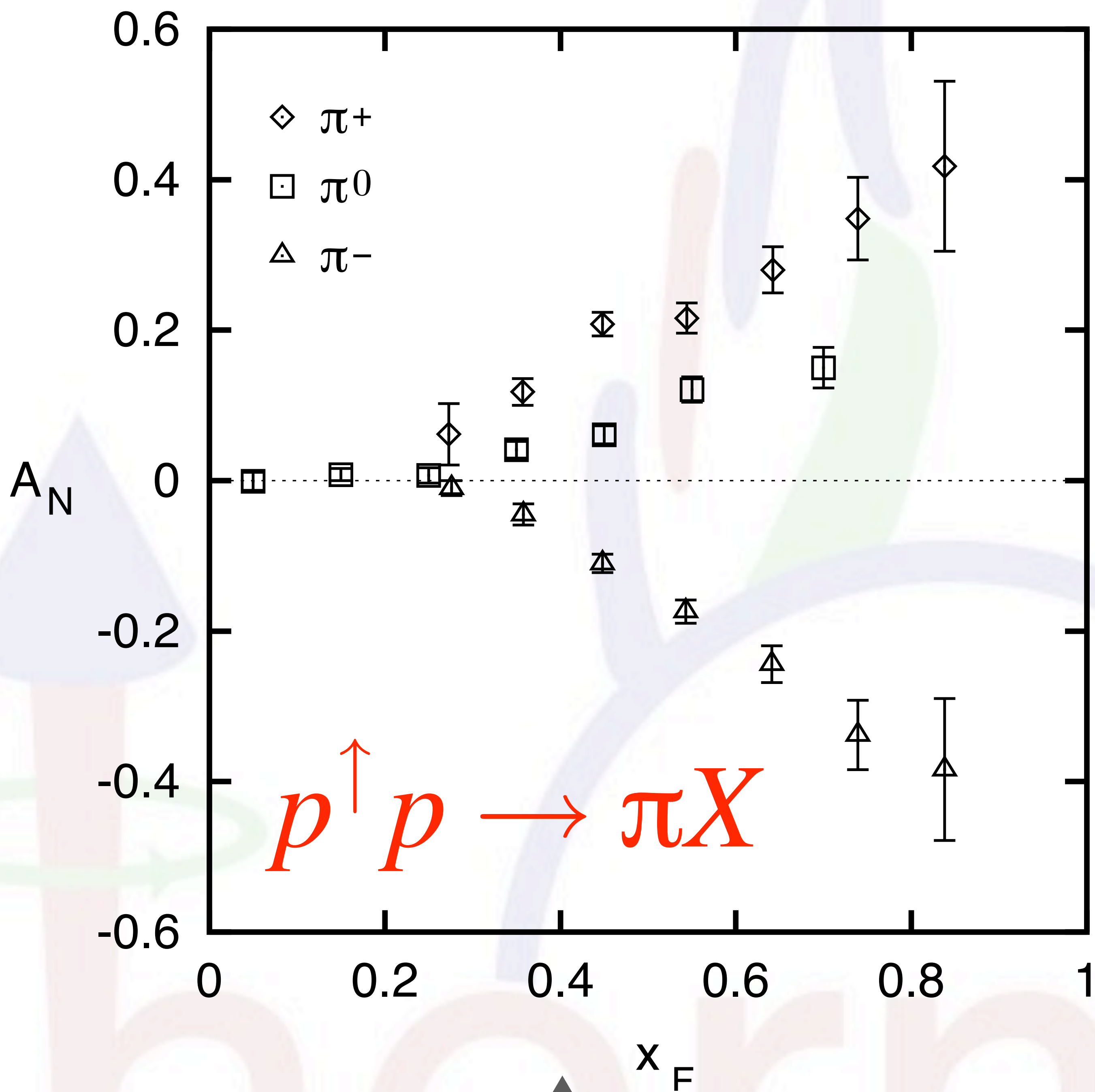
Subleading twist III - $\sin(\phi_s)$

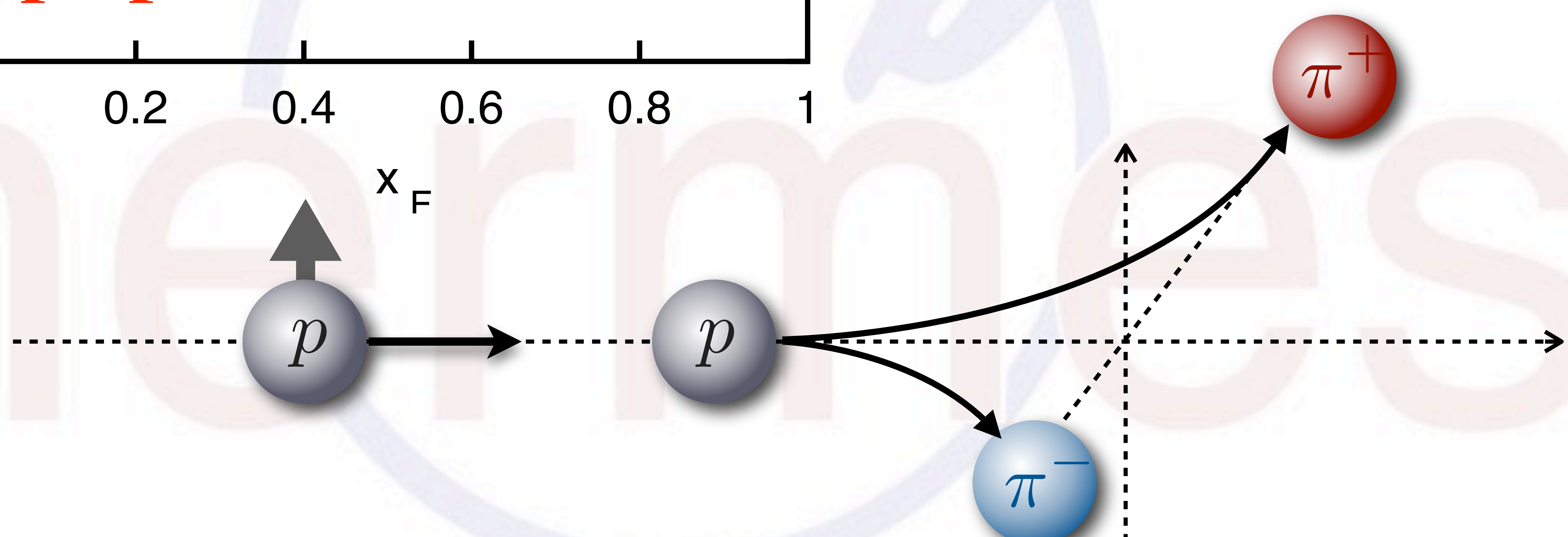




- Q^2 dependence seen in signal for negative pions

Back to the beginning of Sivers effect





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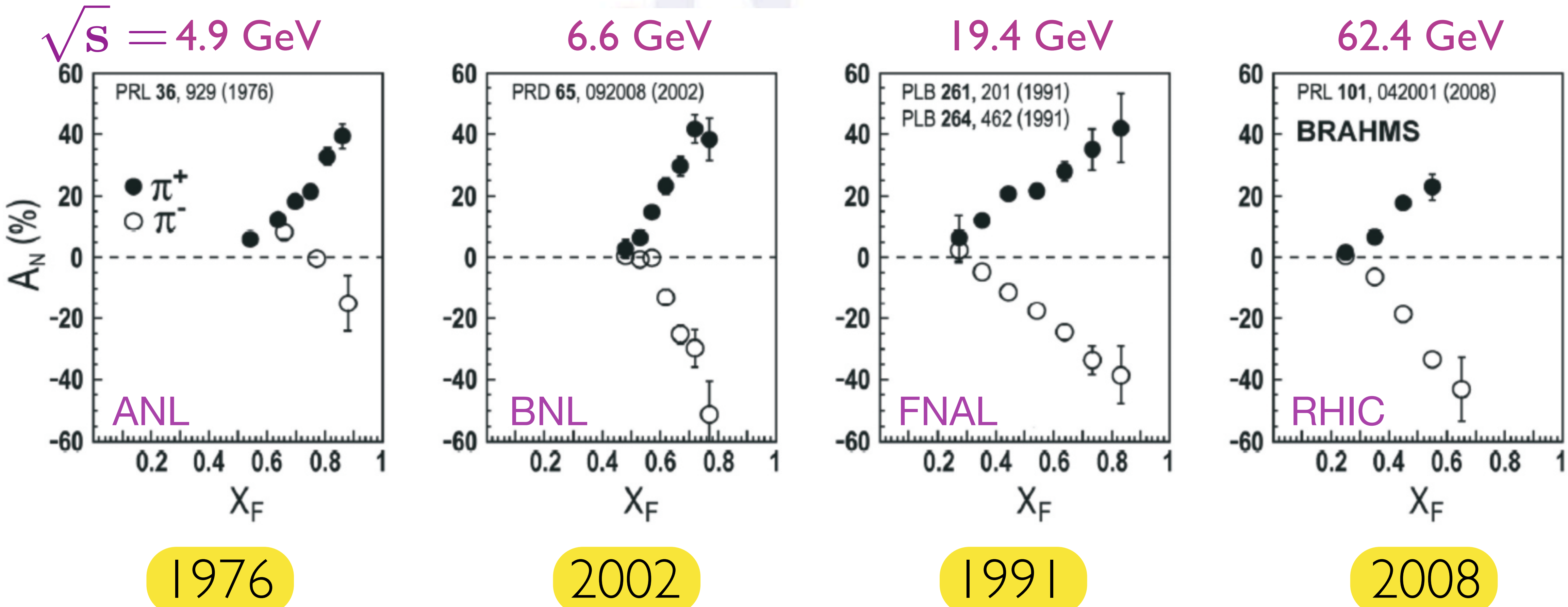
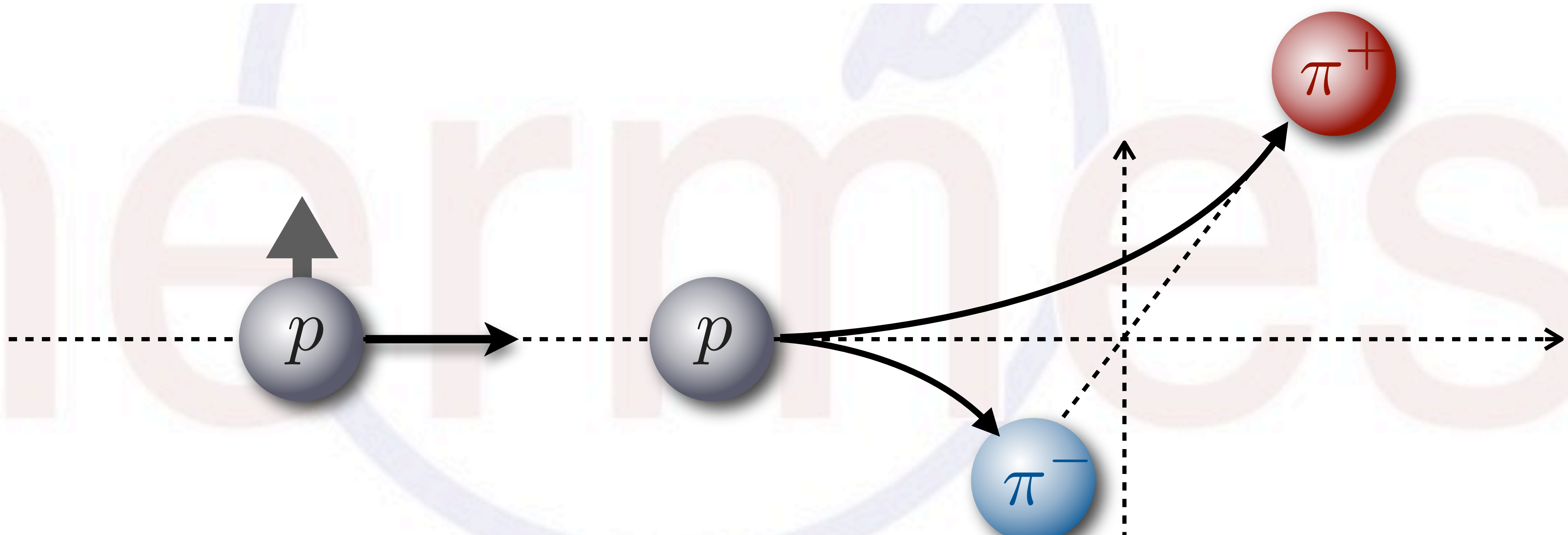
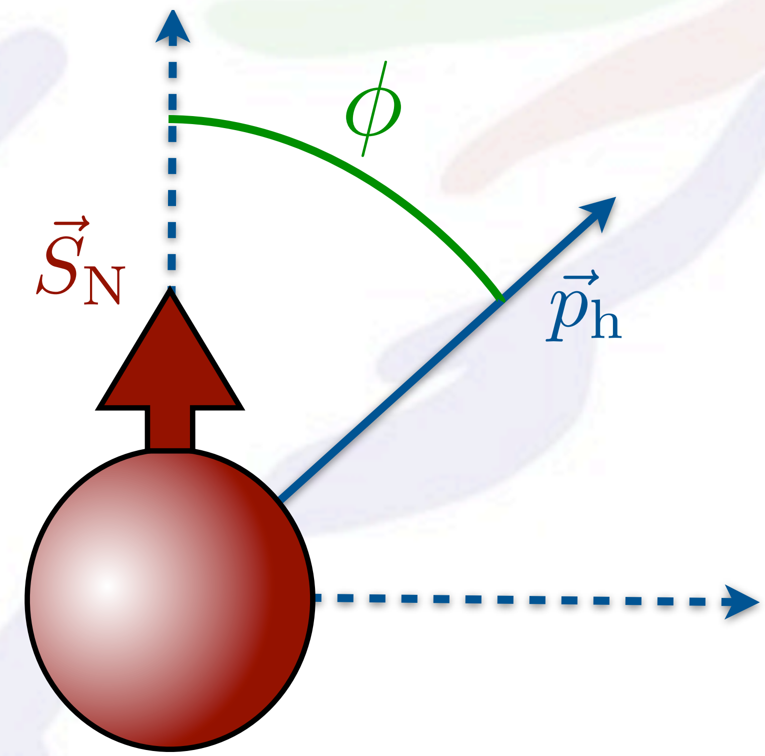




Inclusive hadron electro-production

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



lepton beam going
into the page

Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

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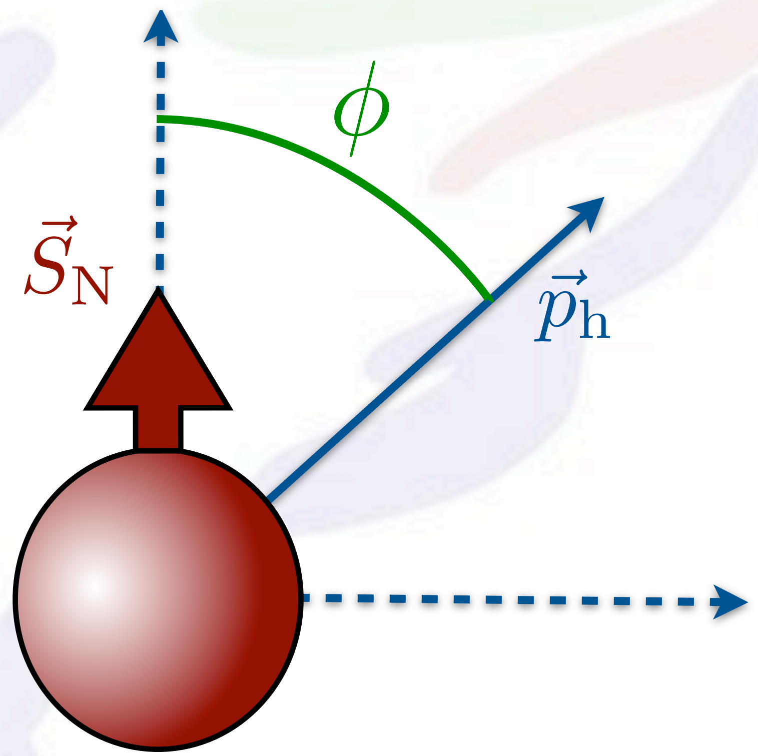

lepton beam going into the page

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

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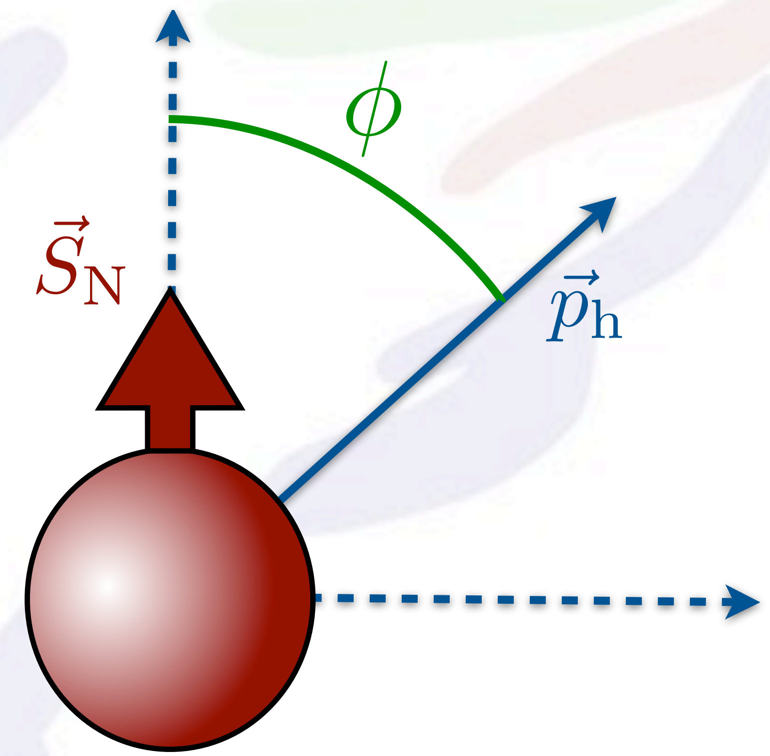

lepton beam going into the page

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- cross section proportional to $S_N (k \times p_h) \sim \sin\phi$

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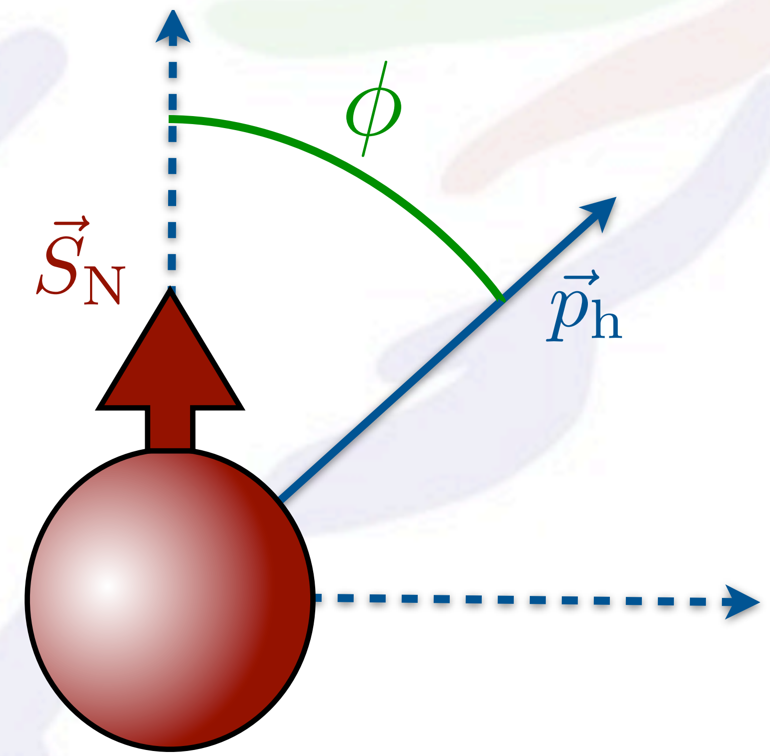

lepton beam going into the page

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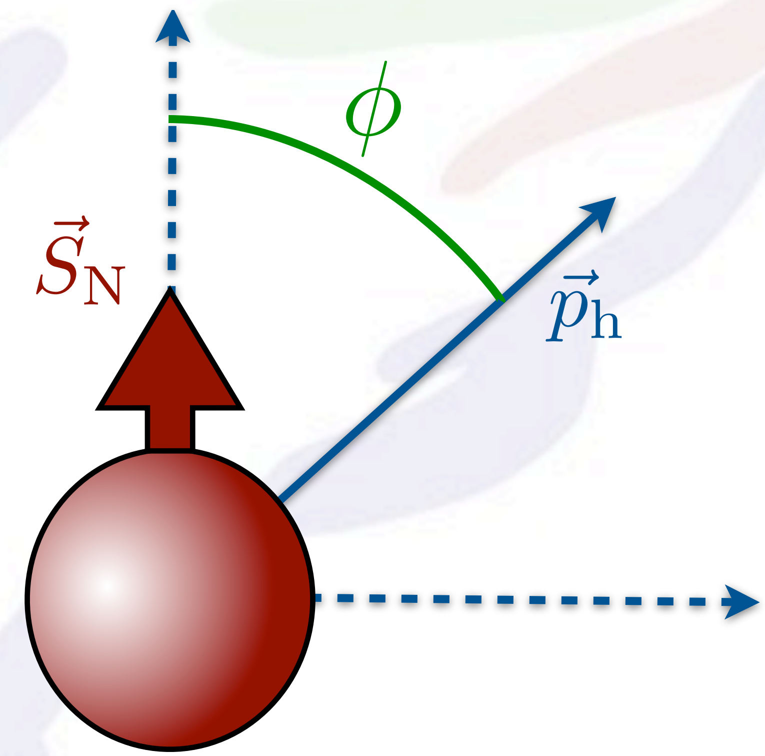


lepton beam going into the page

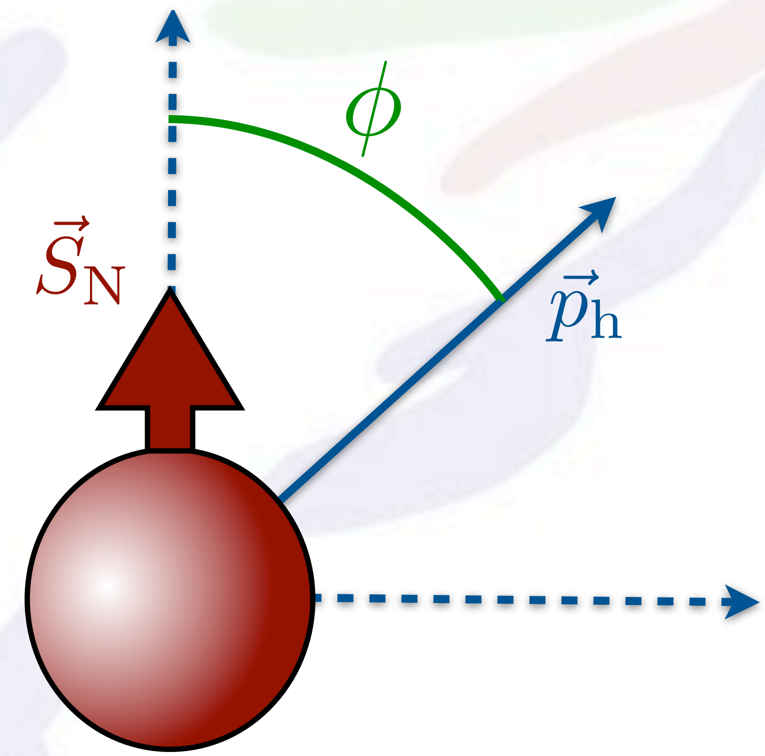
$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

this is what we measure!

Inclusive hadron electro-production

- 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 ($k \times p_h$) ~ $\sin\phi$

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



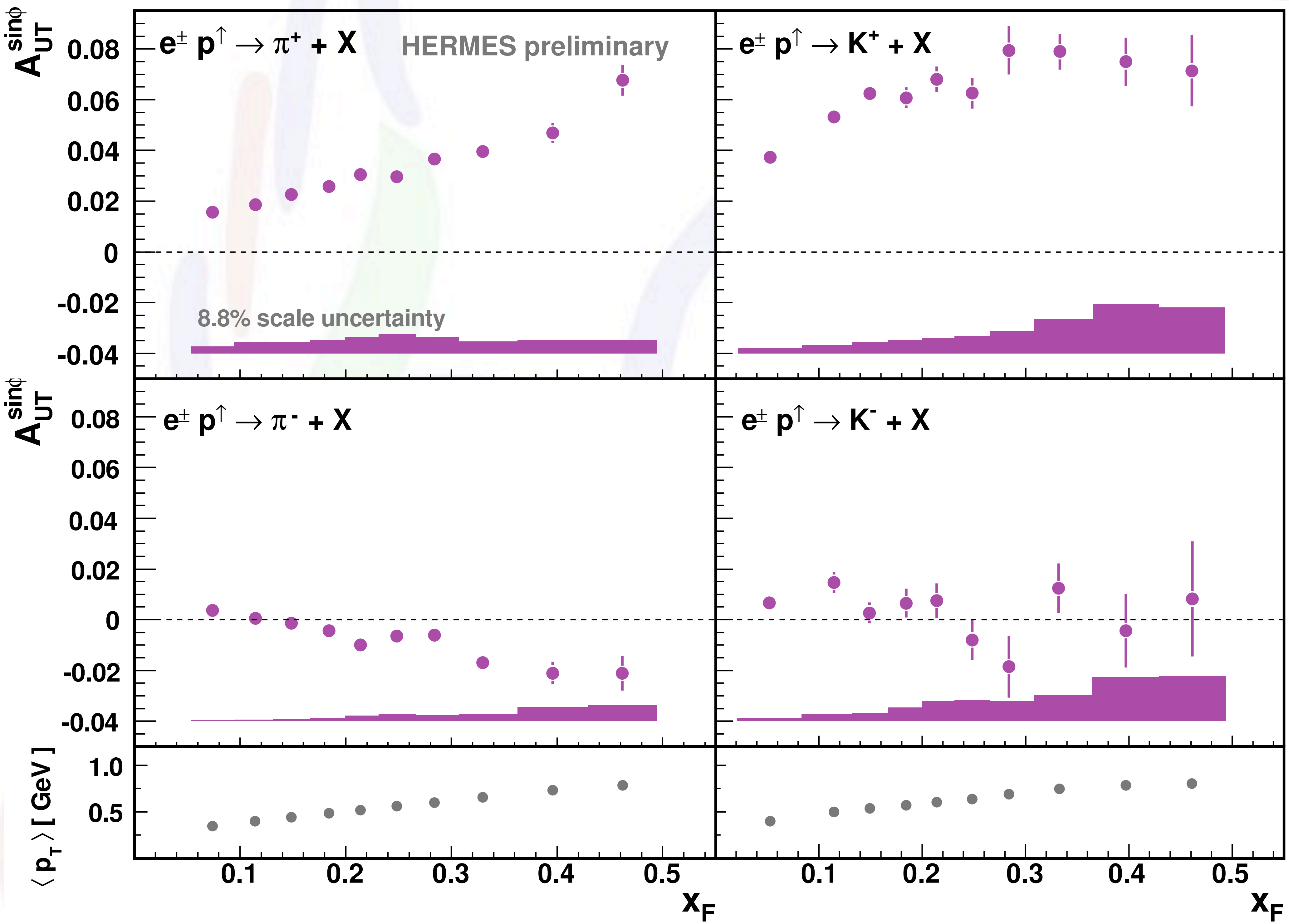
lepton beam going into the page

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F)\sin\phi$$

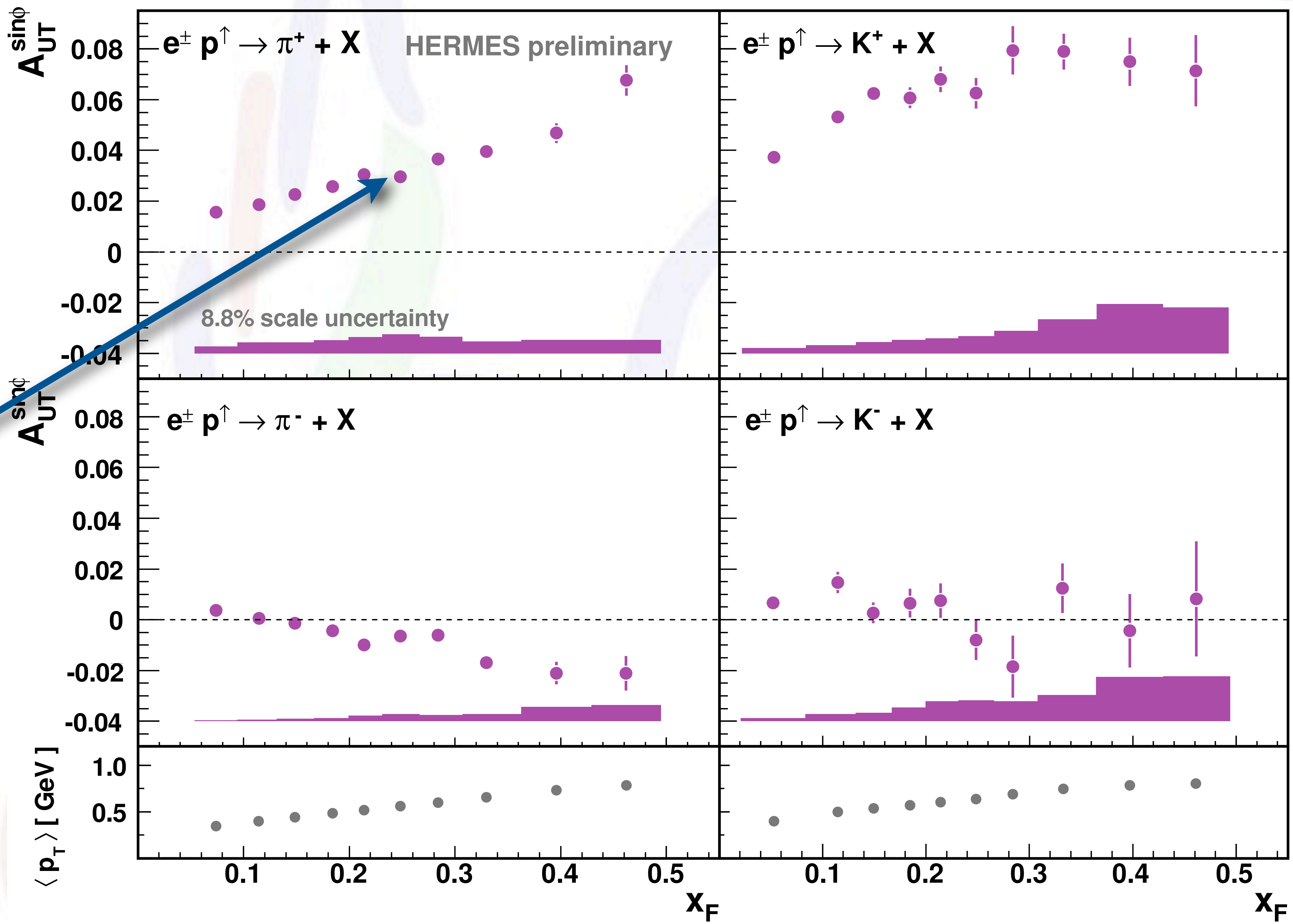
this is what we measure!

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

x_F dependence of A_{UT} $\sin\phi$ amplitude

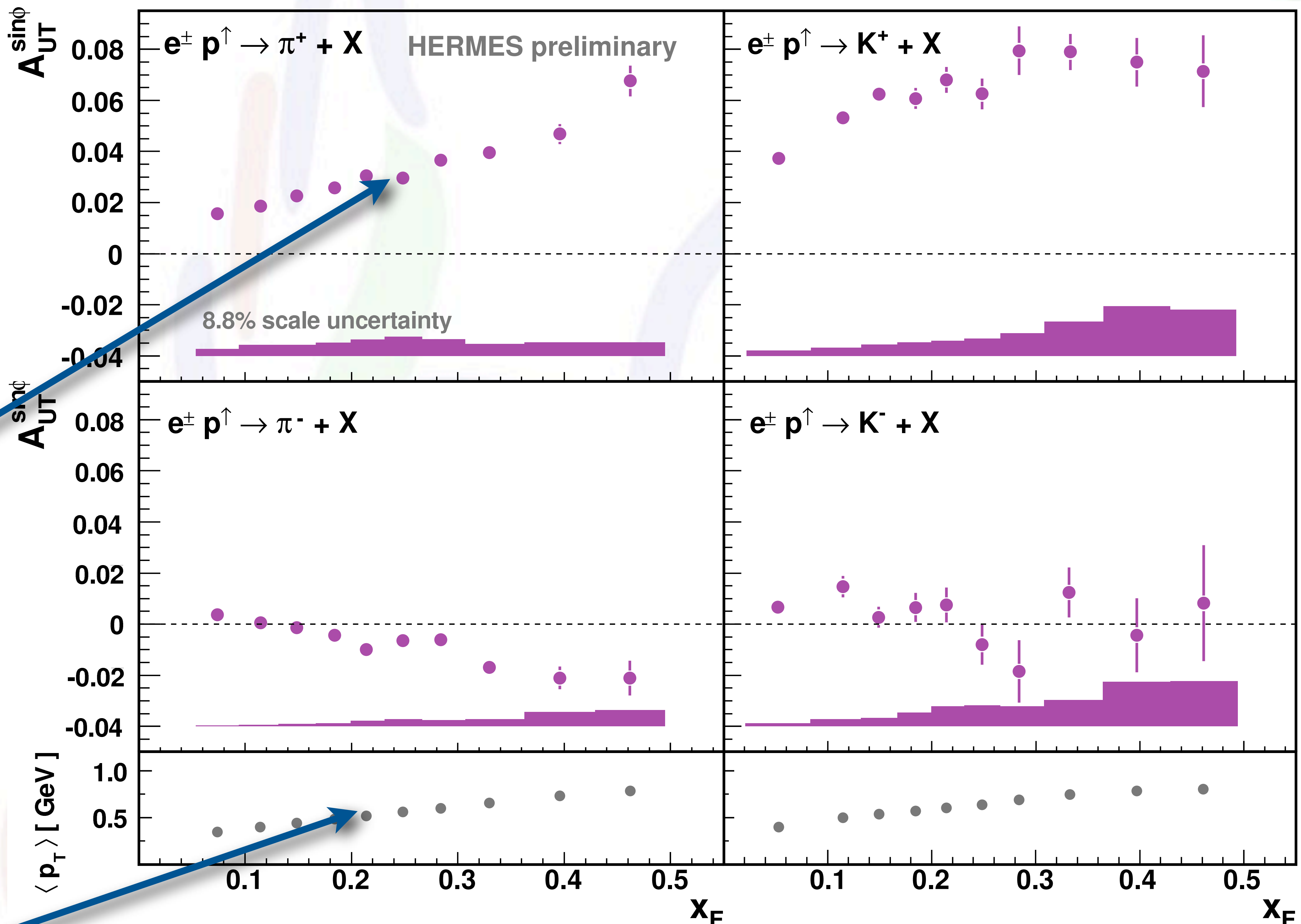


x_F dependence of A_{UT} sinϕ amplitude



- opposite in sign to pp
- increasing amplitudes

x_F dependence of A_{UT} sinϕ amplitude

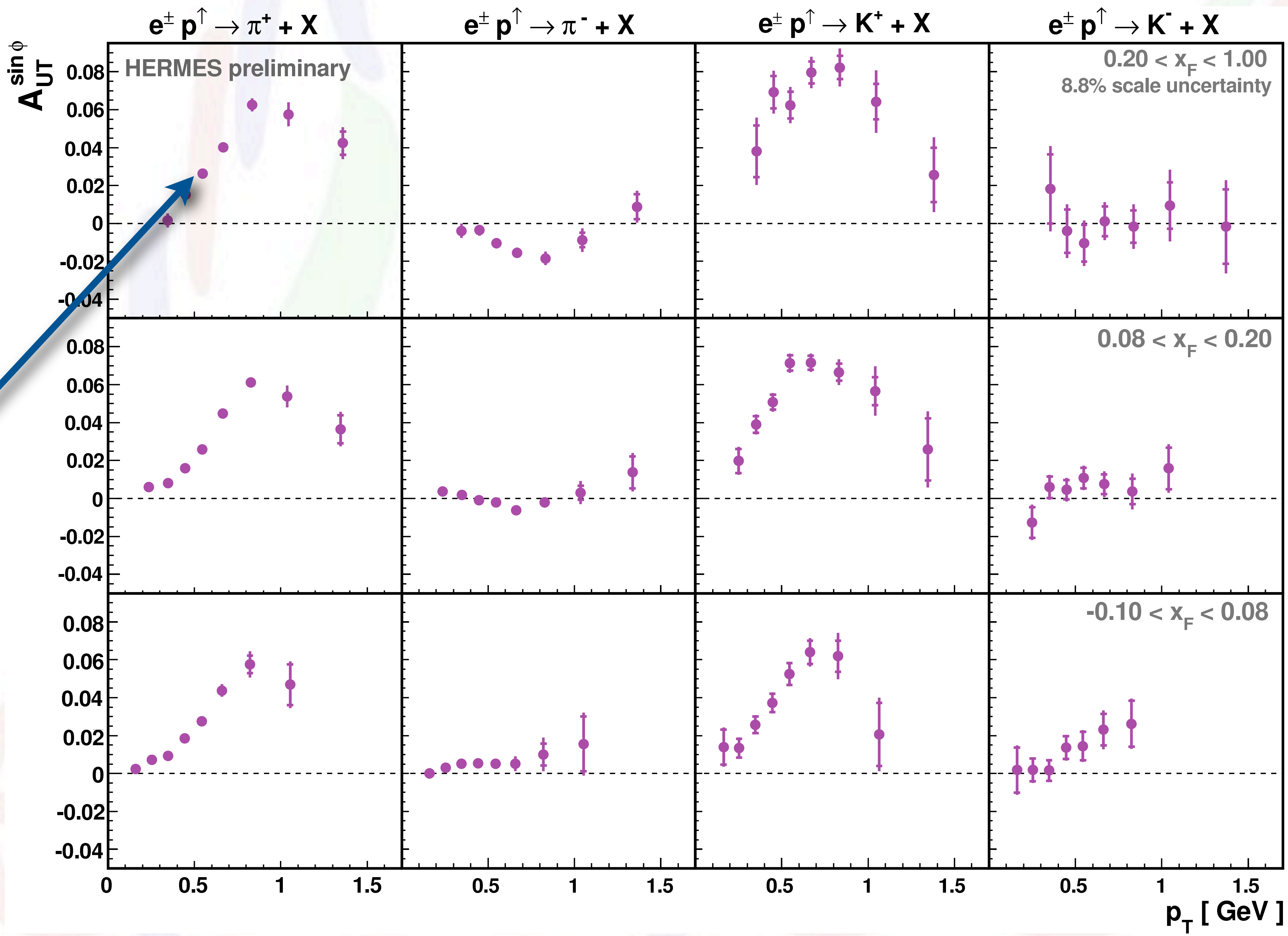


- opposite in sign to pp
- increasing amplitudes

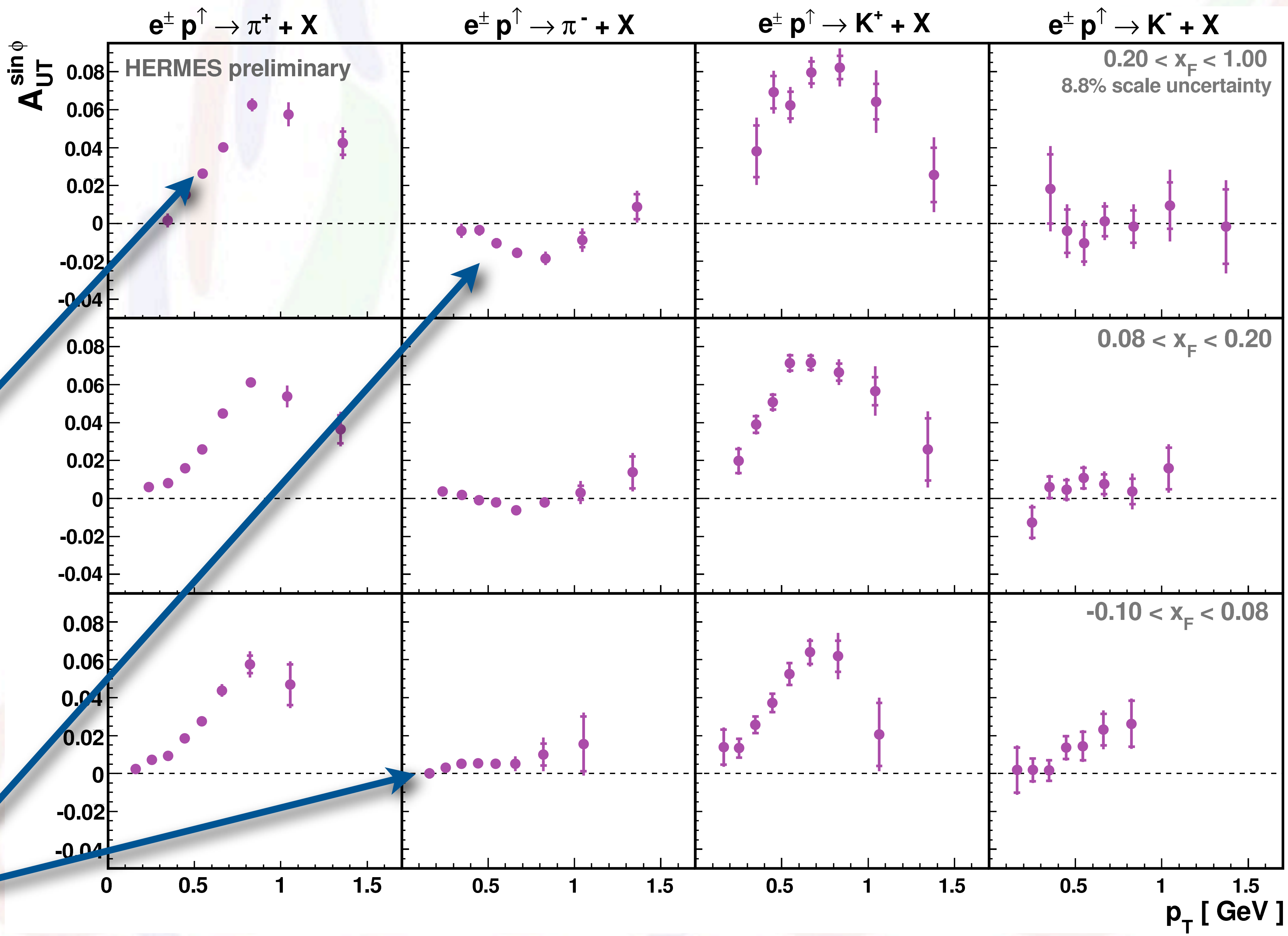
increasing p_T

p_T dependence of A_{UT} sinϕ amplitude

increasing amplitudes with turnover



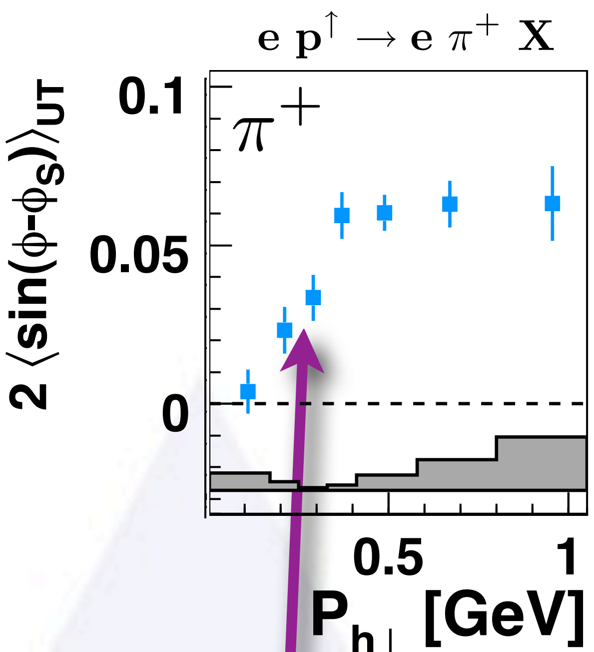
p_T dependence of A_{UT} $\sin\phi$ amplitude

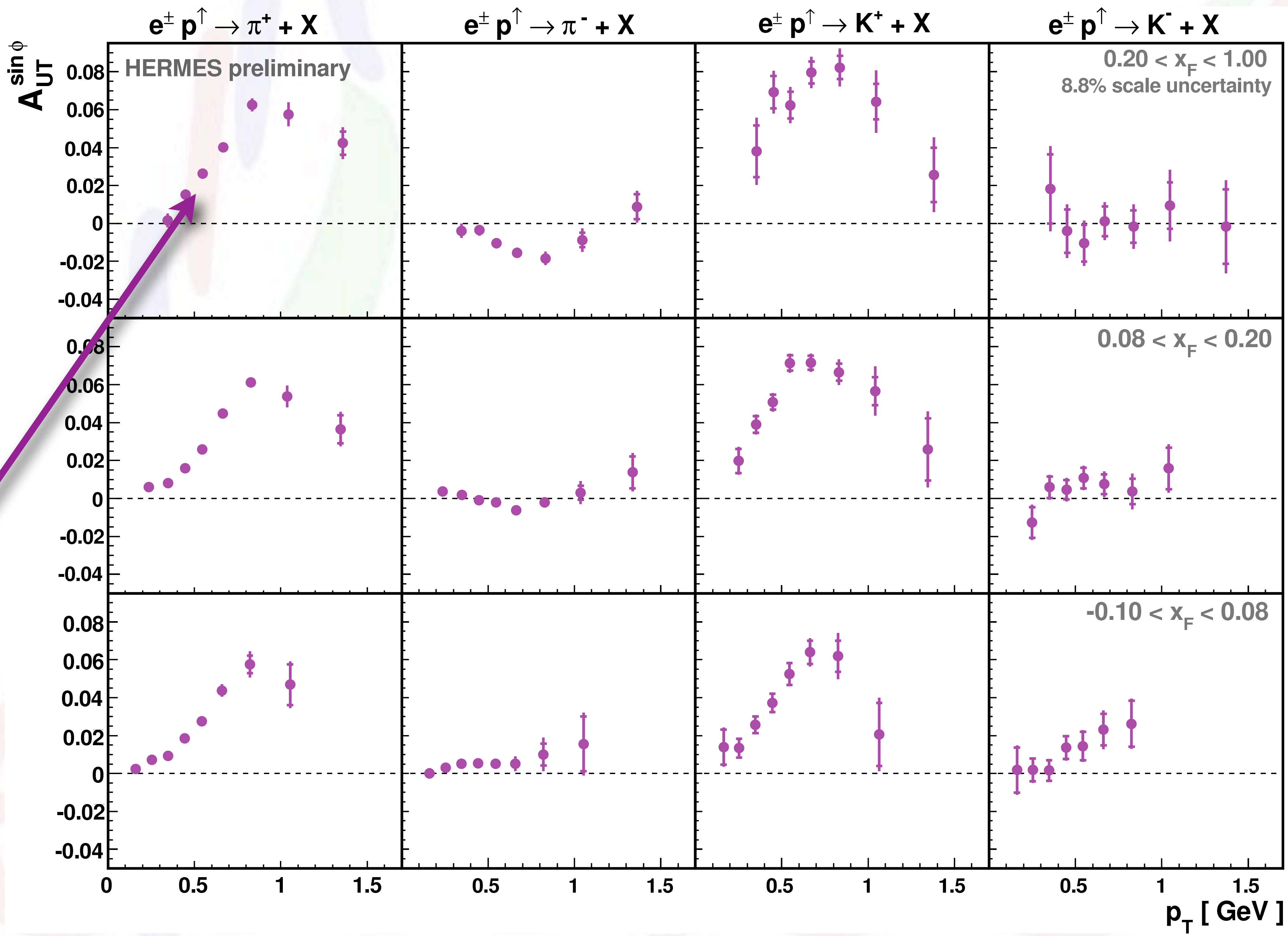


increasing amplitudes with turnover

sign change

p_T dependence of A_{UT} $\sin\phi$ amplitude





behavior and size similar to SIDIS Sivers

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 $\sin(2\phi \pm \phi_S)$ modulations seen
- significant (and surprising?) non-zero $\sin(\phi_S)$ modulation for π^-
- SSA in inclusive hadron electro-production resemble Sivers effect but different in sign to pp collision
- final Collins results coming out soon