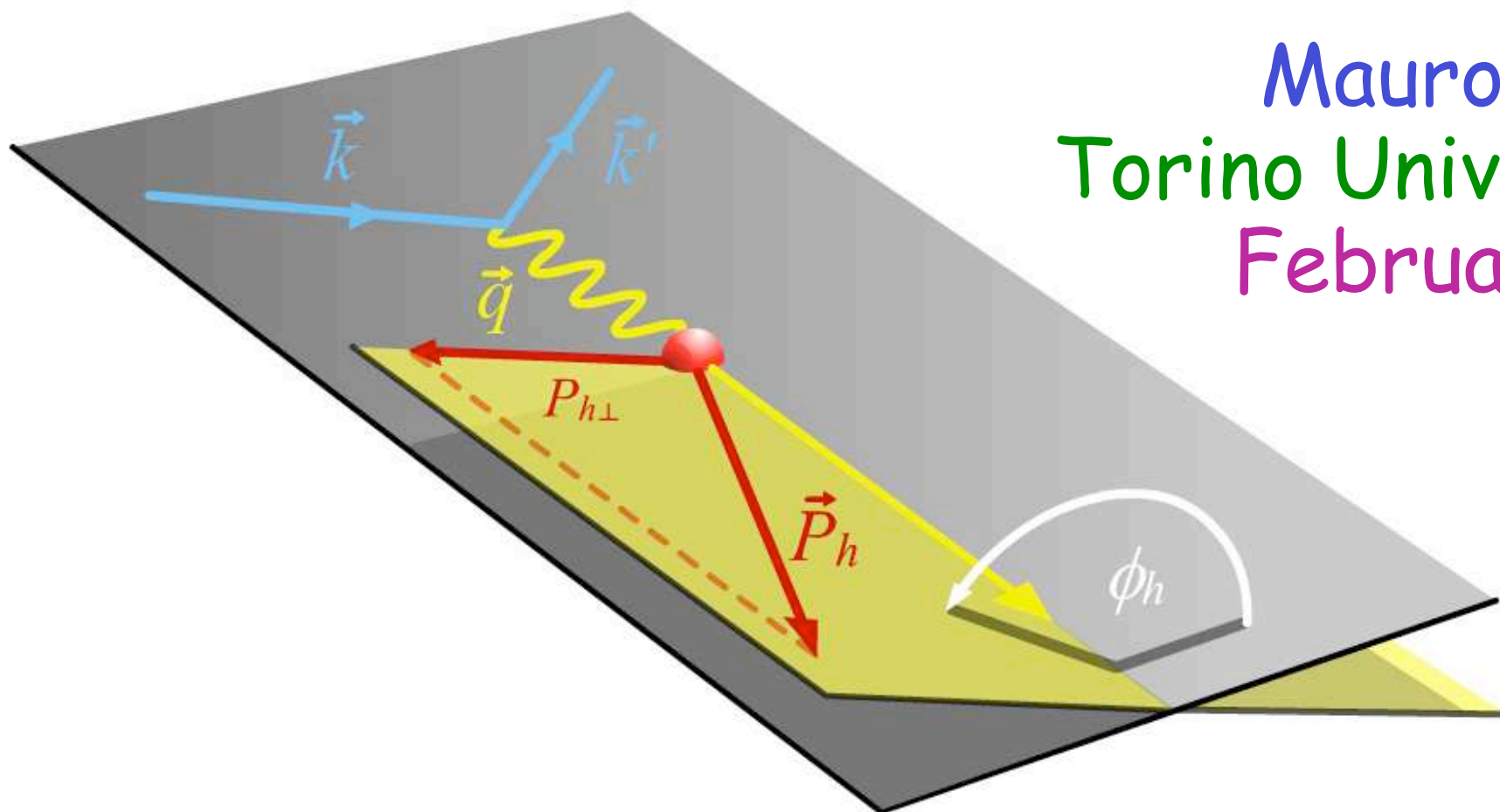




TMDs in SIDIS

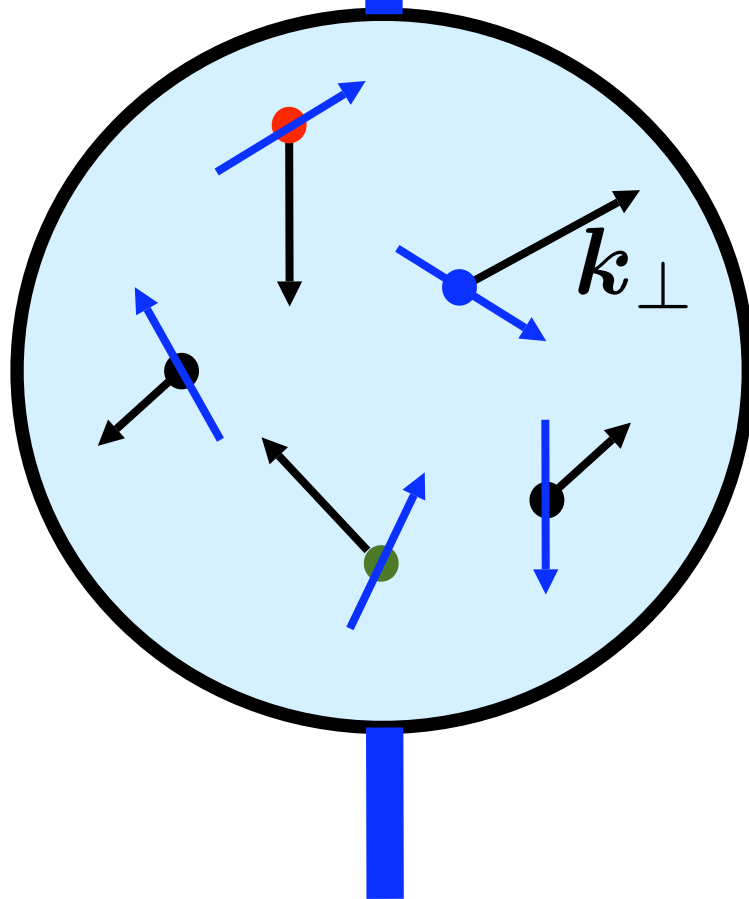
CLAS12 European
Workshop
February 25-28, 2009
Genova, Italy



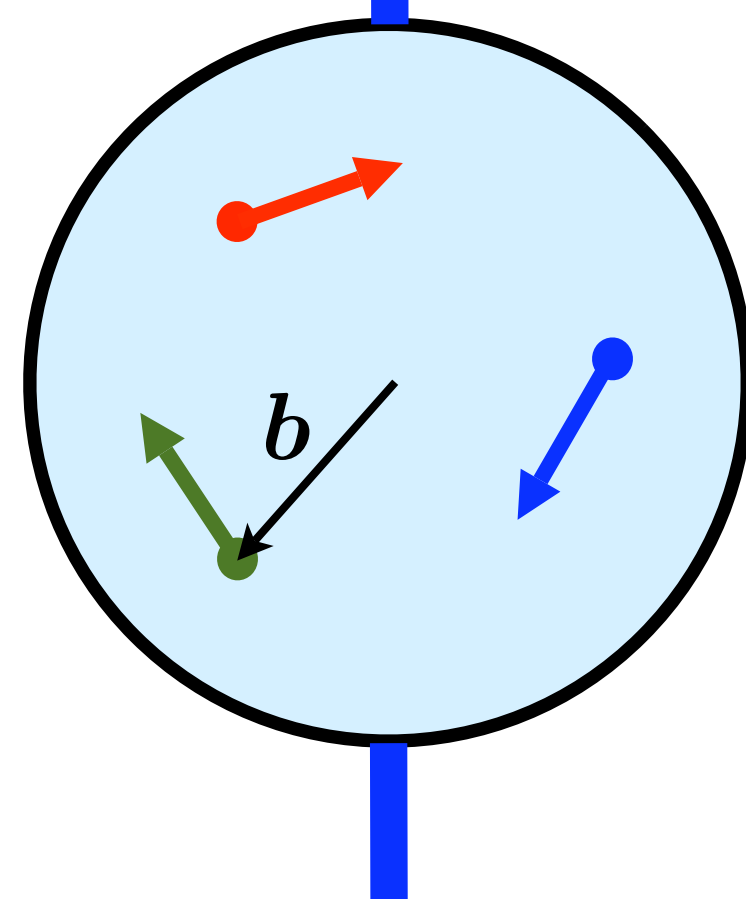
Mauro Anselmino,
Torino University and INFN
February 25, 2009

Exploring the transverse structure of the nucleon (not only spin)

spin- k_{\perp} correlations?

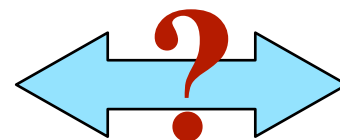


orbiting quarks?



Transverse Momentum Dependent
distribution functions (TMDs)

$$q(x, \mathbf{k}_{\perp}; Q^2)$$

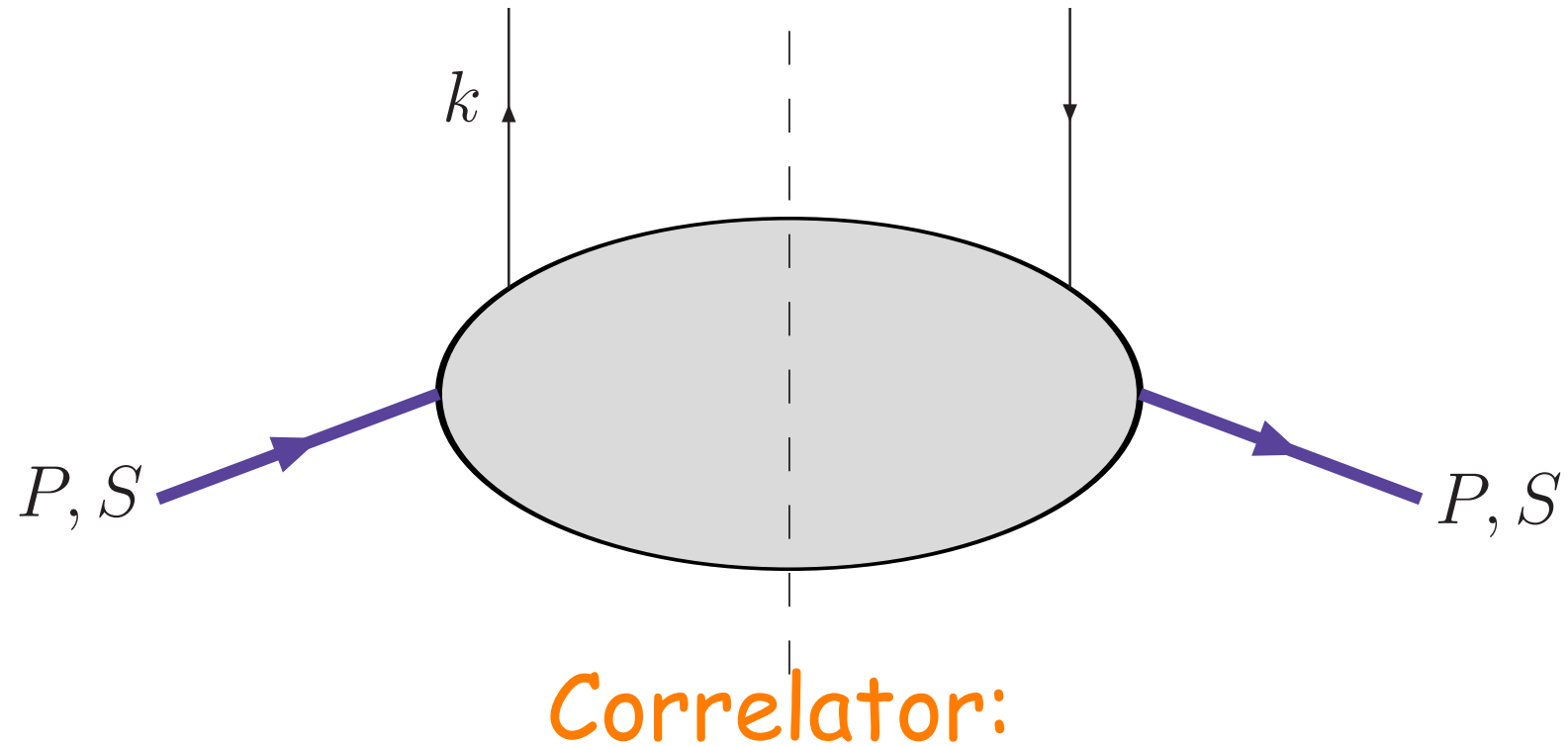


Space dependent
distribution functions

$$q(x, \mathbf{b}; Q^2)$$

talk by M. Vanderhaeghen

The nucleon, as probed in DIS, in collinear configuration: 3 distribution functions



$$\begin{aligned} \Phi_{ij}(k; P, S) &= \sum_X \int \frac{d^3 \mathbf{P}_X}{(2\pi)^3 2E_X} (2\pi)^4 \delta^4(P - k - P_X) \langle PS | \bar{\Psi}_j(0) | X \rangle \langle X | \Psi_i(0) | PS \rangle \\ &= \int d^4 \xi e^{ik \cdot \xi} \langle PS | \bar{\Psi}_j(0) \Psi(\xi) | PS \rangle \end{aligned}$$

$$\Phi(x, S) = \frac{1}{2} \left[\underbrace{f_1(x)}_{\mathbf{q}} \not{n}_+ + S_L \underbrace{g_{1L}(x)}_{\Delta \mathbf{q}} \gamma^5 \not{n}_+ + \underbrace{h_{1T}}_{\Delta_T \mathbf{q}} i\sigma_{\mu\nu} \gamma^5 n_+^\mu S_T^\nu \right]$$

Partonic intrinsic motion

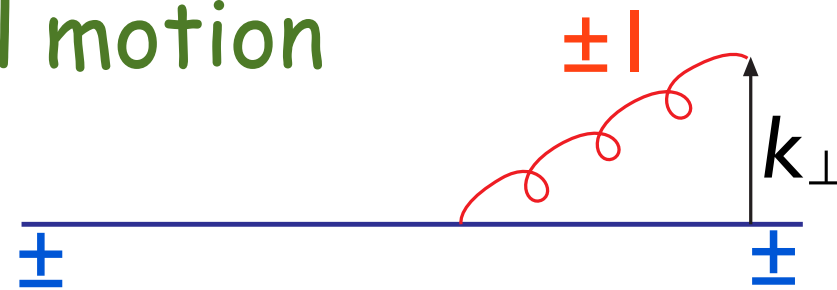
Plenty of theoretical and experimental evidence for transverse motion of partons within nucleons and of hadrons within fragmentation jets

uncertainty principle $\Delta x \simeq 1 \text{ fm} \Rightarrow \Delta p \simeq 0.2 \text{ GeV}/c$

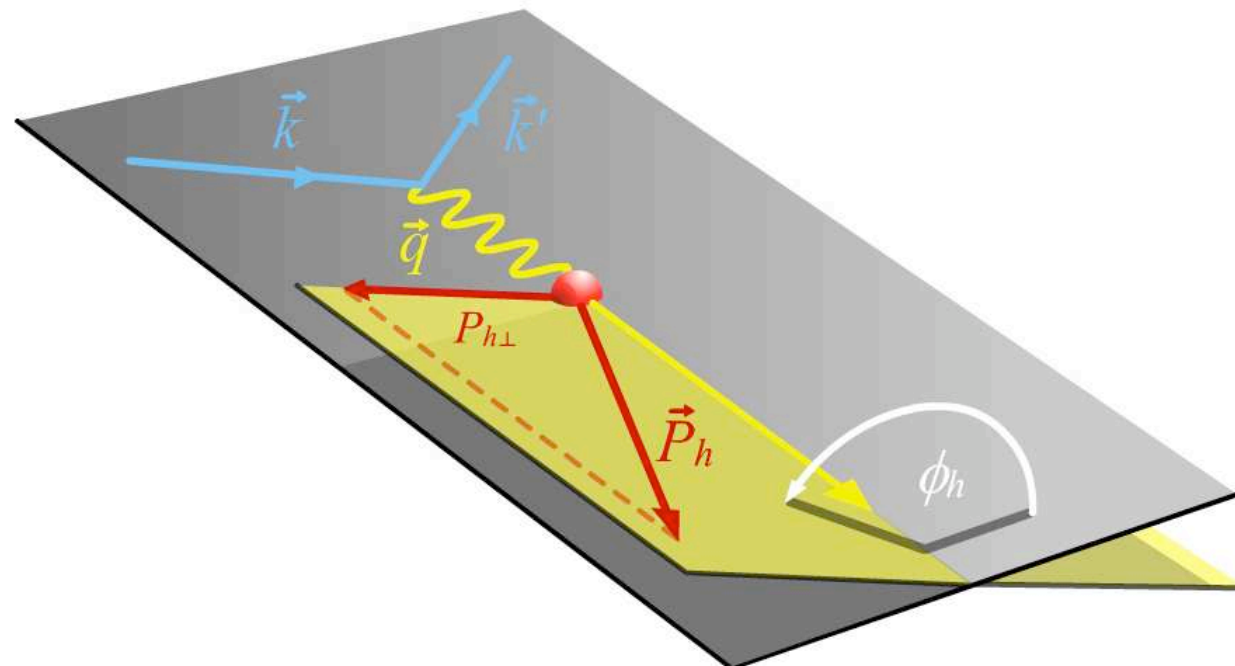
primordial intrinsic motion

orbital motion

gluon radiation

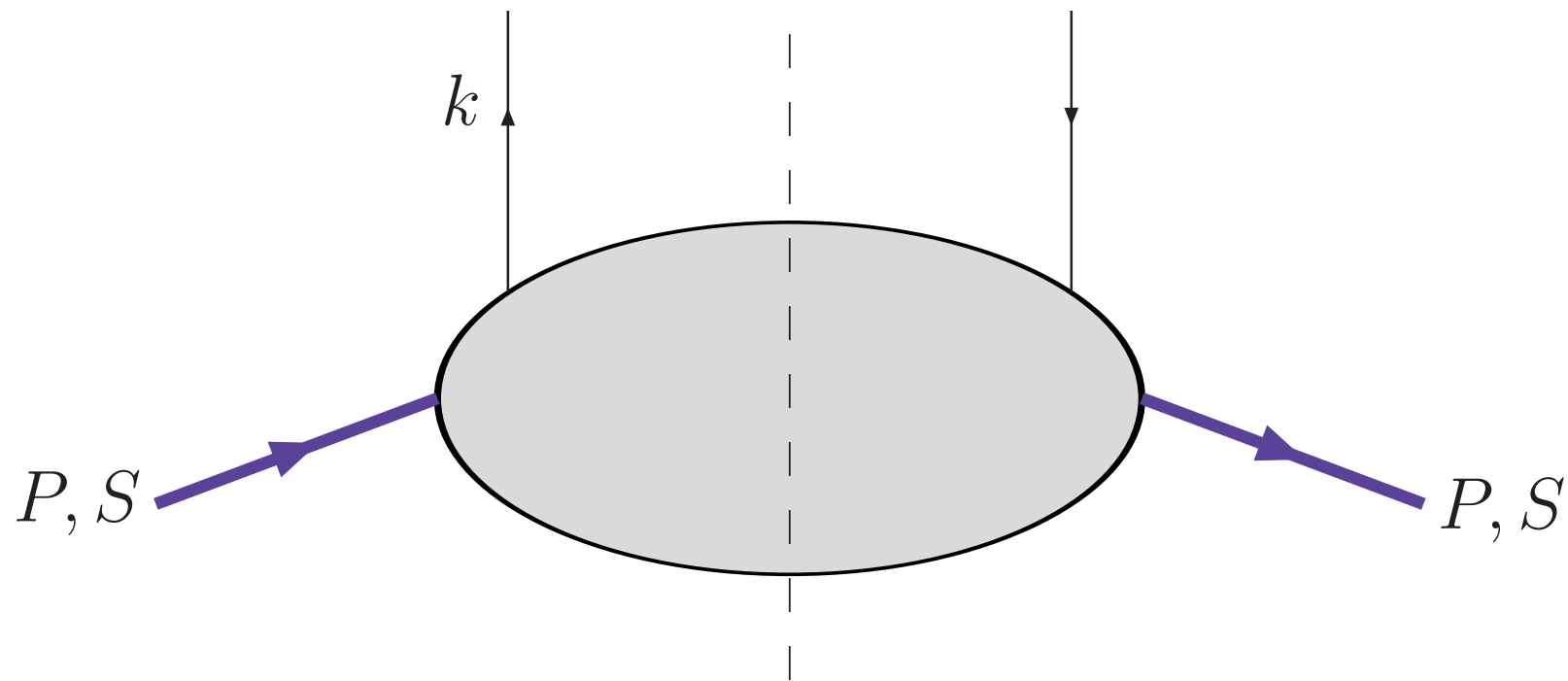


resummation of soft gluon emission



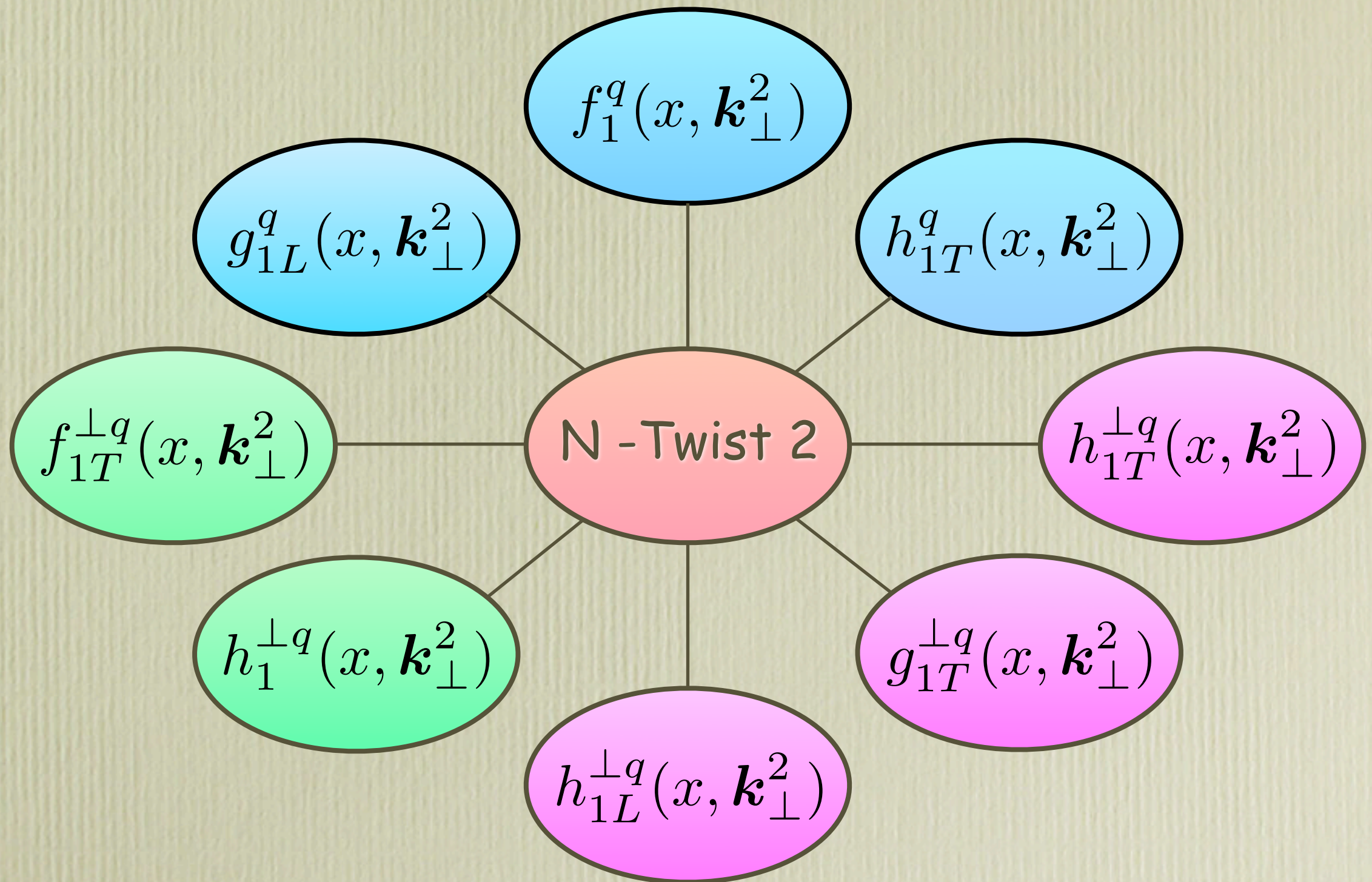
The leading-twist correlator, with intrinsic k_{\perp} , contains several other functions

$$\begin{aligned} \Phi(x, \mathbf{k}_{\perp}) = & \frac{1}{2} \left[f_1 \not{n}_+ + f_{1T}^{\perp} \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^{\mu} n_+^{\nu} k_{\perp}^{\rho} S_T^{\sigma}}{M} + \left(S_L g_{1L} + \frac{\mathbf{k}_{\perp} \cdot \mathbf{S}_T}{M} g_{1T}^{\perp} \right) \gamma^5 \not{n}_+ \right. \\ & + h_{1T} i\sigma_{\mu\nu} \gamma^5 n_+^{\mu} S_T^{\nu} + \left(S_L h_{1L}^{\perp} + \frac{\mathbf{k}_{\perp} \cdot \mathbf{S}_T}{M} h_{1T}^{\perp} \right) \frac{i\sigma_{\mu\nu} \gamma^5 n_+^{\mu} k_{\perp}^{\nu}}{M} \\ & \left. + h_1^{\perp} \frac{\sigma_{\mu\nu} k_{\perp}^{\mu} n_+^{\nu}}{M} \right] \end{aligned}$$

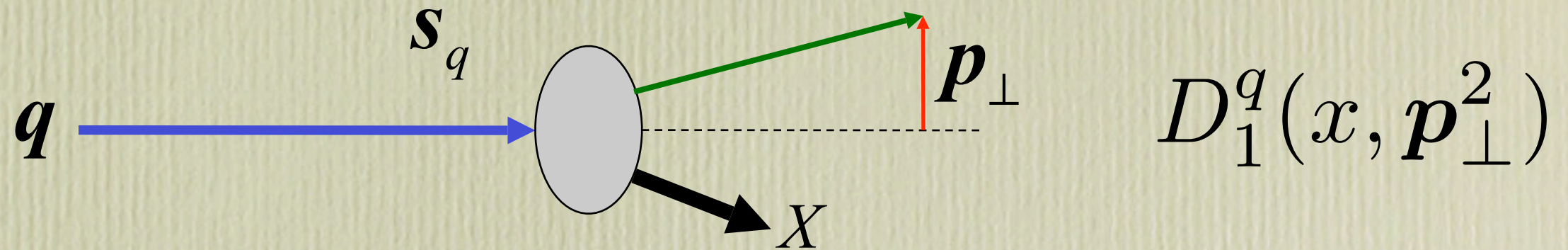


... with partonic interpretation

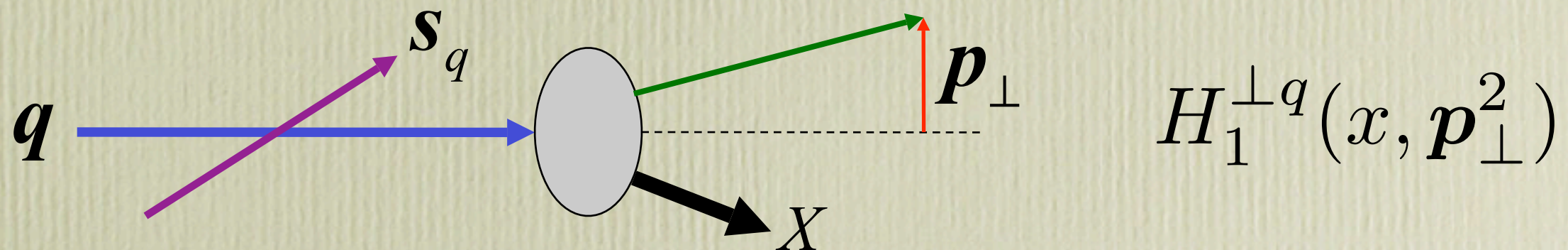
The nucleon at twist-2



similar spin- \mathbf{p}_\perp correlations in fragmentation process
(case of final spinless hadron)

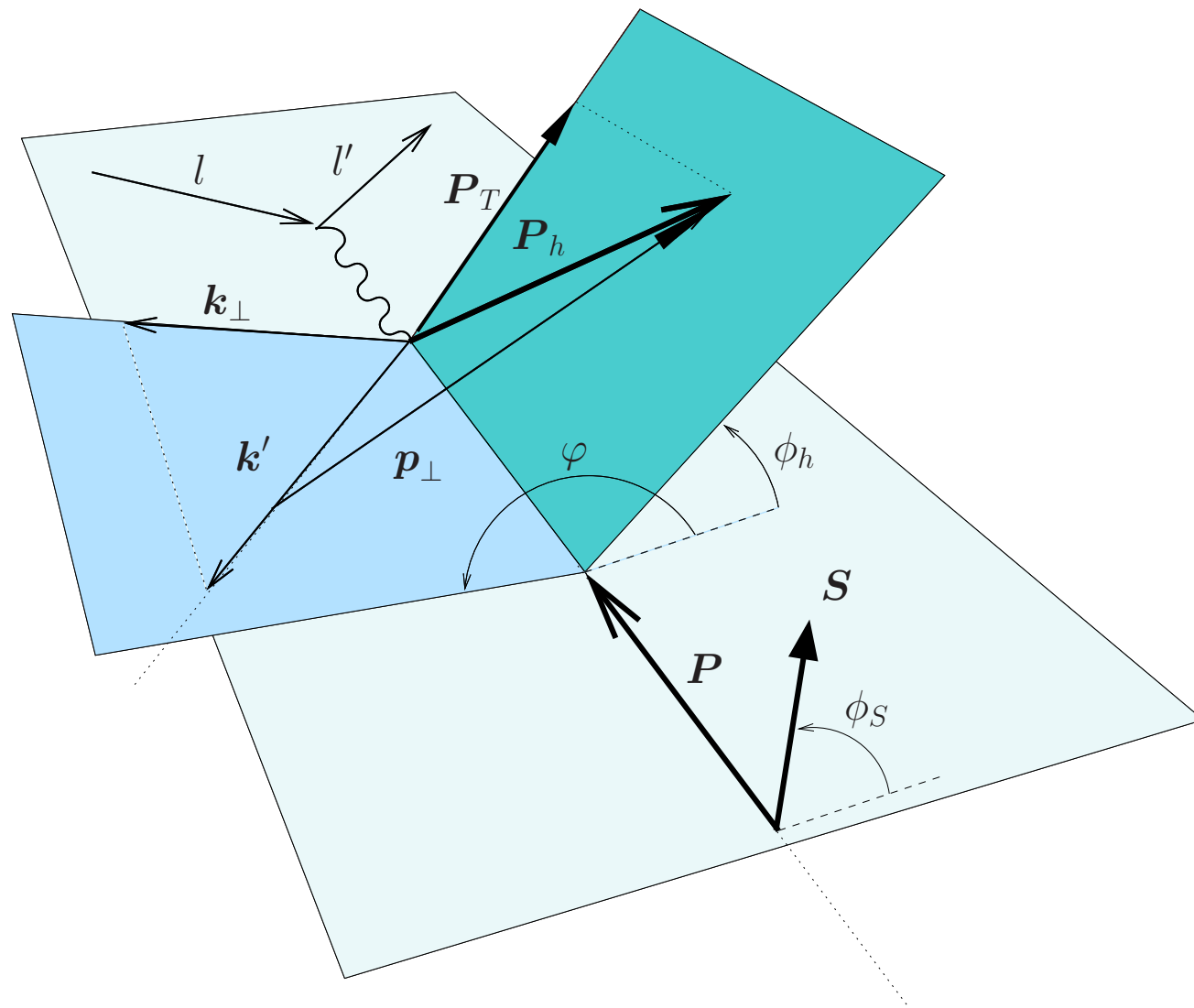


$$D_1^q(x, \mathbf{p}_\perp^2)$$



$$H_1^{\perp q}(x, \mathbf{p}_\perp^2)$$

SIDIS in parton model with intrinsic \mathbf{k}_\perp



$$d^6\sigma \equiv \frac{d^6\sigma^{lp^\uparrow \rightarrow lhX}}{dx_B dQ^2 dz_h d^2\mathbf{P}_T d\phi_S}$$

$$\mathbf{p}_\perp \simeq \mathbf{P}_T - z_h \mathbf{k}_\perp$$

factorization holds at large Q^2 , and $P_T \approx k_\perp \approx \Lambda_{\text{QCD}}$

Two scales: $P_T \ll Q^2$

$$d\sigma^{lp \rightarrow lhX} = \sum_q f_q(x, \mathbf{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q \rightarrow \ell q}(y, \mathbf{k}_\perp; Q^2) \otimes D_q^h(z, \mathbf{p}_\perp; Q^2)$$

(Collins, Soper, Ji, J.P. Ma, Yuan, Qiu, Vogelsang, Collins, Metz)

SIDISLAND

$$\begin{aligned}
 \frac{d\sigma}{d\phi} = & F_{UU} + \cos(2\phi) F_{UU}^{\cos(2\phi)} + \frac{1}{Q} \cos \phi F_{UU}^{\cos \phi} + \lambda \frac{1}{Q} \sin \phi F_{LU}^{\sin \phi} \\
 & + S_L \left\{ \sin(2\phi) F_{UL}^{\sin(2\phi)} + \frac{1}{Q} \sin \phi F_{UL}^{\sin \phi} + \lambda \left[F_{LL} + \frac{1}{Q} \cos \phi F_{LL}^{\cos \phi} \right] \right\} \\
 & + S_T \left\{ \sin(\phi - \phi_S) F_{UT}^{\sin(\phi - \phi_S)} + \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \right. \\
 & + \frac{1}{Q} \left[\sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi - \phi_S)} + \sin \phi_S F_{UT}^{\sin \phi_S} \right] \\
 & \left. + \lambda \left[\cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} + \frac{1}{Q} \left(\cos \phi_S F_{LT}^{\cos \phi_S} + \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi - \phi_S)} \right) \right] \right\}
 \end{aligned}$$

many spin
asymmetries

$$d\sigma(\mathbf{S}) \neq d\sigma(-\mathbf{S})$$

$F_{S_B S_T}^{(\dots)}$ contains the TMDs

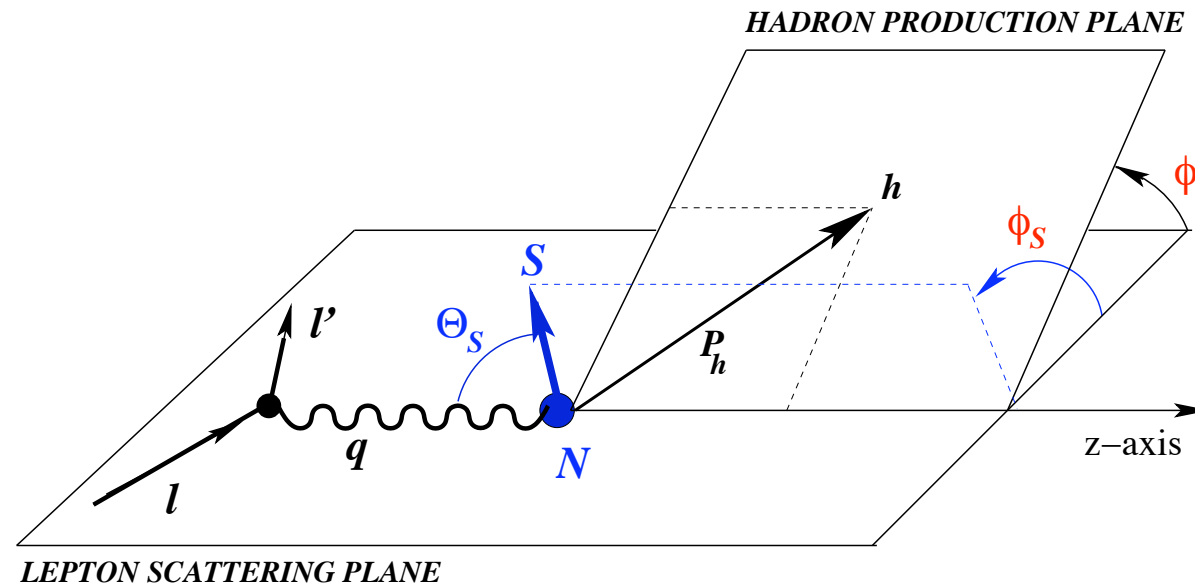
Kotzinian, NP B441 (1995) 234

Mulders and Tangermann, NP B461 (1996) 197

Boer and Mulders, PR D57 (1998) 5780

Bacchetta et al., PL B595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

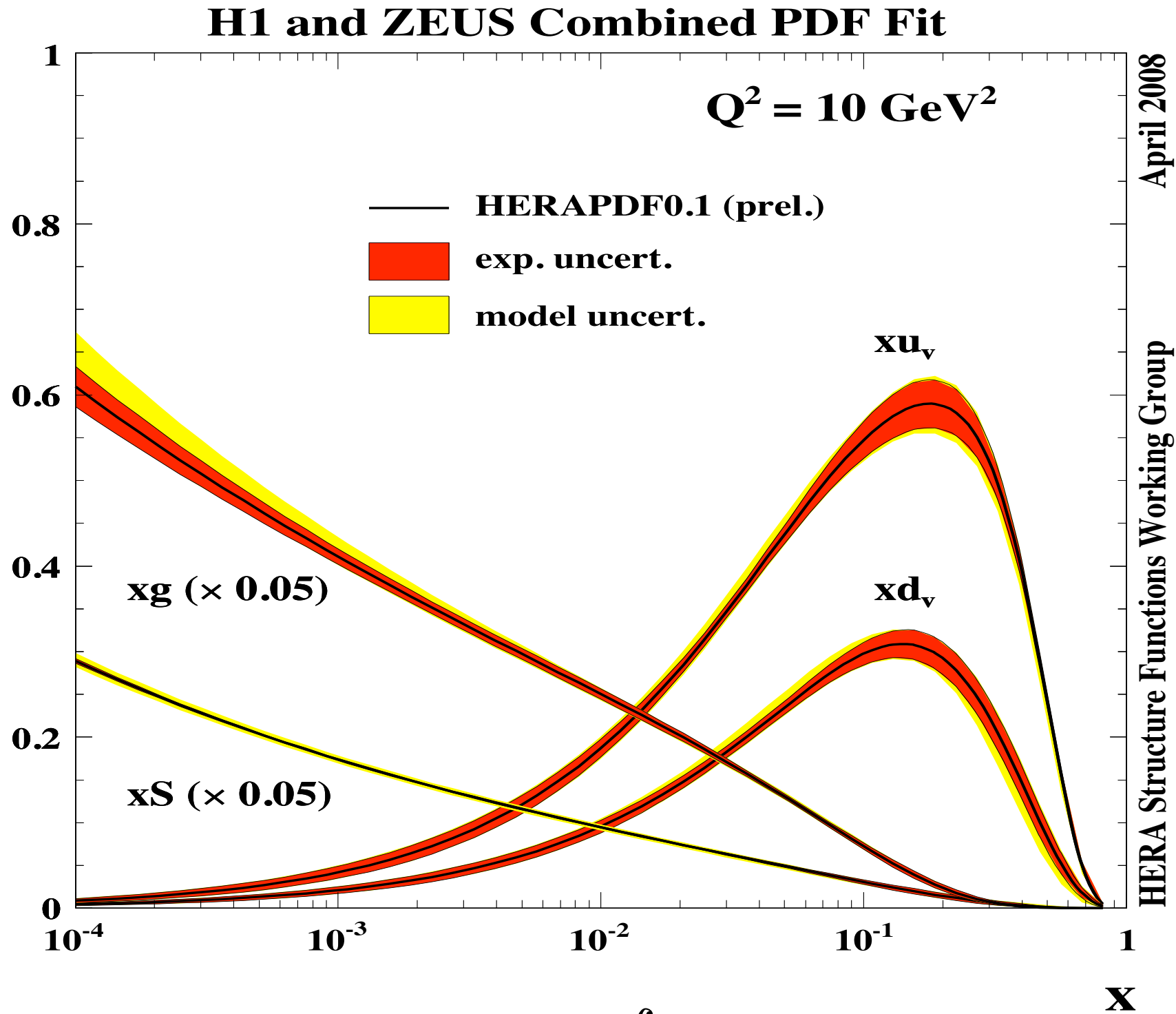


$$\begin{array}{ll}
 F_{UU} \sim \sum_a e_a^2 f_1^a \otimes D_1^a & F_{LT}^{\cos(\phi-\phi_s)} \sim \sum_a e_a^2 g_{1T}^{\perp a} \otimes D_1^a \\
 F_{LL} \sim \sum_a e_a^2 g_{1L}^a \otimes D_1^a & F_{UT}^{\sin(\phi-\phi_s)} \sim \sum_a e_a^2 f_{1T}^{\perp a} \otimes D_1^a
 \end{array}
 \left. \vphantom{\begin{array}{ll}} \right\} \text{chiral-even TMDs}$$

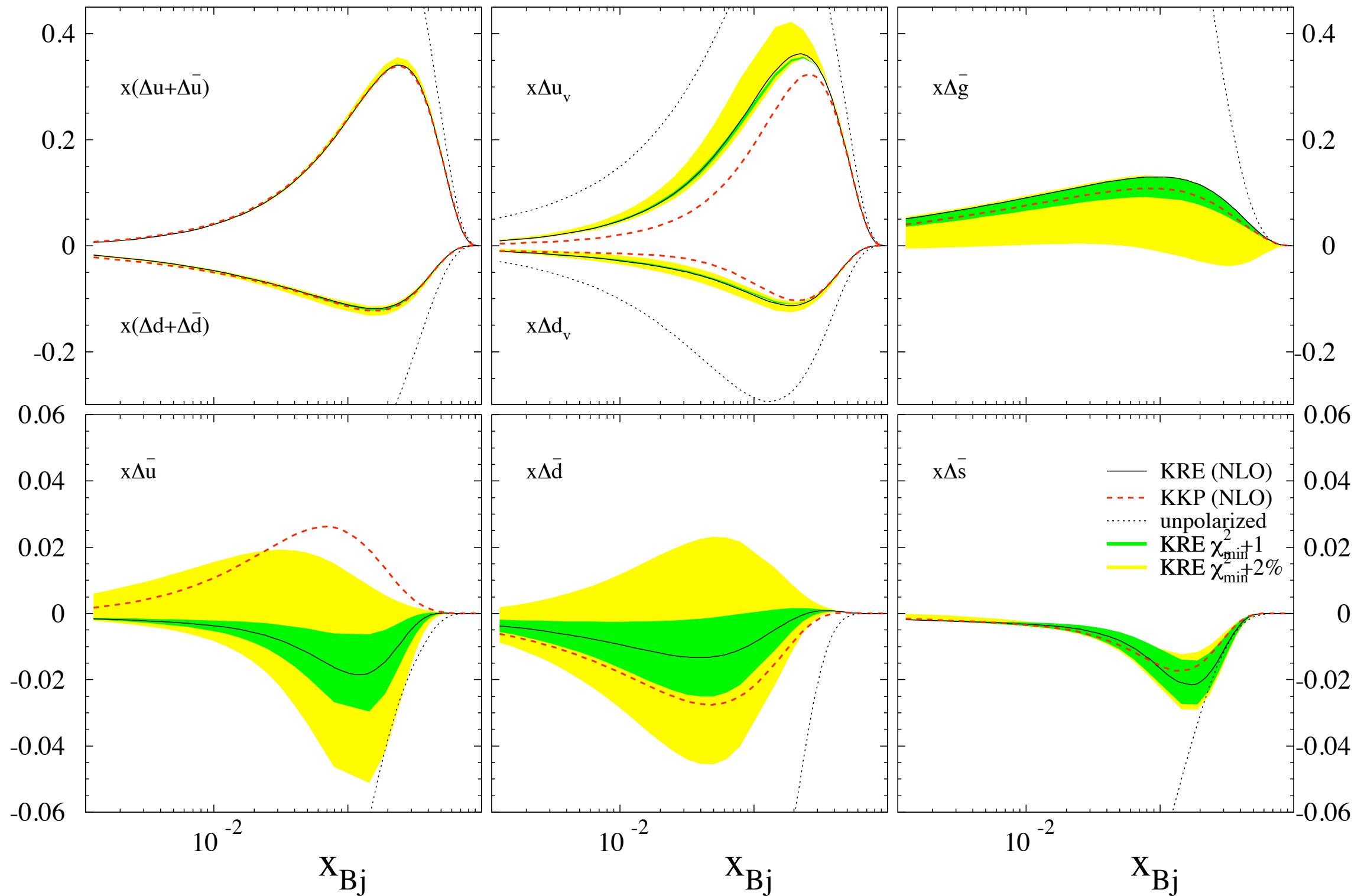
$$\begin{array}{ll}
 F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 h_1^{\perp a} \otimes H_1^{\perp a} & F_{UT}^{\sin(\phi+\phi_s)} \sim \sum_a e_a^2 h_{1T}^a \otimes H_1^{\perp a} \\
 F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 h_{1L}^{\perp a} \otimes H_1^{\perp a} & F_{UT}^{\sin(3\phi-\phi_s)} \sim \sum_a e_a^2 h_{1T}^{\perp a} \otimes H_1^{\perp a}
 \end{array}
 \left. \vphantom{\begin{array}{ll}} \right\} \text{chiral-odd TMDs}$$

$$\frac{1}{Q} \cos \phi F_{UU}^{\cos \phi} \sim f_1^q \otimes D_1^q \otimes d\hat{\sigma} + \left(h_1^{q\perp} \otimes H_1^{q\perp} \otimes d\Delta\hat{\sigma} \right) \quad \text{Cahn kinematical effects}$$

integrated parton distribution functions, PDF



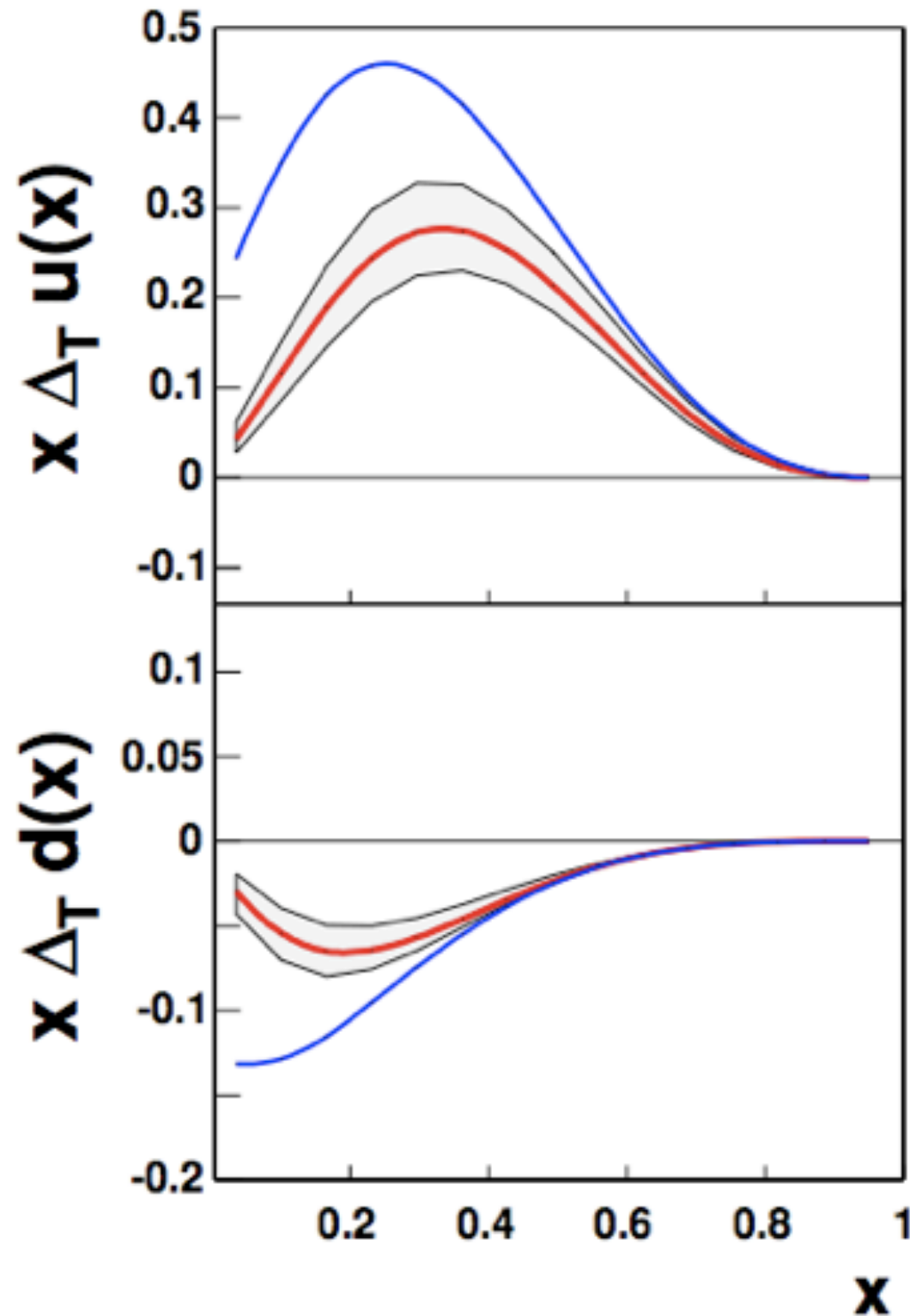
$$q(x) = f_1^q(x) = \int d^2 \mathbf{k}_\perp f_1^q(x, k_\perp^2)$$



D. de Florian, G. A. Navarro, and R. Sassot

$$\Delta q(x) = g_1^q(x) = \int d^2 \mathbf{k}_\perp g_{1L}^q(x, k_\perp^2)$$

transversity distributions (blue lines = Soffer's bound)

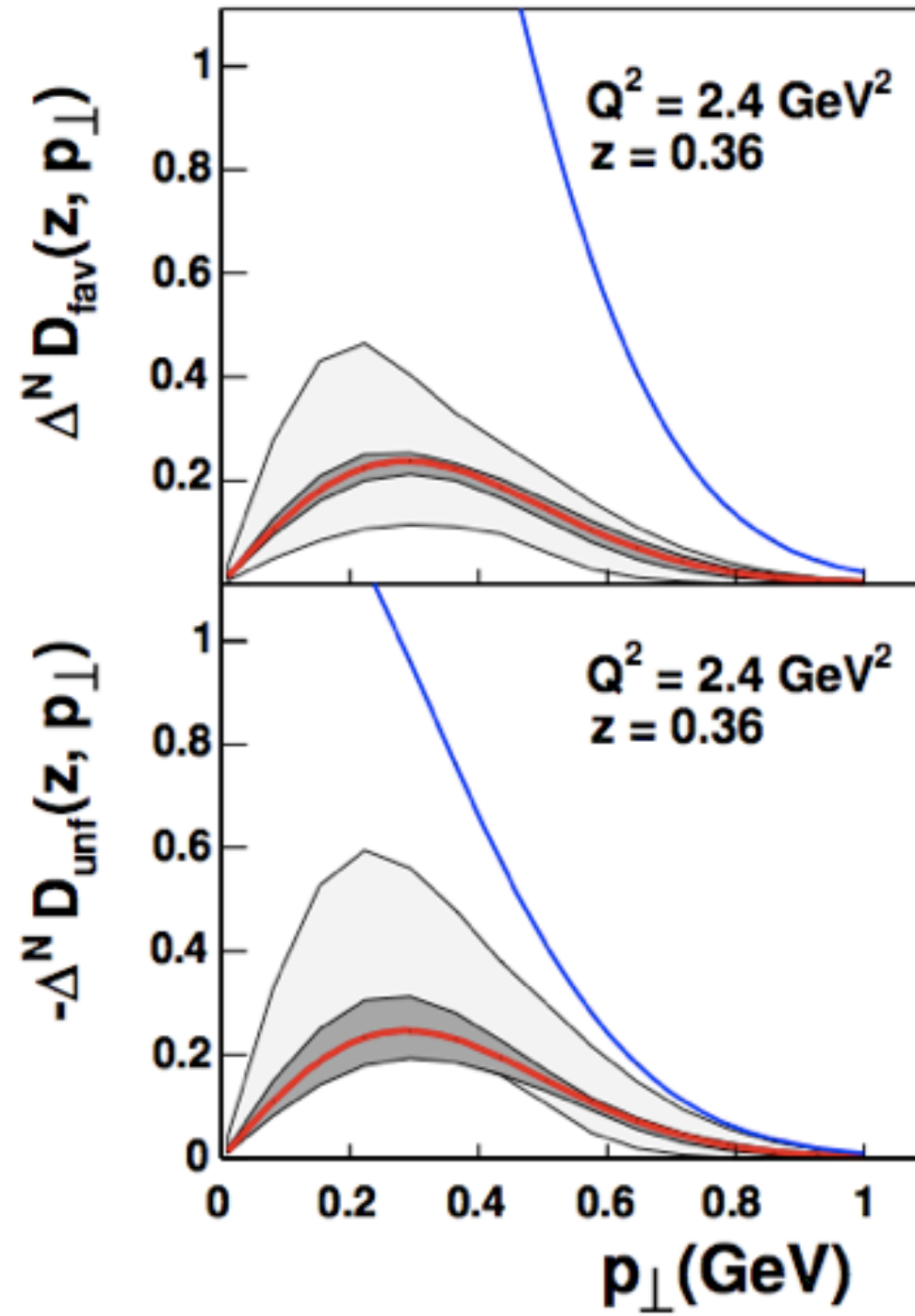
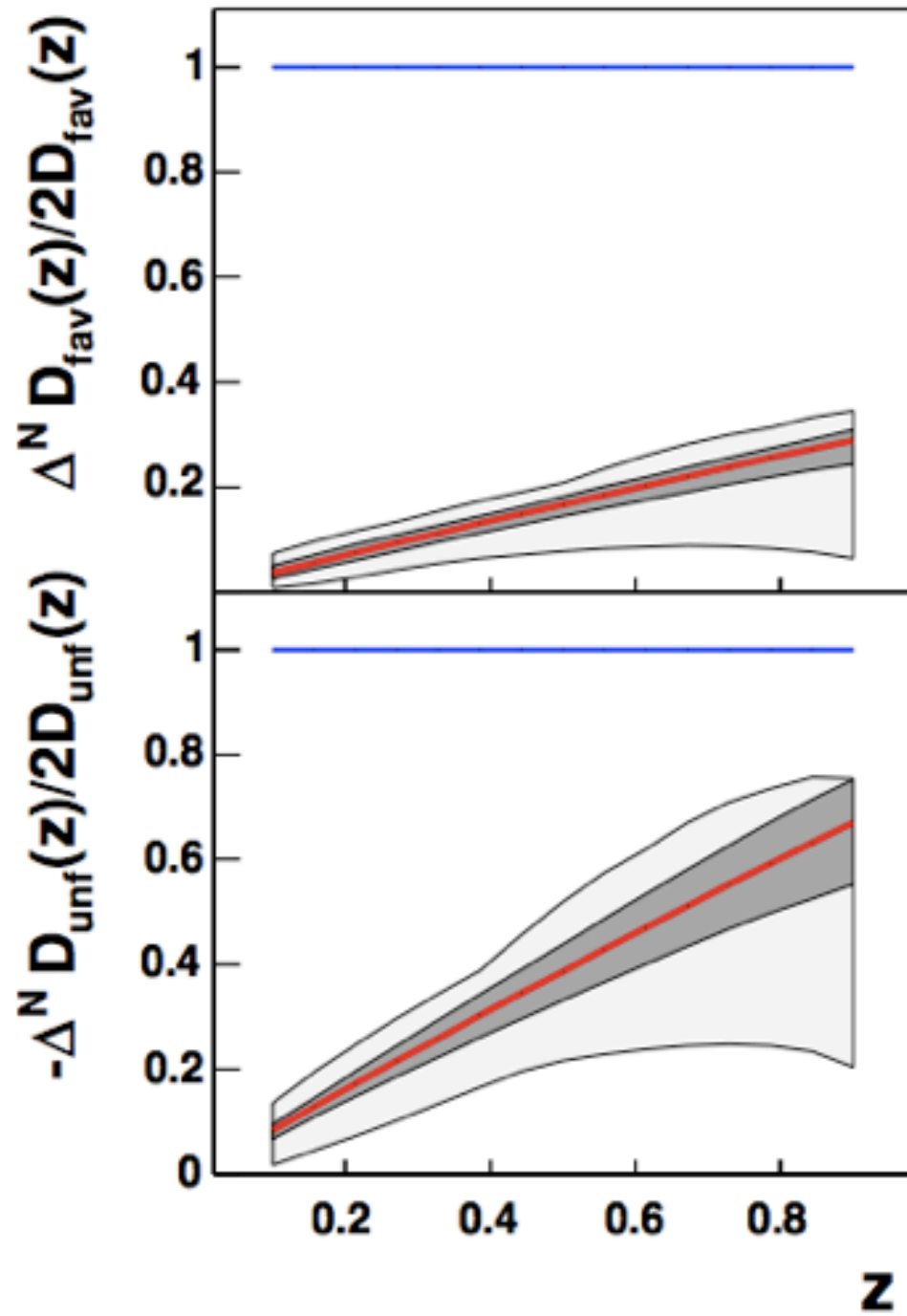


M.A., M. Boglione, U. D'Alesio,
A. Kotzinian, S. Melis, F. Murgia,
A. Prokudin, C. Türk

Extraction from SIDIS
(HERMES, COMPASS-D) +
 e^+e^- (Belle) data, $h_1 \otimes H_1^\perp$

$$\Delta_T q(x) = h_1^q(x) = \int d^2 \mathbf{k}_\perp \left[h_{1T}^q(x, k_\perp^2) + \frac{k_\perp^2}{2m_N^2} h_{1T}^{\perp q}(x, k_\perp^2) \right]$$

extracted Collins functions



TMDs: "Cahn effect" at $\mathcal{O}(k_{\perp}/Q)$

$$\frac{1}{Q} \cos \phi F_{UU}^{\cos \phi} \sim \underbrace{f_1^q \otimes D_1^q \otimes d\hat{\sigma}}_{\text{blue}} + \underbrace{\left(h_1^{q\perp} \otimes H_1^{q\perp} \otimes d\Delta\hat{\sigma} \right)}_{\text{red}}$$

$$x = x_B$$

$$z = z_h$$

$$\mathbf{P}_T = z \mathbf{k}_{\perp} + \mathbf{p}_{\perp}$$

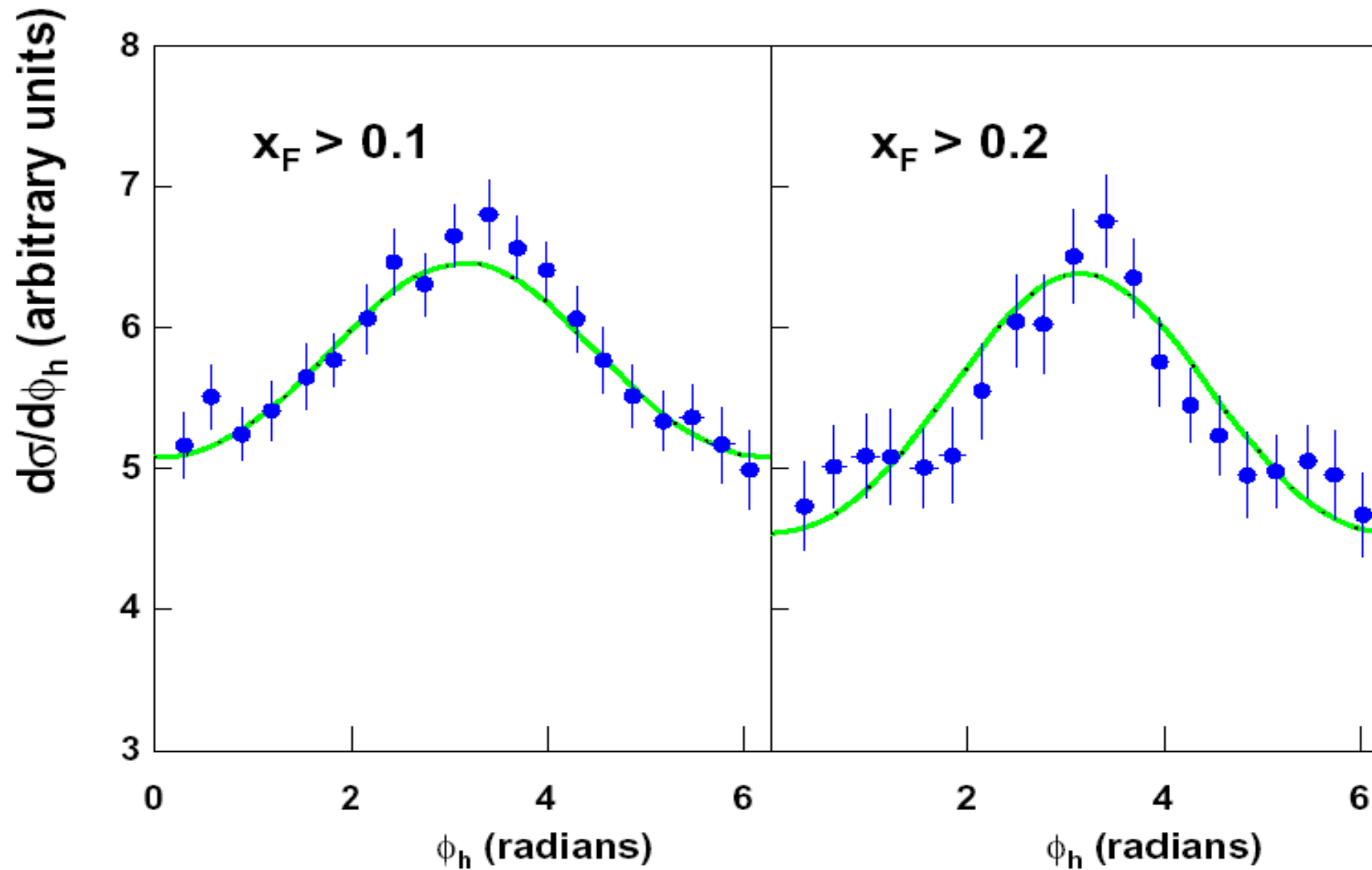
$$d\hat{\sigma}^{\ell q \rightarrow \ell q} \propto \hat{s}^2 + \hat{u}^2 = \frac{Q^4}{y^2} \left[1 + (1-y)^2 \ominus 4 \frac{k_{\perp}}{Q} (2-y) \sqrt{1-y} \cos \varphi \right]$$

kinematical effect directly related to quark intrinsic motion

$\mathcal{O}(k_{\perp}^2/Q^2)$: also a $\cos(2\phi)$ dependence

$\cos \Phi$ dependence generated also by Boer-Mulders

⊗ Collins term, via a kinematical effect in $d\Delta\hat{\sigma}$



EMC data, μp and μd , E between 100 and 280 GeV

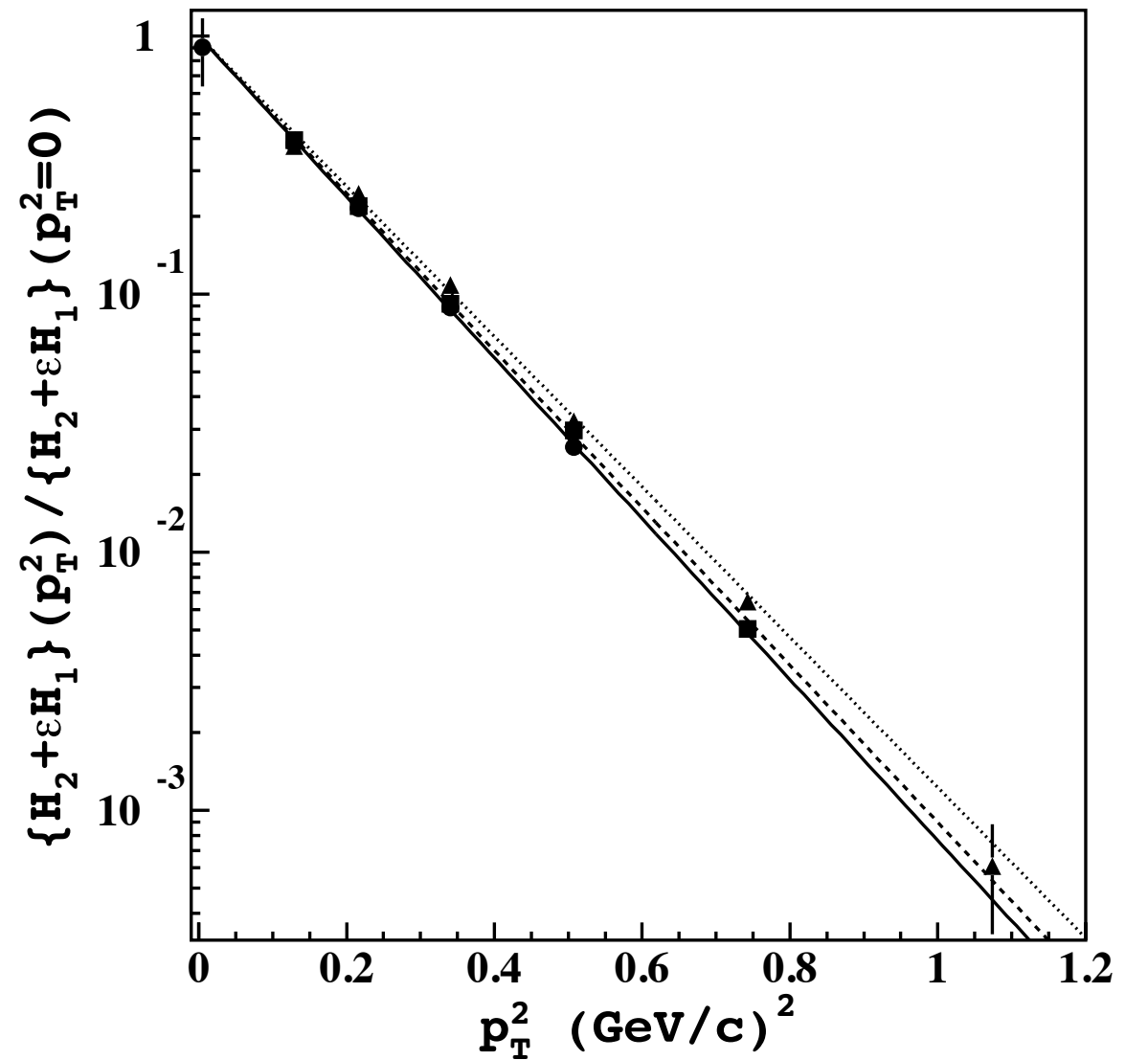
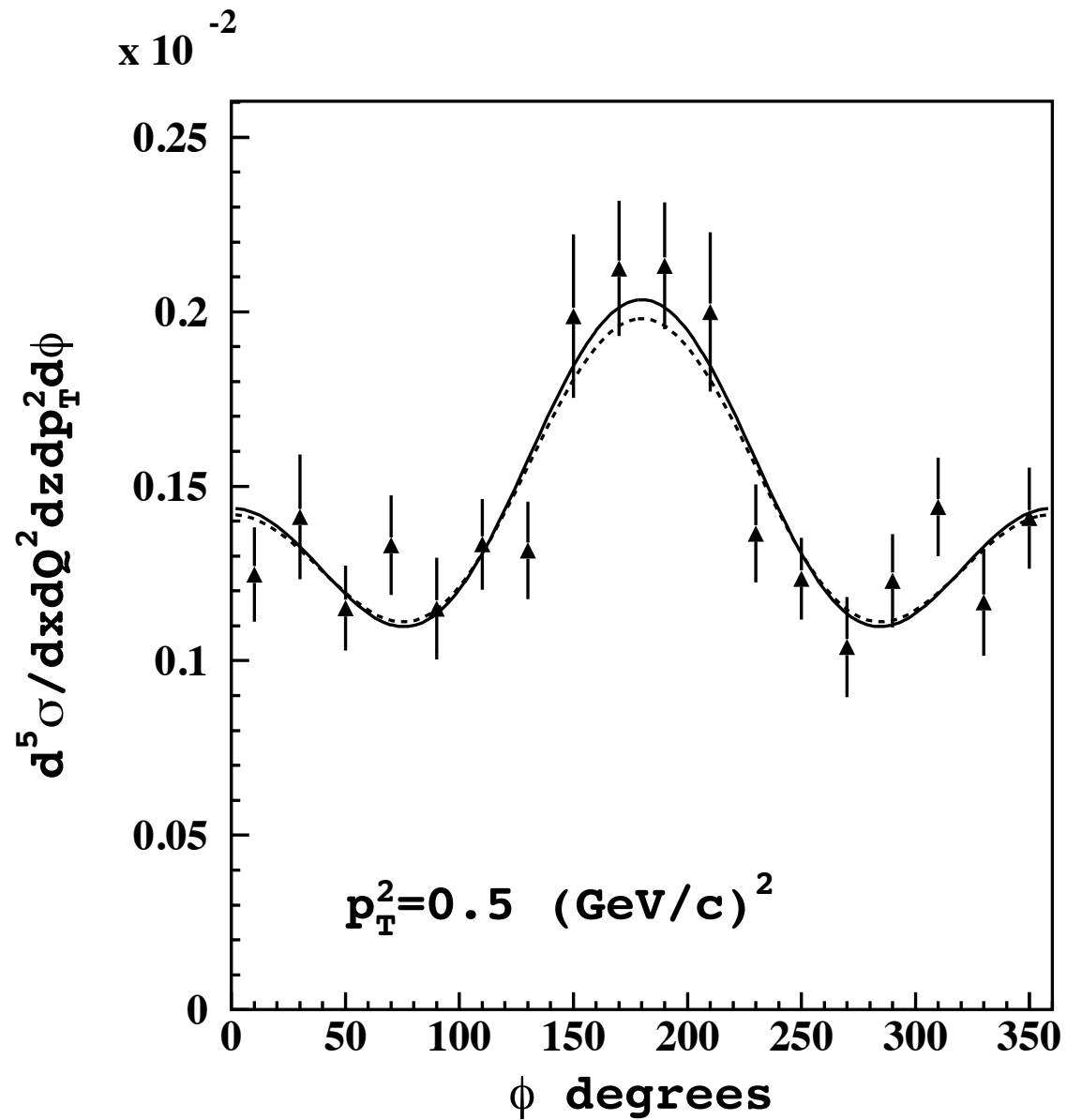
$$\langle k_{\perp}^2 \rangle = 0.28 \text{ (GeV)}^2 \quad \langle p_{\perp}^2 \rangle = 0.25 \text{ (GeV)}^2$$

(no B-M \otimes Collins contribution)

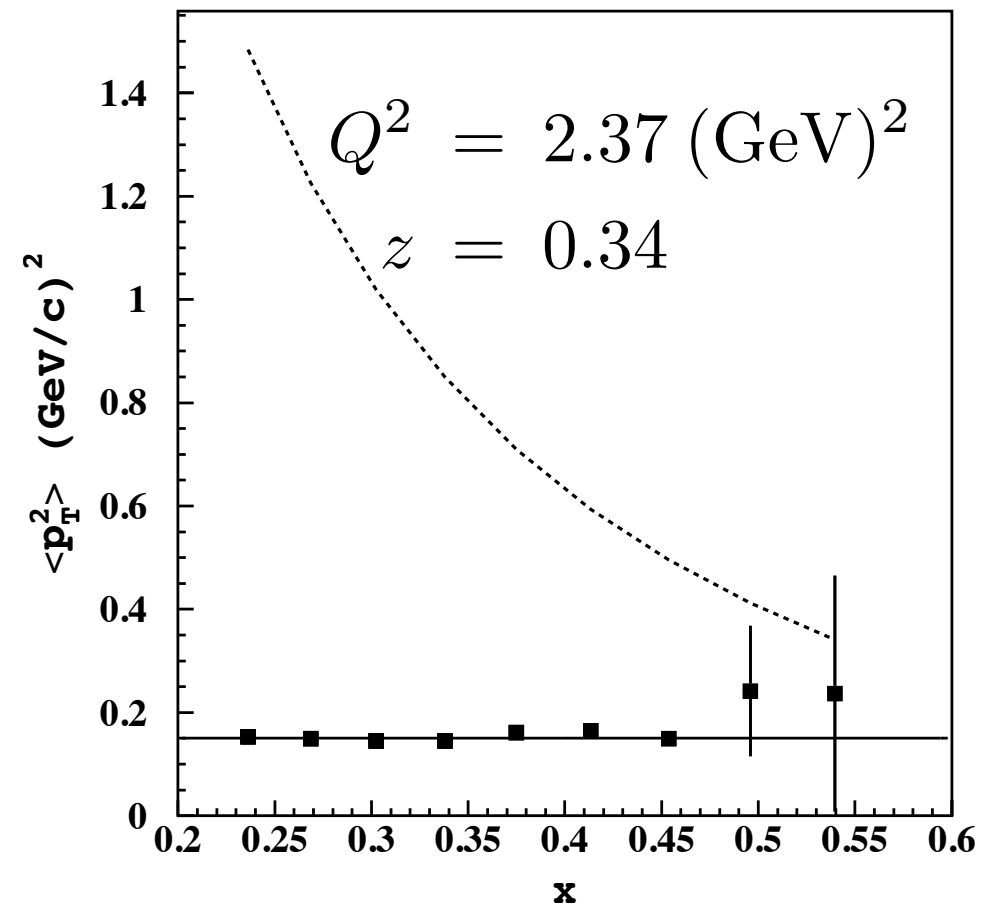
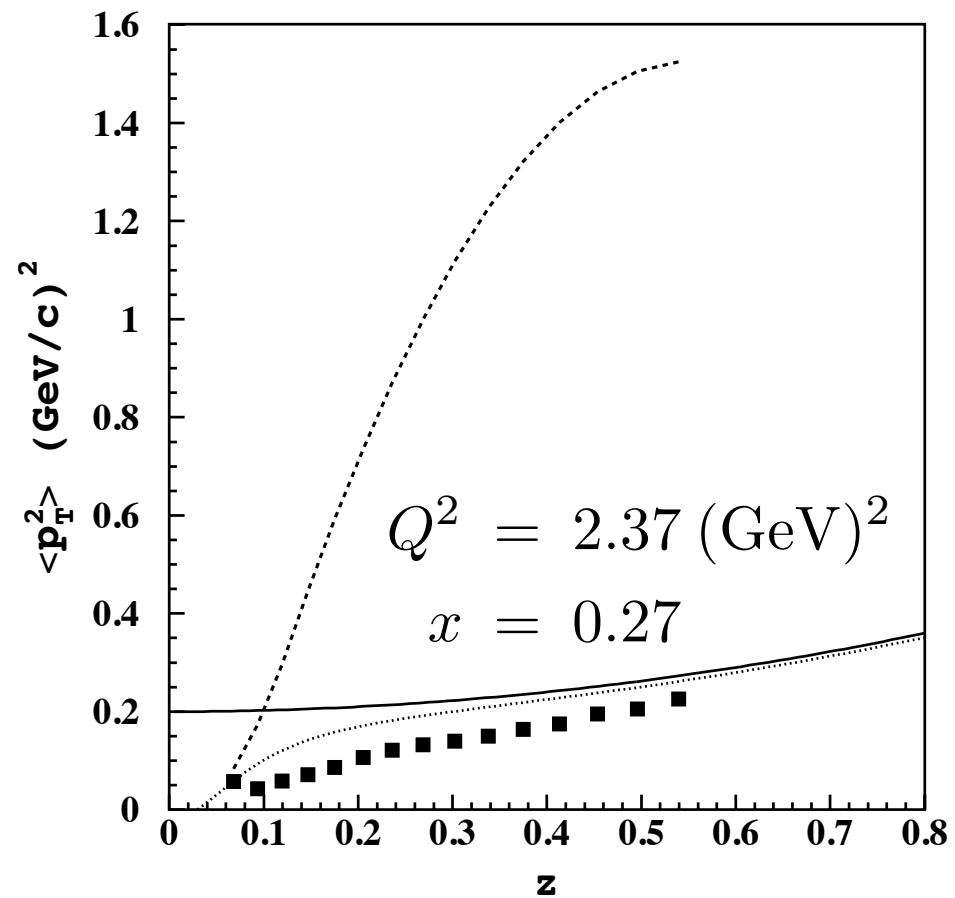
M.A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin

CLAS data, arXiv:0809.1153

$$\frac{d^5\sigma}{dx dQ^2 dz dP_T^2 d\phi} = C [\epsilon\mathcal{H}_1 + \mathcal{H}_2 + A \cos \phi + B \cos(2\phi)]$$



P_T dependence of data in agreement with a Gaussian k_{\perp} dependence of unpolarized TMDs



solid line =

$$\langle P_T^2 \rangle = z^2 \langle k_{\perp}^2 \rangle + \langle p_{\perp}^2 \rangle$$

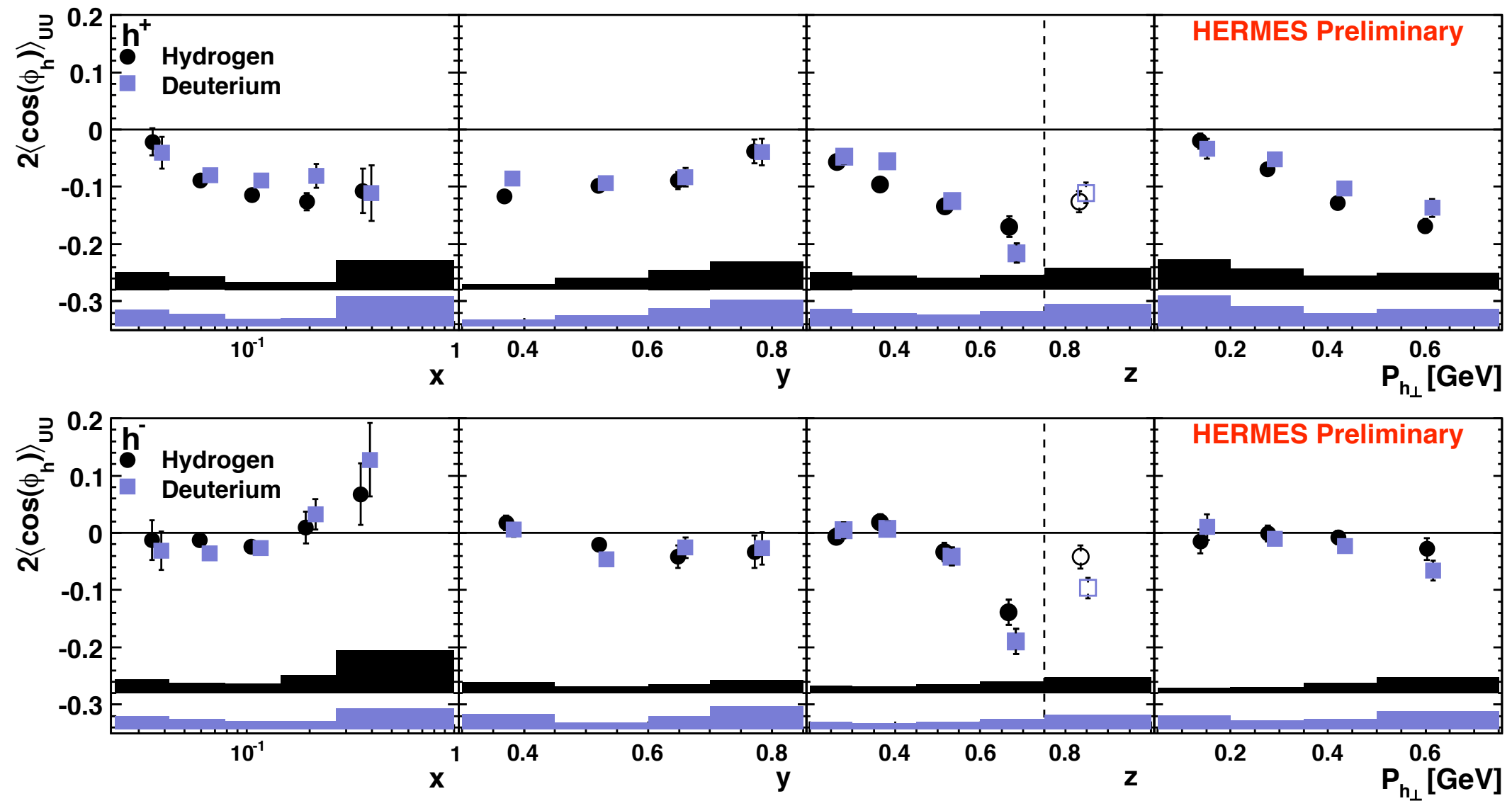
$$\langle k_{\perp}^2 \rangle = 0.25 \quad \langle p_{\perp}^2 \rangle = 0.20$$

z dependence at small z values

no hint of x dependence in explored region

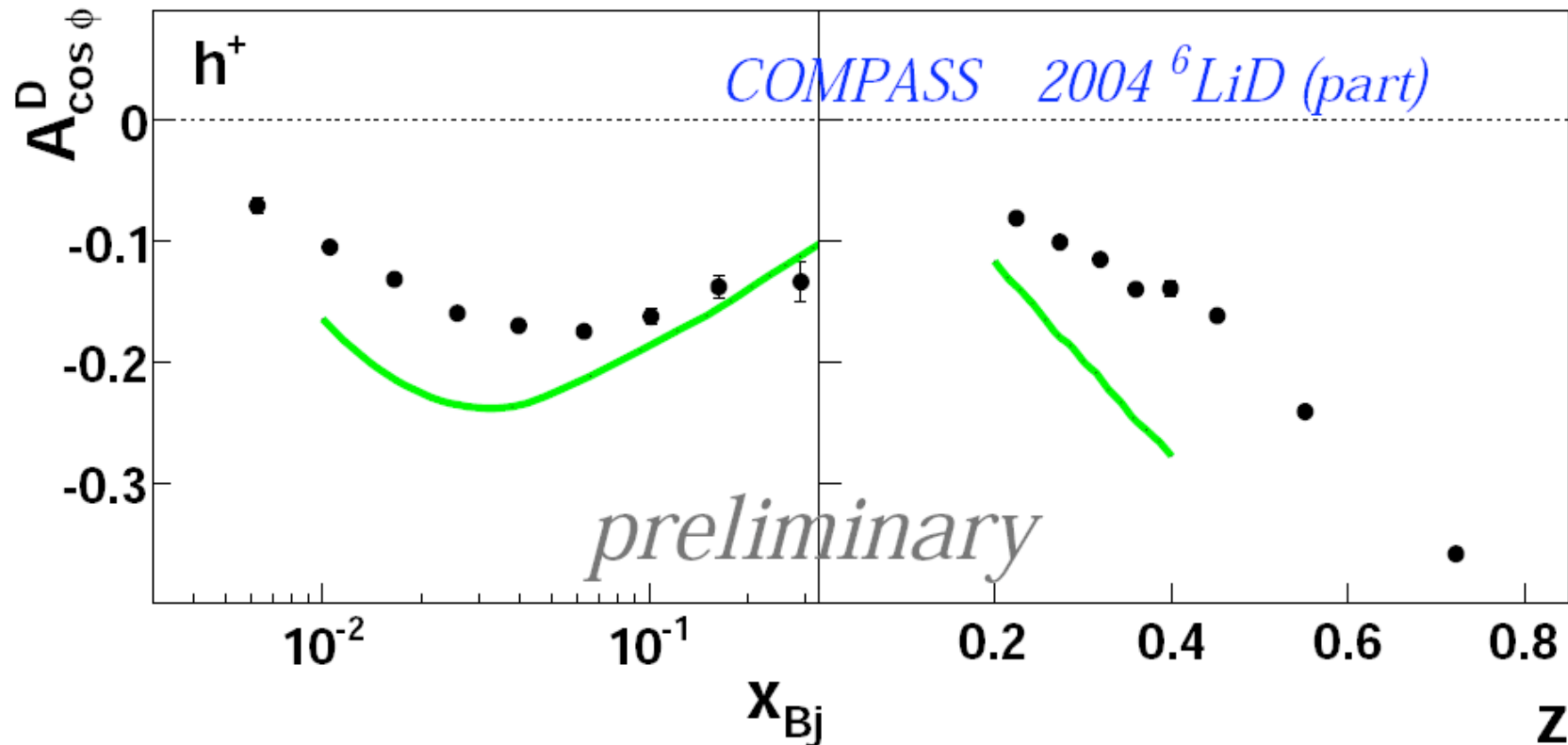
$\cos \phi$ dependence observed by HERMES

F. Giordano and R. Lamb, arXiv:0901.2438 [hep-ex]



and by COMPASS

W. Käfer, on behalf of the COMPASS collaboration, talk at
Transversity 2008, Ferrara



errors shown are statistical only

comparison with:

M. Anselmino, M. Boglione, A. Prokudin, C. Türk

Eur. Phys. J. A 31, 373-381 (2007)

does not include Boer - Mulders contribution

Sivers effect in SIDIS - $F_{UT}^{\sin(\phi - \phi_S)}$

$$d\sigma^{\uparrow, \downarrow} = \sum_q f_{q/p^{\uparrow, \downarrow}}(x, \mathbf{k}_\perp; Q^2) \otimes d\hat{\sigma}(y, \mathbf{k}_\perp; Q^2) \otimes D_{h/q}(z, \mathbf{p}_\perp; Q^2)$$

$$f_{q/p^{\uparrow, \downarrow}}(x, \mathbf{k}_\perp) = f_{q/p}(x, k_\perp) \pm \frac{1}{2} \Delta^N f_{q/p^\uparrow}(x, k_\perp) \mathbf{S} \cdot (\hat{\mathbf{p}} \times \hat{\mathbf{k}}_\perp)$$

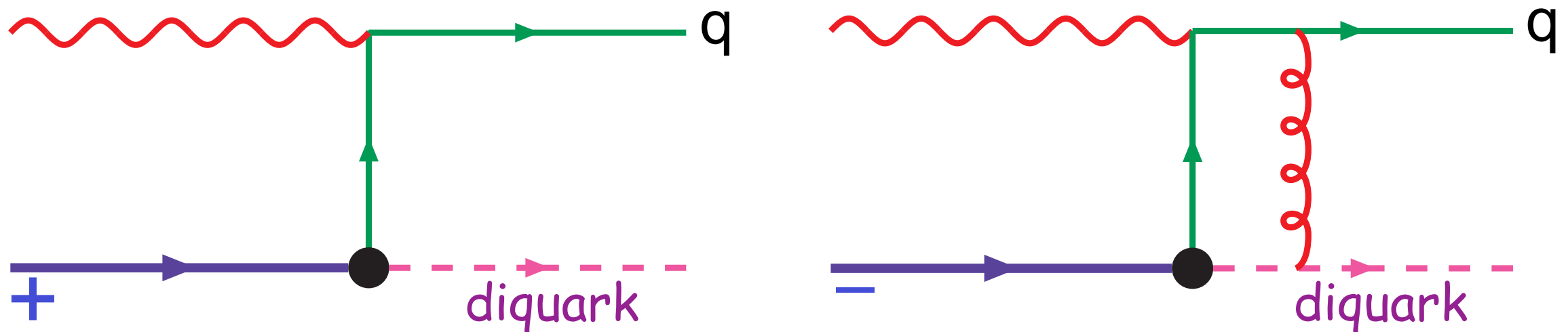
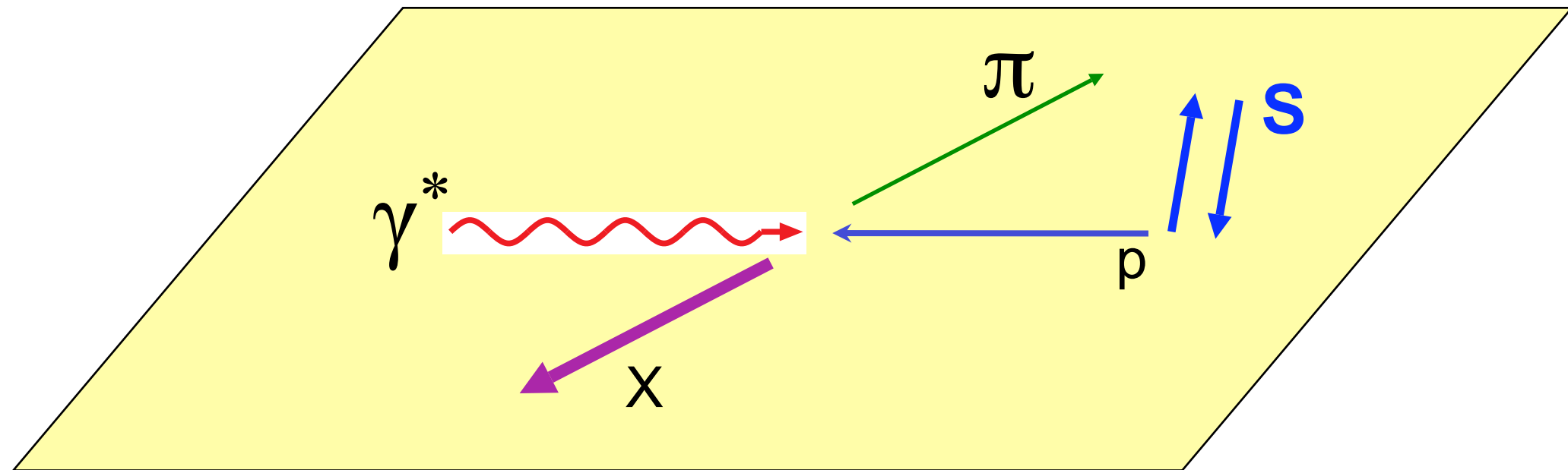
$$d\sigma^\uparrow - d\sigma^\downarrow =$$

$$\sum_q \Delta^N f_{q/p^\uparrow}(x, k_\perp) \underbrace{\mathbf{S} \cdot (\hat{\mathbf{p}} \times \mathbf{k}_\perp)}_{\sin(\varphi - \Phi_S)} \otimes d\hat{\sigma}(y, \mathbf{k}_\perp) \otimes D_{h/q}(z, \mathbf{p}_\perp)$$

$$2 \langle \sin(\phi - \phi_S) \rangle = A_{UT}^{\sin(\phi - \phi_S)}$$

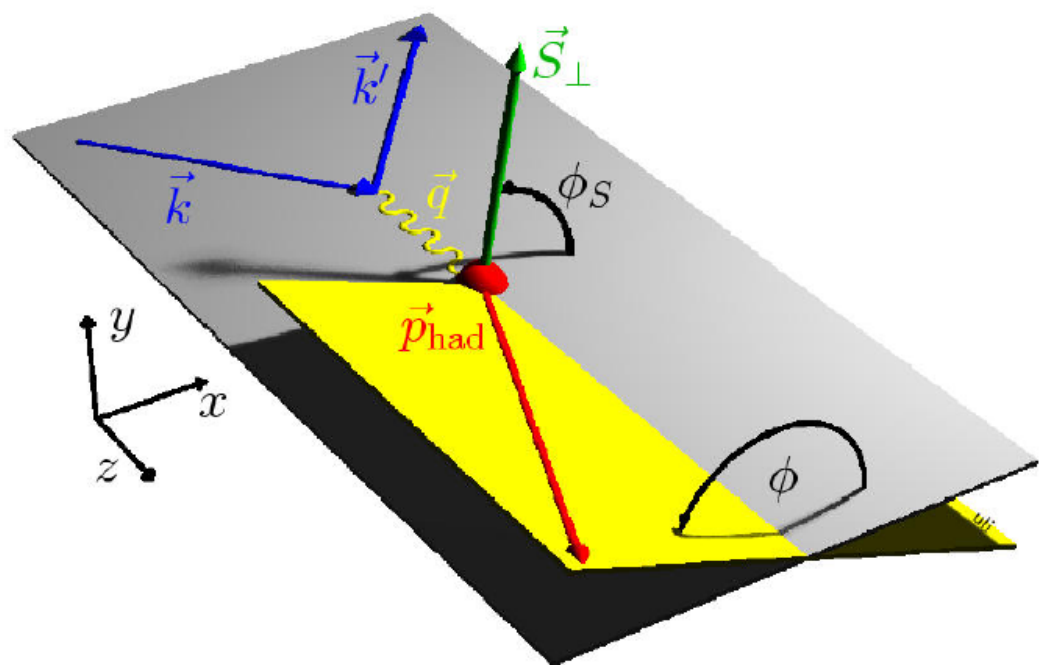
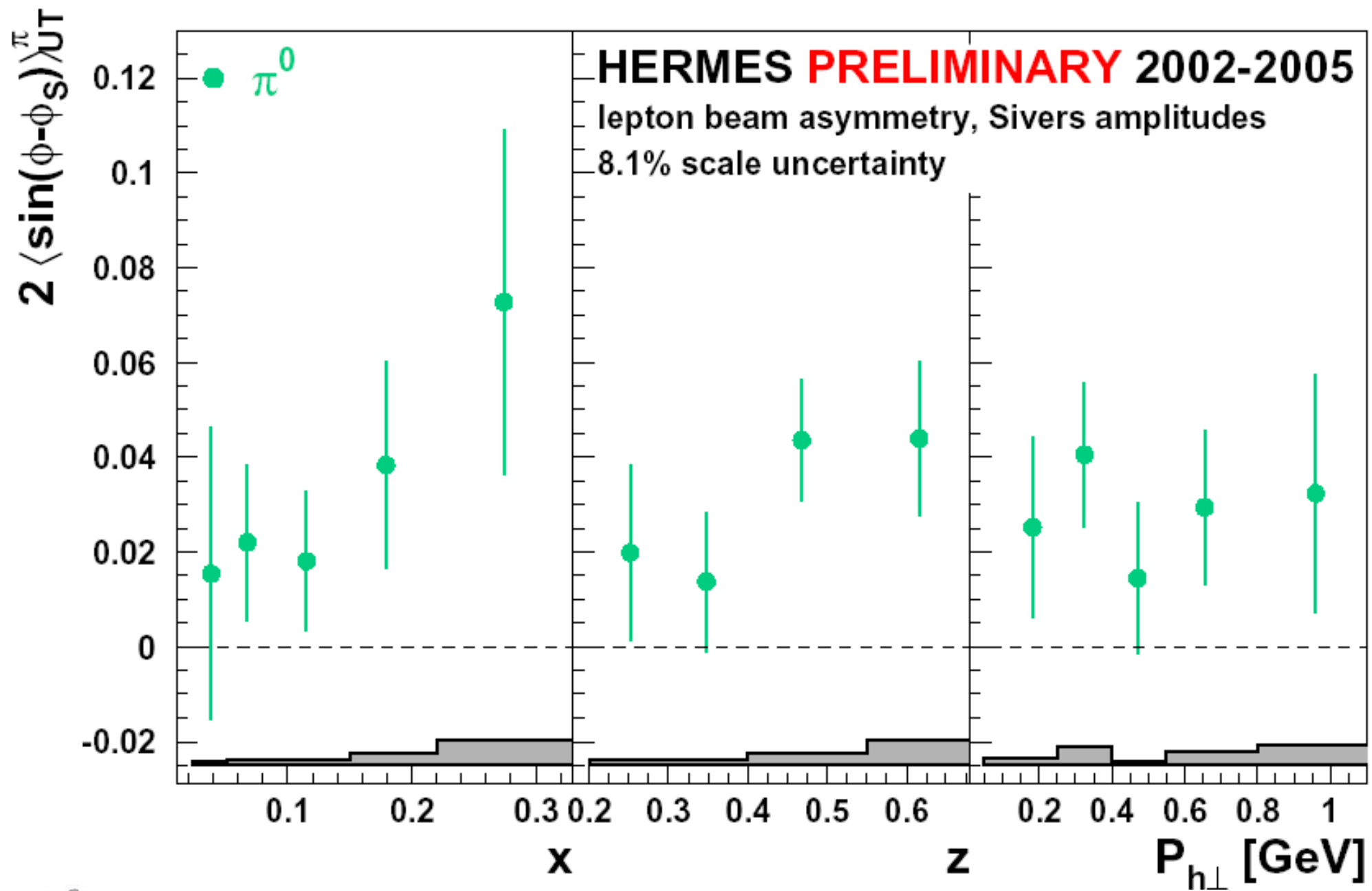
$$\equiv 2 \frac{\int d\phi d\phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi - \phi_S)}{\int d\phi d\phi_S [d\sigma^\uparrow + d\sigma^\downarrow]}$$

Brodsky, Hwang, Schmidt model for Sivers function



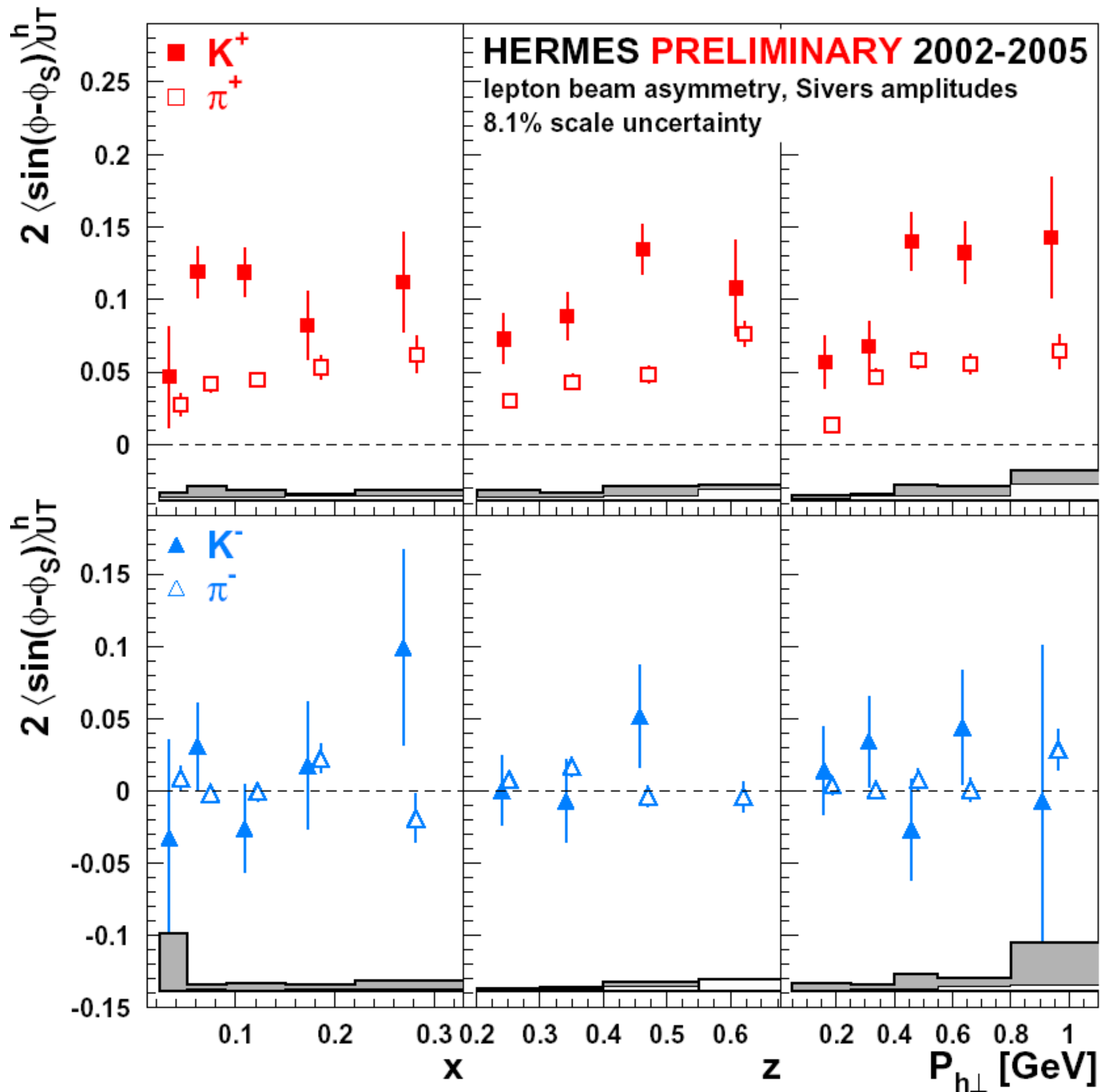
$$A_N \propto \mathbf{S} \cdot (\mathbf{p} \times \mathbf{P}_T) \propto P_T \sin(\phi_\pi - \phi_S)$$

needs \mathbf{k}_\perp dependent quark distribution in p^\uparrow and final state interactions



$$2\langle\sin(\phi - \phi_S)\rangle = A_{UT}^{\sin(\phi - \phi_S)}$$

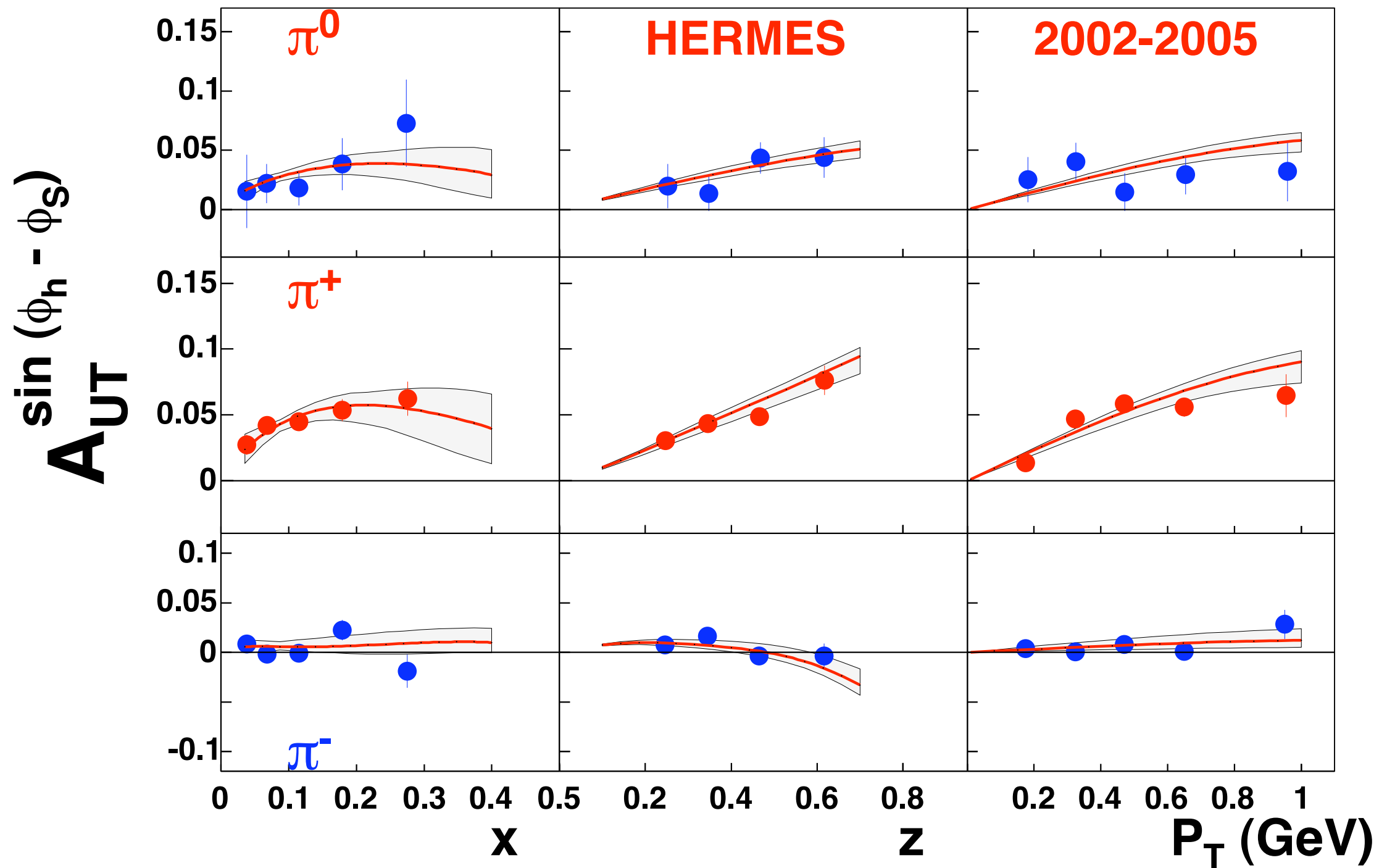
$$\equiv 2 \frac{\int d\phi d\phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi - \phi_S)}{\int d\Phi_h d\Phi_S [d\sigma^\uparrow + d\sigma^\downarrow]}$$

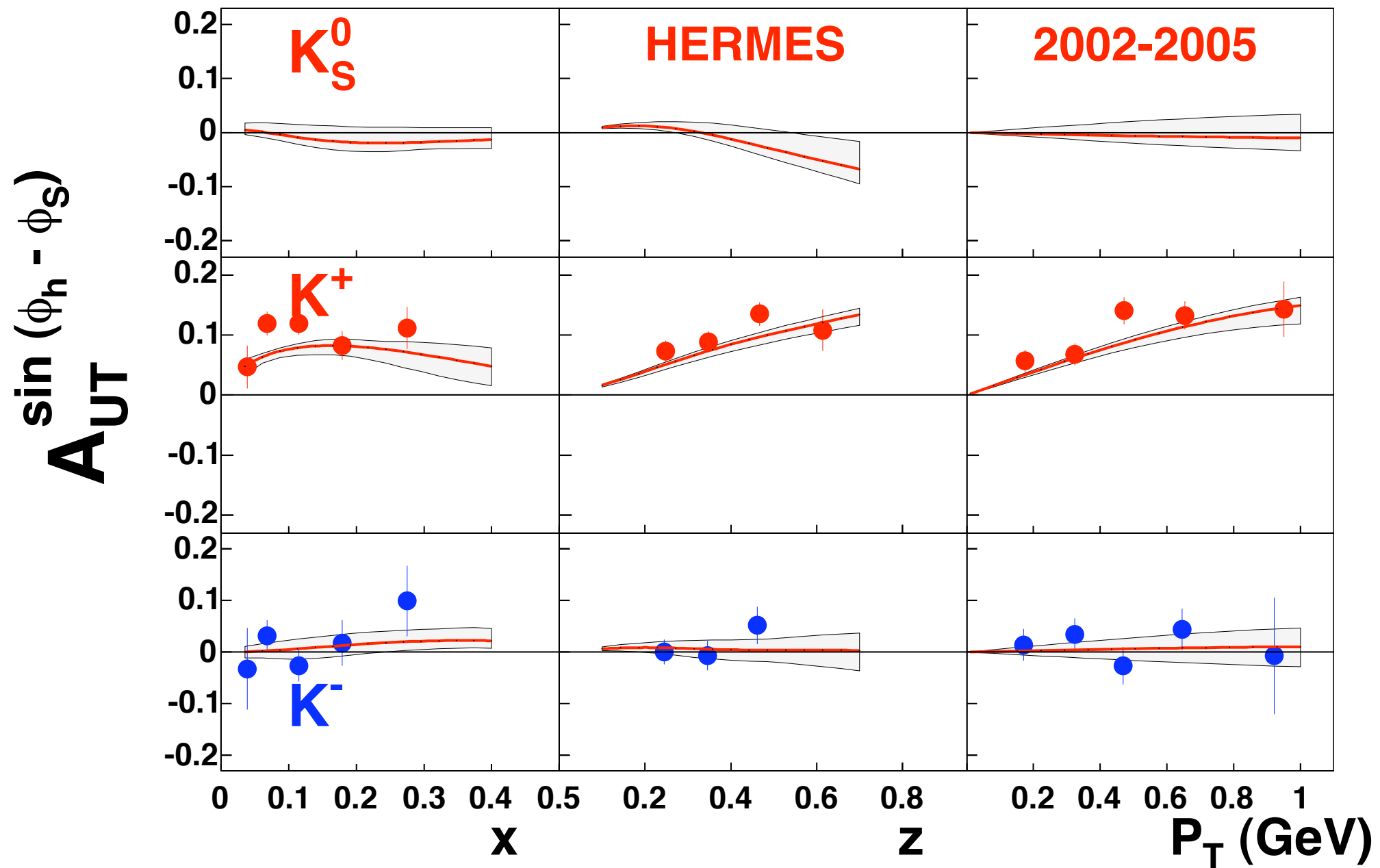


New kaon
 data, large K^+
 asymmetry!

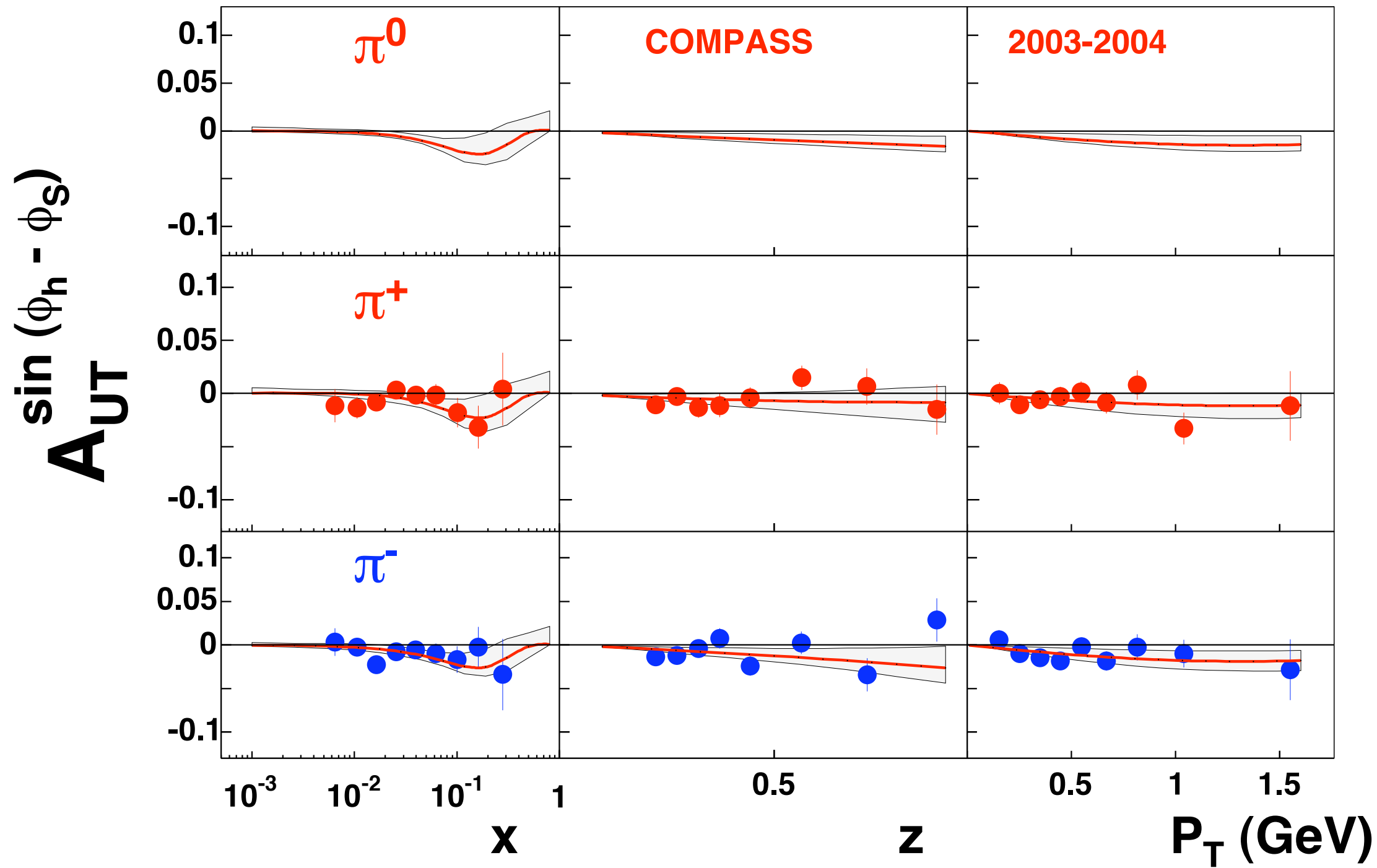
Sivers asymmetry best fits

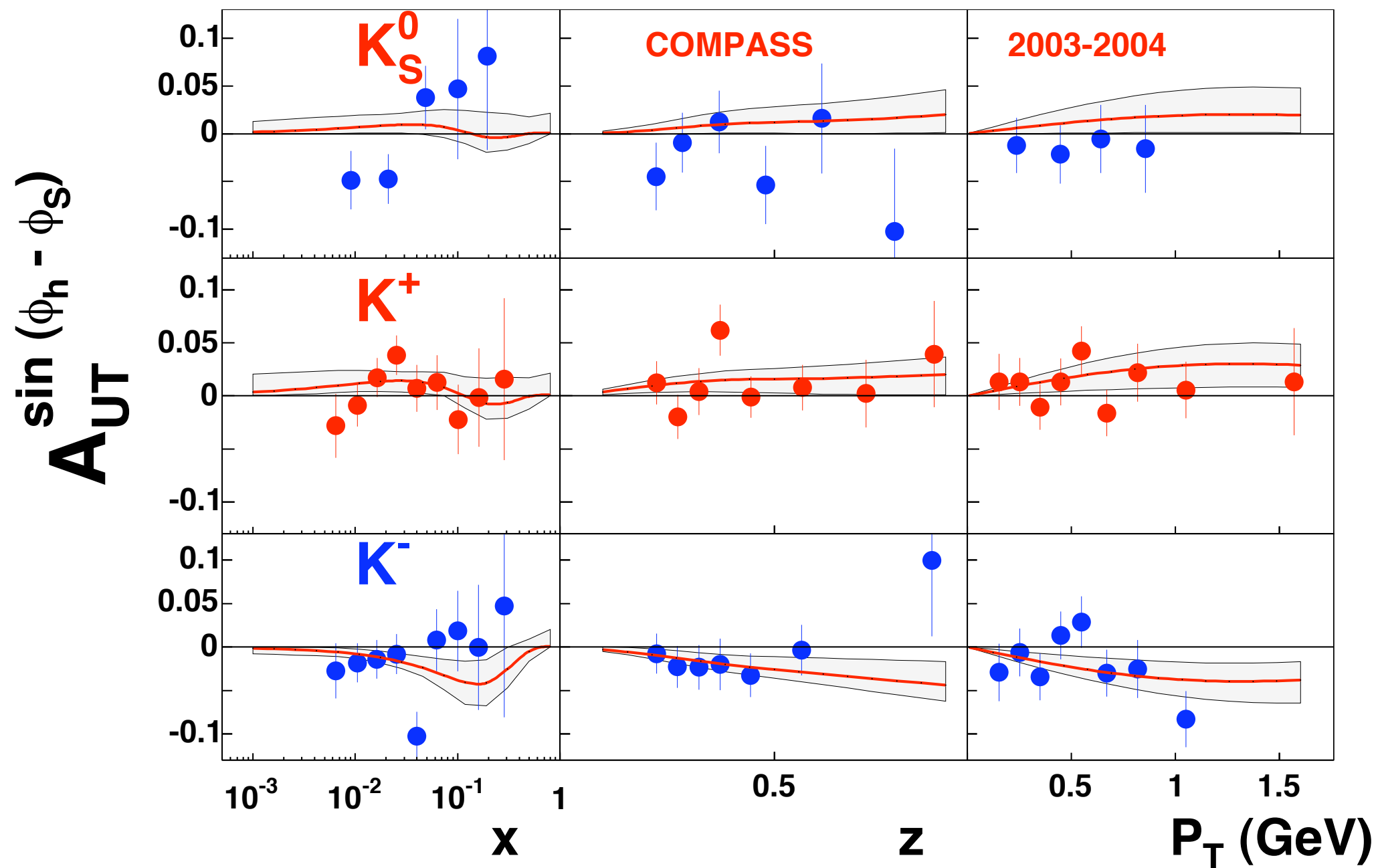
M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Turk,
Eur. Phys. J. A39 (2009) 89



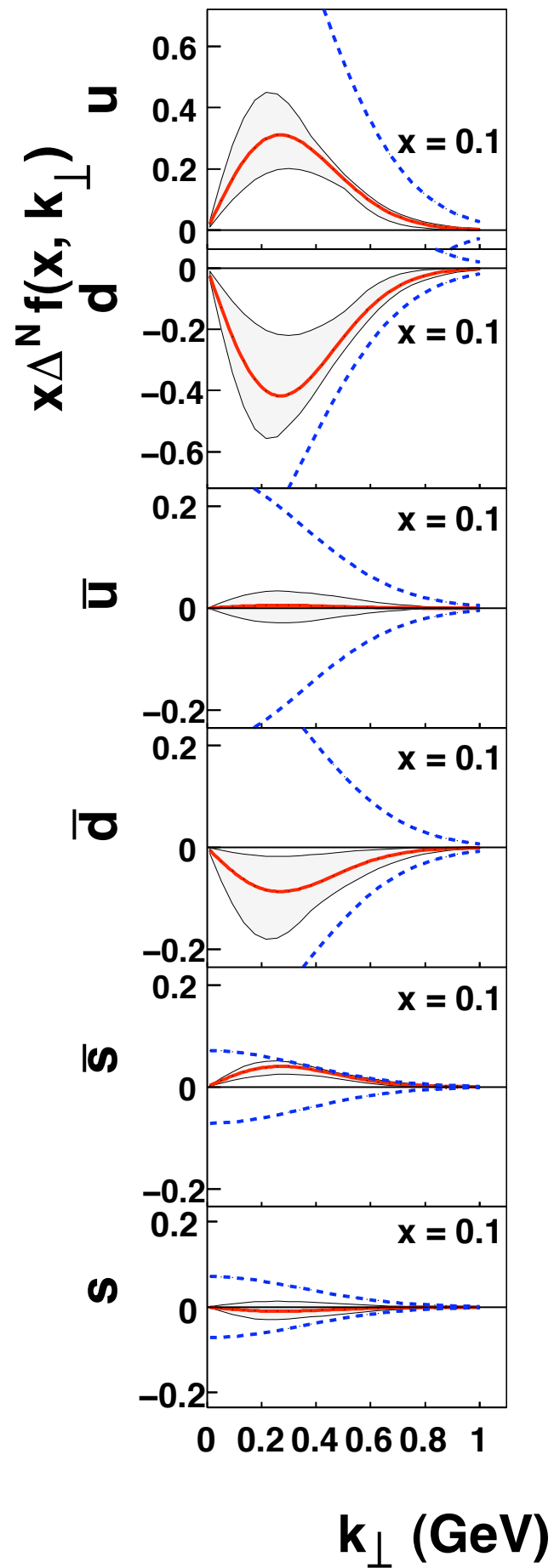
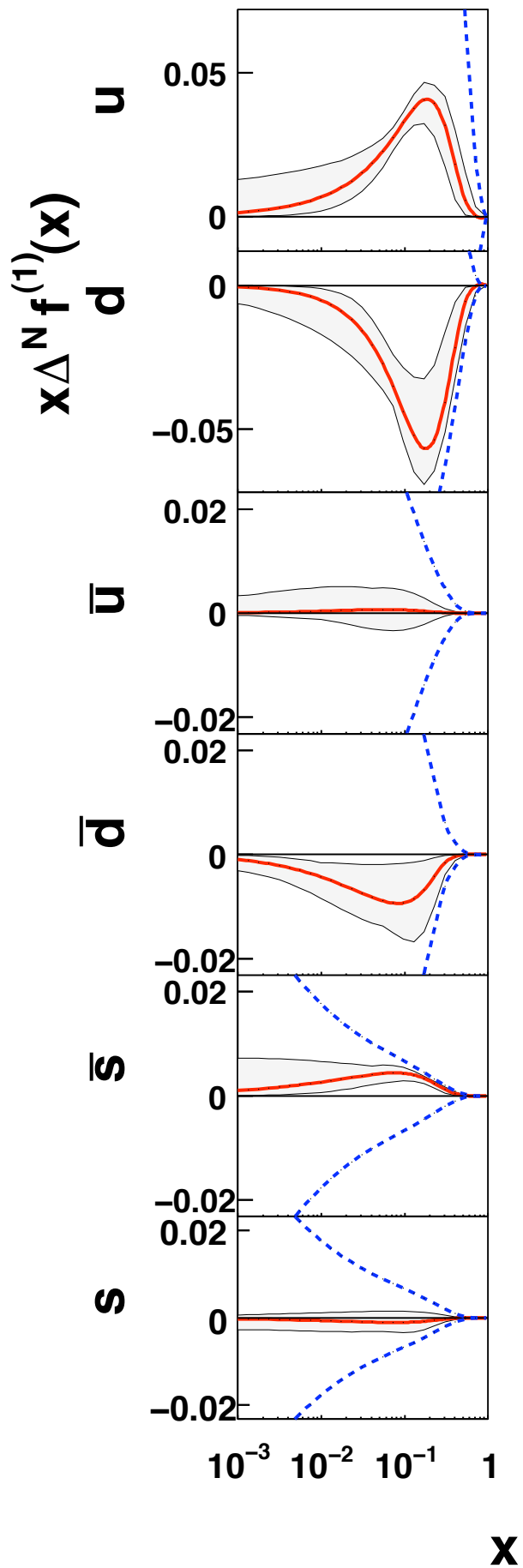


$$D_d^{K_S^0} = D_{\bar{d}}^{K_S^0} = \frac{1}{2} \left[D_u^{K^+} + D_{sea}^{K^+} \right]$$





K_S^0 not included in the fit: computed



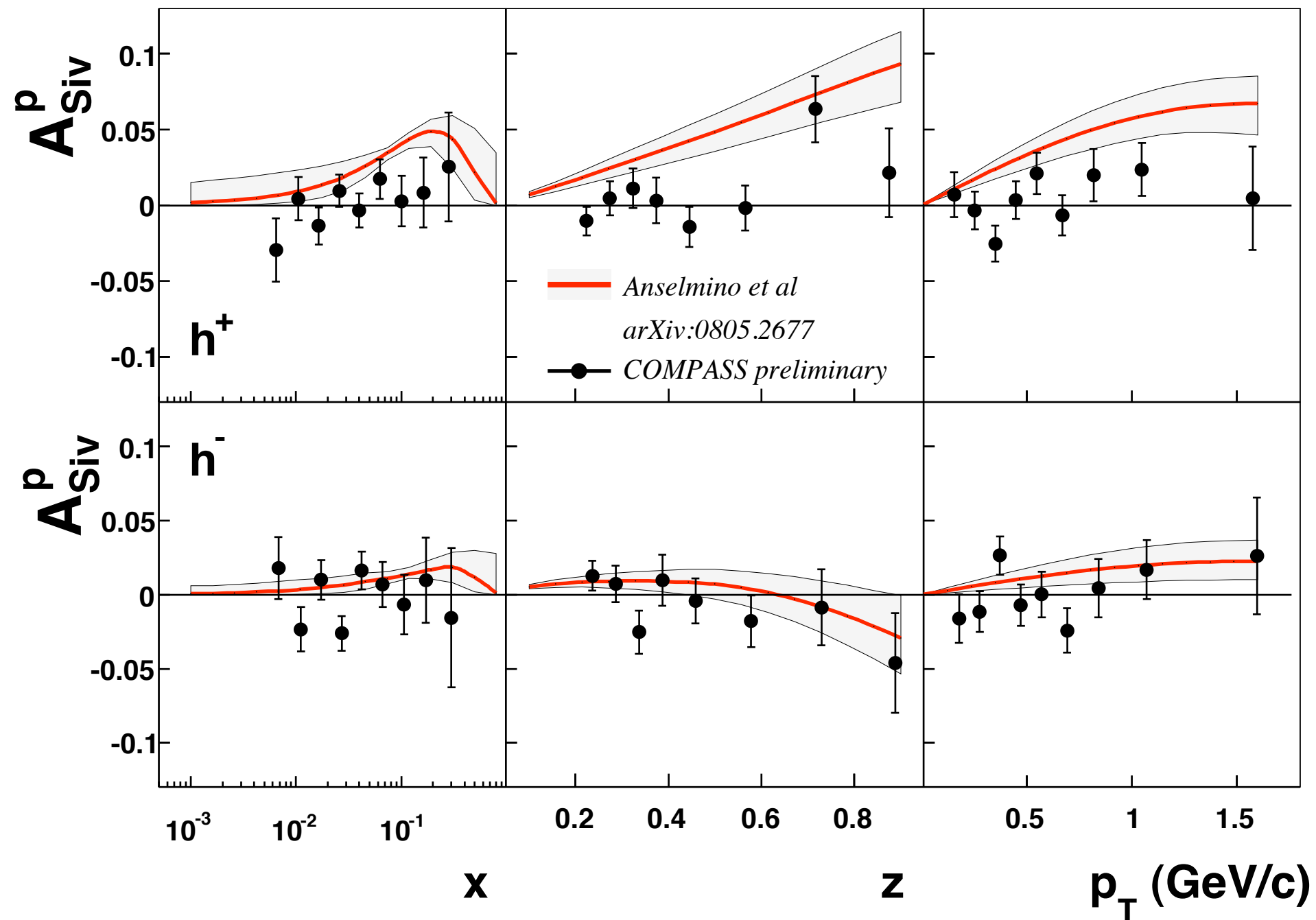
extracted
 Sivers
 functions

$$\Delta^N f_{u/p^\uparrow} > 0$$

$$\Delta^N f_{d/p^\uparrow} < 0$$

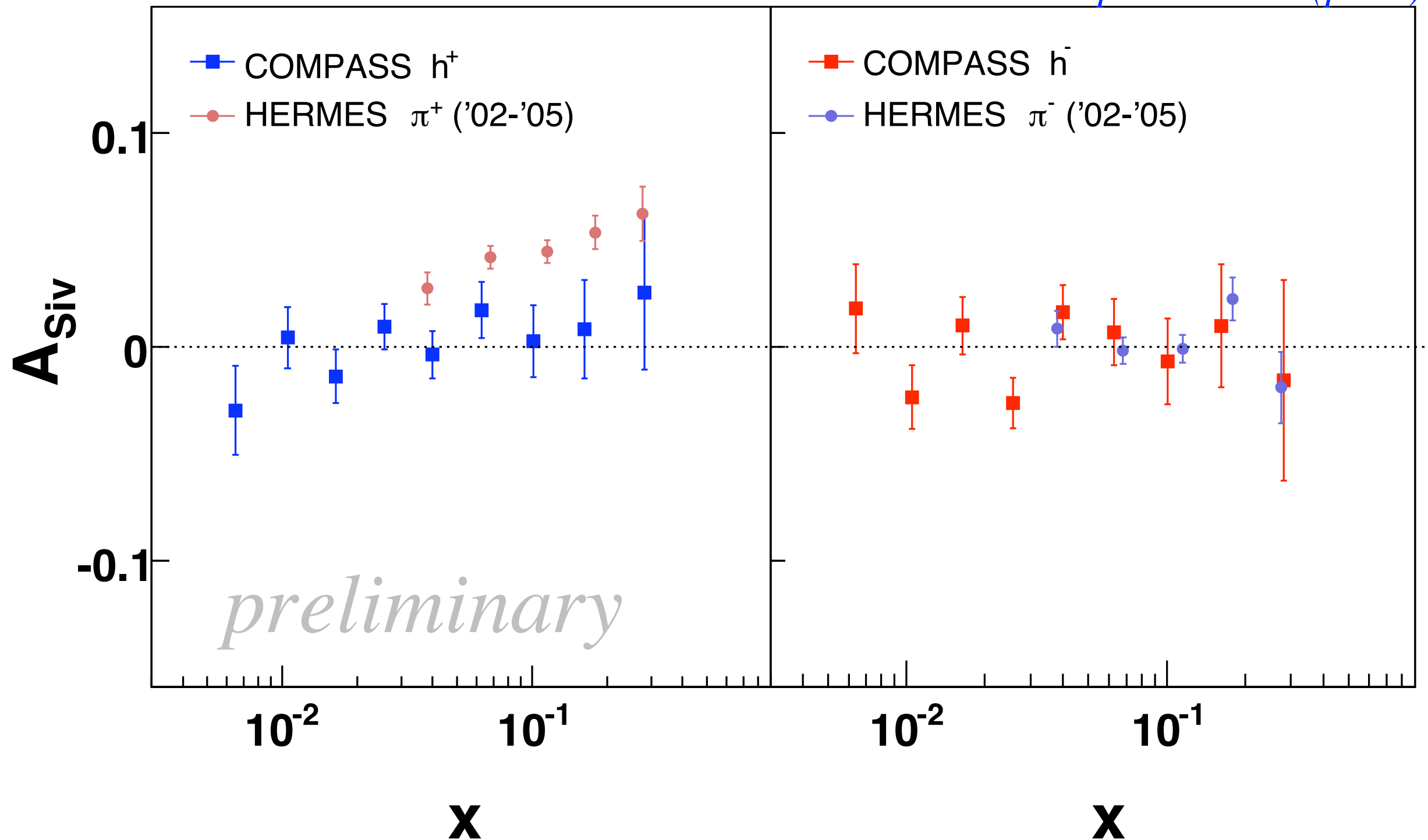
$$\Delta^N f_{\bar{s}/p^\uparrow} > 0$$

Predictions for COMPASS, with a proton target, and comparison with data (arXiv:0808.0086)



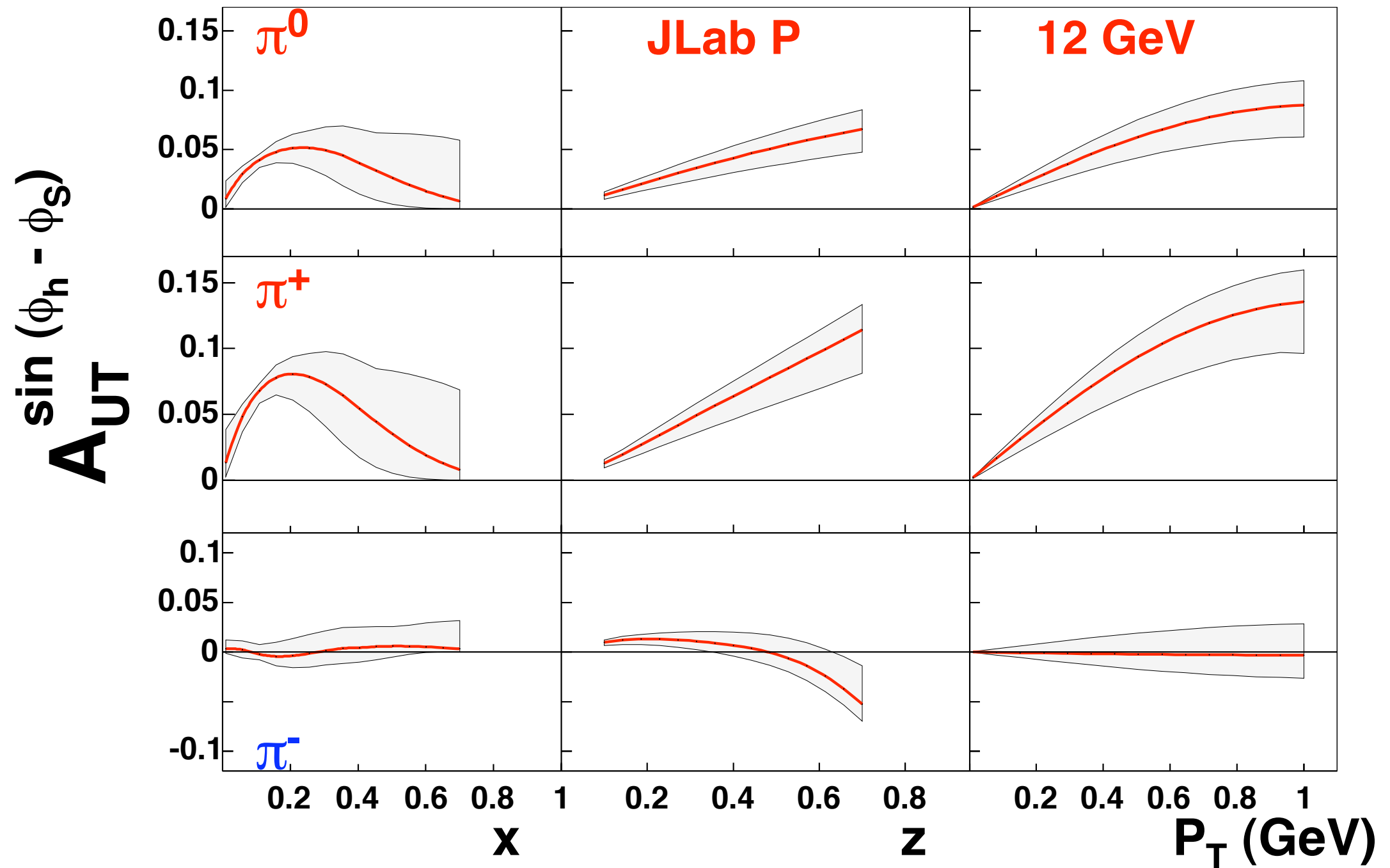
Sivers asymmetry: COMPASS vs HERMES, problems?

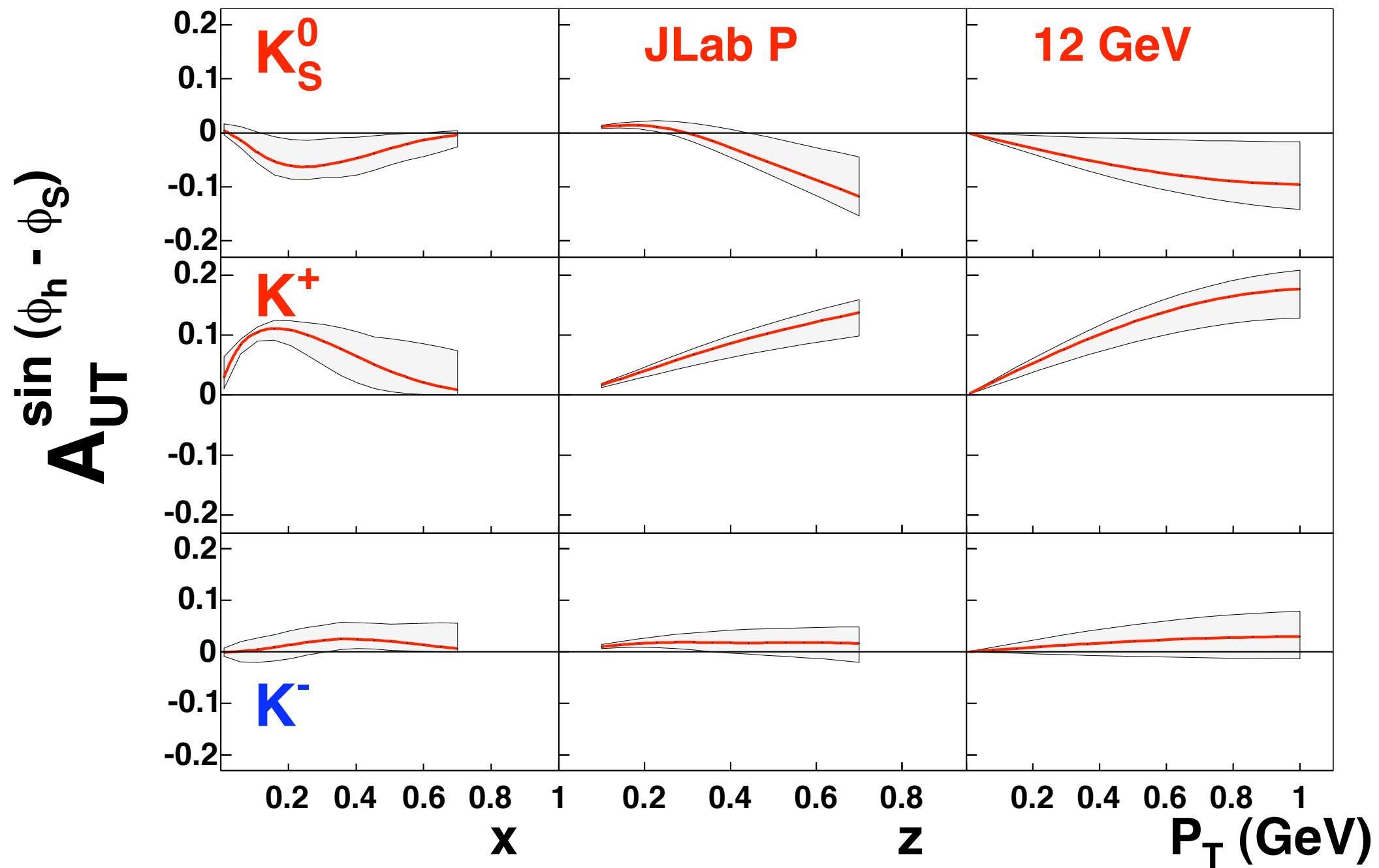
COMPASS 2007 proton data (part.)



courtesy of F. Bradamante

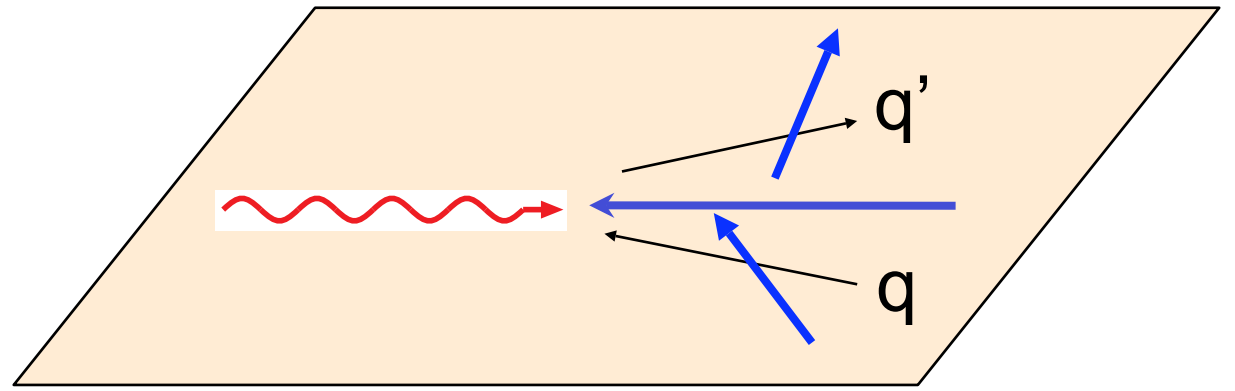
Predictions for JLab12, hydrogen target





Collins effect in SIDIS - $F_{UT}^{\sin(\phi+\phi_S)}$

$$D_{h/q, \mathbf{s}_q}(z, \mathbf{p}_\perp) = D_{h/p}(z, p_\perp) + \frac{1}{2} \Delta^N D_{h/q^\uparrow}(z, p_\perp) \mathbf{s}_q \cdot (\hat{\mathbf{p}}_q \times \hat{\mathbf{p}}_\perp)$$



$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q h_{1q}(x, k_\perp) \otimes d\Delta\hat{\sigma}(y, \mathbf{k}_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z, \mathbf{p}_\perp)$$

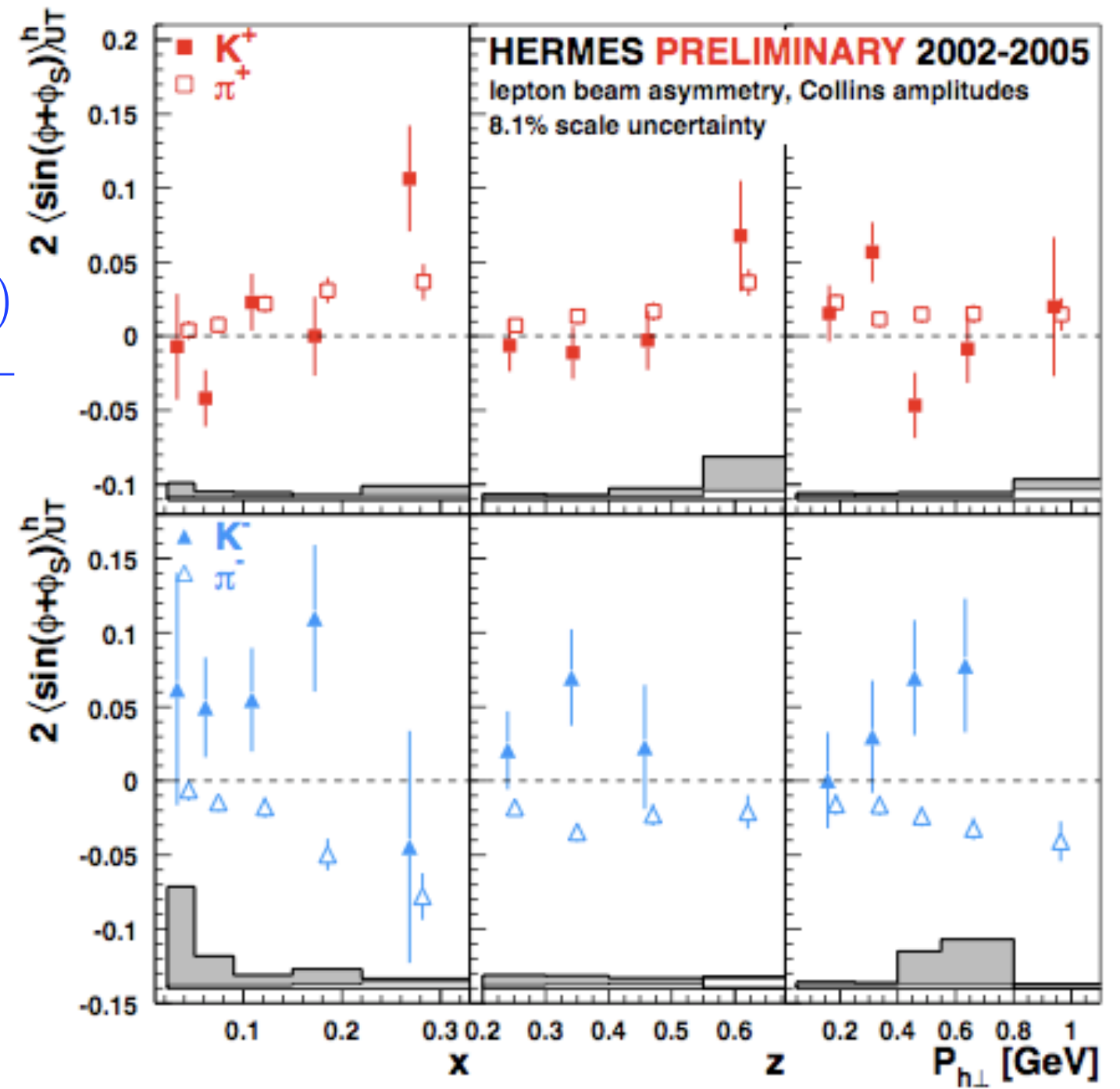
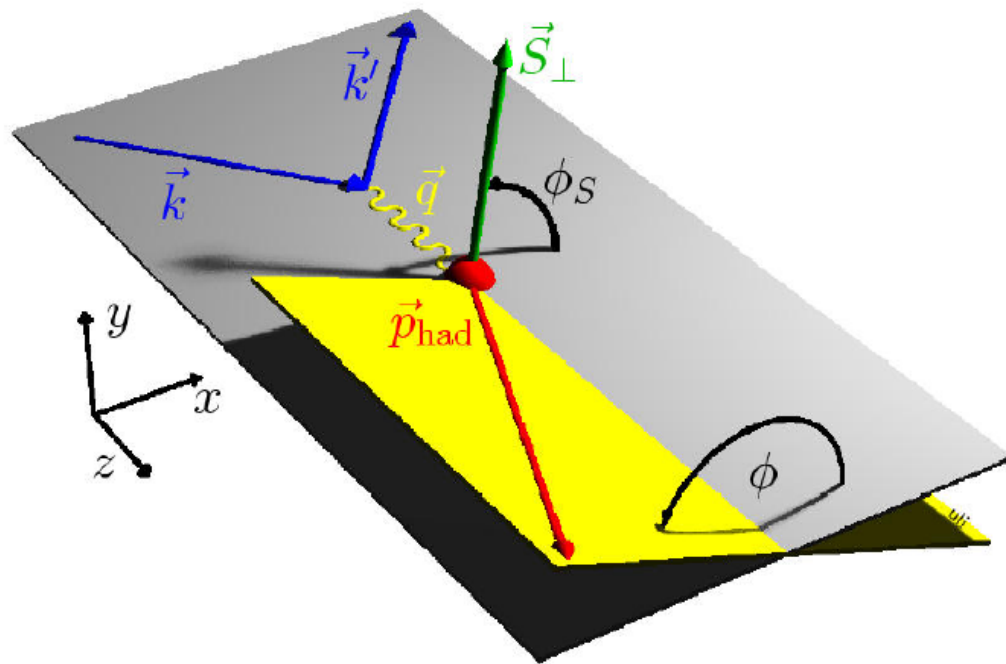
$$A_{UT}^{\sin(\phi+\phi_S)} \equiv 2 \frac{\int d\phi d\phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi + \phi_S)}{\int d\phi d\phi_S [d\sigma^\uparrow + d\sigma^\downarrow]}$$

$$d\Delta\hat{\sigma} = d\hat{\sigma}^{\ell q^\uparrow \rightarrow \ell q^\uparrow} - d\hat{\sigma}^{\ell q^\uparrow \rightarrow \ell q^\downarrow}$$

Collins effect in SIDIS couples to transversity

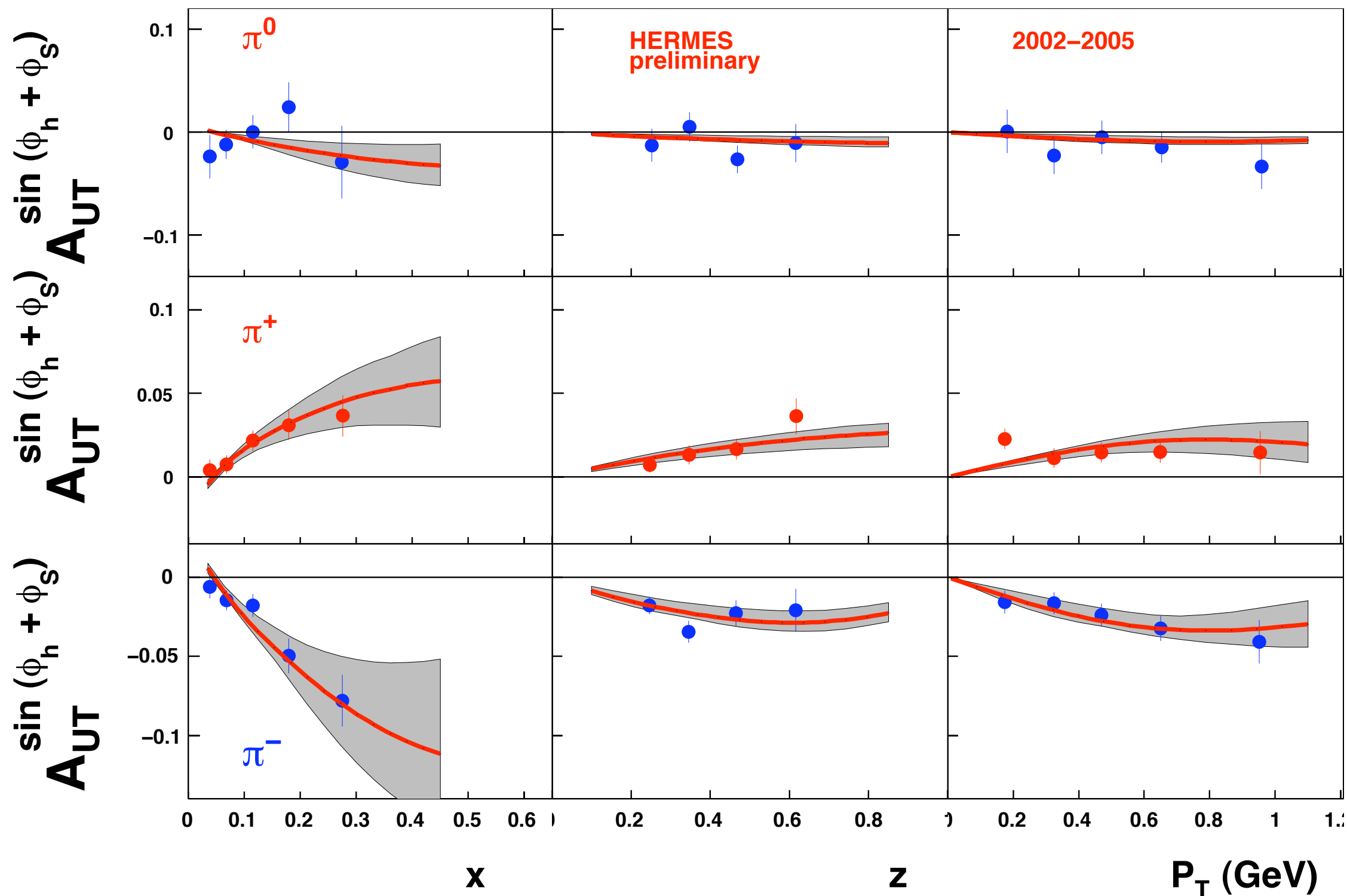
$$2\langle \sin(\phi + \phi_S) \rangle = A_{UT}^{\sin(\phi + \phi_S)}$$

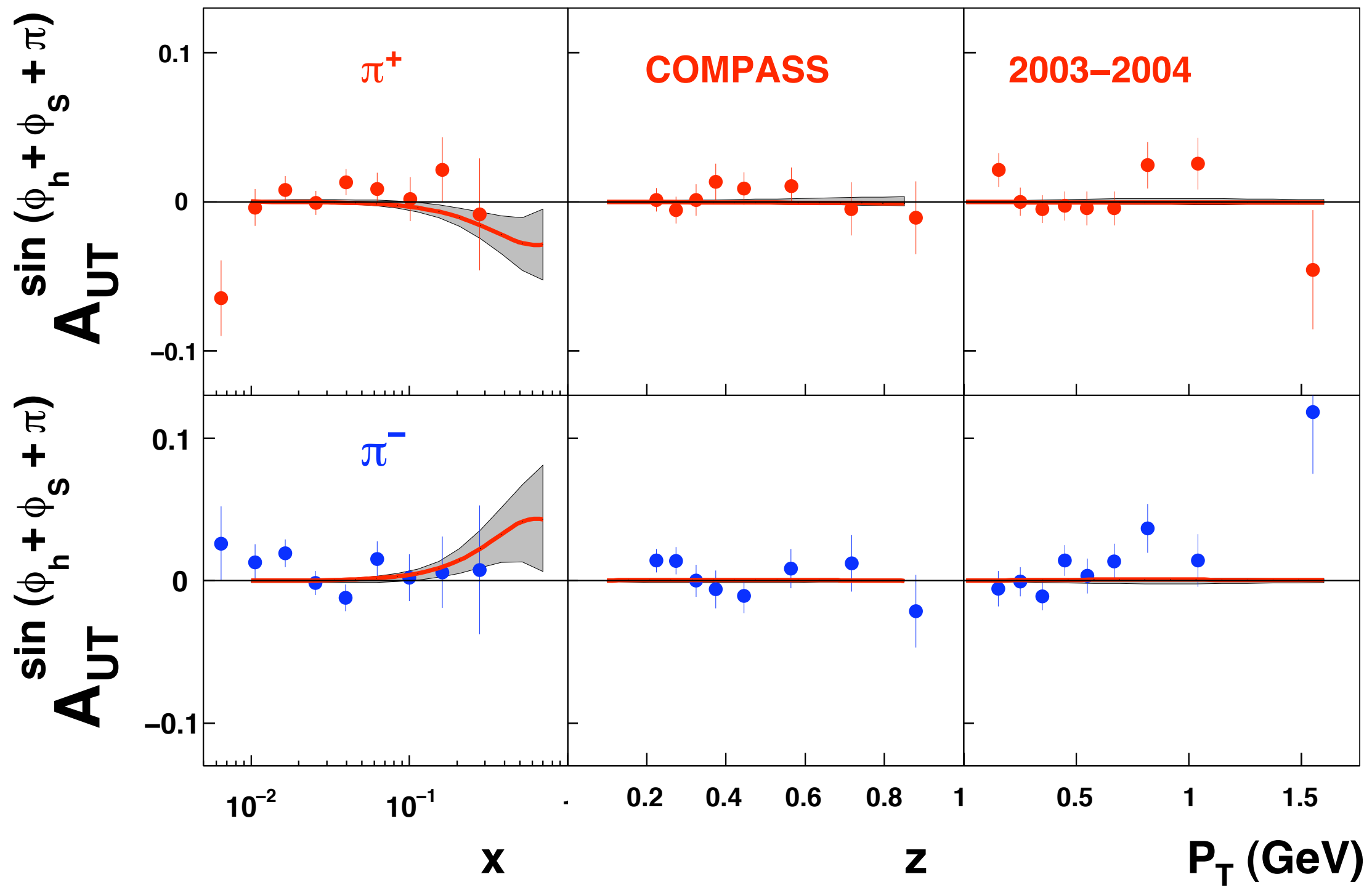
$$\equiv 2 \frac{\int d\phi d\phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi + \phi_S)}{\int d\phi d\phi_S [d\sigma^\uparrow + d\sigma^\downarrow]}$$



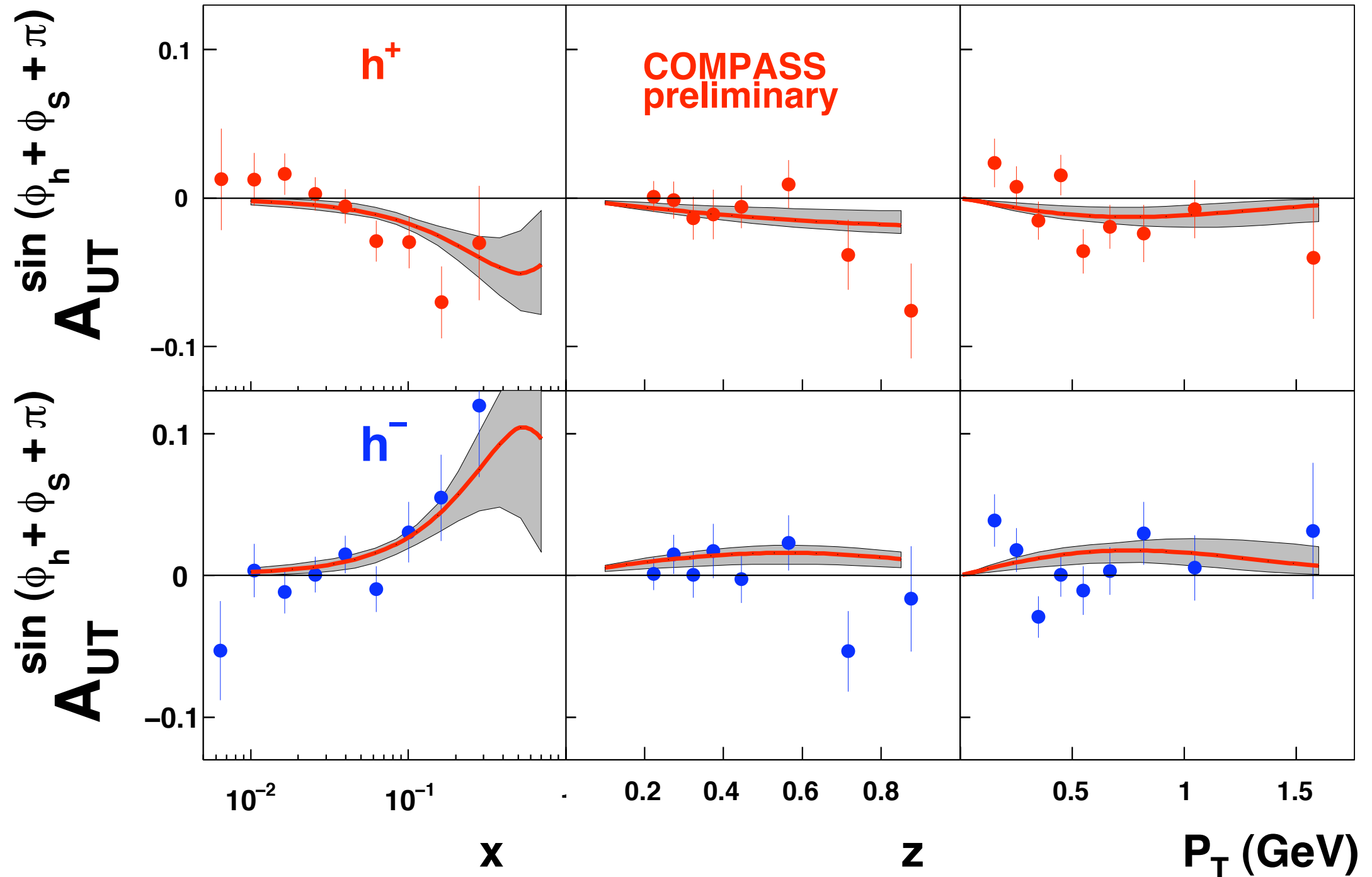
Collins asymmetry best fit

M. A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia,
A. Prokudin, S. Melis, e-Print: arXiv:0812.4366 [hep-ph]

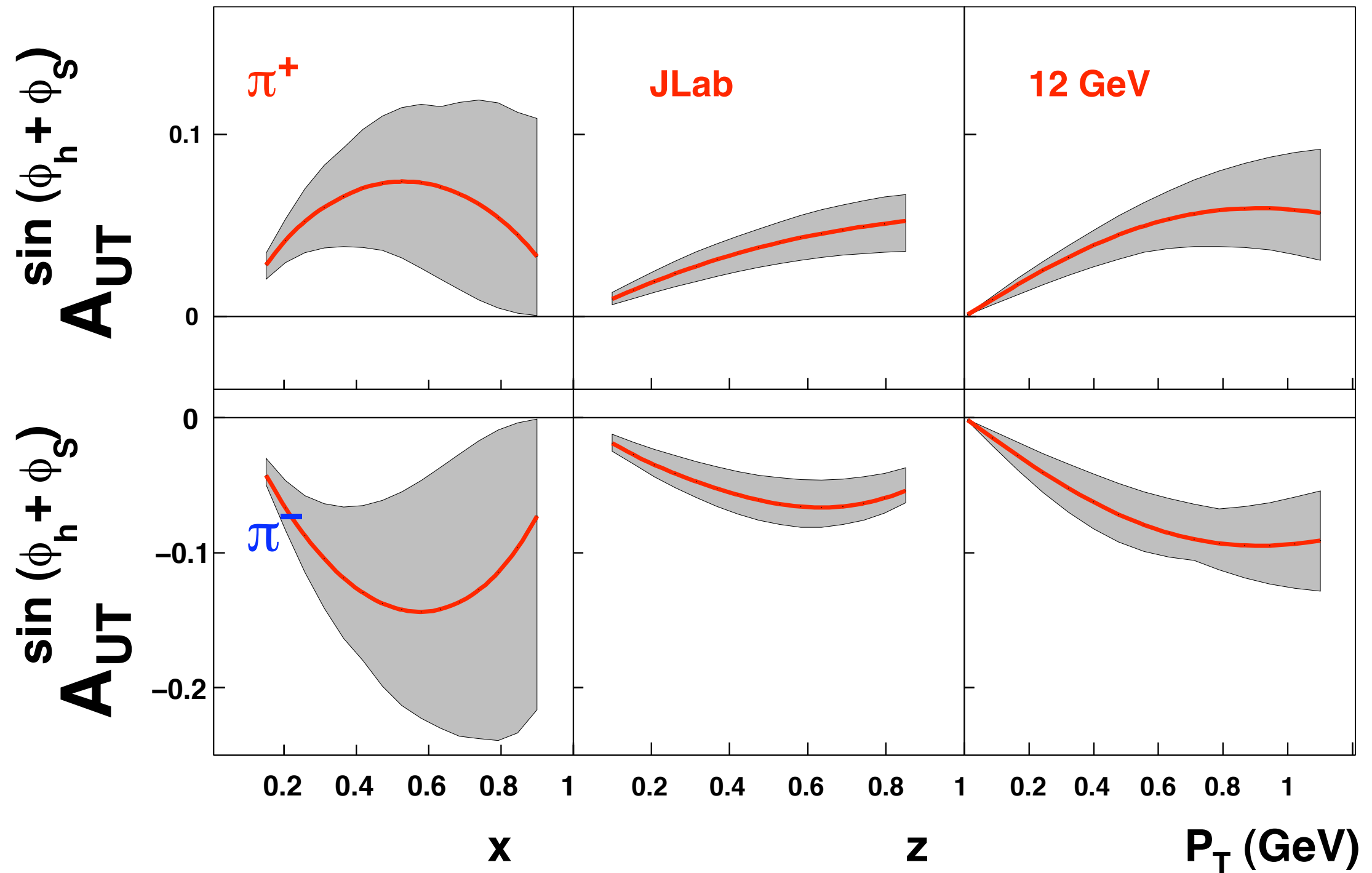




Predictions for COMPASS, with a proton target, and comparison with data

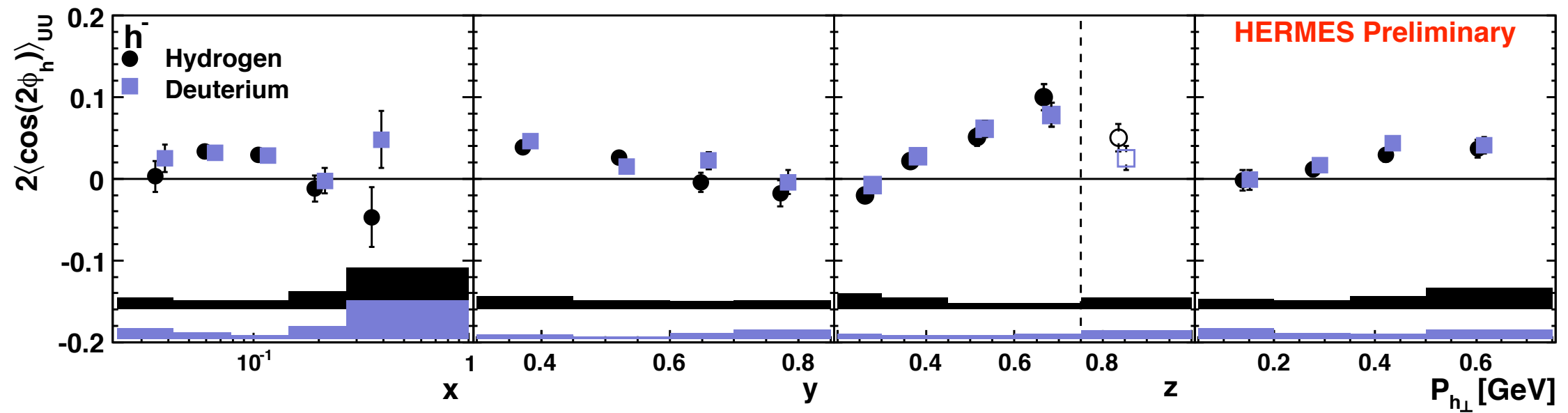
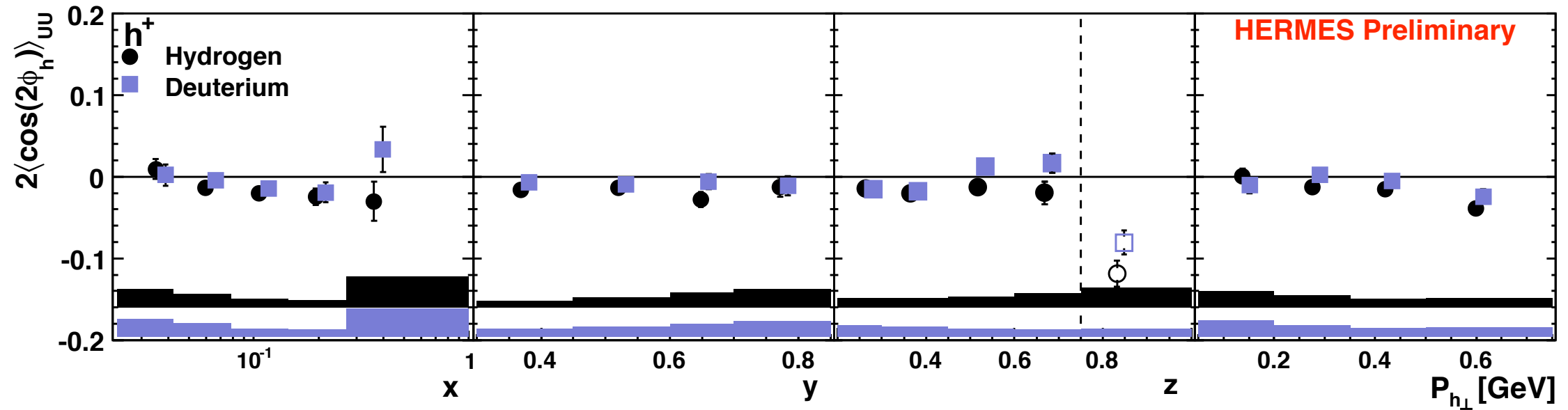


Predictions for JLab12, hydrogen target



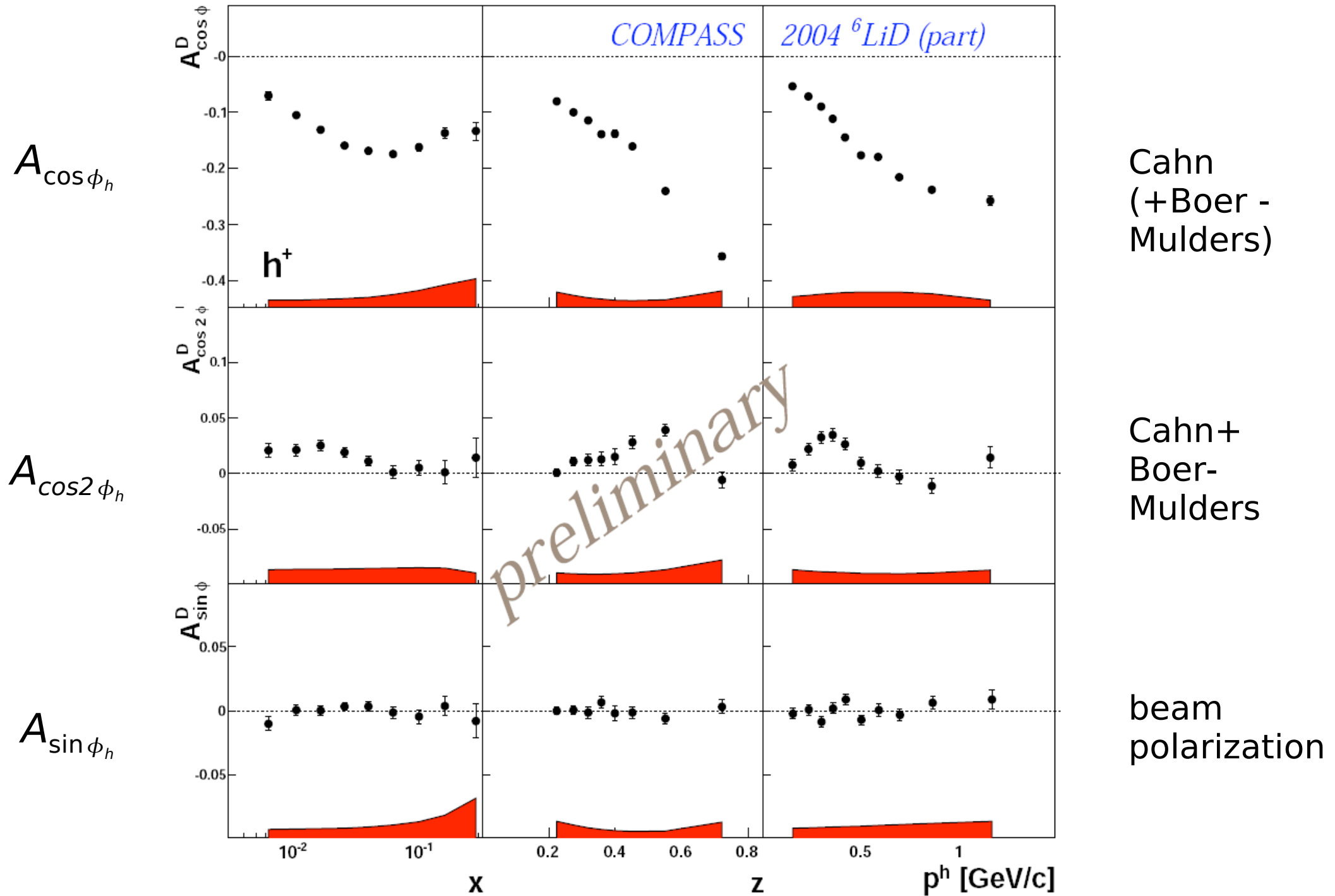
Boer-Mulders effect in SIDIS - $F_{UU}^{\cos(2\phi)}$

F. Giordano and R. Lamb, on behalf of the HERMES Collaboration, arXiv:0901.2438 [hep-ex]

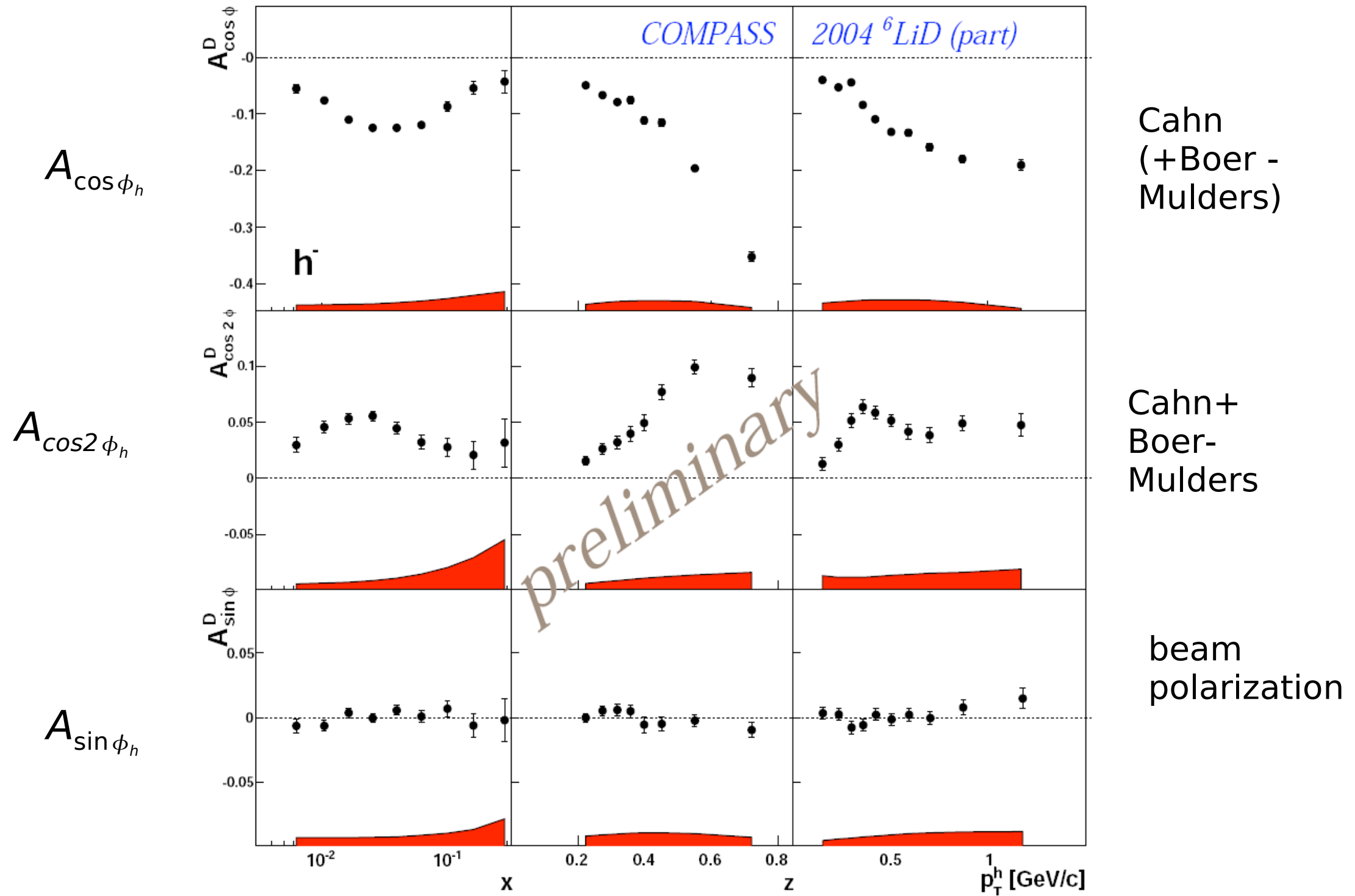


W. Käfer, on behalf of the COMPASS collaboration, talk at
Transversity 2008, Ferrara

h⁺:

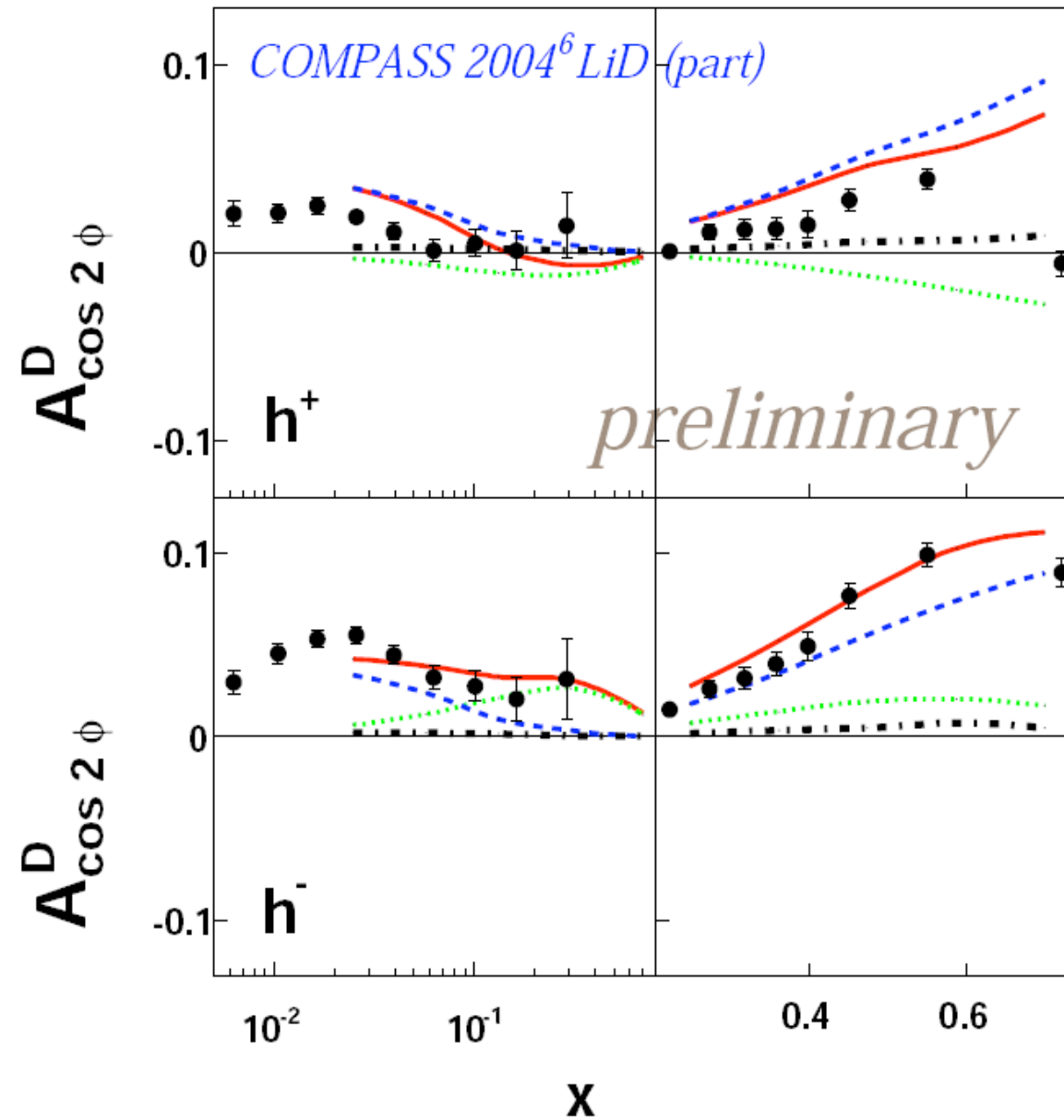


h⁻:



Gamberg, Goldstein, Oganessyan; Lu, Ma, Schmidt; Barone, Prokudin

Comparison with theory



V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

— total ⋯ Boer Mulders
- - - Cahn - · - · pQCD

errors shown are statistical only

what about the last 3 TMDs? any relation with the others?

$$g_{1T}^{\perp(1)a}(x) \simeq x \int_x^1 \frac{dy}{y} g_1^a(y)$$

$$h_{1L}^{\perp(1)a}(x) \simeq -x^2 \int_x^1 \frac{dy}{y^2} h_1^a(y)$$

$$h_{1T}^{\perp(1)a}(x) \simeq g_1^a(x) - h_1^a(x)$$

neglecting
twist-3
contributions

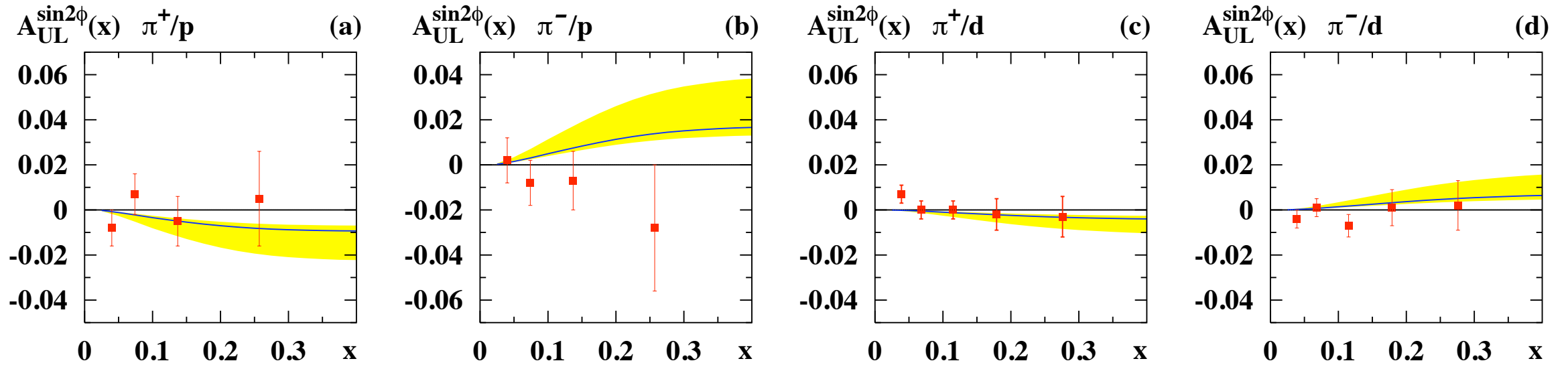
similar to the Wandzura-Wilczek relation

$$g_T^a(x) \simeq \int_x^1 \frac{dy}{y} g_1^a(y) \quad \text{supported by experiment}$$

$$g_{1T}^{\perp(1)a}(x) = \int d^2 \mathbf{k}_\perp \frac{k_\perp^2}{2m_N^2} g_{1T}^{\perp a}(x, k_\perp^2)$$

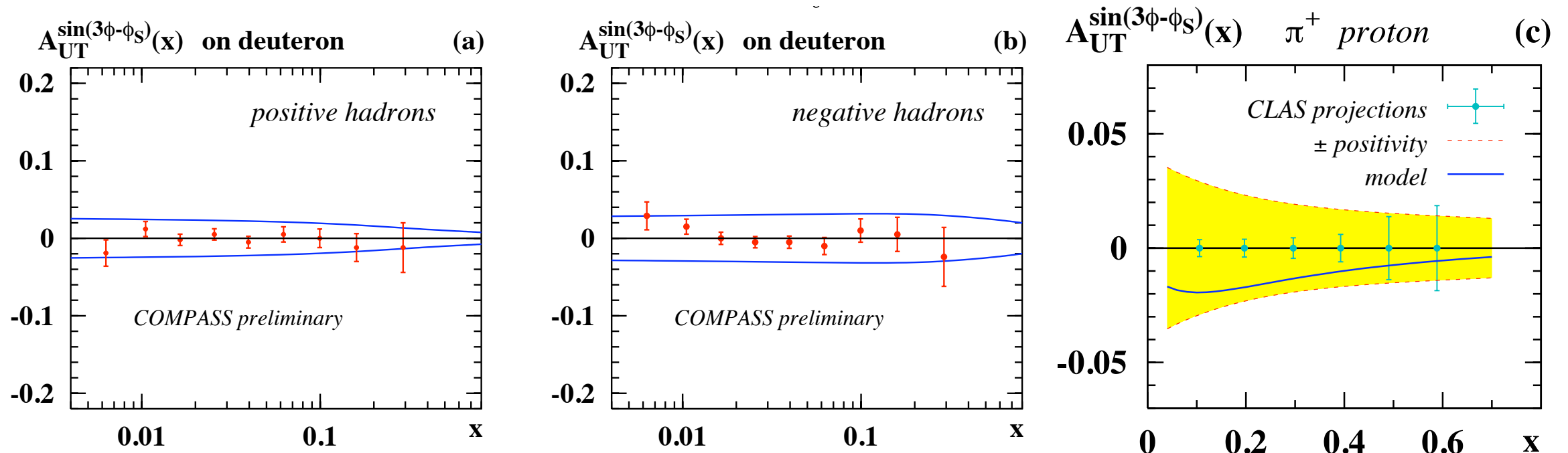
for a recent model of all twist-2 TMDs see Bacchetta et al.,
arXiv:0807.0323

HERMES data, PRL 84 (2000) 4047; PL B562 (2003) 182



$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 h_{1L}^{\perp a} \otimes H_1^{\perp a}$$

COMPASS data, arXiv:0705.2402



$$F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

Conclusions

Sivers effect: is it there in SIDIS?

Sivers effect in hadronic, $A^\uparrow B \rightarrow h + X$, and Drell-Yan processes. SSAs.

(non) universality of the Sivers function:

$$[f_{1T}^{q\perp}]_{\text{SIDIS}} = -[f_{1T}^{q\perp}]_{\text{DY}}$$

TMDs: factorized gaussian k_\perp dependence?
flavour dependence?

$$\langle k_\perp^2 \rangle^q(x) ? \quad \langle p_\perp^2 \rangle^q(z) ?$$

relations among TMDs? and between TMDs and GPDs?

Orbital angular momentum

QCD evolution of TMDs