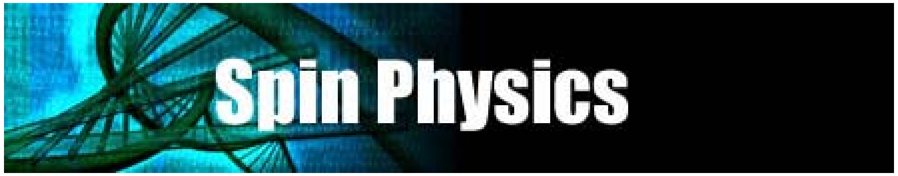


JLab, Dec. 14, 2006

Mauro Anselmino
Torino University
and INFN

Theory overview on transversity

(The long way to transversity in SIDIS)

- **Azimuthal asymmetries and P_{hT} dependence in unpolarized SIDIS and in $d\sigma_{LL}$**
- **Learning about the quark intrinsic motion**
- **SSA, Sivers and Collins effects**
- **Collins functions from BELLE data**
- **Coupling Collins function and transversity**

Work in collaboration with: M. Boglione, U. D'Alesio, A. Efremov, A. Kotzinian, F. Murgia, B. Parsamyan, A. Prokudin, C. Türk

Polarized SIDIS cross section, up to subleading order in 1/Q

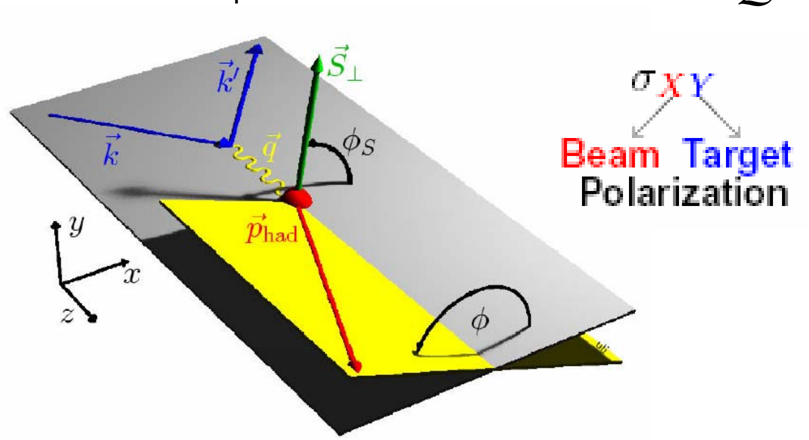
$$d\sigma = d\sigma_{UU}^{0} + \cos 2\Phi_h \, d\sigma_{UU}^{1} + \frac{1}{Q}\cos\Phi_h \, d\sigma_{UU}^{2} + \lambda_e \frac{1}{Q}\sin\Phi_h \, d\sigma_{LU}^{3}$$

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

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

$$+ \frac{1}{Q}\left[\sin(2\Phi_h - \Phi_S) \, d\sigma_{UT}^{11} + \sin\Phi_S \, d\sigma_{UT}^{12} \right]$$

$$\left. + \lambda_e \left[\cos(\Phi_h - \Phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q}\left(\cos\Phi_S \, d\sigma_{LT}^{14} + \cos(2\Phi_h - \Phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\}$$



Kotzinian, **NP B441** (1995) 234

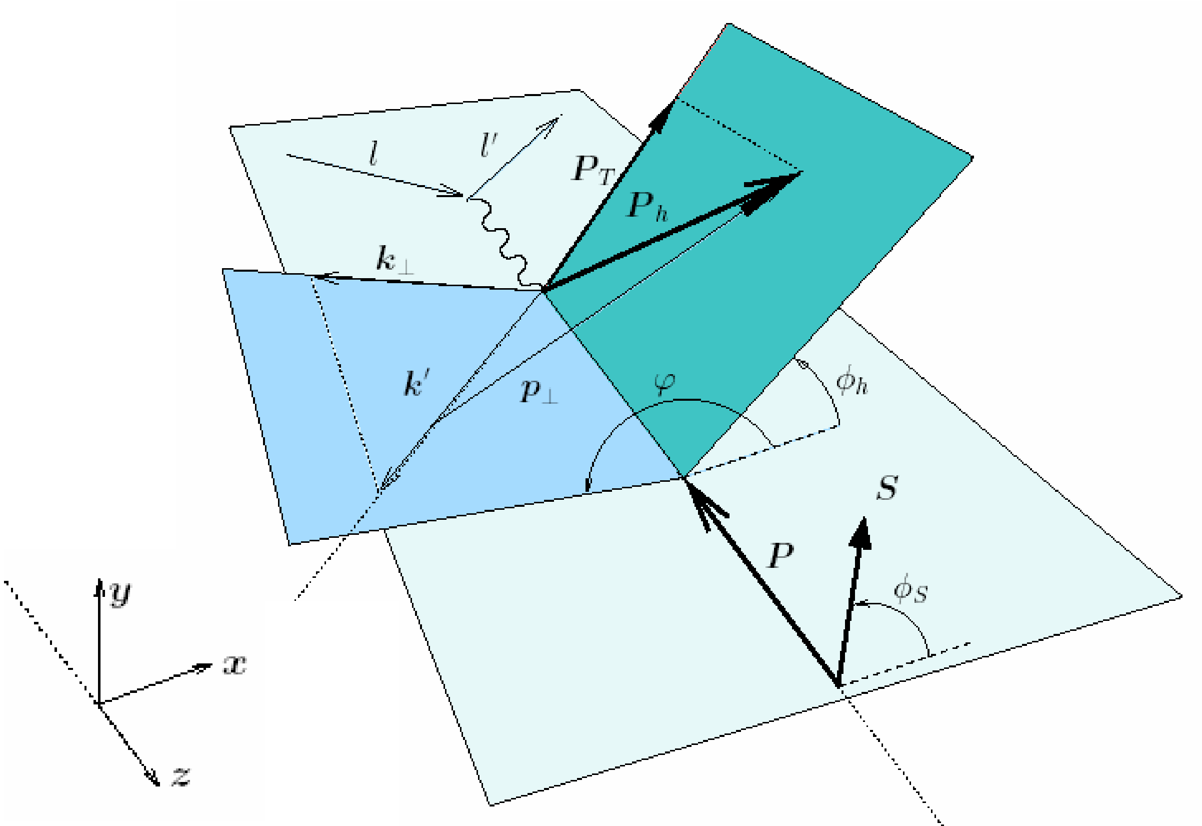
Mulders and Tangermann, **NP B461** (1996) 197

Boer and Mulders, **PR D57** (1998) 5780

Bacchetta et al., **PL B595** (2004) 309

Bacchetta et al., hep-ph/0611265

Unpolarized SIDIS with intrinsic $k_\perp$



$$x_B = \frac{Q^2}{2p \cdot q}$$

$$Q^2 = -q^2$$

$$y = \frac{p \cdot q}{l \cdot p}$$

$$z_h = \frac{P \cdot P_h}{P \cdot q}$$

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

$$\mathrm{d}\sigma^{lp \to lhX} = \sum_q f_q(x, k_\perp; Q^2) \otimes \mathrm{d}\hat{\sigma}^{lq \to lq}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, p_\perp; Q^2)$$

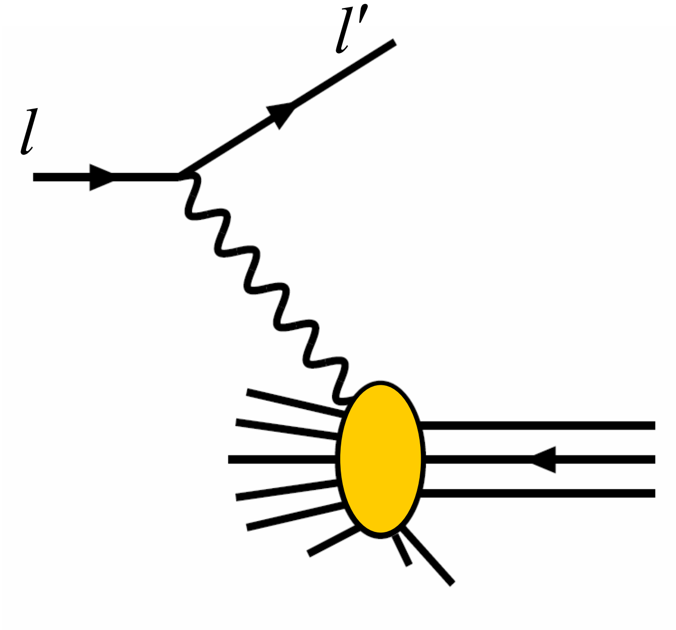
Exact kinematics

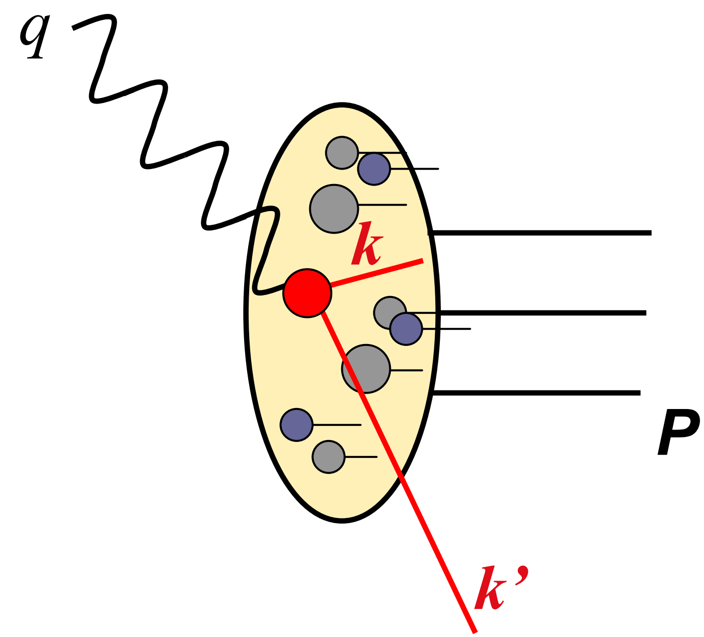
$$\frac{d^5\sigma^{\ell p\to \ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T} = \sum_q \int d^2\boldsymbol{k}_\perp\; f_q(x,k_\perp)\; \frac{d\hat{\sigma}^{\ell q\to \ell q}}{dQ^2}\; J\; \frac{z}{z_h}\; D_q^h(z,p_\perp)$$

$$= \sum_q e_q^2 \int d^2\boldsymbol{k}_\perp\; f_q(x,k_\perp)\; \frac{2\pi\alpha^2}{x_B^2 s^2}\, \frac{\hat{s}^2+\hat{u}^2}{Q^4}\; D_q^h(z,p_\perp)\; \frac{z}{z_h}\, \frac{x_B}{x} \left(1+\frac{x_B^2}{x^2}\frac{k_\perp^2}{Q^2}\right)^{-1}$$

$$J = \frac{x_B}{x}\left(1+\frac{x_B^2}{x^2}\frac{k_\perp^2}{Q^2}\right)^{-1} \qquad x = \frac{1}{2}\, x_B \left(1+\sqrt{1+\frac{4k_\perp^2}{Q^2}}\right)$$

$$z \;=\; z_h + \frac{k_\perp P_T}{Q^2}\, \frac{2x_B}{1-x_B}\, \cos(\phi_h-\varphi) + \mathcal{O}\left(\frac{k_\perp^2}{Q^2}\right)$$





struck parton carries 4-momentum k

$$k = \left(xP_0 + \frac{k_\perp^2}{4xP_0}, \boldsymbol{k}_\perp, -xP_0 + \frac{k_\perp^2}{4xP_0} \right) \qquad k' = k + q$$

$$k^2 = 0 \qquad \boldsymbol{k}_\perp = k_\perp(\cos\varphi, \sin\varphi, 0) \qquad x = k^- / P^-$$

$$P = (P_0, 0, 0, -P_0)$$

neglecting $\mathcal{O}(k_\perp^2/Q^2)$ terms one has

$$\hat{s} = (l+k)^2 = sx\left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\varphi\right]$$

$$\hat{t} = (l-l')^2 = -Q^2$$

$$\hat{u} = (l-k')^2 = -sx\,(1-y)\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\varphi\right]$$

$$x = x_B \qquad z = z_h \qquad \boldsymbol{P}_\mathrm{T} = \boldsymbol{p}_\perp + z\,\boldsymbol{k}_\perp$$

“Cahn effect”

$$d\hat{\sigma}^{lq\to lq} \propto \hat{s}^2 + \hat{u}^2 = \frac{Q^4}{y^2}\left(1 + (1-y)^2 - 4\frac{k_\perp}{Q}(2-y)\sqrt{1-y}\cos\varphi\right)$$

$$\frac{\mathrm{d}\sigma^{lp\to lhX}}{\mathrm{d}\Phi_h} \propto A + B\cos\Phi_h$$

assuming:

$$\begin{cases} f_q(x, k_\perp) = f_q(x)\,\dfrac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle} \\[2ex] D_q^h(z, p_\perp) = D_q^h(z)\,\dfrac{1}{\pi\langle p_\perp^2\rangle}\,e^{-p_\perp^2/\langle p_\perp^2\rangle} \end{cases}$$

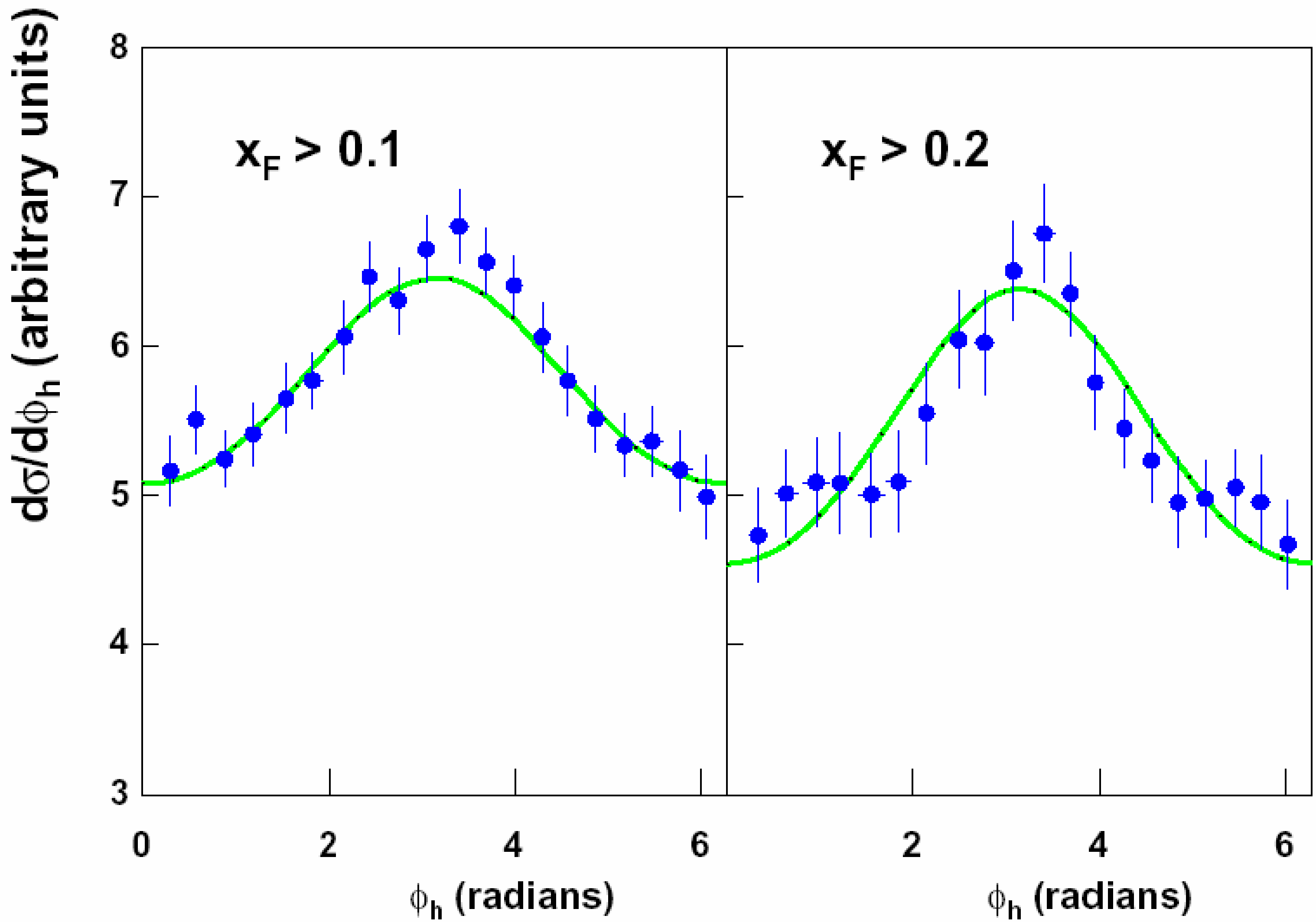
one finds:

$$\frac{d^5\sigma^{\ell p\to \ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4}\, f_q(x_B)\, D_q^h(z_h) \Big[1 + (1-y)^2 - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q}\,\cos\phi_h\Big] \frac{1}{\pi\langle P_T^2\rangle}\, e^{-P_T^2/\langle P_T^2\rangle}$$

with $\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$ ➡

clear dependence on $\langle p_\perp^2\rangle$ and $\langle k_\perp^2\rangle$ (assumed to be constant)

Find best values by fitting data on Φ_h and P_T dependences

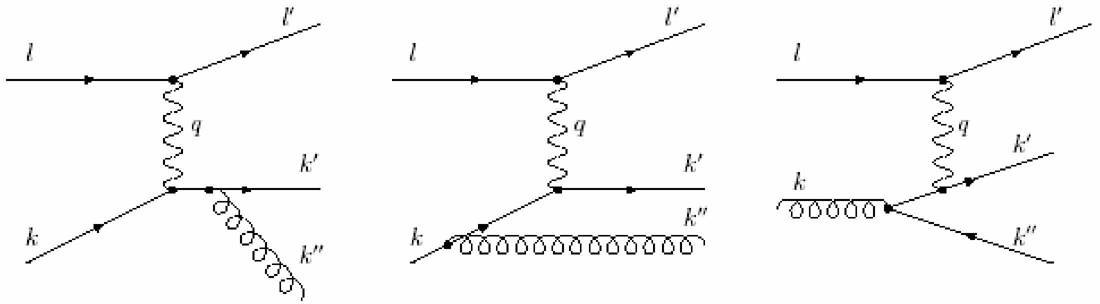


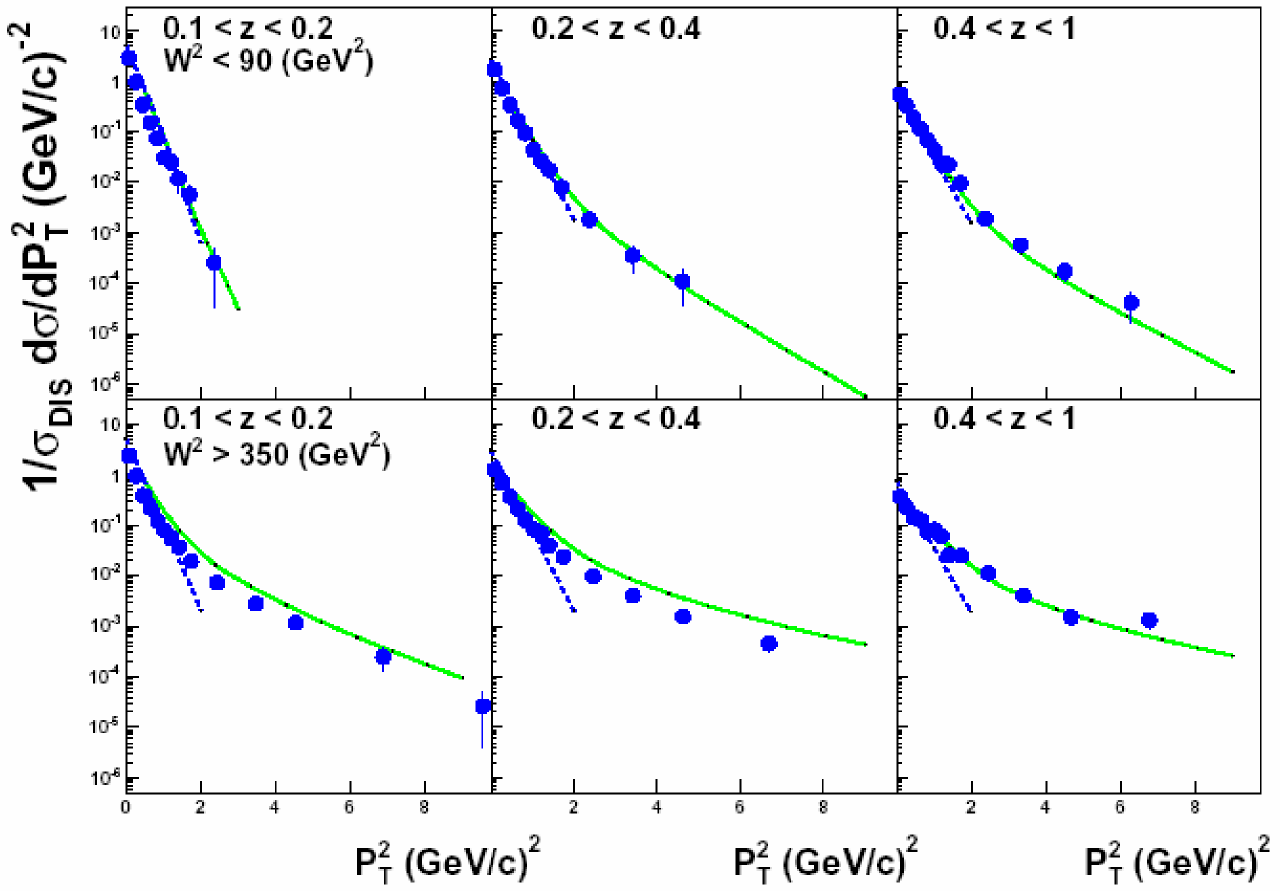
EMC data, μp and μd, *E* between 100 and 280 GeV

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

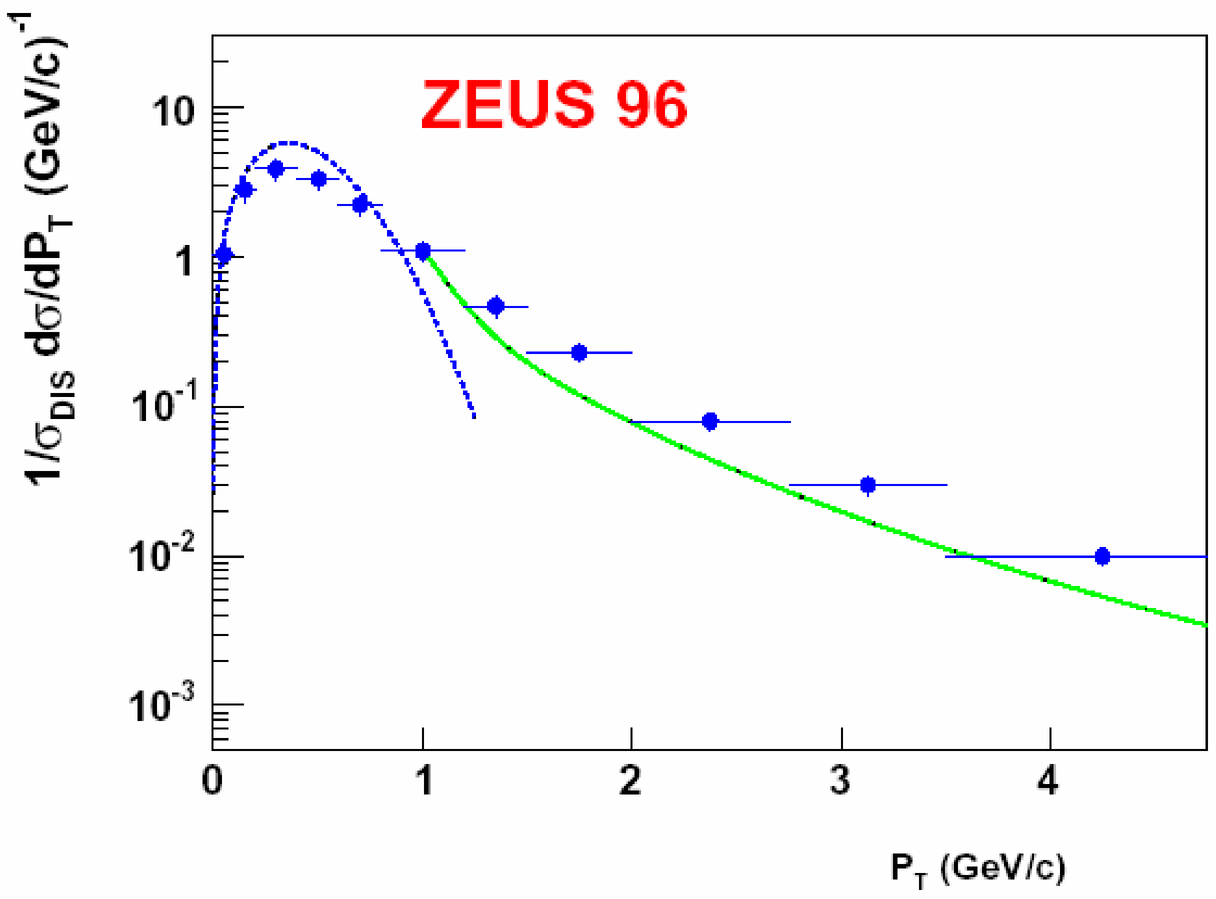
M.A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin

Large P_T data explained by NLO QCD corrections





EMC data



dashed line: parton model with unintegrated distribution and fragmentation functions
solid line: pQCD contributions at LO and a *K* factor (*K* = 1.5) to account for NLO effects

Longitudinal polarization (here means along the lepton direction)

$$\frac{d^5\sigma^{\rightleftarrows}}{dx\,dy\,dz\,d^2P_{hT}} = \frac{2\alpha^2}{xy^2 s}\{\mathcal{H}_{f_1} + \lambda(S_L\mathcal{H}_{g_{1L}} + S_T\mathcal{H}_{g_{1T}})\}$$

$\Rightarrow, \Leftarrow$ implies $S_T = \pm S\sin\vartheta_\gamma \cong \pm S\frac{2m_N x\sqrt{1-y}}{Q}$ $\quad S_L = \pm S\cos\vartheta_\gamma$

helicity-helicity $(d\sigma_{LL}^6, d\sigma_{LL}^7)$

$$\mathcal{H}_{g_{1L}} = \sum_q e_q^2 \int d^2\boldsymbol{k}_\perp \underbrace{g_{1L}^q(x,k_\perp)}_{\Delta q(x,k_\perp)}\,\pi y^2 \underbrace{\frac{\hat{s}^2-\hat{u}^2}{Q^4}}_{d\hat{\sigma}^{++}-d\hat{\sigma}^{+-}} D_q^h(z,p_\perp),$$

helicity-S_T $(d\sigma_{LT}^{13})$

$$\mathcal{H}_{g_{1T}} = -\sum_q e_q^2 \int d^2\boldsymbol{k}_\perp \underbrace{\frac{k_\perp}{M}\cos\varphi\, g_{1T}^{q\perp}(x,k_\perp)}_{\Delta f_{+/S_T}(x,\vec{s}_q\cdot\vec{S}_T)}\,\pi y^2 \underbrace{\frac{\hat{s}^2-\hat{u}^2}{Q^4}}_{d\hat{\sigma}^{++}-d\hat{\sigma}^{+-}} D_q^h(z,p_\perp)$$

$$d\hat{\sigma}^{++} - d\hat{\sigma}^{+-} \propto \hat{s}^2 - \hat{u}^2 = \frac{Q^4}{y^2}\left(y(2-y) - 4\frac{k_\perp}{Q}\underbrace{y\sqrt{1-y}\cos\varphi}_{\text{Cahn effect}}\right)$$

study

$$A_{LL}(x,y,z,P_{hT}) = \frac{\int_0^{2\pi} d\phi_h \,[\, d\sigma^{\rightleftarrows} - d\sigma^{\rightrightarrows} \,]}{\lambda S \int_0^{2\pi} d\phi_h \,[\, d\sigma^{\rightleftarrows} + d\sigma^{\rightrightarrows} \,]}$$

$$A_{LL}^{\cos\phi_h}(x,y,z,P_{hT}) = \frac{2\int_0^{2\pi} d\phi_h \,[\, d\sigma^{\rightleftarrows} - d\sigma^{\rightrightarrows} \,] \cos\phi_h}{\lambda S \int_0^{2\pi} d\phi_h \,[\, d\sigma^{\rightleftarrows} + d\sigma^{\rightrightarrows} \,]}$$

assuming

$$f_1^q(x,k_\perp) = f_1^q(x)\,\frac{1}{\pi\mu_0^2}\,\exp\left(-\frac{k_\perp^2}{\mu_0^2}\right), \qquad \mu_0^2 = \langle k_\perp^2 \rangle$$

$$D_q^h(z,p_\perp) = D_q^h(z)\,\frac{1}{\pi\mu_D^2}\,\exp\left(-\frac{p_\perp^2}{\mu_D^2}\right), \qquad \mu_D^2 = \langle p_\perp^2 \rangle$$

$$g_{1T}^{q\perp}(x,k_\perp) = g_{1T}^q(x)\,\frac{1}{\pi\mu_1^2}\,\exp\left(-\frac{k_\perp^2}{\mu_1^2}\right),$$

$$g_{1L}^q(x,k_\perp) = g_1^q(x)\,\frac{1}{\pi\mu_2^2}\,\exp\left(-\frac{k_\perp^2}{\mu_2^2}\right)$$

$$\mu_{1,2}^2 \leq \langle k_\perp^2 \rangle$$

notice: different average $\langle k_\perp^2 \rangle$ for different distributions

$$A_{LL}(x,y,z,P_{hT}) = \frac{\Delta\sigma_{LL}}{\sigma_0}$$

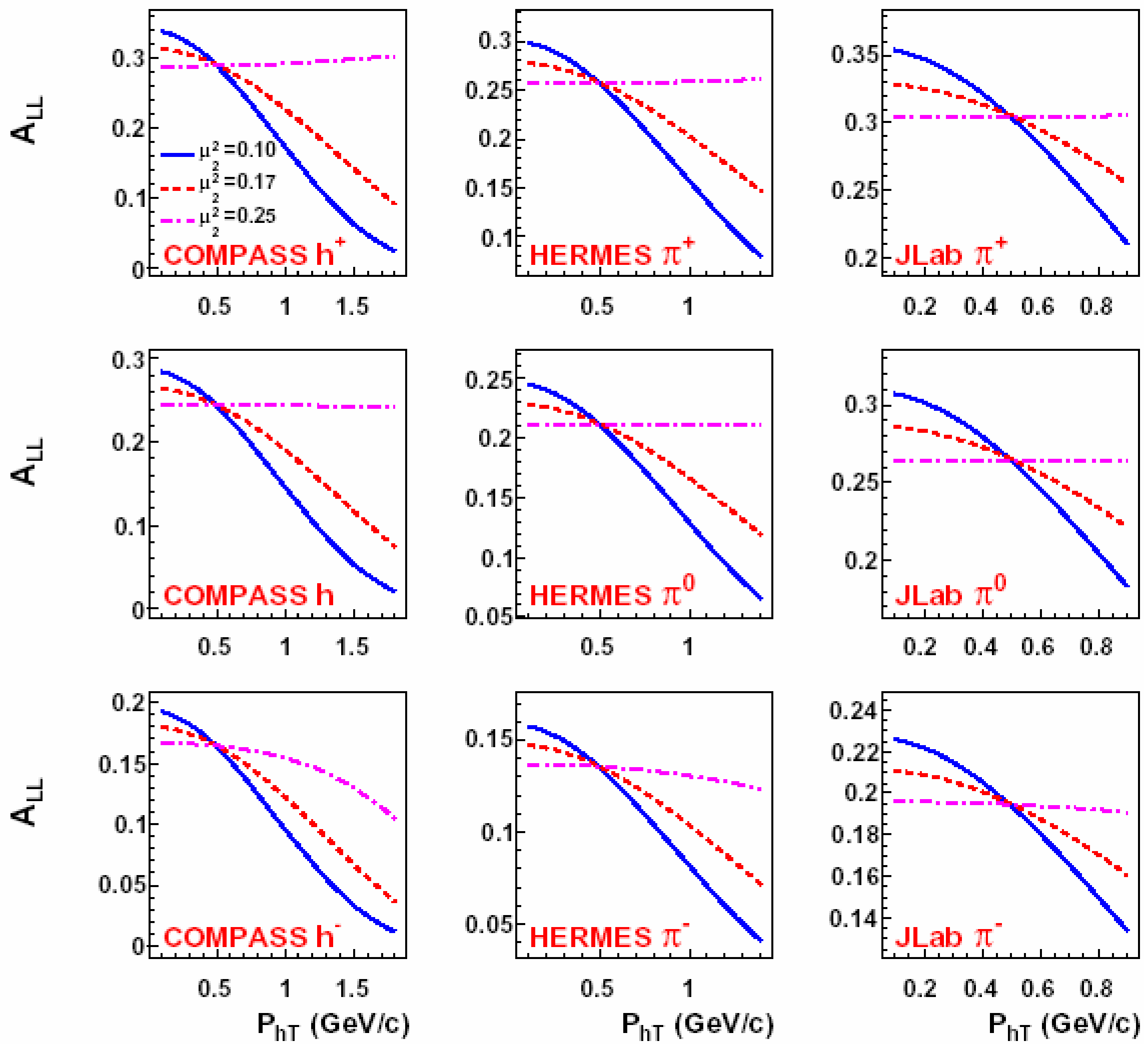
$$\Delta\sigma_{LL} = \frac{y(2-y)}{xy^2}\frac{1}{\mu_D^2 + z^2\mu_2^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2 + z^2\mu_2^2}\right)\sum_q e_q^2\, g_1^q(x)\, D_q^h(z)$$

$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\frac{1}{\mu_D^2 + z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2 + z^2\mu_0^2}\right)\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

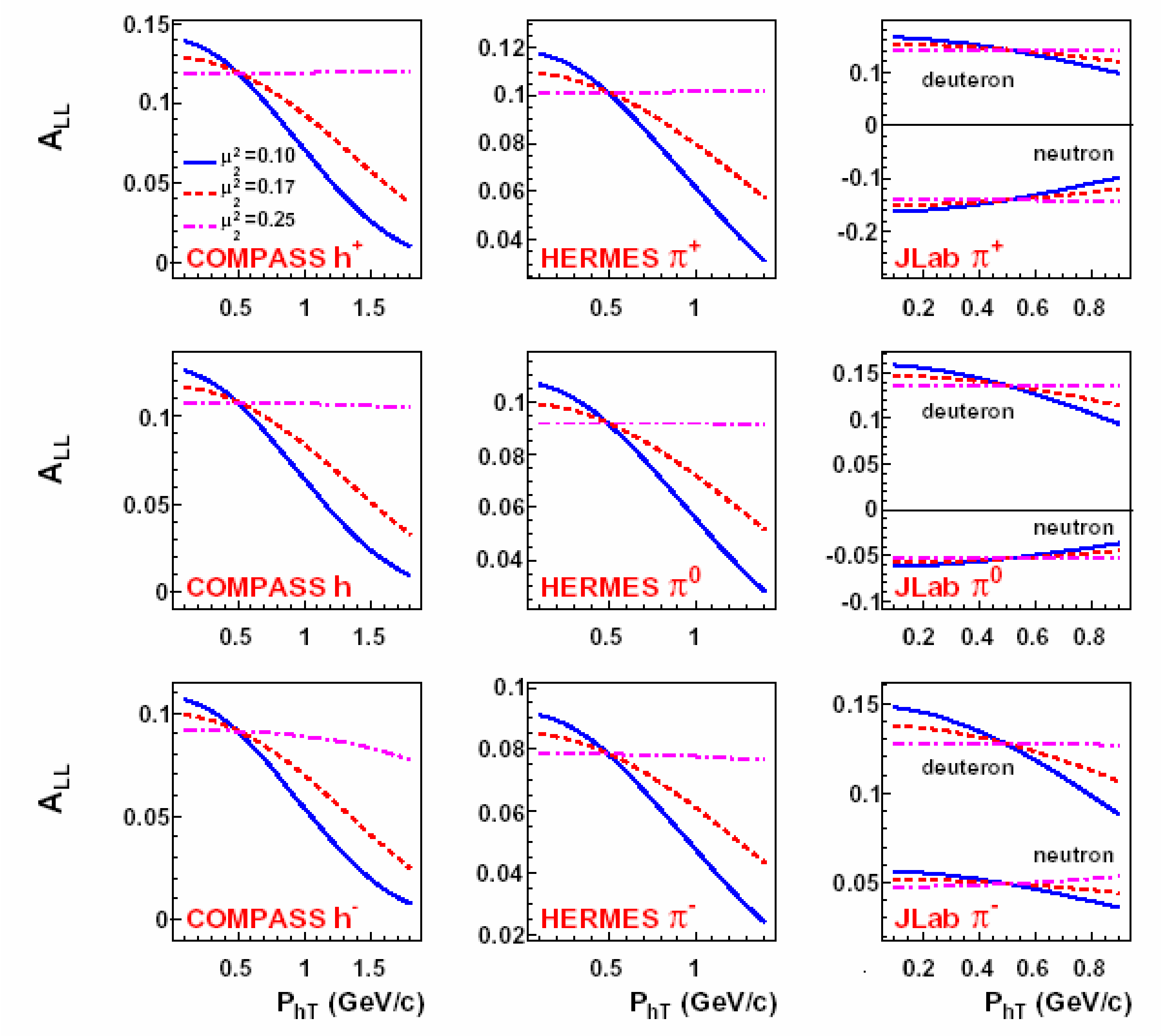
sensitive to the relative values of μ_0^2 and μ_2^2, intrinsic $k_\perp$ of quarks inside an unpolarized or a longitudinally polarized proton

COMPASS: positive (h^+), all (h) and negative (h^-) hadron production,
$Q^2 > 1.0\ (\mathrm{GeV/c})^2$, $W^2 > 25\ \mathrm{GeV}^2$, $0.1 < x < 0.6$, $0.5 < y < 0.9$ and $0.4 < z < 0.9$
HERMES: π^+, π^0 and π^- production, $Q^2 > 1.0\ (\mathrm{GeV/c})^2$, $W^2 > 10\ \mathrm{GeV}^2$,
$0.1 < x < 0.6$, $0.45 < y < 0.85$ and $0.4 < z < 0.7$
JLab at 6 GeV: π^+, π^0 and π^- production, $Q^2 > 1.0\ (\mathrm{GeV/c})^2$, $W^2 > 4\ \mathrm{GeV}^2$,
$0.2 < x < 0.6$, $0.4 < y < 0.85$ and $0.4 < z < 0.7$

M. A., A. Efremov, A. Kotzinian and B. Parsamyan



Predicted dependence of A_{LL} on P_{hT}, for scattering off a proton target, with different choices of μ_2^2: 0.1 $(GeV/c)^2$ – continuous, 0.17 $(GeV/c)^2$ – dashed and 0.25 $(GeV/c)^2$ – dot-dashed lines.



Predicted dependence of A_{LL} on P_{hT} , for scattering off a deuteron (and neutron for JLab) target, with different choices of μ_2^2:

0.1 $(GeV/c)^2$ – continuous, 0.17 $(GeV/c)^2$ – dashed and 0.25 $(GeV/c)^2$ – dot-dashed lines.

$$A_{LL}^{\cos\phi_h}(x,y,z,P_{hT}) = \frac{\Delta\sigma_{LL}^{\cos\phi_h} + \Delta\sigma_{LT}^{\cos\phi_h}}{\sigma_0}$$

$$\Delta\sigma_{LL}^{\cos\phi_h} = -4\,\frac{\sqrt{1-y}}{xy}\,\frac{z\,\mu_2^2\,P_{hT}}{Q\,(\mu_D^2+z^2\mu_2^2)^2}\,\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2\,g_1^q(x)\,D_q^h(z),$$

Cahn effect

$$\Delta\sigma_{LT}^{\cos\phi_h} = \frac{-2(2-y)\sqrt{1-y}}{y}\,\frac{z\,\mu_1^2\,P_{hT}}{Q\,(\mu_D^2+z^2\mu_1^2)^2}\,\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_1^2}\right)\sum_q e_q^2\,g_{1T}^q(x)\,D_q^h(z)$$

contains new function, needs assumptions and approximations:

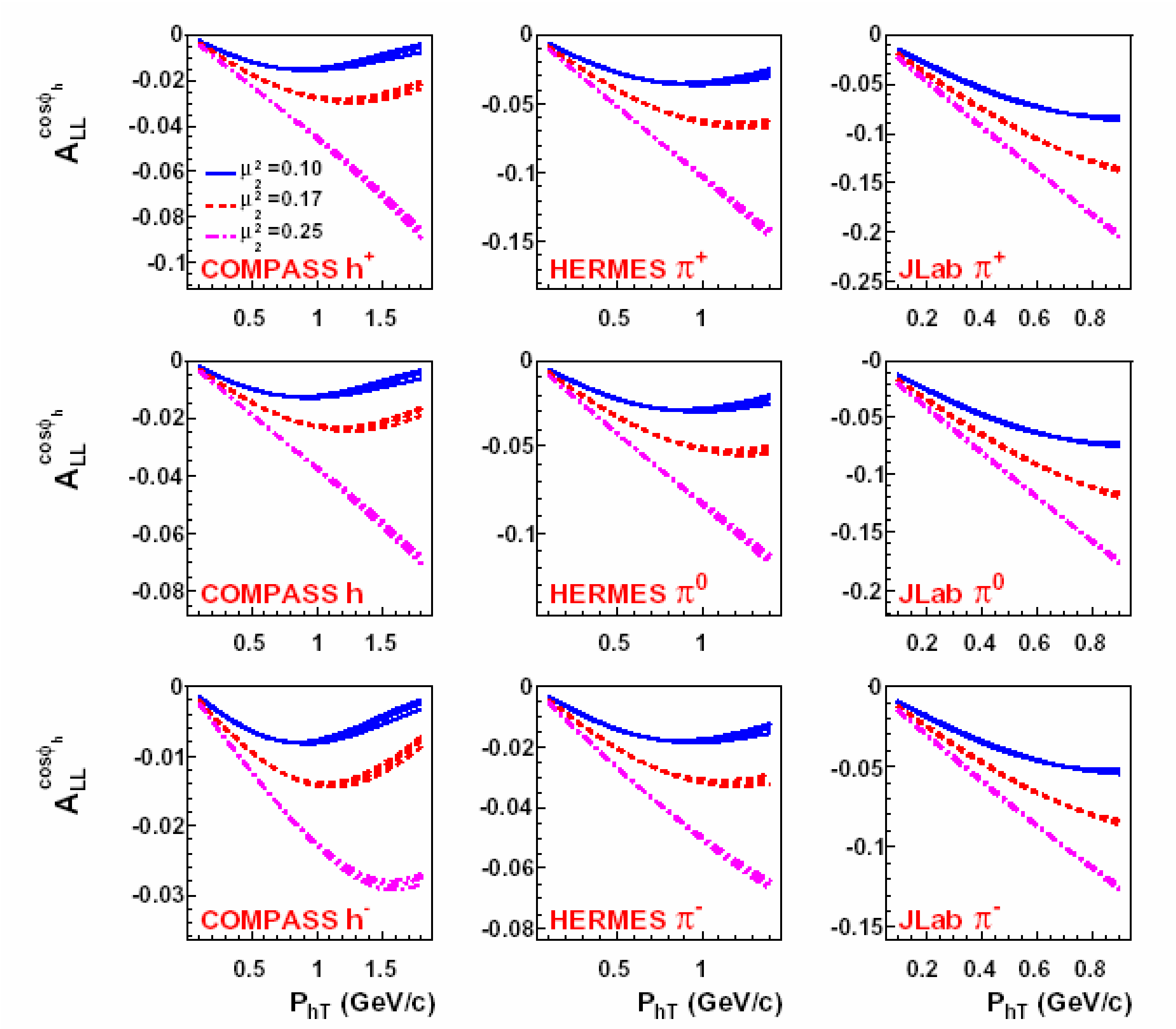
$$g_{1T}^{q\,(1)}(x) \equiv \int d^2k_\perp\,\frac{k_\perp^2}{2M^2}\,g_{1T}^{q\perp}(x,k_T^2) = \frac{\mu_1^2}{2M^2}\,g_{1T}^q(x)$$

$$g_2^q(x) = \frac{d}{dx}\,g_{1T}^{q\,(1)}(x)$$

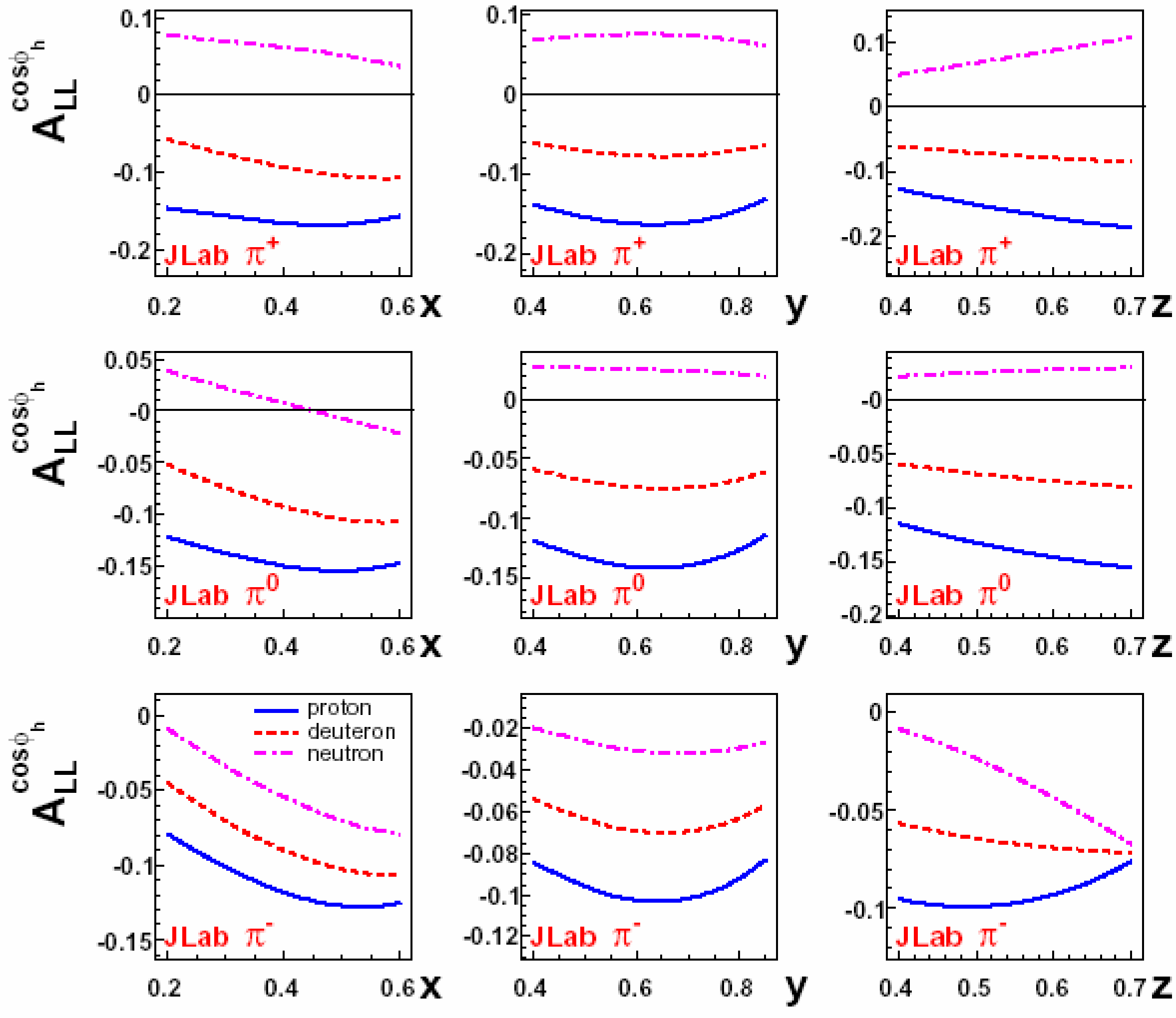
$$g_2^q(x) \simeq -g_1^q(x) + \int_x^1 dx'\,\frac{g_1^q(x')}{x'}$$

$\Rightarrow$

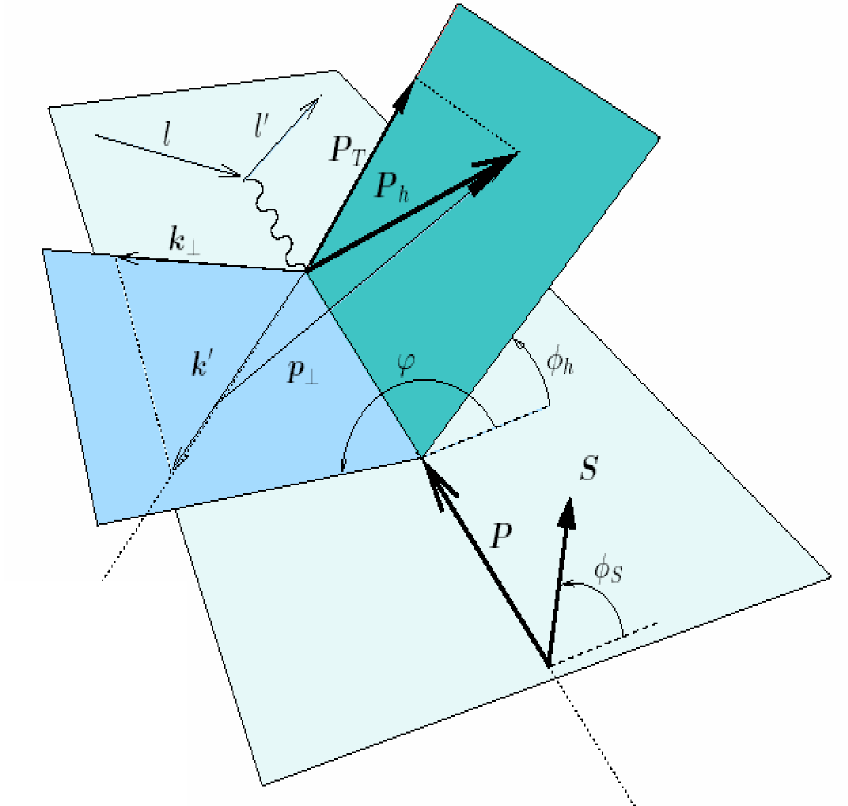
$$g_{1T}^{q(1)}(x) \simeq x\int_x^1 dx'\,\frac{g_1^q(x')}{x'}$$



Predicted dependence of $A_{LL}^{\cos\phi_h}$ on P_{hT} for scattering off a proton target with different choices of μ_2^2: 0.1 (GeV/c)2 – continuous, 0.17 (GeV/c)2 – dashed and 0.25 (GeV/c)2 – dot-dashed lines. Each line splits into three almost overlapping lines corresponding, for each value of μ_2^2, to three different values of μ_1^2 = (up-down) 0.1, 0.15 and 0.2 $(GeV/c)^2$.



Predicted dependence of $A_{LL}^{\cos\phi_h}$ on *x, y* and *z*, for proton, neutron and deuteron targets, for JLab.



Sivers effect in SIDIS

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

$$\Delta^N f_{q/p^\uparrow} = -\frac{2k_\perp}{M} f_{1T}^{\perp q}$$

$$\boldsymbol{p}_\perp \cong \boldsymbol{P}_T - z\boldsymbol{k}_\perp$$

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

$$= \frac{\sum_q \int d\Phi_h\, d\Phi_S\, d^2\boldsymbol{k}_\perp\, \Delta^N f_{q/p^\uparrow}(x,k_\perp)\sin(\varphi-\Phi_S)\frac{d\hat{\sigma}^{lq\to lq}}{dQ^2} D_q^h(z,p_\perp)\sin(\Phi_h-\Phi_S)}{\sum_q \int d\Phi_h\, d\Phi_S\, d^2\boldsymbol{k}_\perp\, f_{q/p}(x,k_\perp)\frac{d\hat{\sigma}^{lq\to lq}}{dQ^2} D_q^h(z,p_\perp)}$$

Parameterization of the Sivers function

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x, k_\perp)$$

$$\mathcal{N}_q(x) = N_q\,x^{a_q}(1-x)^{b_q}\,\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\,b_q^{b_q}}$$

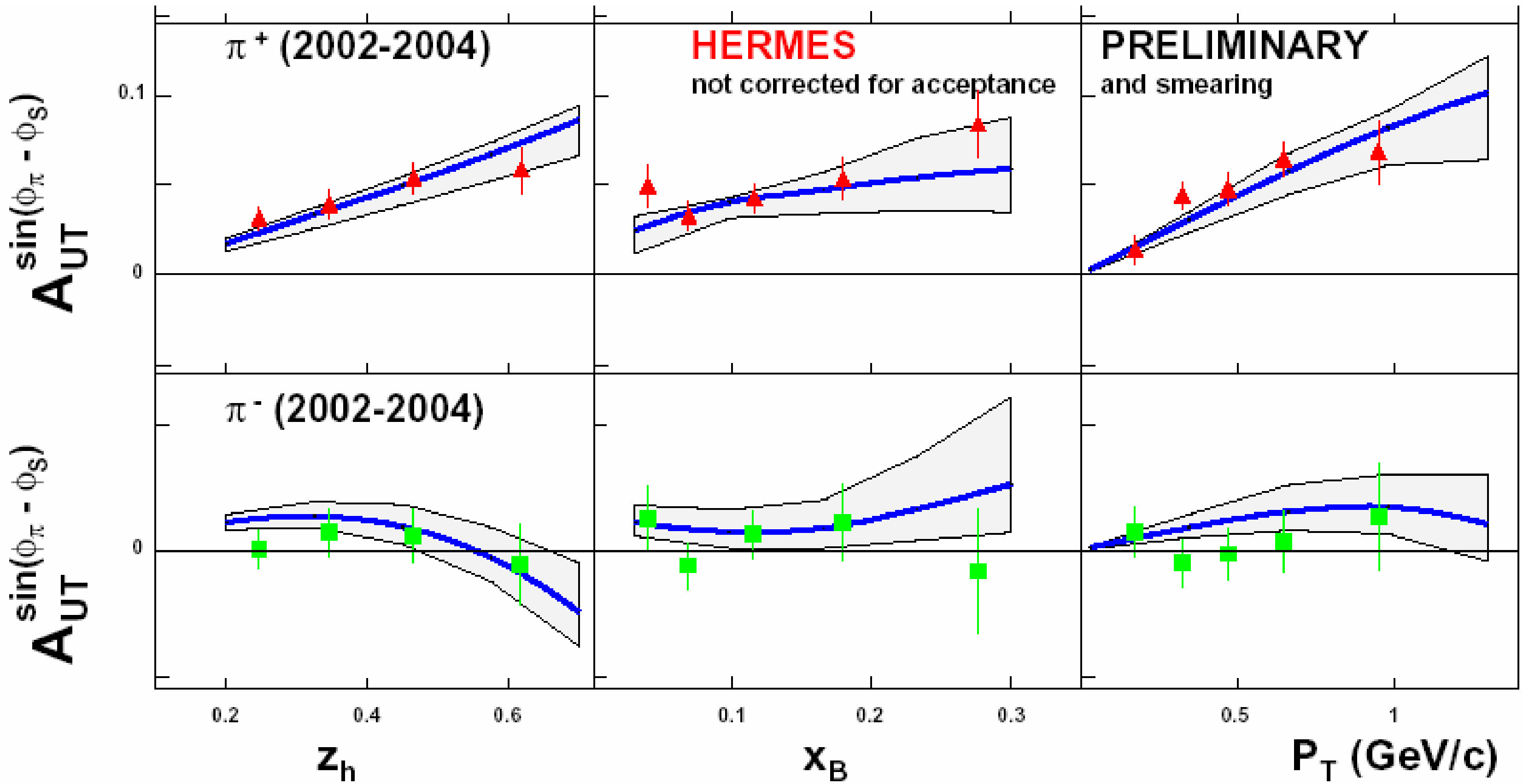
$$-1 \le N_q \le 1 \qquad |\mathcal{N}_q(x)| \le 1$$

$$h(k_\perp) = \frac{2k_\perp\,M}{k_\perp^2 + M^2} \qquad \frac{|\Delta^N f_{q/p^\uparrow}(x, k_\perp)|}{2f_{q/p}(x, k_\perp)} \le 1$$

$q = u, d$. The Sivers function for sea quarks and antiquarks is assumed to be zero.

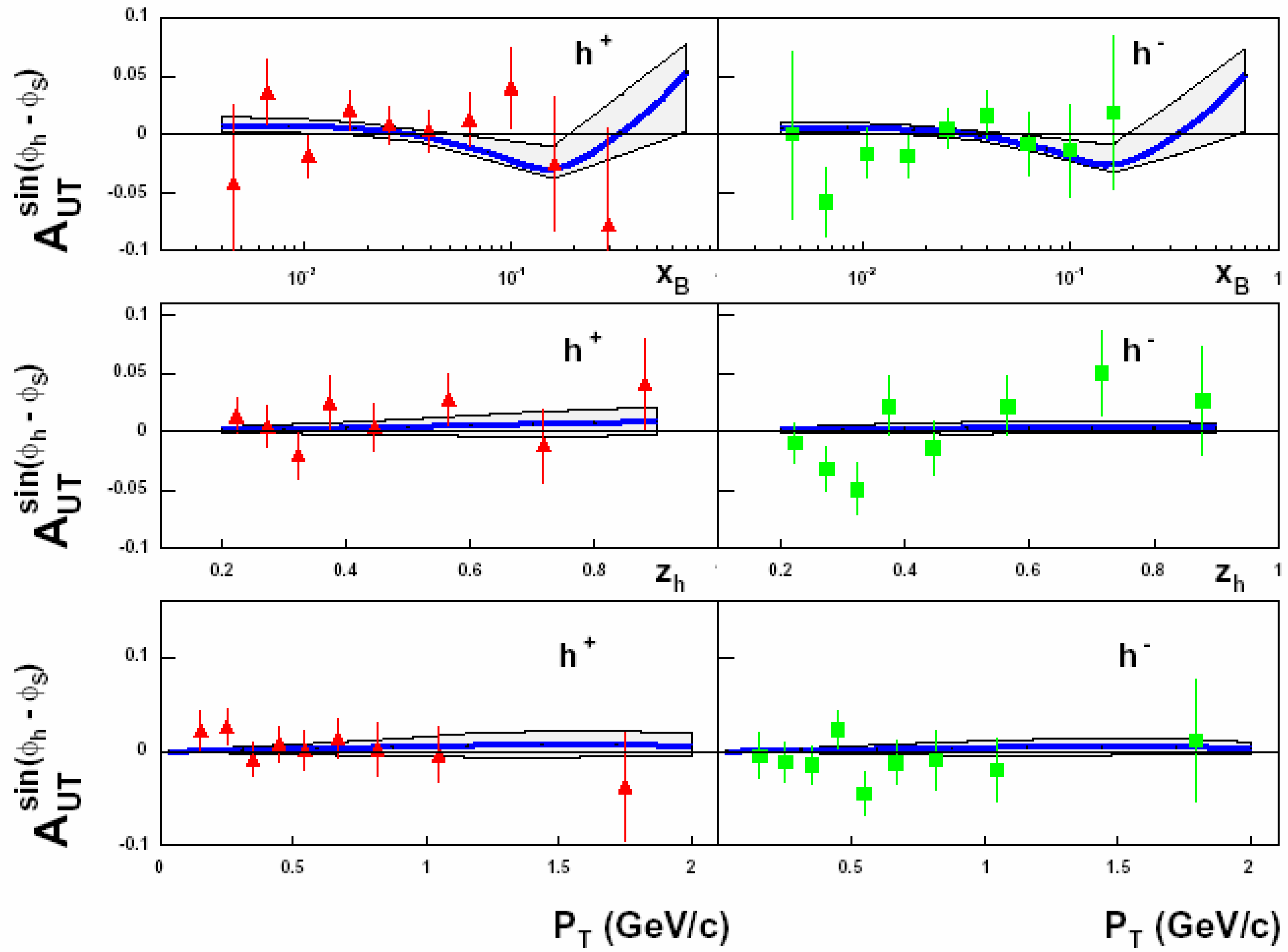
$A_{UT}^{\sin(\Phi-\Phi_S)}$ from Sivers mechanism

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

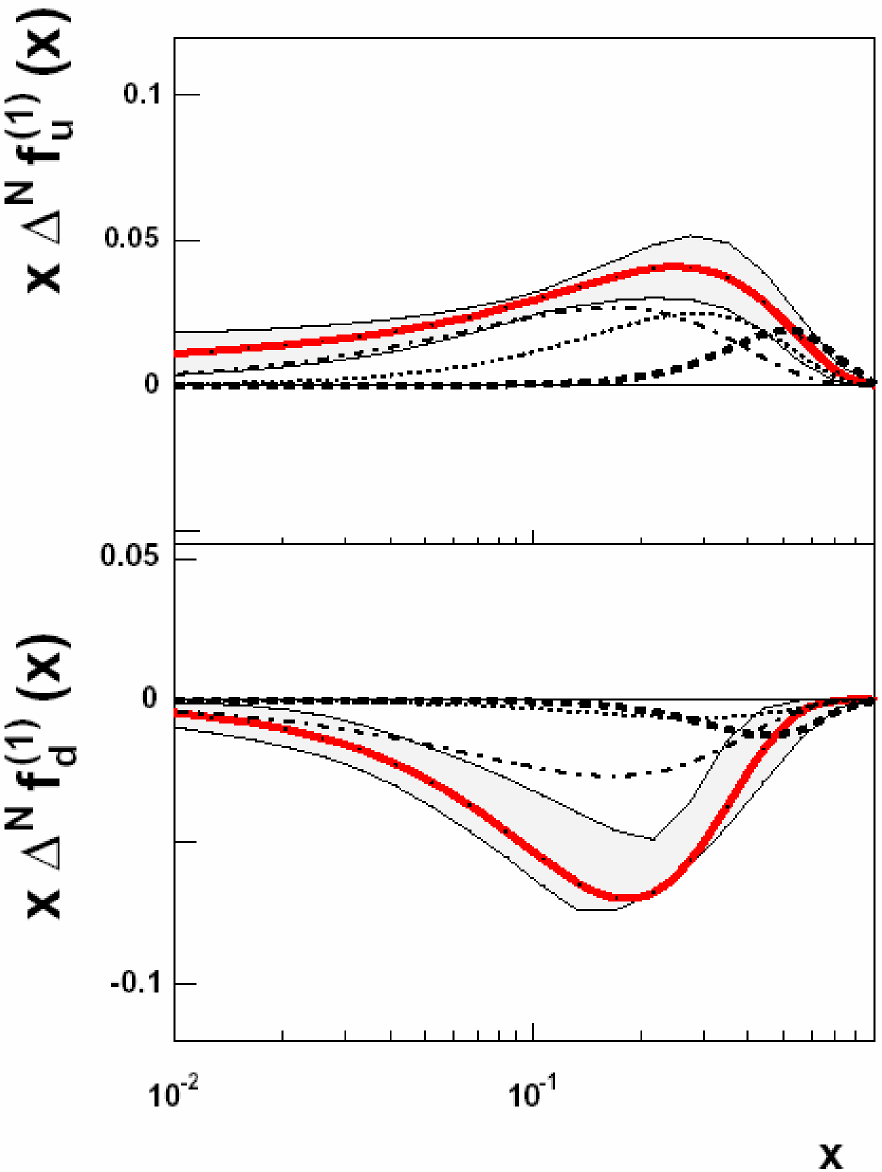


Deuteron target

$$A_{UT}^{\sin(\Phi_h-\Phi_S)} \propto \left(\Delta^N f_{u/p^\uparrow} + \Delta^N f_{d/p^\uparrow}\right)\left(4D_u^h + D_d^h\right)$$



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



hep-ph/0511017

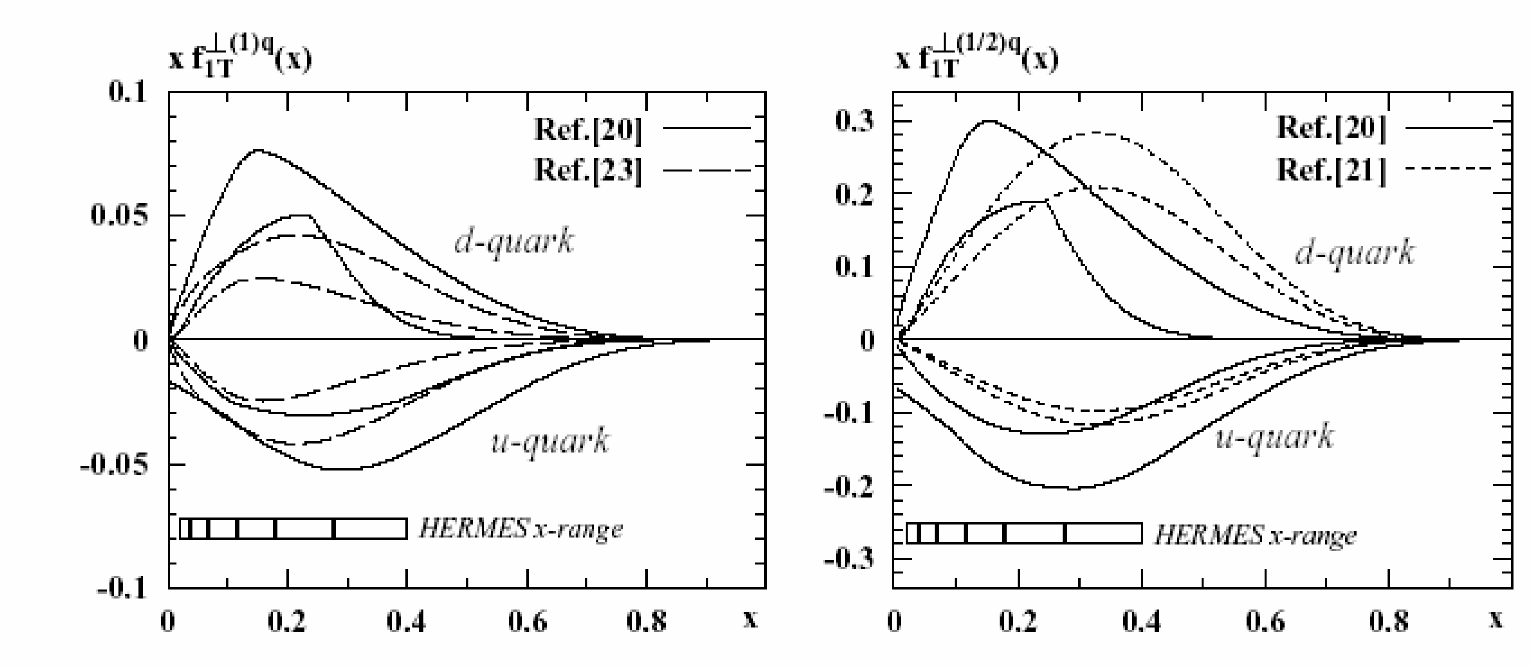
First $p_\perp$ moments of extracted Sivers functions, compared with models

data from HERMES and COMPASS

$$\Delta^N f_q^{(1)} = -f_{1T}^{\perp(1)q} = \int d^2k \, \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp)$$

$$f_{1T}^{\perp u} = -f_{1T}^{\perp d} \; ?$$

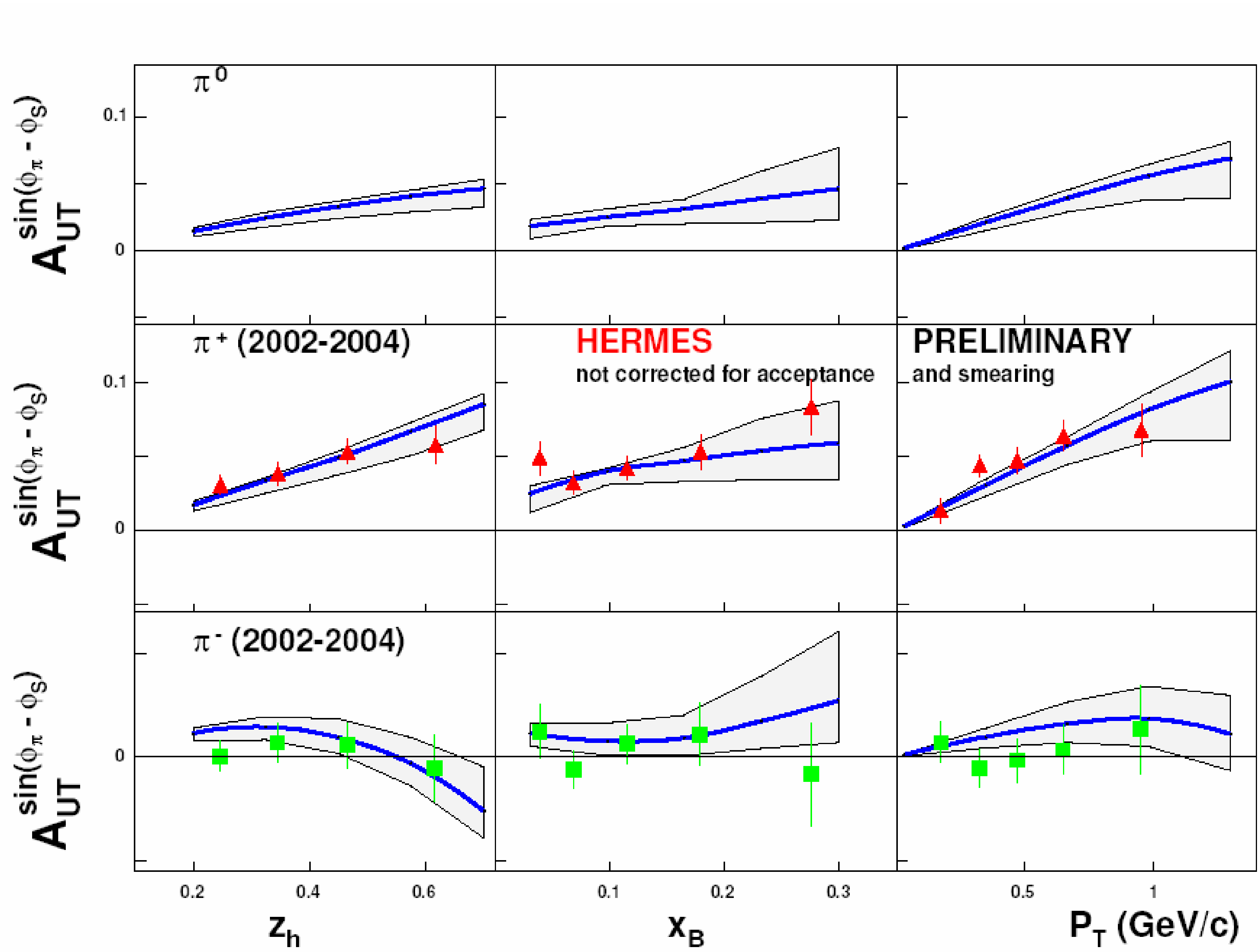
M. Anselmino, M. Boglione, J.C. Collins, U. D'Alesio, A.V. Efremov, K. Goeke, A. Kotzinian,
S. Menze, A. Metz, F. Murgia, A. Prokudin, P. Schweitzer, W. Vogelsang, F. Yuan



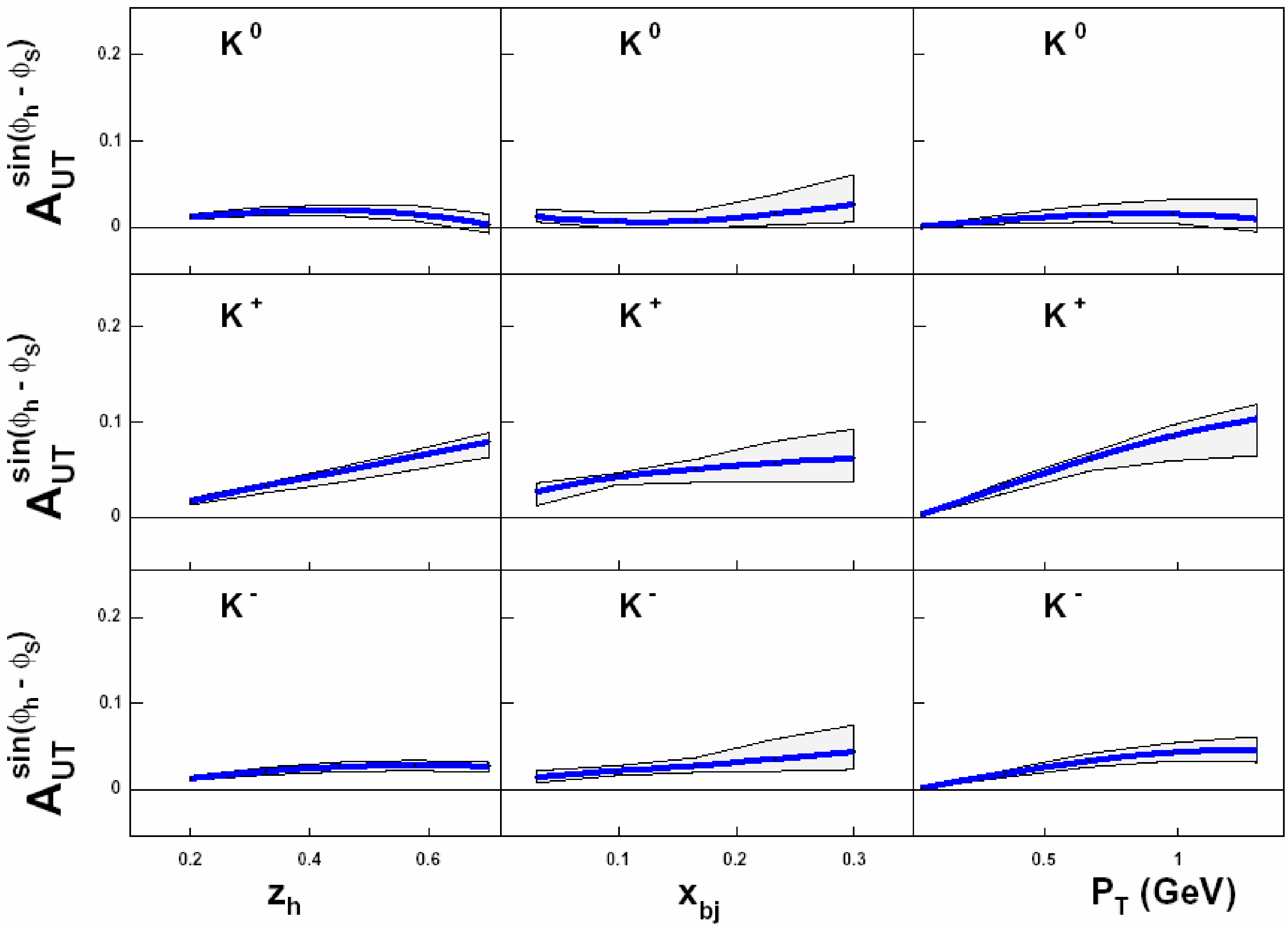
The first and 1/2-transverse moments of the Sivers quark distribution functions, defined in Eqs. (3, 9), as extracted in Refs. [20, 21, 23]. The fits were constrained mainly (or solely) by the preliminary HERMES data in the indicated x-range. The curves indicate the 1-σ regions of the various parameterizations.

$$f_{1T}^{\perp(1)q} = \int d^2\boldsymbol{k}_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x, k_\perp) \qquad f_{1T}^{\perp(1/2)q}(x) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp)$$

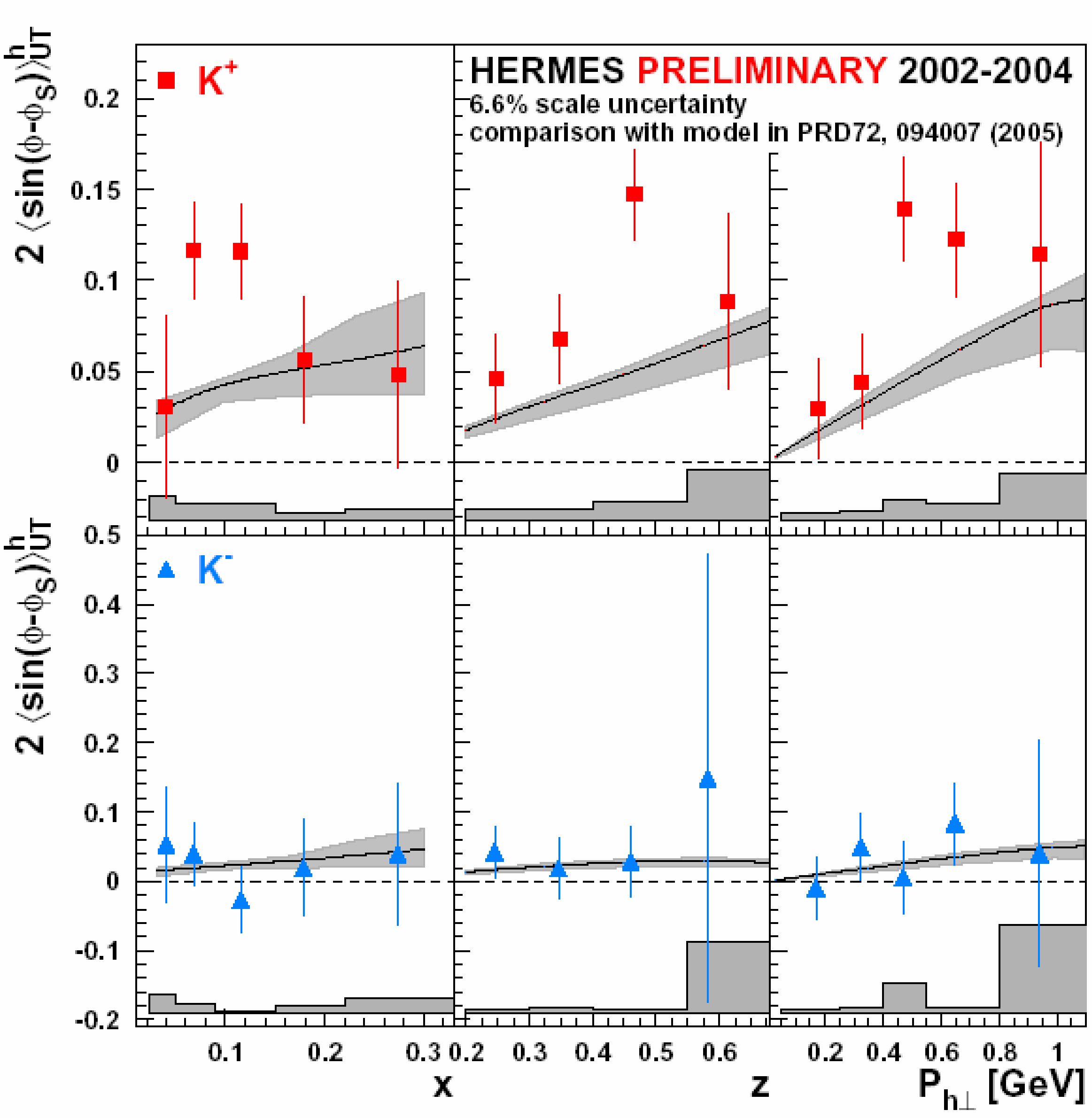
Predictions for π^0 production at HERMES

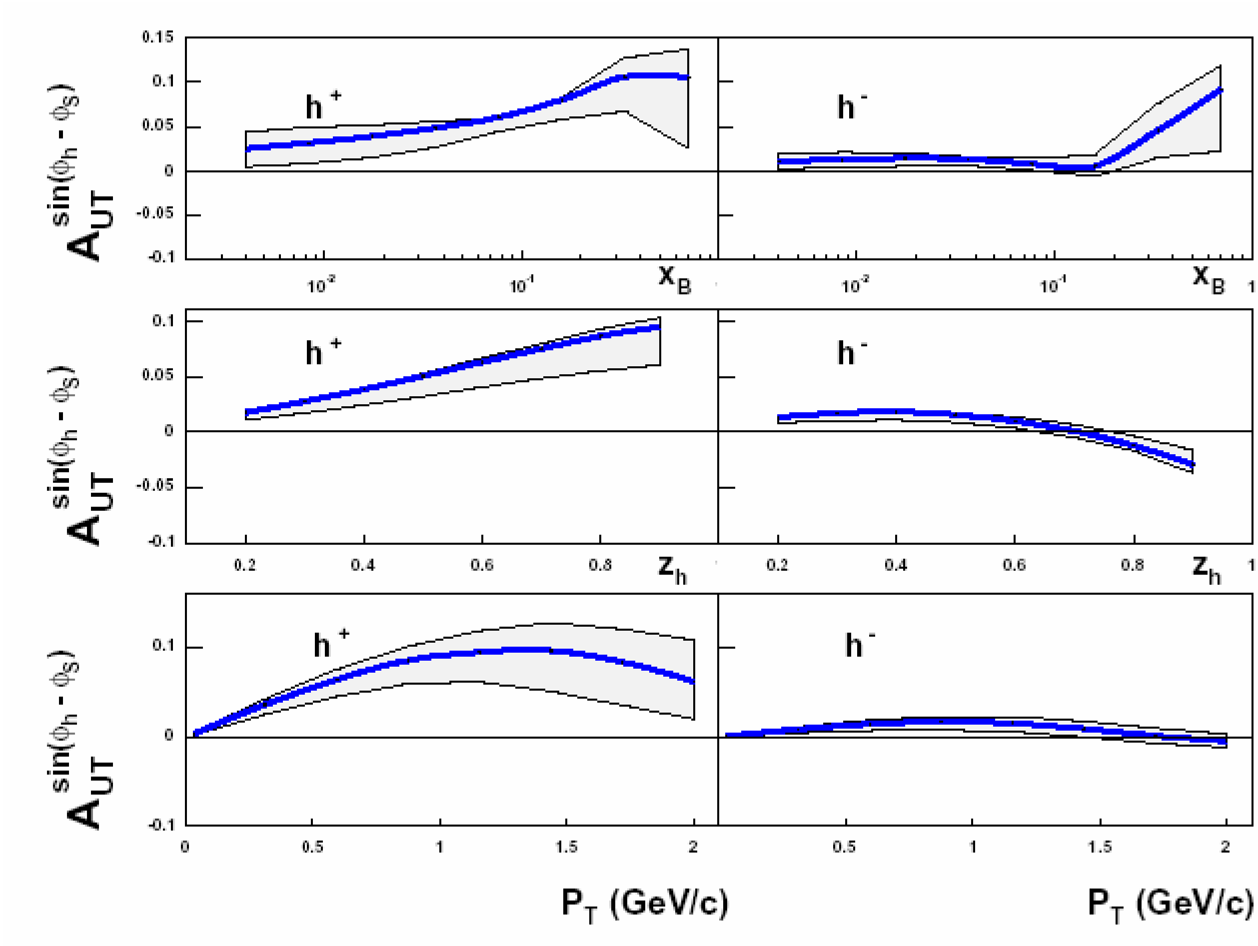


Predictions for K production at HERMES …



… and comparison with data. Role of *s* quarks?





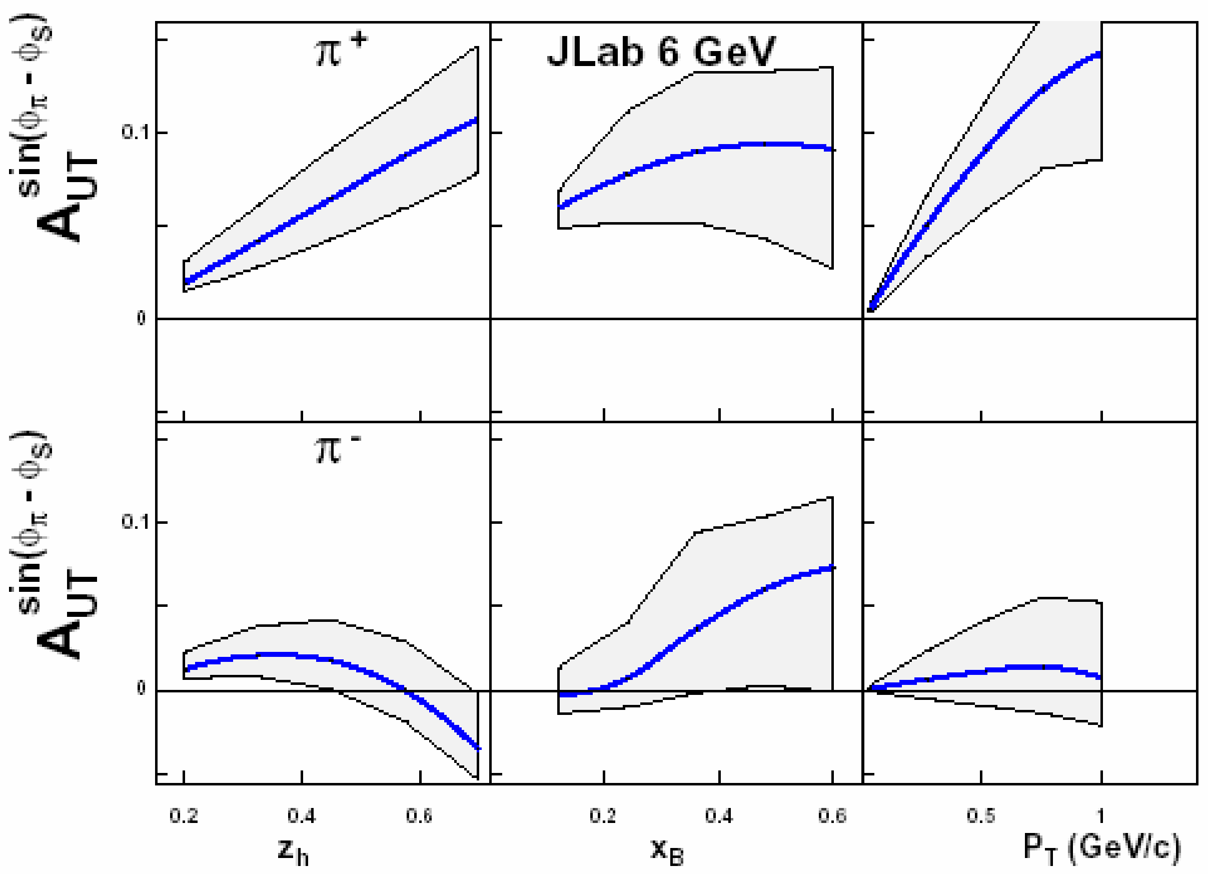
Predictions for COMPASS, hydrogen target

suggested kinematical cuts:

$Q^2 > 1\ (GeV/c)^2$ $W^2 > 25\ GeV^2$

$P_T > 0.1\ GeV/c$ $E_h > 4\ GeV$

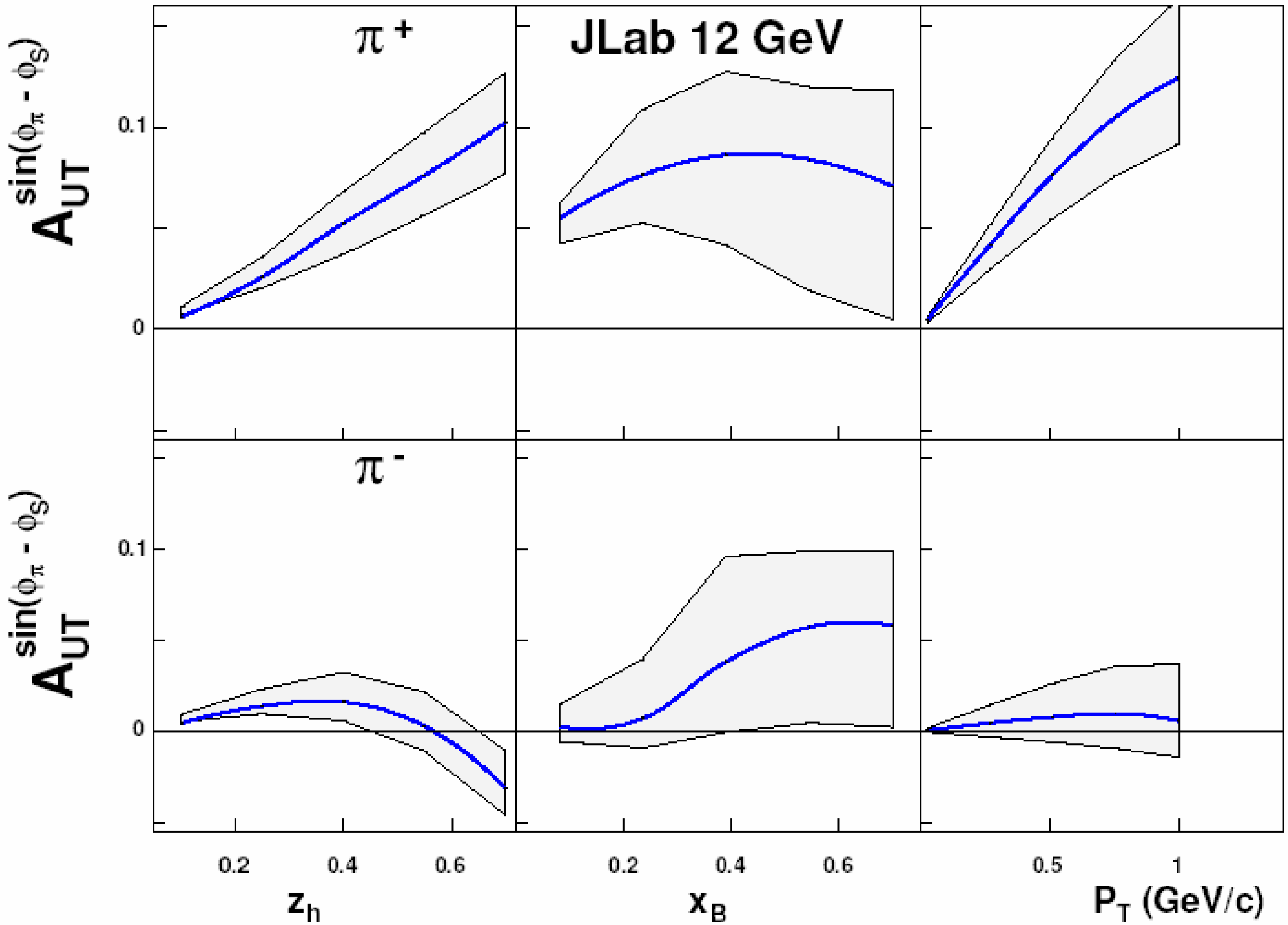
$0.2 < z_h < 0.9$ $0.1 < y < 0.9$



predictions for JLab, proton target, 6 GeV

$0.4 \leq z_h \leq 0.7 \qquad 0.02 \leq P_T \leq 1$ GeV/c $\qquad 0.1 \leq x_B \leq 0.6$

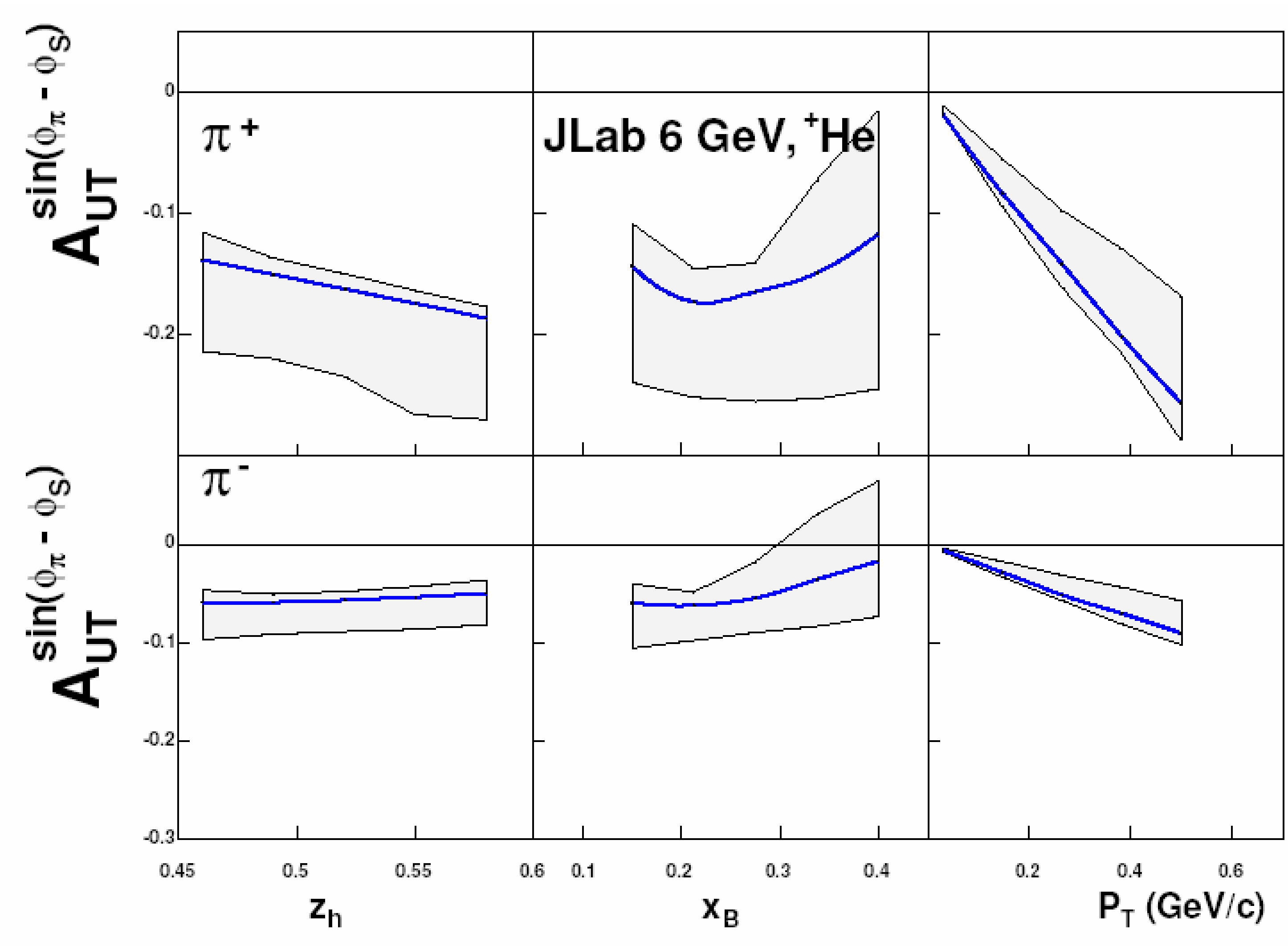
$0.4 \leq y \leq 0.85 \qquad Q^2 \geq 1$ (GeV/c)$^2 \qquad W^2 \geq 4$ GeV$^2 \qquad 1 \leq E_h \leq 4$ GeV



predictions for JLab, proton target, 12 GeV

$0.4 \leq z_h \leq 0.7 \qquad 0.02 \leq P_T \leq 1.4$ GeV/c $\qquad 0.05 \leq x_B \leq 0.7$

$0.2 \leq y \leq 0.85 \qquad Q^2 \geq 1$ (GeV/c)$^2 \qquad W^2 \geq 4$ GeV$^2 \qquad 1 \leq E_h \leq 7$ GeV



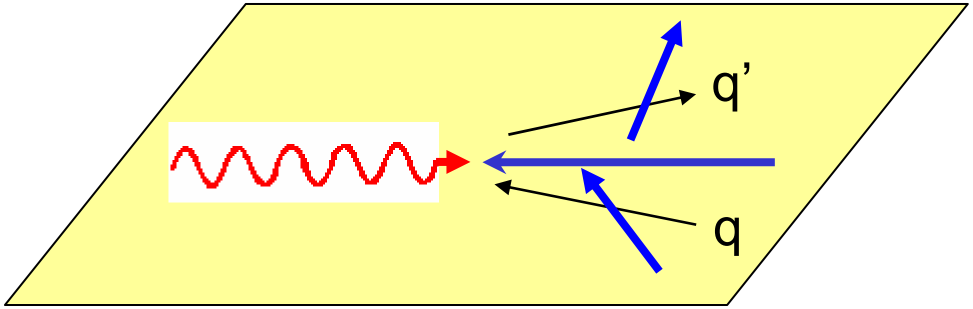
predictions for JLab, neutron target, 6 GeV

Collins mechanism for SSA

Asymmetry in the fragmentation of a transversely polarized quark

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

$$\Delta^N D_{h/q^\uparrow} = 2\frac{p_\perp}{z\,M_h}H_1^{\perp q}$$

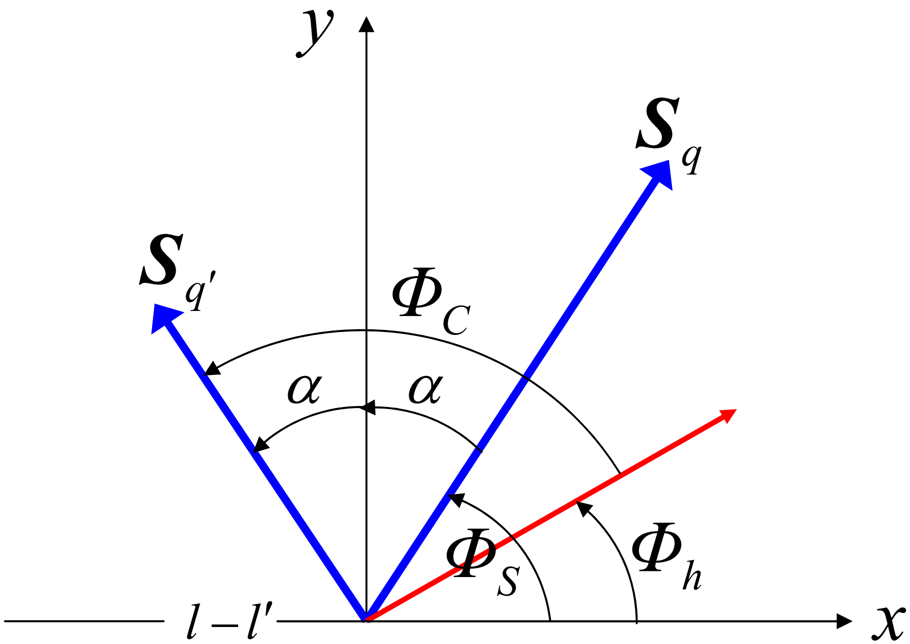


initial q spin is transferred to final q', which fragments

$$\boldsymbol{S}_{q'}\cdot(\hat{\boldsymbol{p}}_{q'}\times\hat{\boldsymbol{p}}_\perp)\propto\sin(\Phi_h+\Phi_S)$$

$$\Phi_C = \pi - \Phi_h - \Phi_S$$

(neglecting intrinsic motion in partonic distributions)



Collins effect in SIDIS

$$A_{UT}^{\sin(\Phi_h+\Phi_S)} \equiv 2\,\frac{\int d\Phi_h d\Phi_S [\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}]\sin(\Phi_h+\Phi_S)}{\int d\Phi_h d\Phi_S [d\sigma^{\uparrow} + d\sigma^{\downarrow}]}$$

$$A_{UT}^{\sin(\Phi_h+\Phi_S)} =$$

$$\frac{\sum_q \int d\Phi_h\, d\Phi_S d^2\boldsymbol{k}_\perp\, h_{1q}(x,k_\perp)\, \frac{d\Delta\hat{\sigma}^{lq\to lq}}{dQ^2}\, \Delta^N D_{h/q^\uparrow}(z,\boldsymbol{p}_\perp) \sin(\Phi_h+\Phi_S)}{\sum_q \int d\Phi_h\, d\Phi_S d^2\boldsymbol{k}_\perp\, \frac{d\hat{\sigma}^{lq\to lq}}{dQ^2}\, f_{q/p}(x,k_\perp)\, D_{q/p}(z,p_\perp)}$$

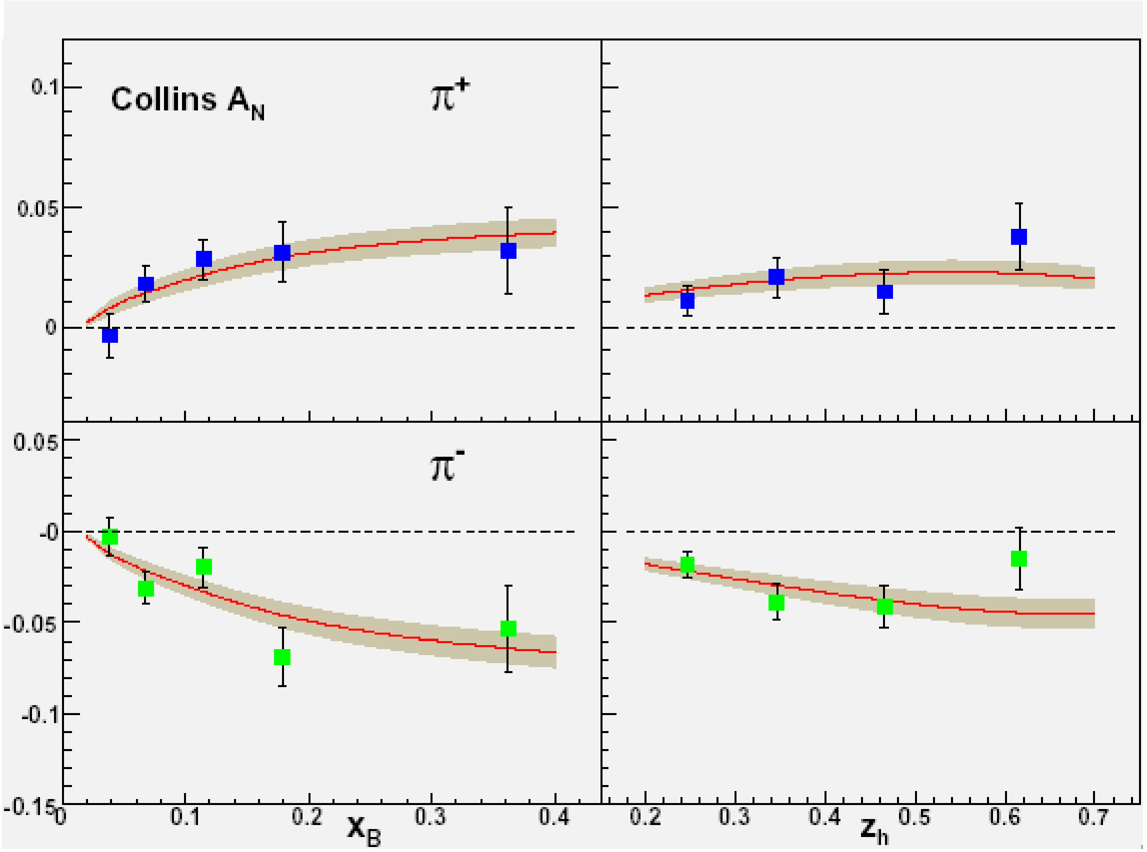
h_{1q} or $\Delta_T q$: **transversity distribution**

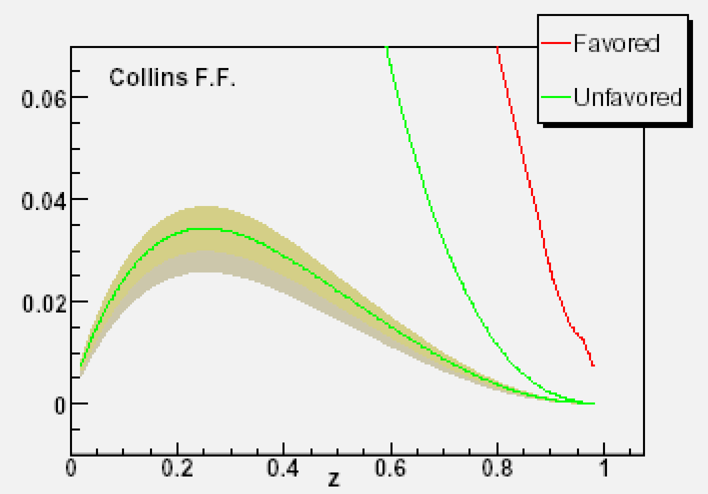
$$d\Delta\hat{\sigma} = d\hat{\sigma}^{lq^\uparrow \to lq^\uparrow} - d\hat{\sigma}^{lq^\uparrow \to lq^\downarrow}$$

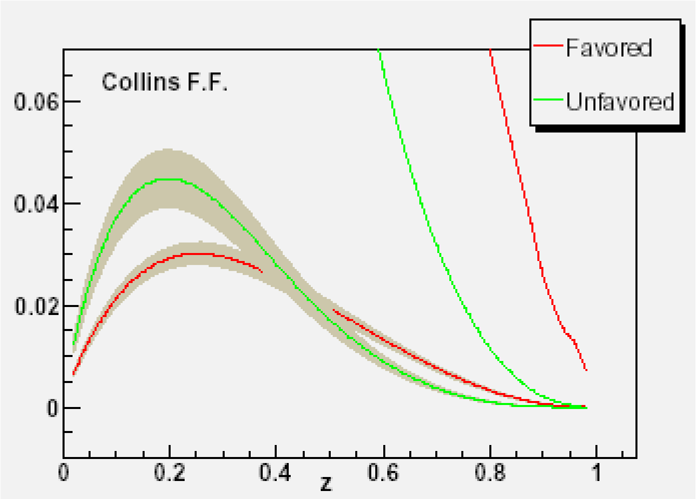
$$\Delta^N D_{h/q^\uparrow}(z,\boldsymbol{p}_\perp) = \Delta^N D_{h/q^\uparrow}(z,p_\perp)\, \boldsymbol{S}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp)$$

fit to HERMES data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$

W. Vogelsang and F. Yuan



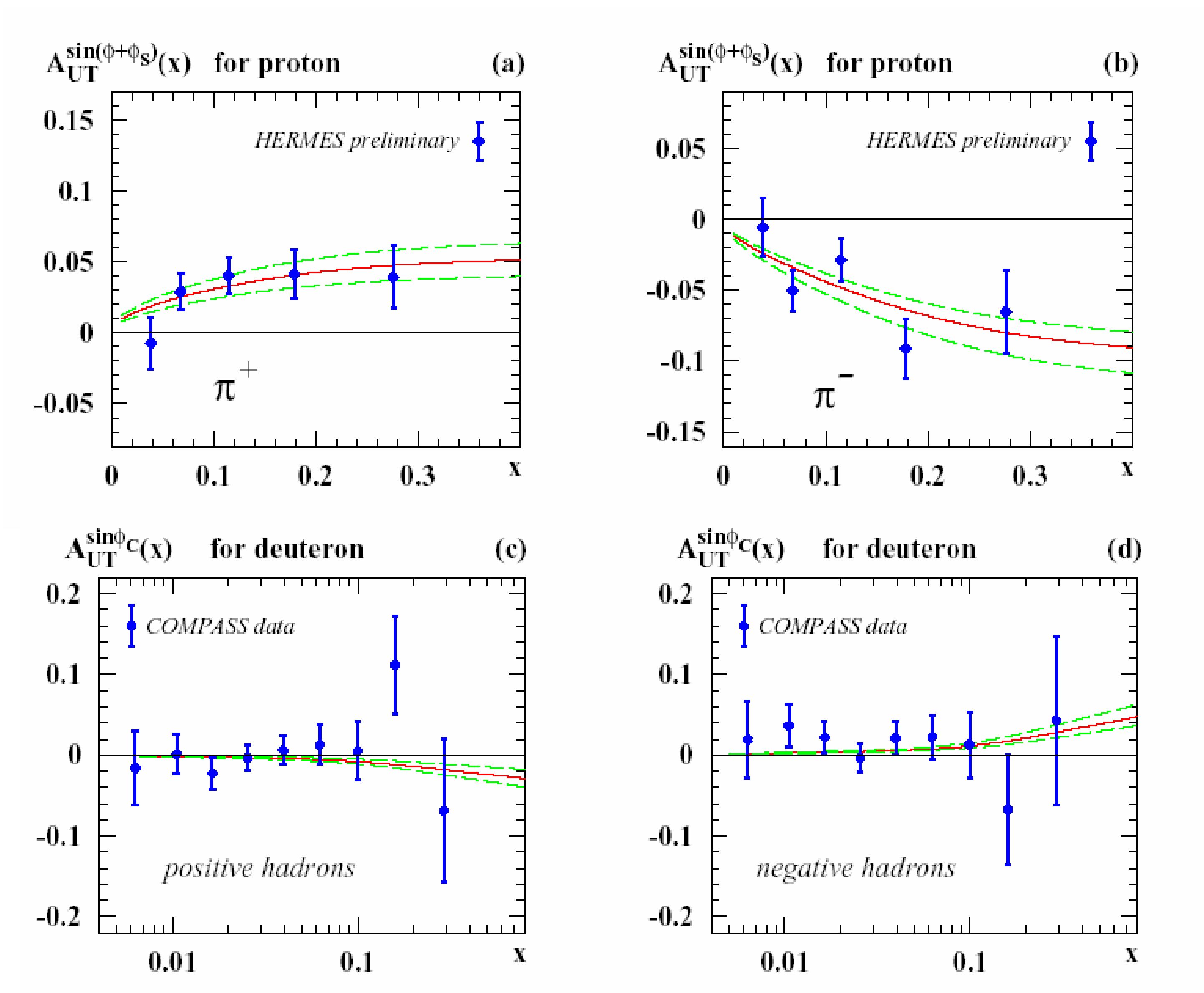




Soffer-saturated h_1 $\left(2|h_1| = \Delta q + q\right)$

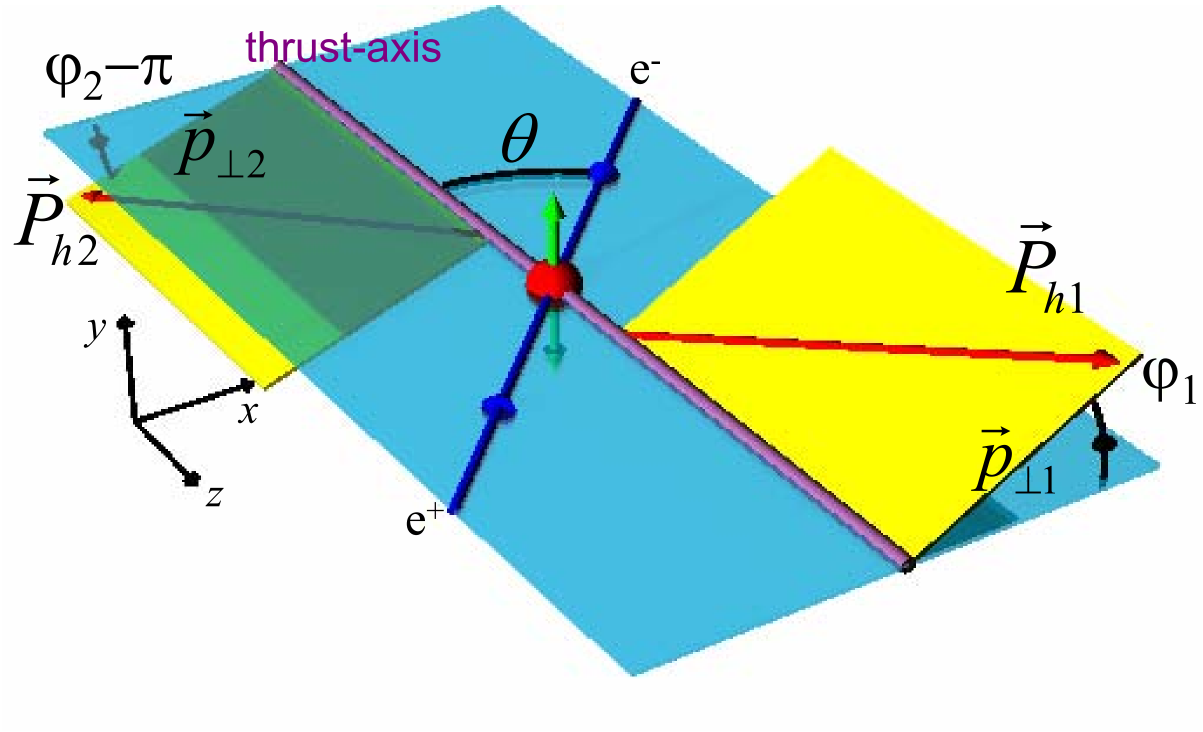
A. V. Efremov, K. Goeke and P. Schweitzer

(h_1 from quark-soliton model)



Collins function from e^+e^- processes

(spin effects without polarization, Boer, Jakob, Mulders)



$$e^+e^- \rightarrow q\,\bar{q} \rightarrow h^+h^-X$$

e^+e^- CMS frame:

BELLE @ KEK

$$z = \frac{2E_h}{\sqrt{s}},\ \sqrt{s} = 10.52\,\text{GeV}$$

single quark or antiquark are not polarized, but there is a strong correlation between their spins

$$\frac{d\hat{\sigma}^{\uparrow\downarrow}}{d\cos\theta} - \frac{d\hat{\sigma}^{\uparrow\uparrow}}{d\cos\theta} = \frac{3\pi\alpha^2}{4s} e_q^2 \sin^2\theta$$

⇒ cross section for detecting the final hadrons inside the jets

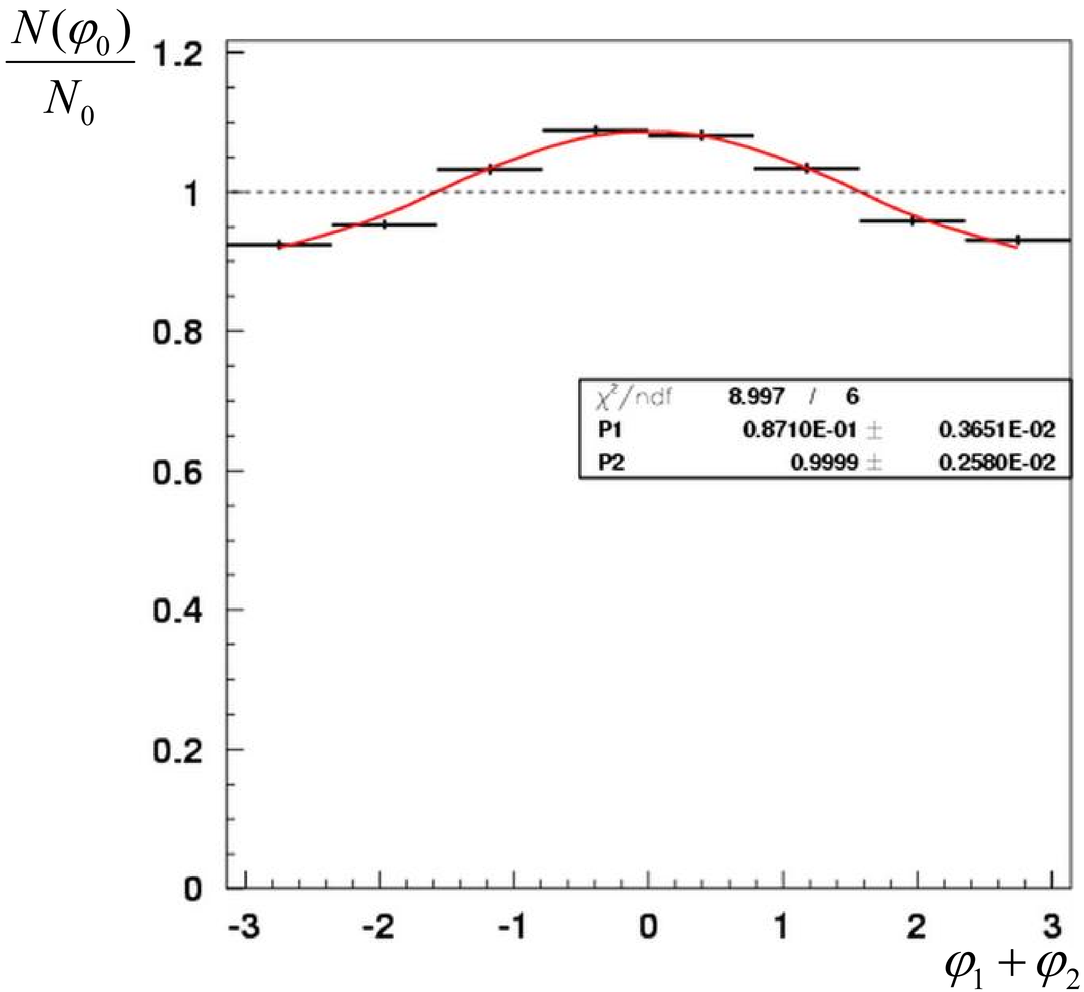
$$\frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\, dz_2\, d^2\boldsymbol{p}_{\perp 1}\, d^2\boldsymbol{p}_{\perp 2}\, d\cos\theta} = \sum_{q,spins} \frac{d\hat{\sigma}^{spins}}{d\cos\theta} D_{h_1/q^\uparrow}(z_1, \boldsymbol{p}_{\perp 1}) D_{h_2/\bar{q}^\uparrow}(z_2, \boldsymbol{p}_{\perp 2})$$

contains the product of two Collins functions

$$A_1 \equiv \frac{\dfrac{d\sigma}{dz_1\, dz_2\, d\varphi_0\, d\cos\theta}}{\dfrac{1}{2\pi}\dfrac{d\sigma}{dz_1\, dz_2\, d\cos\theta}} = 1 + \frac{1}{8}\frac{\sin^2\theta}{1+\cos^2\theta}(\cos\varphi_0)\frac{\sum_q e_q^2\, \Delta^N D_{h_1/q^\uparrow}(z_1)\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2\, D_{h_1/q}(z_1) D_{h_2/\bar{q}}(z_2)}$$

$$\Delta^N D_{h/q^\uparrow}(z) = \int d^2\boldsymbol{p}_\perp\, \Delta^N D_{h/q^\uparrow}(z, p_\perp), \quad \text{etc.}$$

$$\varphi_0 \equiv \varphi_1 + \varphi_2$$



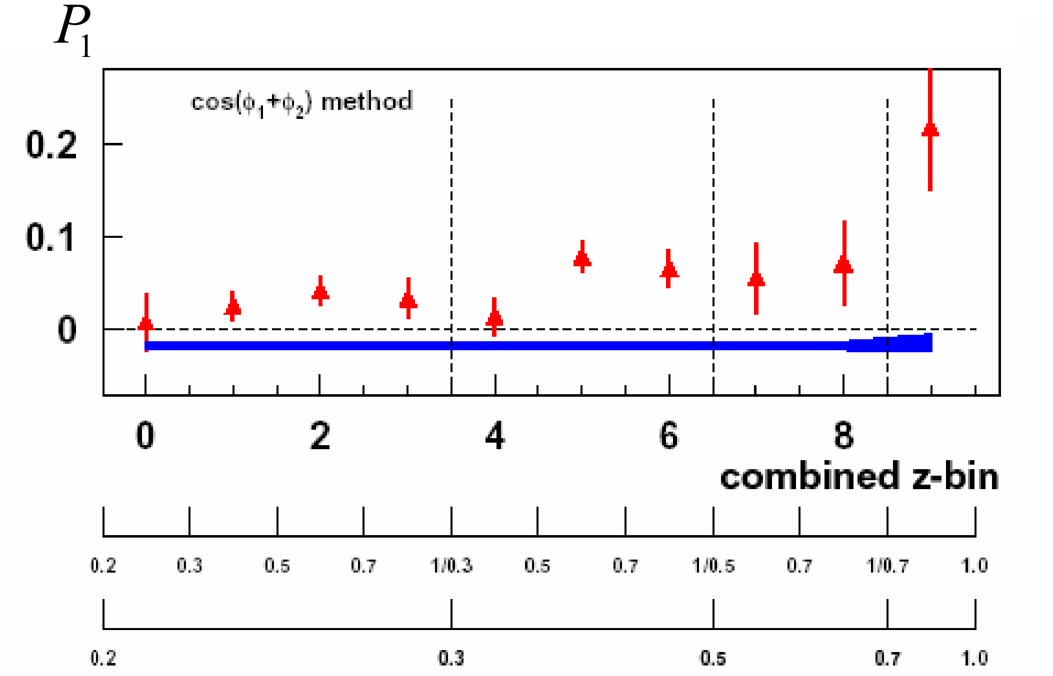
BELLE data

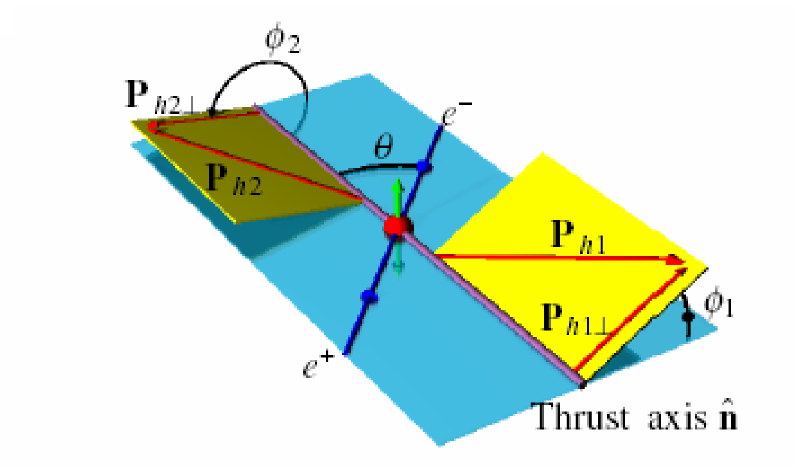
M. Grosse Perdekamp,
A. Ogawa, R. Seidl

Talk at SPIN2006

Cosine modulations clearly visible

$$\frac{N(\varphi_0)}{N_0} = P_1 + P_2 \cos\varphi_0$$





$$\frac{A_1^U}{A_1^L} = 1 + \cos(\varphi_1 + \varphi_2) P_1(z_1, z_2)$$

U = unlike charged pions
L = like charged pions

$$\Delta^N D_{\pi^+/u} \equiv \Delta^N D_F, \;\; \Delta^N D_{\pi^-/u} \equiv \Delta^N D_U, \quad \text{etc.}$$

$$P_1(z_1,z_2) = \frac{1}{8}\frac{\sin^2\theta}{1+\cos^2\theta}\left[\frac{5\Delta^N D_F(z_1)\Delta^N D_F(z_2) + 7\Delta^N D_U(z_1)\Delta^N D_U(z_2)}{5D_F(z_1)D_F(z_2) + 7D_U(z_1)D_U(z_2)} - \frac{5\Delta^N D_F(z_1)\Delta^N D_U(z_2) + 5\Delta^N D_U(z_1)\Delta^N D_F(z_2) + 2\Delta^N D_U(z_1)\Delta^N D_U(z_2)}{5D_F(z_1)D_U(z_2) + 5D_U(z_1)D_F(z_2) + 2D_U(z_1)D_U(z_2)}\right]$$

Collins functions and transversity distributions from a global best fit of HERMES, COMPASS and BELLE data

M.A., M. Boglione, U.D'Alesio, A.Kotzinian, F. Murgia, A. Prokudin, C. Türk, in preparation

$$\Delta_T q(x,k_\perp) = \mathrm{N}_q^T(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}\,\underbrace{\frac{1}{2}[f_{q/p}(x)+\Delta q(x)]}_{\text{Soffer bound}}$$

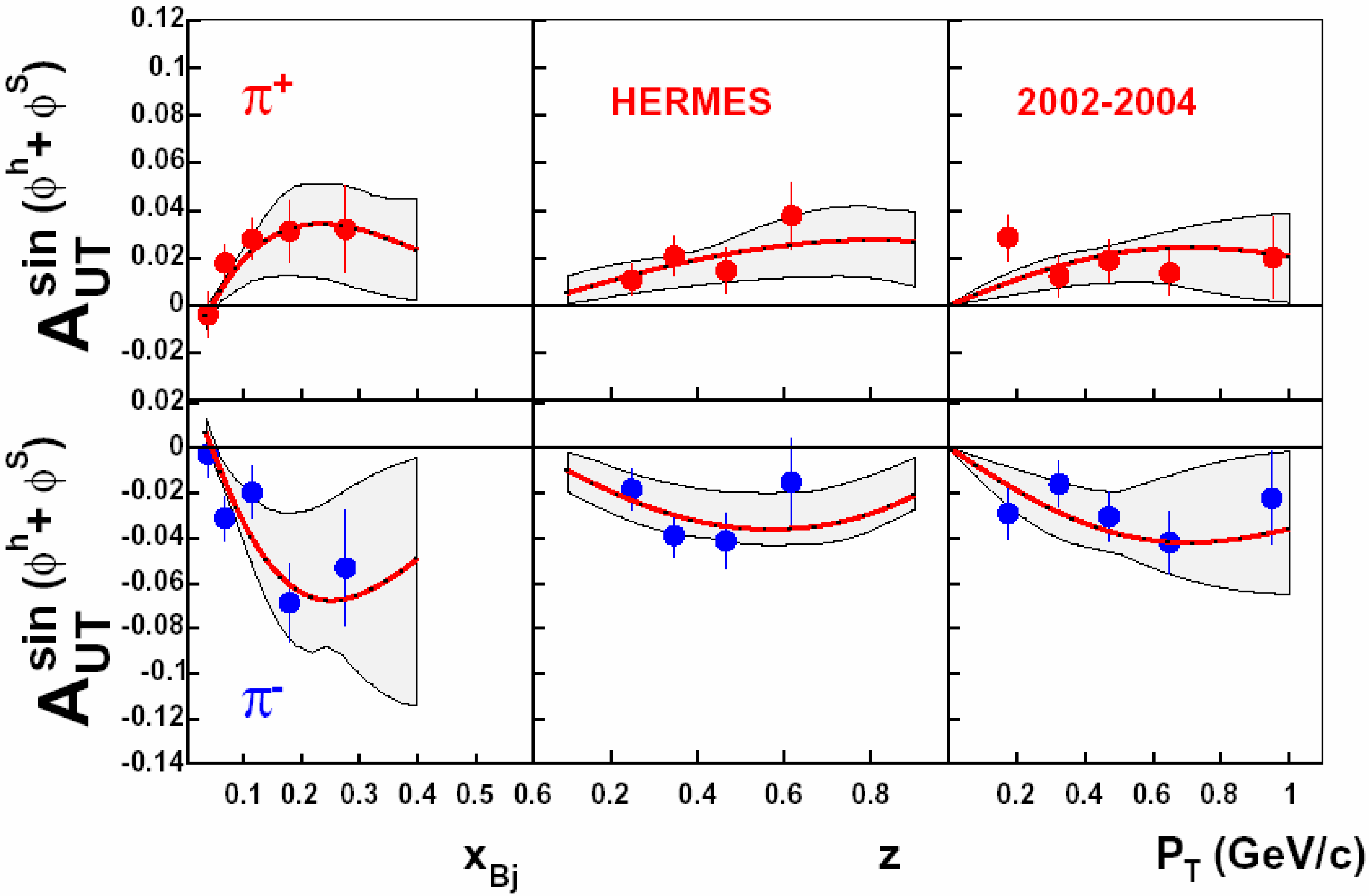
$$\Delta^N D_{h/q^\uparrow}(z,p_\perp) = \mathrm{N}_q^C(z)\,h(p_\perp)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,\underbrace{2D_{h/q}(z)}_{\text{positivity bound}}$$

$$\mathrm{N}_q^T(x) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta} \qquad |N_q^T| \geq 1, \quad |\mathrm{N}_q^T(x)| \leq 1$$

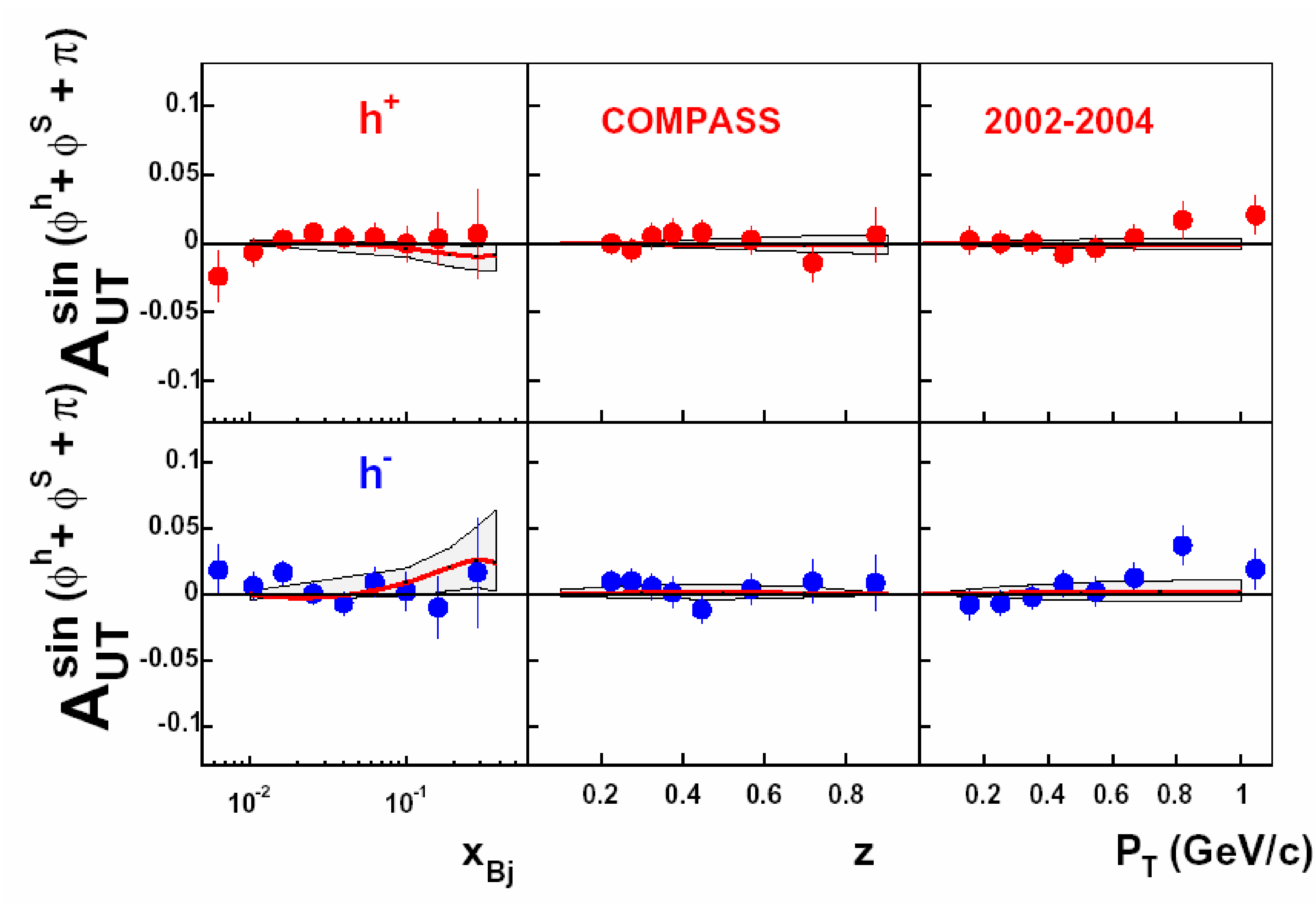
$$\mathrm{N}_q^C(x) = N_q^C z^\gamma (1-z)^\delta \frac{(\gamma+\delta)^{(\gamma+\delta)}}{\gamma^\gamma \delta^\delta} \qquad |N_q^C| \geq 1, \quad |\mathrm{N}_q^C(z)| \leq 1$$

$$h(p_\perp) = \sqrt{2e}\,\frac{p_\perp}{M_h}\,e^{-p_\perp^2/M_h^2}$$

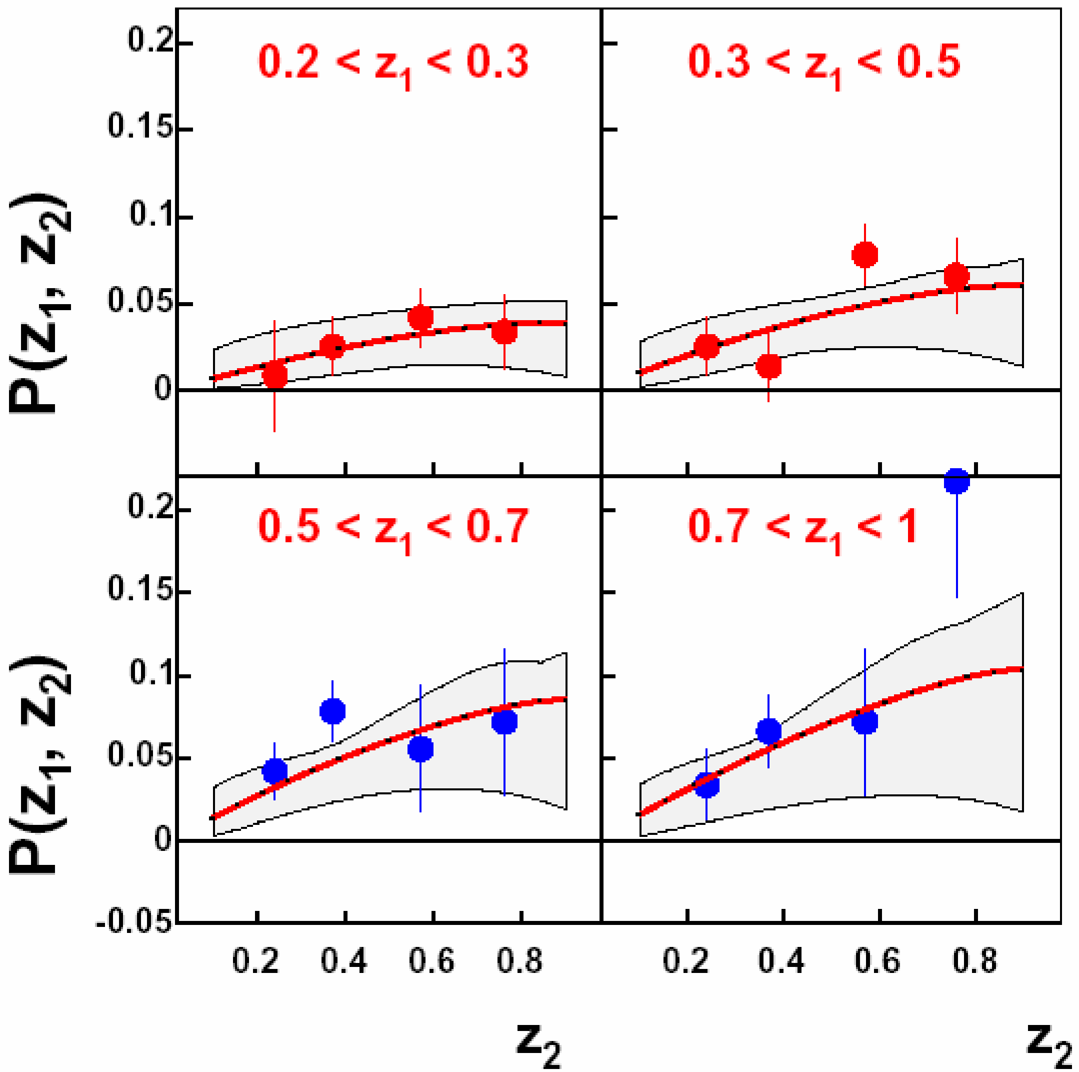
fit of HERMES data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$



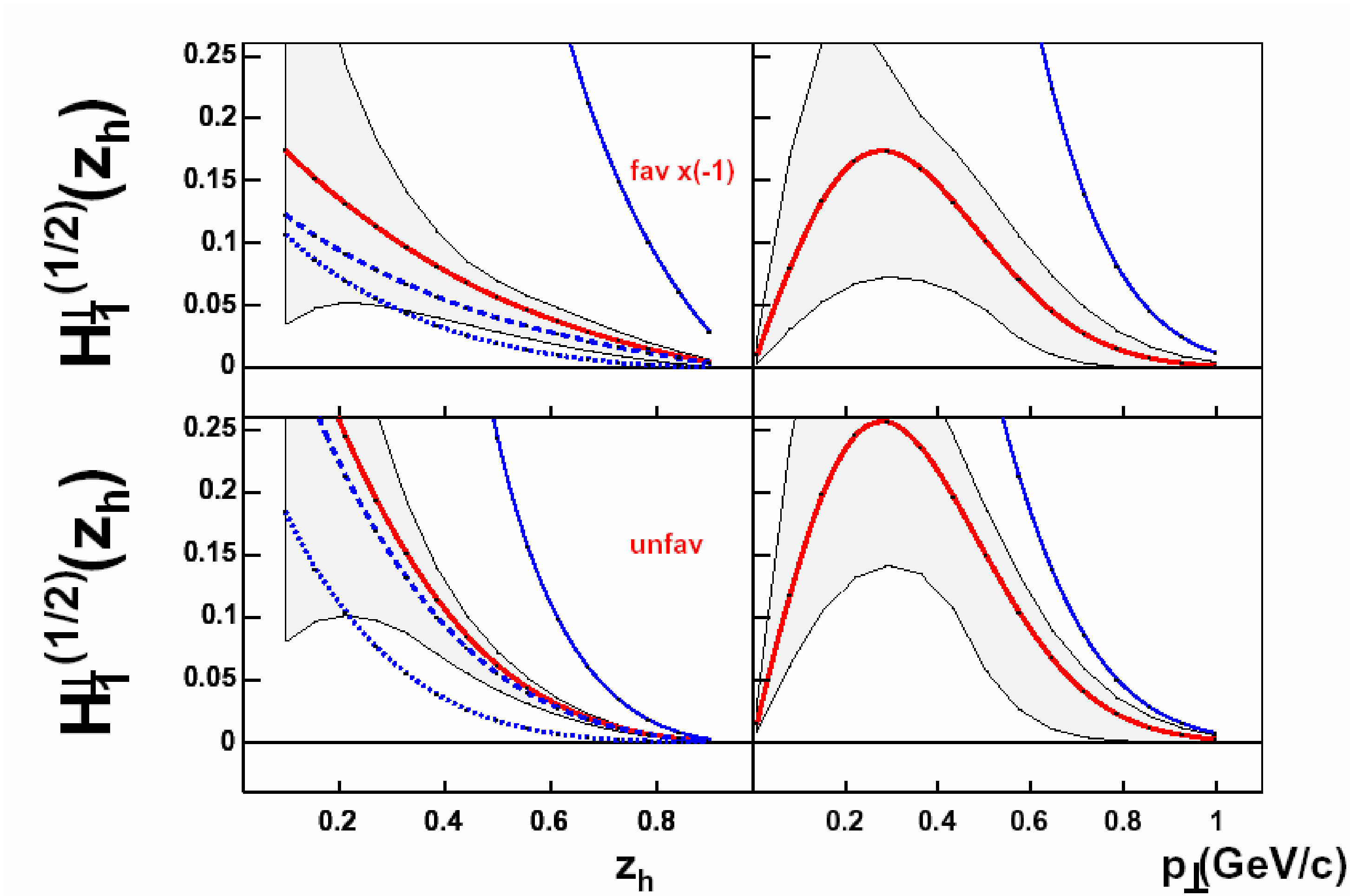
fit of COMPASS data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$



fit of BELLE data on $P_1(z_1, z_2)$



Extracted favoured and unfavoured Collins functions

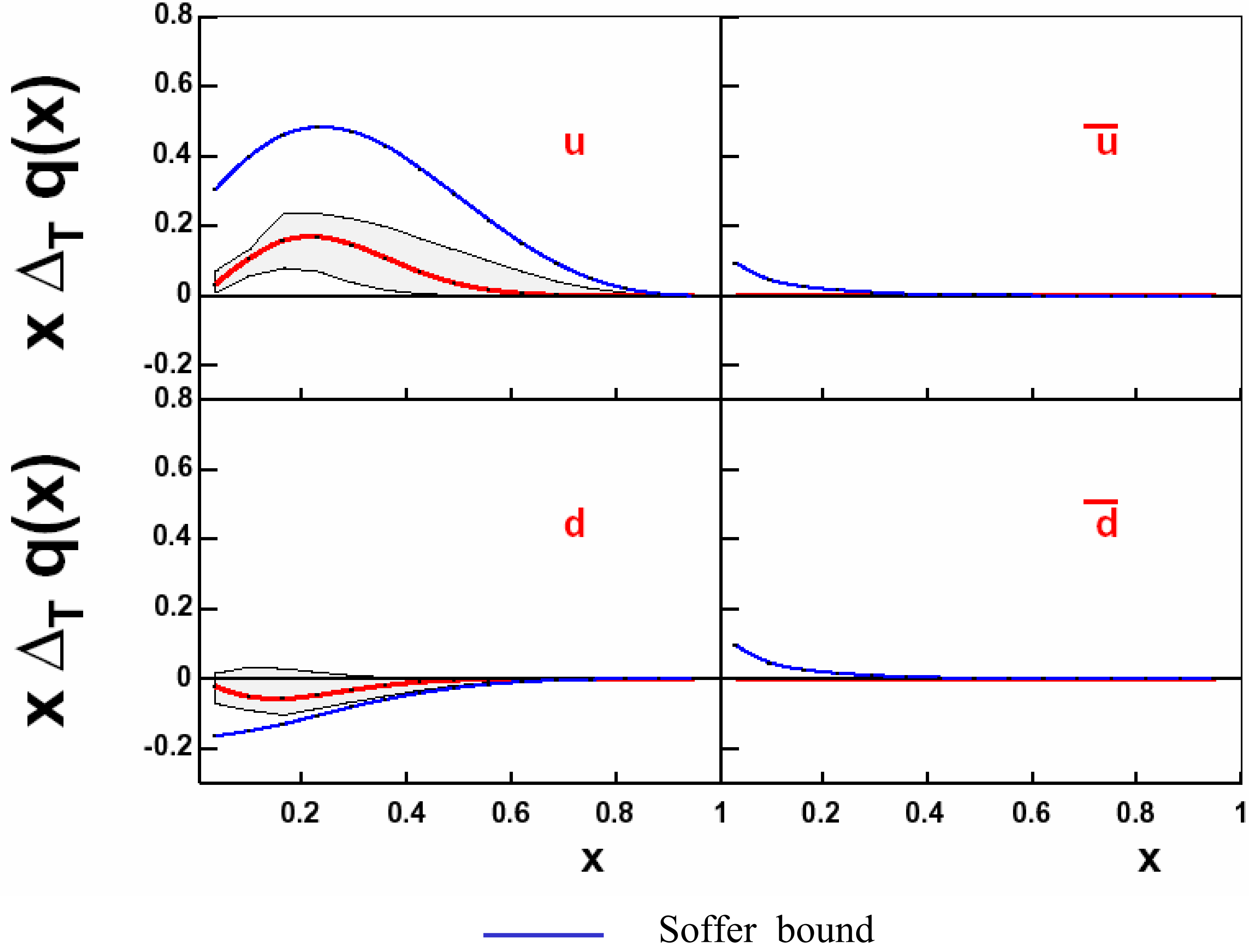


positivity bound

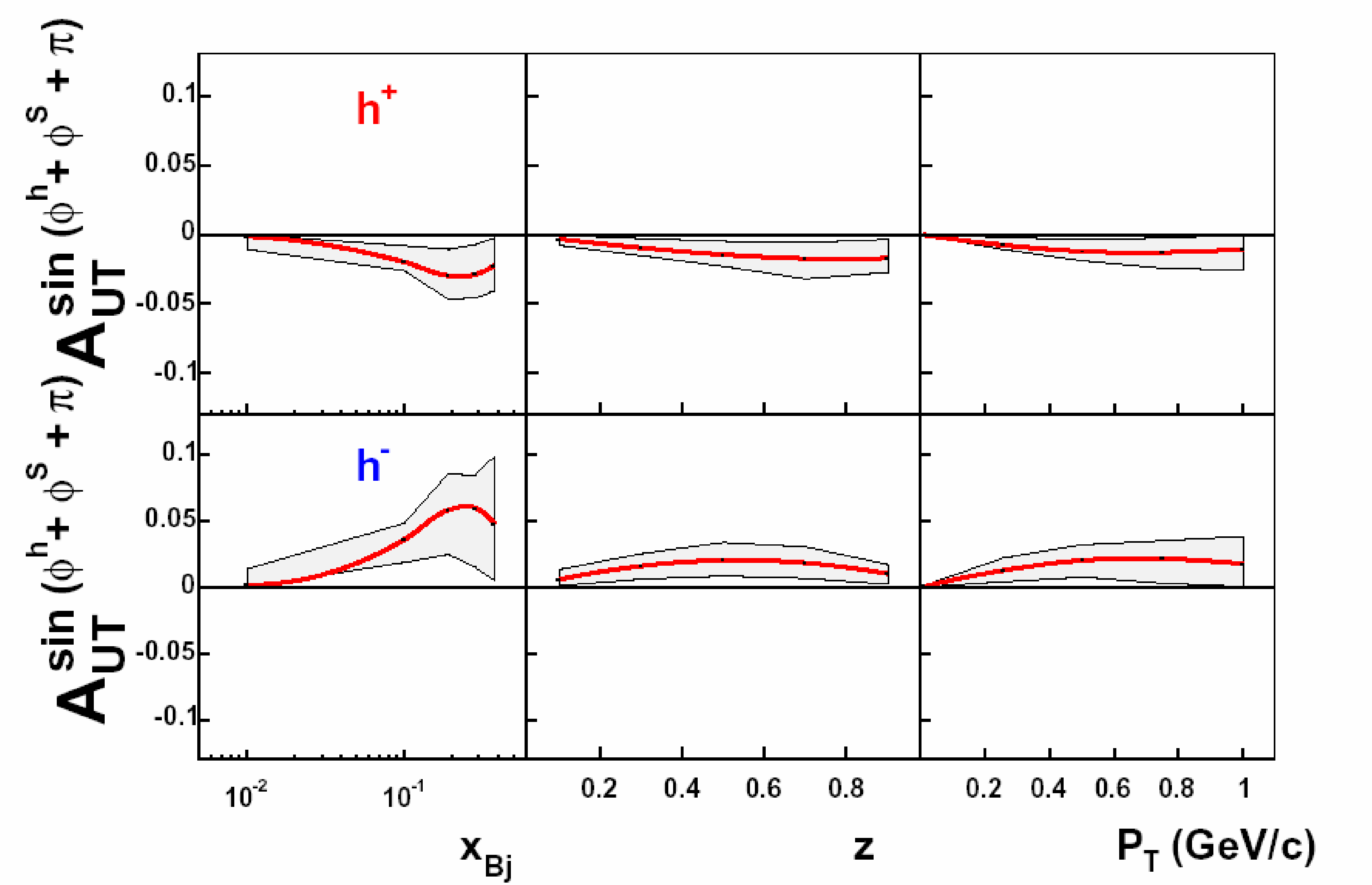
Efremov et al.

Vogelsang, Yuan

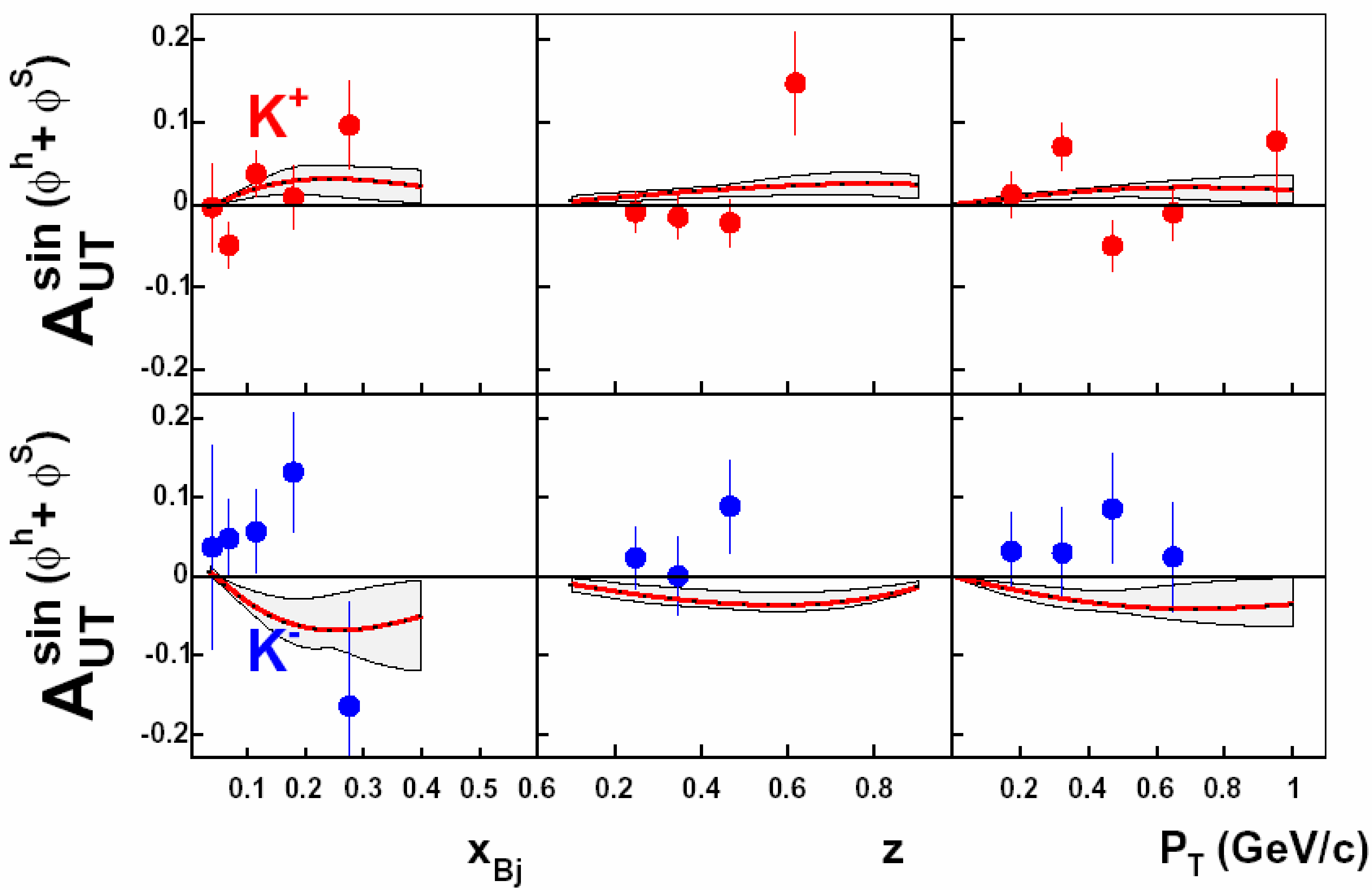
Extracted transversity distributions



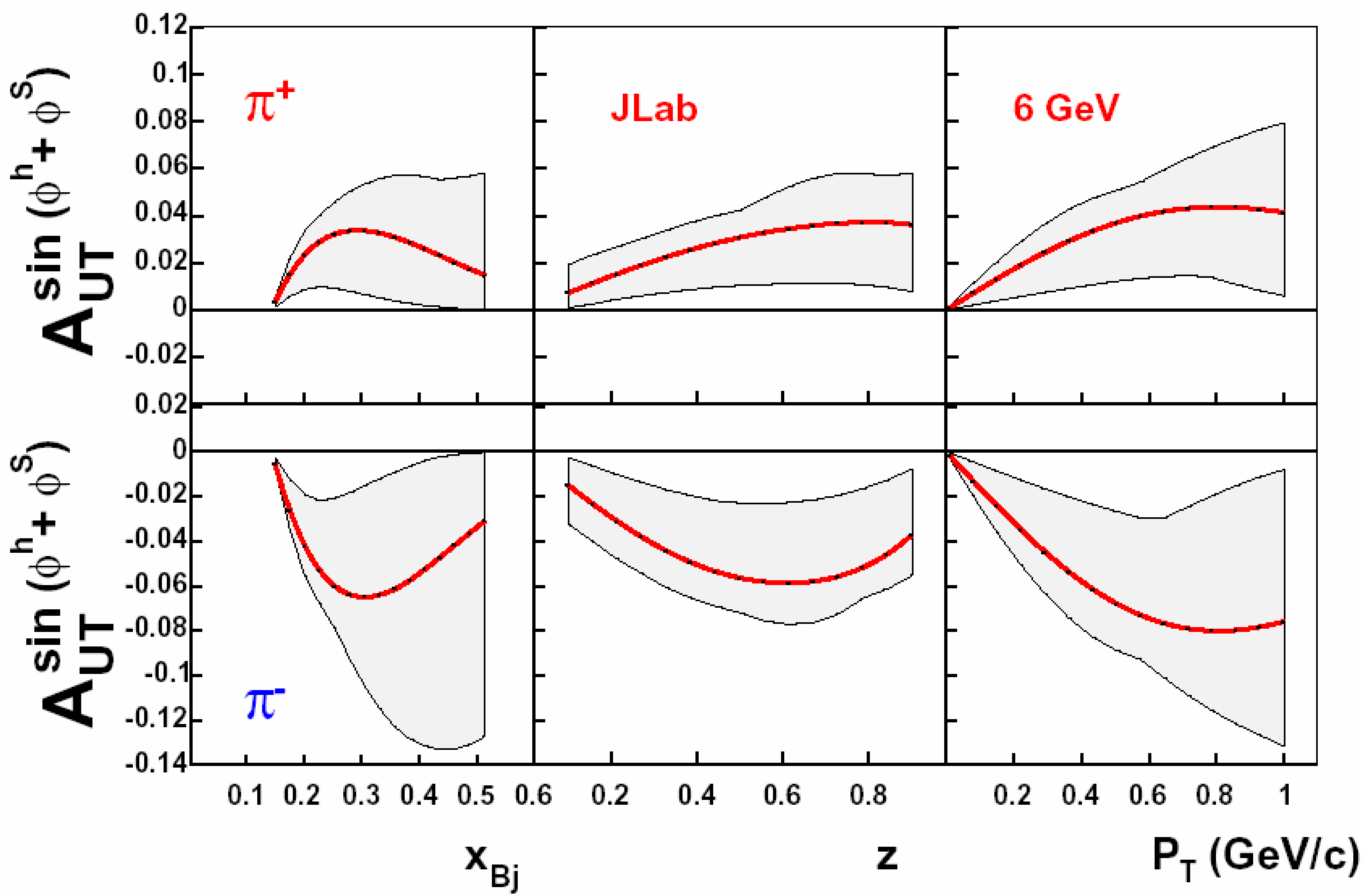
Predictions for Collins asymmetry at COMPASS, proton target



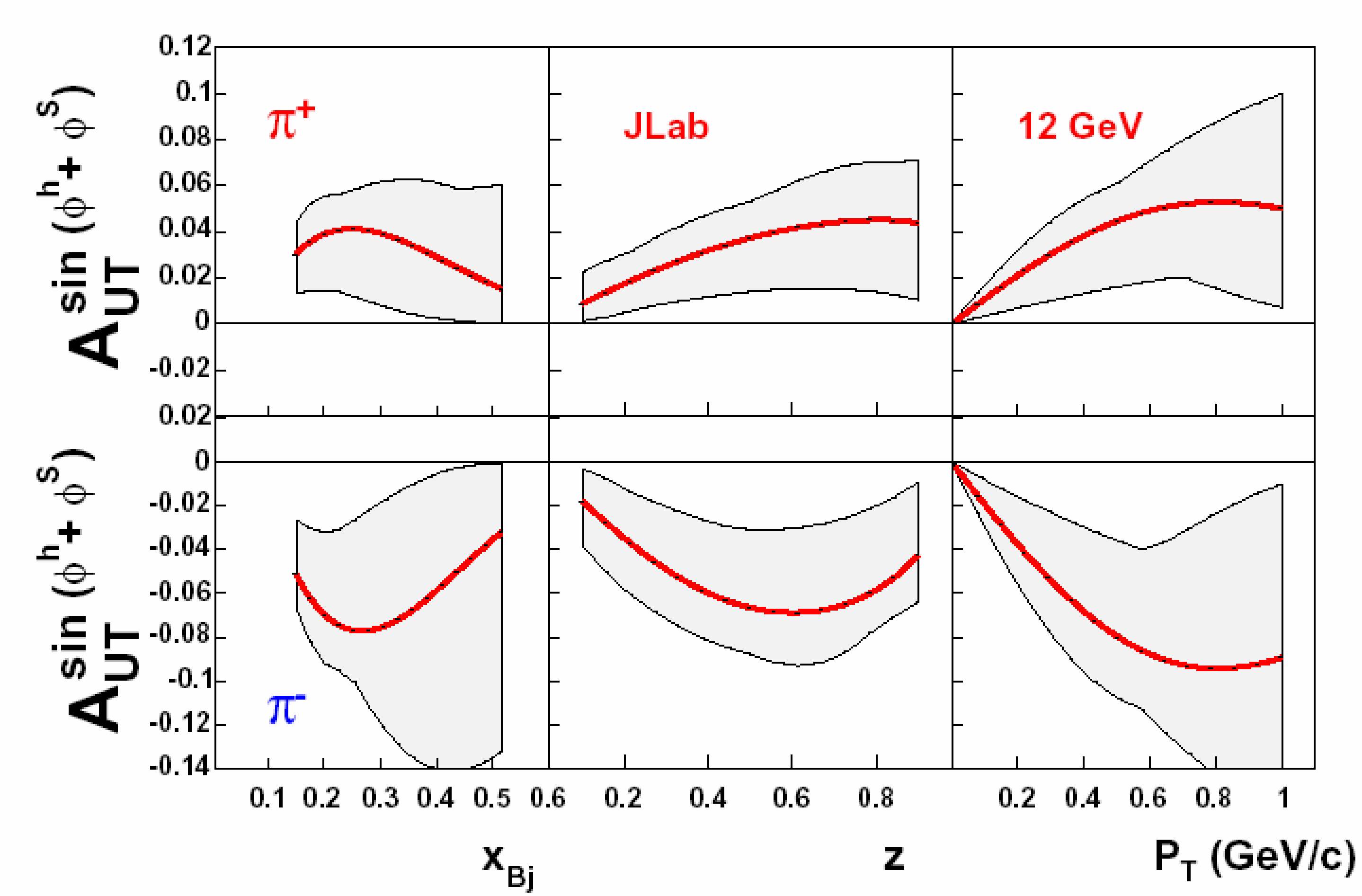
Collins asymmetry for kaons, HERMES



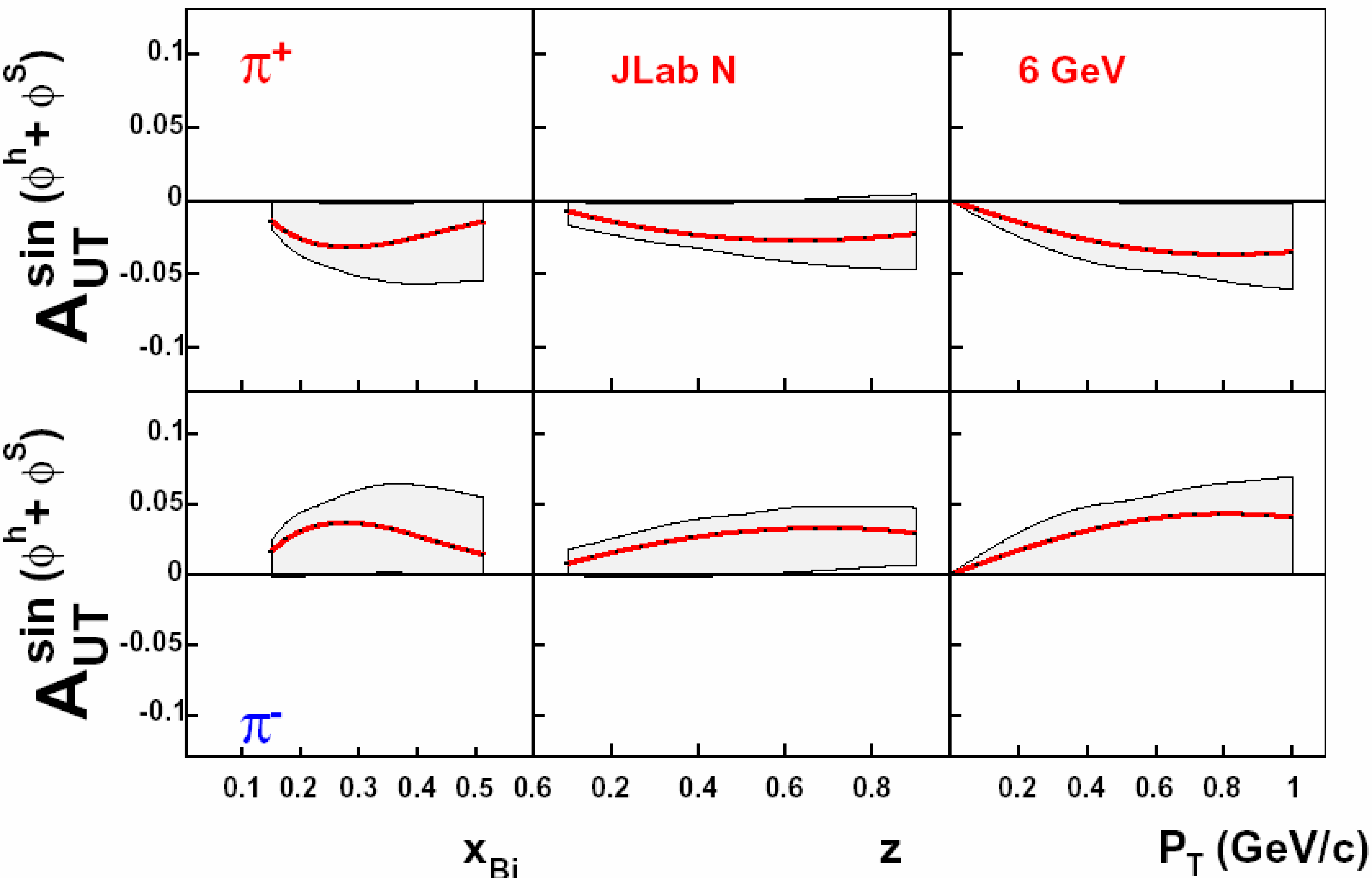
Predictions for Collins asymmetry at JLab, proton target, 6 GeV



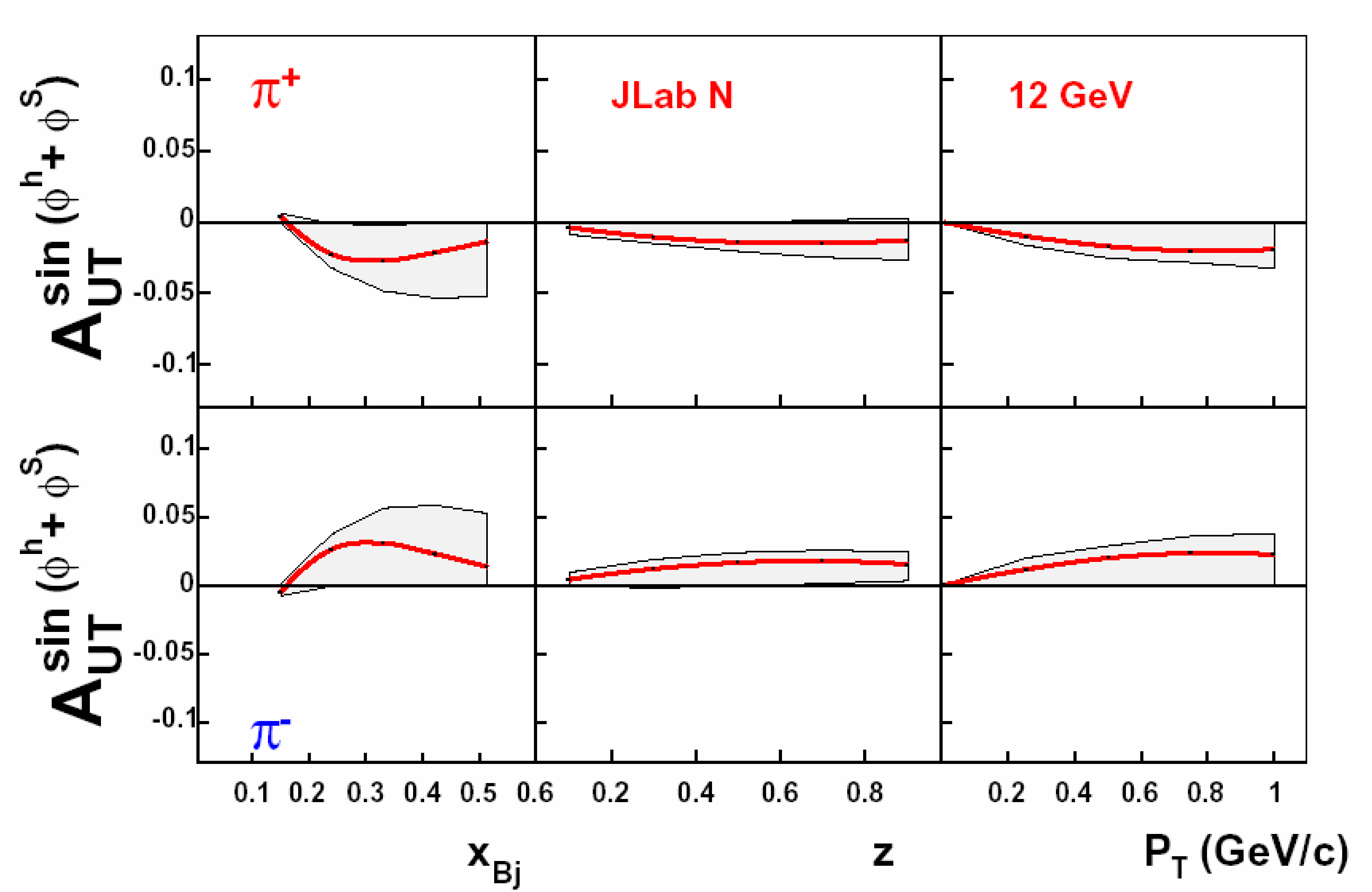
Predictions for Collins asymmetry at JLab, proton target, 12 GeV



Predictions for Collins asymmetry at JLab, neutron target, 6 GeV



Predictions for Collins asymmetry at JLab, neutron target, 12 GeV



Conclusions

Shaping up the nucleon spin and momentum transverse structure

Information on quark intrinsic motion

Spin-$k_\perp$ correlation from Sivers function

Extracting Collins functions

Accessing transversity

Plenty of new data expected from JLab