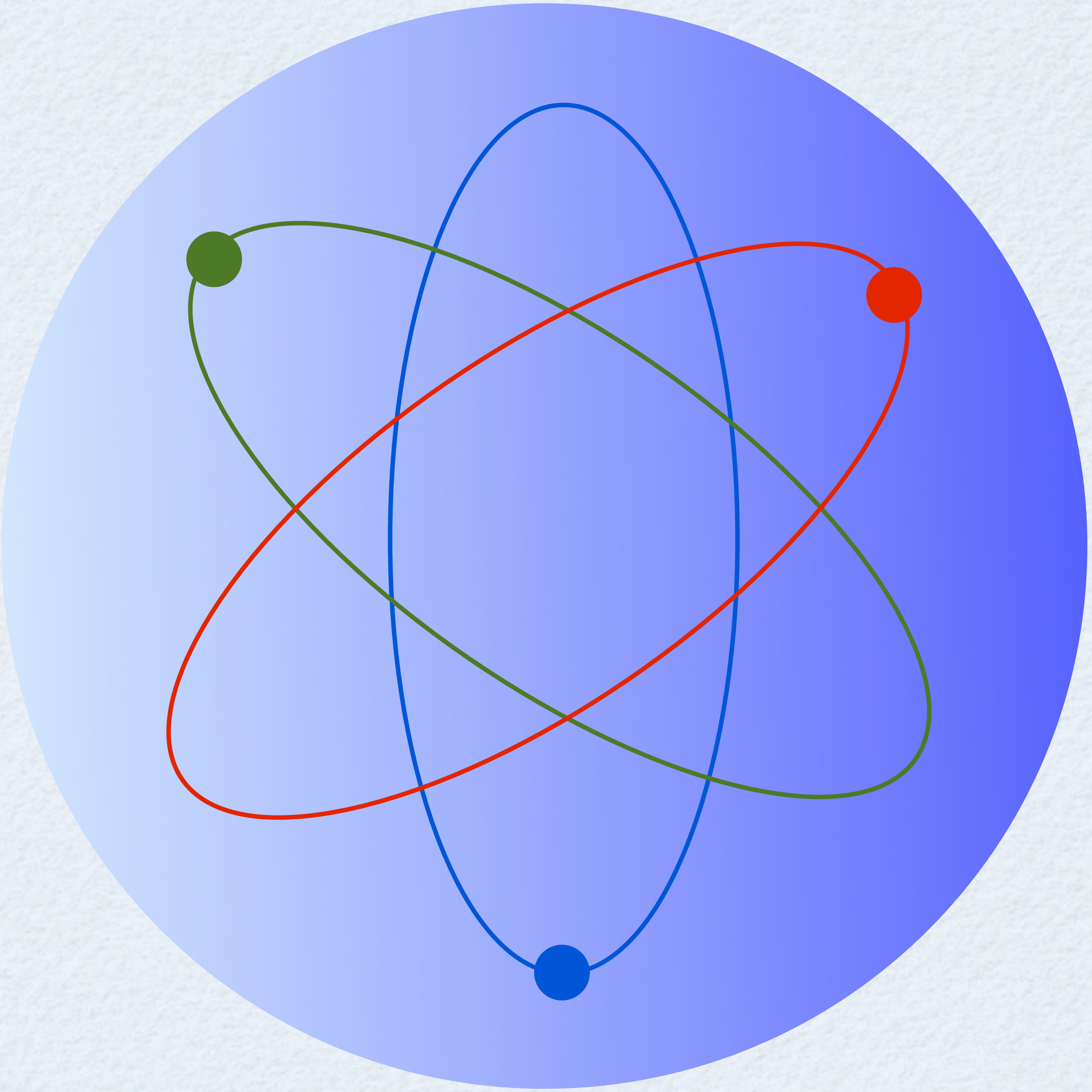
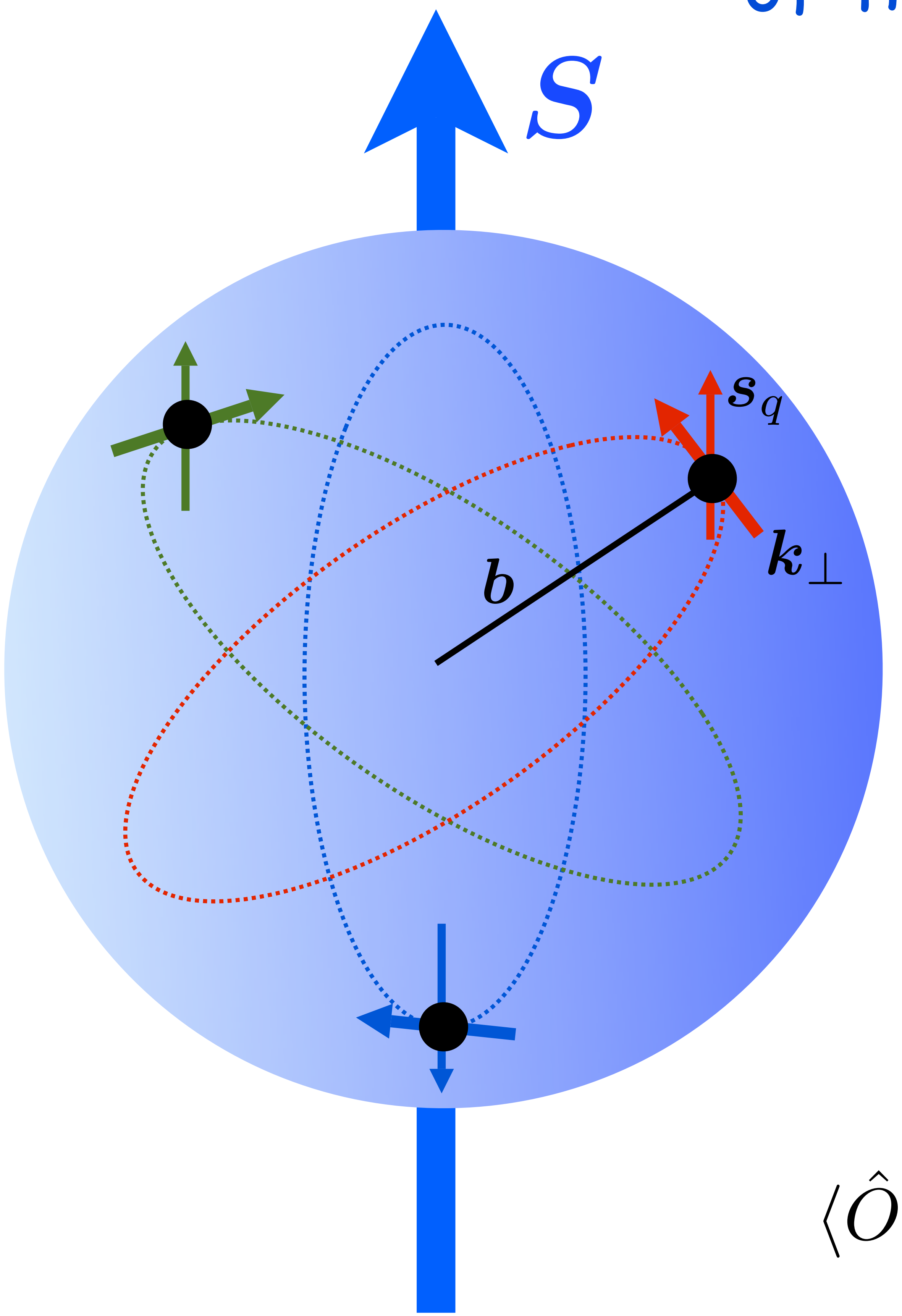
Towards the 3-dimensional nucleon structure
(TMDs and SIDIS)



Mauro Anselmino, Torino University & CPHT

Saclay, May 7, 2010

Exploring the 3-dimensional phase-space structure of the nucleon



intrinsic motion
spin-$k_\perp$ correlations?
orbiting quarks?

Ideally: obtain a quantum phase-space distribution (like the Wigner function)

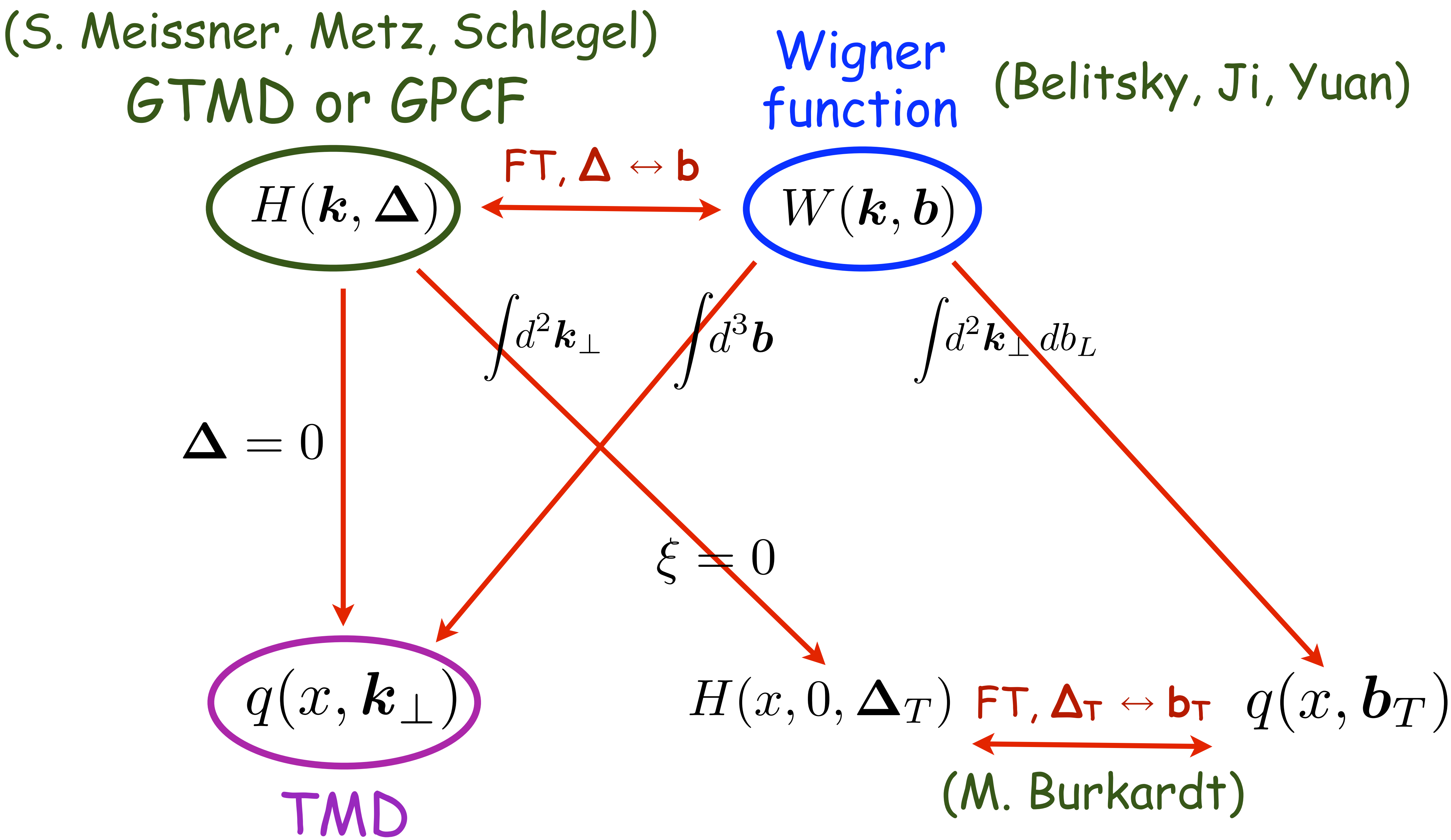
in 1-dimensional QM:

$$\int dp\, W(x,p) = |\psi(x)|^2$$

$$\int dx\, W(x,p) = |\phi(p)|^2$$

$$\langle \hat{O}(x,p) \rangle = \int dx\, dp\, W(x,p)\, O(x,p)$$

phase-space parton distribution, $W(\boldsymbol{k}, \boldsymbol{b})$

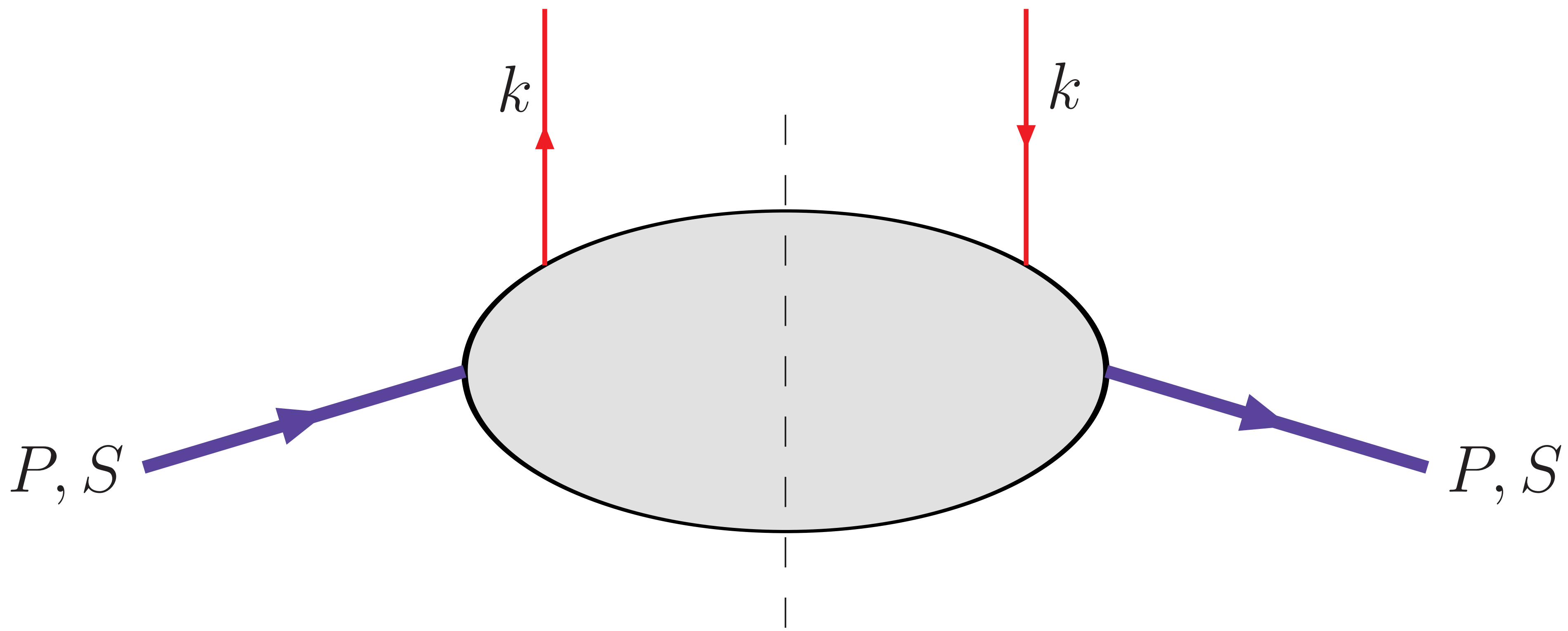


$$\int d^2\boldsymbol{k}_\perp \, H(\boldsymbol{k}, \boldsymbol{\Delta}) = H(x, \xi, \boldsymbol{\Delta}_T)$$

new probes and concepts to explore the nucleon structure

TMDs - Transverse Momentum Dependent (distribution and fragmentation functions)

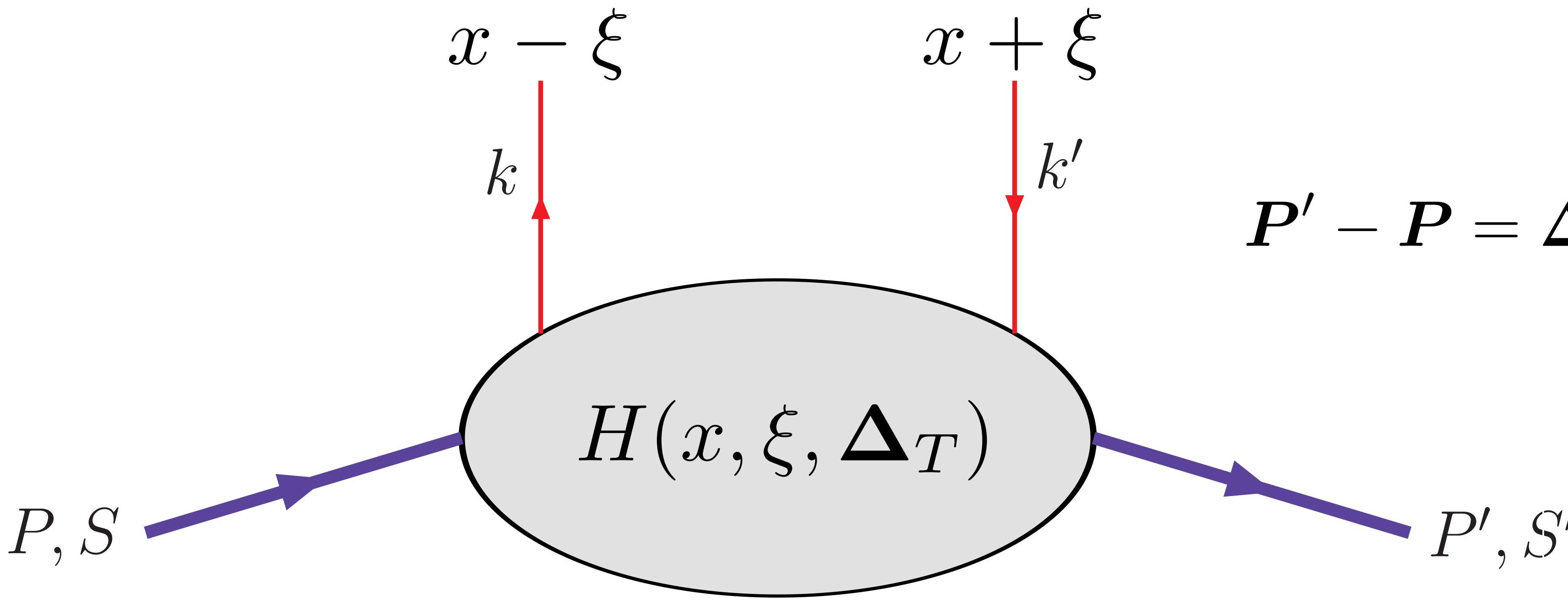
(polarized) SIDIS and Drell-Yan, spin asymmetries in inclusive (large p_T) NN processes



$$f_{a/p}(x, \boldsymbol{k}_\perp; \boldsymbol{s}_a, \boldsymbol{S})$$

GPDs - Generalized Partonic Distributions

exclusive processes in leptonic and hadronic interactions

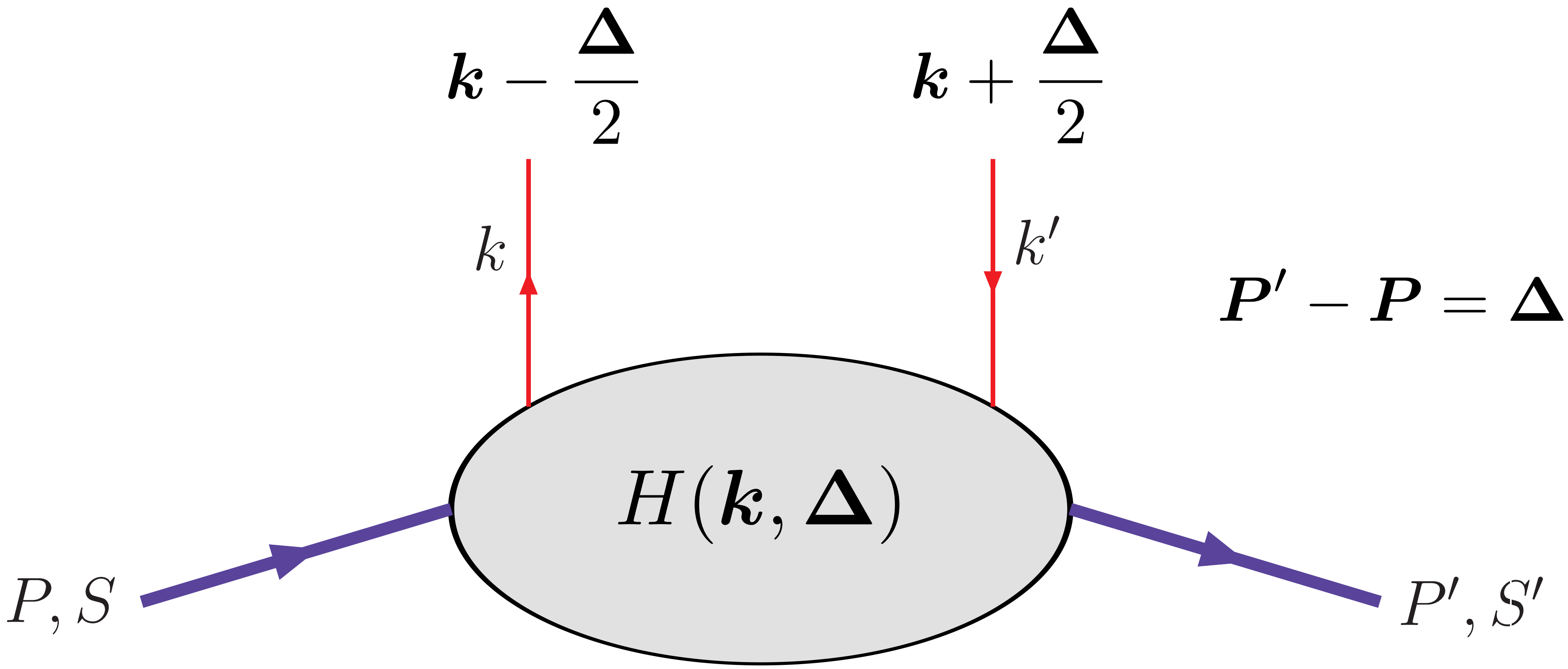


$$\boldsymbol{P}' - \boldsymbol{P} = \mathbf{\Delta}$$

$$q(x, \boldsymbol{b}_T) = \int \frac{d^2 \mathbf{\Delta}_T}{(2\pi)^2} \, H_q(x, 0, -\mathbf{\Delta}_T^2) e^{-i \, \boldsymbol{b}_T \cdot \mathbf{\Delta}_T}$$

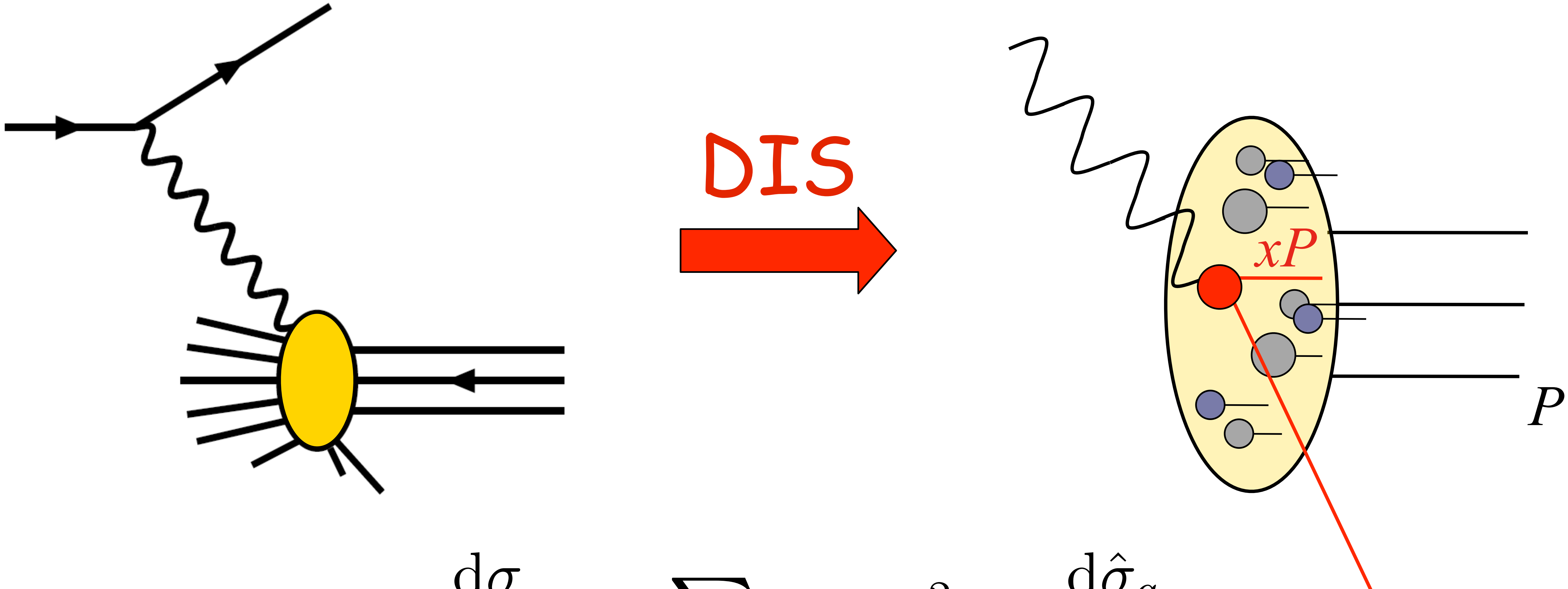
GTMDs - Generalized Transverse Momentum Dependent (partonic distributions)

exclusive processes in leptonic and hadronic interactions

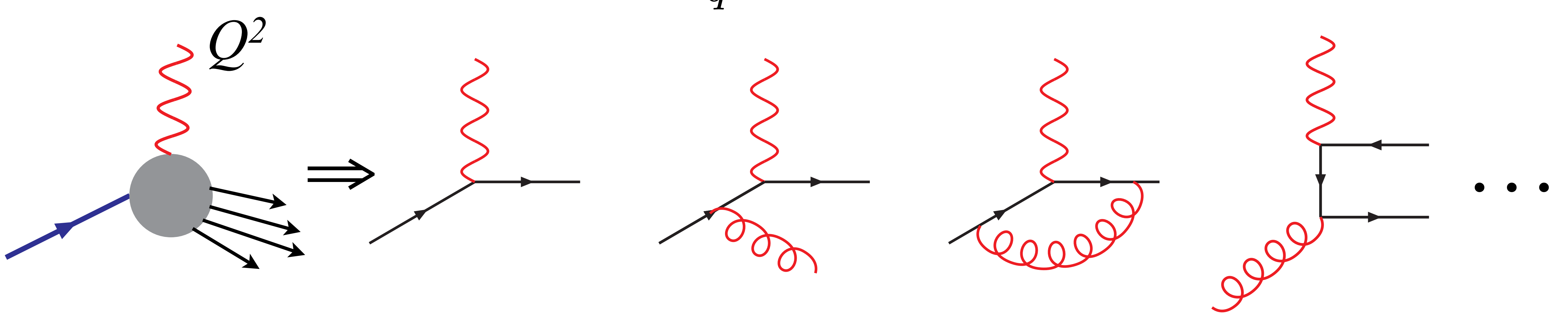


$$\int d^2\boldsymbol{k}_\perp\, H(\boldsymbol{k}, \boldsymbol{\Delta}) = H(x, \xi, \boldsymbol{\Delta}_T)$$

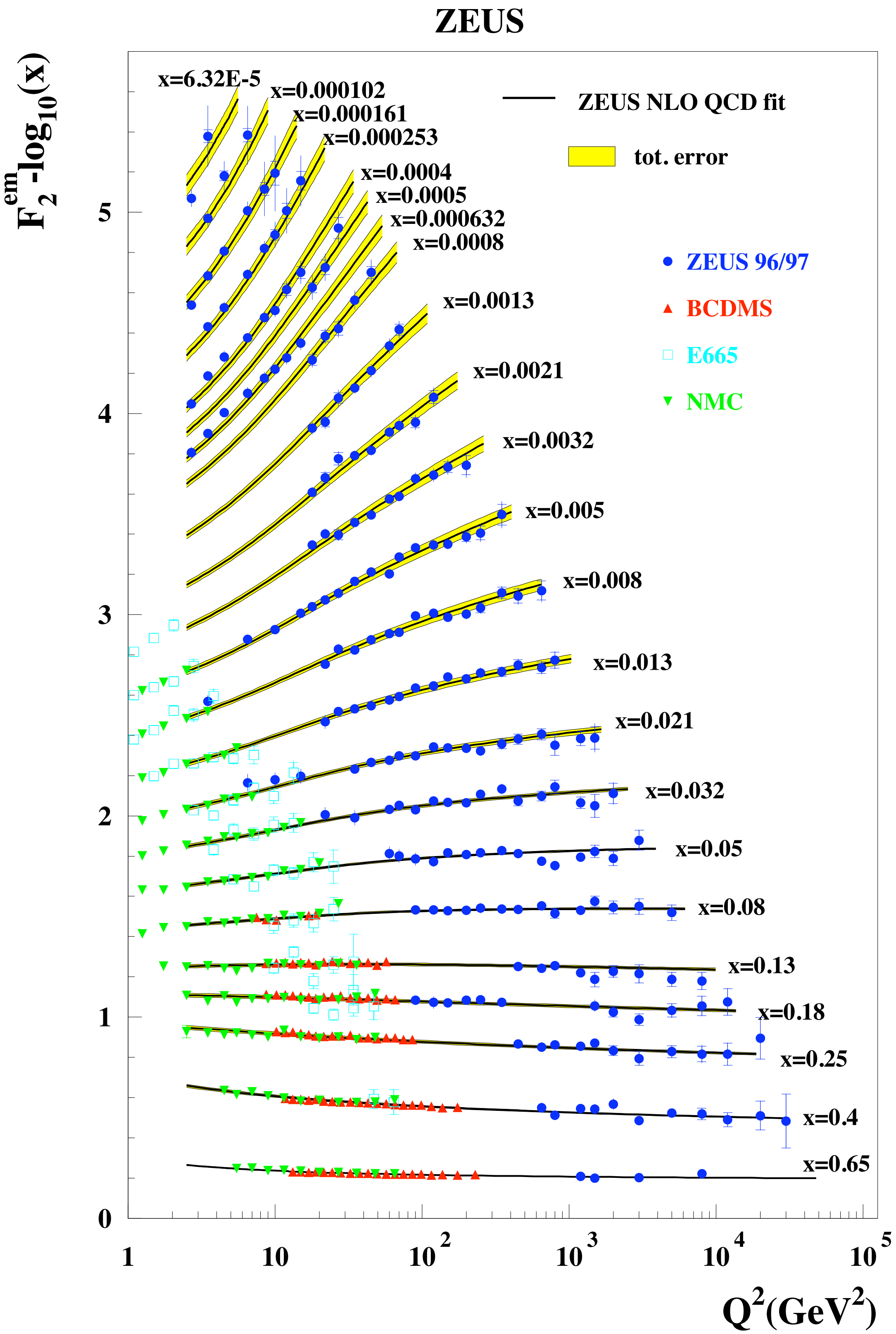
Usual way of exploring the nucleon structure: collinear QCD parton model

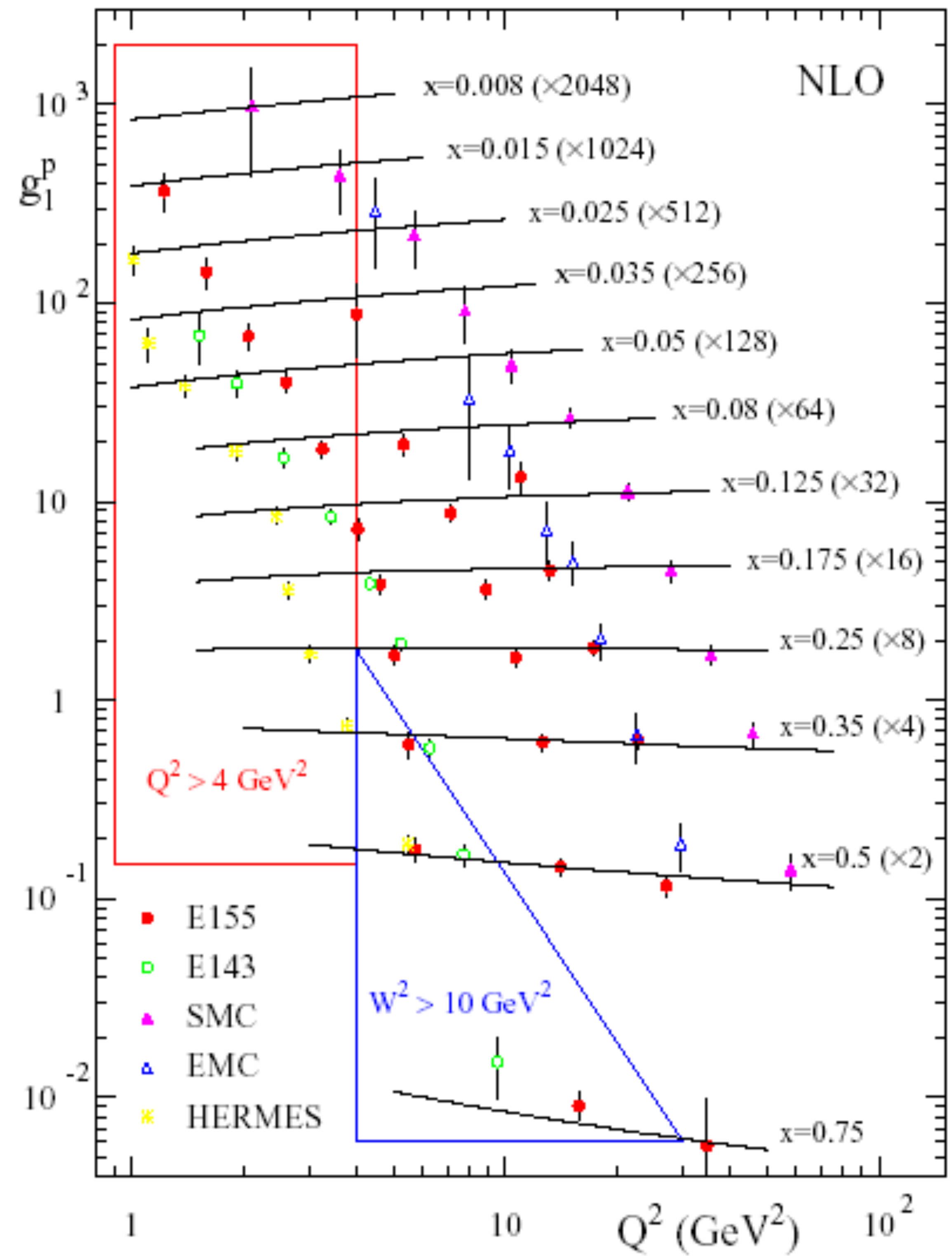


$$\frac{d\sigma}{dx\,dQ^2} = \sum_q q(x, Q^2) \otimes \frac{d\hat{\sigma}_q}{dQ^2}$$



great success, but essentially x and Q^2 degrees of freedom ….

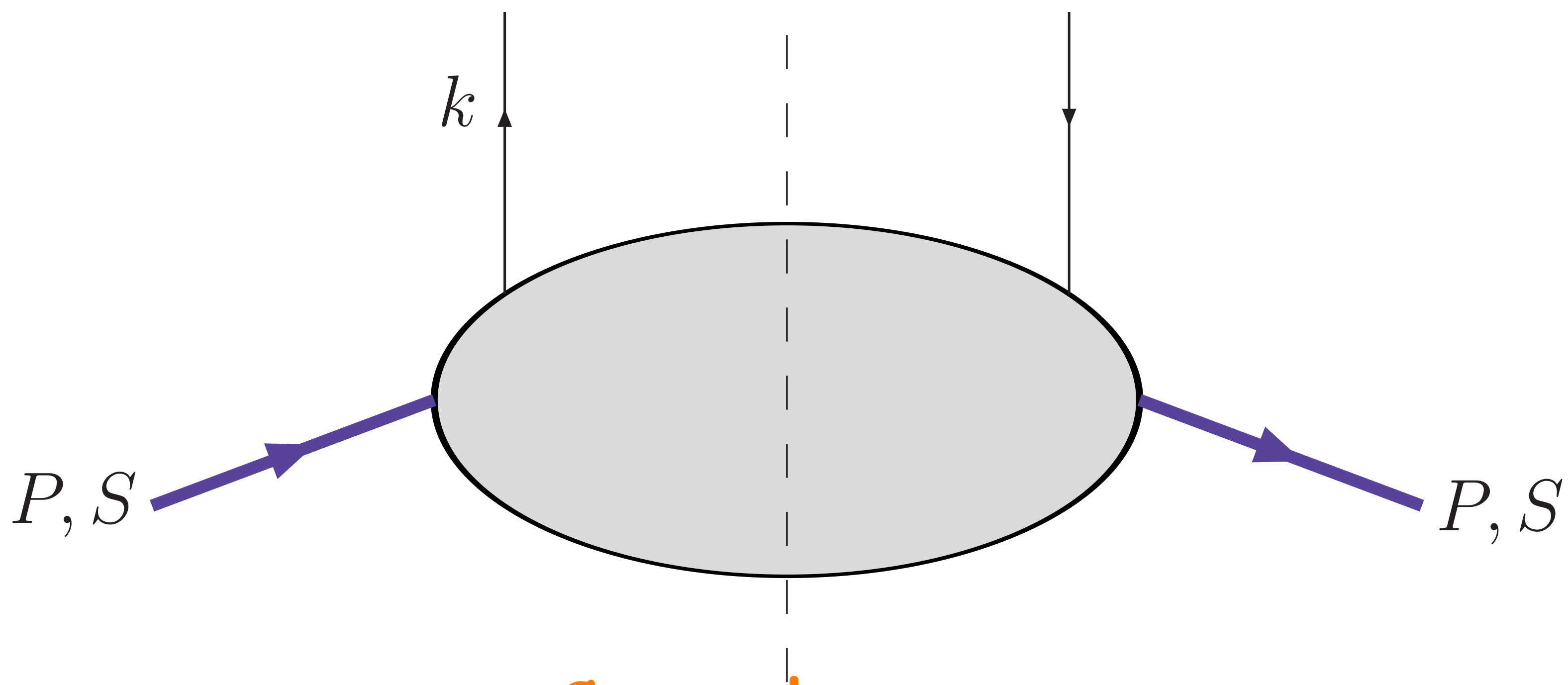




$$F_2 = \sum_q x\, q(x, Q^2)$$

$$g_1 = \frac{1}{2} \sum_q e_q^2\, \Delta q(x, Q^2)$$

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



Correlator:

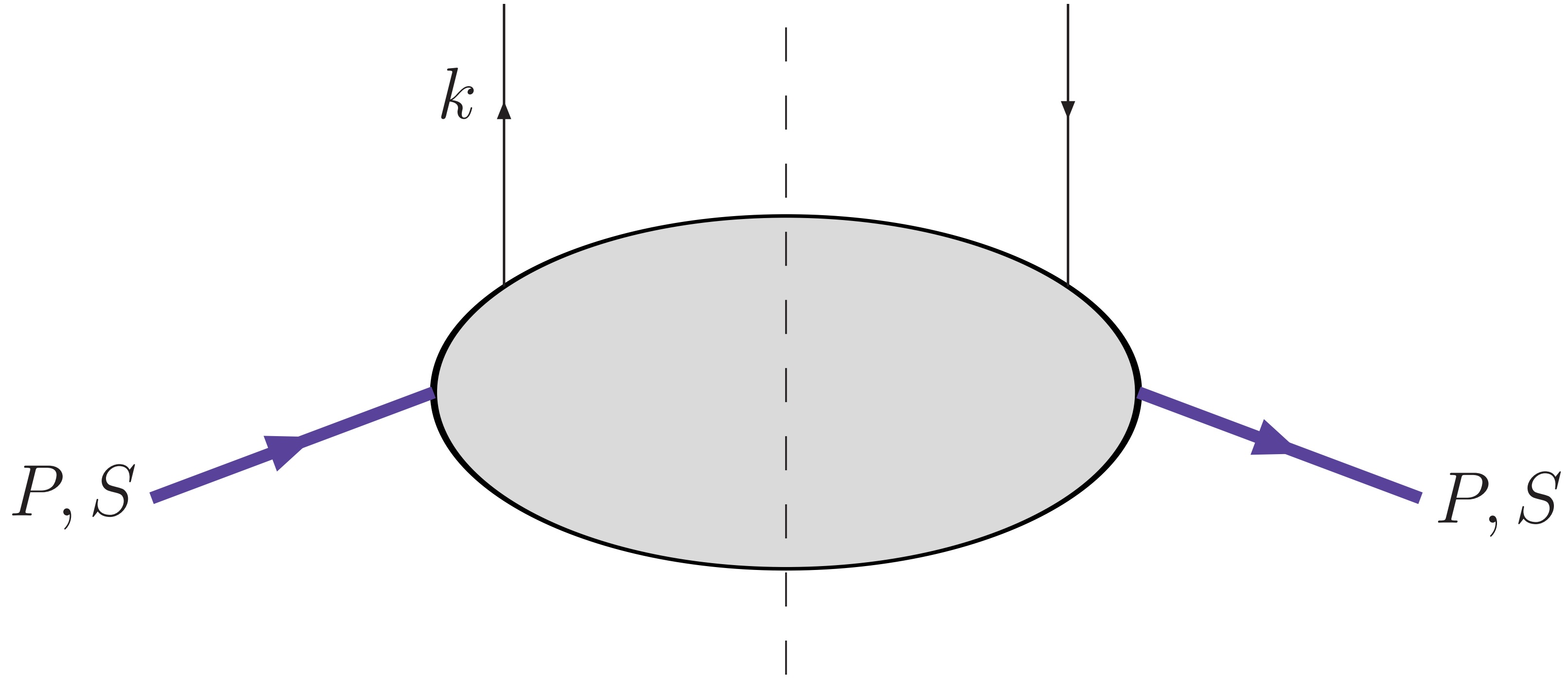
$$\Phi_{ij}(k;P,S) = \sum_X \int \frac{d^3 \boldsymbol{P}_X}{(2\pi)^3\, 2E_X} (2\pi)^4\, \delta^4(P-k-P_X) \langle PS|\overline{\Psi}_j(0)|X\rangle\langle X|\Psi_i(0)|PS\rangle$$

$$= \int d^4\xi\, e^{ik\cdot\xi} \langle PS|\overline{\Psi}_j(0)\Psi_i(\xi)|PS\rangle$$

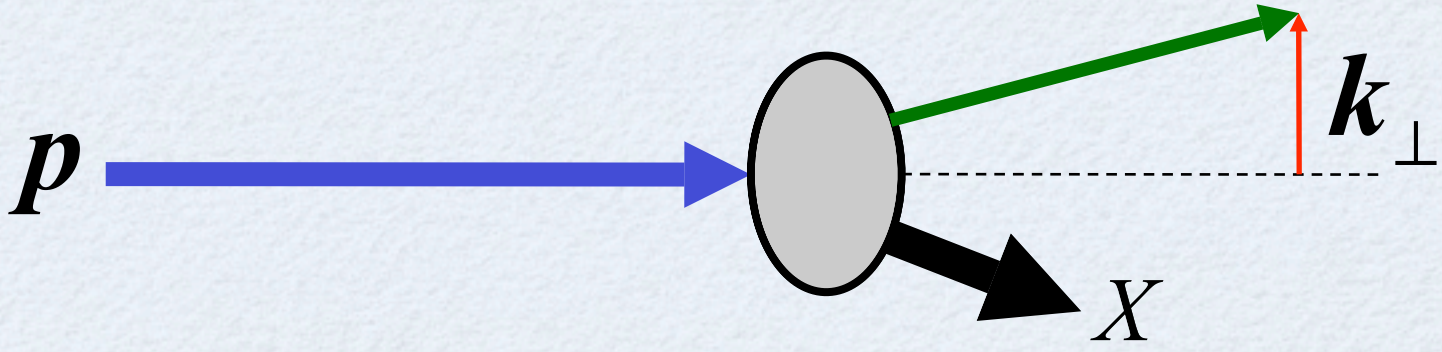
$$\Phi(x,S) = \frac{1}{2}\left[f_1(x)\, \not{n}_+ + S_L\, g_{1L}(x)\, \gamma^5\, \not{n}_+ + h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

$f_1(x)$: q $g_{1L}(x)$: Δq h_{1T}: Δ_Tq but the leading-twist correlator, with intrinsic $k_\perp$, contains several other functions .....

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

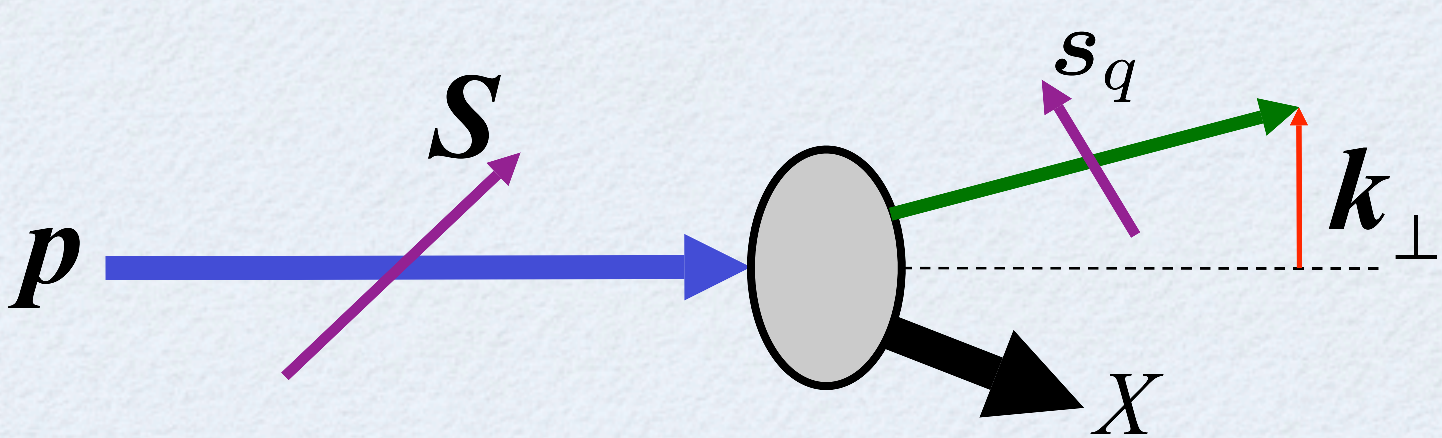


... with partonic interpretation



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

several spin-$\mathbf{k}_\perp$ correlations in TMDs



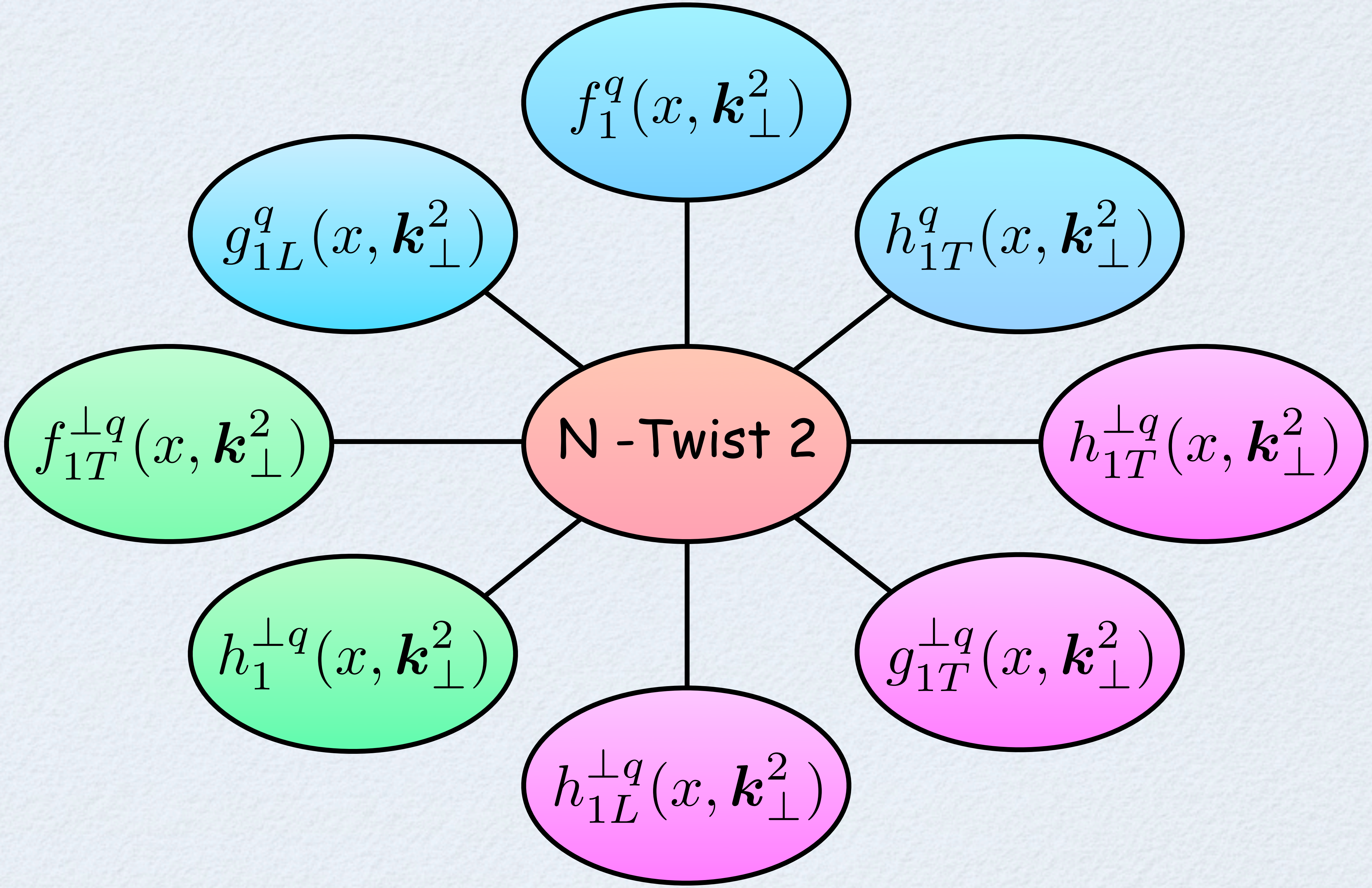
$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$ "Sivers effect"

$\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$ "Boer-Mulders effect"

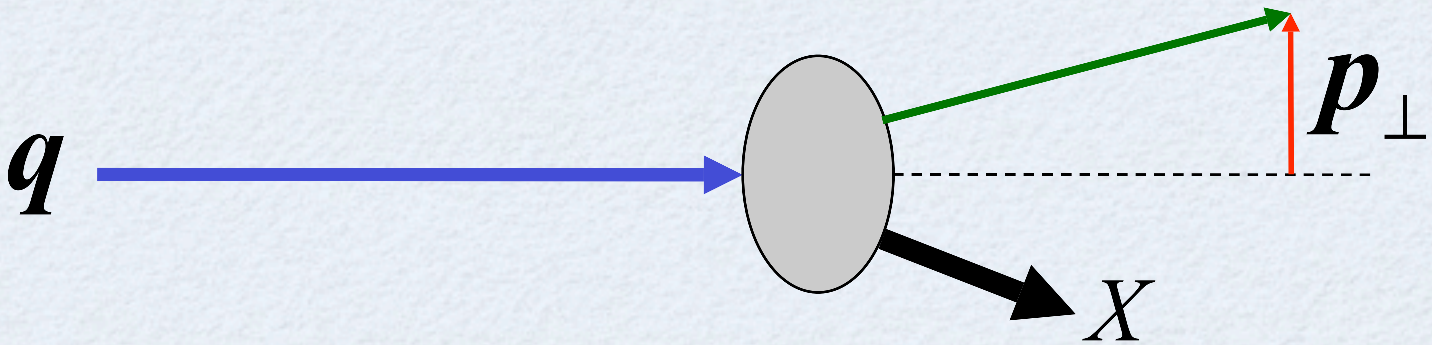
$\boldsymbol{S} \cdot \boldsymbol{s}_q$

$\cdots$

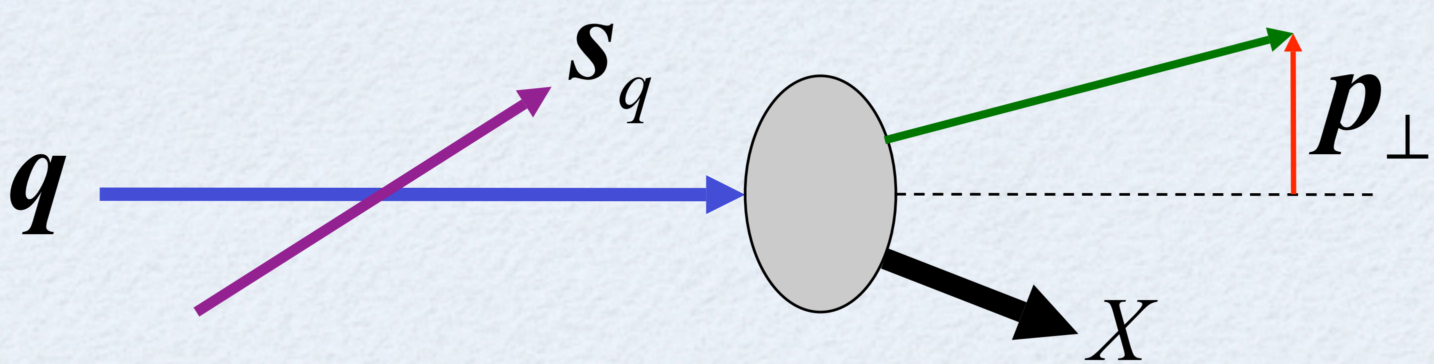
The nucleon at twist-2,



similar spin-$p_\perp$ correlations in fragmentation process (case of final spinless hadron)



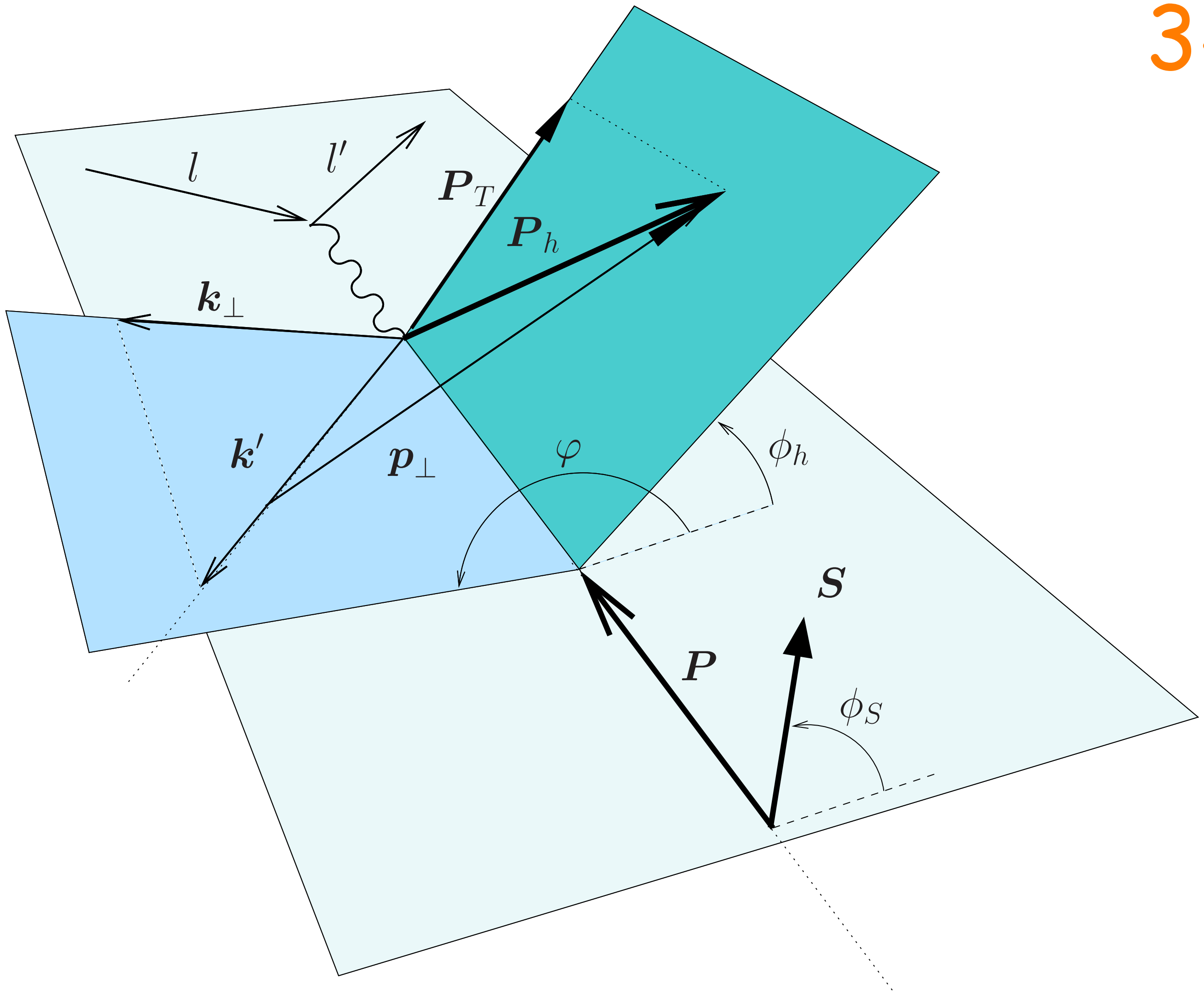
$$D_1^q(x, \boldsymbol{p}_\perp^2)$$



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

$$\boldsymbol{s}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_\perp)$$

"Collins effect"



3-dimensional probe of nucleons: SIDIS in parton model with intrinsic motion

$$\mathrm{d}^6\sigma \equiv \frac{\mathrm{d}^6\sigma^{\ell p^\uparrow \to \ell h X}}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}z_h\,\mathrm{d}^2\boldsymbol{P}_T\,\mathrm{d}\phi_S}$$

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

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

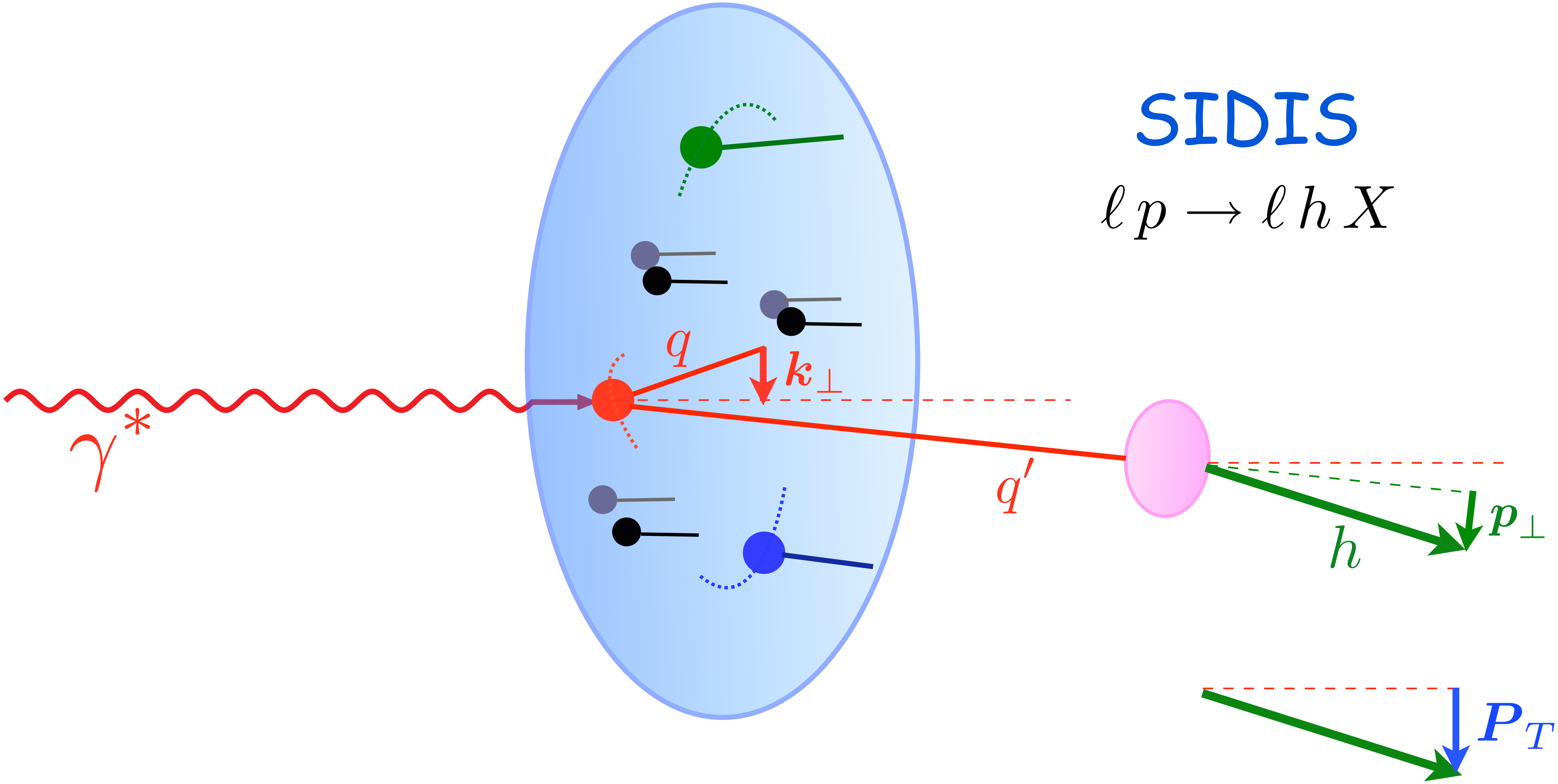
Two scales: $P_T \ll Q^2$

$$\mathrm{d}\sigma^{\ell p \to \ell h X} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes \mathrm{d}\hat{\sigma}^{\ell q \to \ell q}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

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

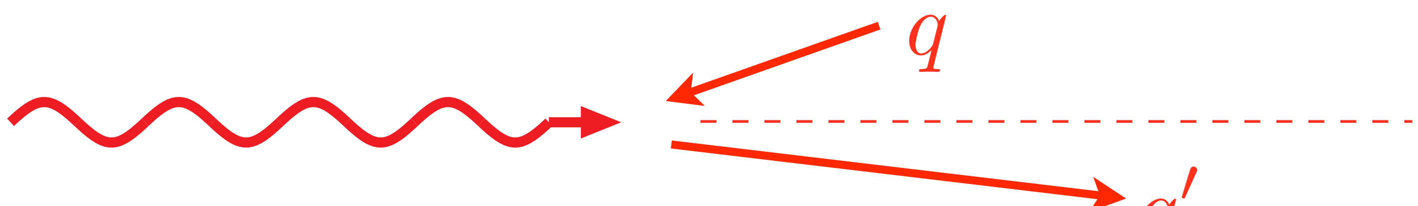
SIDIS

$$\ell\, p \to \ell\, h\, X$$

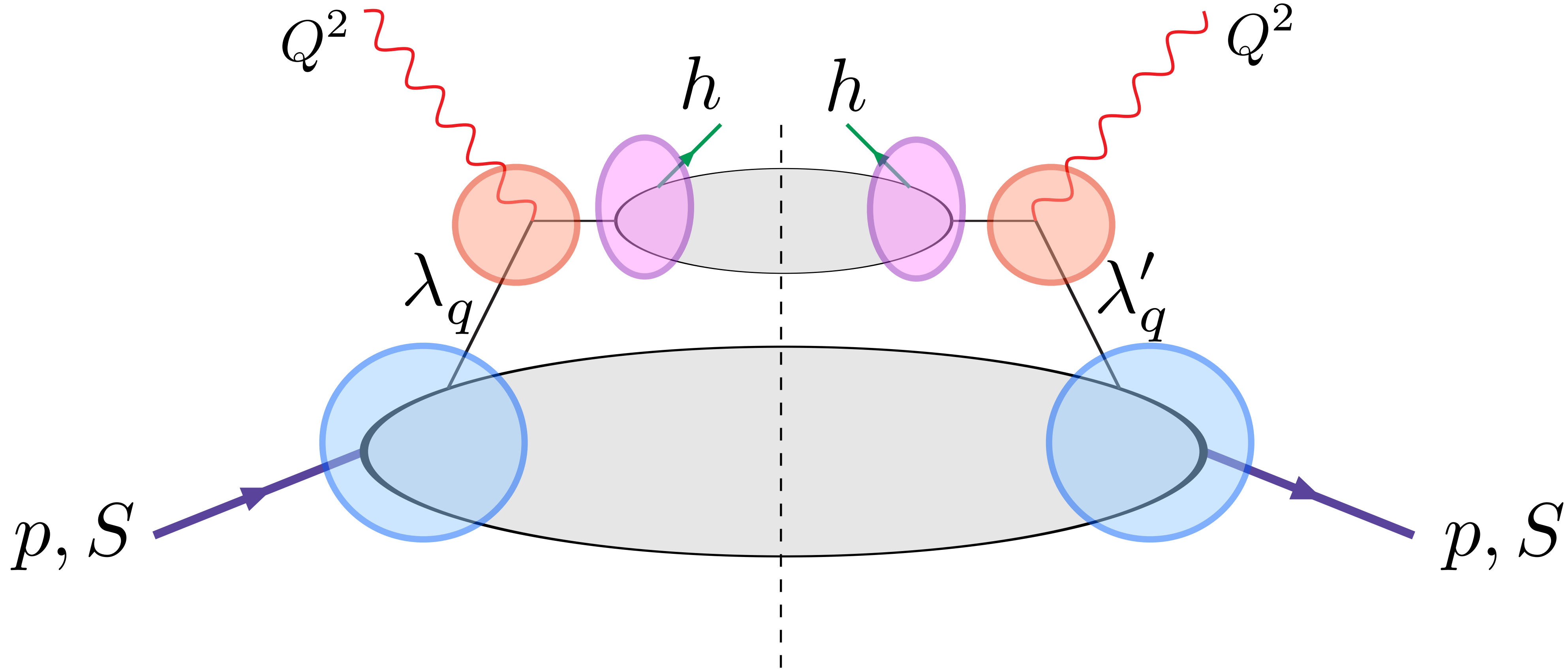


$$\Lambda_{\rm QCD} \simeq k_\perp \simeq P_T \ll Q \qquad\qquad \boldsymbol{P}_T \simeq \boldsymbol{p}_\perp + z_h\, \boldsymbol{k}_\perp$$

elementary interaction: $\gamma^*\, q \to q'$



SIDIS factorization



$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell'+h+X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T\, d\phi_S} = \rho^{\ell,S_\ell}_{\lambda_\ell,\lambda'_\ell} \otimes \rho^{q/p,S}_{\lambda_q,\lambda'_q}\, \hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp) \otimes \hat{M}_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q}\, \hat{M}^*_{\lambda'_\ell,\lambda'_q;\lambda'_\ell,\lambda'_q} \otimes \hat{D}^h_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)$$

TMD-PDF hard scattering TMD-FF

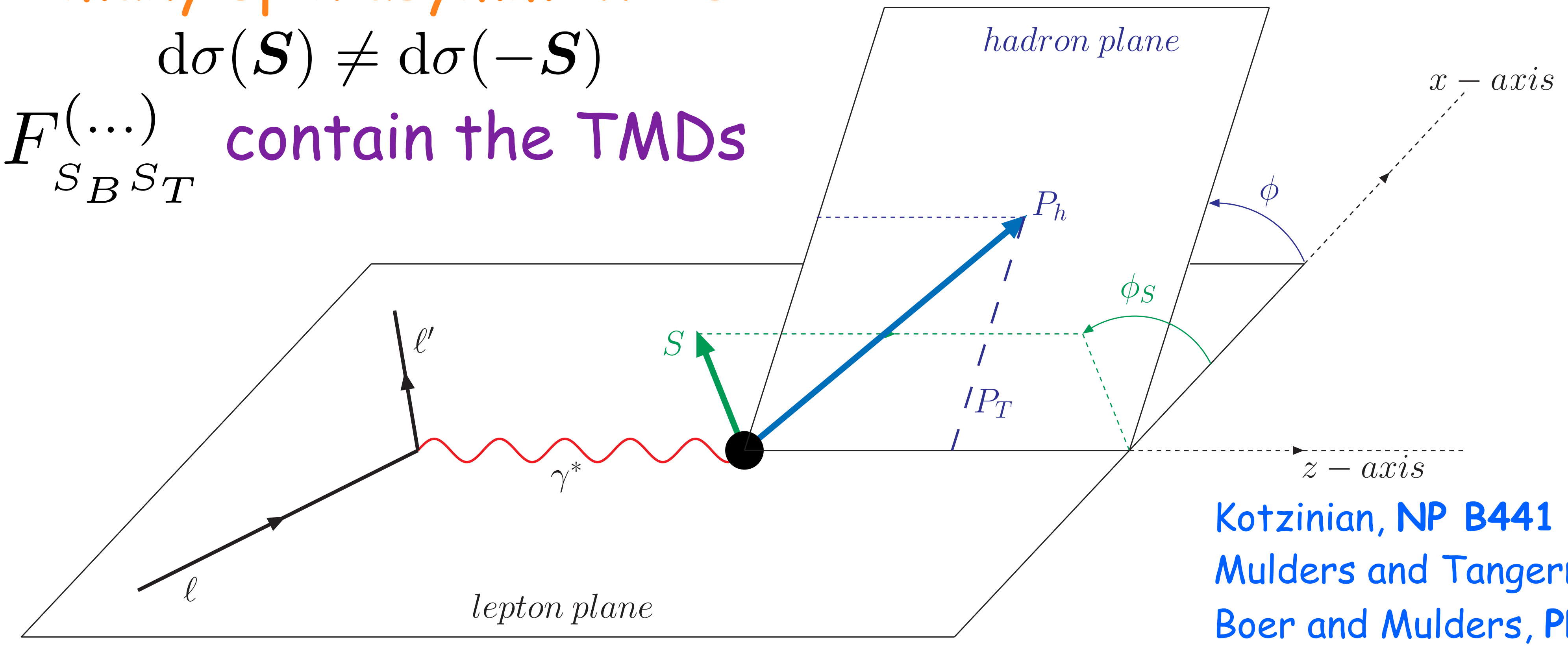
all pieces contain phases and keeping them into account one obtains the most general expression for the cross-section:

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

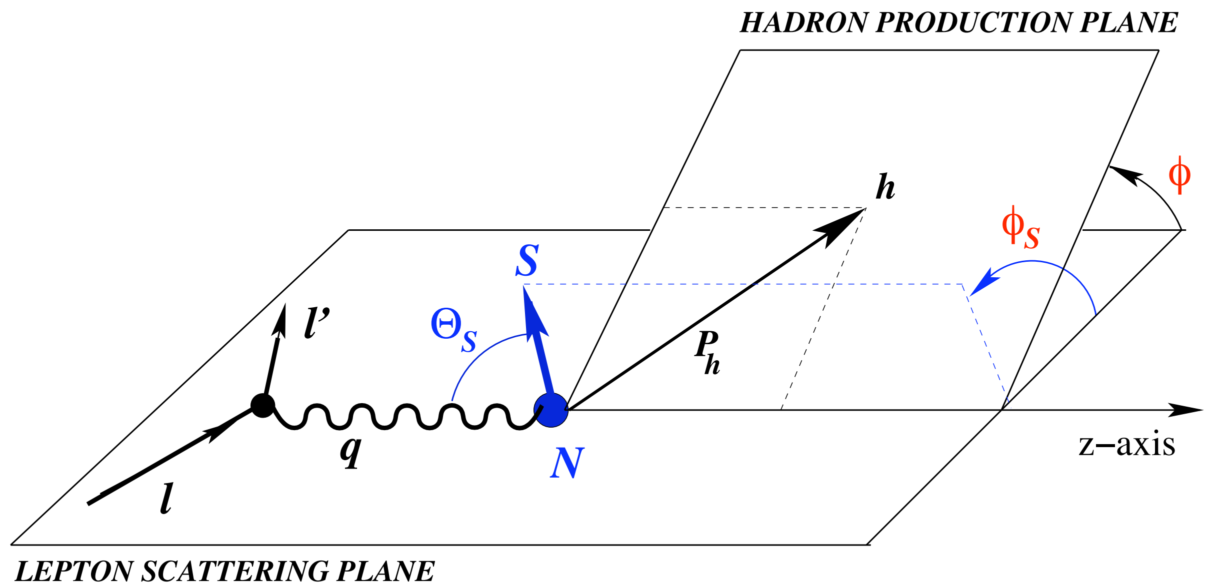
many spin asymmetries

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

$F_{S_B S_T}^{(\ldots)}$ contain 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
Anselmino et al., in preparation



$$F_{UU} \sim \sum_a e_a^2 f_1^a \otimes D_1^a \qquad F_{LT}^{\cos(\phi-\phi_S)} \sim \sum_a e_a^2 g_{1T}^{\perp a} \otimes D_1^a$$

$$F_{LL} \sim \sum_a e_a^2 g_{1L}^a \otimes D_1^a \qquad F_{UT}^{\sin(\phi-\phi_S)} \sim \sum_a e_a^2 f_{1T}^{\perp a} \otimes D_1^a$$

chiral-even TMDs

$$F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 h_1^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(\phi+\phi_S)} \sim \sum_a e_a^2 h_{1T}^a \otimes H_1^{\perp a}$$

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

chiral-odd TMDs

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

Cahn kinematical effects

integrated $f_1^q(x)$ and $g_{1L}^q(x)$ can be measured in usual DIS

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

$$\frac{1}{Q}\cos\phi\, F_{UU}^{\cos\phi} \sim \underbrace{f_1^q \otimes D_1^q \otimes \mathrm{d}\hat{\sigma}} + \Big(\underbrace{h_1^{q\perp} \otimes H_1^{q\perp} \otimes \mathrm{d}\Delta\hat{\sigma}}\Big)$$

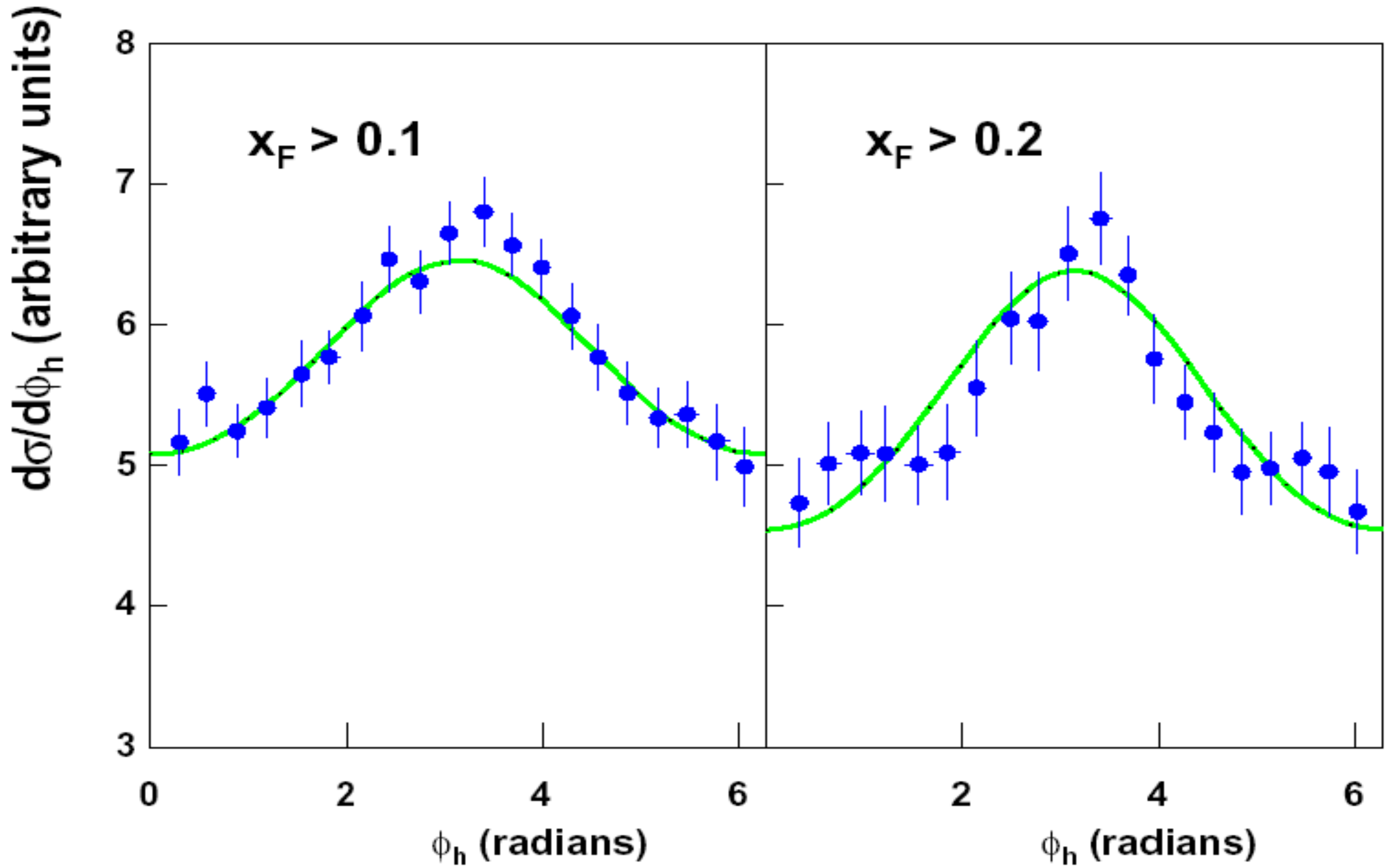
$$x = x_{_B} \qquad z = z_h \qquad \boldsymbol{P}_T = z\,\boldsymbol{k}_\perp + \boldsymbol{p}_\perp$$

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

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



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

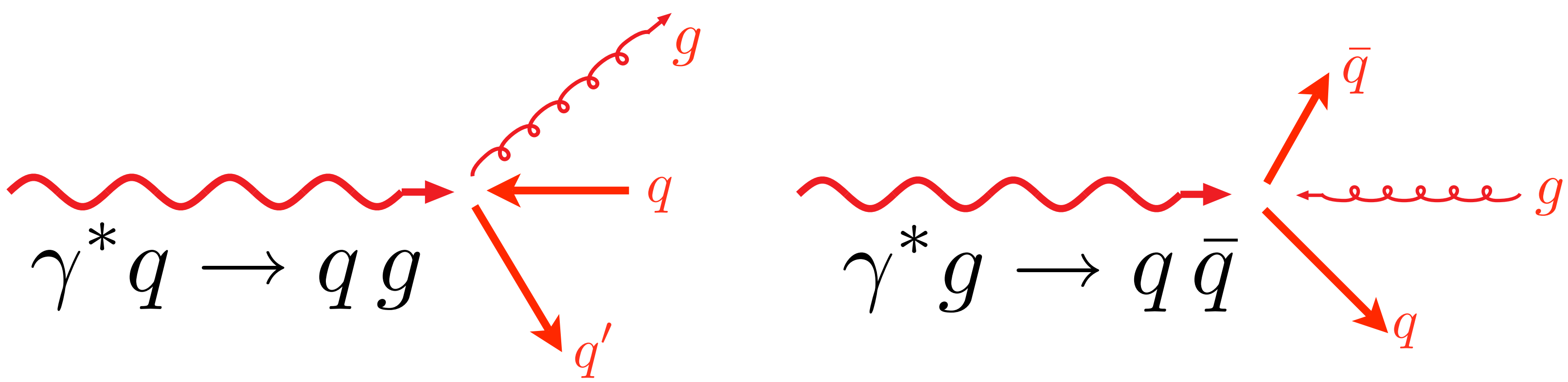
assuming gaussian $k_\perp$ and $p_\perp$ dependences:

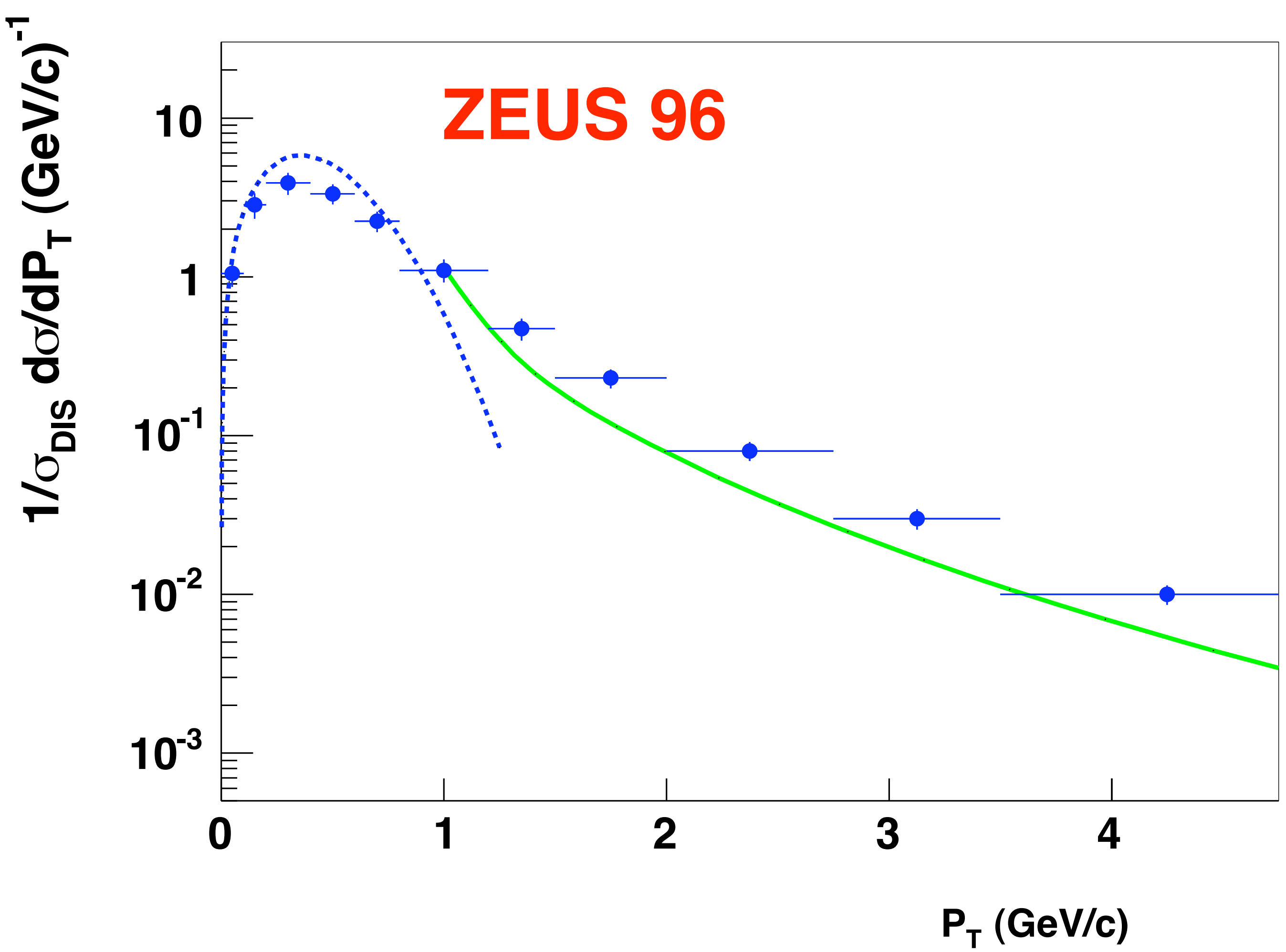
$$\langle k_\perp^2 \rangle = 0.28 \ (\mathrm{GeV})^2 \qquad \langle p_\perp^2 \rangle = 0.25 \ (\mathrm{GeV})^2$$

(no B-M ⊗ Collins contribution)

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

Large P_T data explained by NLO QCD corrections



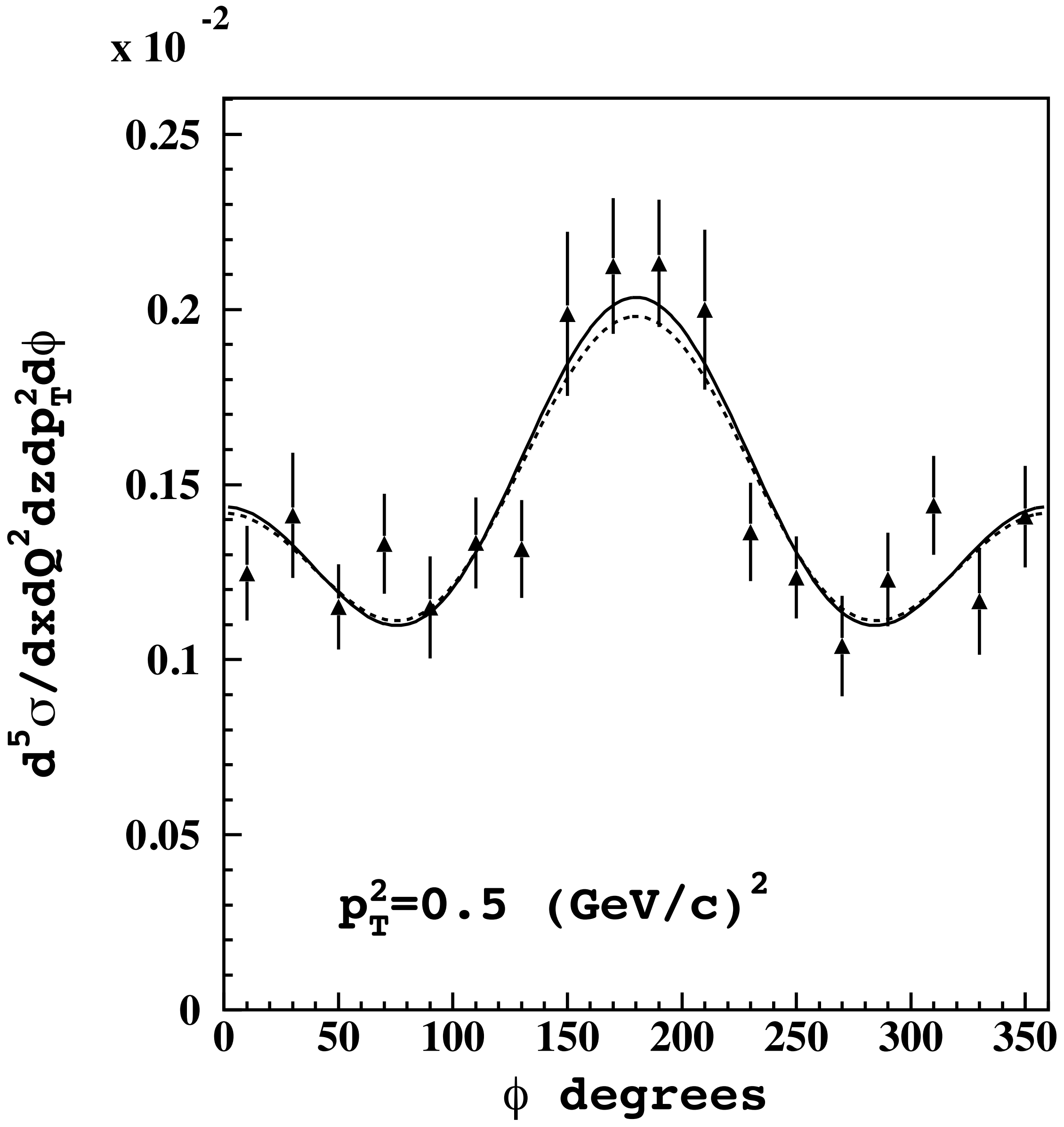


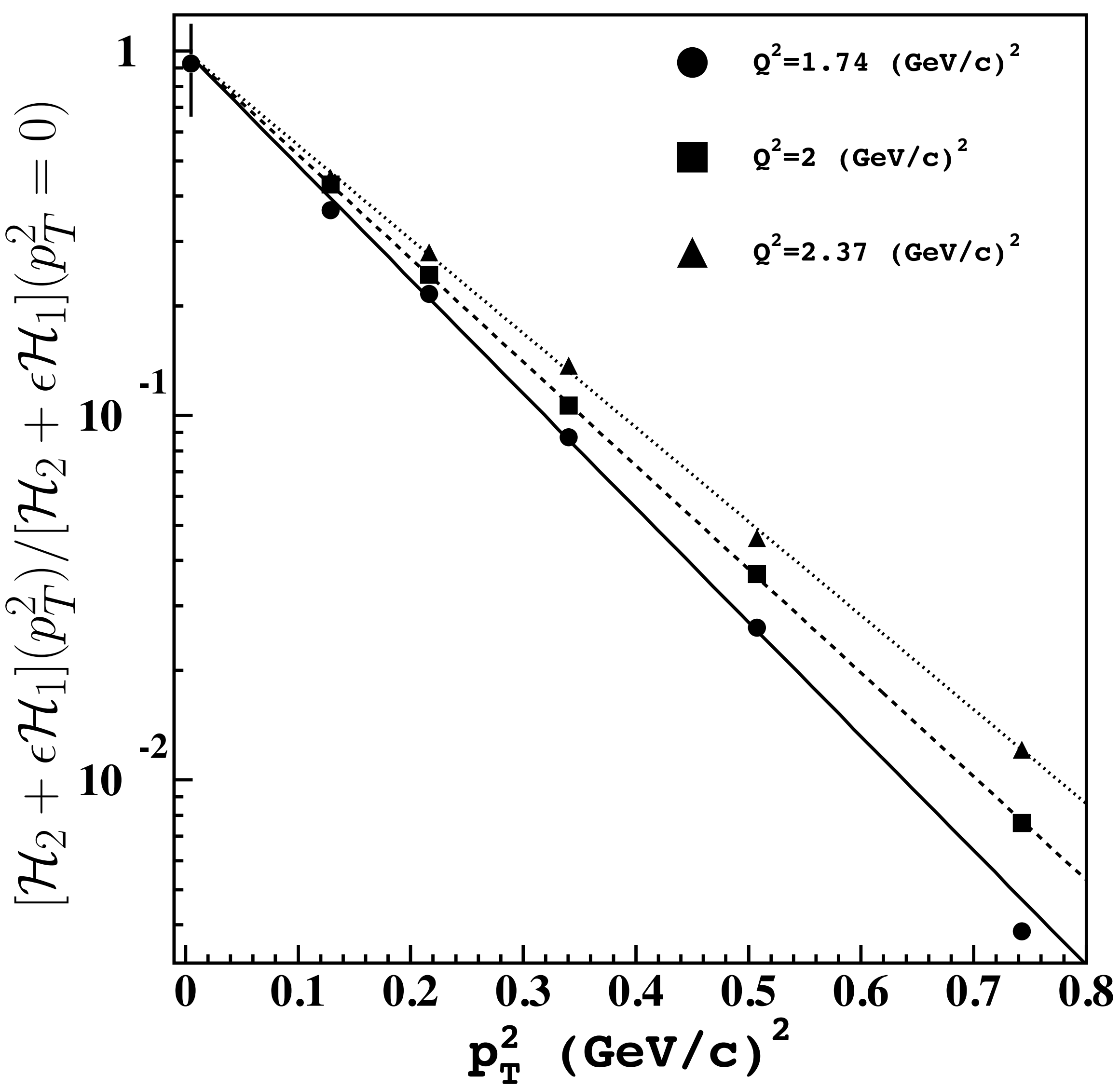
transition between TMDs and pQCD at $P_T \simeq 1\,\mathrm{GeV}/c$

CLAS data

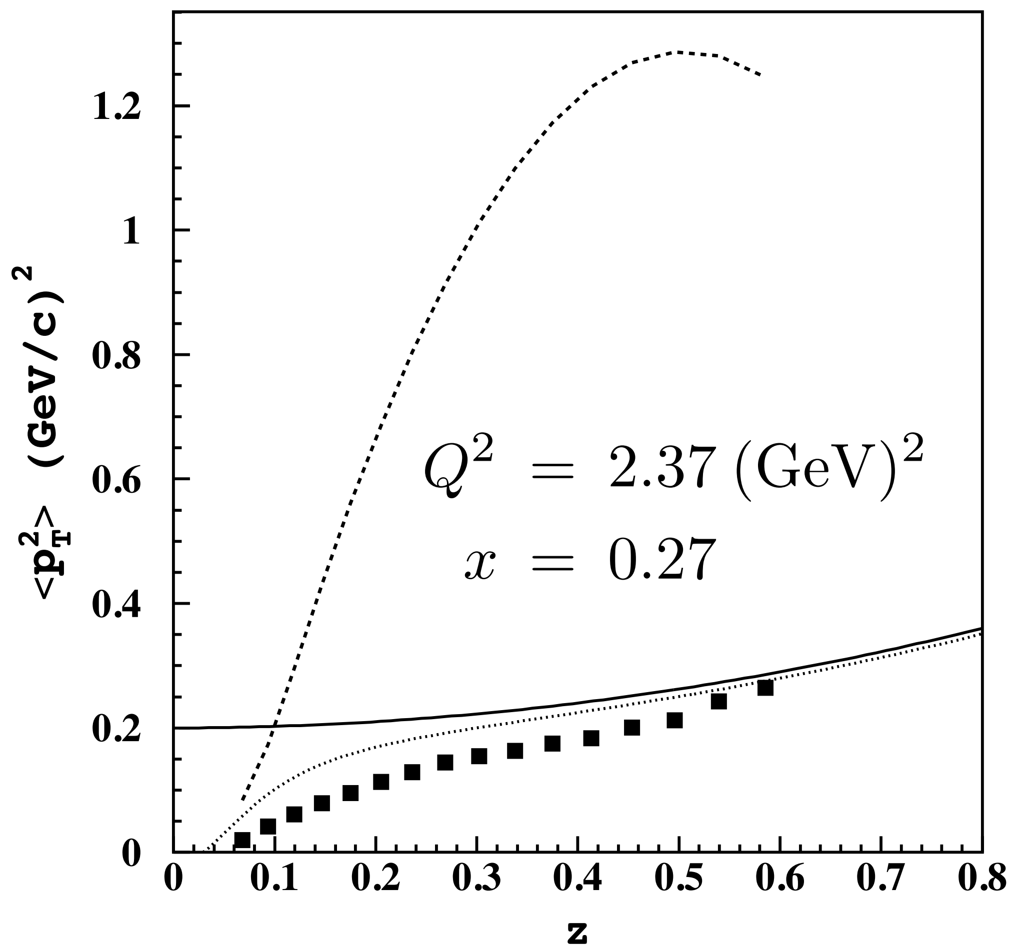
arXiv:. 0809.1153v5, PRD 80,032004 (2009)

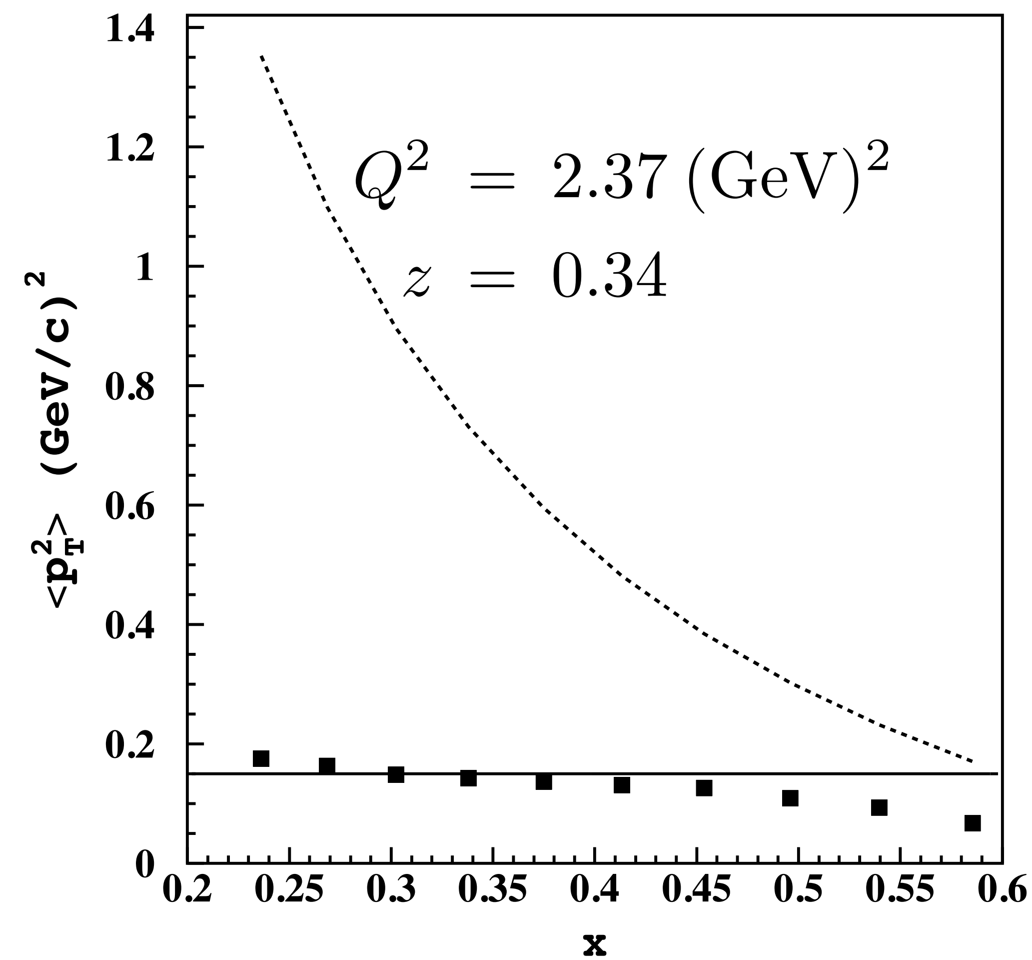
$$\frac{d^5\sigma}{dx\,dQ^2\,dz\,dP_T^2\,d\phi} = C\left[\epsilon\mathcal{H}_1 + \mathcal{H}_2 + A\cos\phi + B\cos(2\phi)\right]$$





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





solid line =

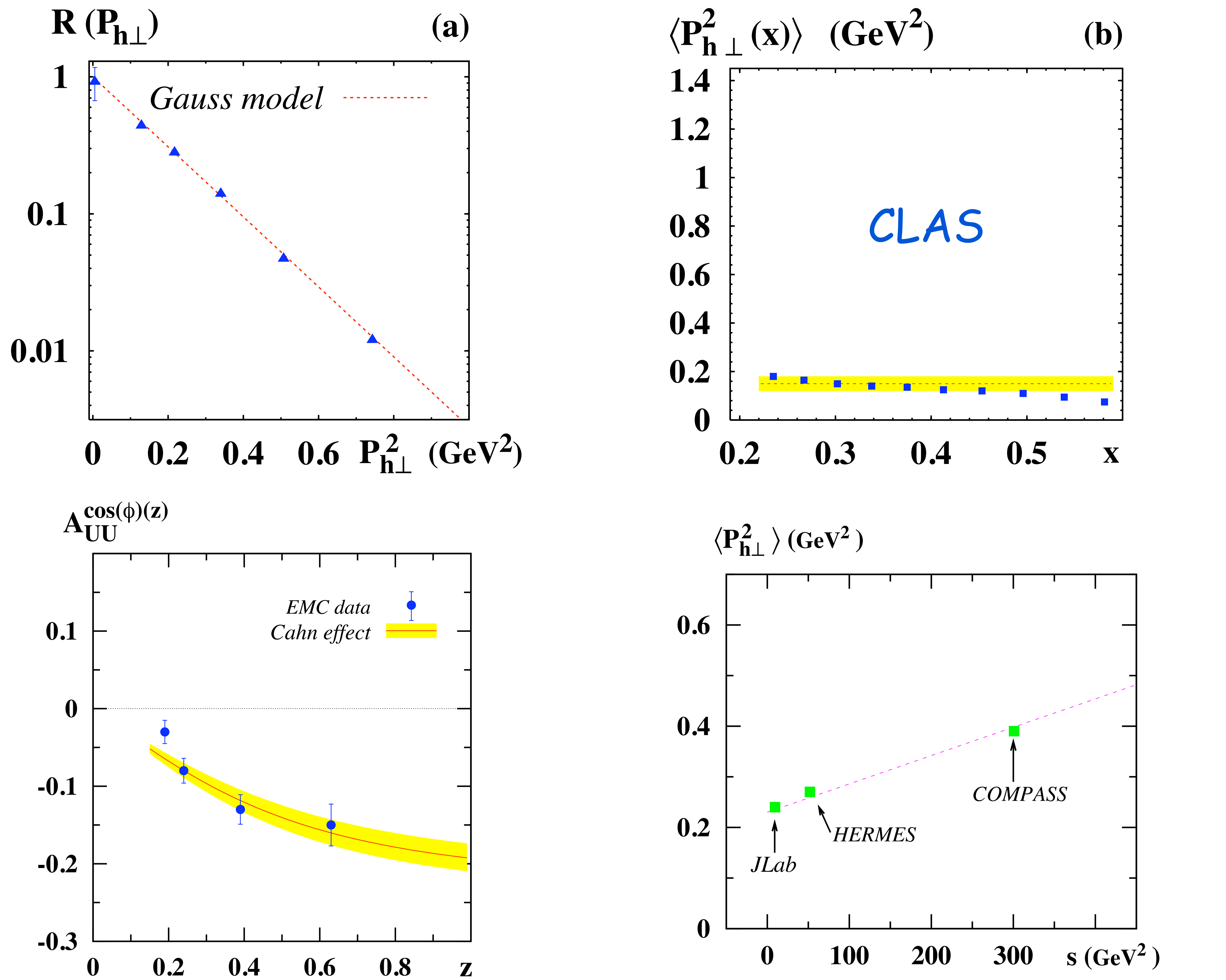
$$\langle P_T^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$$

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

z dependence at small z values

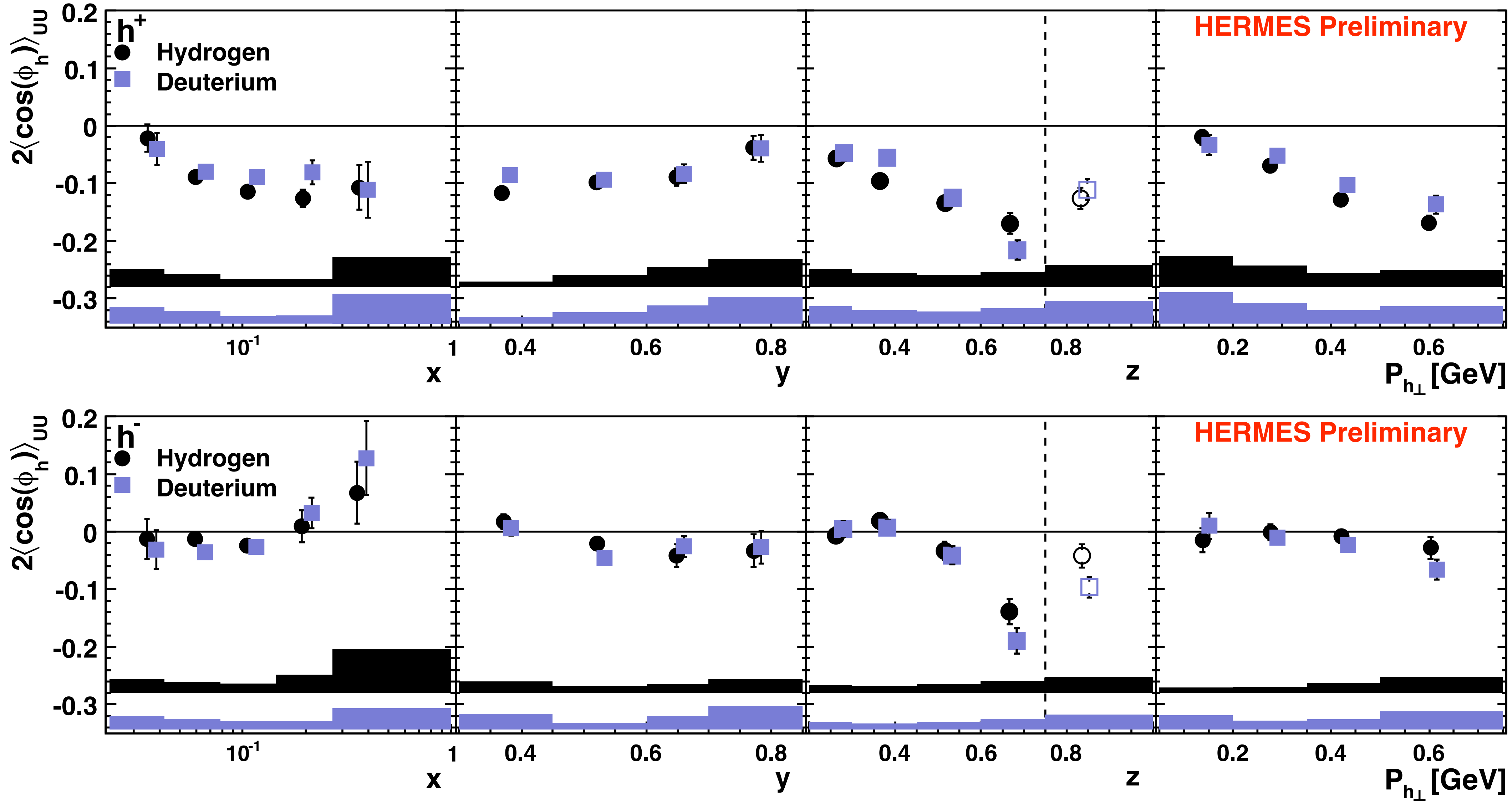
not much x dependence in explored valence region

Schweitzer, Teckentrup, Metz, arXiv:1003.2190



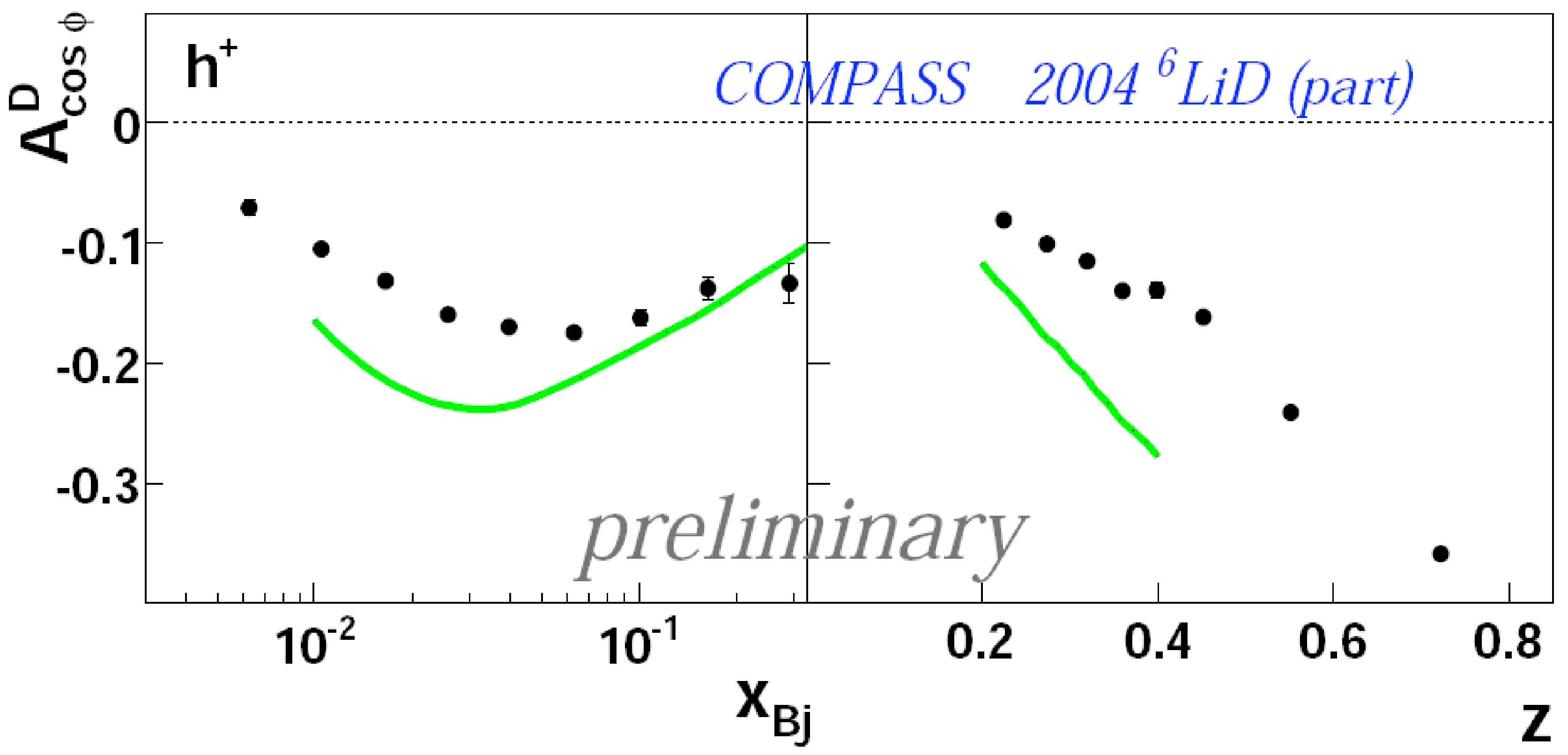
$\cos\phi$ dependence observed by HERMES

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

the azimuthal dependence induced by intrinsic motion is clearly observed

phenomenolgical analysis and data need much improvement

Gaussian $k_\perp$ distribution of TMDs?

$$\langle k_\perp^2 \rangle (x, Q^2) \quad \langle p_\perp^2 \rangle (z, Q^2)$$

x, z dependence?

flavour dependence?

energy dependence?

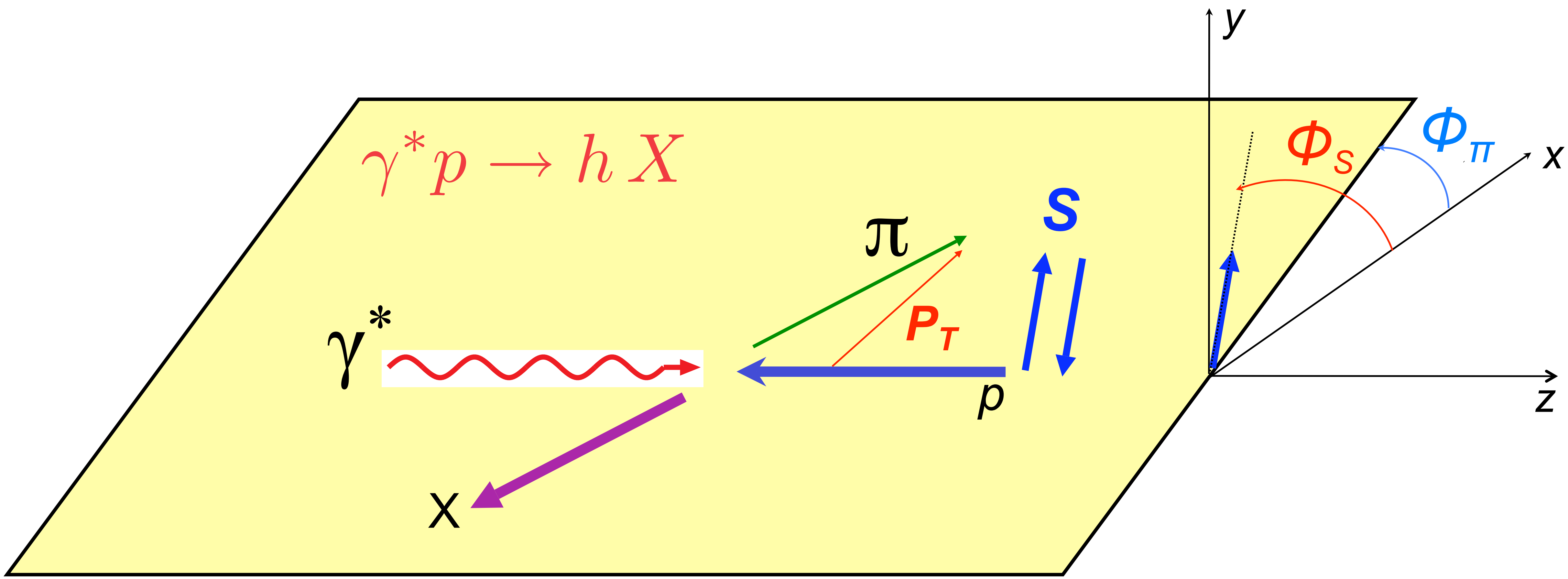
$k_\perp$ dependence of Δq vs. q?

....

Spin dependent TMDs

probing polarized nucleons:
transverse single spin
asymmetries in SIDIS

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$



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

Large Q^2: the virtual photon explores the nucleon structure.
In collinear configurations there cannot be (at LO) any P_T

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

$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$

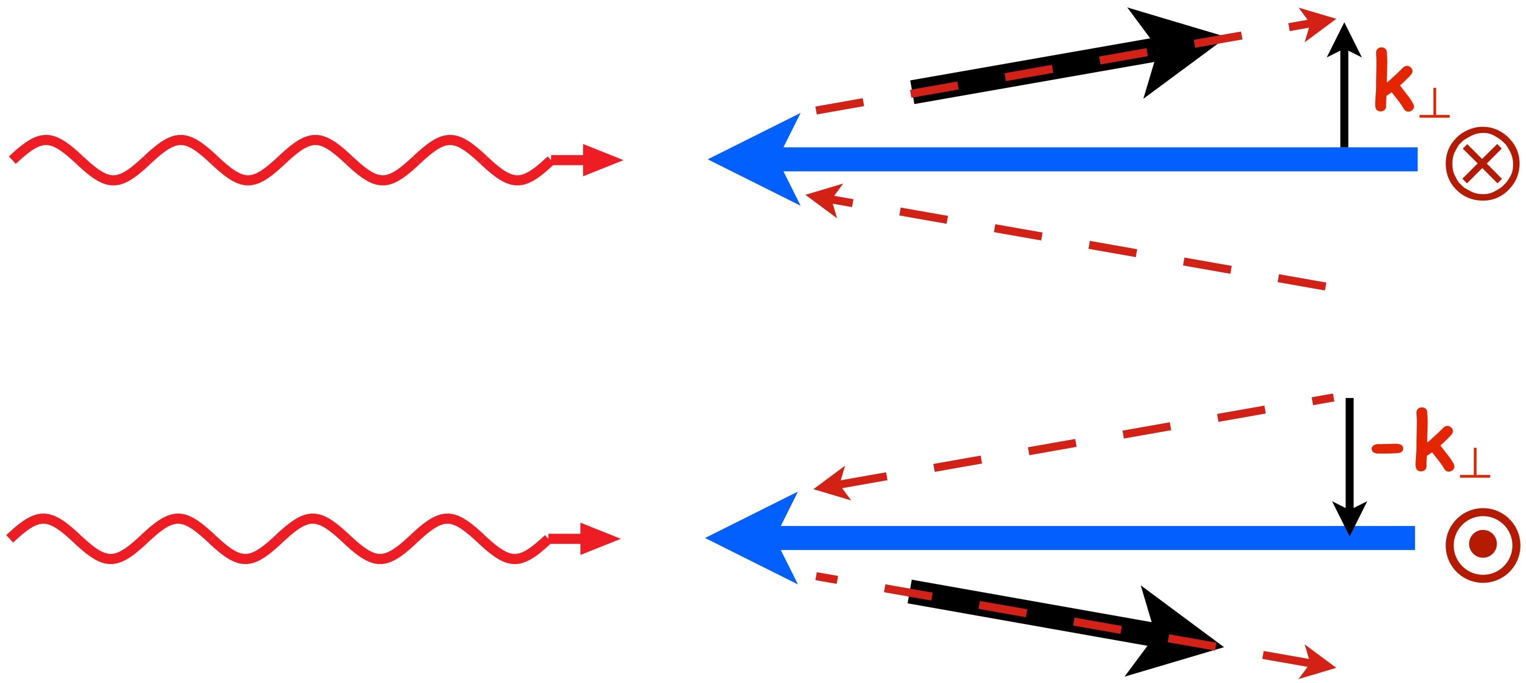
$$d\sigma^{\uparrow,\downarrow} = \sum_q f_{q/p^{\uparrow,\downarrow}}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_{h/q}(z, \boldsymbol{p}_\perp; Q^2)$$

$$\begin{aligned} f_{q/p^{\uparrow,\downarrow}}(x, \boldsymbol{k}_\perp) &= f_{q/p}(x, k_\perp) \pm \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x, k_\perp)\, \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp) \\ &= f_{q/p}(x, k_\perp) \mp \frac{k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp)\, \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp) \end{aligned}$$

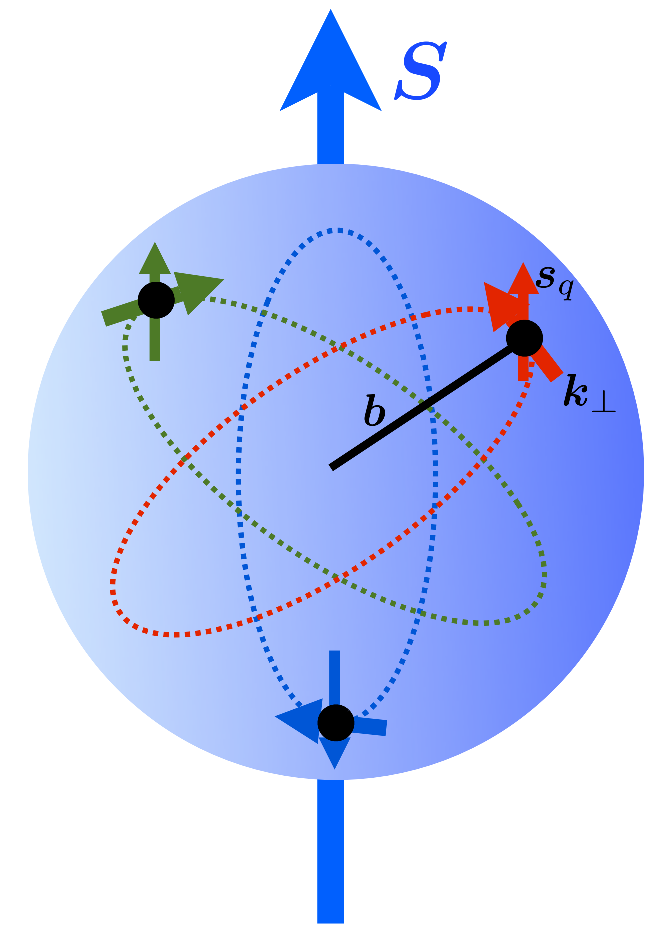
$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q \Delta^N f_{q/p^\uparrow}(x, k_\perp)\, \underbrace{\boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)}_{\sin(\varphi - \phi_S)} \otimes d\hat{\sigma}(y, \boldsymbol{k}_\perp) \otimes D_{h/q}(z, \boldsymbol{p}_\perp)$$

$$\sim F_{UT}^{\sin(\phi-\phi_S)} \sin(\phi - \phi_S)$$

simple physical picture for Sivers effect



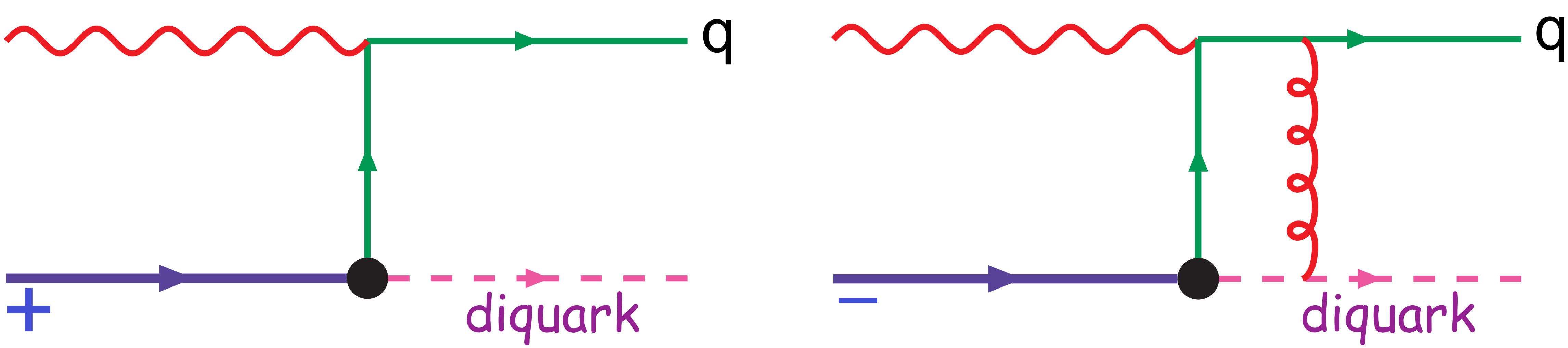
$$P_T \sim k_\perp$$



the large Q^2 virtual photon "sees" the spin-$\mathbf{k}_\perp$ correlation

Quark models for Sivers function

Brodsky, Hwang, Schmidt: final state interactions

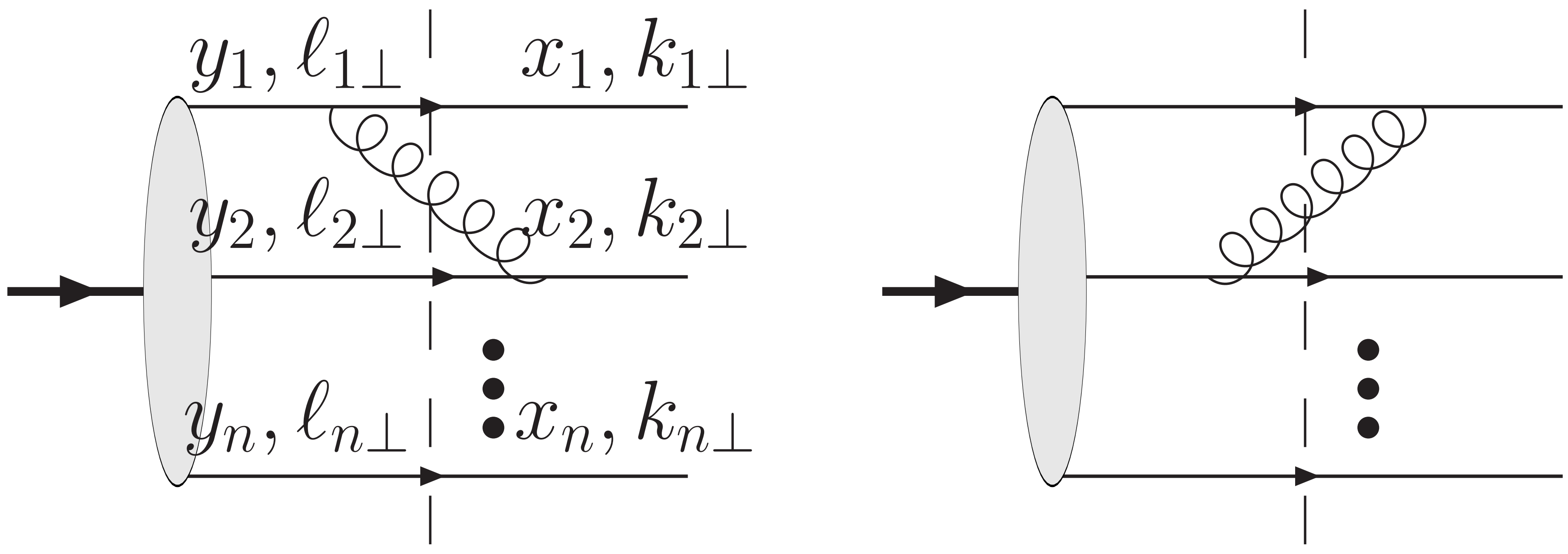


recent quark-diquark model of all twist-2 TMDs: Bacchetta, Conti, Radici, arXiv:0807.0323 (PRD 78, 074010, 2008); Bacchetta, Radici, Conti, Guagnelli, arXiv:1003.1328

very recent quark bag model of all twist-2 and twist-3 TMDs: Avakian, Efremov, Schweitzer, Yuan, arXiv:1001.5467 (supports Gaussian $k_\perp$ dependence of TMDs in valence x-region)

Sivers function from light-front wave function

Brodsky, Pasquini, Xiao, Yuan, arXiv:1001.1163
Pasquini, Yuan, arXiv:1001.5398



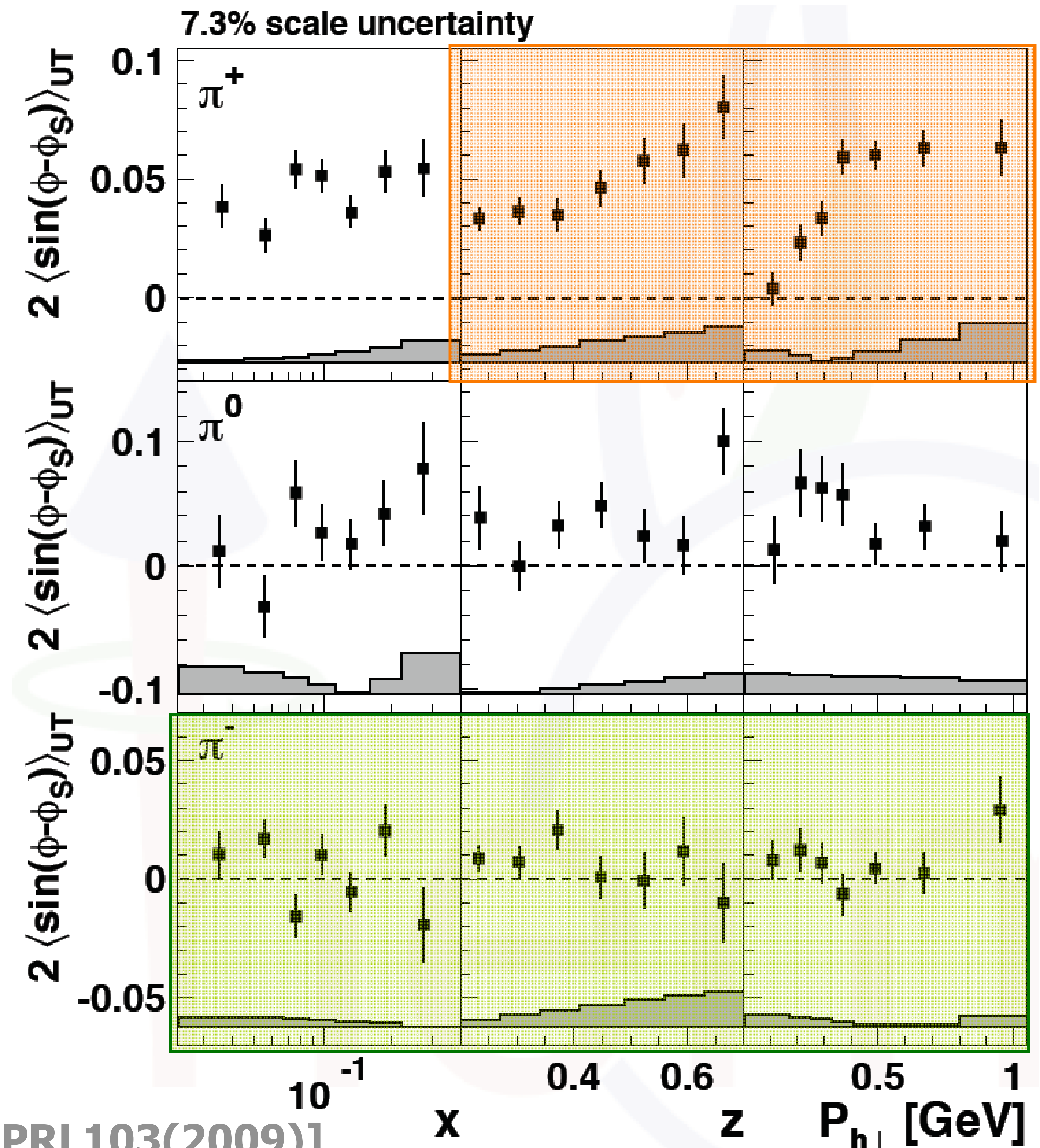
(a) (b)

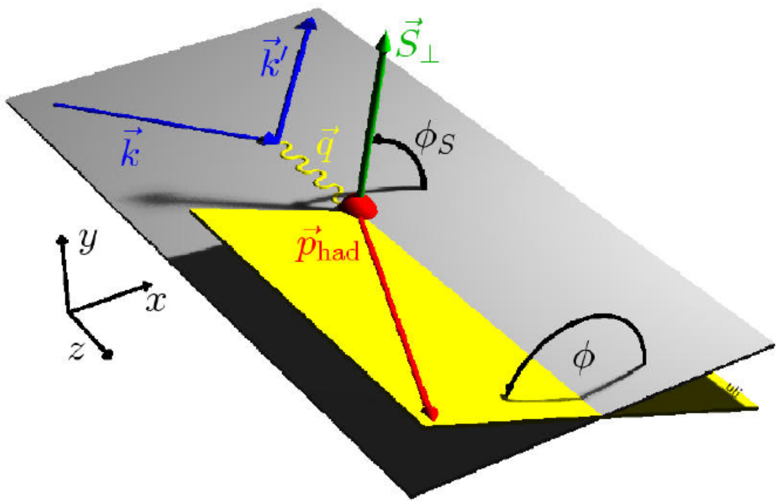
in all models one has:

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

see also Hwang, arXiv:1003.0867 - incorporation of final state interactions into the light-cone wave function

HERMES data on pion Sivers asymmetry



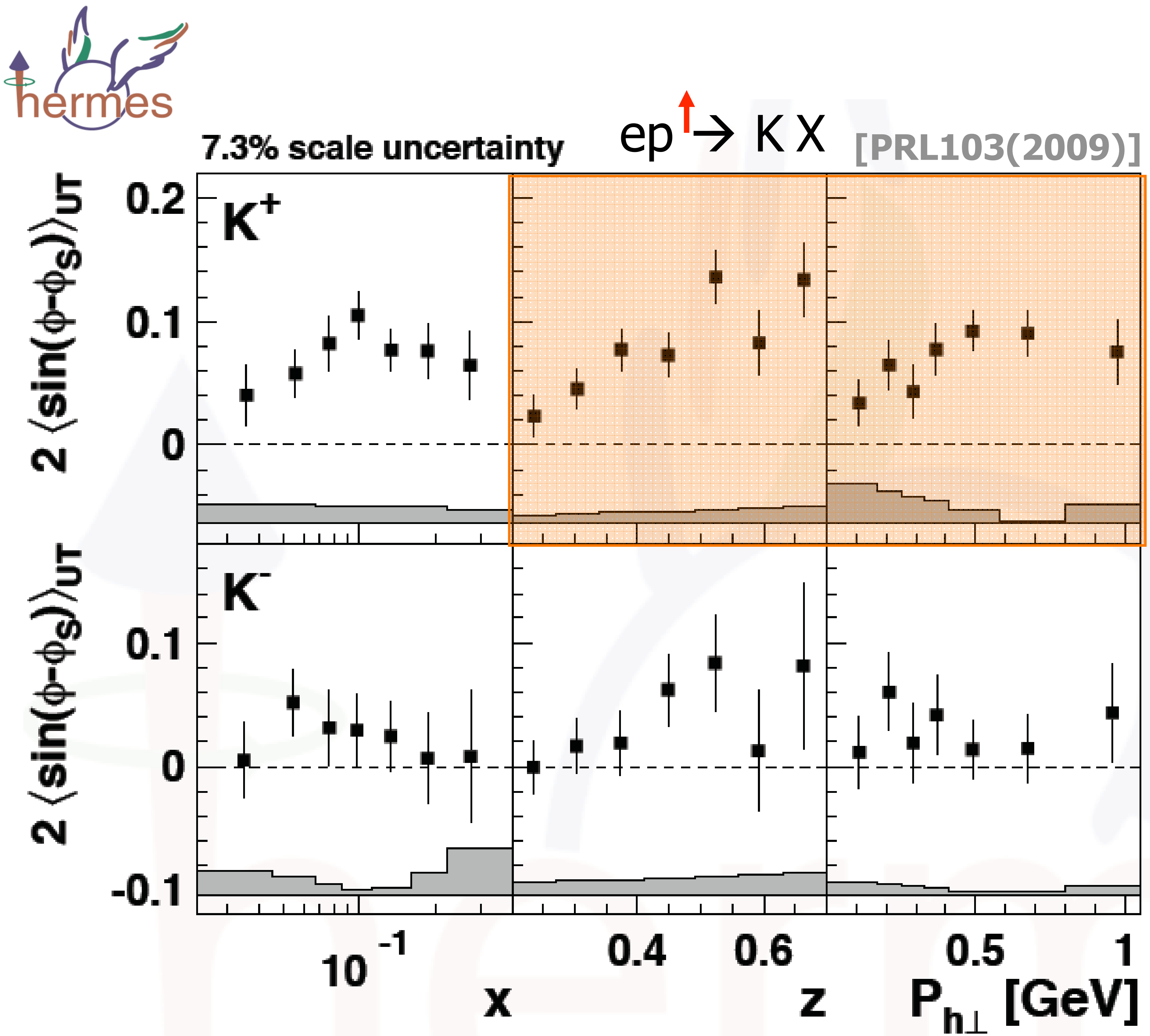


$$2\,\langle\sin(\phi-\phi_S)\rangle = A_{UT}^{\sin(\phi-\phi_S)}$$

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

[PRL103(2009)]

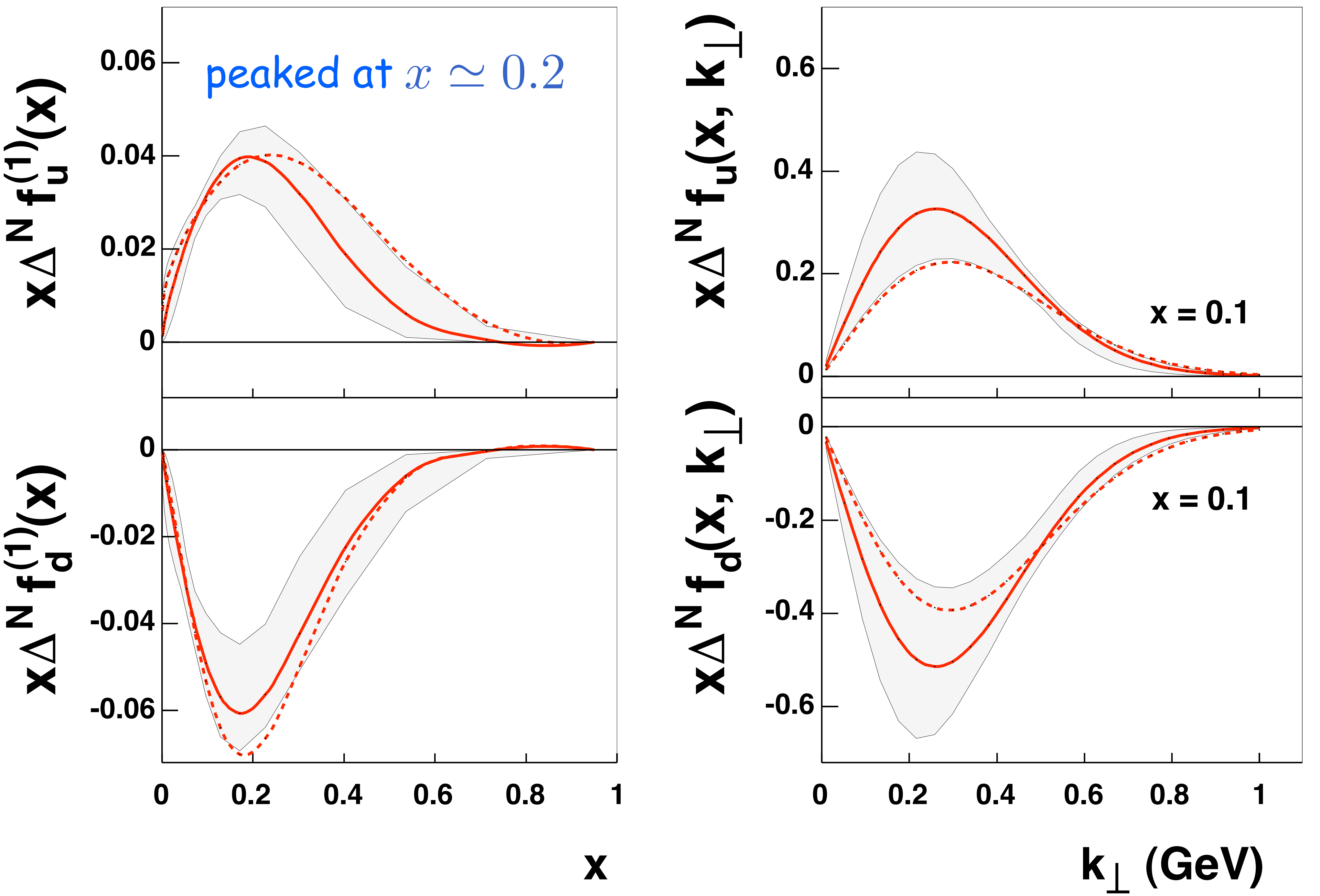
HERMES kaon Sivers asymmetry



extraction of Sivers functions from SIDIS data

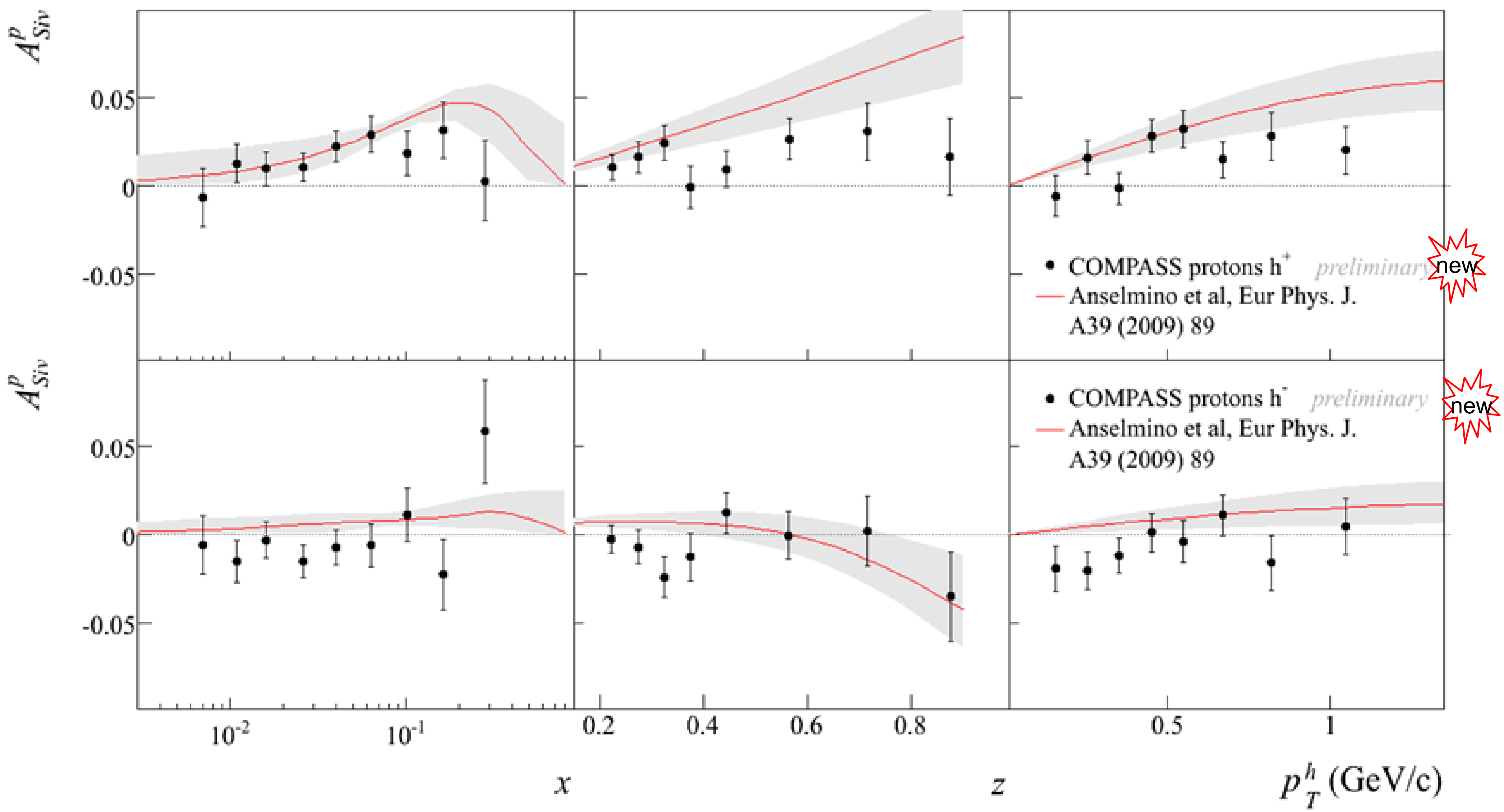
(from HERMES proton and COMPASS deuteron data)

u and d functions rather well determined



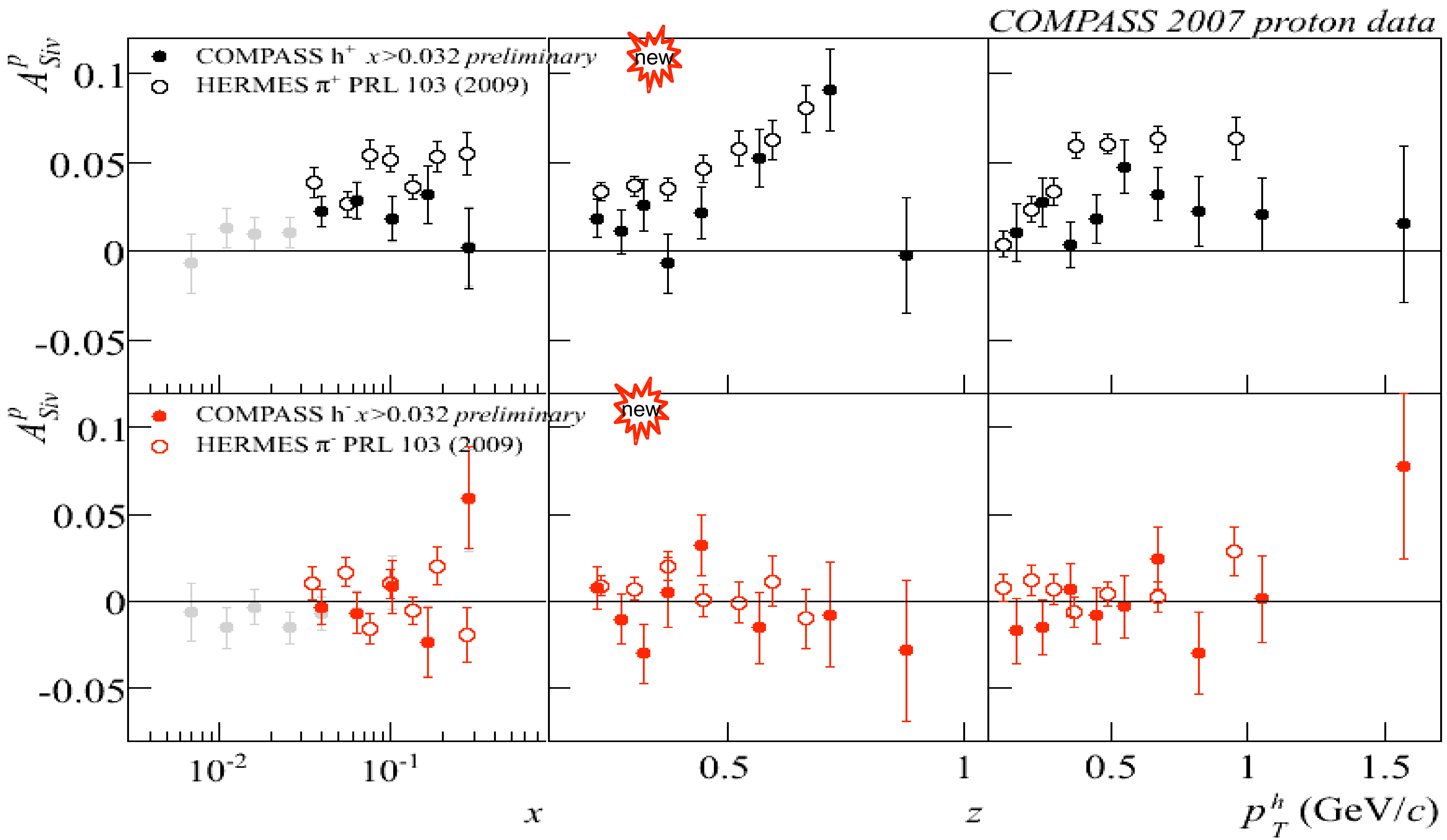
M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Türk

predictions for Sivers asymmetry at COMPASS, off a proton target - comparison with new data



A. Martin, DIS2010

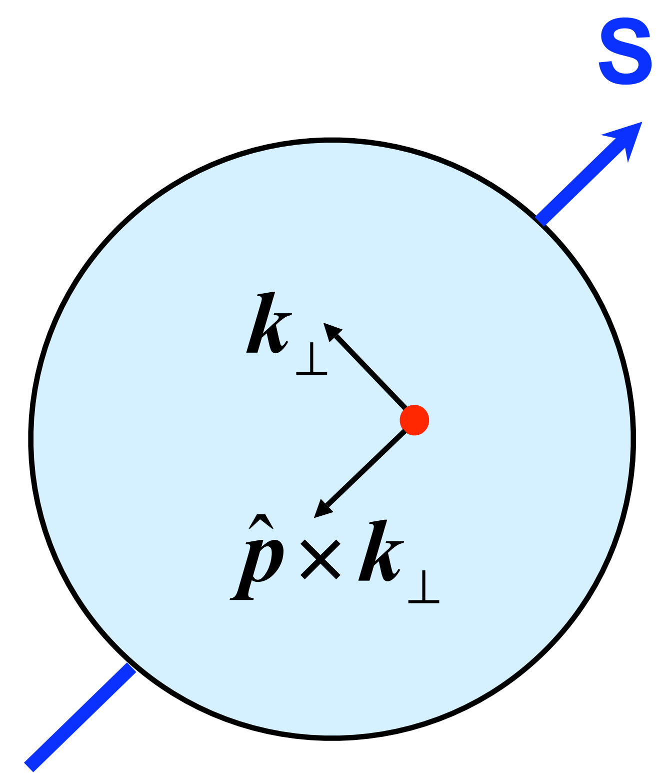
Sivers asymmetry off a proton target - comparison of HERMES and COMPASS data



A. Martin, DIS2010

What could we learn from the Sivers distribution?

number density of partons with longitudinal momentum fraction x and transverse momentum $\boldsymbol{k}_\perp$, inside a proton with spin $\mathbf{S}$



$$\boxed{\sum_a \int dx\, d^2\boldsymbol{k}_\perp\, \boldsymbol{k}_\perp\, f_{a/p^\uparrow}(x, \boldsymbol{k}_\perp) \equiv \sum_a \langle \boldsymbol{k}_\perp^a \rangle = 0}$$

M. Burkardt, PR **D69**, 091501 (2004)

same naive sum rule as expected for free partons (no final state interactions)

Total amount of intrinsic momentum carried by partons of flavour a

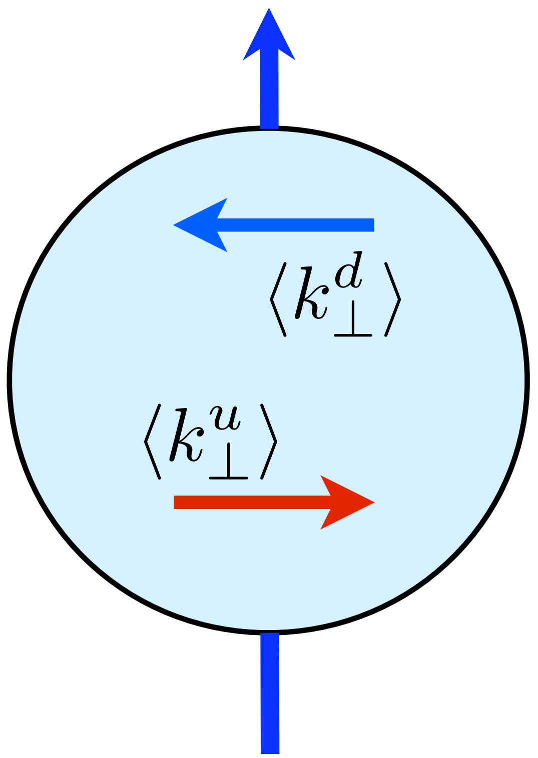
$$\langle \boldsymbol{k}_\perp^a \rangle = \left[\frac{\pi}{2} \int_0^1 dx \int_0^\infty dk_\perp \, k_\perp^2 \, \Delta^N f_{a/p^\uparrow}(x, k_\perp) \right] (\boldsymbol{S} \times \hat{\boldsymbol{P}})$$

$$= m_p \int_0^1 dx \, \Delta^N f^{(1)}_{q/p^\uparrow}(x) \, (\boldsymbol{S} \times \hat{\boldsymbol{P}}) \equiv \langle k_\perp^a \rangle \, (\boldsymbol{S} \times \hat{\boldsymbol{P}})$$

$$\langle k_\perp^u \rangle + \langle k_\perp^d \rangle = -17^{+37}_{-55} \ (\mathrm{MeV}/c)$$

$$[\, \langle k_\perp^u \rangle = 96^{+60}_{-28} \qquad \langle k_\perp^d \rangle = -113^{+45}_{-51} \,]$$

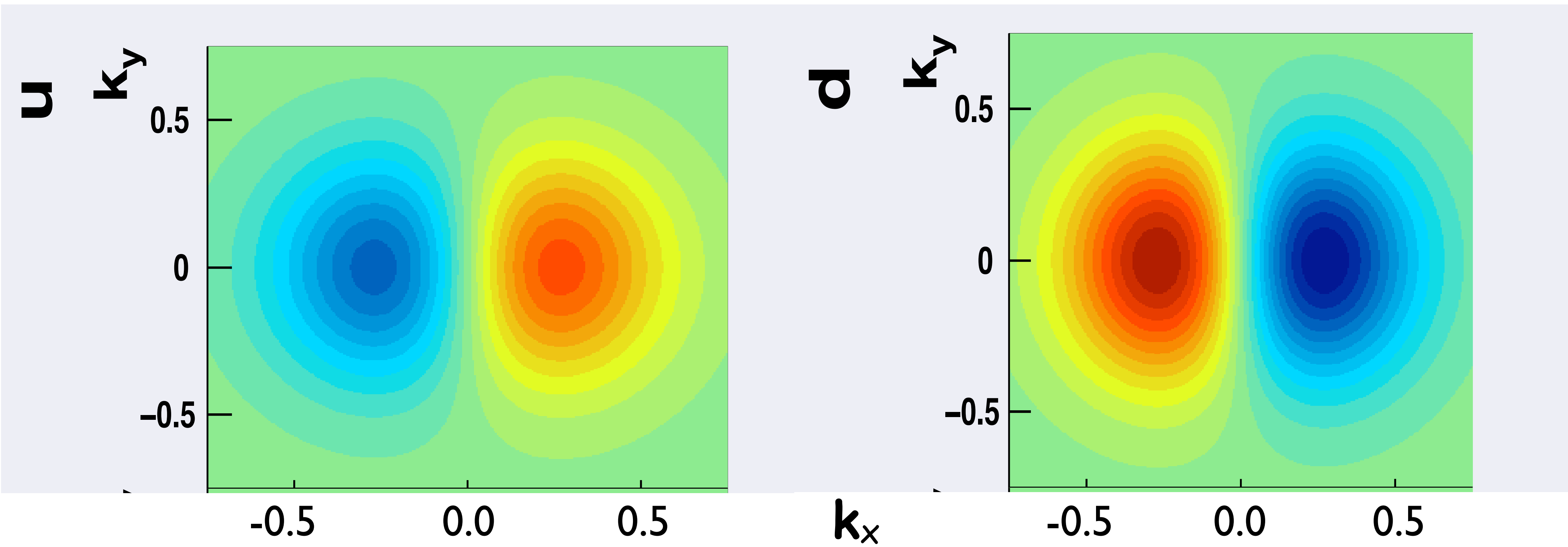
$$\langle k_\perp^{\bar{u}} \rangle + \langle k_\perp^{\bar{d}} \rangle + \langle k_\perp^s \rangle + \langle k_\perp^{\bar{s}} \rangle = -14^{+43}_{-66} \ (\mathrm{MeV}/c)$$



Burkardt sum rule almost saturated by u and d quarks alone; little residual contribution from gluons

$$-10 \le \langle k_\perp^g \rangle \le 48 \ (\mathrm{MeV}/c)$$

Sivers u and d quark densities in transverse momentum space

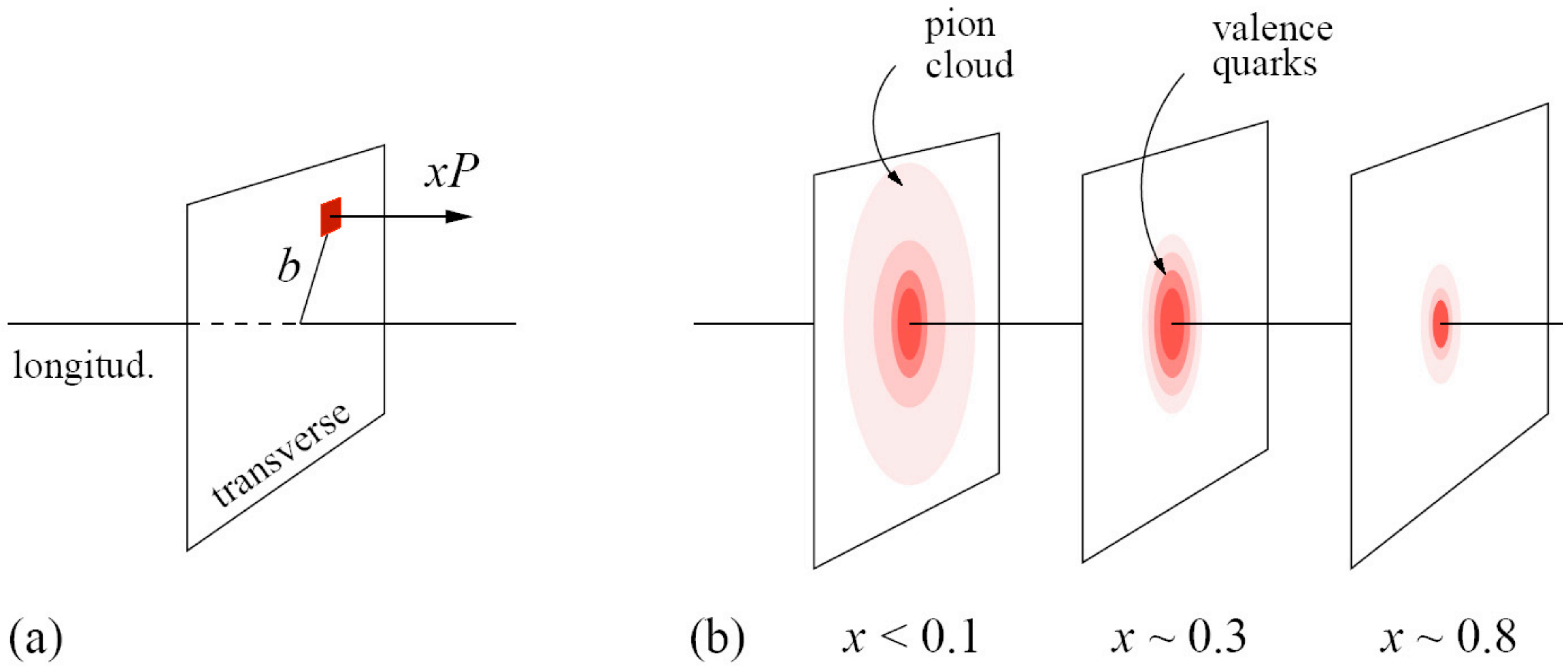


proton moving into the screen, polarization along y-axis

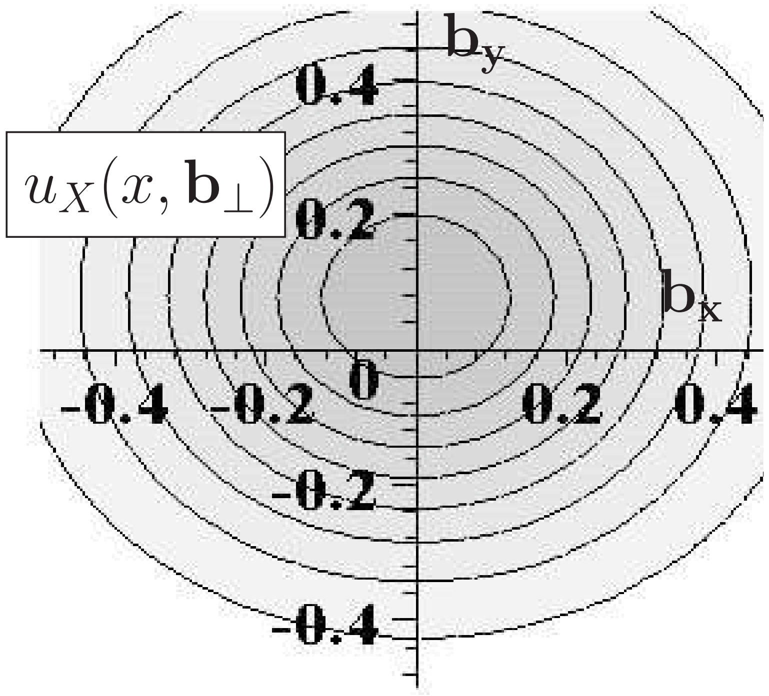
blue: less quarks red: more quarks $x = 0.2$ k in GeV/c

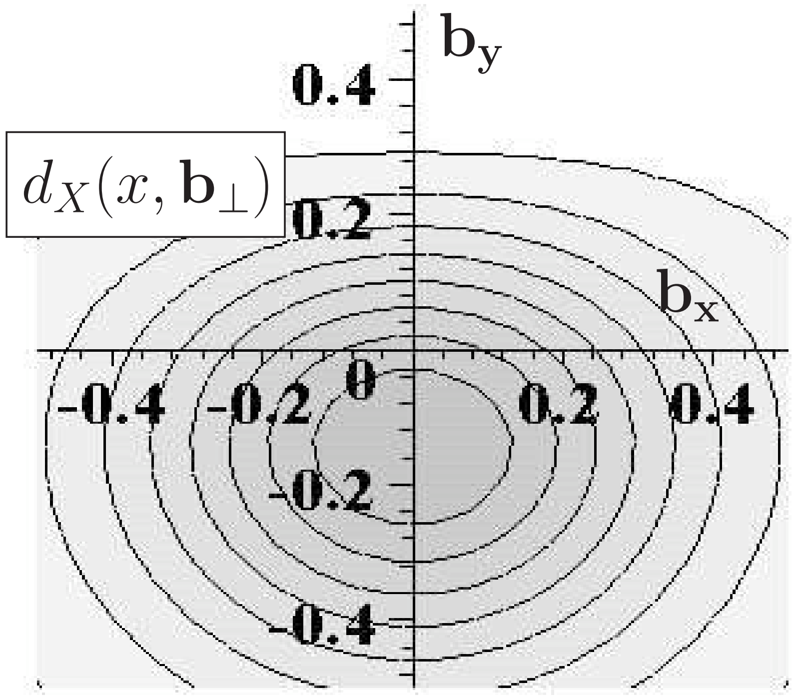
courtesy of A. Prokudin

$q(x, \boldsymbol{b}_T)$: femtophotography or tomography of the nucleon



Sivers distribution in impact parameter space (M. Burkardt)





Sivers function and orbital angular momentum

D. Sivers

Sivers mechanism originates from $\boldsymbol{S} \cdot \boldsymbol{L}_q$ then it is related to the quark orbital angular momentum

Sivers function and proton anomalous magnetic moment

M. Burkardt, S. Brodsky, Z. Lu, I. Schmidt

Both the Sivers function and the proton anomalous magnetic moment are related to correlations of proton wave functions with opposite helicities

$$\int_0^1 \mathrm{d}x \, \mathrm{d}^2\boldsymbol{k}_\perp \, \Delta^N f_{q/p^\uparrow}(x, k_\perp) = C \, \kappa_q$$

in qualitative agreement with large z data:

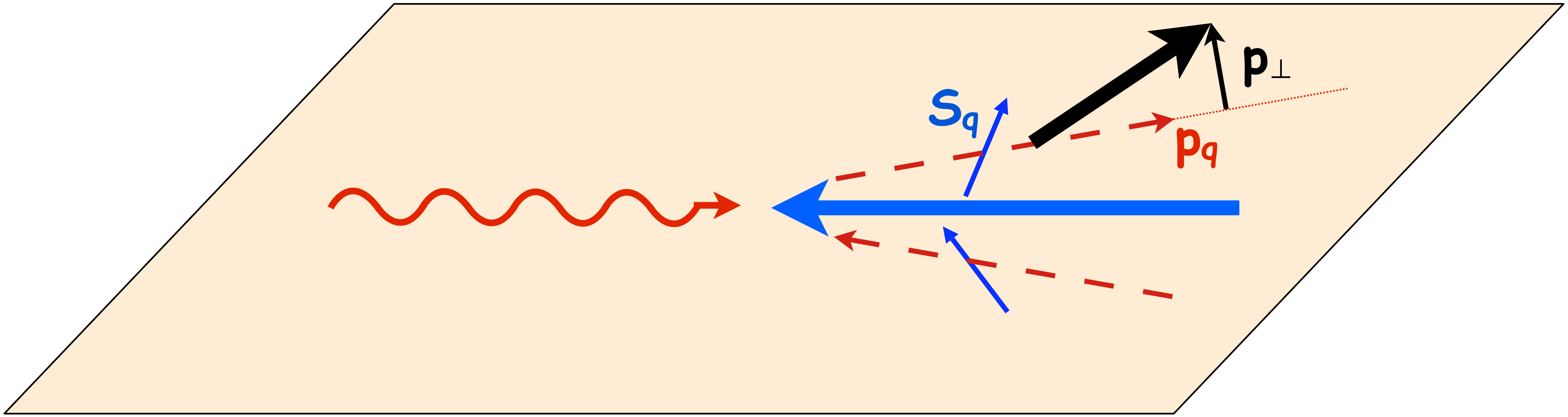
$$\frac{A_{UT}^{\sin(\phi_{\pi^+} - \phi_S)}}{A_{UT}^{\sin(\phi_{\pi^-} - \phi_S)}} \sim \frac{\kappa_u}{\kappa_d}$$

Sivers effect now observed by two experiments,
... but needs further measurements

and if the Sivers function is zero?
and if $(\text{Sivers})_{SIDIS} \neq -(\text{Sivers})_{D\text{-}Y}$?

A_N in $AB \to CX$, which Sivers function? other mechanisms? Collins effect?

Collins effect

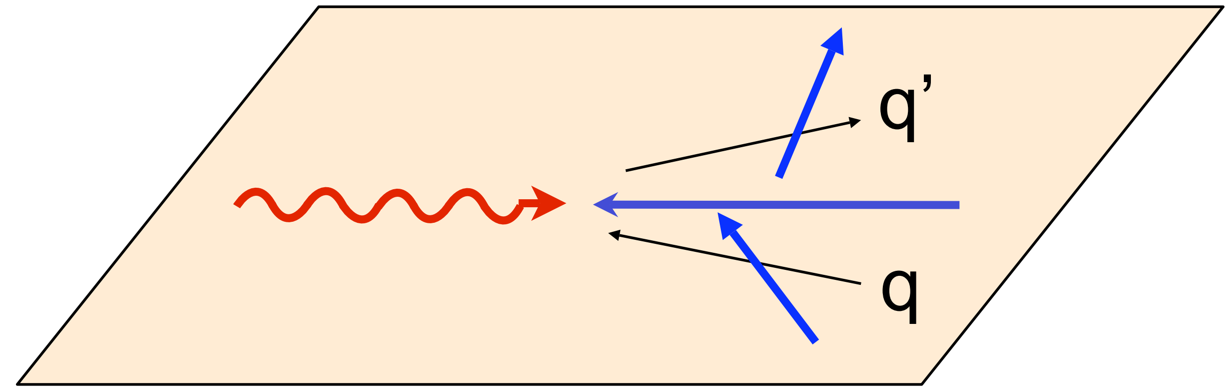


$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\,\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{zM_h}\,H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

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

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



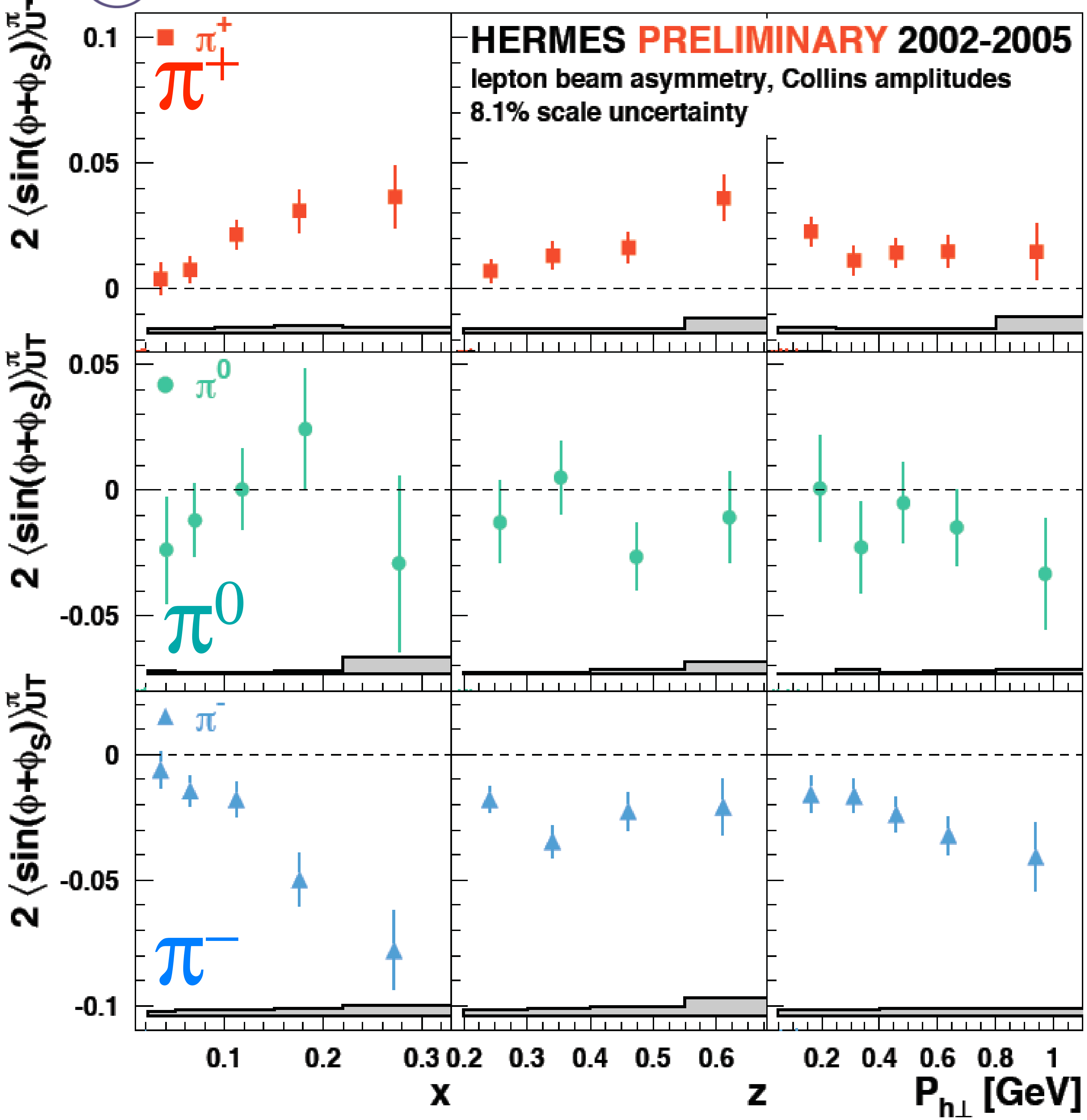
$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow = \sum_q h_{1q}(x,k_\perp) \otimes \mathrm{d}\Delta\hat{\sigma}(y,\boldsymbol{k}_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z,\boldsymbol{p}_\perp)$$

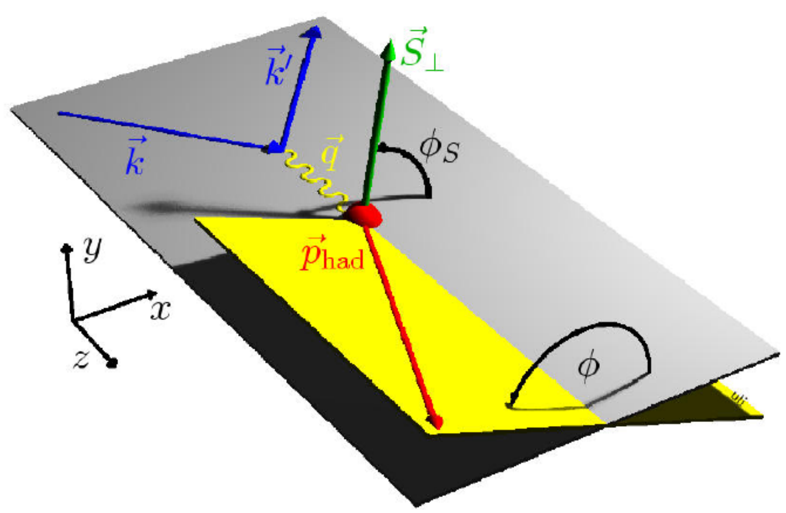
$$A_{UT}^{\sin(\phi+\phi_S)} \equiv 2\,\frac{\int \mathrm{d}\phi\,\mathrm{d}\phi_S\,[\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow]\,\sin(\phi+\phi_S)}{\int \mathrm{d}\phi\,\mathrm{d}\phi_S\,[\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$

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

Collins effect in SIDIS couples to transversity

$ep^{\uparrow} \rightarrow \pi X$ E_b=27GeV, $\sqrt{s}$~7 GeV

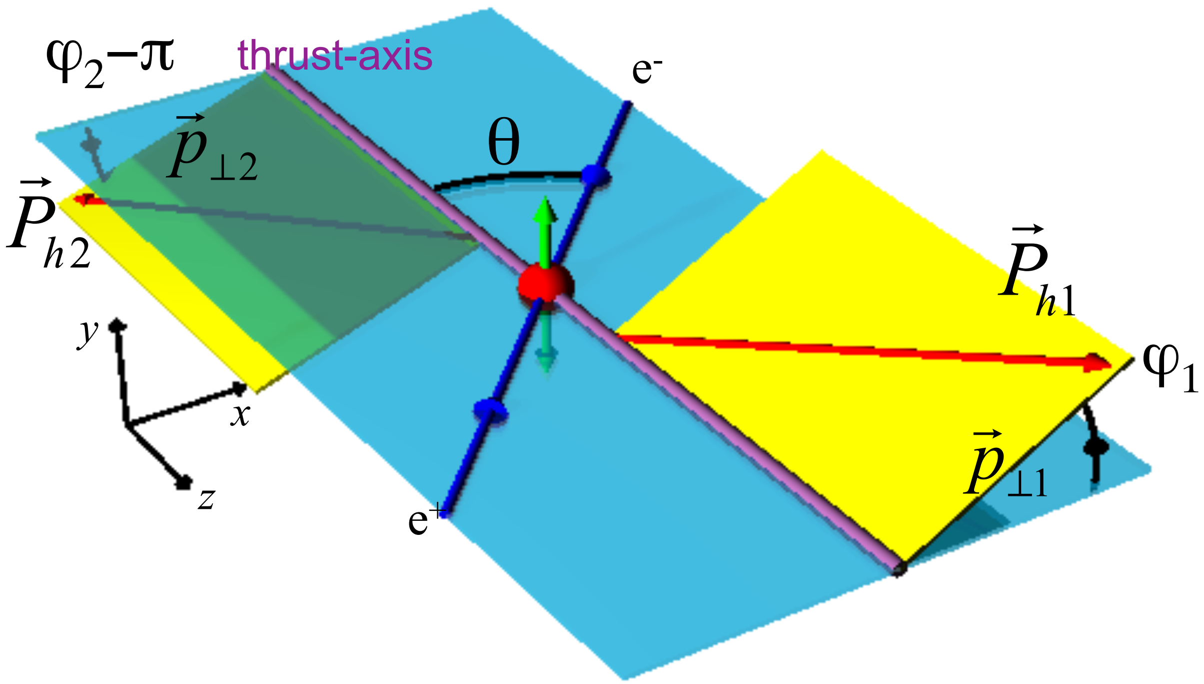


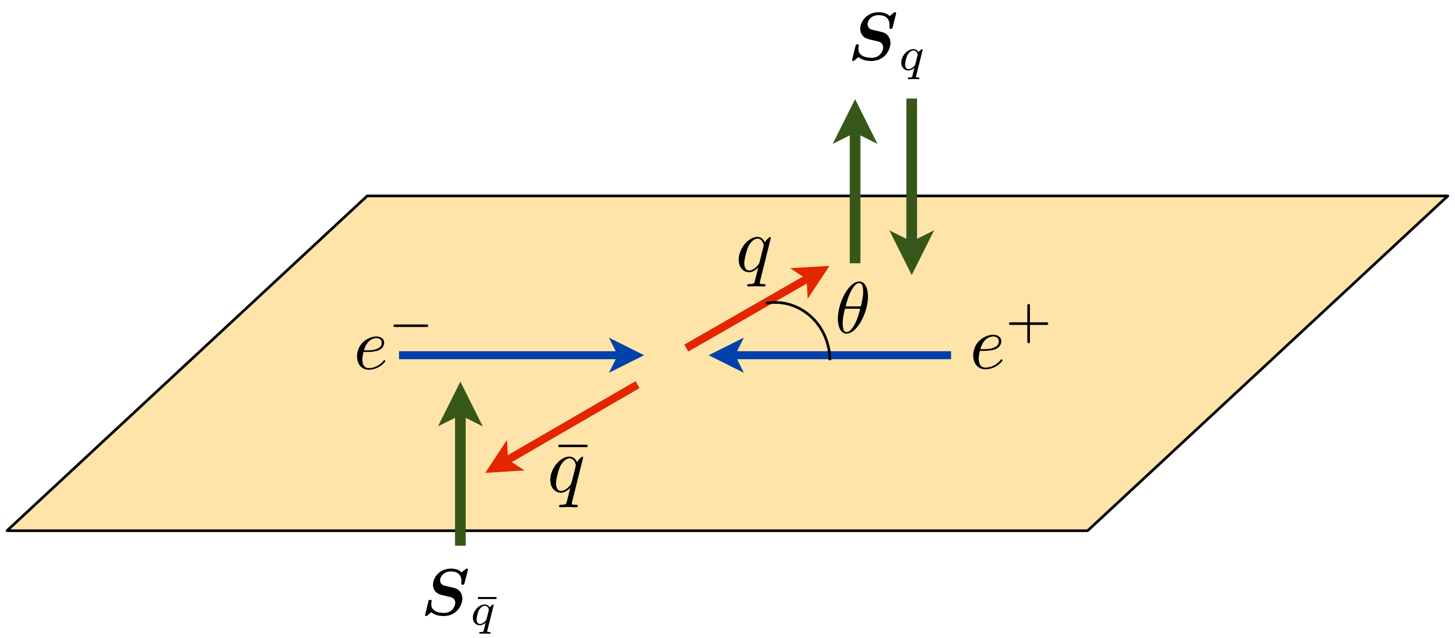


HERMES Collins asymmetry

Collins function from e^+e^- processes

BELLE @ KEK





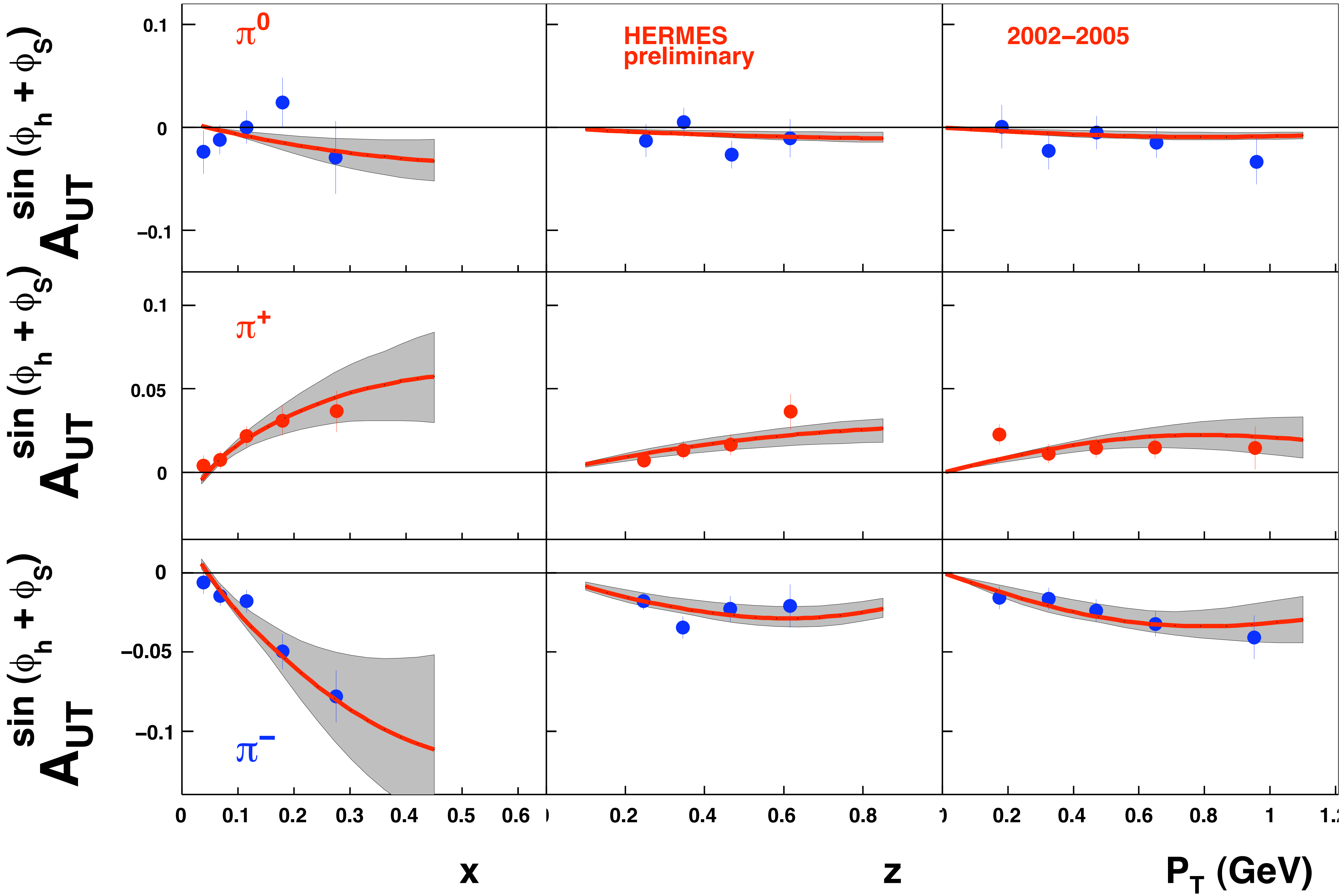
$$\frac{d\sigma^{e^+e^-\to q^\uparrow \bar{q}^\uparrow}}{d\cos\theta} = \frac{3\pi\alpha^2}{4s}\, e_q^2\, \cos^2\theta \qquad \frac{d\sigma^{e^+e^-\to q^\downarrow \bar{q}^\uparrow}}{d\cos\theta} = \frac{3\pi\alpha^2}{4s}\, e_q^2$$

$$A_{12}(z_1, z_2, \theta, \varphi_1+\varphi_2) \equiv \frac{1}{\langle d\sigma\rangle}\, \frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\, dz_2\, d\cos\theta\, d(\varphi_1+\varphi_2)}$$

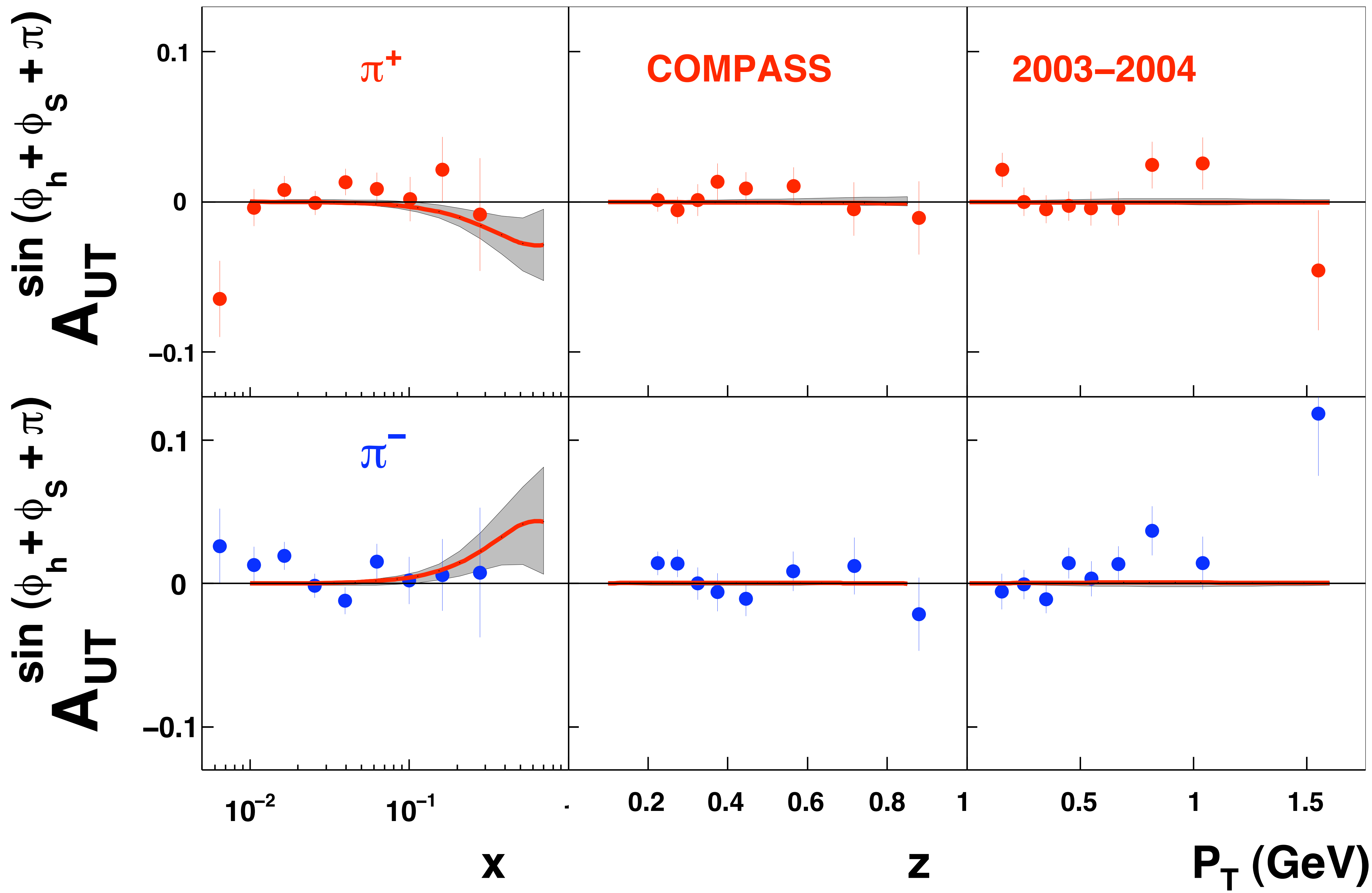
$$= 1 + \frac{1}{4}\, \frac{\sin^2\theta}{1+\cos^2\theta}\, \cos(\varphi_1+\varphi_2) \times \frac{\sum_q e_q^2\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2)}$$

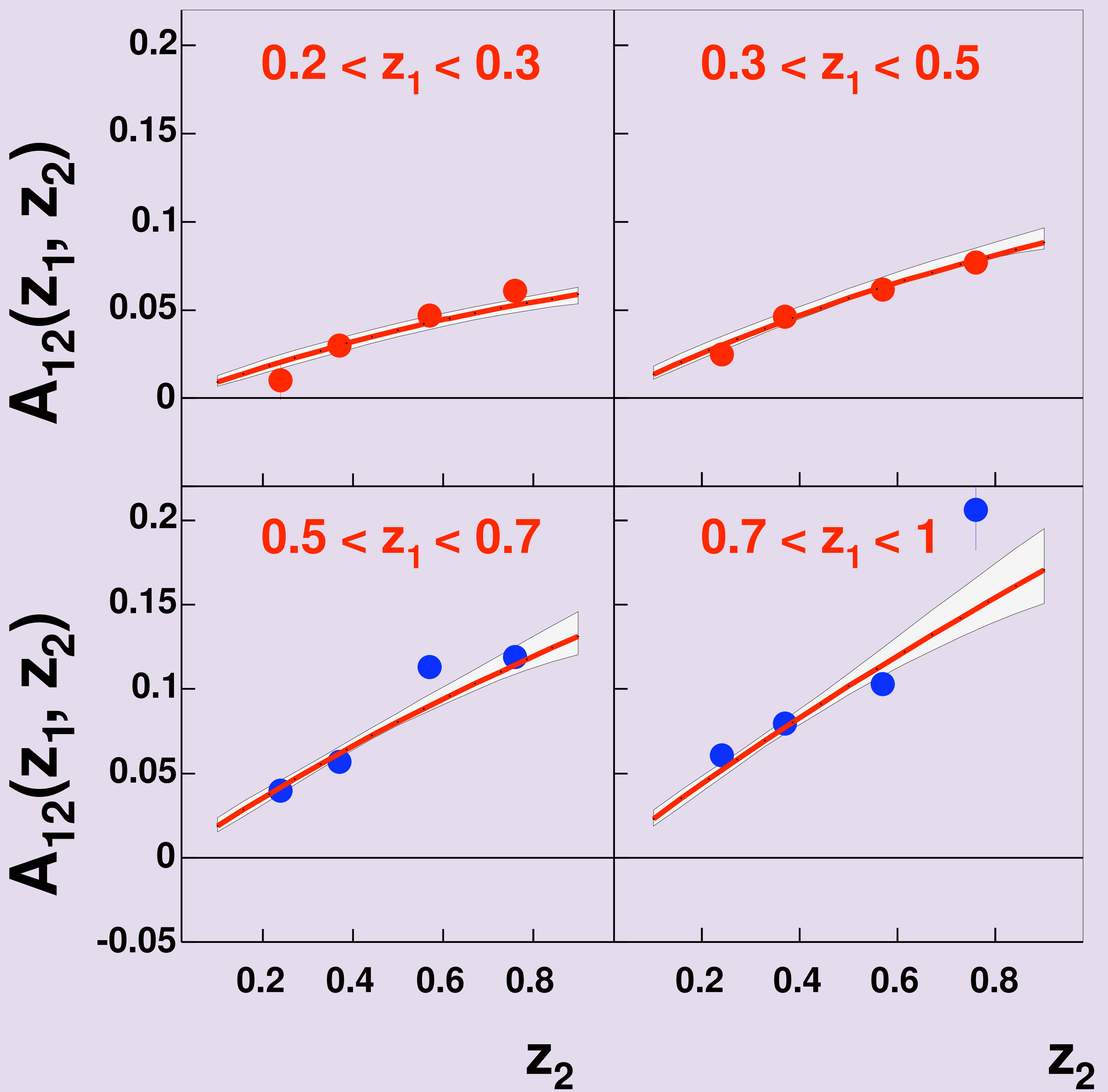
Collins asymmetry best fit

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



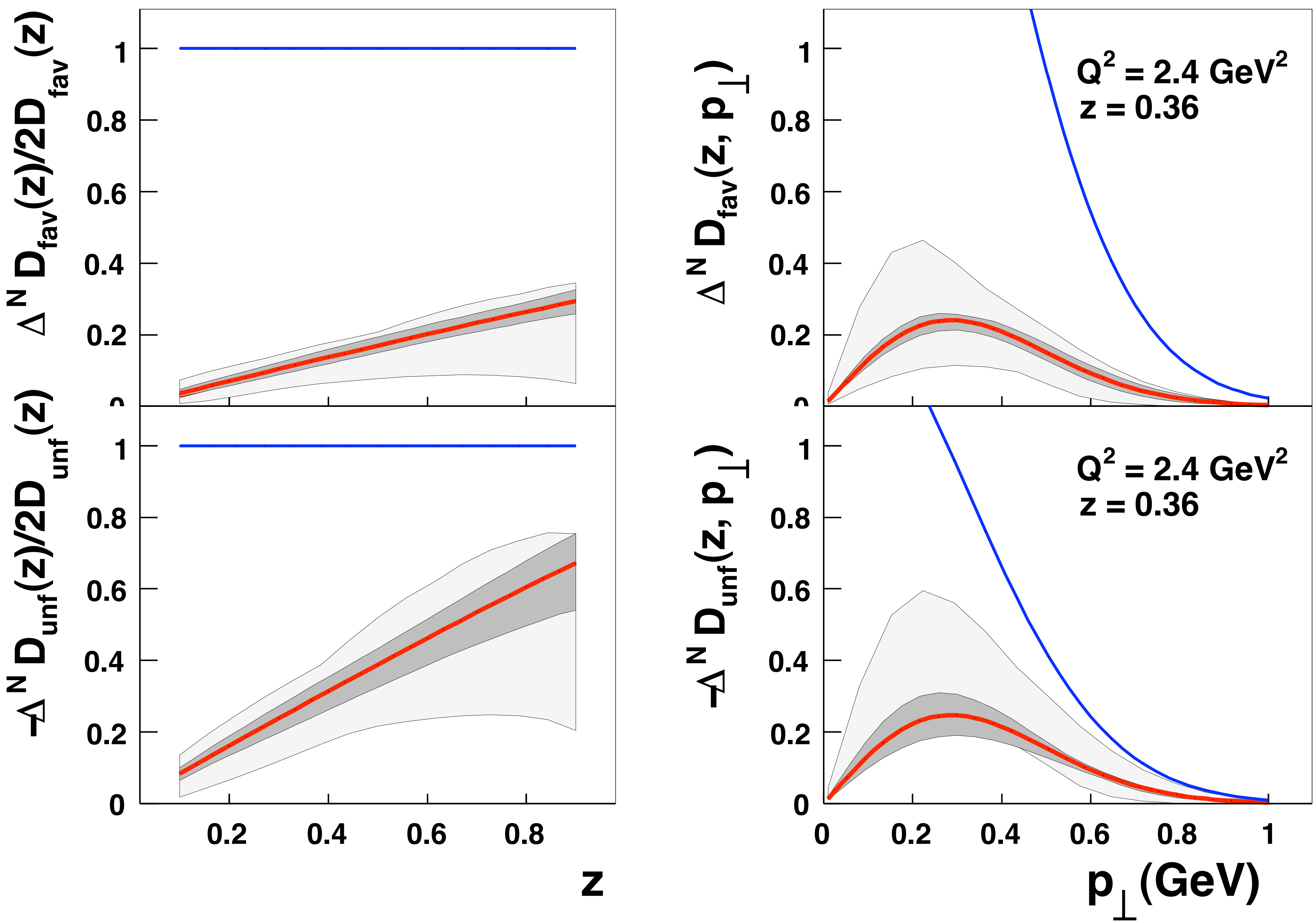
fit of COMPASS data, deuteron target

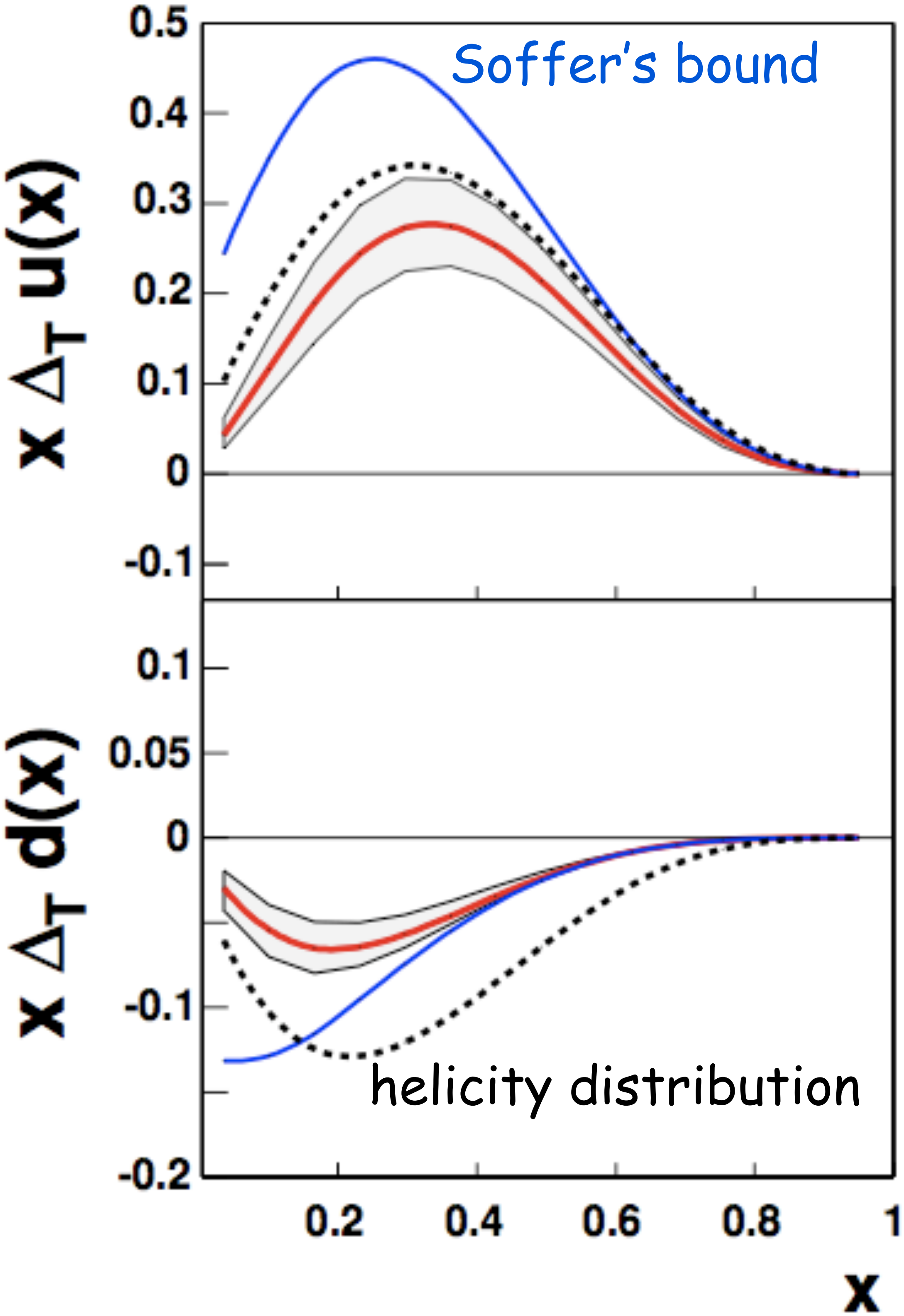




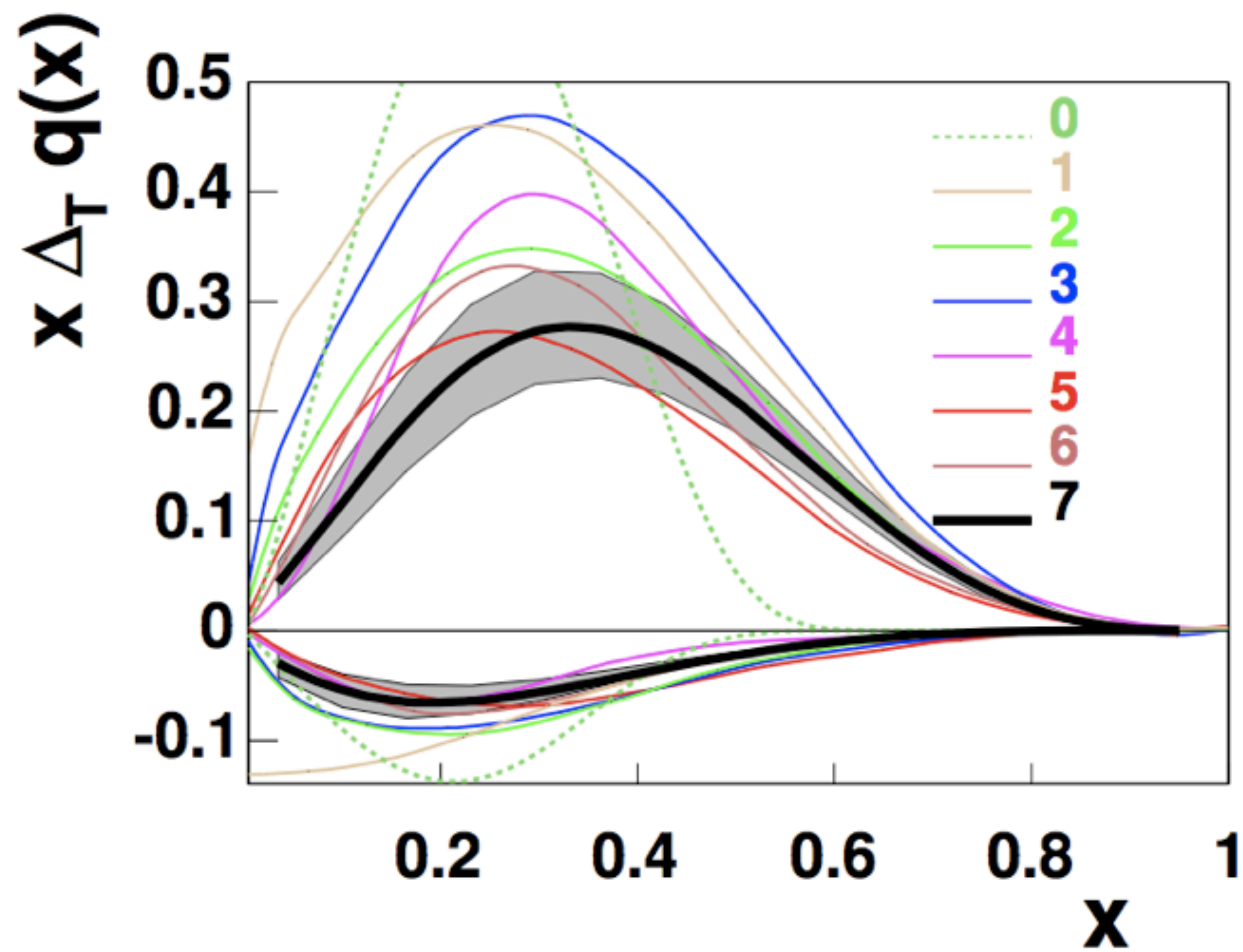
best fit of Belle data

extracted Collins functions



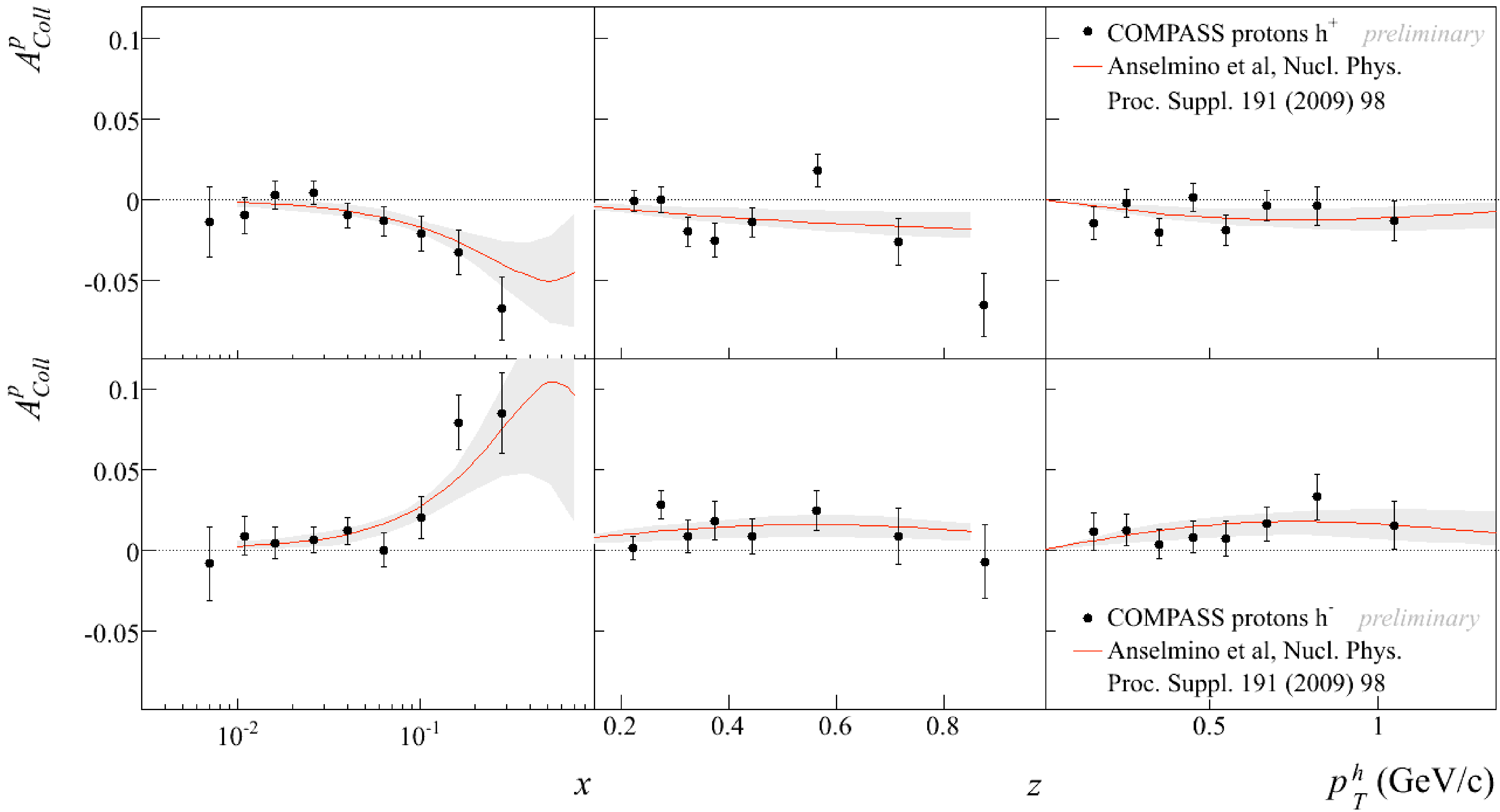


extracted transversity and comparison with models



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

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



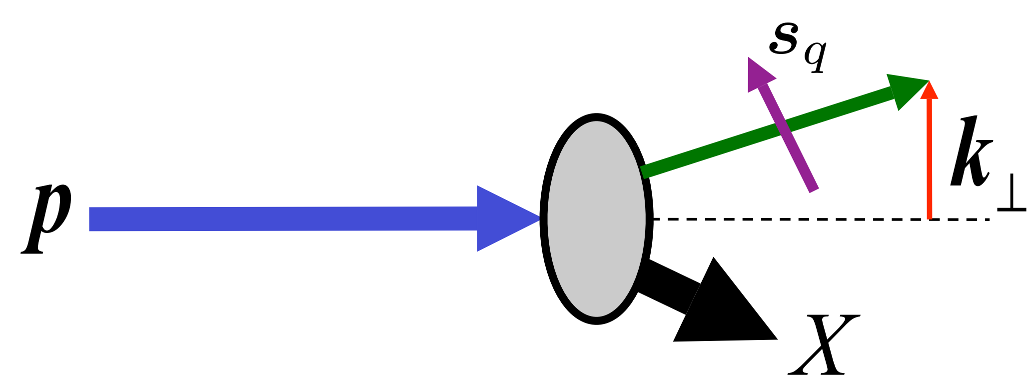
A. Martin, DIS2010

Collins effect observed by three independent experiments: HERMES, BELLE and COMPASS

Collins function expected to be universal

Collins function couples to Boer-Mulders function in unpolarized SIDIS to give a $\cos(2\Phi)$ asymmetry

Boer-Mulders effect



$$
\begin{aligned}
f_{q,\boldsymbol{s}_q/p}(x,\boldsymbol{k}_\perp) &= \frac{1}{2}\,f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q^\uparrow/p}(x,k_\perp)\;\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp) \\
&= \frac{1}{2}\,f_{q/p}(x,k_\perp) - \frac{k_\perp}{2M}\,h_1^{\perp q}(x,k_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)
\end{aligned}
$$

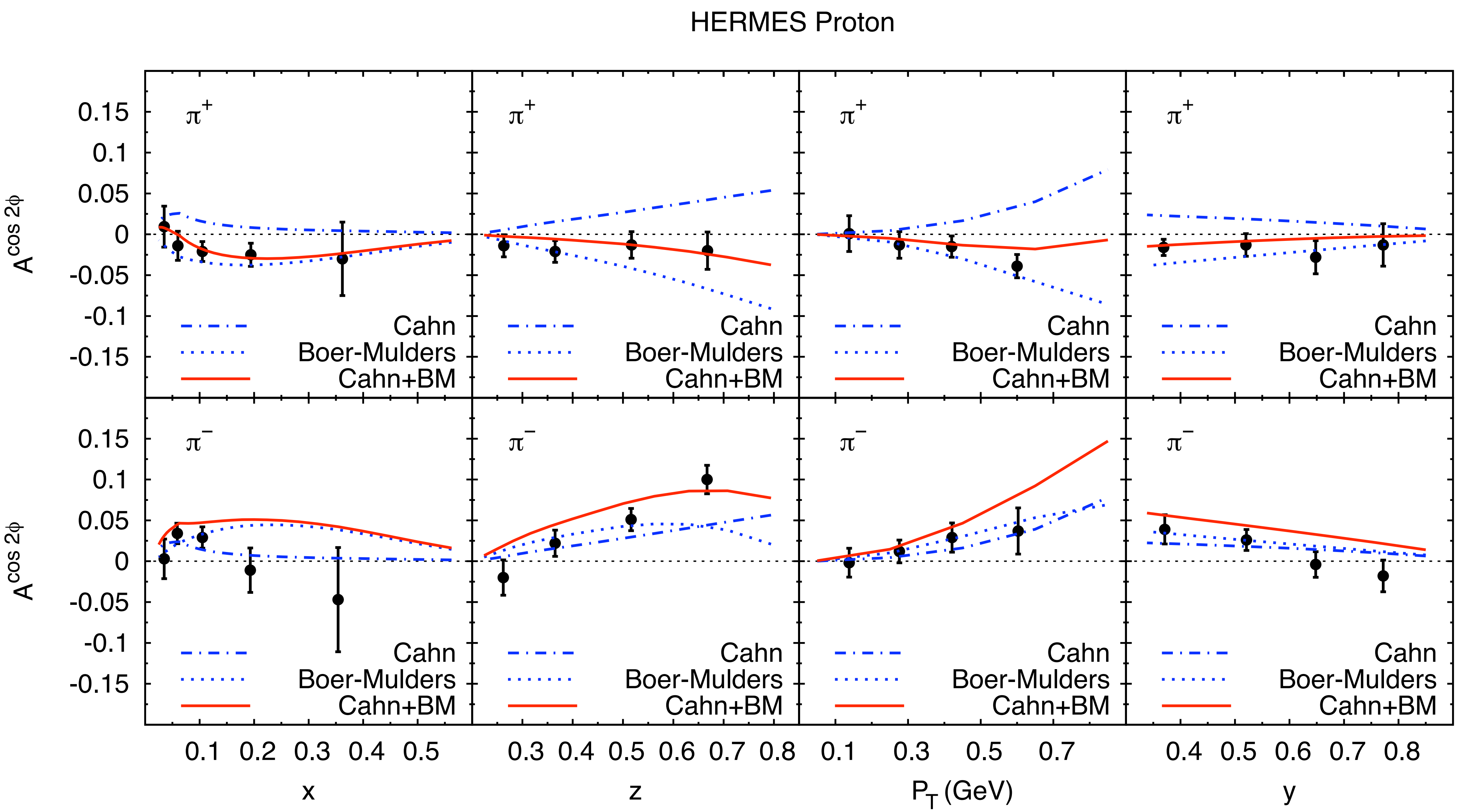
transversely polarized quarks inside unpolarized nucleons; interesting spin effects in unpolarized processes

possible strategy: combined analysis of cos(2Φ) asymmetries in unpolarized Drell-Yan (B-M $\otimes$ B-M) and in SIDIS (B-M $\otimes$ Collins)

B-M function from SIDIS data alone

contributions from Cahn effect at order $\mathcal{O}(k_\perp^2/Q^2)$

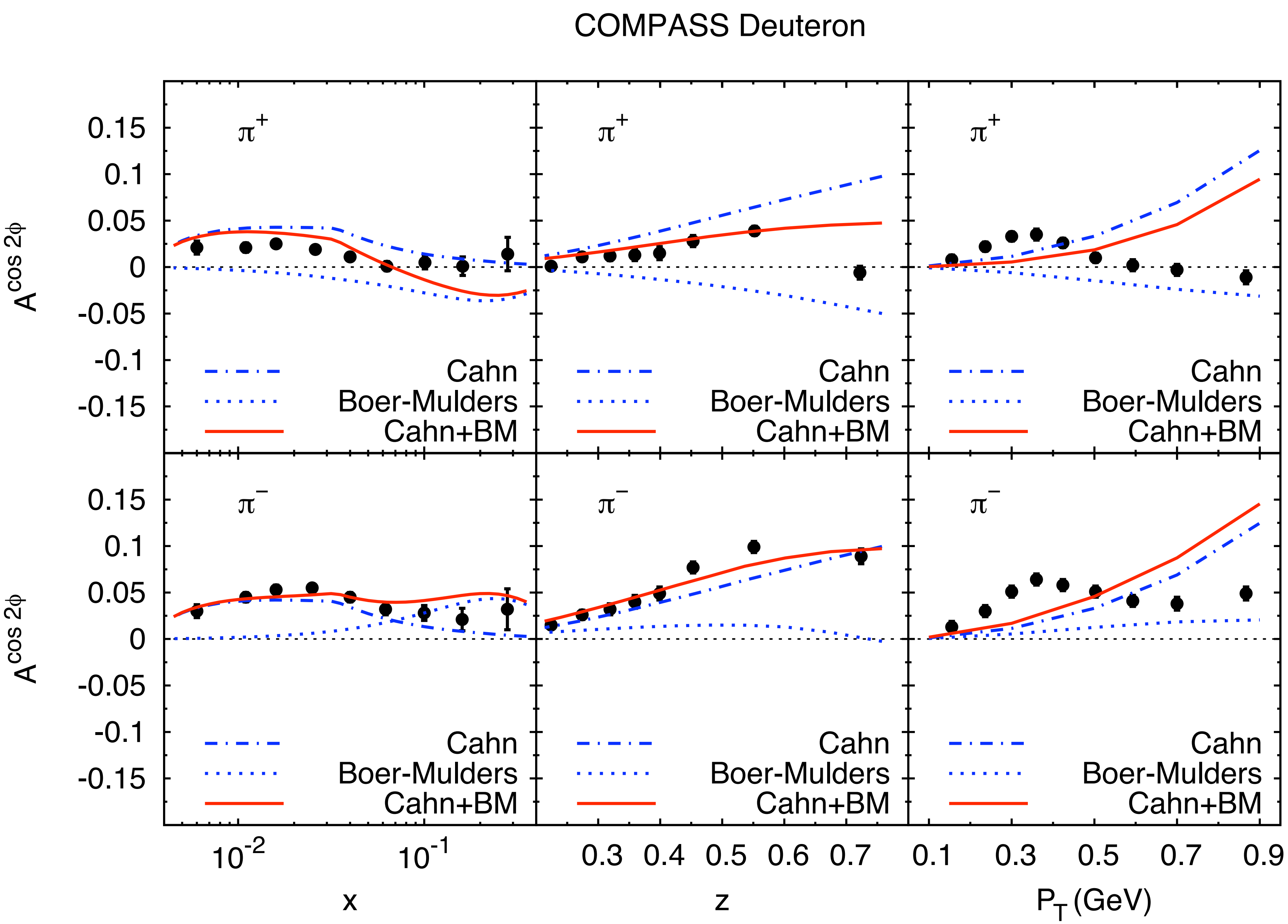
Barone, Melis, Prokudin, arXiv:0912.5194



opposite contribution to π^+, π^- given by B-M effect only

fit based on simple phenomenological assumption

$$h_1^{\perp q}(x, k_\perp^2) = \lambda_q \, f_{1T}^{\perp q}(x, k_\perp^2)$$



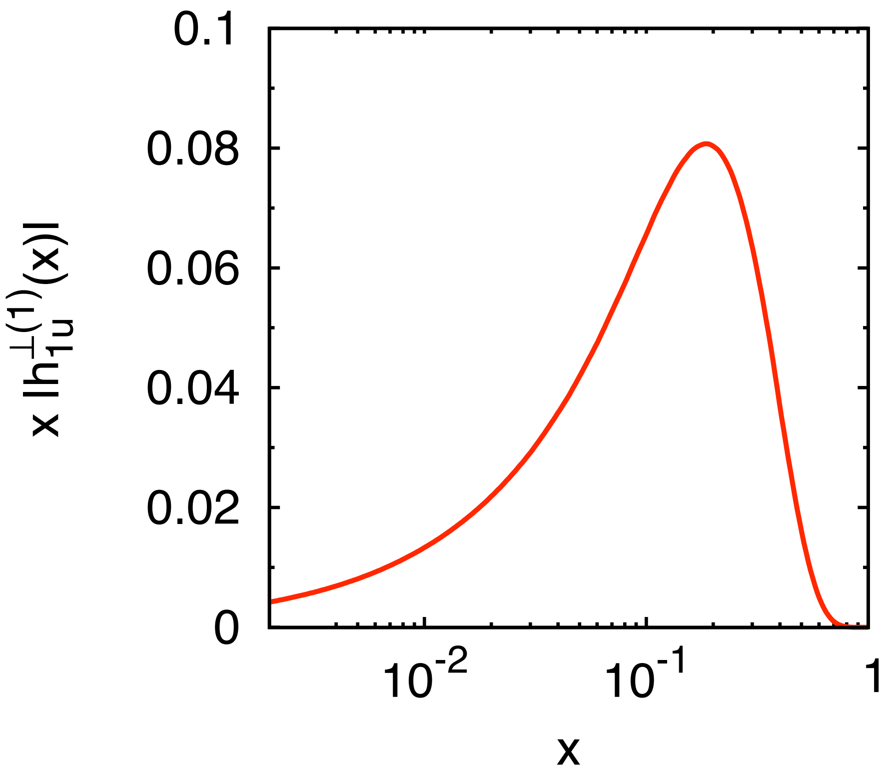
COMPASS and HERMES P_T data quite different

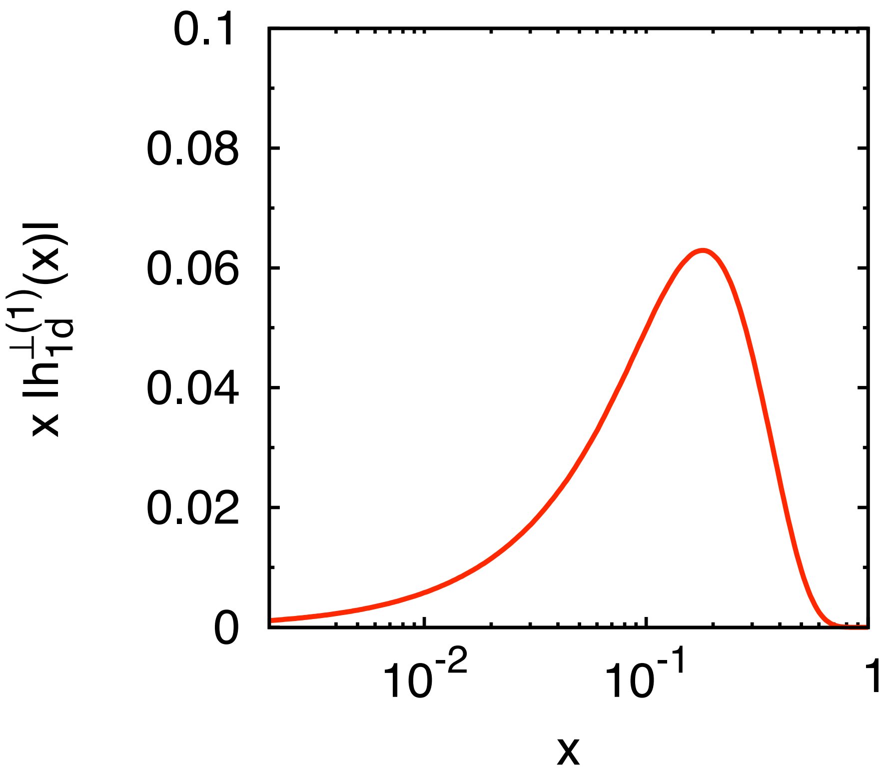
$h_1^{\perp u,d}$ both negative, as expected from models

$$\lambda_u \simeq 2.1 \qquad \lambda_d \simeq -1.1$$

Gaussian dependence of TMDs assumed,
Sivers and Collins distributions from other fits

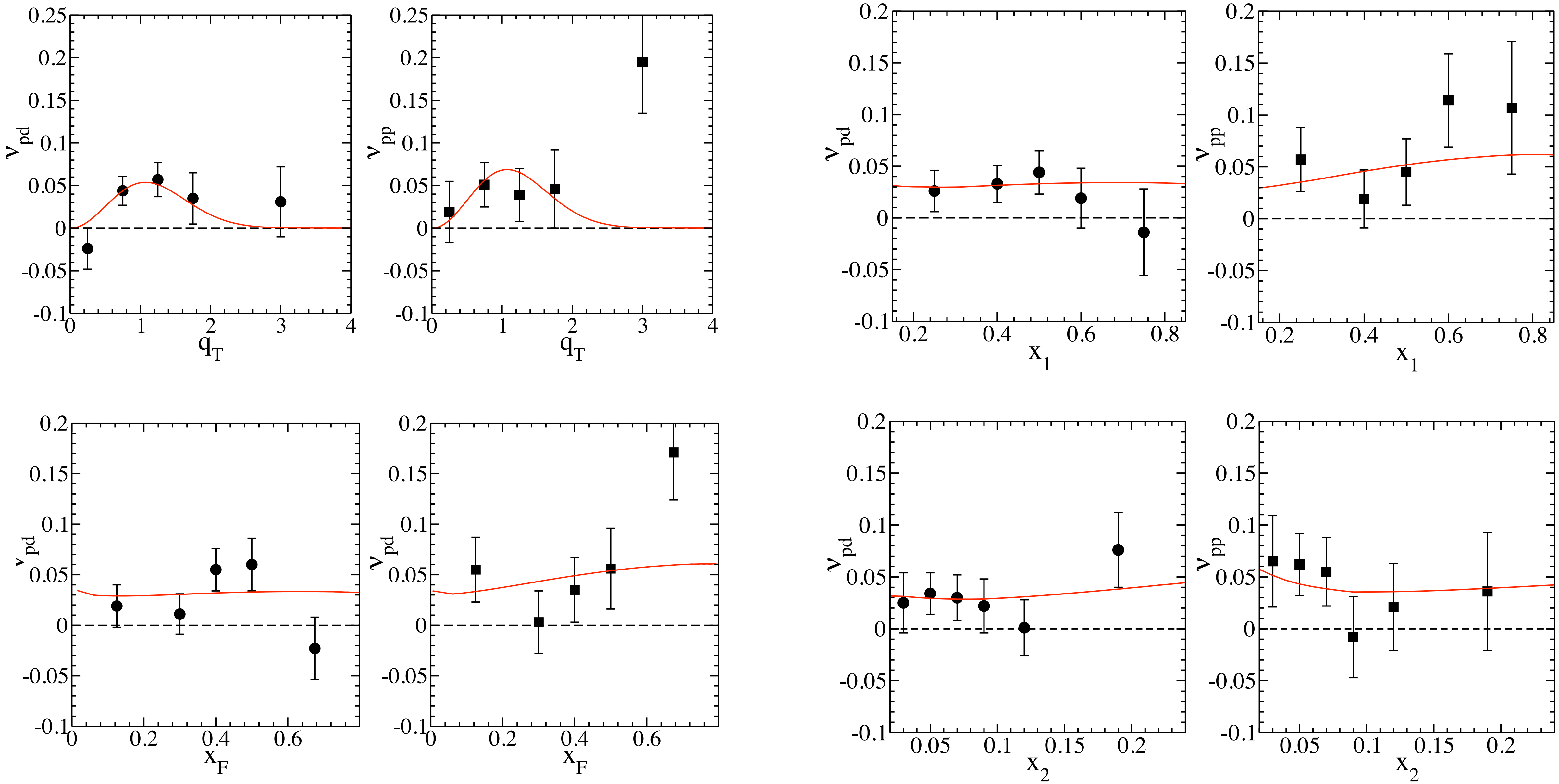
$$\langle k_\perp^2 \rangle = 0.18 \,(\mathrm{GeV}/c)^2 \qquad\qquad \langle k_\perp^2 \rangle = 0.20 \,(\mathrm{GeV}/c)^2$$





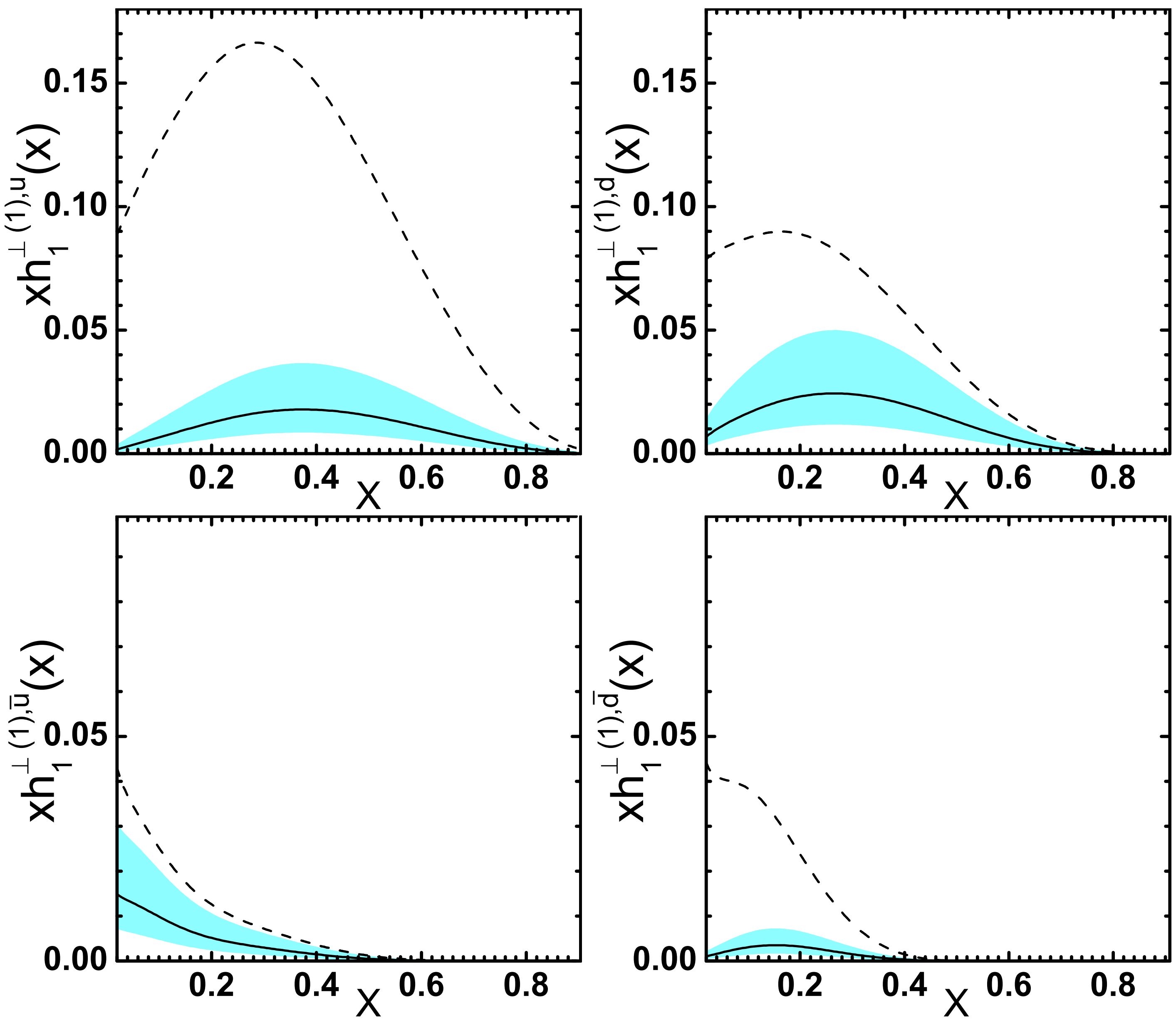
B-M function from Drell-Yan data alone

Lu, Schmidt, arXiv:0912.2031



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\,\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

best fit results, antiquark distribution needed



only relative signs of B-M functions can be fixed

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

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

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

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

neglecting twist-3 contributions

similar to the Wandzura-Wilczek relation

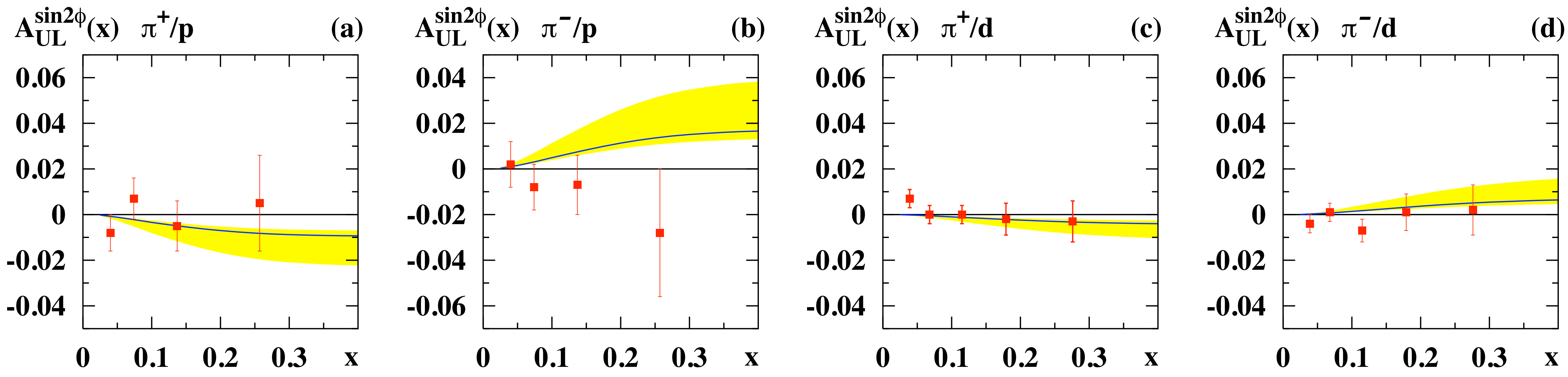
$$g_T^a(x) \simeq \int_x^1 \frac{\mathrm{d}y}{y}\, g_1^a(y)$$

supported by experiment

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

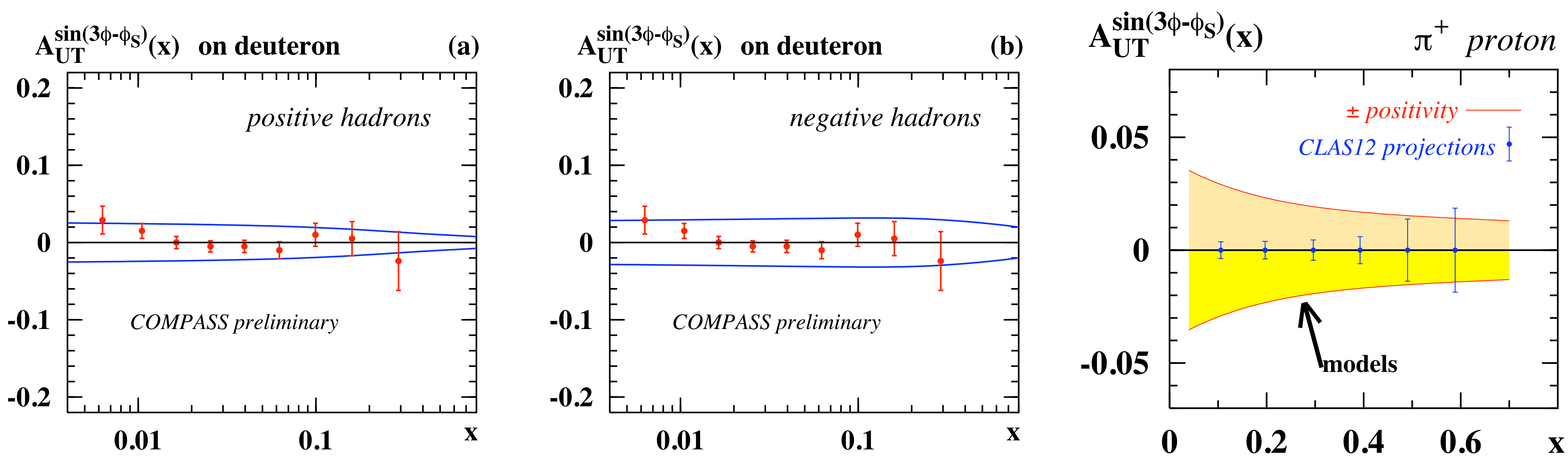
Avakian, Efremov, Schweitzer, Yuan, arXiv:0805.3355

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



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

Future ....

3-dimensional exploration of nucleon has just started:
collect as much data as possible on TMDs and GPDs and try to reconstruct the complete phase-space distribution

ideal machine:

high luminosity

x-range including the valence region

Q^2 high enough to neglect higher-twist corrections

P_T high enough to see transition from TMDs to pQCD

precise P_T-Q^2 bins ....

plenty of challenging theoretical issues....