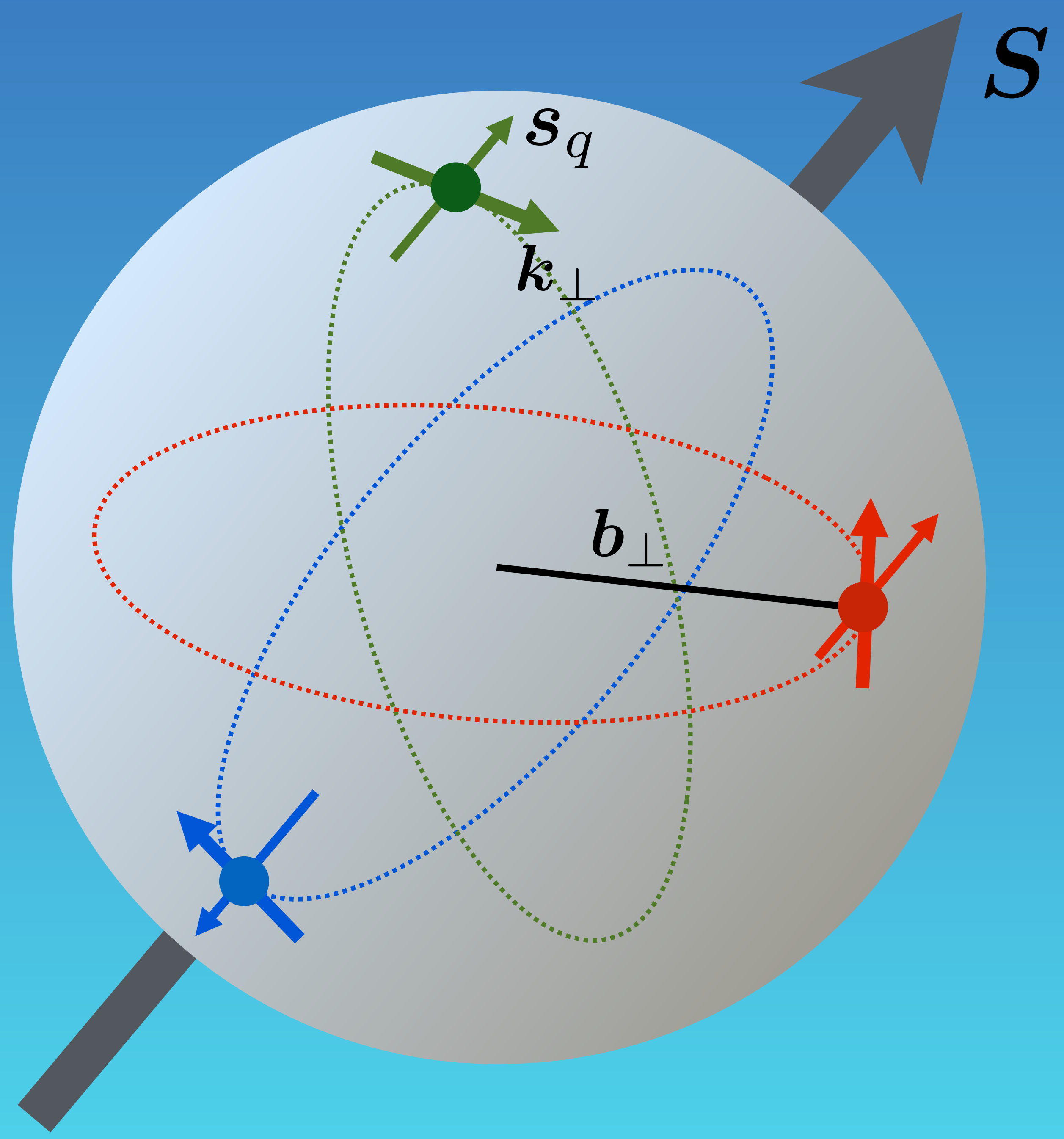
The 3-D nucleon structure

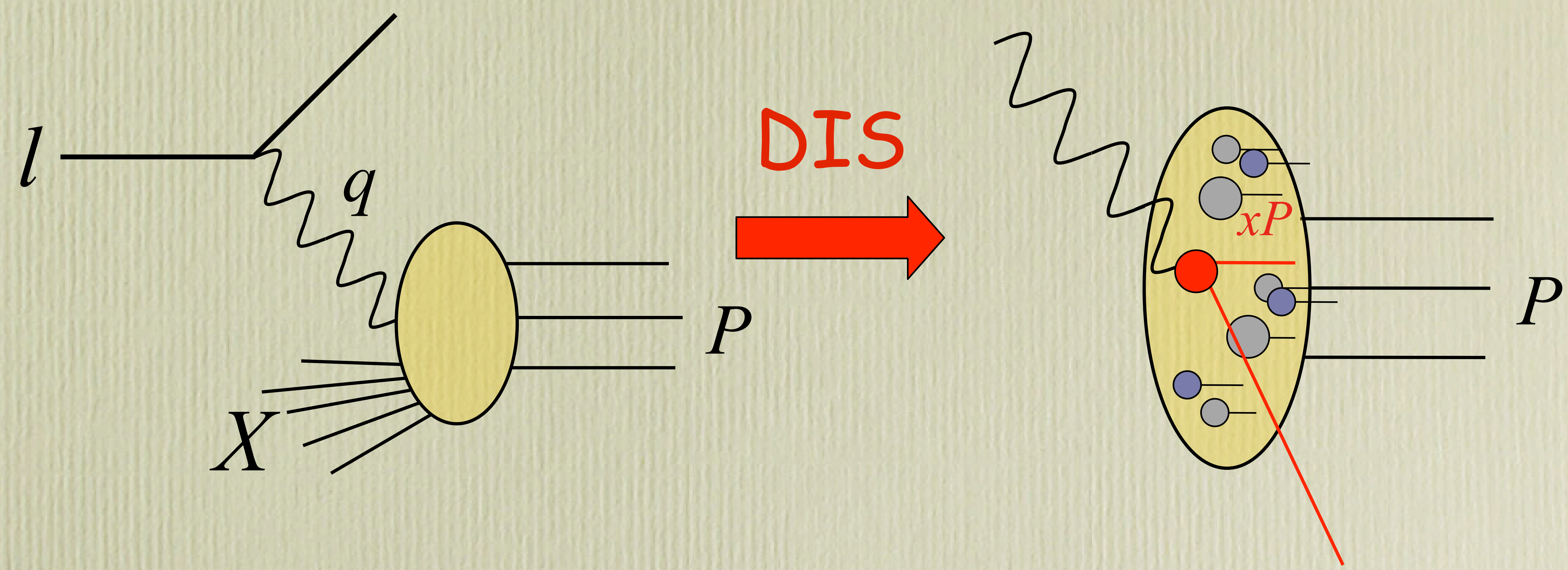
(and the EIC - Talk by R. Yoshida)



Mauro Anselmino - Torino University & INFN

Lepton-Nucleus Scattering XIV - Elba June 27, 2016

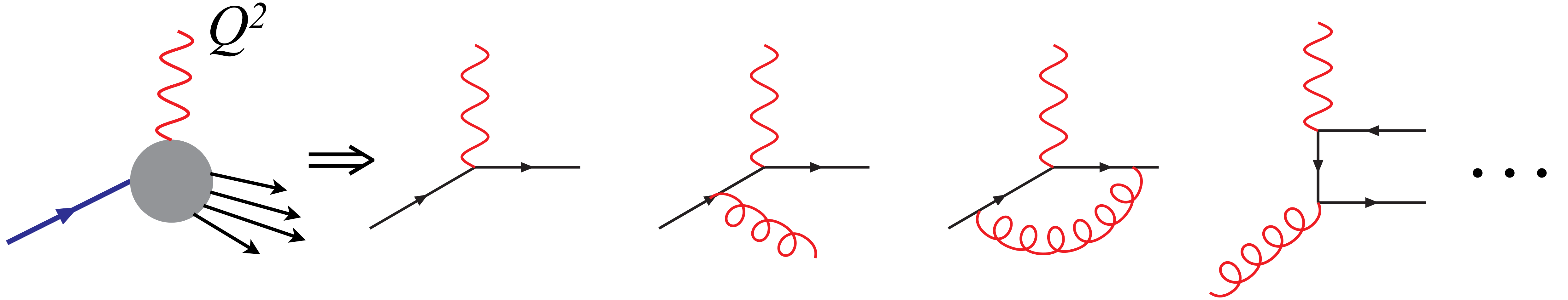
usual (successful) way of exploring the proton structure (collinear parton model)



$$\text{DIS}: \ \ell\, p \to \ell\, X \qquad Q^2 = -q^2 \qquad x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot \ell}{P\cdot q}$$

Naive parton model: $$\frac{\mathrm{d}\sigma^{\ell p\to \ell X}}{\mathrm{d}x\,\mathrm{d}Q^2} = \sum_q e_q^2\, q(x)\, \frac{\mathrm{d}\hat{\sigma}^{\ell q\to \ell q}}{\mathrm{d}Q^2}$$

QCD interactions induce a well known Q^2 dependence



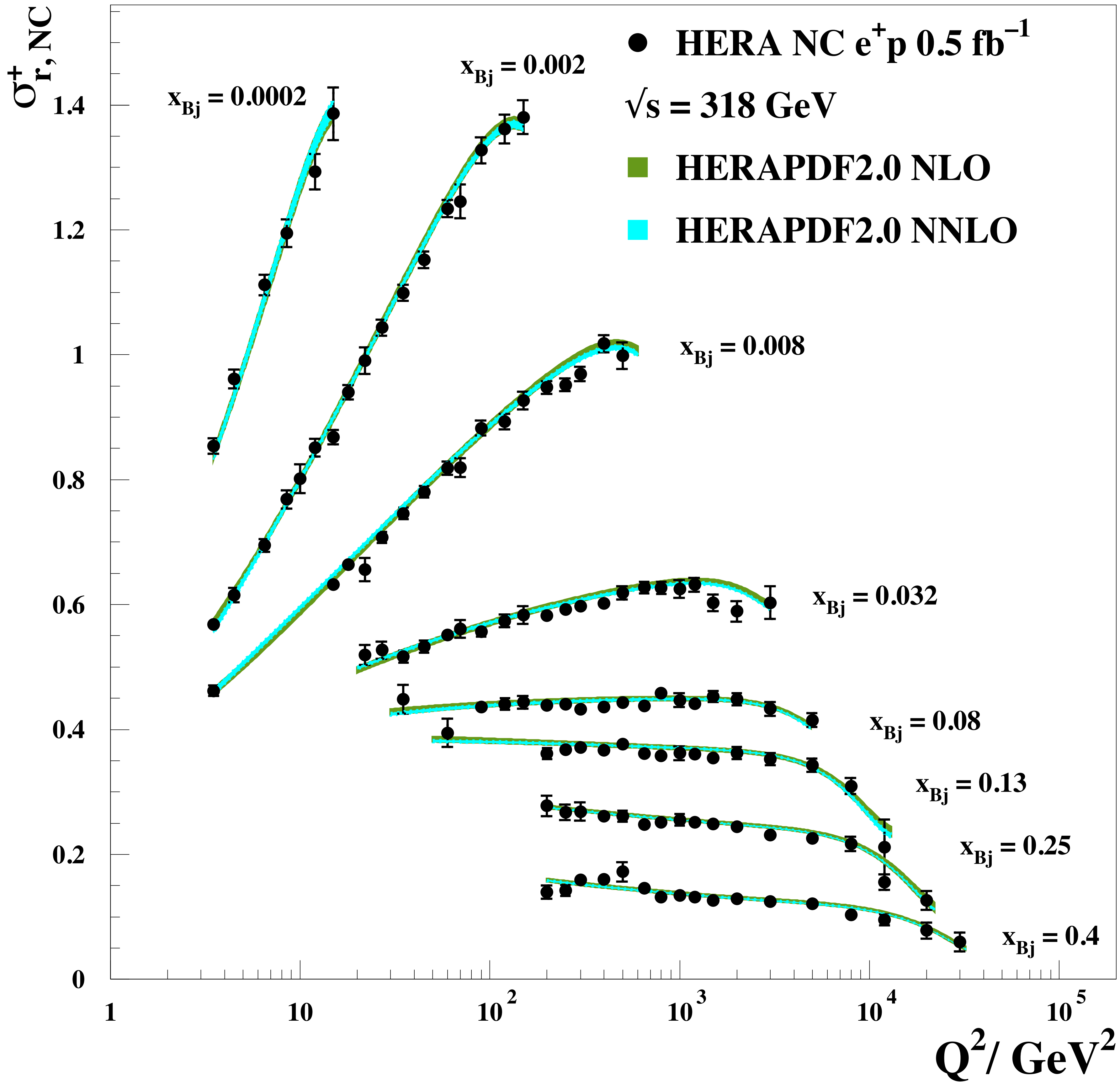
$$\mathrm{DIS-pQCD}: \quad q(x) \Rightarrow \underbrace{q(x, Q^2)}_{\text{PDFs}}$$

factorization:

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

universality: same $q(x,Q^2)$ measured in DIS can be used in other processes

H1 and ZEUS



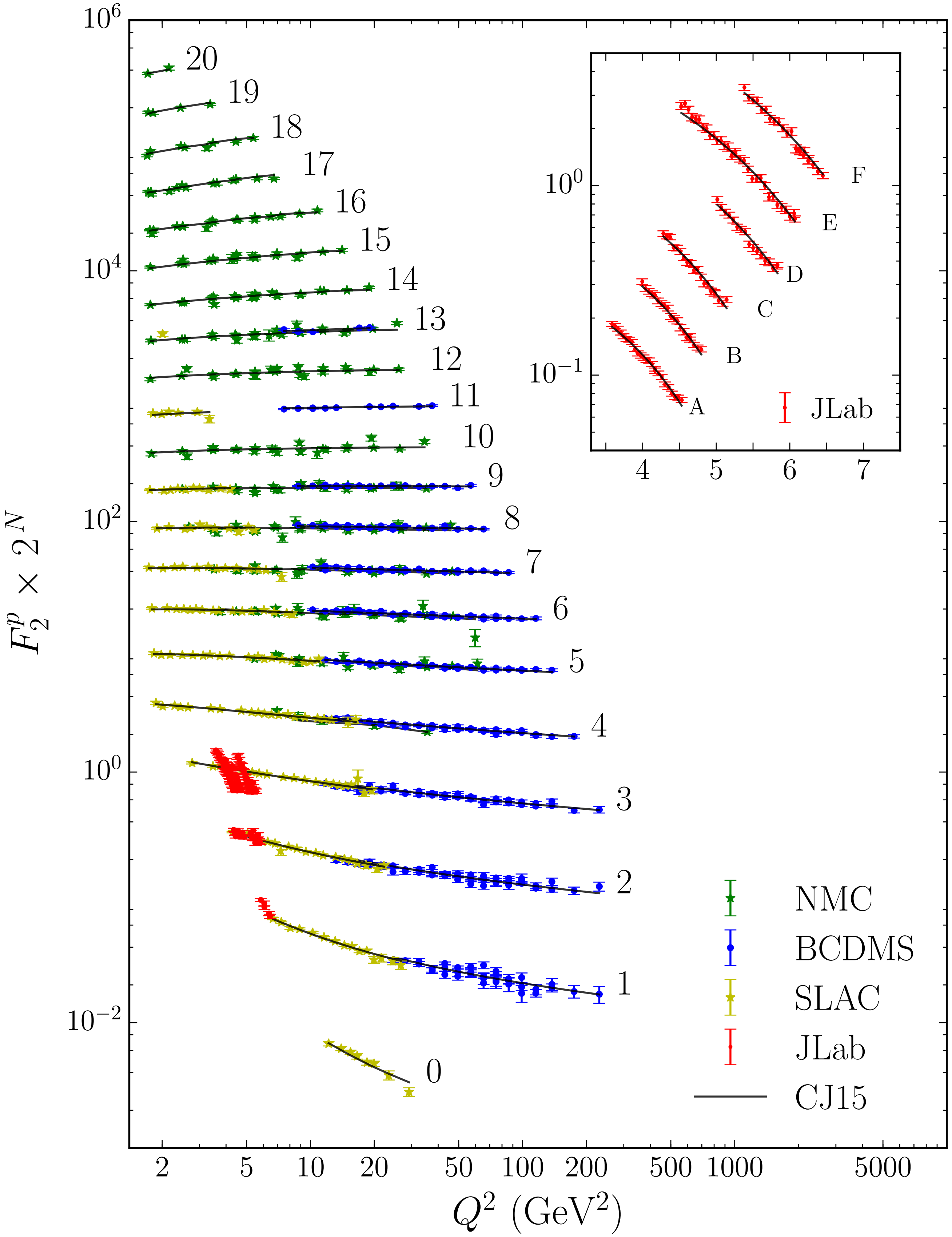
$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^\pm p}_{\mathrm{NC}}}{dx_{\mathrm{Bj}}dQ^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+}$$

$$Y_\pm = 1 \pm (1-y)^2$$

Eur. Phys. J. C75 (2015) 580

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

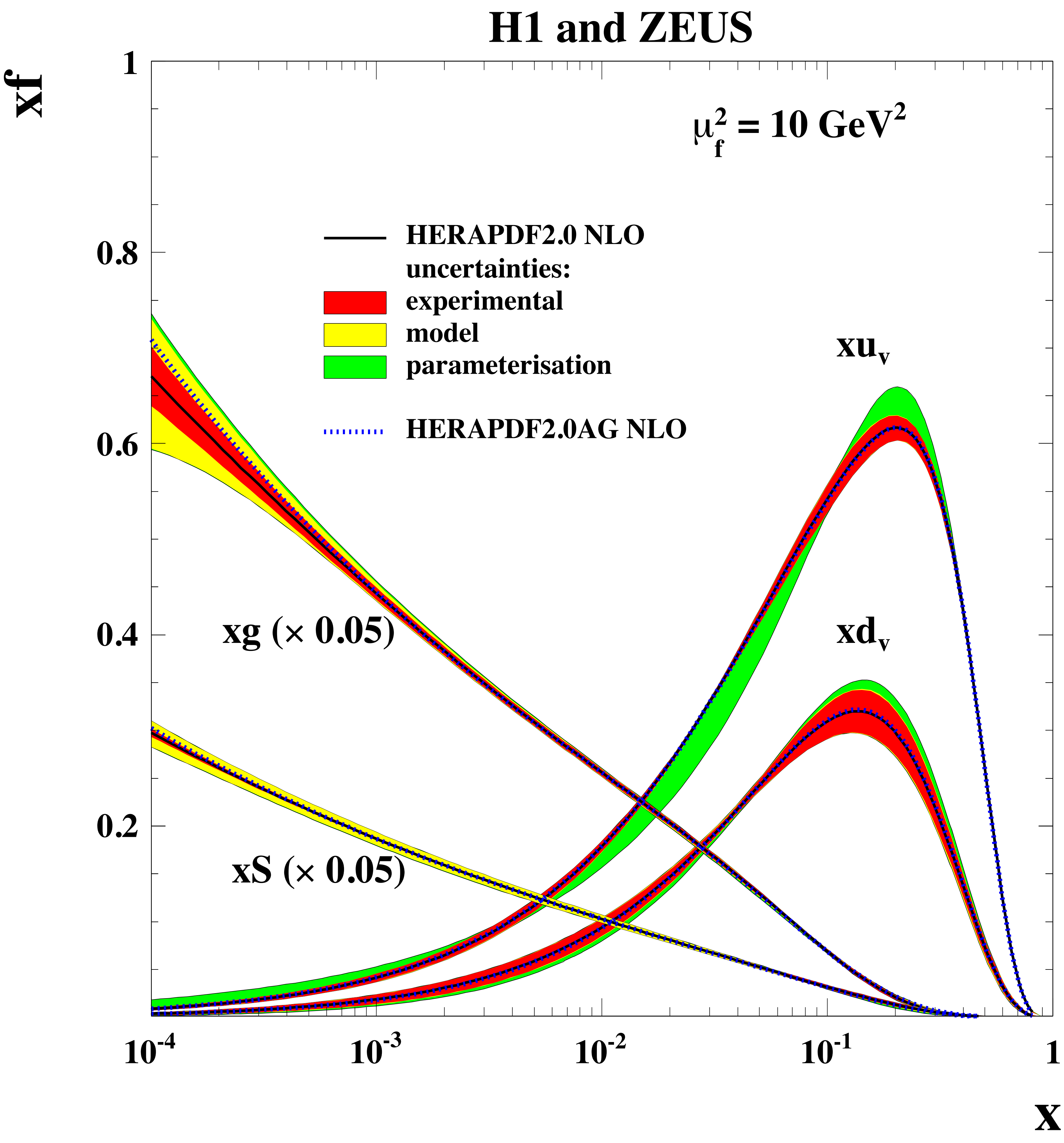
from M. Pennington, arXiv:1604.01441



N	x
0	0.85
1	0.74
2	0.65
3	0.55
4	0.45
5	0.34
6	0.28
7	0.23
8	0.18
9	0.14
10	0.11
11	0.10
12	0.09
13	0.07
14	0.05
15	0.04
16	0,026
17	0,018
18	0,013
19	0,008
20	0,005

JLab insert

I	°	N
A	38°	0
B	41°	1
C	45°	2
D	55°	3
E	60°	4
F	70°	5



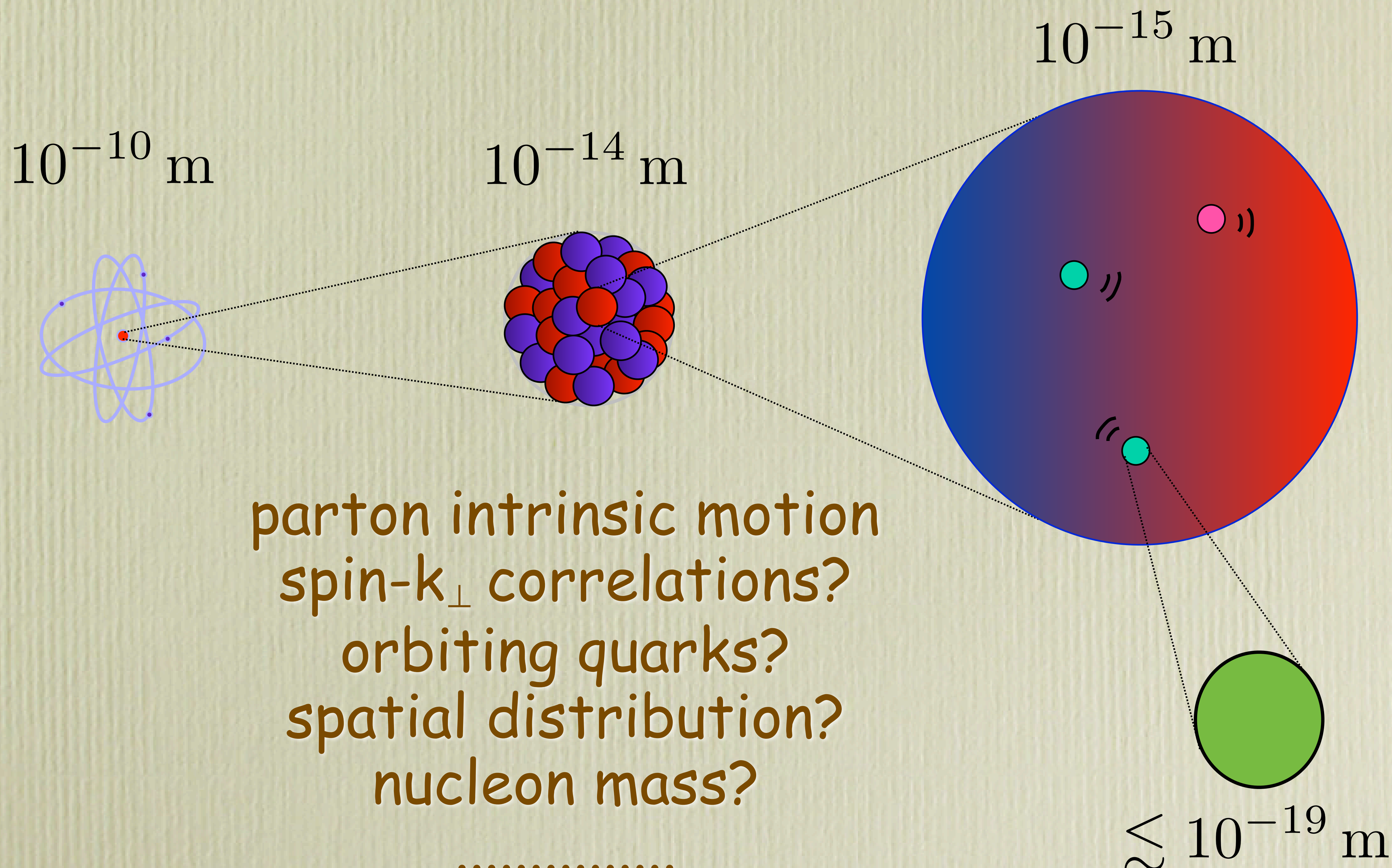
unpolarized distribution

$$x f_a(x, Q^2)$$

H. Abramowicz et al., Eur. Phys. J. C75 (2015) 580

PDFs are very useful, but do we really know the partonic nucleon structure?

despite 50 years of studies the nucleon is still a very mysterious object, and the most abundant piece of matter in the visible Universe



parton intrinsic motion

spin-$k_\perp$ correlations?

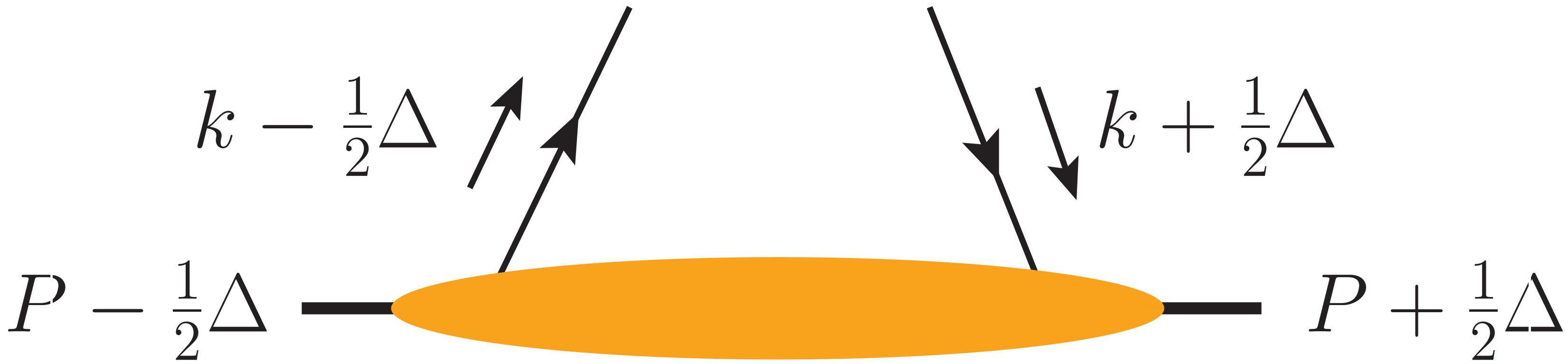
orbiting quarks?

spatial distribution?

nucleon mass?

....

what would we like to know ? how ?



$$H(k,P,\Delta) = (2\pi)^{-4}\int d^4z\, e^{izk} \times \langle p(P+\tfrac{1}{2}\Delta)|\bar{q}(-\tfrac{1}{2}z)\,\Gamma\, q(\tfrac{1}{2}z)|p(P-\tfrac{1}{2}\Delta)\rangle$$

two-quark correlation function

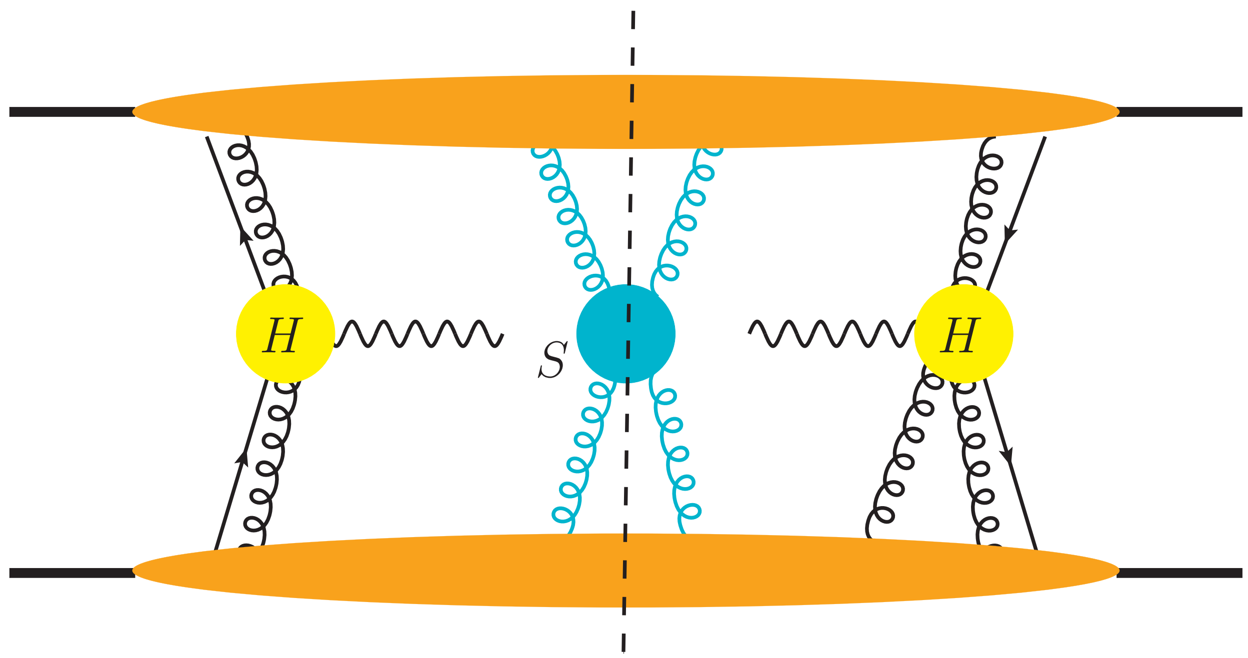
light-cone variables $v = (v^+, v^-, \boldsymbol{v})$ $\quad v^\pm = \frac{1}{\sqrt{2}}(v^0 \pm v^3)$

$$x = \frac{k^+}{P^+} \qquad 2\xi = -\frac{\Delta^+}{P^+}$$

$\Delta = 0$ inclusive processes, cross sections

$\Delta \neq 0$ exclusive processes, amplitudes

actually, things are not so simple… (example of D-Y process)



…the physical effects of these gluons are represented by Wilson line operators between the fields in the parton correlation function (integrated over k⁻) and by so called soft factors, which are vacuum expectation values of further Wilson lines and can be absorbed in the definition of the TMDs…

$$\langle p(P+\frac{1}{2}\Delta)|\bar{q}(-\frac{1}{2}z)\,\Gamma\,q(\frac{1}{2}z)|p(P-\frac{1}{2}\Delta)\rangle \to \langle p(P+\frac{1}{2}\Delta)|\bar{q}(-\frac{1}{2}z)\,\Gamma\,\mathcal{W}\,q(\frac{1}{2}z)|p(P-\frac{1}{2}\Delta)\rangle$$

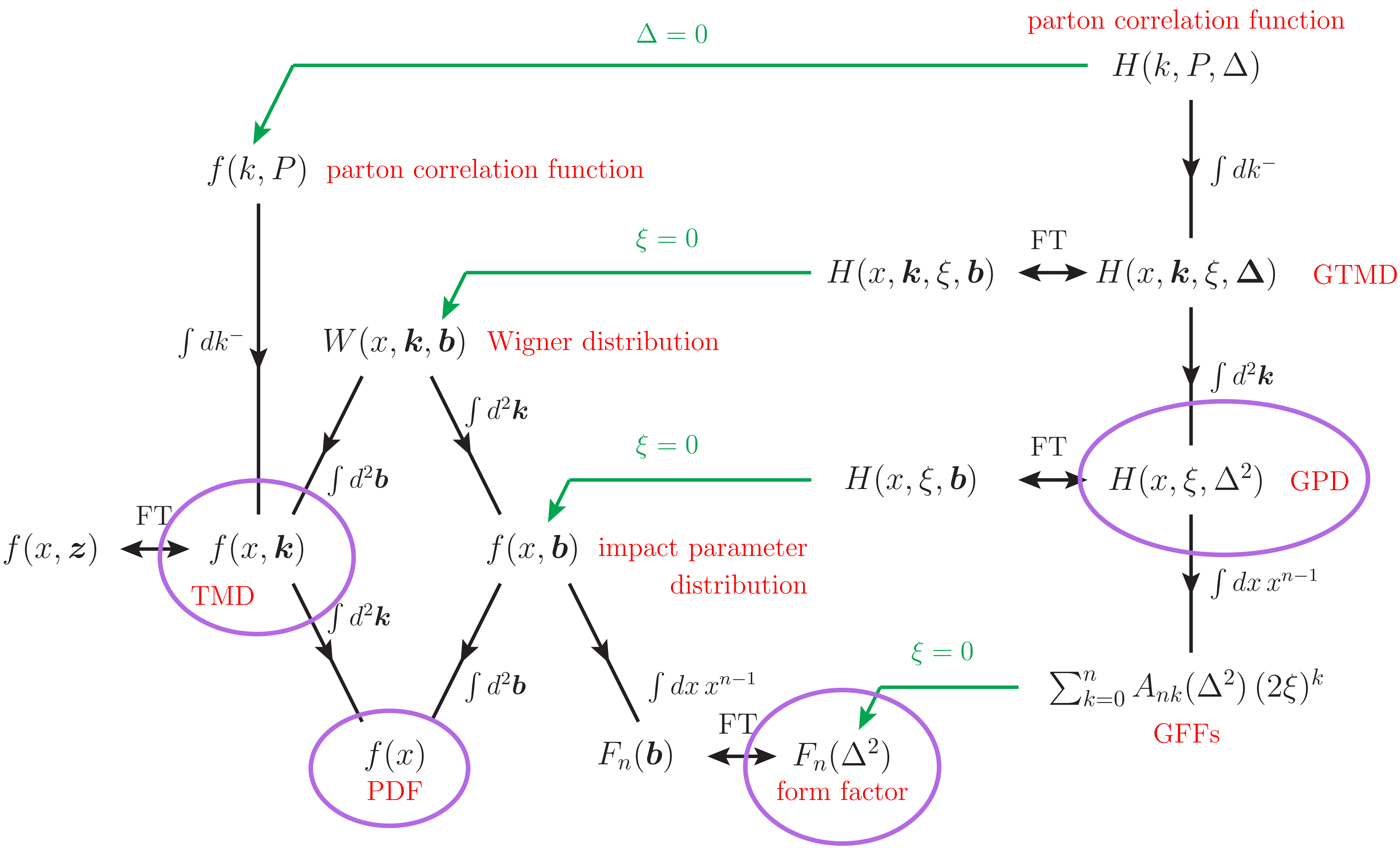
the Wilson lines are path-ordered exponential of the gauge field and turn the operator product into a gauge invariant operator, but induce some process dependence

M. Diehl, arXiv:1512.01328

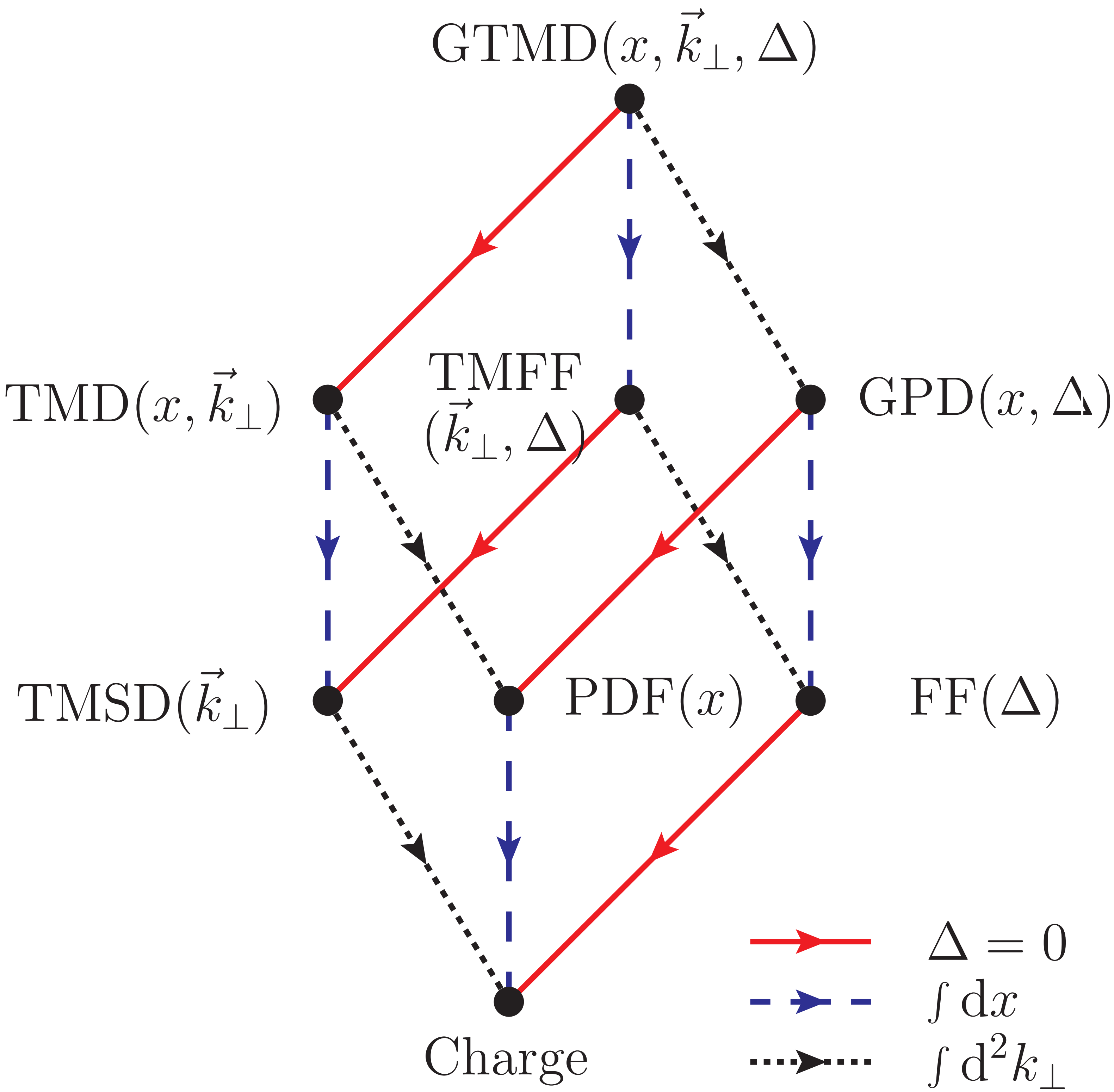
J. Collins, Cambridge University Press (2011)

The nucleon landscape

Markus Diehl, arXiv:1512.01328



Burkardt, Pasquini, arXiv:1510.02567

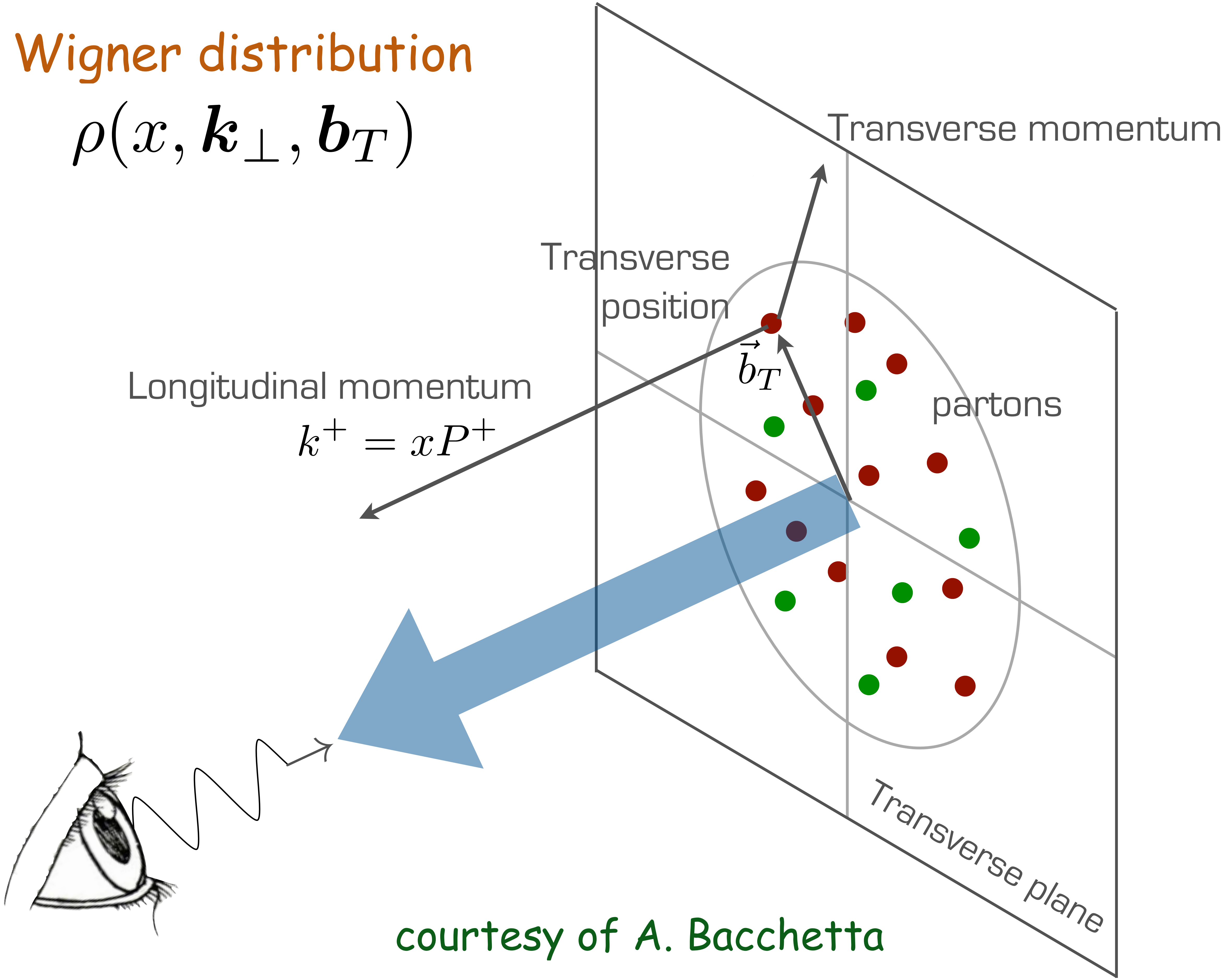


special issue of EPJA dedicated to the 3D nucleon structure, to appear soon

(15 contributions, Editors M.A., P. Rossi. M. Guidal)

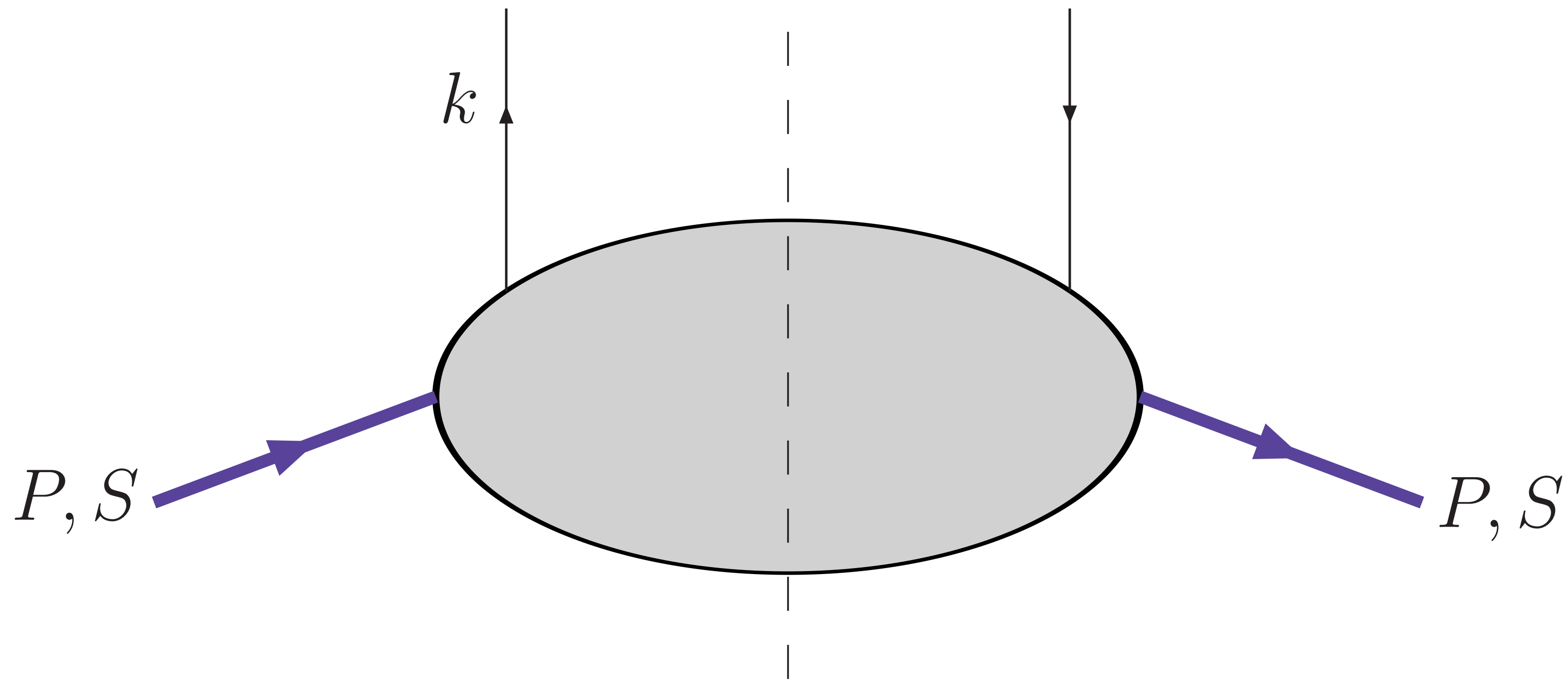
Wigner distribution

$$\rho(x, \boldsymbol{k}_\perp, \boldsymbol{b}_T)$$



courtesy of A. Bacchetta

TMD formalism - The nucleon correlator, in collinear configuration: 3 distribution functions



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

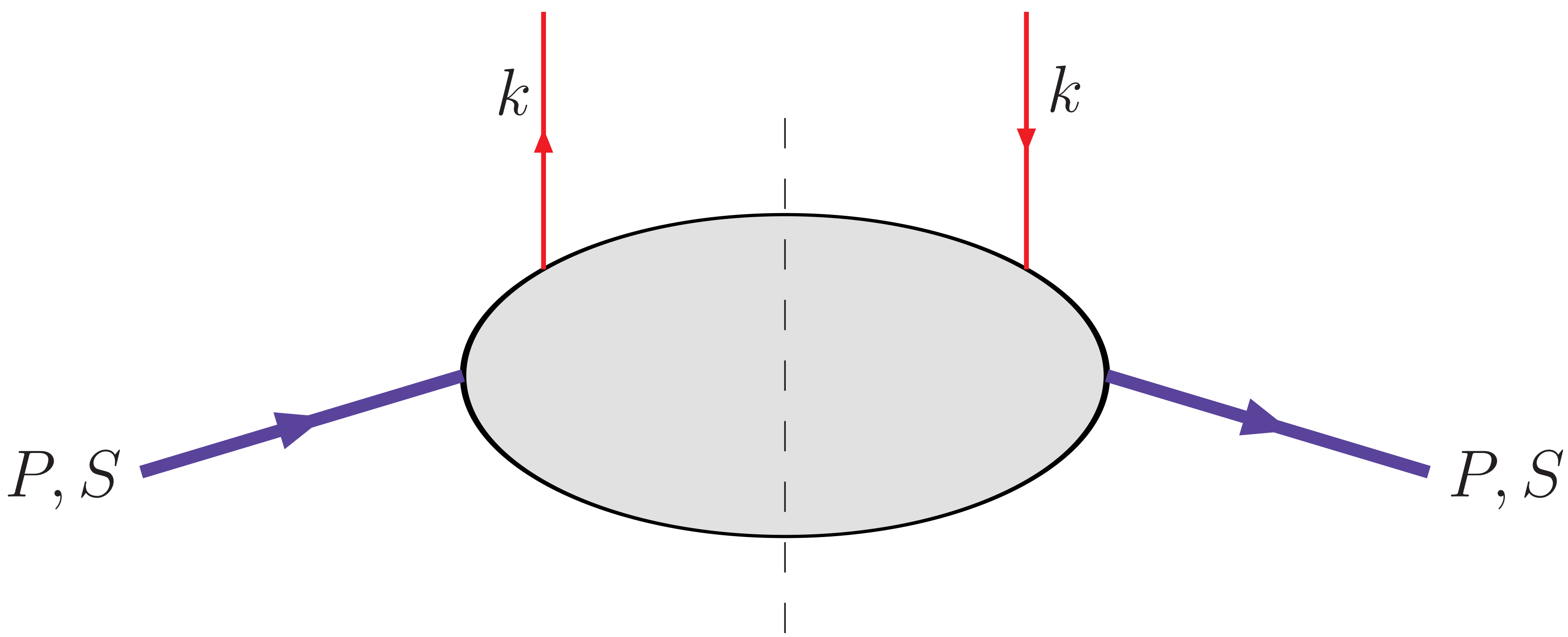
$$= \int d^4\xi\, e^{ik\cdot\xi} \langle PS|\overline{\Psi}_j(0)\Psi_i(\xi)|PS\rangle$$

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

$f_1(x)$: q — $g_{1L}(x)$: Δq — h_{1T}: $\Delta_T q$

TMD-PDFs: the leading-twist correlator, with intrinsic $k_\perp$, contains 8 independent functions

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

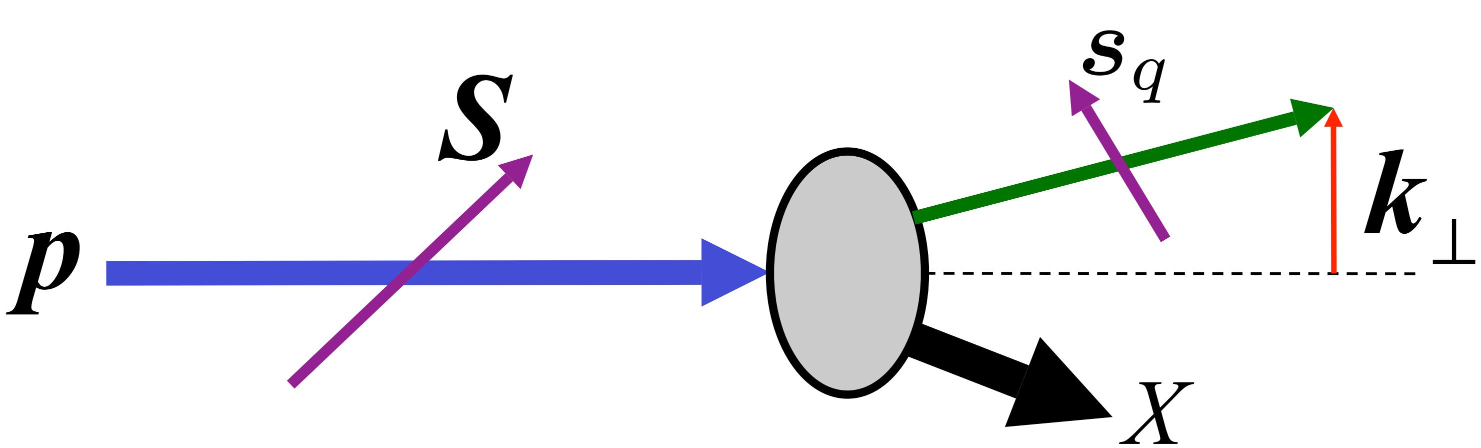


with partonic interpretation

TMDs in simple parton model

TMDs = Transverse Momentum Dependent Parton Distribution Functions (TMD-PDF) or Transverse Momentum Dependent Fragmentation Functions (TMD-FF)

TMD-PDFs give the number density of partons, with their intrinsic motion and spin, inside a fast moving proton, with its spin.



$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$ $\quad$ $\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$ $\quad$ $\boldsymbol{S} \cdot \boldsymbol{s}_q$ $\quad \cdots$

"Sivers effect" "Boer-Mulders effect"

there are 8 independent TMD-PDFs

$f_1^q(x, \boldsymbol{k}_\perp^2)$ unpolarized quarks in unpolarized protons
unintegrated unpolarized distribution

$g_{1L}^q(x, \boldsymbol{k}_\perp^2)$ correlate s_L of quark with S_L of proton
unintegrated helicity distribution

$h_{1T}^q(x, \boldsymbol{k}_\perp^2)$ correlate s_T of quark with S_T of proton
unintegrated transversity distribution

only these survive in the collinear limit

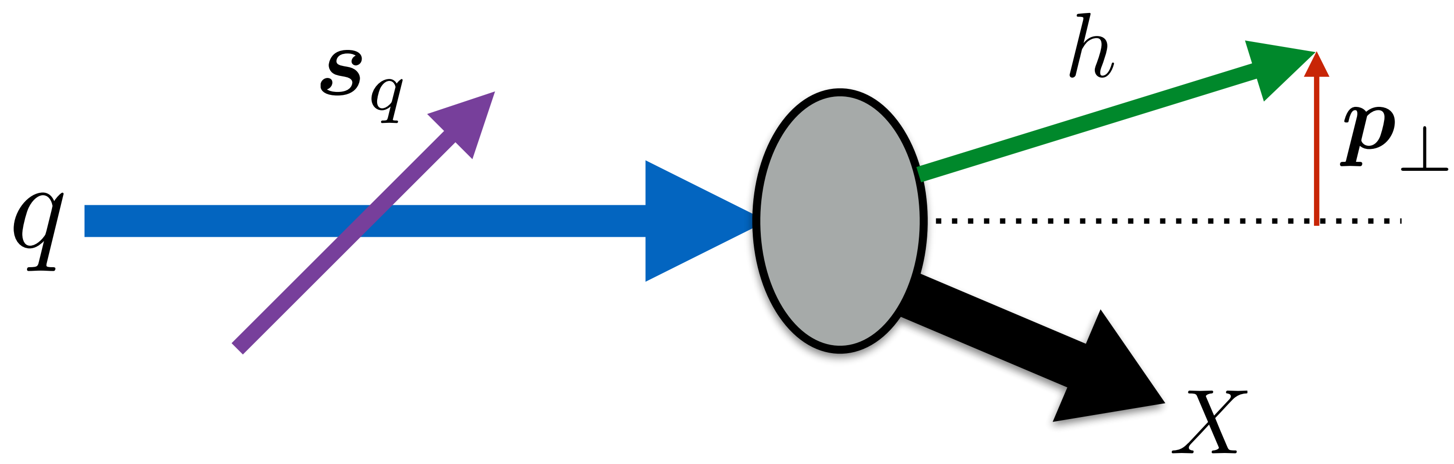
$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ of quark with S_T of proton (Sivers)

$h_1^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ and s_T of quark (Boer-Mulders)

$$g_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2) \quad h_{1L}^{\perp q}(x, \boldsymbol{k}_\perp^2) \quad h_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$$

different double-spin correlations

TMD-FFs give the number density of hadrons, with their momentum, originated in the fragmentation of a fast moving parton, with its spin.



$$s_q \cdot (p_q \times p_\perp)$$ "Collins effect"

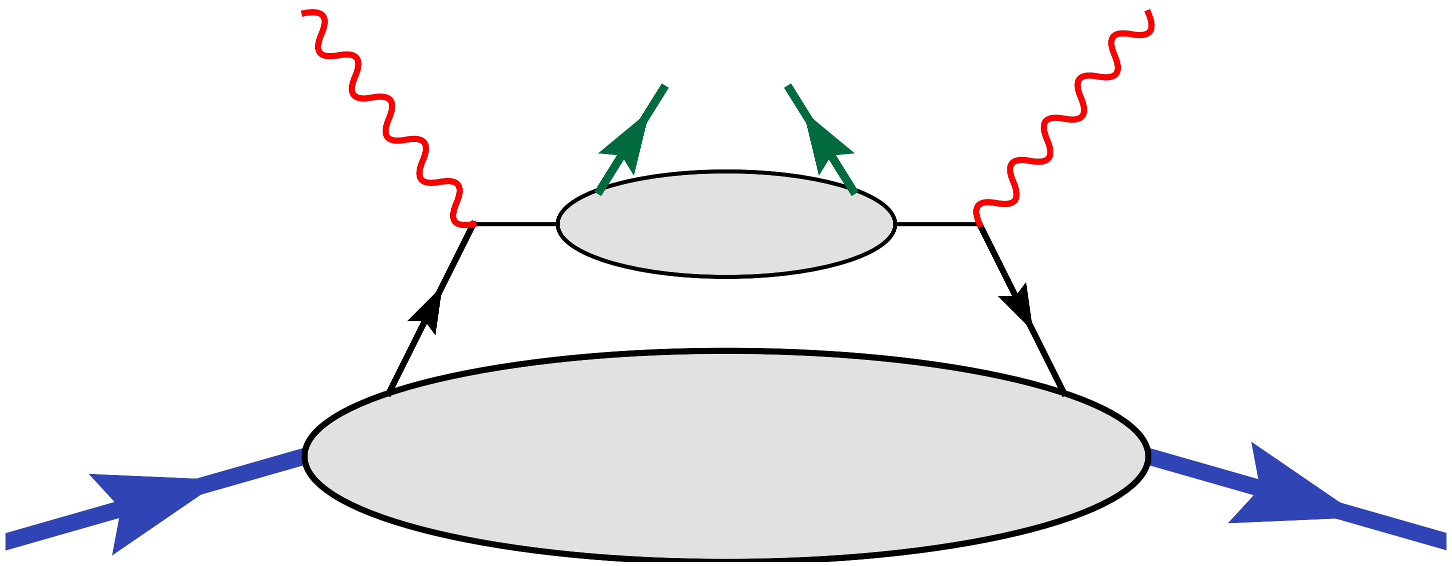
there are 2 independent TMD-FFs for spinless hadrons

$D_1^q(z, p_\perp^2)$ unpolarized hadrons in unpolarized quarks unintegrated fragmentation function

$H_1^{\perp q}(z, p_\perp^2)$ correlate $p_\perp$ of hadron with s_T of quark (Collins)

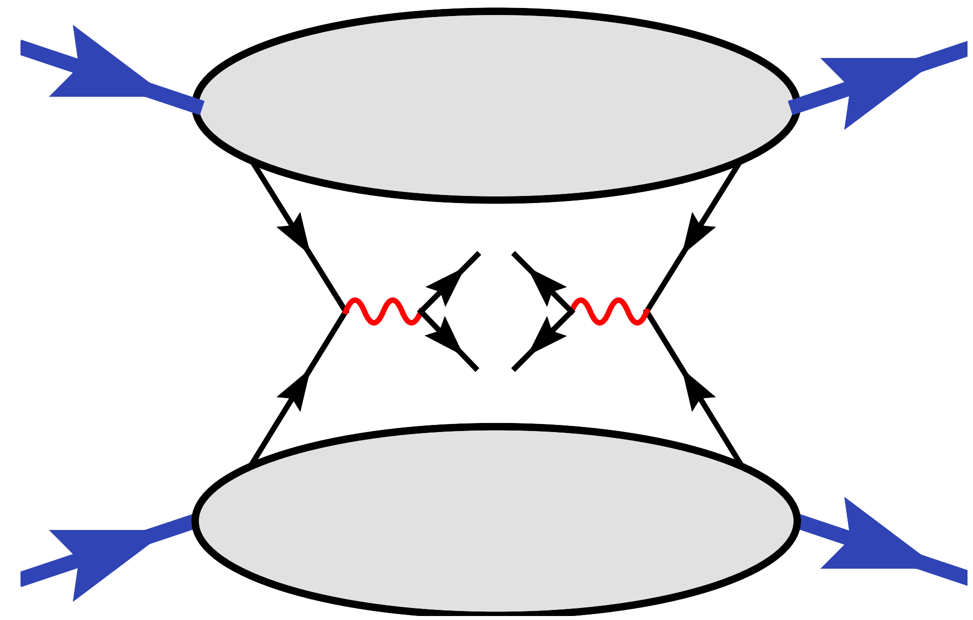
how to "measure" TMDs?

needs processes which relate physical observables
to parton intrinsic motion



SIDIS

$\ell \, N \to \ell \, h \, X$

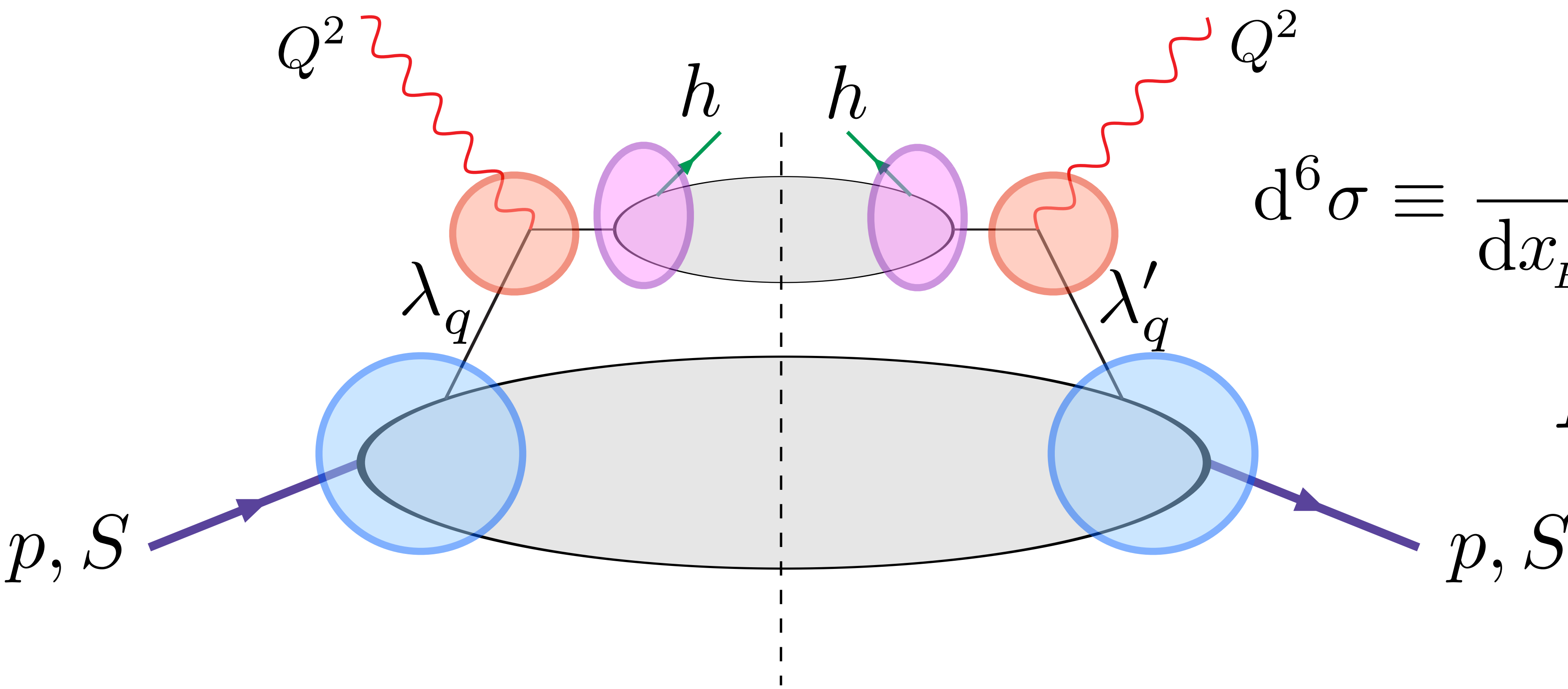


Drell-Yan processes

$p \, N \to \ell^+ \ell^- X$

a similar diagram for $e^+ e^- \to h_1 \, h_2 \, X$
and, possibly, for $p \, N \to h \, X$

TMDs in SIDIS



$$d^6\sigma \equiv \frac{d^6\sigma^{\ell p^\uparrow \to \ell h X}}{dx_B \, dQ^2 \, dz_h \, d^2\boldsymbol{P}_T \, d\phi_S}$$

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

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

Two scales: $P_T \ll Q^2$

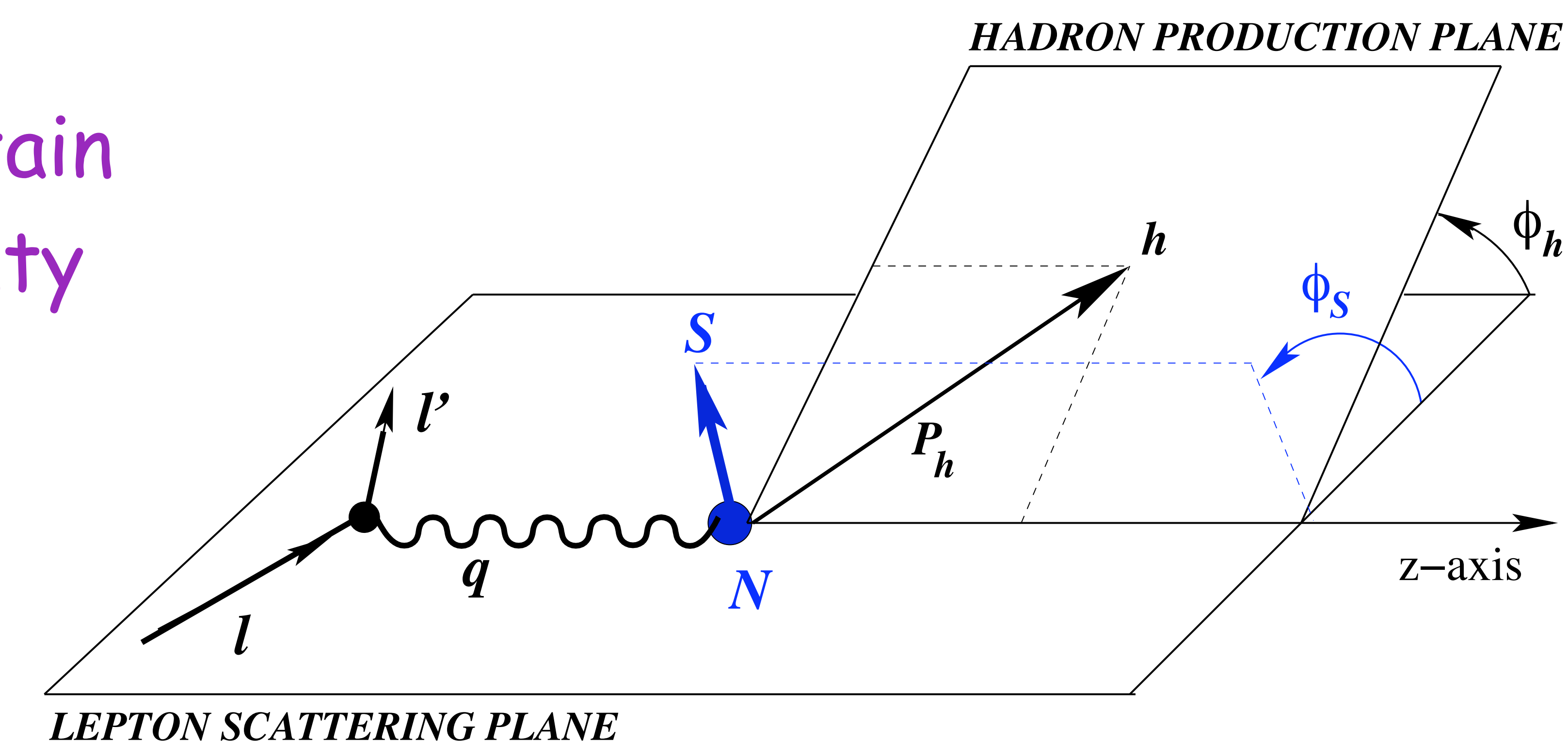
TMD-PDFs hard scattering TMD-FFs

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

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

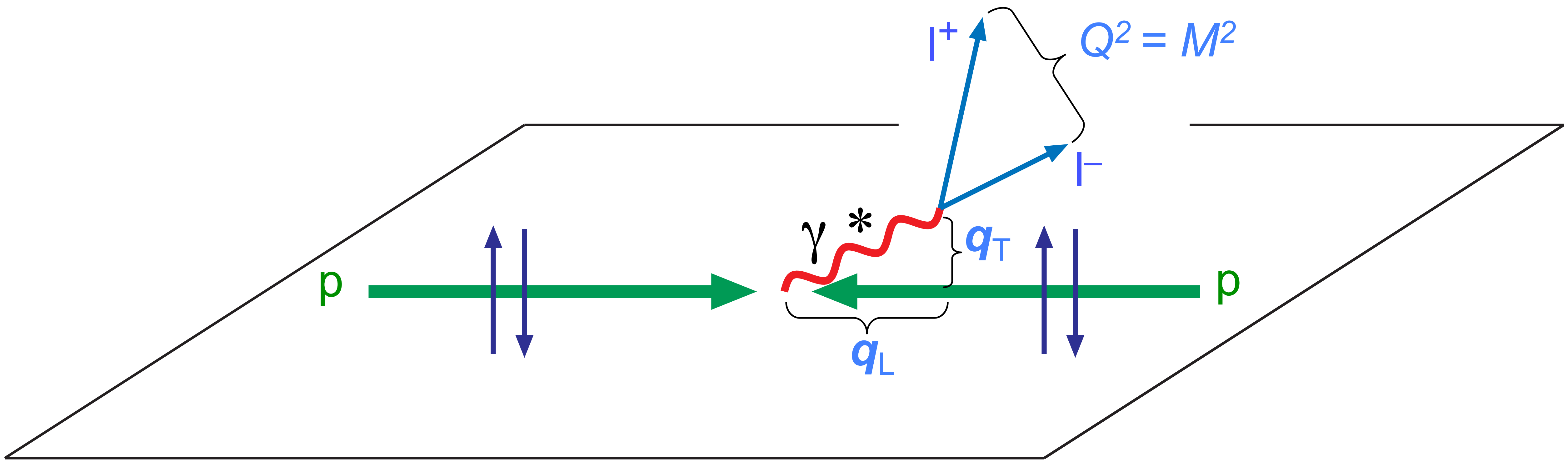
$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \;=\;& F_{UU} + \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \frac{1}{Q}\,\cos\phi\, F_{UU}^{\cos\phi} + \lambda\,\frac{1}{Q}\,\sin\phi\, F_{LU}^{\sin\phi} \\
&+\; S_L \left\{ \sin(2\phi)\, F_{UL}^{\sin(2\phi)} + \frac{1}{Q}\,\sin\phi\, F_{UL}^{\sin\phi} + \lambda \left[F_{LL} + \frac{1}{Q}\,\cos\phi\, F_{LL}^{\cos\phi} \right] \right\} \\
&+\; S_T \Big\{ \underbrace{\sin(\phi-\phi_S)\, F_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers}} + \underbrace{\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins}} + \sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)} \\
&+\; \frac{1}{Q} \left[\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)} + \sin\phi_S\, F_{UT}^{\sin\phi_S} \right] \\
&+\; \lambda \left[\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \frac{1}{Q} \left(\cos\phi_S\, F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)} \right) \right] \Big\}
\end{aligned}
$$

the $F^{(\cdots)}_{S_B\,S_T}$ contain the TMDs; plenty of Spin Asymmetries



TMDs in Drell-Yan processes

COMPASS, RHIC, Fermilab, NICA, AFTER...



factorization holds, two scales, M^2, and $q_T \ll M$

$$d\sigma^{D-Y} = \sum_a f_q(x_1, \boldsymbol{k}_{\perp 1}; Q^2) \otimes f_{\bar{q}}(x_2, \boldsymbol{k}_{\perp 2}; Q^2)\, d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}$$

direct product of TMDs, no fragmentation process

Case of one polarized nucleon only

$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha^2}{\Phi\, q^2}\Big\{(1+\cos^2\theta)\, F_U^1 + (1-\cos^2\theta)\, F_U^2 + \sin 2\theta \cos\phi\, F_U^{\cos\phi} + \sin^2\theta\cos 2\phi\, F_U^{\cos 2\phi}$$

B-M ⊗ B-M

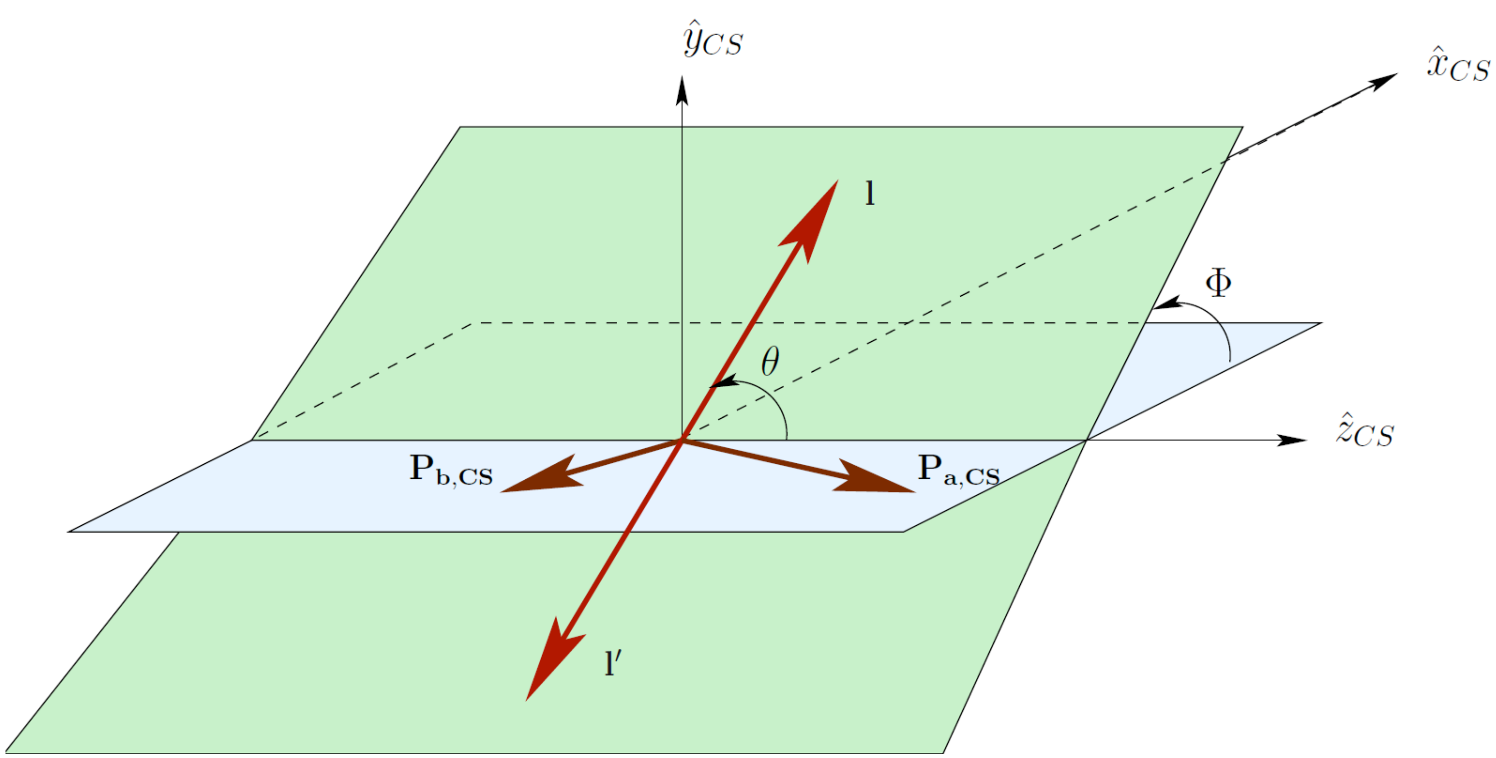
$$+\ S_L\left(\sin 2\theta \sin\phi\, F_L^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_L^{\sin 2\phi}\right)$$

$$+\ S_T\Big[\left(F_T^{\sin\phi_S} + cos^2\theta\, \tilde{F}_T^{\sin\phi_S}\right)\sin\phi_S + \sin 2\theta\,\Big(\sin(\phi+\phi_S)\, F_T^{\sin(\phi+\phi_S)}$$

$$+\ \sin(\phi-\phi_S)\, F_T^{\sin(\phi-\phi_S)}\Big)$$

Sivers

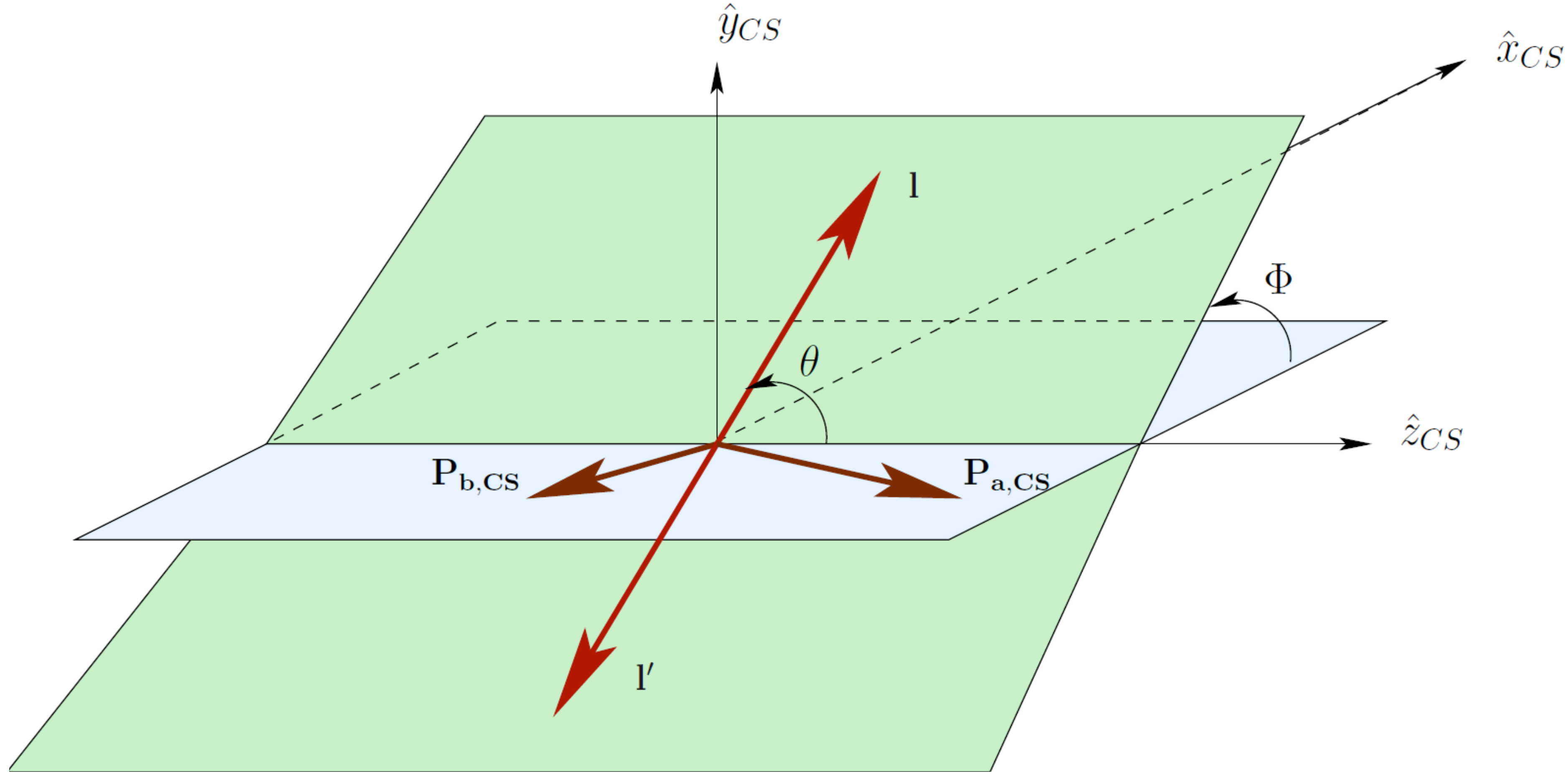
$$+\ \sin^2\theta\left(\sin(2\phi+\phi_S)\, F_T^{\sin(2\phi+\phi_S)} + \sin(2\phi-\phi_S)\, F_T^{\sin(2\phi-\phi_S)}\right)\Big]\Big\}$$



Collins-Soper frame

Unpolarized cross section already very interesting

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

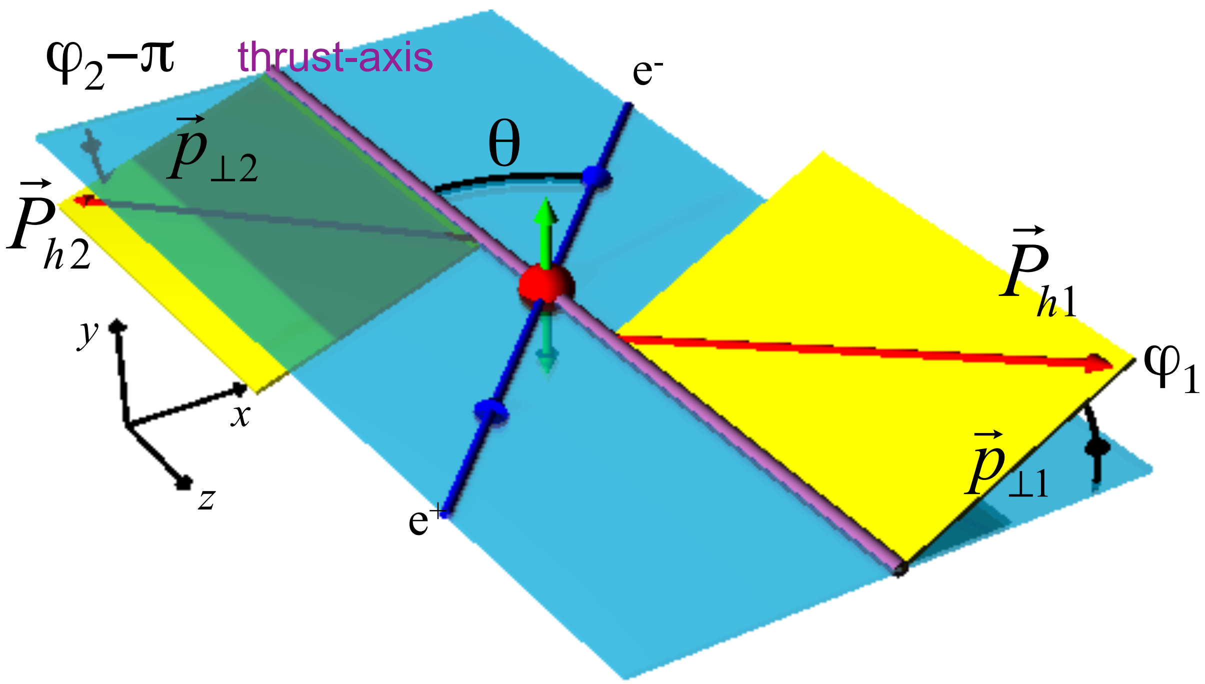


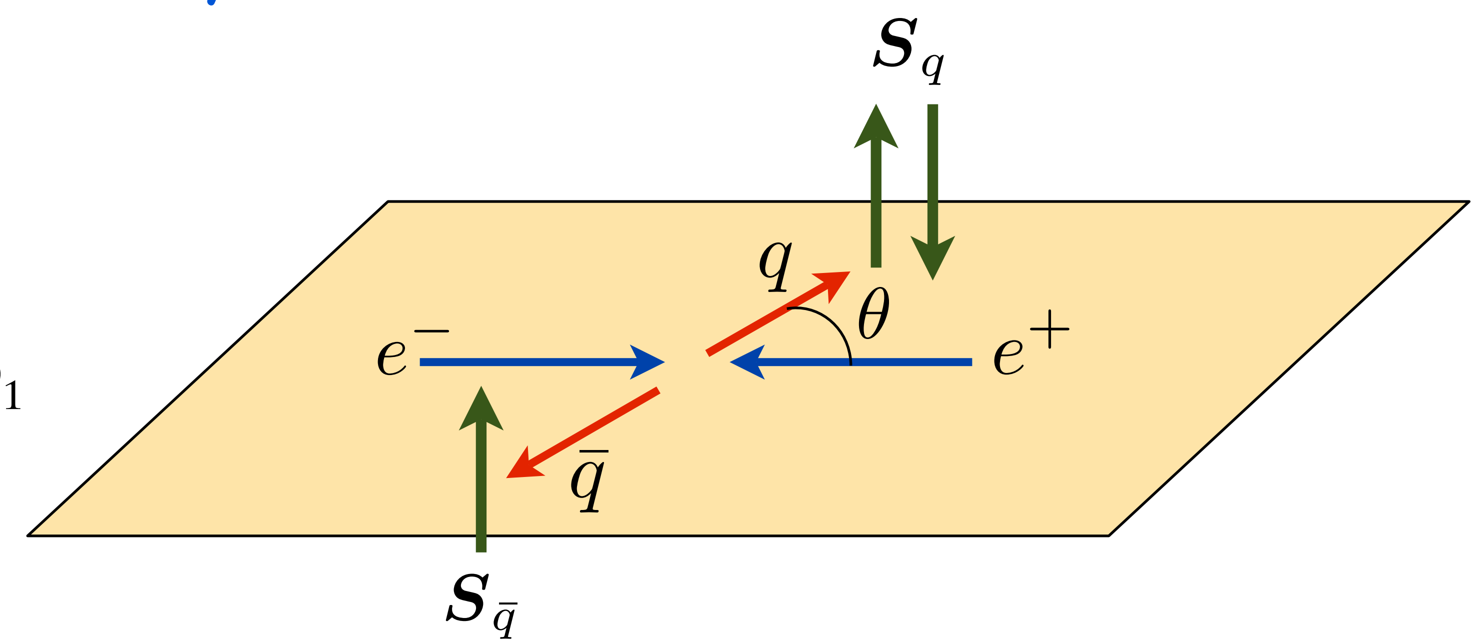
Collins-Soper frame

naive collinear parton model: $\lambda = 1 \quad \mu = \nu = 0$

Collins function from e^+e^- processes

Belle, BaBar, BES-III





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

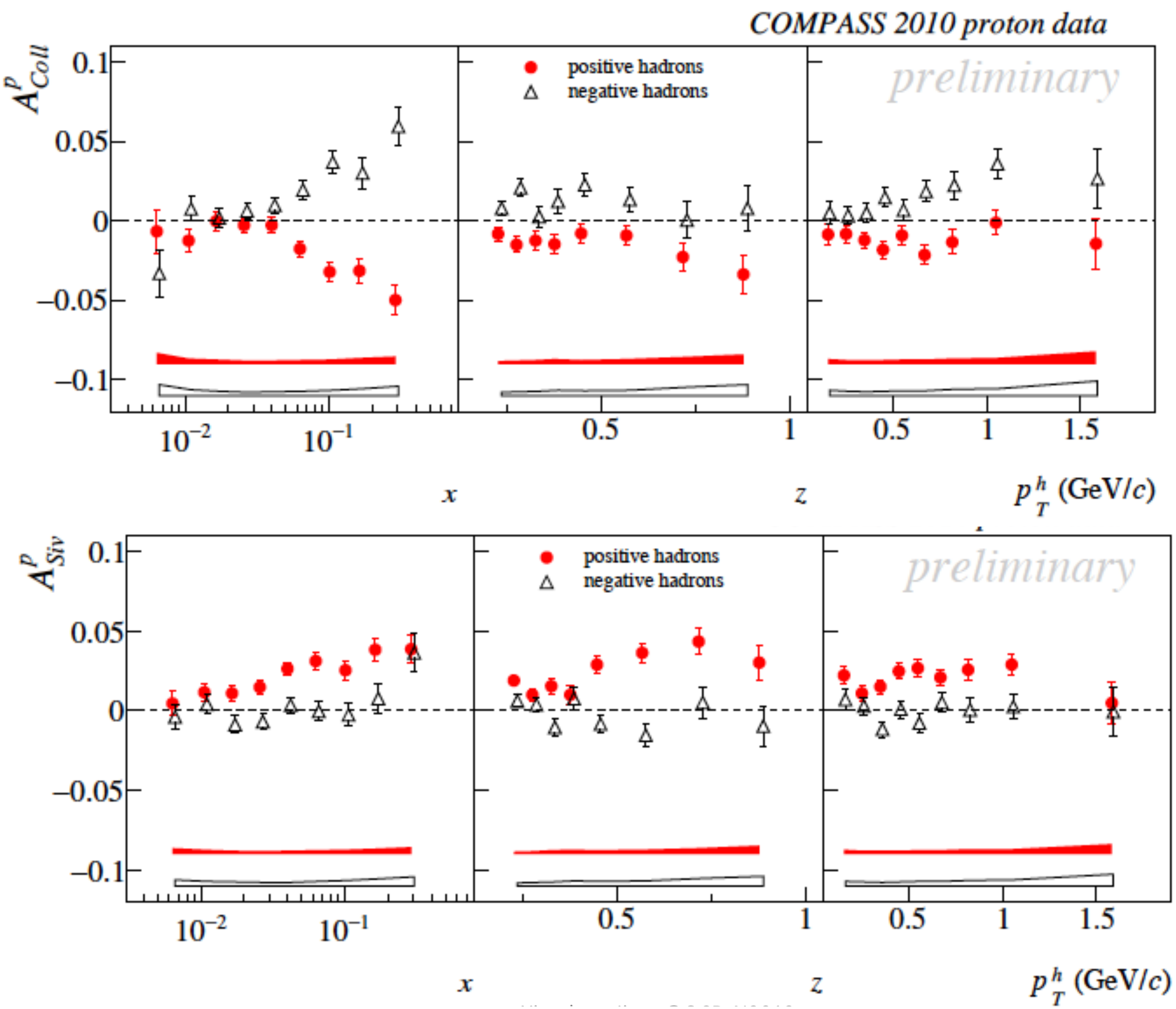
$$A_{12}(z_1, z_2, \theta, \varphi_1+\varphi_2) \equiv \frac{1}{\langle d\sigma \rangle} \frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\, dz_2\, d\cos\theta\, d(\varphi_1+\varphi_2)}$$

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

another similar asymmetry can be measured, A_0

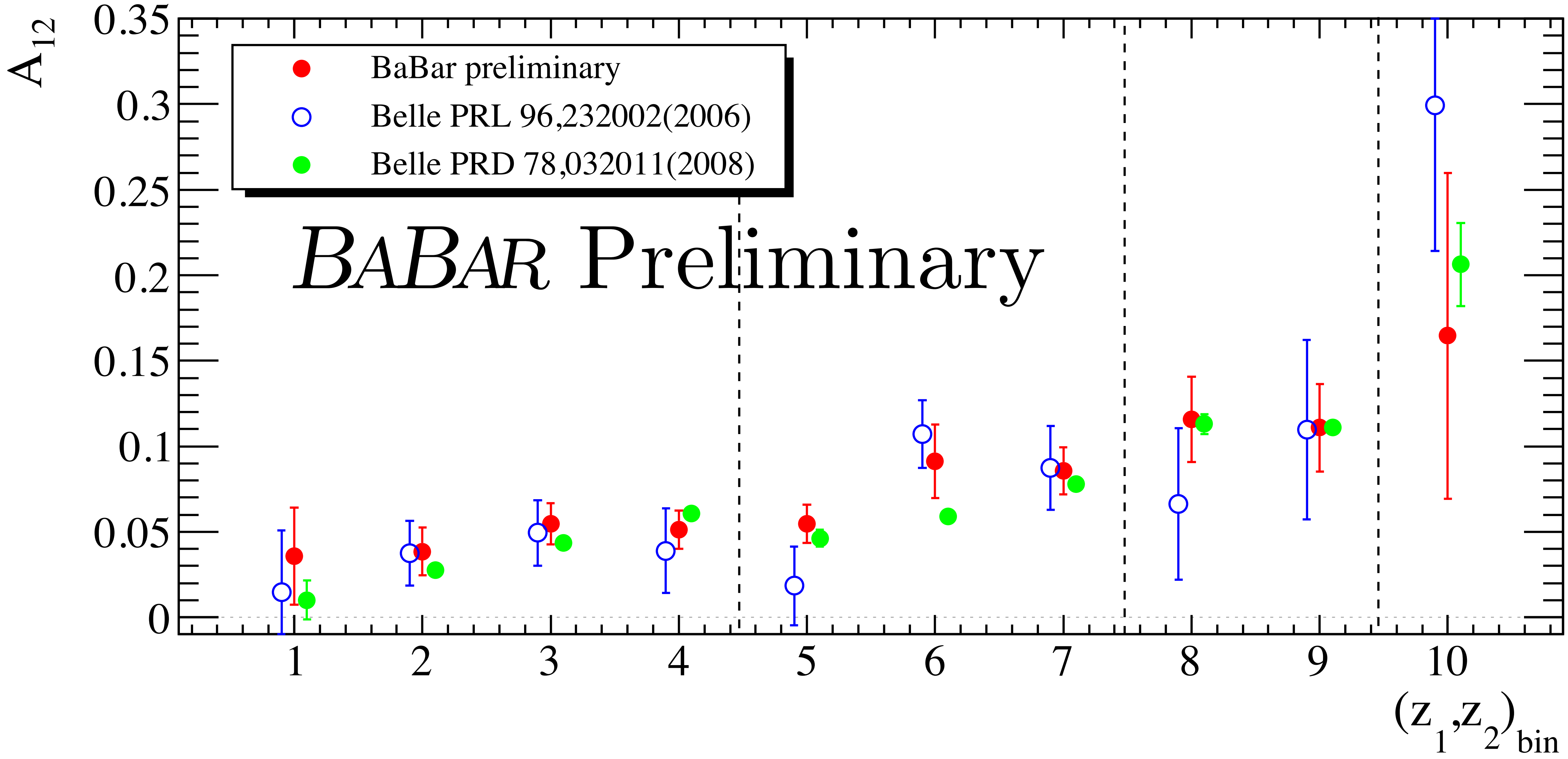
Experimental results:

clear evidence for Sivers and Collins effects from SIDIS data (HERMES, COMPASS, JLab)

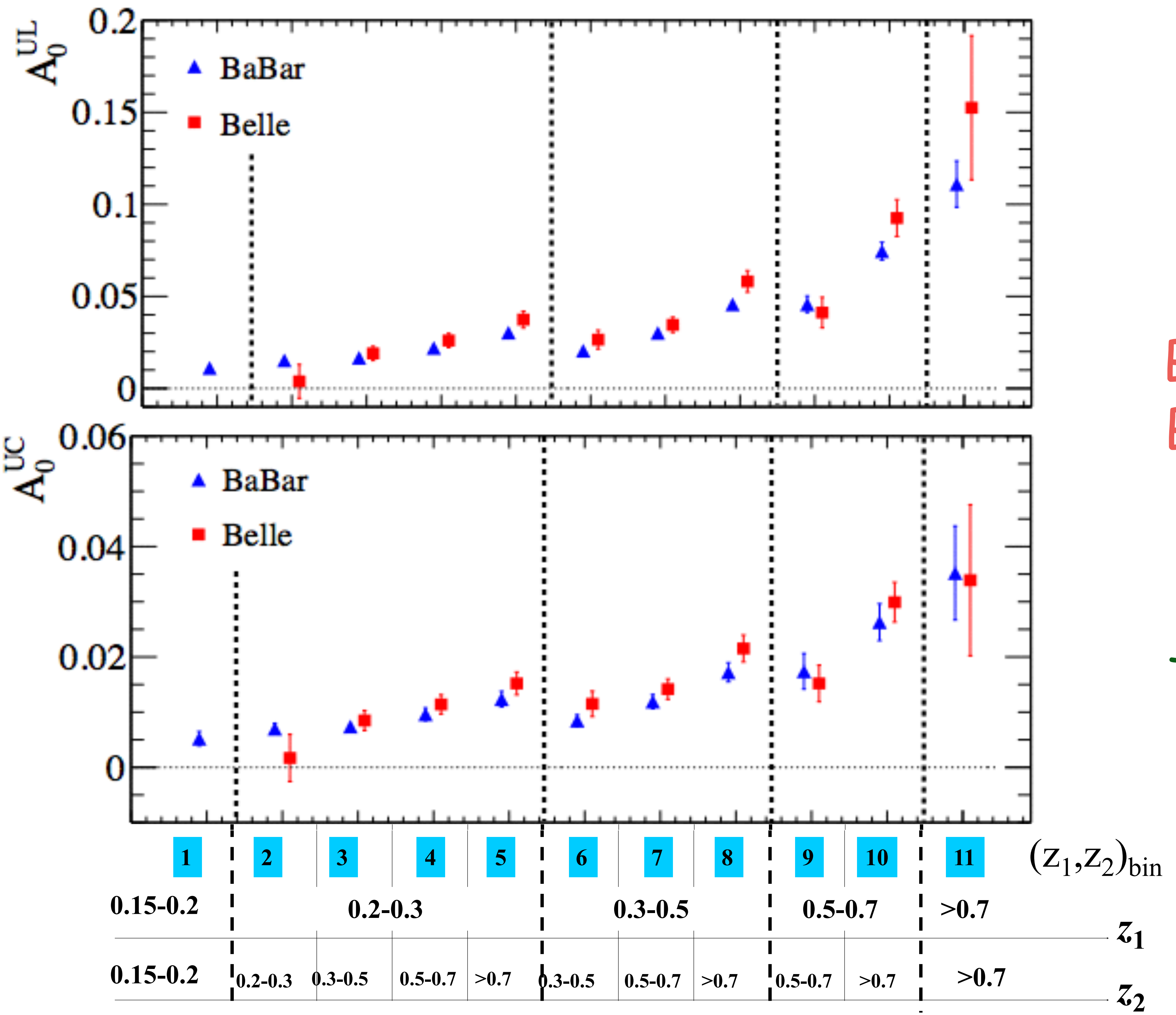


independent evidence for Collins effect from e^+e^- data at Belle, BaBar and BES-III

$$A_{12}(z_1, z_2) \sim \Delta^N D_{h_1/q^\uparrow}(z_1) \otimes \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)$$



I. Garzia, arXiv:1201.4678

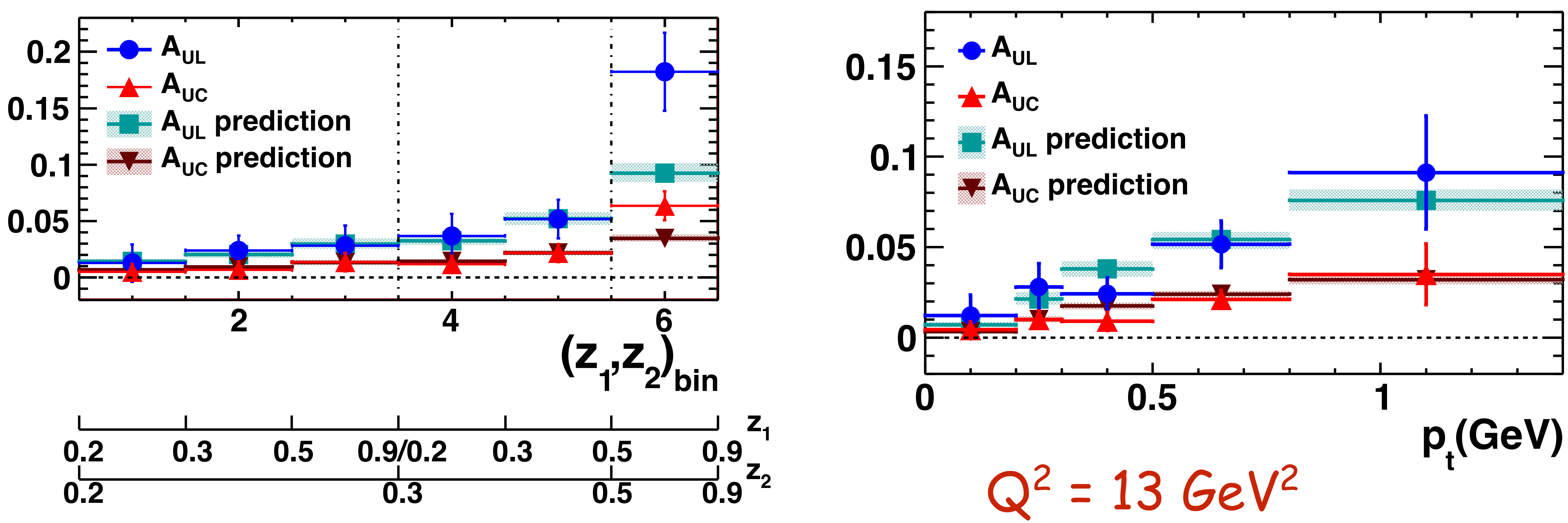


BaBar and Belle data on A_0

(I. Garzia talk at TMDe2015)

a similar asymmetry just measured by BES-III

(arXiv 1507:06824)



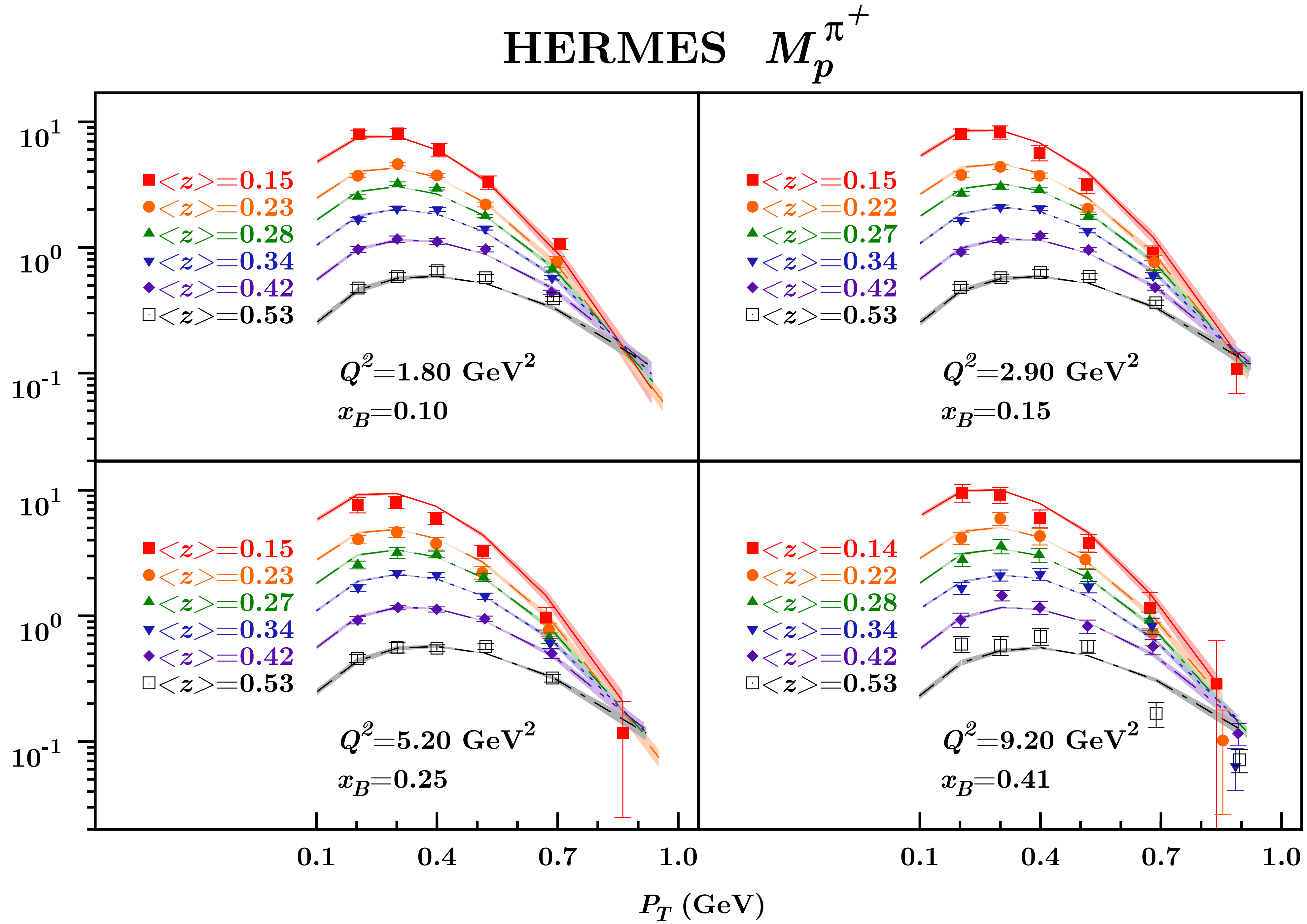
Collins effect clearly observed both in SIDIS and e+e- processes, by several Collaborations

TMD extraction from data - first phase

(simple parameterisation, no TMD evolution, limited number of parameters, ...)

unpolarised TMDs - fit of SIDIS multiplicities

(M.A, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (2014) 005)



clear support for a gaussian distribution

$$\frac{d^2 n^h(x_{_B}, Q^2, z_h, P_T)}{dz_h\, dP_T^2} = \frac{1}{2P_T} M_n^h(x_{_B}, Q^2, z_h, P_T) = \frac{\pi \sum_q e_q^2\, f_{q/p}(x_{_B})\, D_{h/q}(z_h)}{\sum_q e_q^2\, f_{q/p}(x_{_B})} \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

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

$$f_{q/p}(x, k_\perp) = f_{q/p}(x) \, \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle}$$

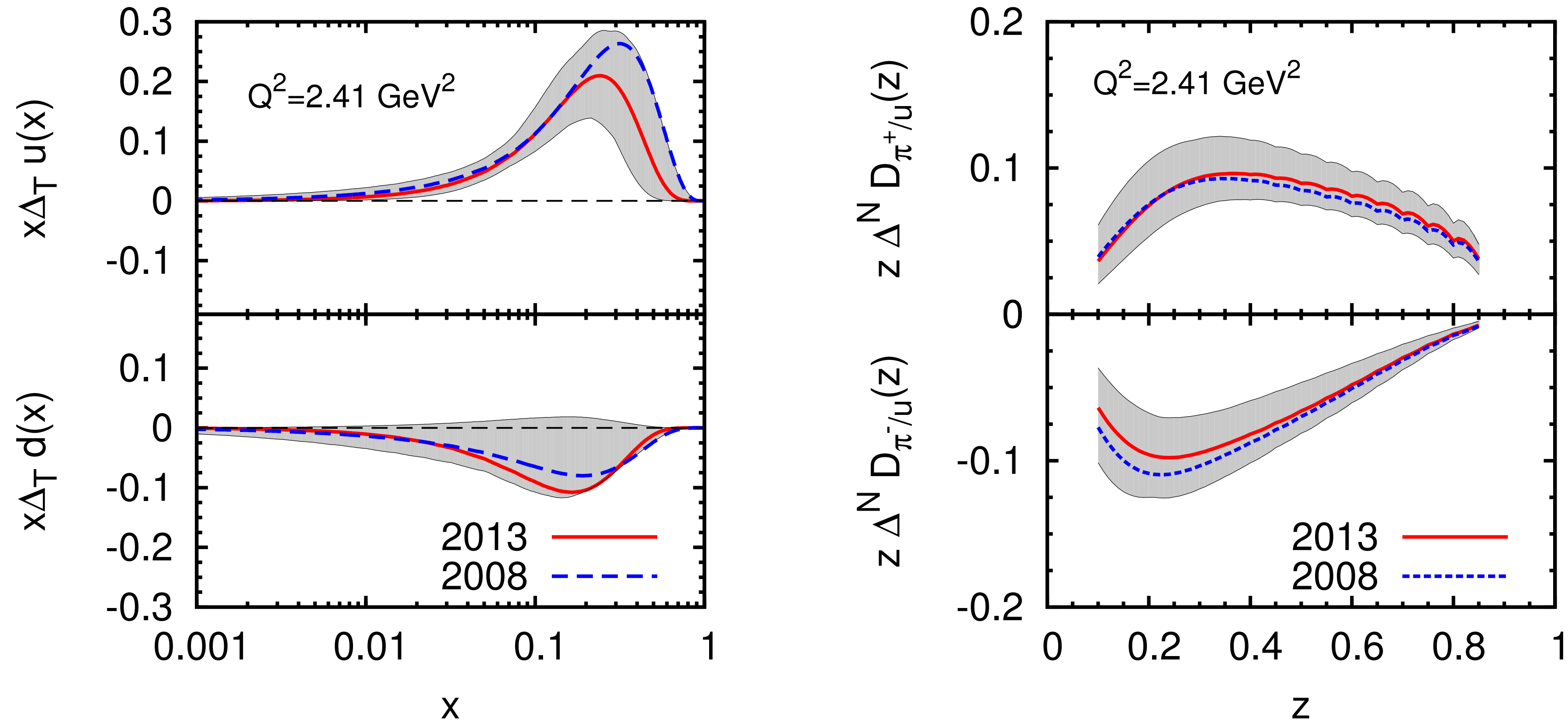
$$D_{h/q}(z, p_\perp) = D_{h/q}(z) \, \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$$

$$\langle k_\perp^2 \rangle = 0.57 \qquad\qquad \langle p_\perp^2 \rangle = 0.12$$

a similar analysis performed by Signori, Bacchetta, Radici, Schnell, JHEP 1311 (2013) 194; it also assumes gaussian behaviour

TMD extraction: transversity and Collins functions - first phase

M. A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, PRD 87 (2013) 094019



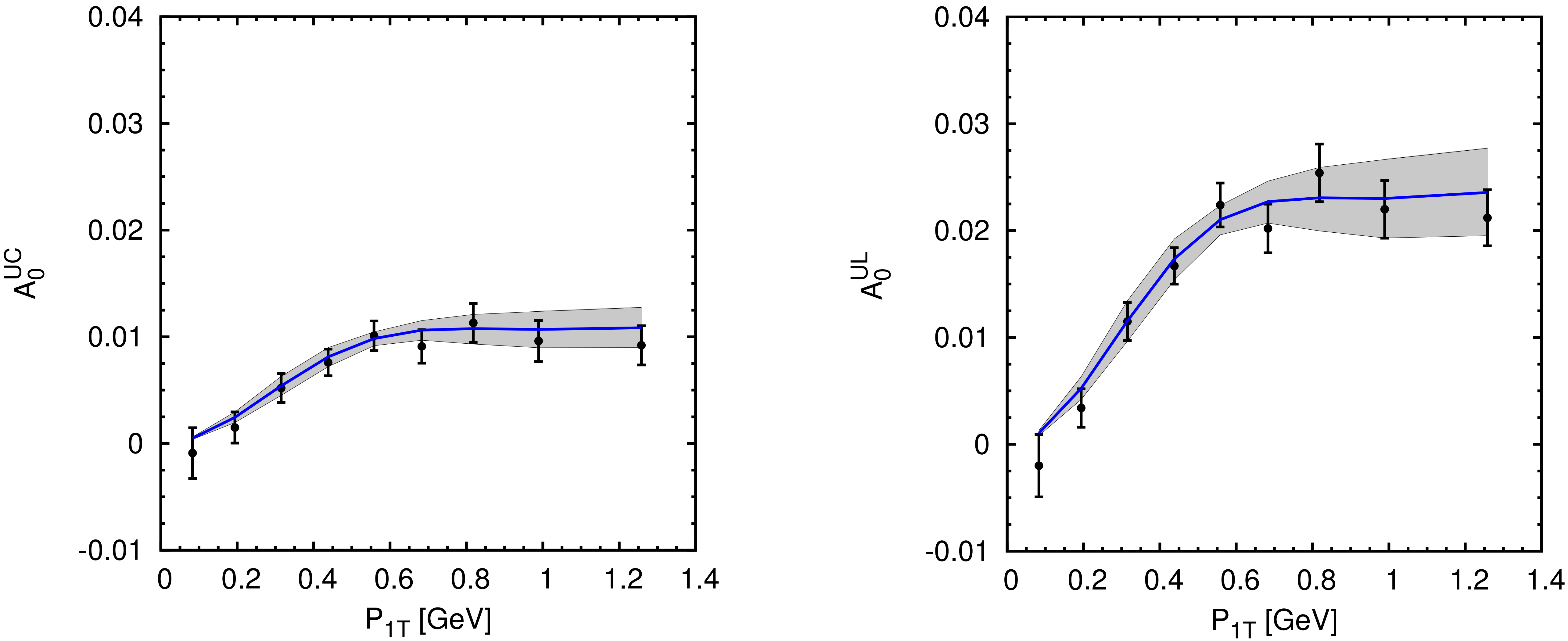
$$\Delta_T q(x, k_\perp) \;=\; \frac{1}{2}\,\mathcal{N}_q^T(x)\,[f_{q/p}(x) + \Delta q(x)]\;\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T}$$

$$\Delta^N D_{h/q^\uparrow}(z, p_\perp) \;=\; 2\,\mathcal{N}_q^C(z)\,D_{h/q}(z)\,h(p_\perp)\;\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

SIDIS and e+e- data, simple parameterization, no TMD evolution, agreement with extraction using di-hadron FF

(recent papers by Bacchetta, Courtoy, Guagnelli, Radici, JHEP 1505 (2015) 123; Kang, Prokudin, Sun, Yuan, Phys. Rev. D91 (2015) 071501; arXiv:1505.05589)

recent BaBar data on the $p_\perp$ dependence of the Collins function (first direct measurement)



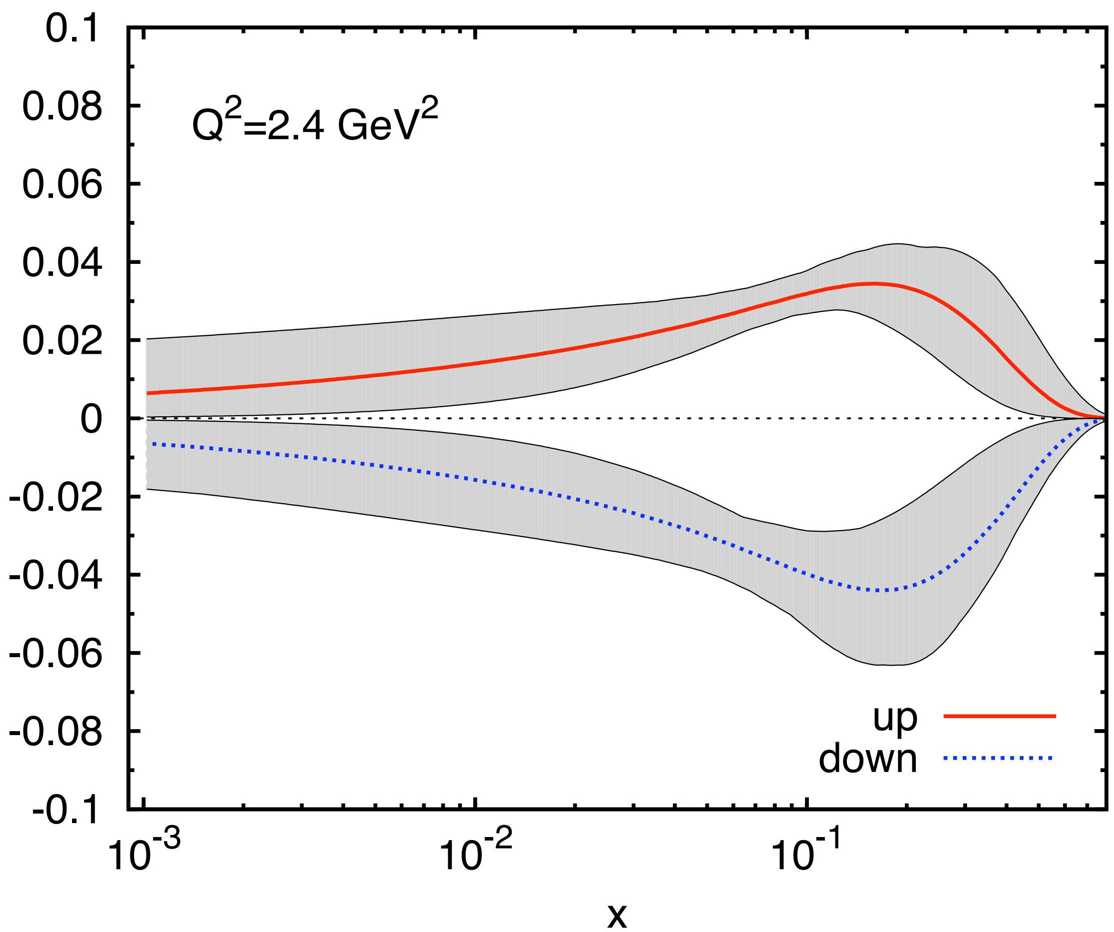
gaussian $p_\perp$ dependence of Collins functions

(M.A., Boglione, D'Alesio, Gonzalez, Melis, Murgia, Prokudin, in preparation)

extraction of u and d Sivers functions - first phase

M.A, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin
(in agreement with several other groups)

$x\,\Delta^N f_q^{(1)}(x,Q)$



$$\Delta^N f_q^{(1)}(x,Q) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4M_p}\,\Delta^N \widehat{f}_{q/p^\uparrow}(x,k_\perp;Q) = -f_{1T}^{\perp(1)q}(x,Q)$$

parameterization of the Sivers function:

$$\Delta^N \widehat{f}_{q/p^\uparrow}(x,k_\perp;Q) = 2\,\mathcal{N}(x)\,h(k_\perp)\,f_q(x,Q)\,\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

Q^2 evolution only taken into account in the collinear part (usual PDF)

Sivers effects induces distortions in the parton distribution

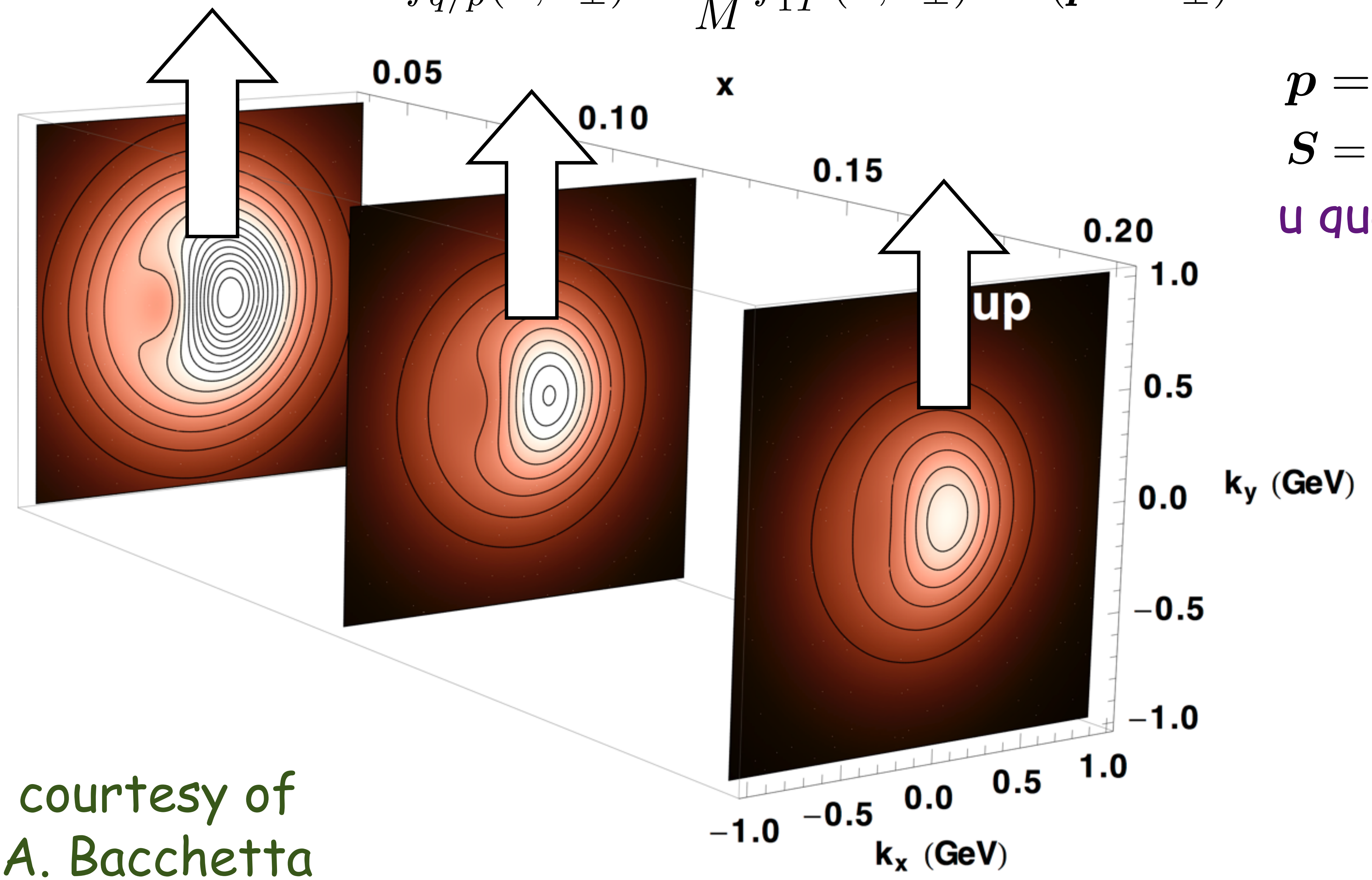
$$f_{q/p,\boldsymbol{S}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$\boldsymbol{p} = p\hat{\boldsymbol{z}}$

$\boldsymbol{S} = S\hat{\boldsymbol{y}}$

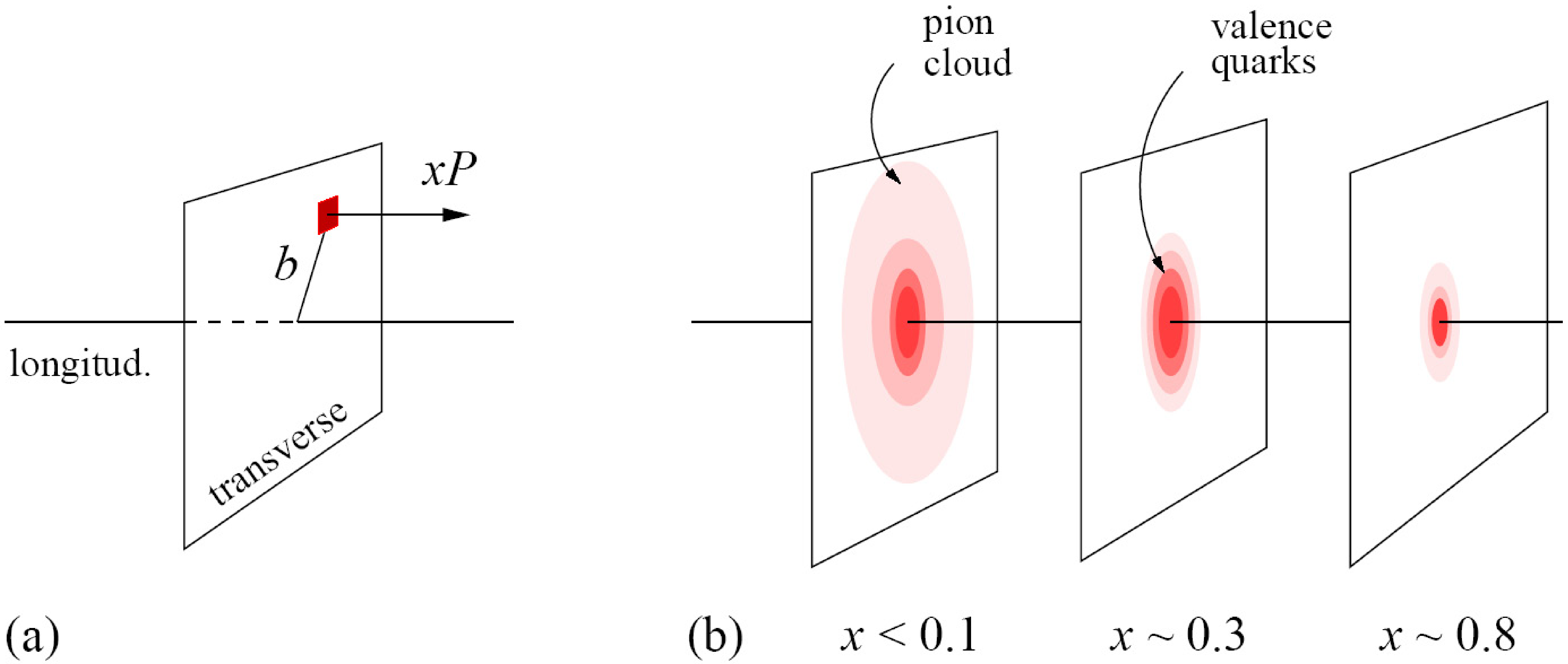
u quark



courtesy of
A. Bacchetta

similar information can be obtained from GPDs and their FT

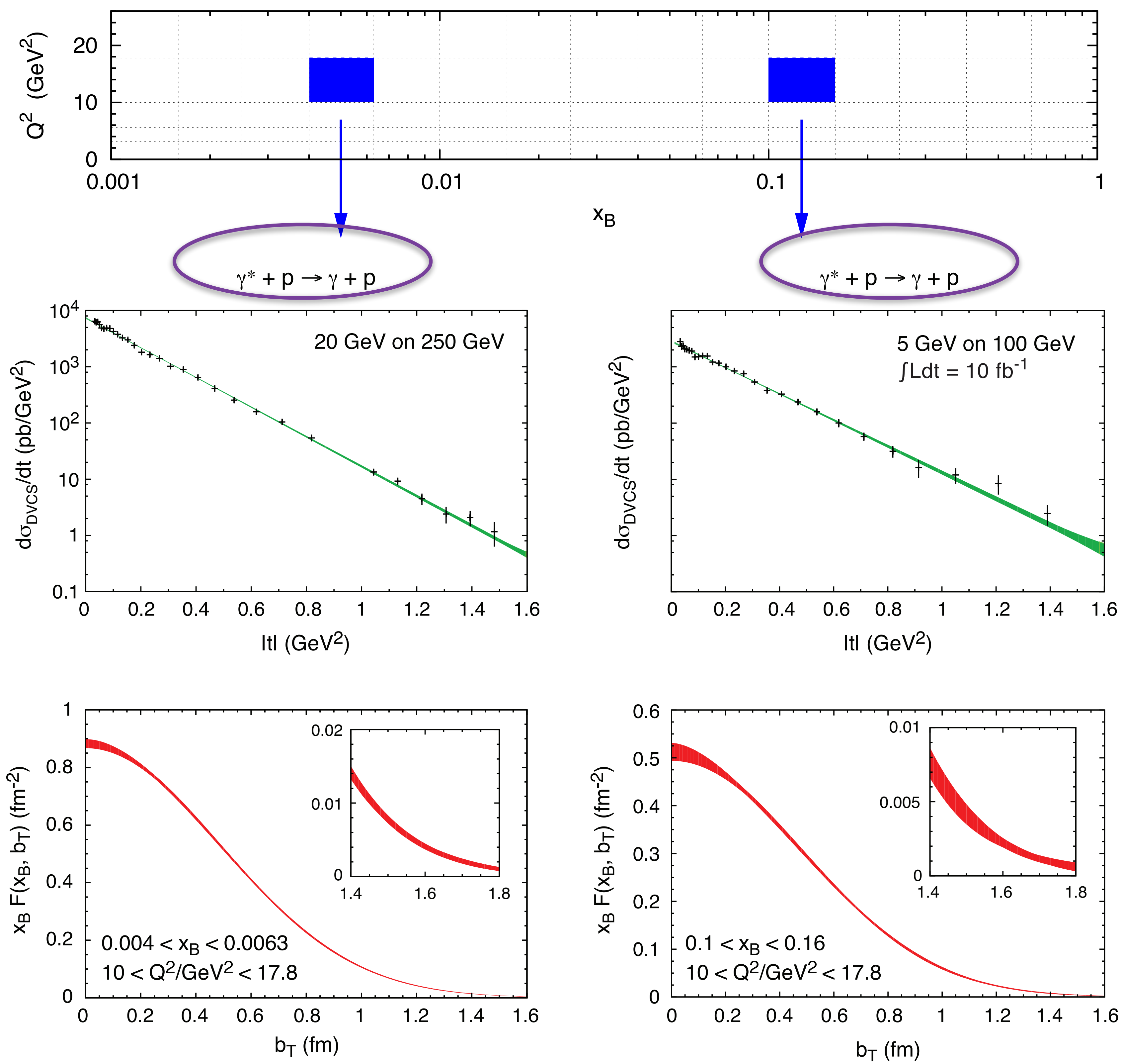
$$q(x, \boldsymbol{b}_T)$$



femtophotography or tomography of the nucleon

expected results at EIC - from DVCS to GPDs to spatial parton distributions

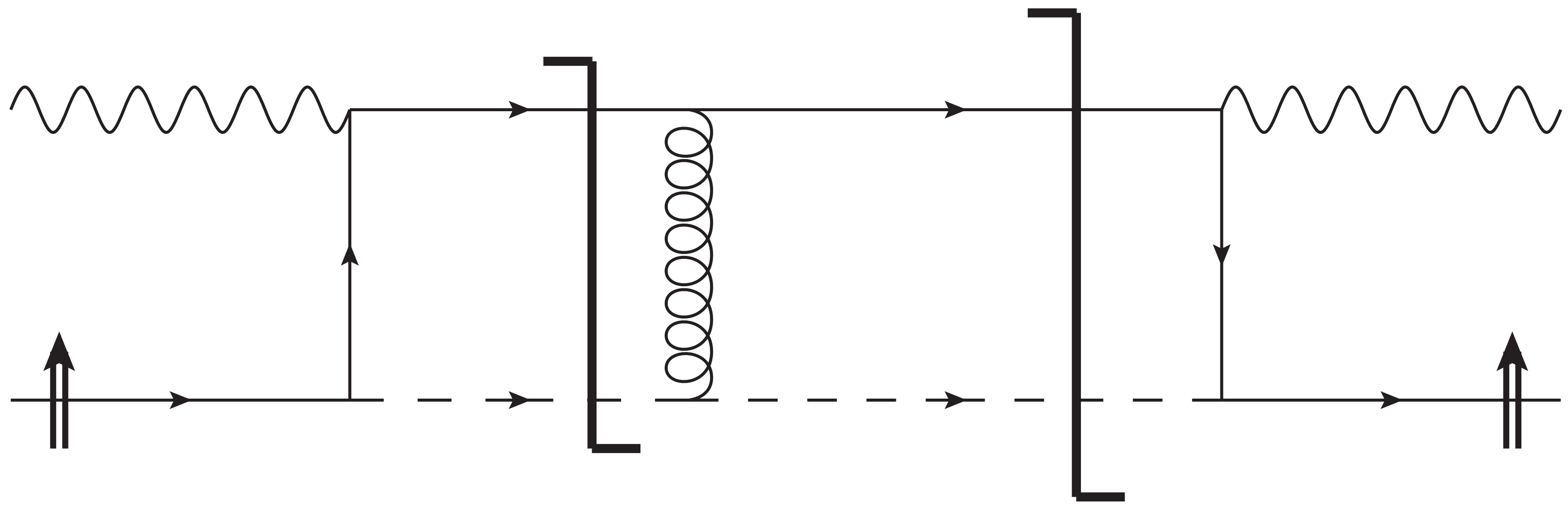
EIC White Paper, arXiv:1212.1701



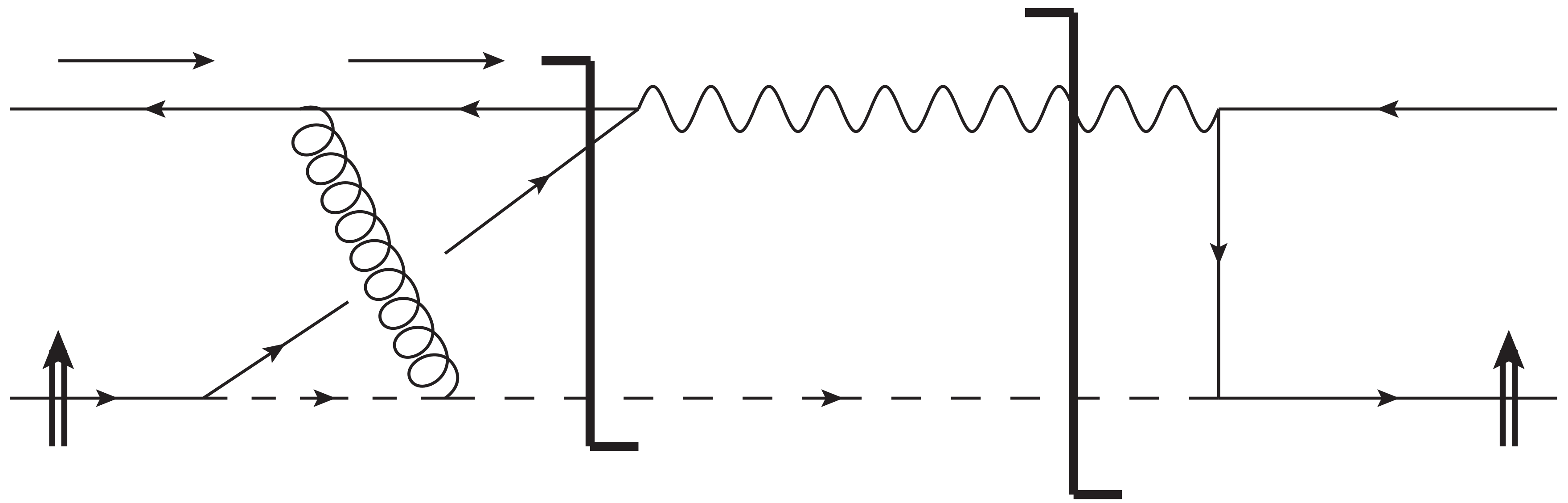
models of Sivers function and gauge links, process dependence

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

SIDIS final state interactions ($\Rightarrow A_N$)

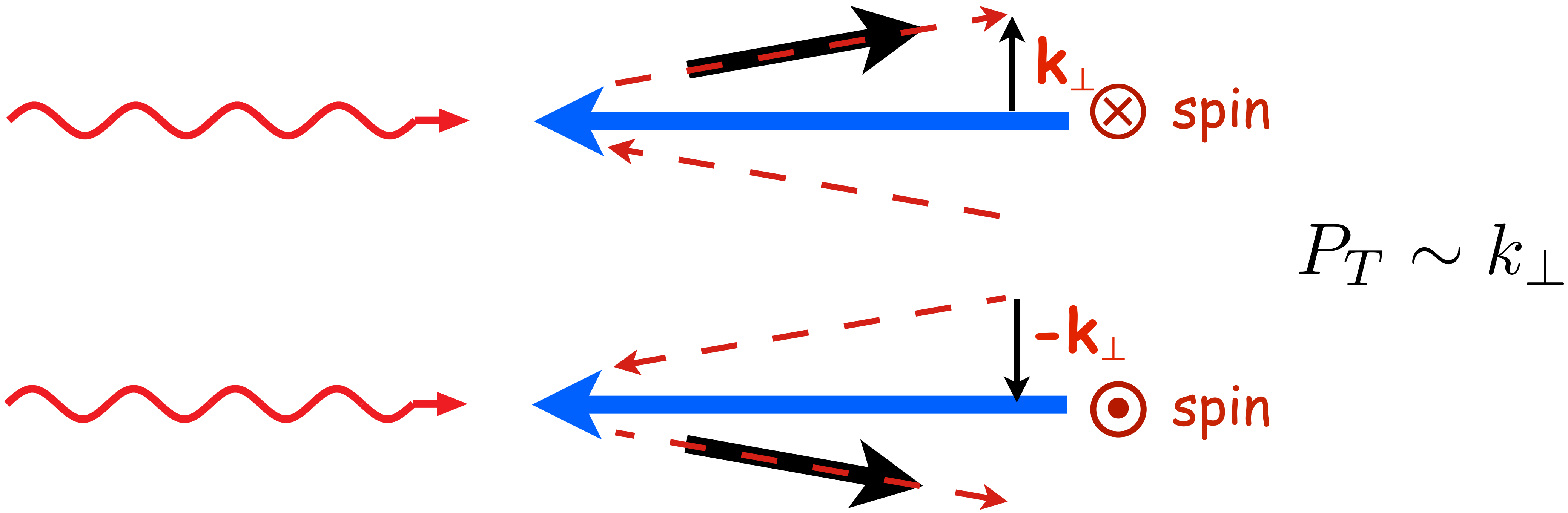


D-Y initial state interactions ($\Rightarrow -A_N$)



Brodsky, Hwang, Schmidt, PL B530 (2002) 99; NP B642 (2002) 344
Brodsky, Hwang, Kovchegov, Schmidt, Sievert, PR D88 (2013) 014032

but the the Sivers effect has a simple physical picture...



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

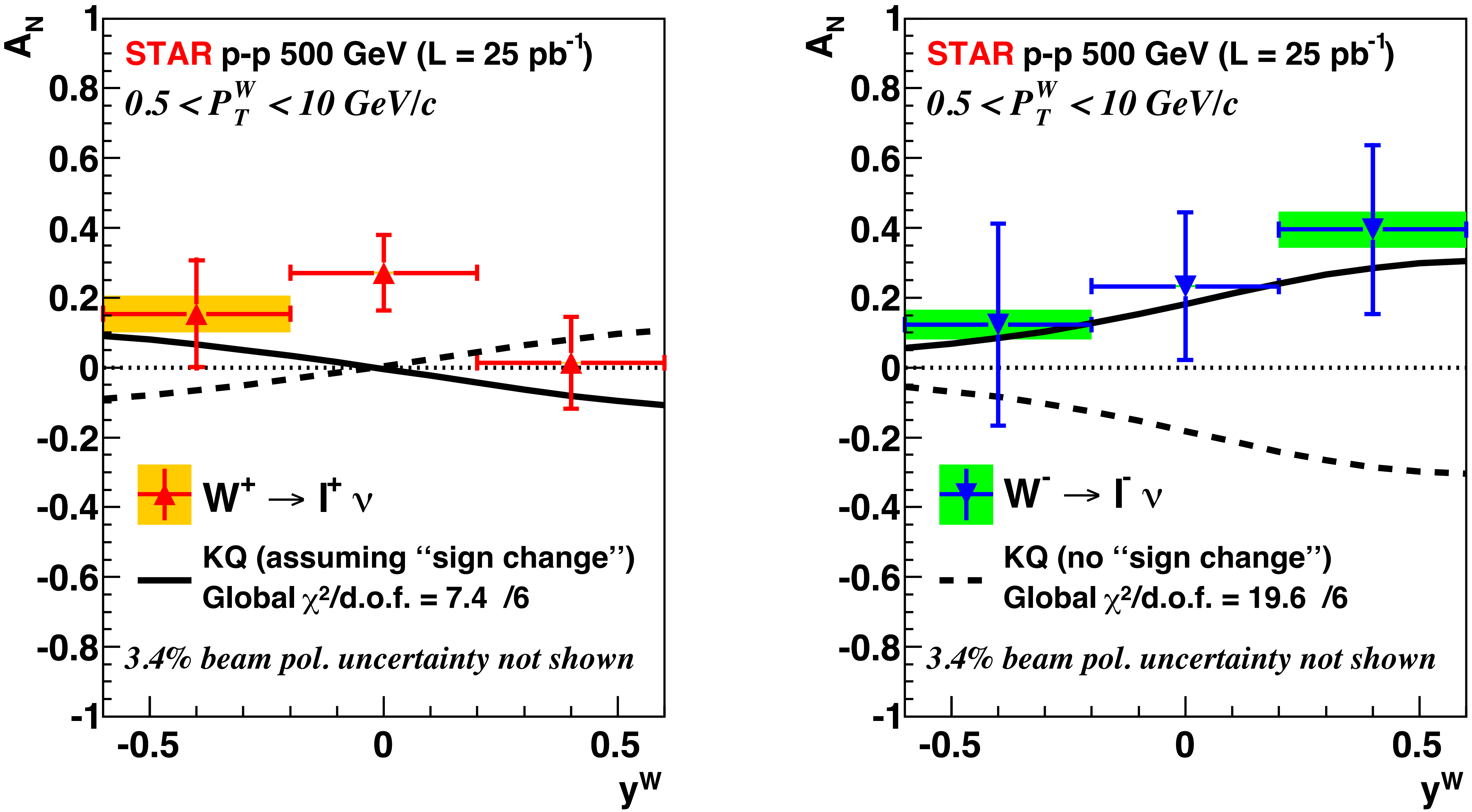
$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

left-right spin asymmetry for the process $\gamma^* q \to q$

the spin-$\mathbf{k}_\perp$ correlation is an intrinsic property of the nucleon; it should be related to the parton orbital motion

First results from RHIC, $p^{\uparrow}p \to W^{\pm}X$

STAR Collaboration, PRL 116 (2016) 132301



some hints at sign change of Sivers function.....

(new results from COMPASS expected soon)

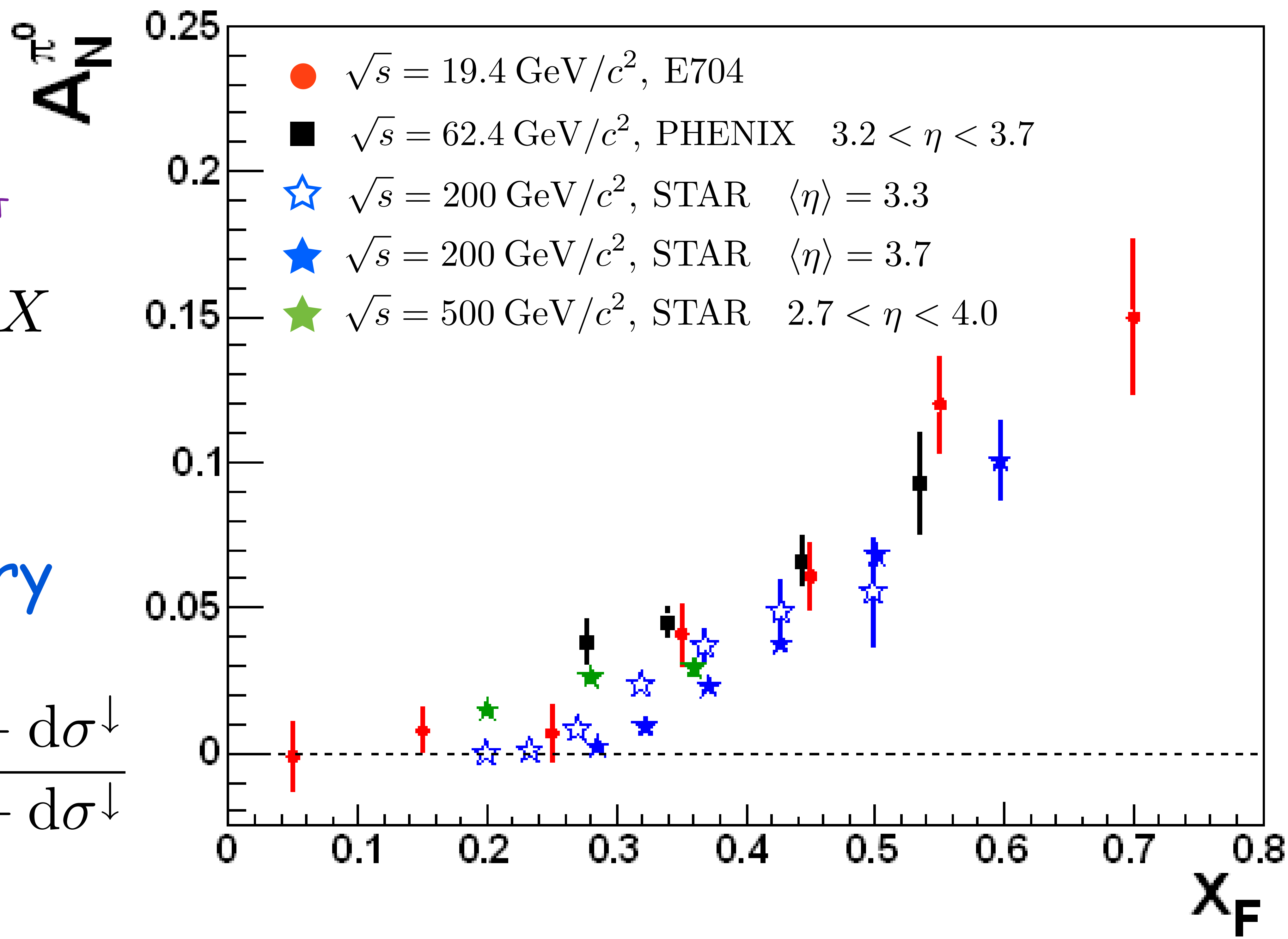
other experimental evidence of the Sivers and Collins effects

large P_T

$$p^{\uparrow}\, p \to \pi\, X$$

Single Spin Asymmetry

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



TMDs and QCD - TMD evolution

study of the QCD evolution of TMDs and TMD factorisation in rapid development

Collins-Soper-Sterman resummation - NP B250 (1985) 199

Idilbi, Ji, Ma, Yuan - PL B597, 299 (2004); PR D70 (2004) 074021

Ji, Ma, Yuan - PL B597 (2004) 299; PR. D71 (2005) 034005

Collins, "Foundations of perturbative QCD", Cambridge University Press (2011)

Aybat, Rogers, PR D83 (2011) 114042

Aybat, Collins, Qiu, Rogers, PR D85 (2012) 034043

Echevarria, Idilbi, Schafer, Scimemi, arXiv:1208.1281

Echevarria, Idilbi, Scimemi, JHEP 1207 (2012) 002

Aybat, Prokudin, Rogers, PRL 108 (2012) 242003

Anselmino, Boglione, Melis, PR D86 (2012) 014028

Aidala, Field, Gamberg, Rogers, PR D89 (2014) 094002

Echevarria, Idilbi, Kang, Vitev, PR D89 (2014) 074013

Bacchetta, Prokudin, NP B875 (2013) 536

Godbole, Misra, Mukherjee, Raswoot, PR D88 (2013) 014029

Boer, Lorcé, Pisano, Zhou, arXiv:1504.04332 (2015)

Boglione, Gonzalez, Melis, Prokudin, JHEP 1502 (2015) 095

Kang, Prokudin, Sun, Yuan, arXiv:1505.05589

+ many more authors...

Different TMD evolution schemes and different implementations within the same scheme.
It needs non perturbative inputs

dedicated workshops, QCD Evolution 2011, 2012, 2013, 2014, 2015, 2016

see, "Transverse momentum dependent (TMD) parton distribution functions: status and prospects", arXiv: 1507.05267 (from "Resummation, Evolution, Factorization", Antwerp 2014)

dedicated tools:

TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions

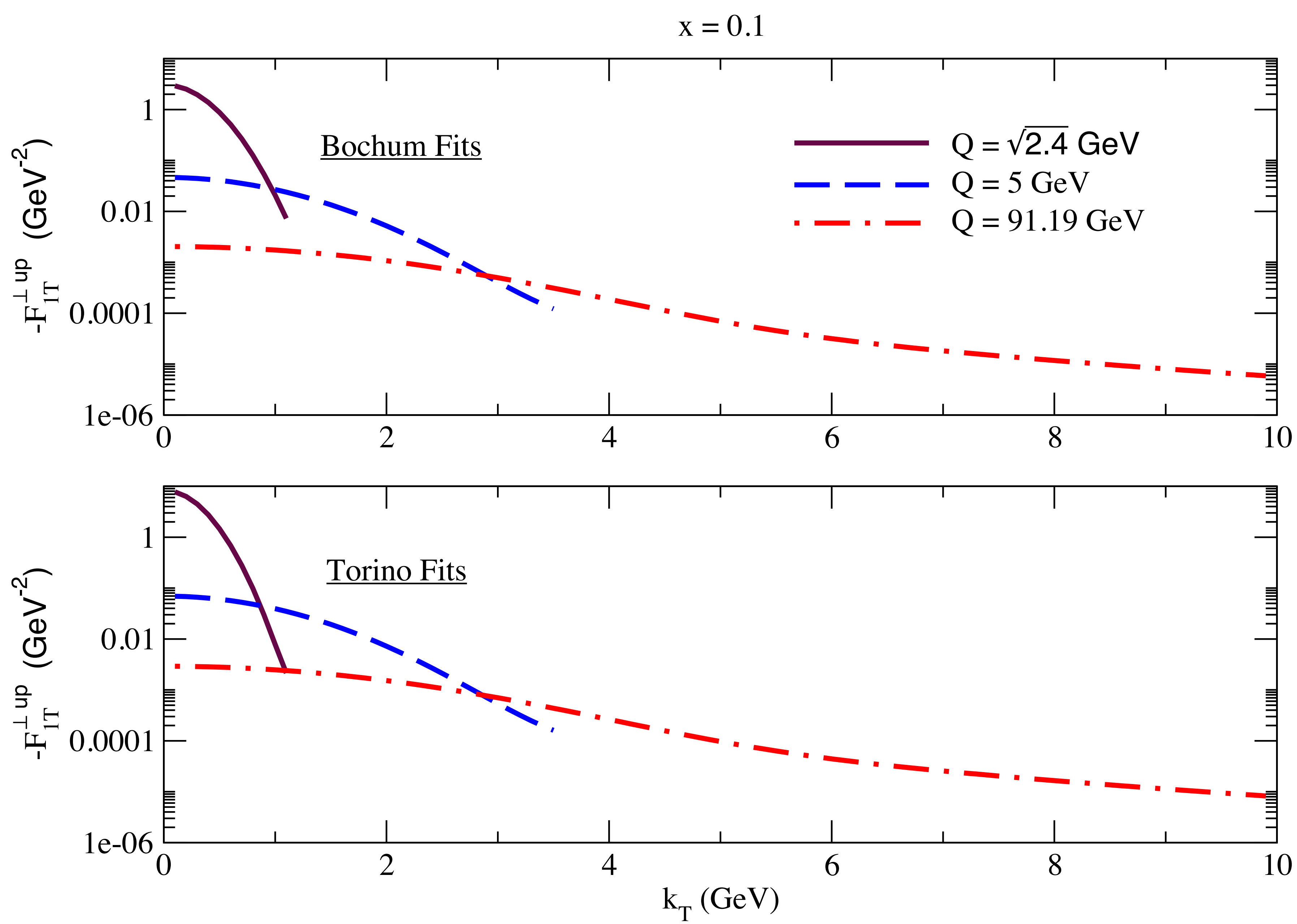
Hautmann, Jung, Kramer, Mulders, Nocera, Rogers, Signori

TMD phenomenology - phase 2

how does gluon emission affect the transverse motion?

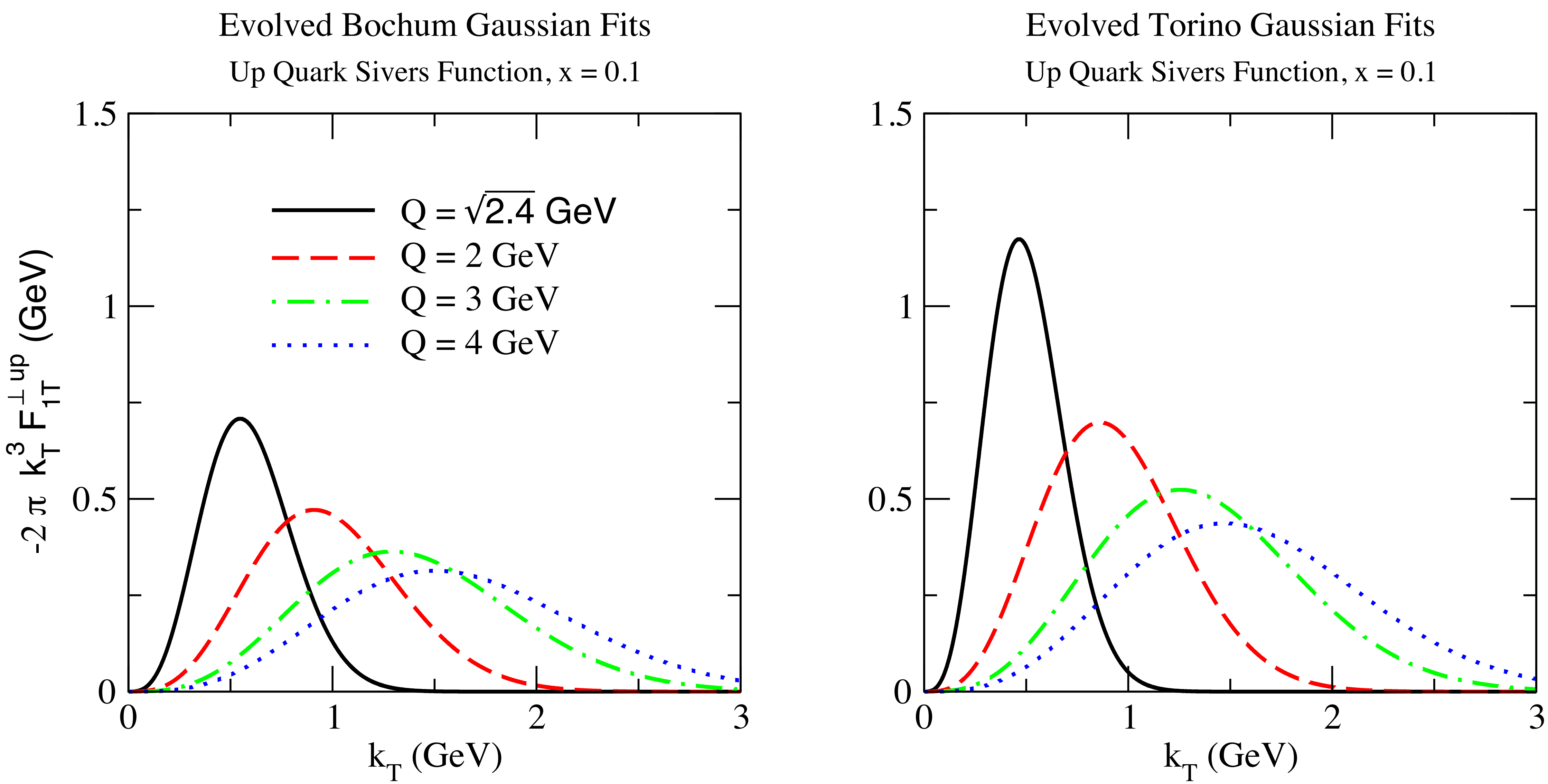
a few selected results

TMD evolution of up quark Sivers function



Aybat, Collins, Qiu, Rogers, Phys. Rev. D85 (2012) 034043

TMD evolution of up quark Sivers function

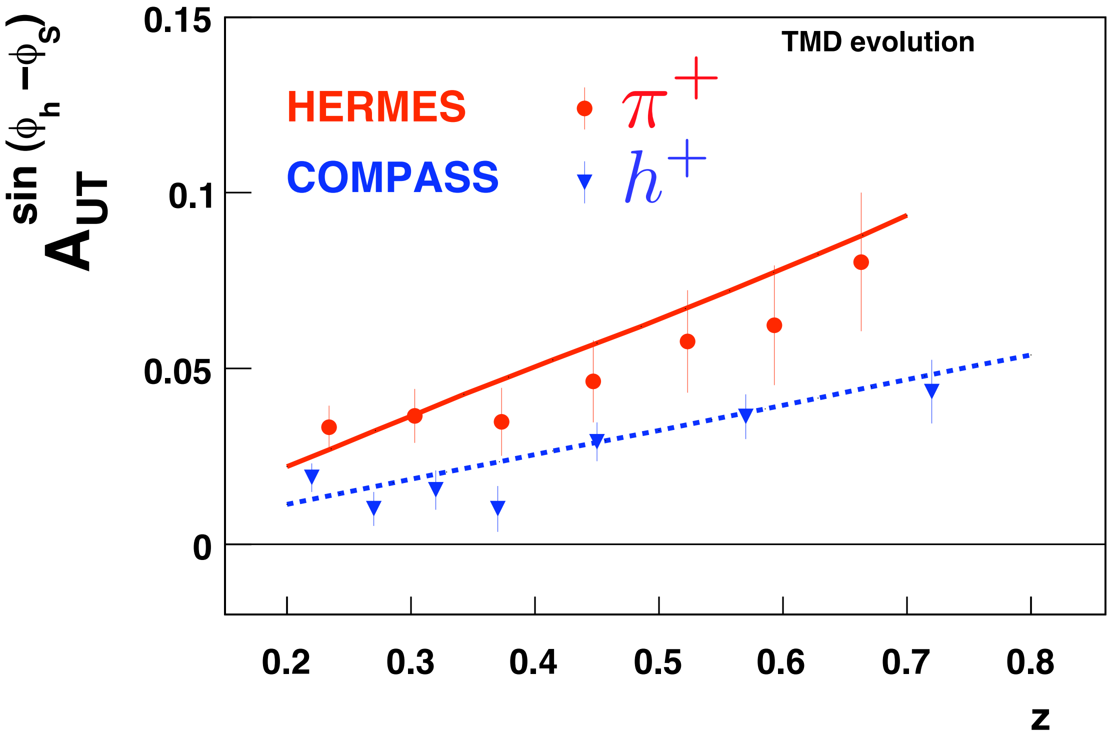


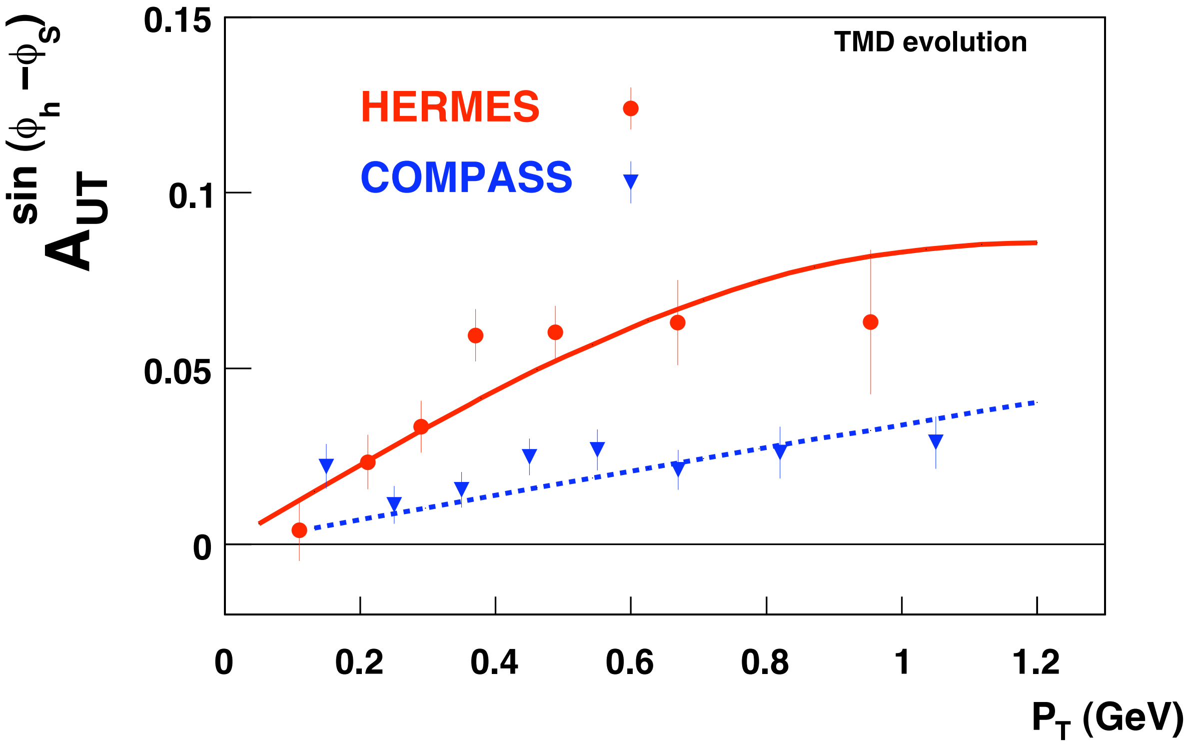
Aybat, Collins, Qiu, Rogers, Phys.Rev. D85 (2012) 034043

TMD evolution of Sivers function studied also by
Echevarria, Idilbi, Kang, Vitev, Phys. Rev. D89 (2014) 074013

first phenomenological applications to data

Aybat, Prokudin, Rogers, PRL 108 (2012) 242003

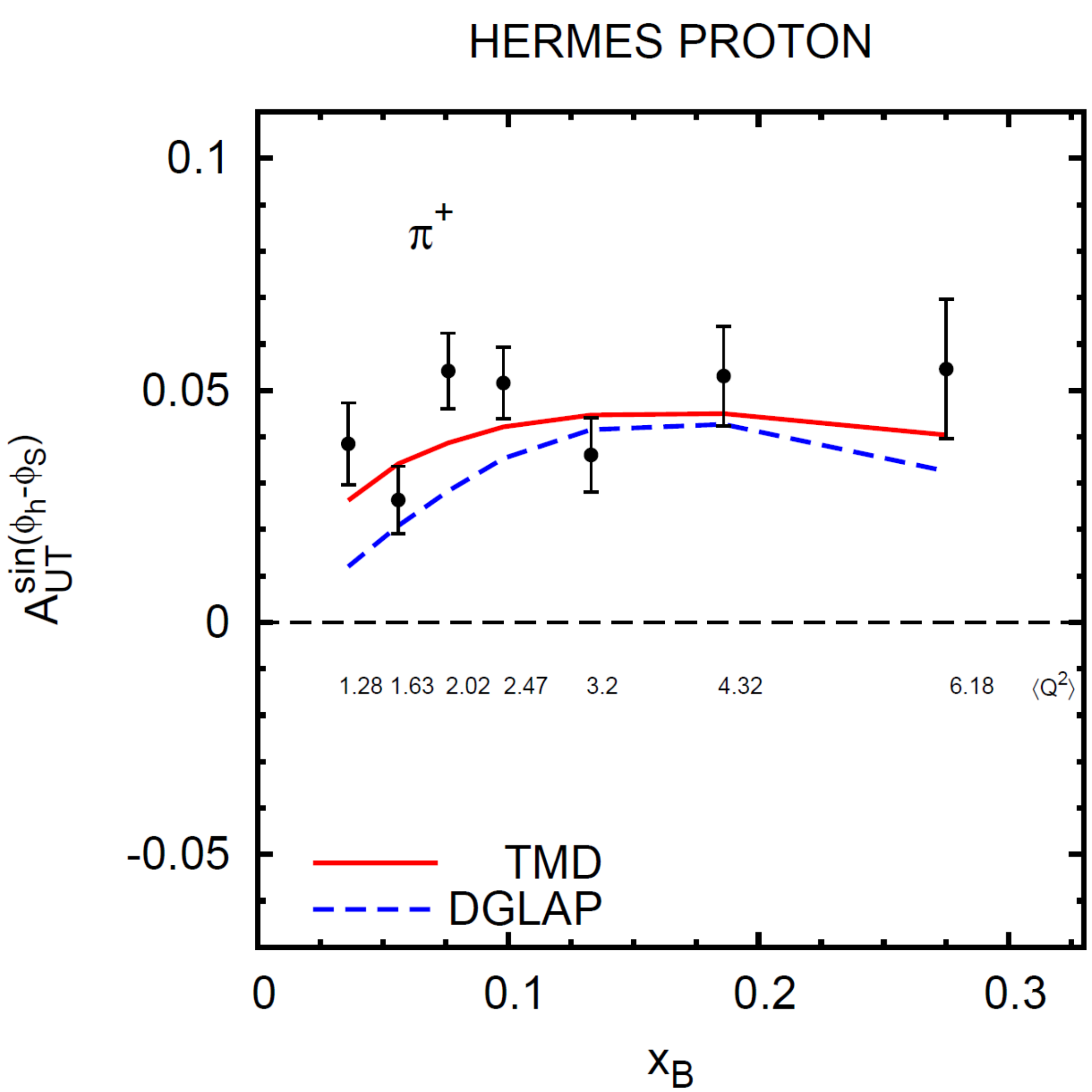


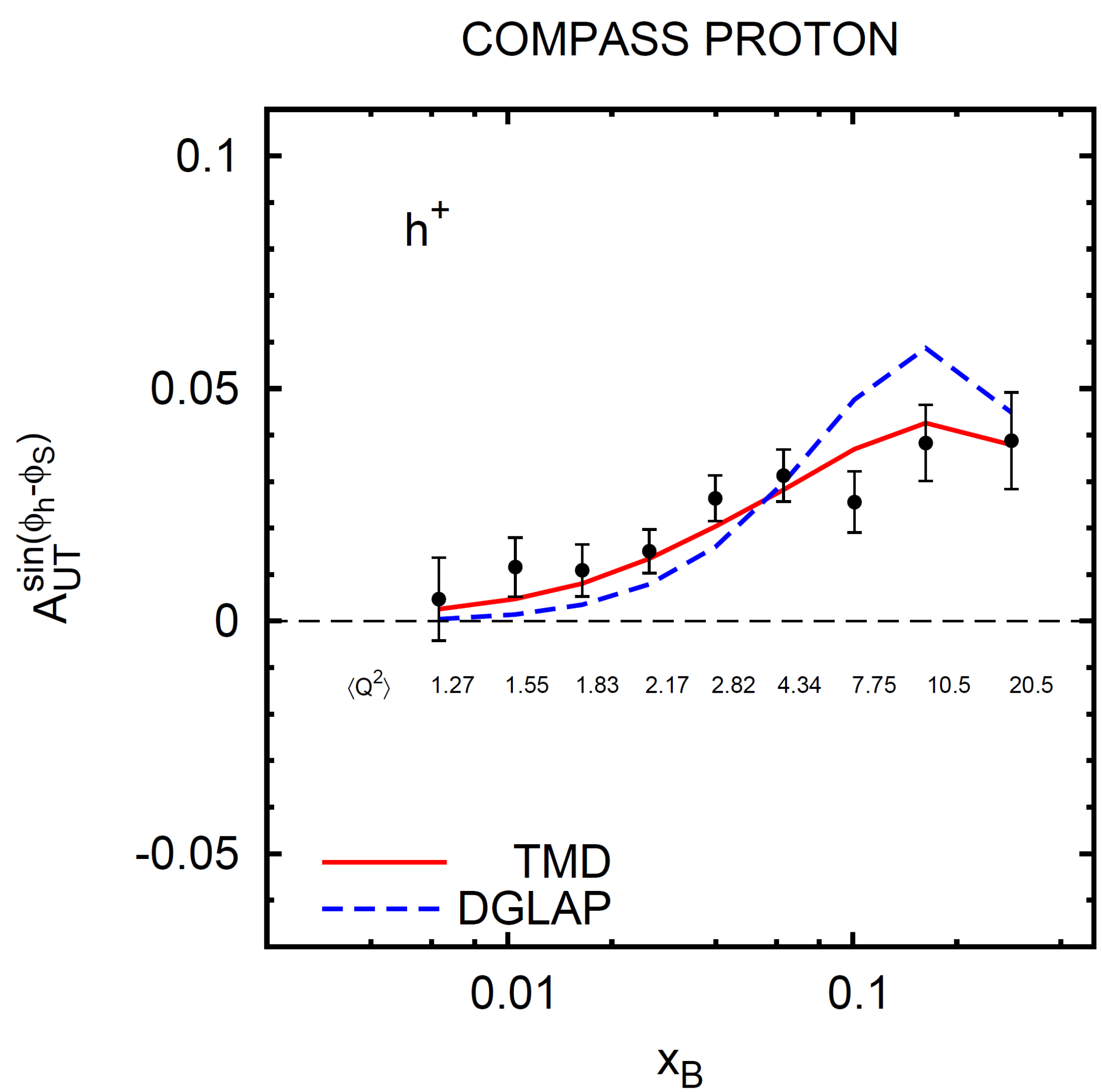


existing fits (red line, Torino) of HERMES data at $\langle Q^2 \rangle$ = 2.4 GeV^2, extrapolated with TMD evolution up to $\langle Q^2 \rangle$ = 3.8 GeV^2 and compared with COMPASS data (dashed line)

fit of SIDIS data with a specific TMD evolution

M.A., M. Boglione, S. Melis, PR D86 (2012) 014028; arXiv:1204.1239





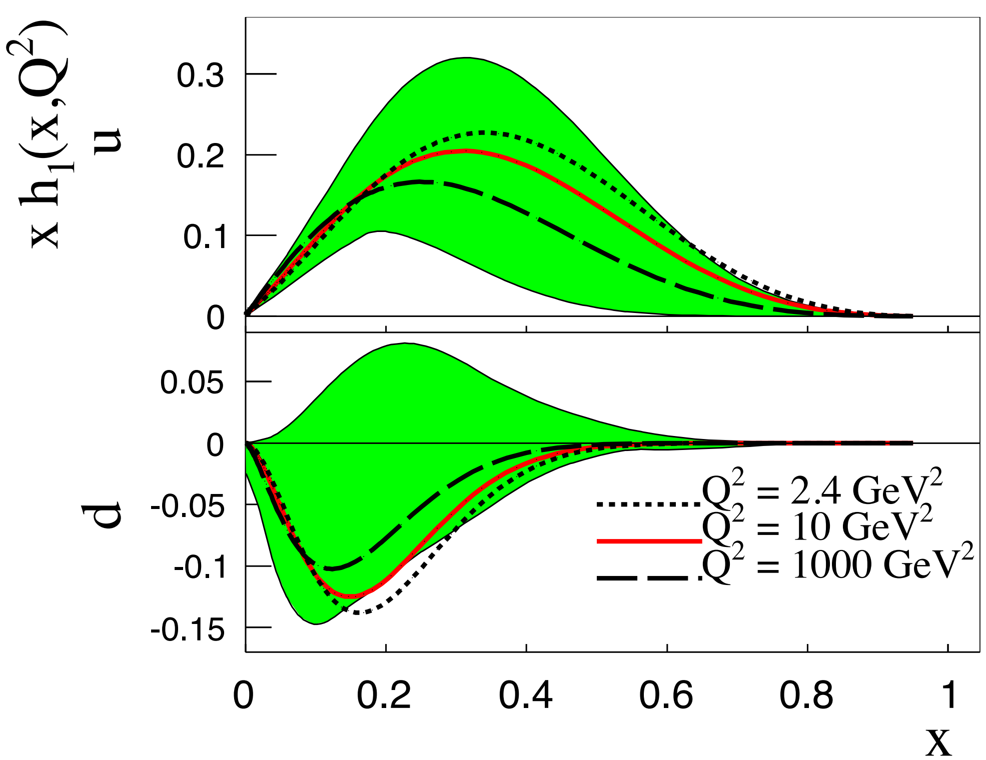
large $x_B \Rightarrow$ large Q^2

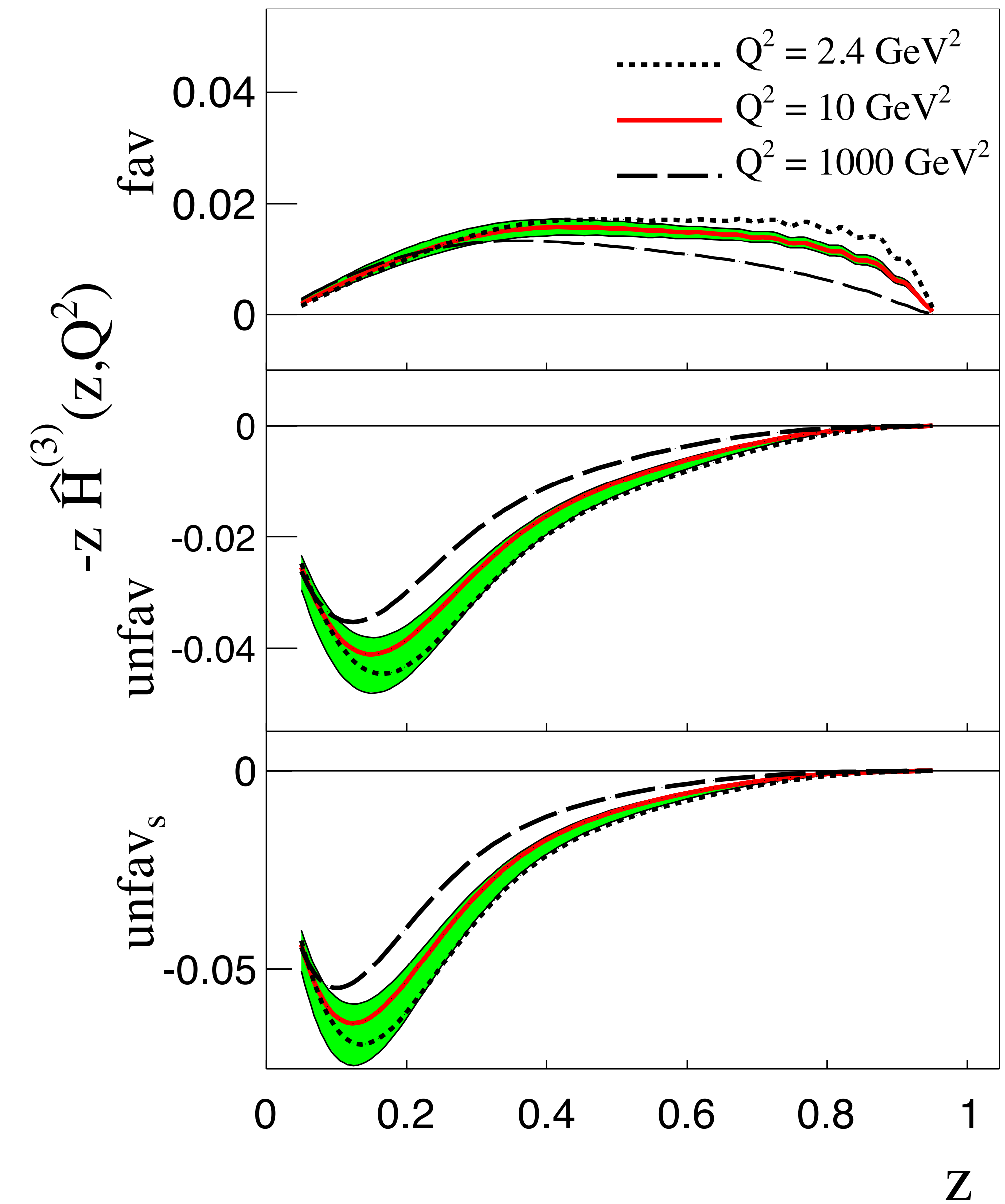
TMD evolution fits better the large Q^2 data

Extraction of transversity and Collins functions with TMD evolution

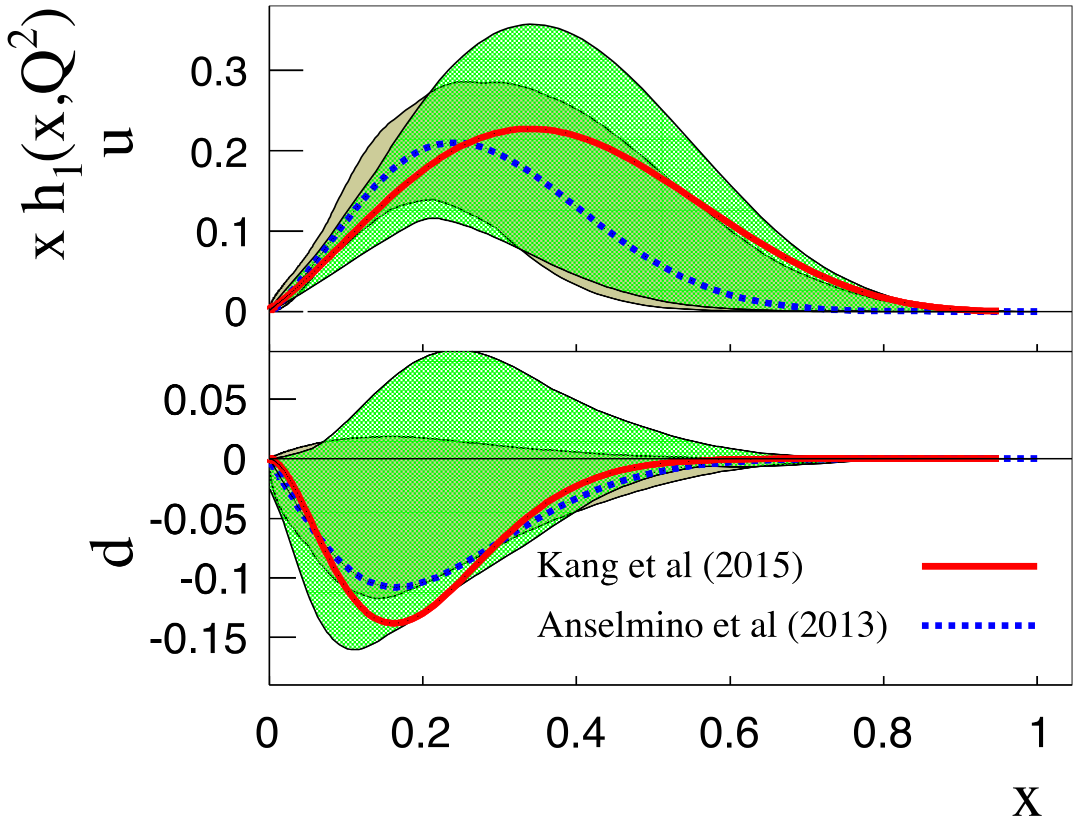
(Kang, Prokudin, Sun, Yuan, arXiv:1505.05589)

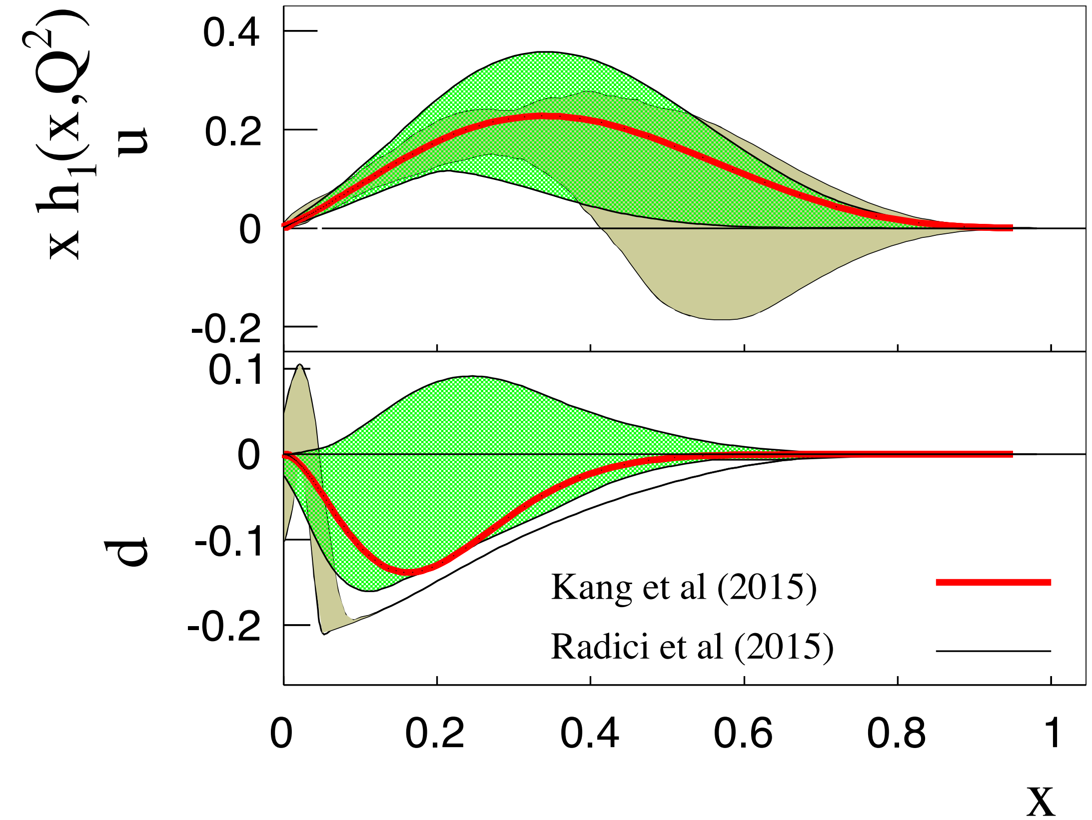
transversity distributions

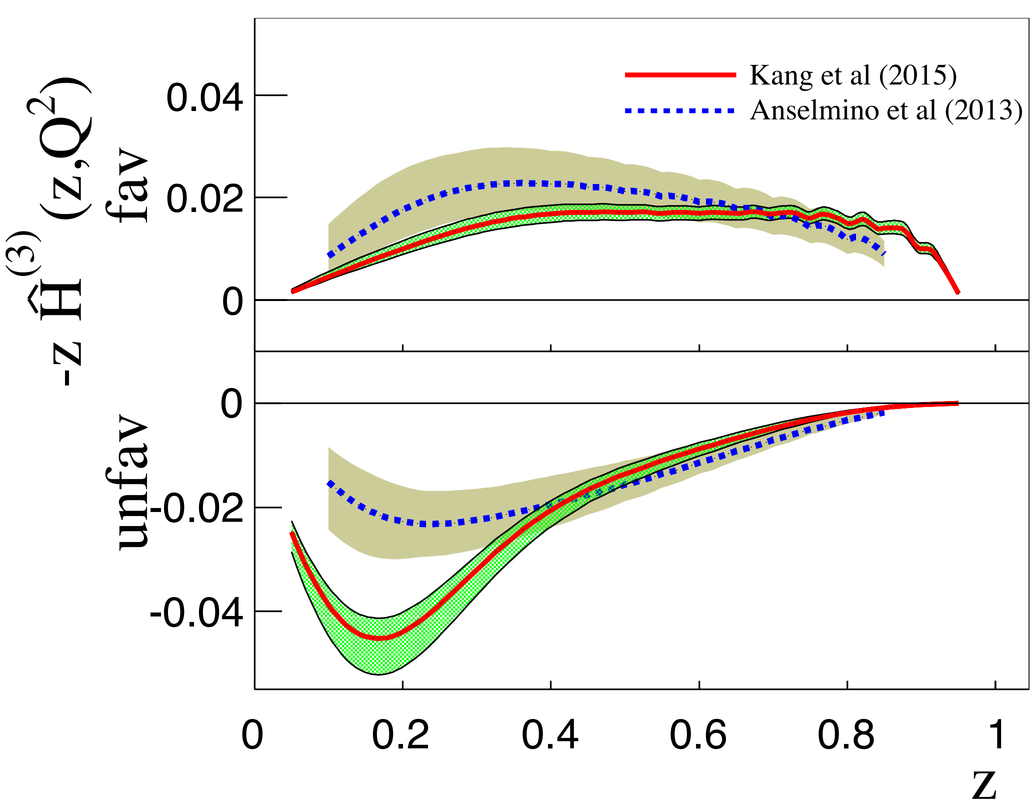




moment of Collins functions



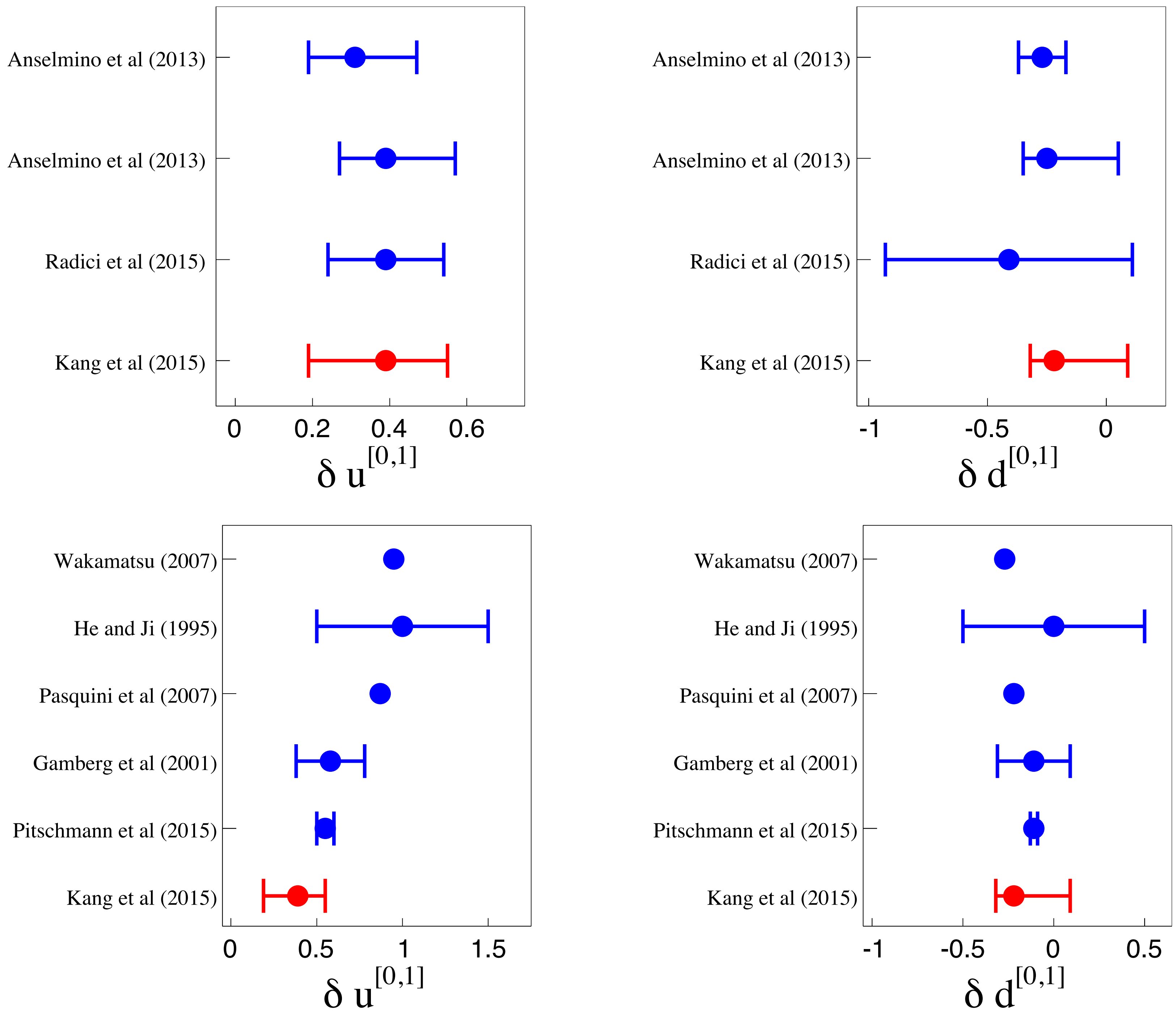




comparison with phase 1 extraction, Q^2 = 2.4 GeV^2

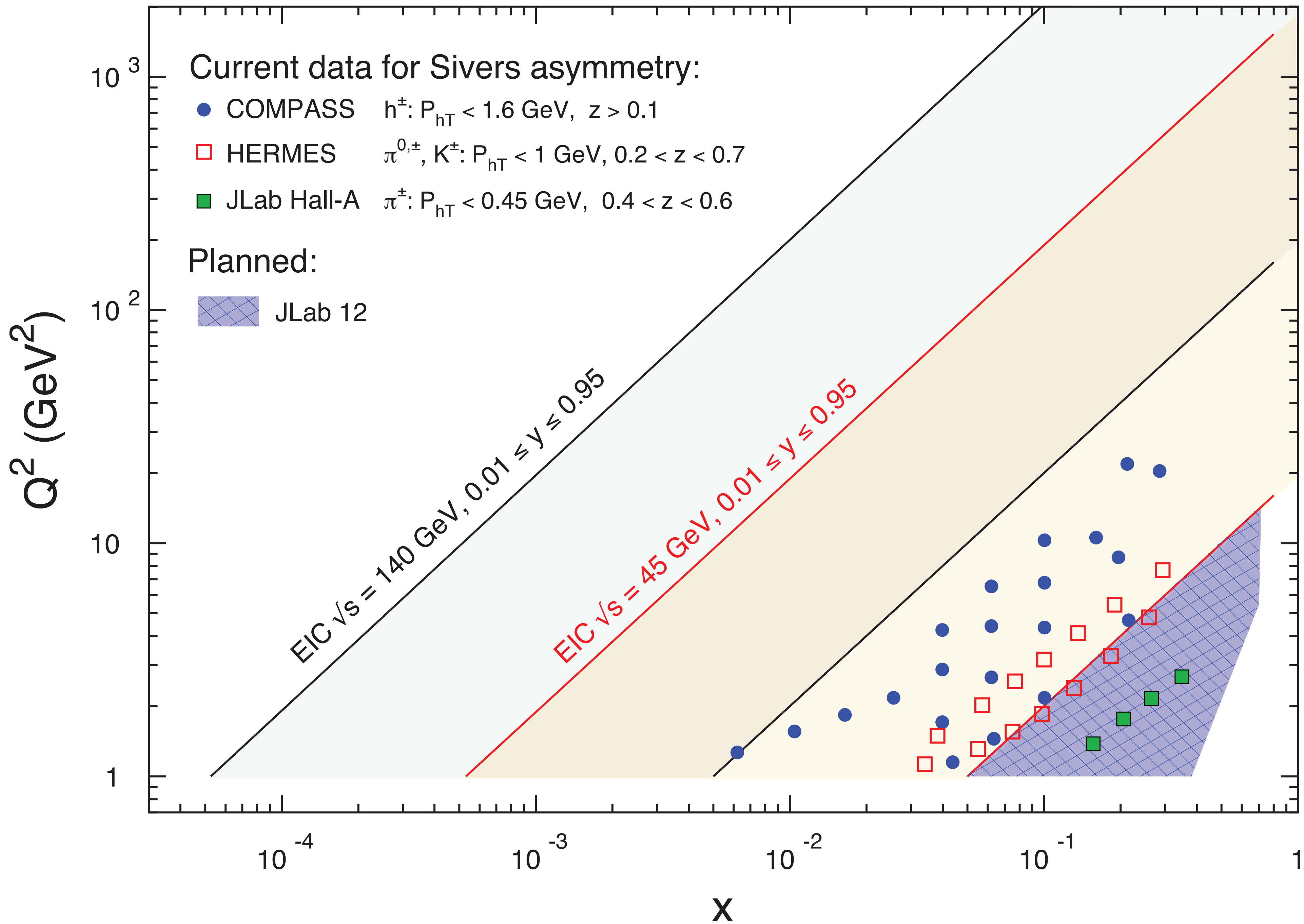
(Kang, Prokudin, Sun, Yuan, arXiv:1505.05589)

comparison of tensor charges from different extractions and models, at Q^2 = 10 GeV^2



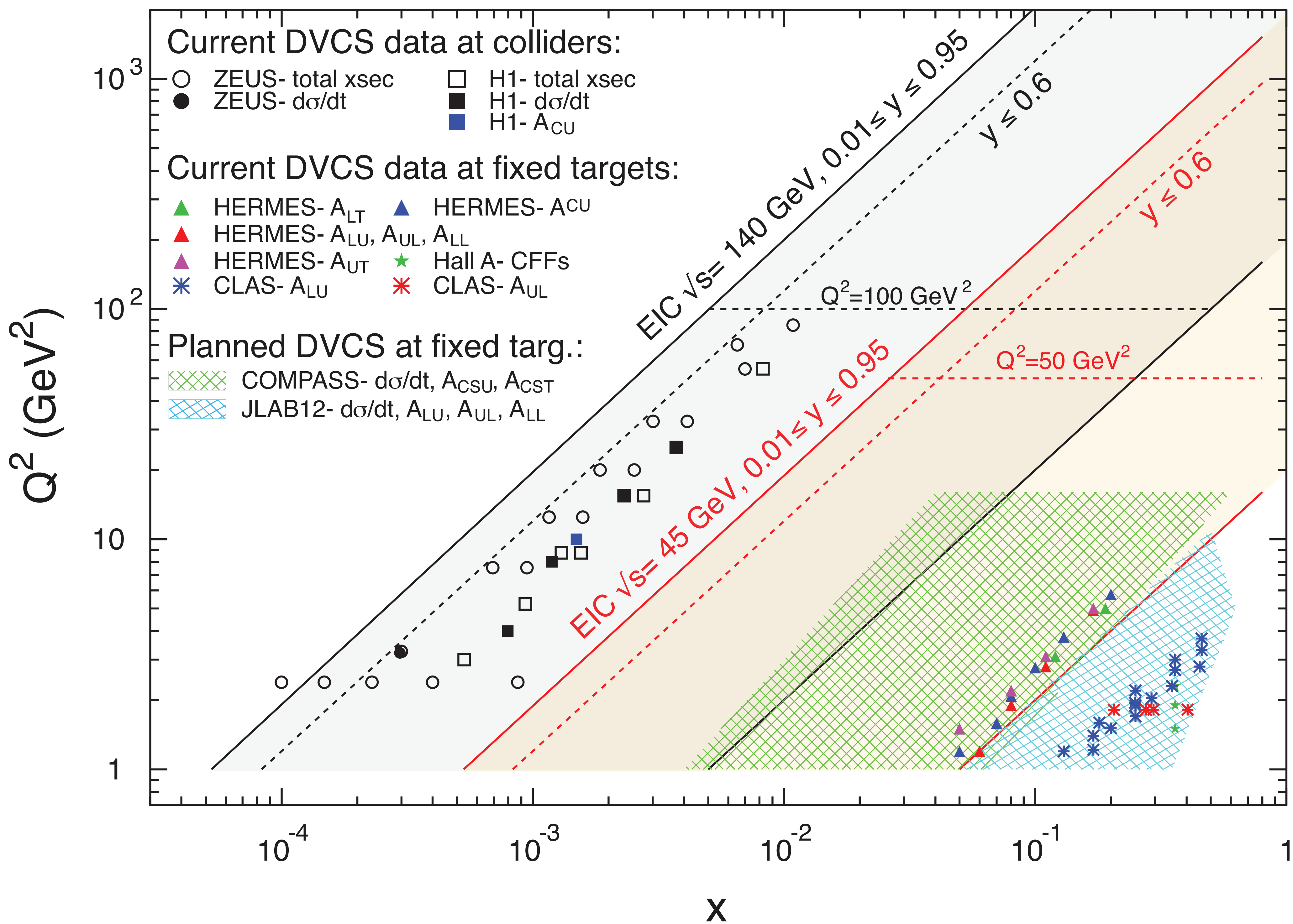
$$\delta q = \int_0^1 dx \left[\Delta_T q(x) - \Delta_T \bar{q}(x)\right]$$

extrapolation to small and large x



possible EIC kinematical coverage - SIDIS

Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all: e-Print: arXiv:1212.1701



possible EIC kinematical coverage - Deeply Virtual Compton Scattering

Conclusions

The 3D nucleon structure is mysterious and fascinating. Many experimental results show the necessity to go beyond the simple collinear partonic picture and give new information. Crucial task is interpreting data and building a consistent 3D description of the nucleon.

Sivers and Collins effects are well established, with many transverse spin asymmetries resulting from them.
Sivers function, TMDs and orbital angular momentum?
QCD analysis of TMDs and GPDs sound and well developed.

Combined data from SIDIS, Drell-Yan, e+e-, with theoretical modelling, should lead to a true 3D imaging of the proton

Waiting for JLab 12, new COMPASS results, and, crucially, for an EIC dedicated facility ....

Thank you!