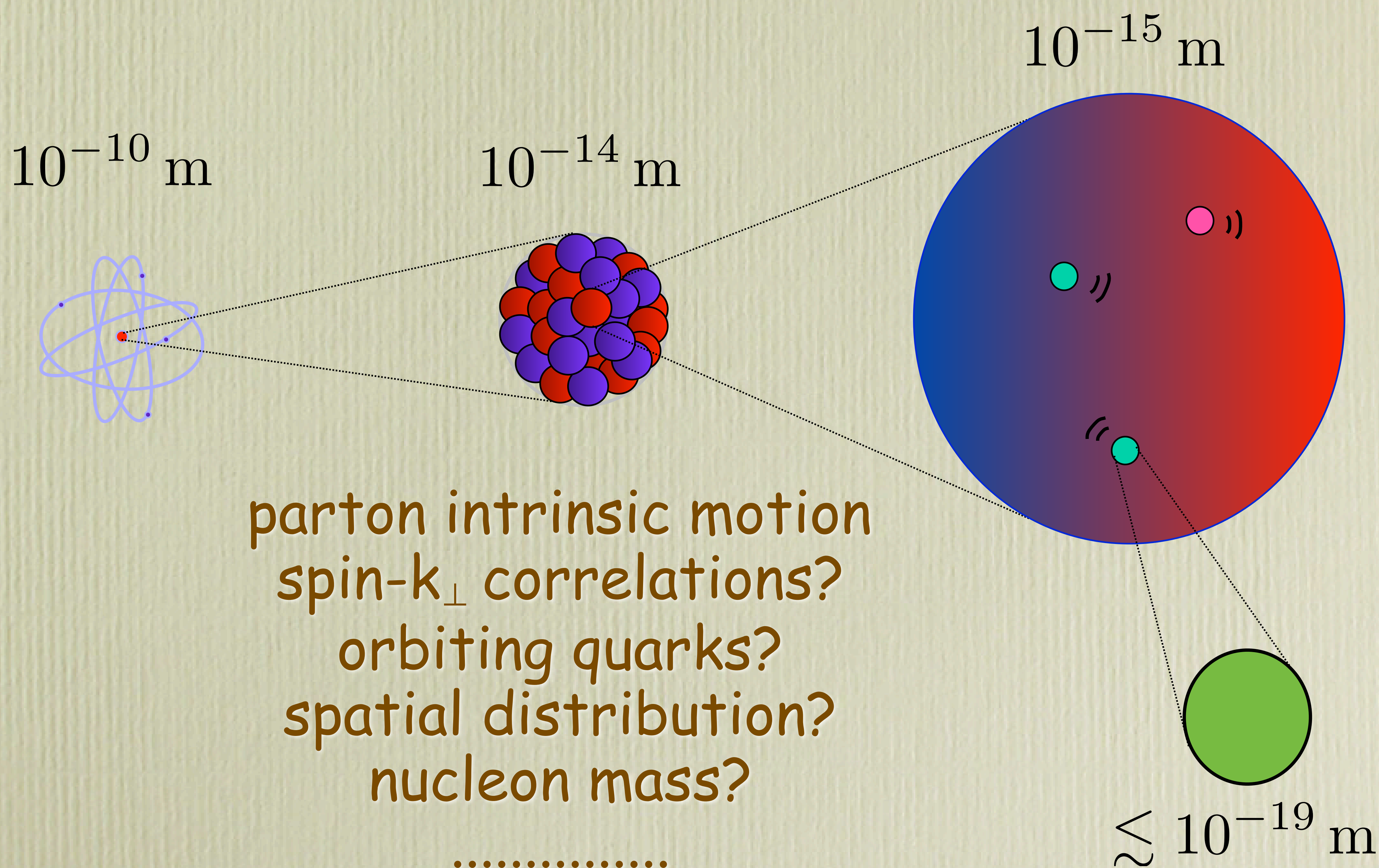
SPIN 2016, September 25-30, 2016

Overview on TMDs

Mauro Anselmino - Torino University & INFN

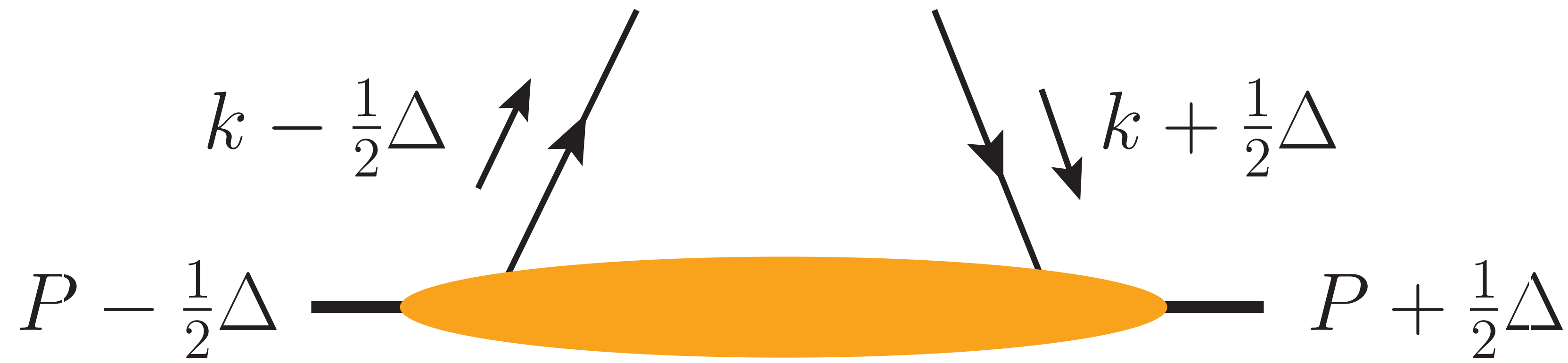
8 parallel sub-sessions, almost 50 talks

despite 50 years of studies the nucleon is still a very mysterious object, yet 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 ?



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

two-quark correlation function

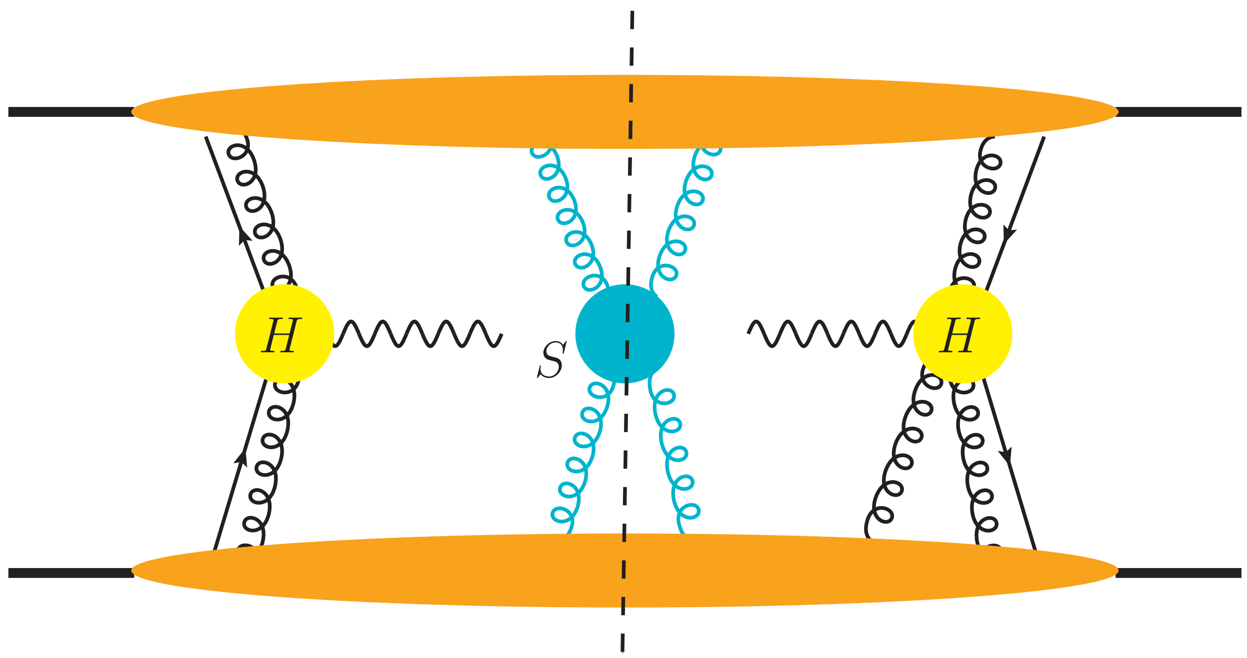
light-cone variables $v = (v^+, v^-, \boldsymbol{v})$ $\quad v^{\pm} = \frac{1}{\sqrt{2}}(v^0 \pm v^3)$

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

$\Delta = 0$ 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…

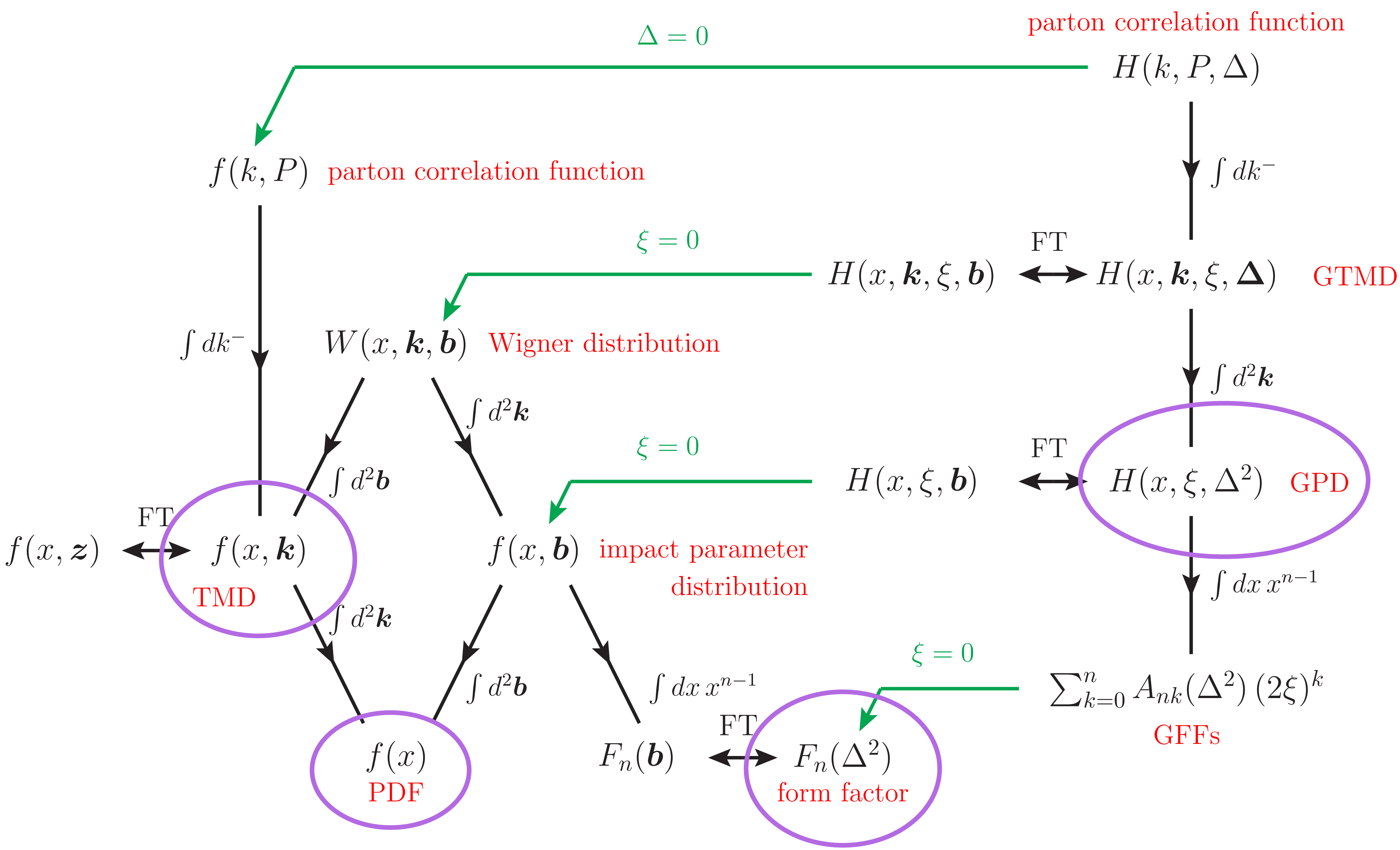
$$\langle p(P+\frac{1}{2}\Delta)|\bar{q}(-\frac{1}{2}z)\,\Gamma\,q(\frac{1}{2}z)|p(P-\frac{1}{2}\Delta)\rangle \to \langle p(P+\frac{1}{2}\Delta)|\bar{q}(-\frac{1}{2}z)\,\Gamma\,\mathcal{W}\,q(\frac{1}{2}z)|p(P-\frac{1}{2}\Delta)\rangle$$

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)

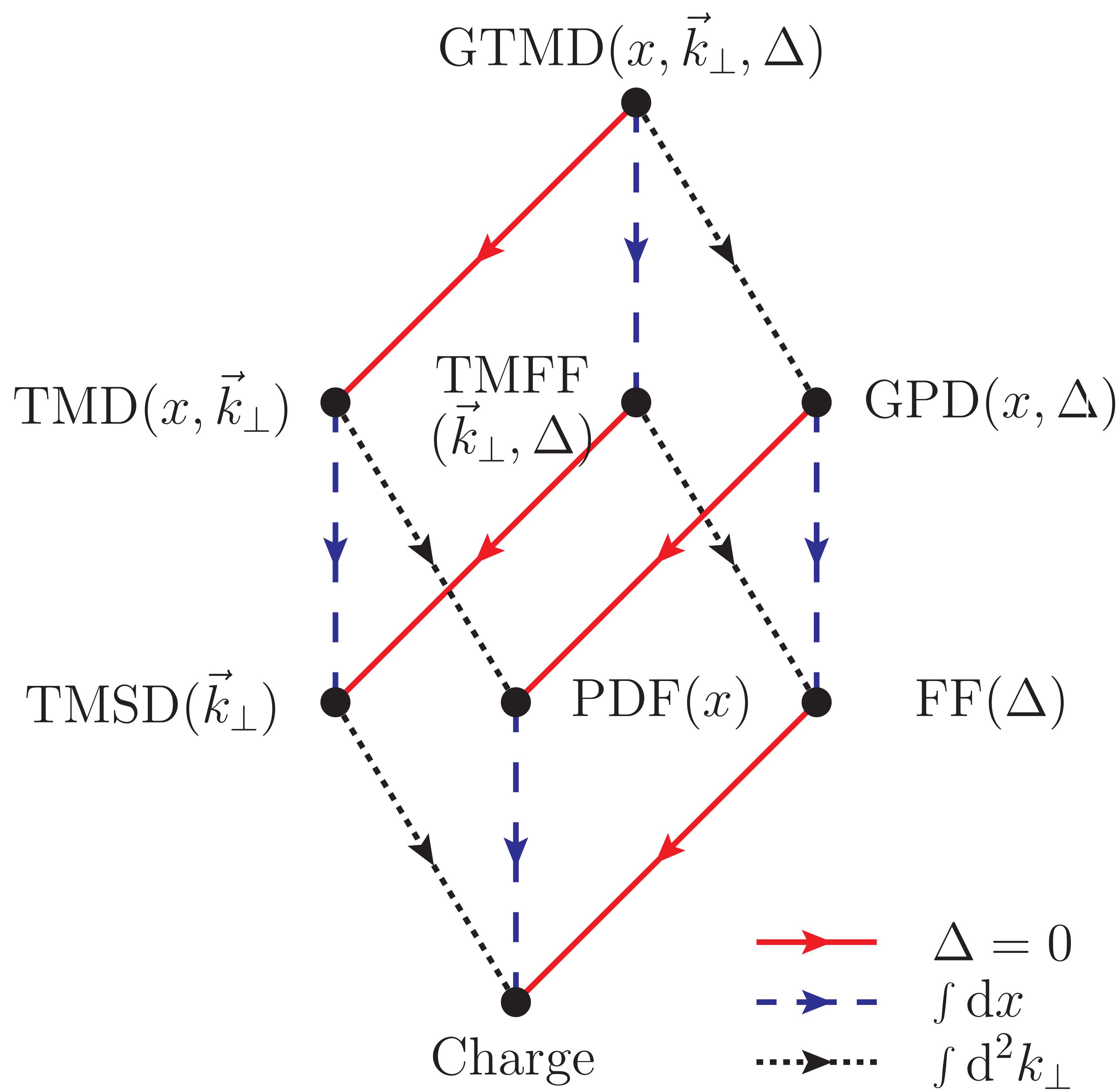
The nucleon landscape

Markus Diehl, arXiv:1512.01328



talks by Schweitzer, Hatta, ...

Burkardt, Pasquini, arXiv:1510.02567

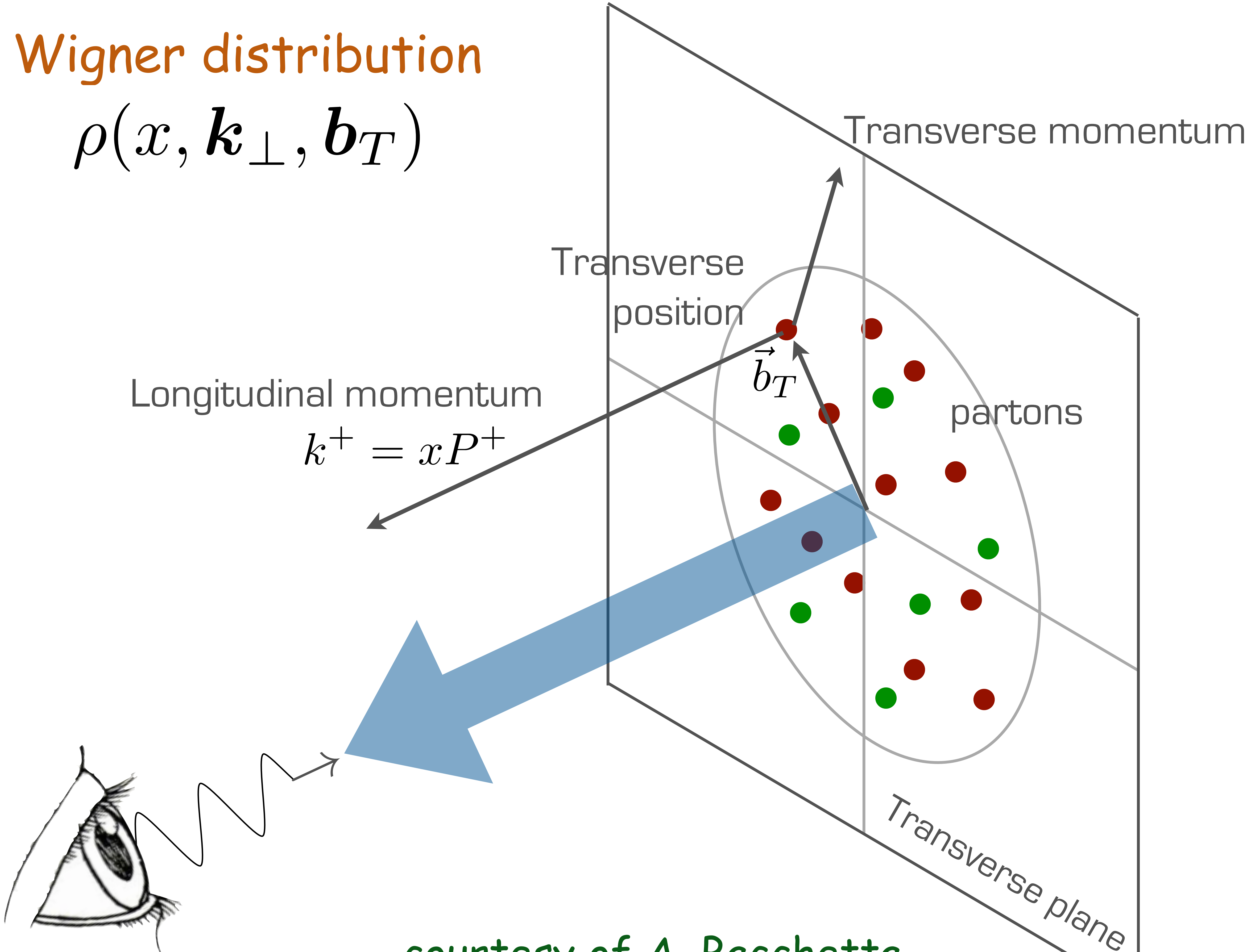


special issue of EPJA dedicated to the 3D nucleon structure, EPJA 52, (2016) 164

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

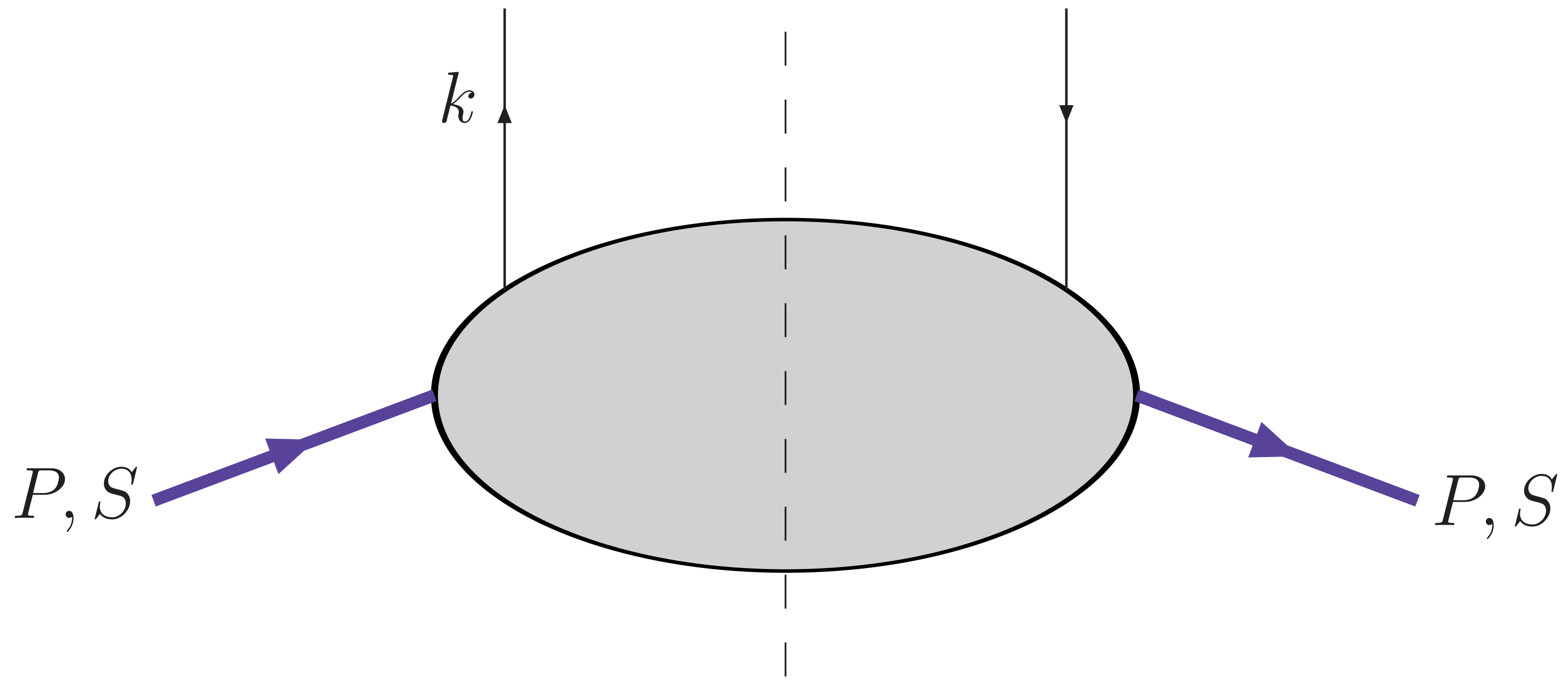
Wigner distribution

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



courtesy of A. Bacchetta

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



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

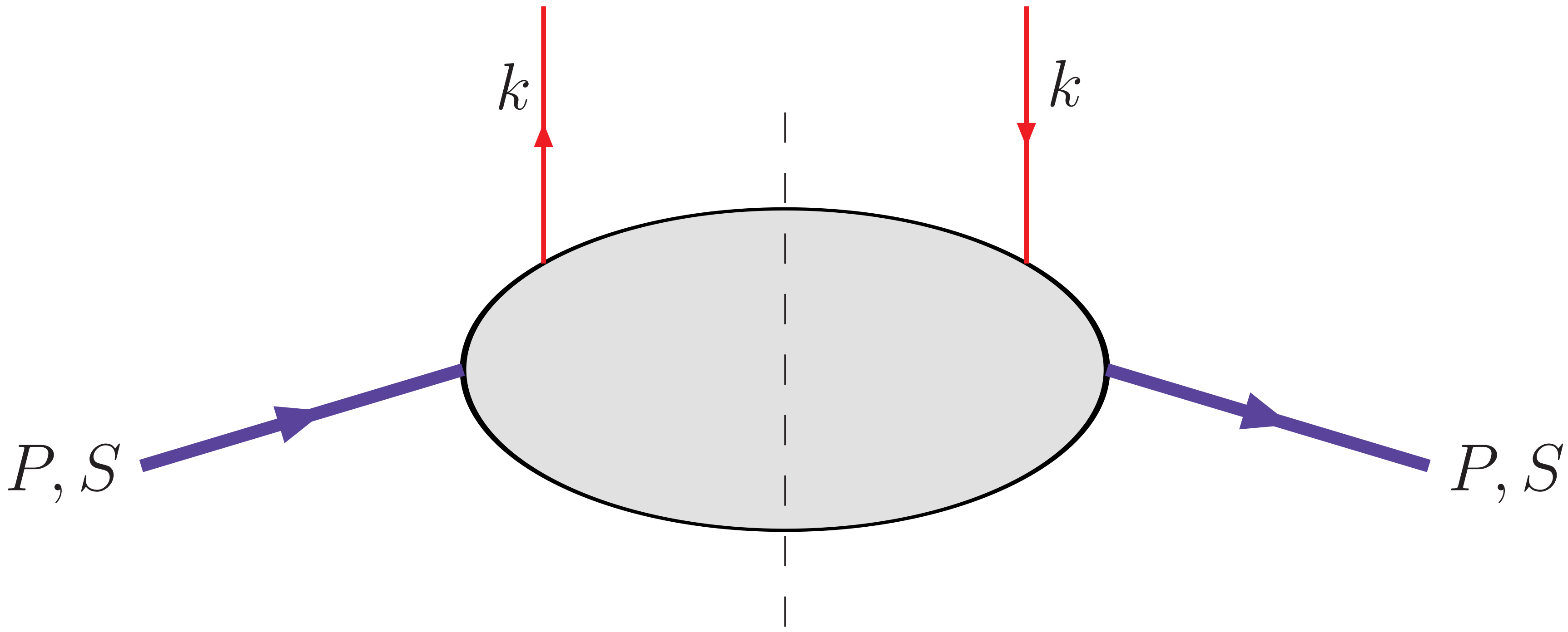
$$= \int d^4\xi\, e^{ik\cdot\xi}\langle PS|\overline{\Psi}_j(0)\Psi_i(\xi)|PS\rangle$$

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

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

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

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

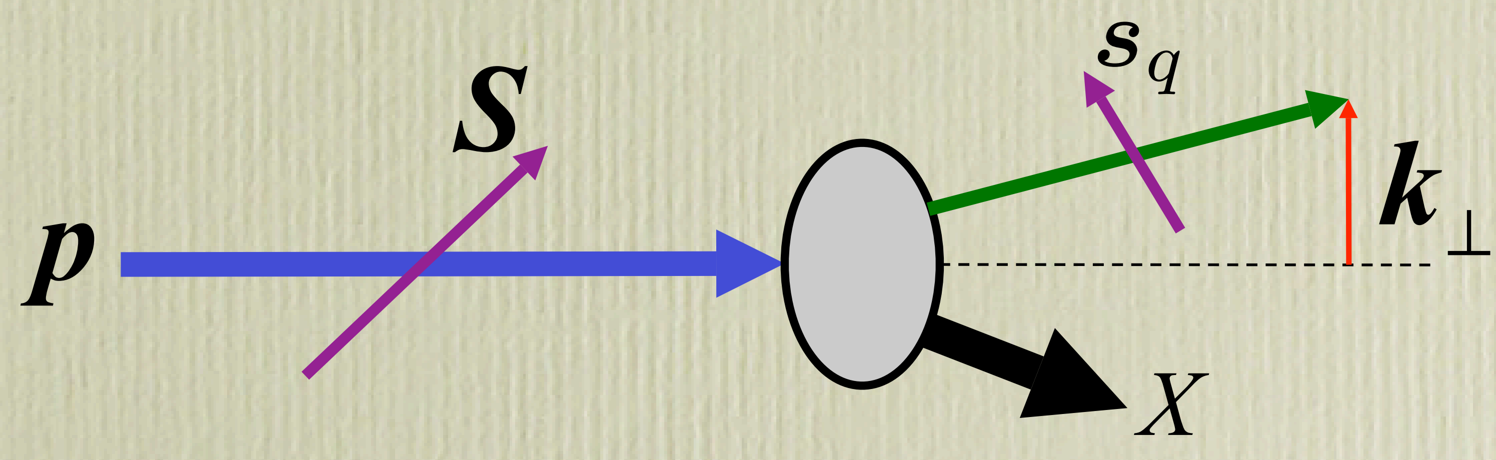


with partonic interpretation

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" $\quad$ "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

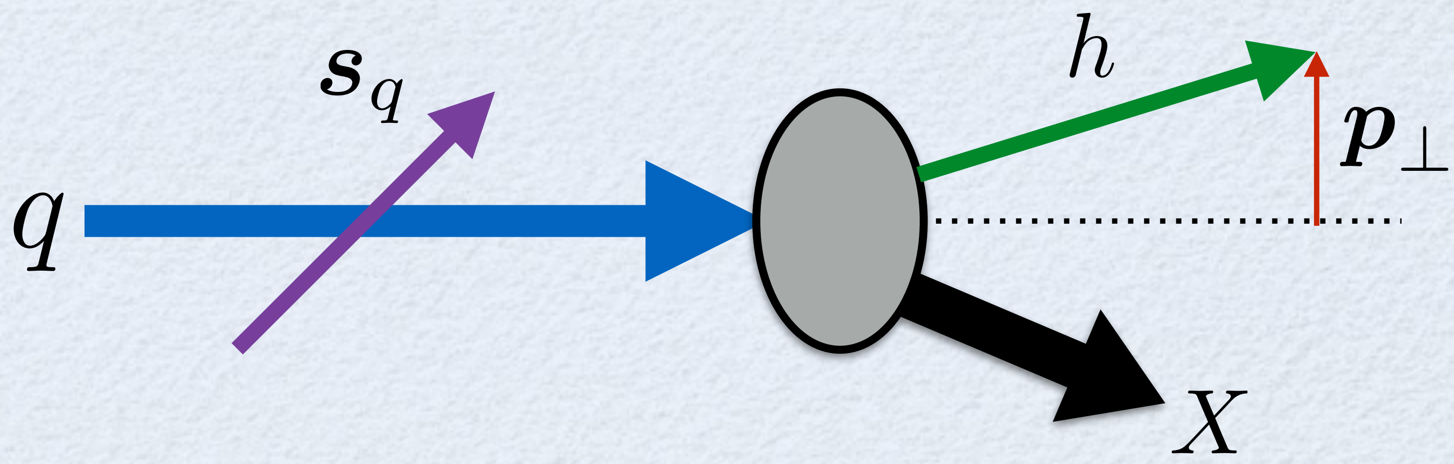
$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ of quark with S_T of proton (Sivers)

$h_1^{\perp q}(x, \boldsymbol{k}_\perp^2)$ 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.



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

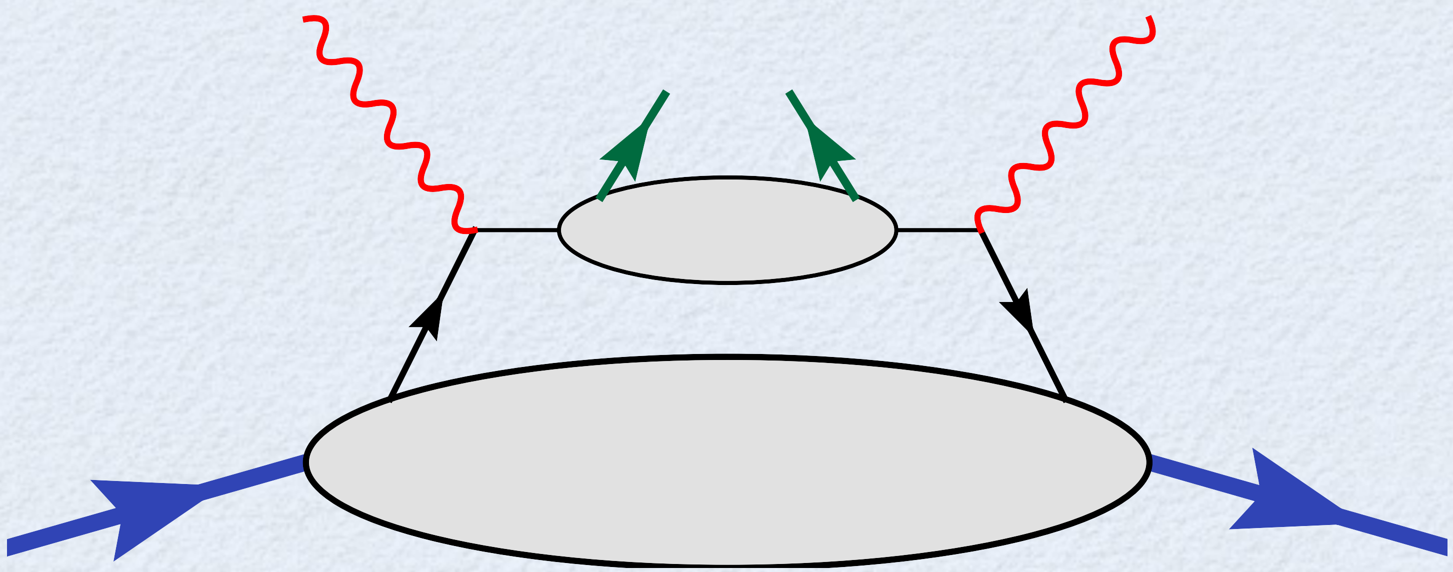
there are 2 independent TMD-FFs for spinless hadrons

$D_1^q(z, \boldsymbol{p}_\perp^2)$ unpolarized hadrons in unpolarized quarks unintegrated fragmentation function

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

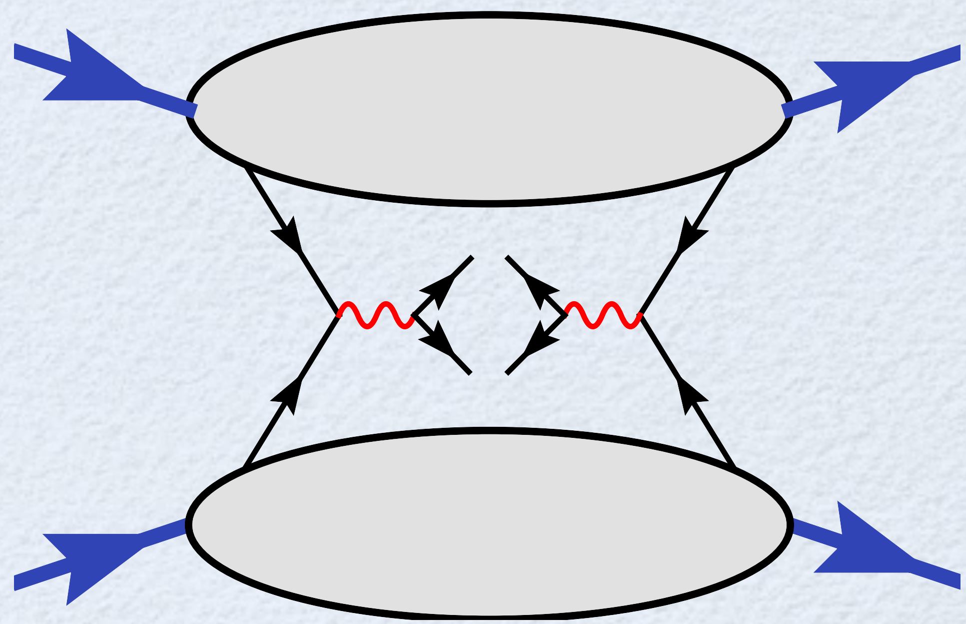
how to "measure" TMDs?

needs processes which relate physical observables
to parton intrinsic motion (and correlators)



SIDIS

$\ell N \to \ell h X$

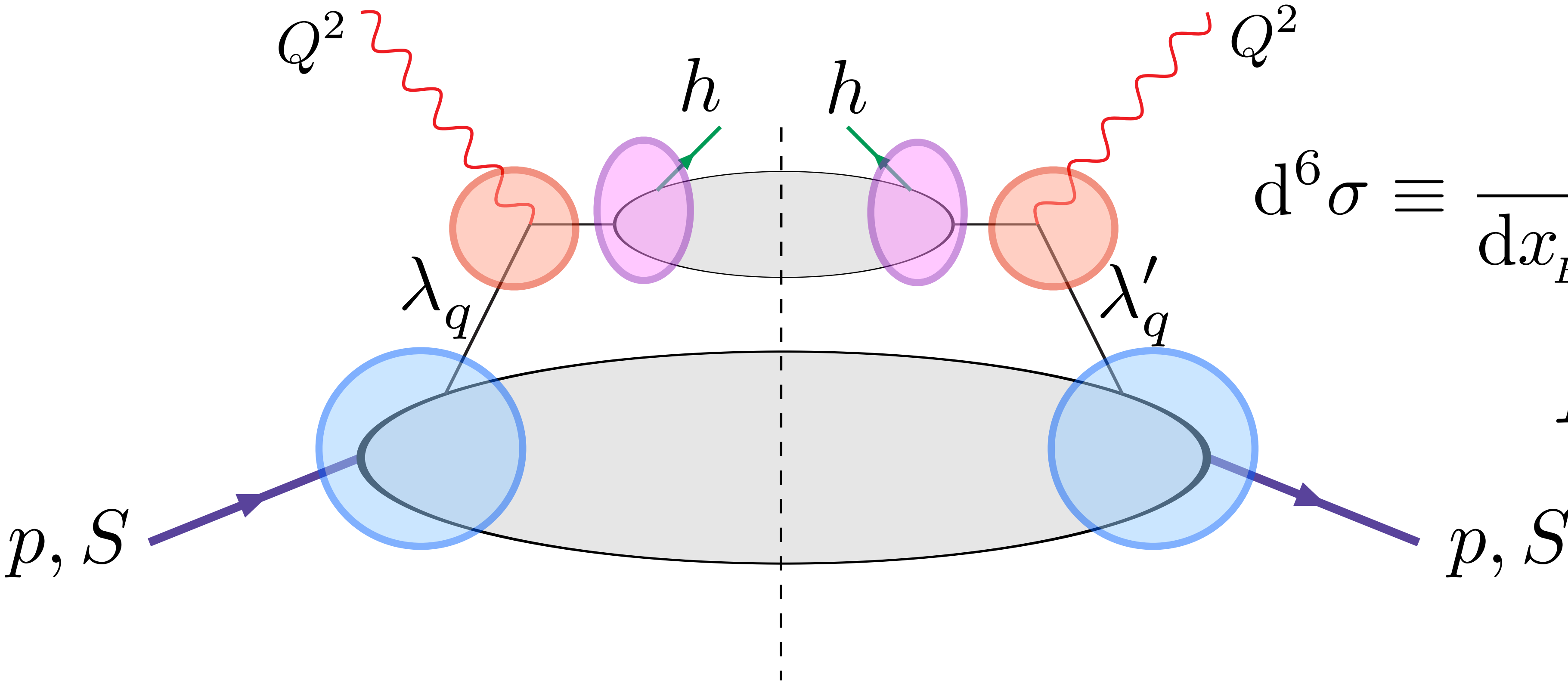


Drell-Yan processes

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

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: $P_T \ll Q^2$

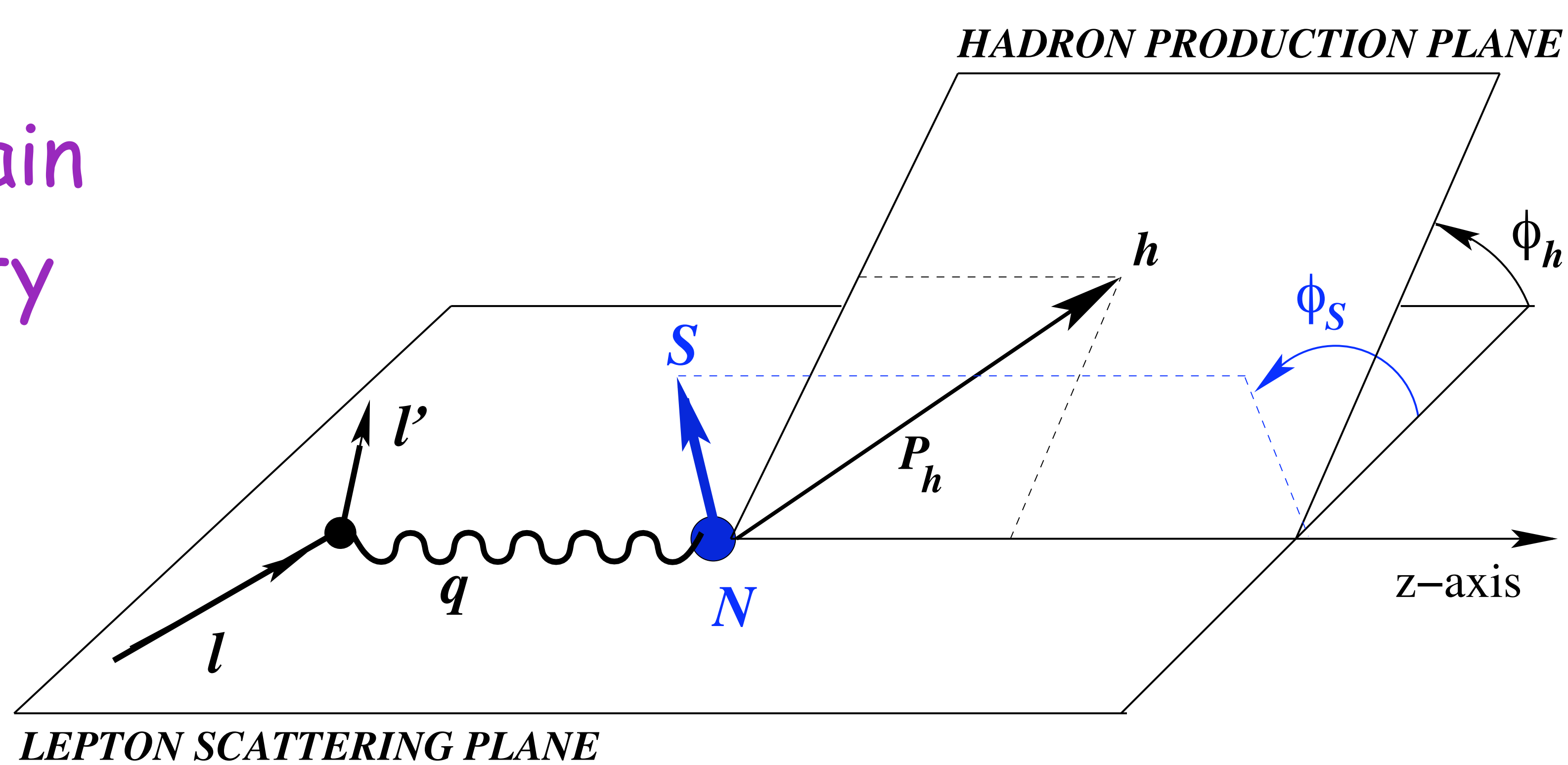
TMD-PDFs / hard scattering / TMD-FFs

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

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

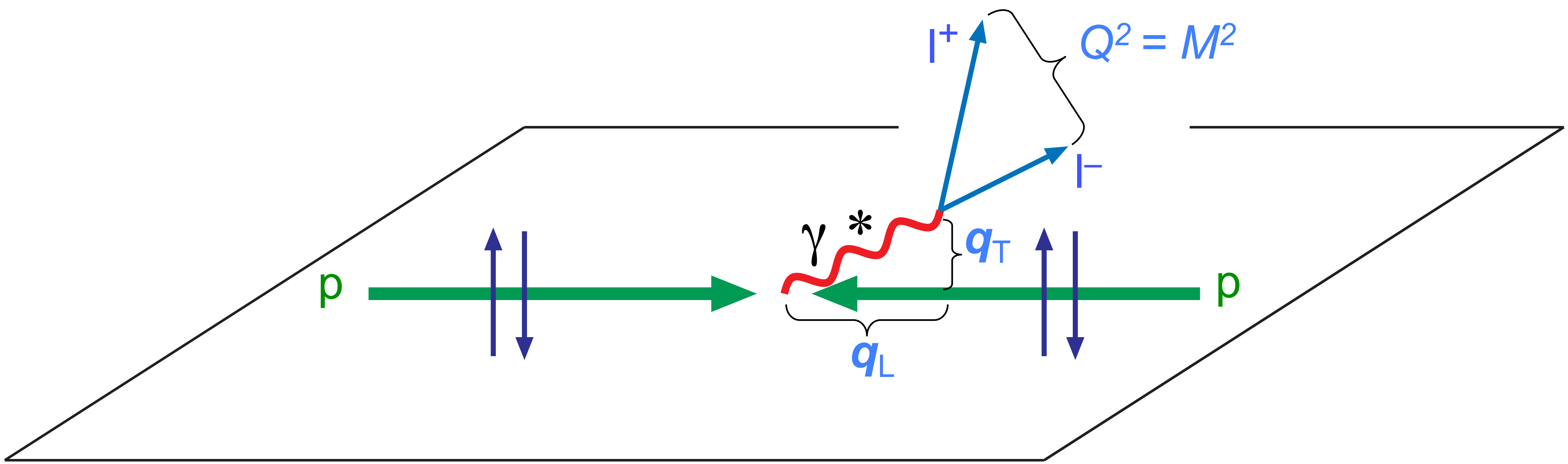
$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \;=\;& F_{UU} + \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \frac{1}{Q}\,\cos\phi\, F_{UU}^{\cos\phi} + \lambda\,\frac{1}{Q}\,\sin\phi\, F_{LU}^{\sin\phi} \\
&+ S_L \left\{ \sin(2\phi)\, F_{UL}^{\sin(2\phi)} + \frac{1}{Q}\,\sin\phi\, F_{UL}^{\sin\phi}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

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

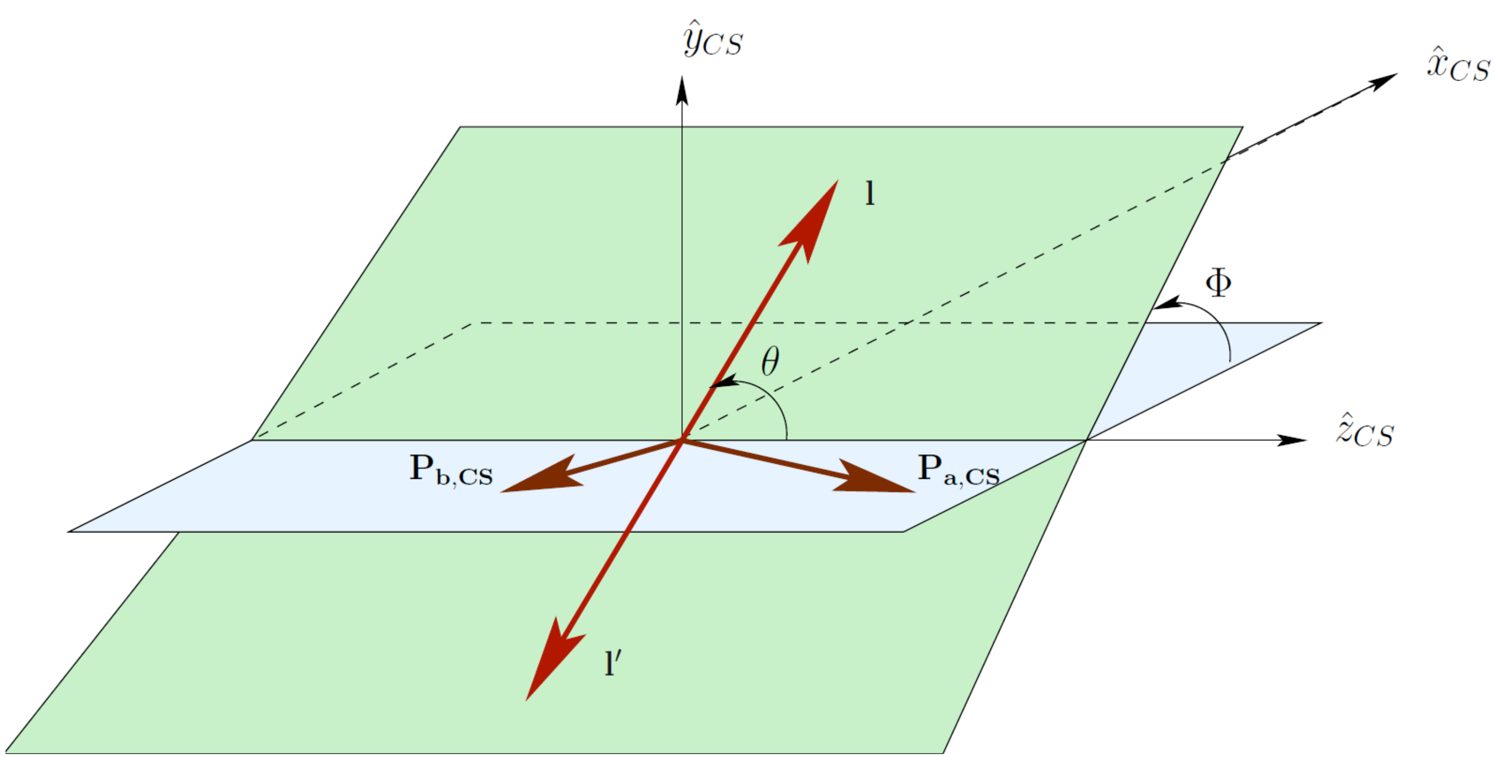
talks by Parsamyan, Ramson, Peng, Quaresma, ...

Case of one polarized nucleon only

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} = \frac{\alpha^2}{\Phi\, q^2}\Bigg\{ & (1+\cos^2\theta)\, F_U^1 + (1-\cos^2\theta)\, F_U^2 + \sin 2\theta \cos\phi\, F_U^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_U^{\cos 2\phi} \\
+ & \, S_L \left(\sin 2\theta \sin\phi\, F_L^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_L^{\sin 2\phi} \right) \\
+ & \, S_T \Bigg[\left(F_T^{\sin\phi_S} + cos^2\theta\, \tilde{F}_T^{\sin\phi_S} \right) \sin\phi_S + \sin 2\theta \Big(\sin(\phi+\phi_S)\, F_T^{\sin(\phi+\phi_S)} \\
& \quad + \sin(\phi-\phi_S)\, F_T^{\sin(\phi-\phi_S)} \Big) \\
+ & \, \sin^2\theta \left(\sin(2\phi+\phi_S)\, F_T^{\sin(2\phi+\phi_S)} + \sin(2\phi-\phi_S)\, F_T^{\sin(2\phi-\phi_S)} \right) \Bigg] \Bigg\}
\end{aligned}
$$

B-M ⊗ B-M

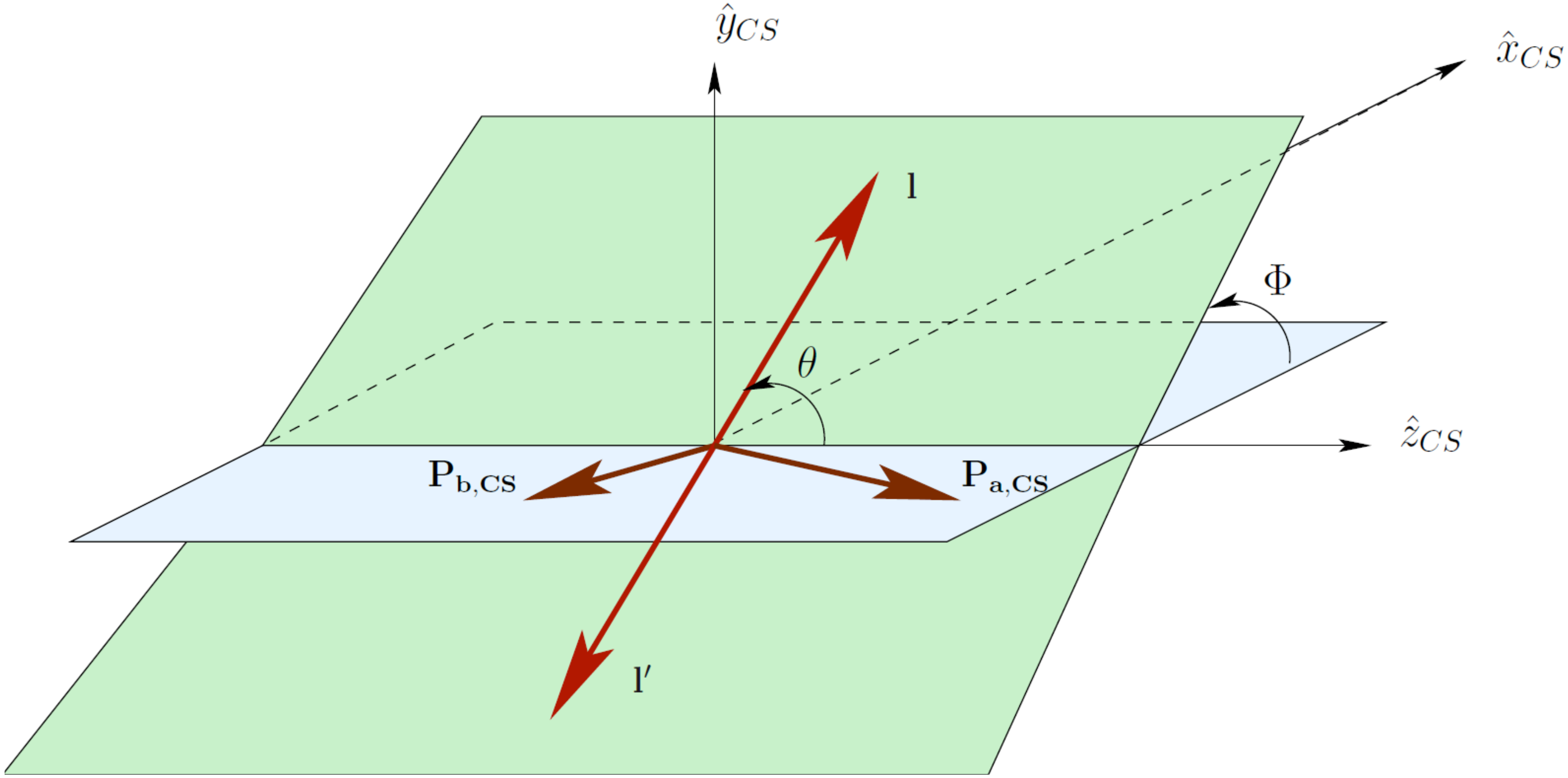
Sivers



Collins-Soper frame

Unpolarized cross section already very interesting

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

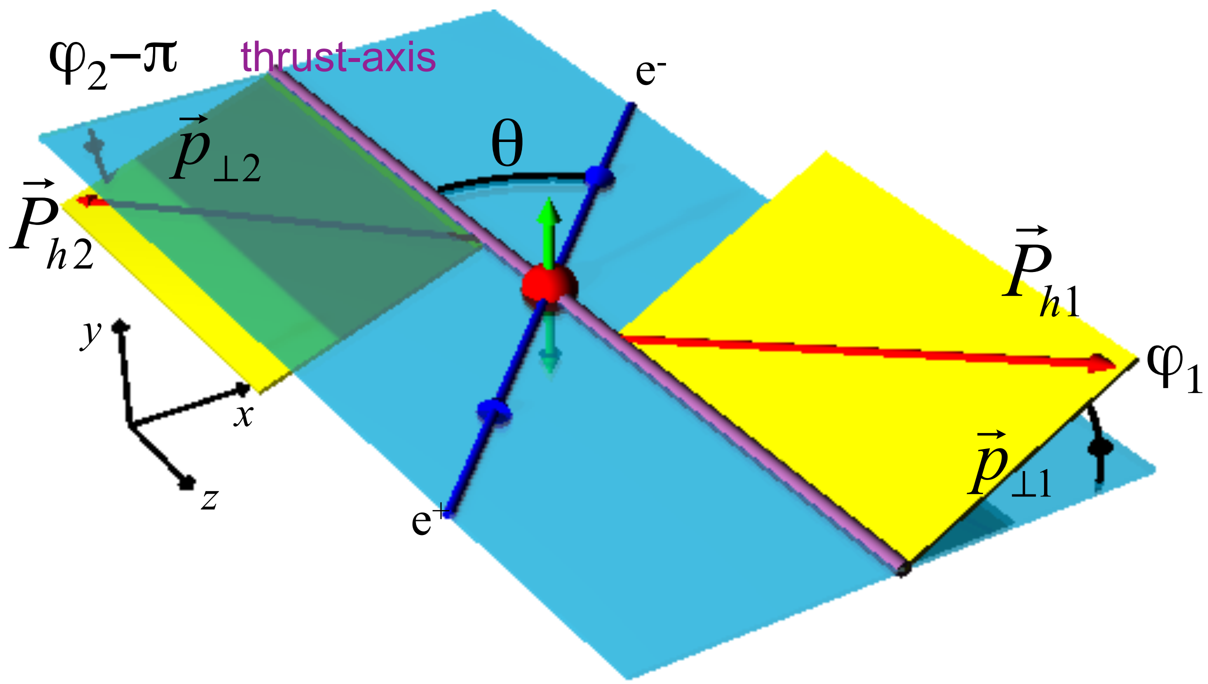


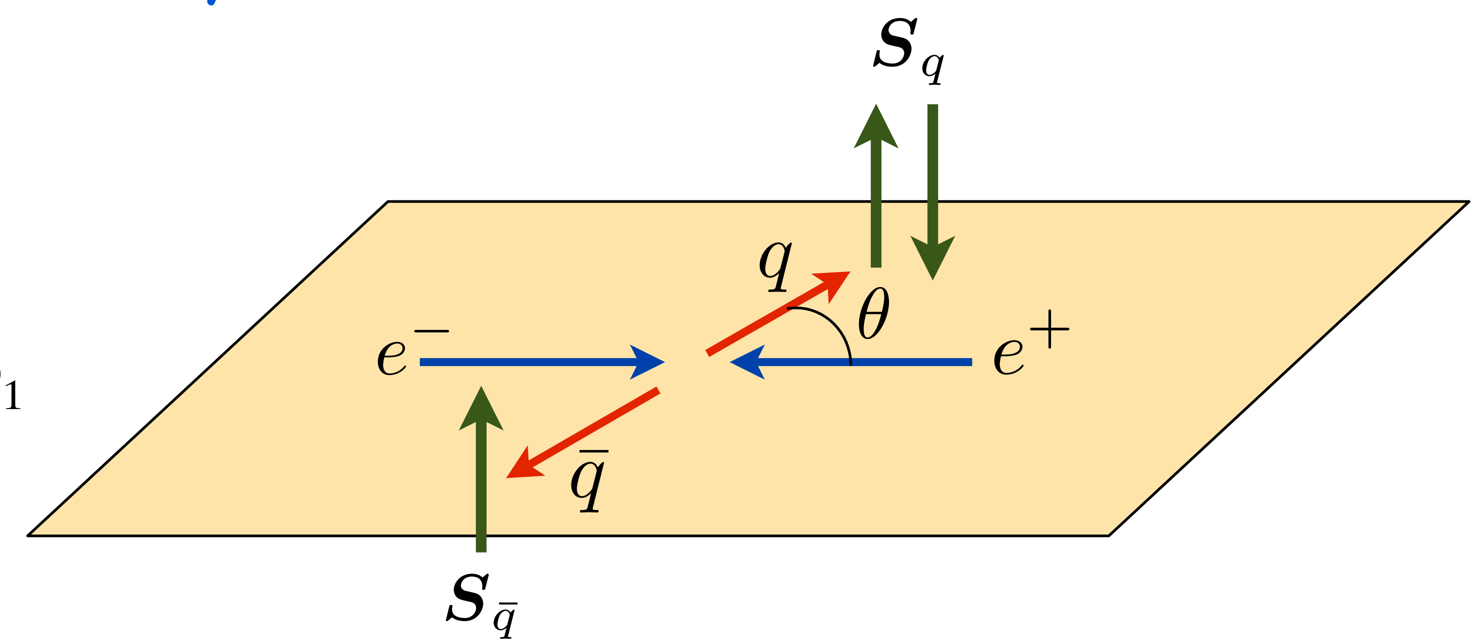
Collins-Soper frame

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

Collins function from e^+e^- processes

Belle, BaBar, BES-III





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

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

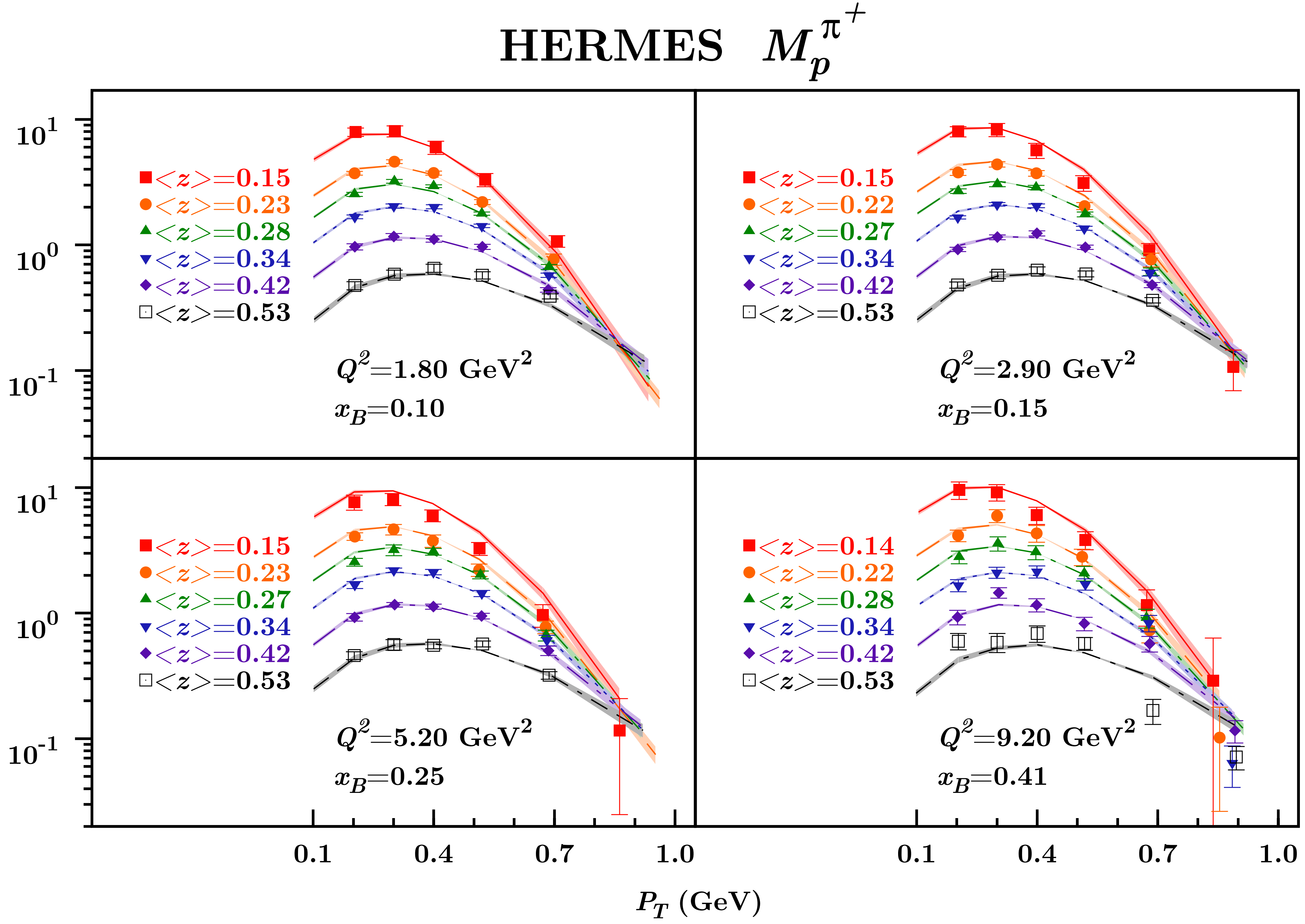
$$= 1 + \frac{1}{4}\, \frac{\sin^2\theta}{1+\cos^2\theta}\, \cos(\varphi_1+\varphi_2) \times \frac{\sum_q e_q^2\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2)}$$

another similar asymmetry can be measured, A_0

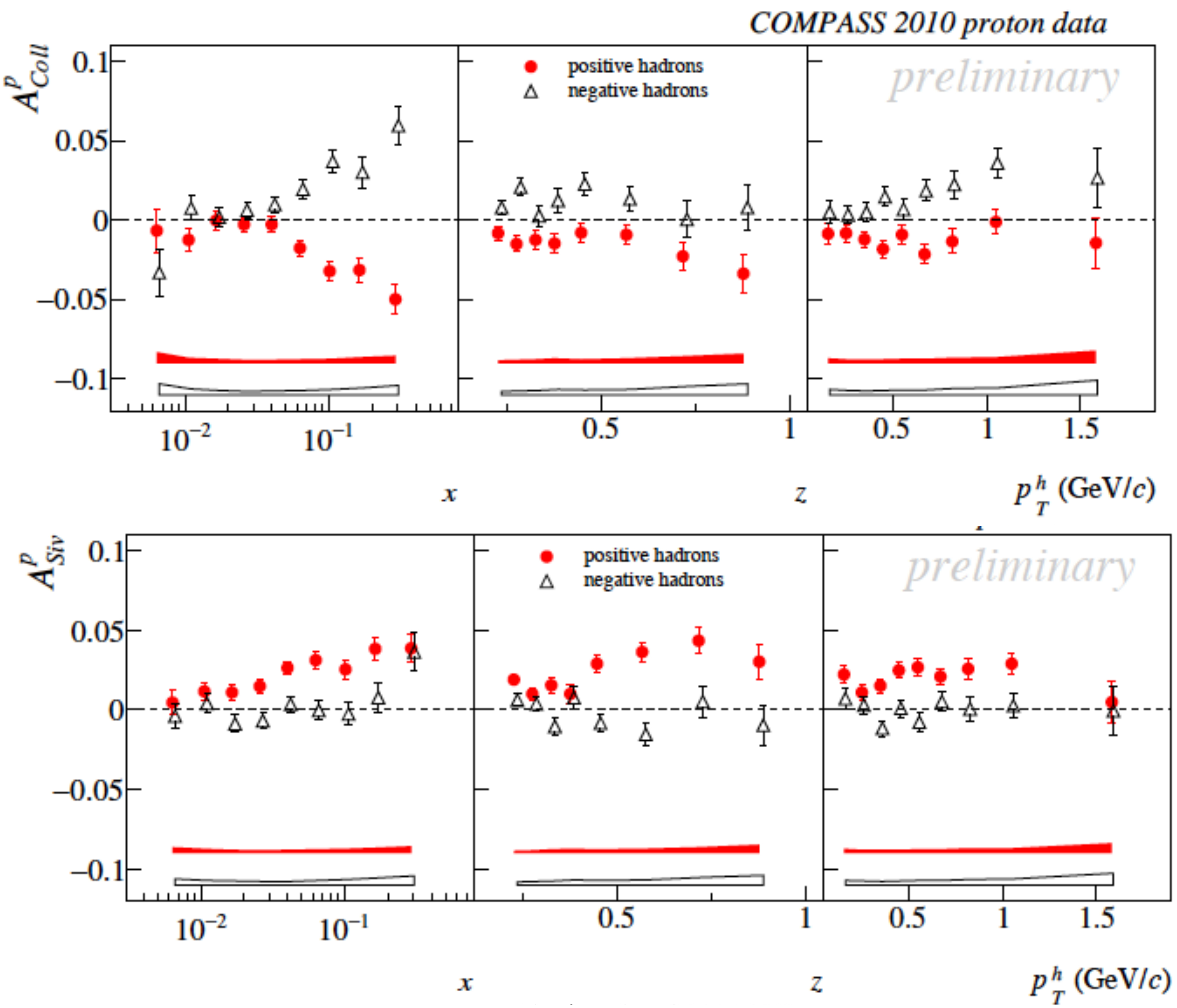
Experimental results:

P_T dependence of unpolarised SIDIS multiplicities

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

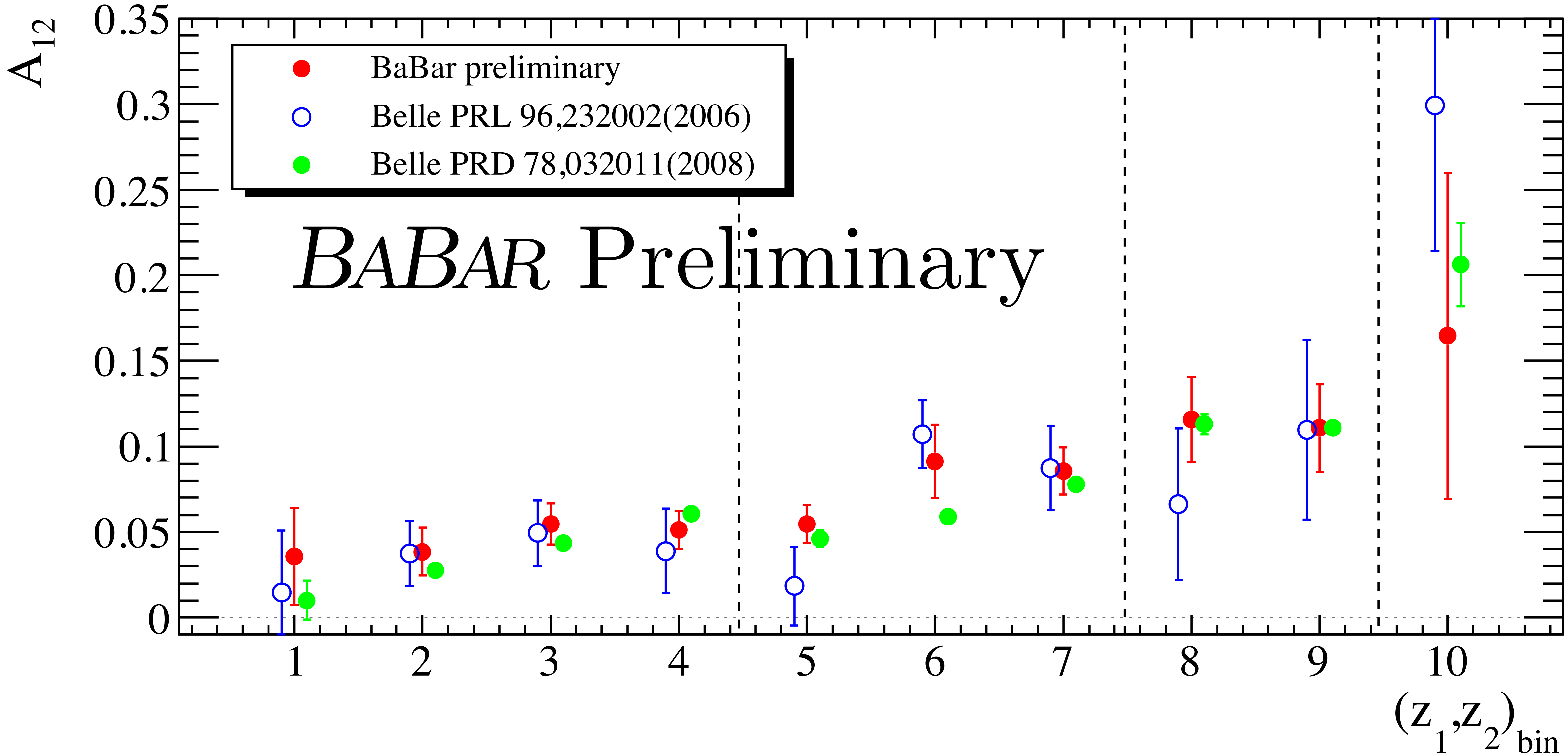


Experimental results:
clear evidence for Sivers and Collins effects from SIDIS data (HERMES, COMPASS, JLab)

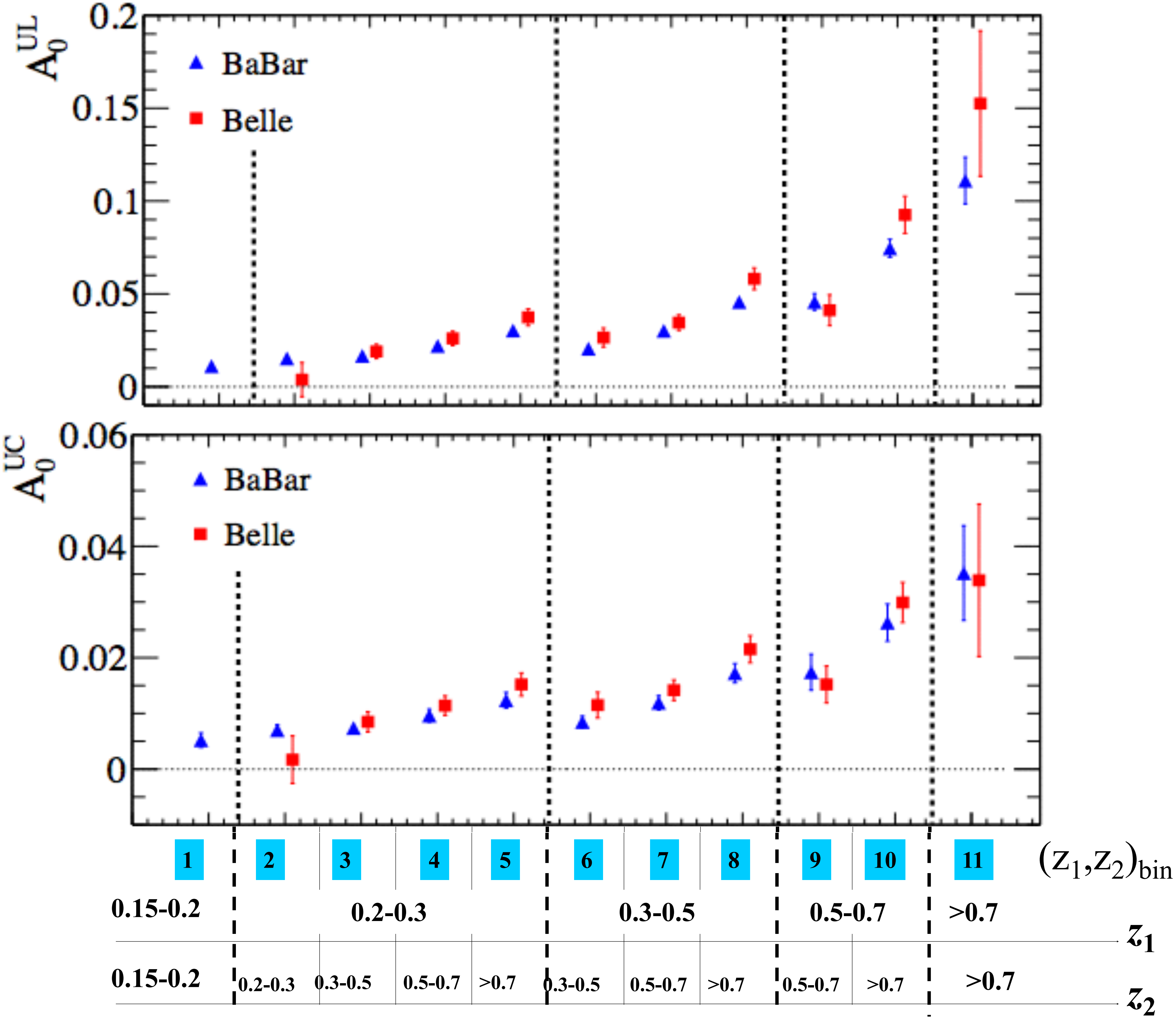


independent evidence for Collins effect from e^+e^- data at Belle, BaBar and BES-III

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



I. Garzia, arXiv:1201.4678

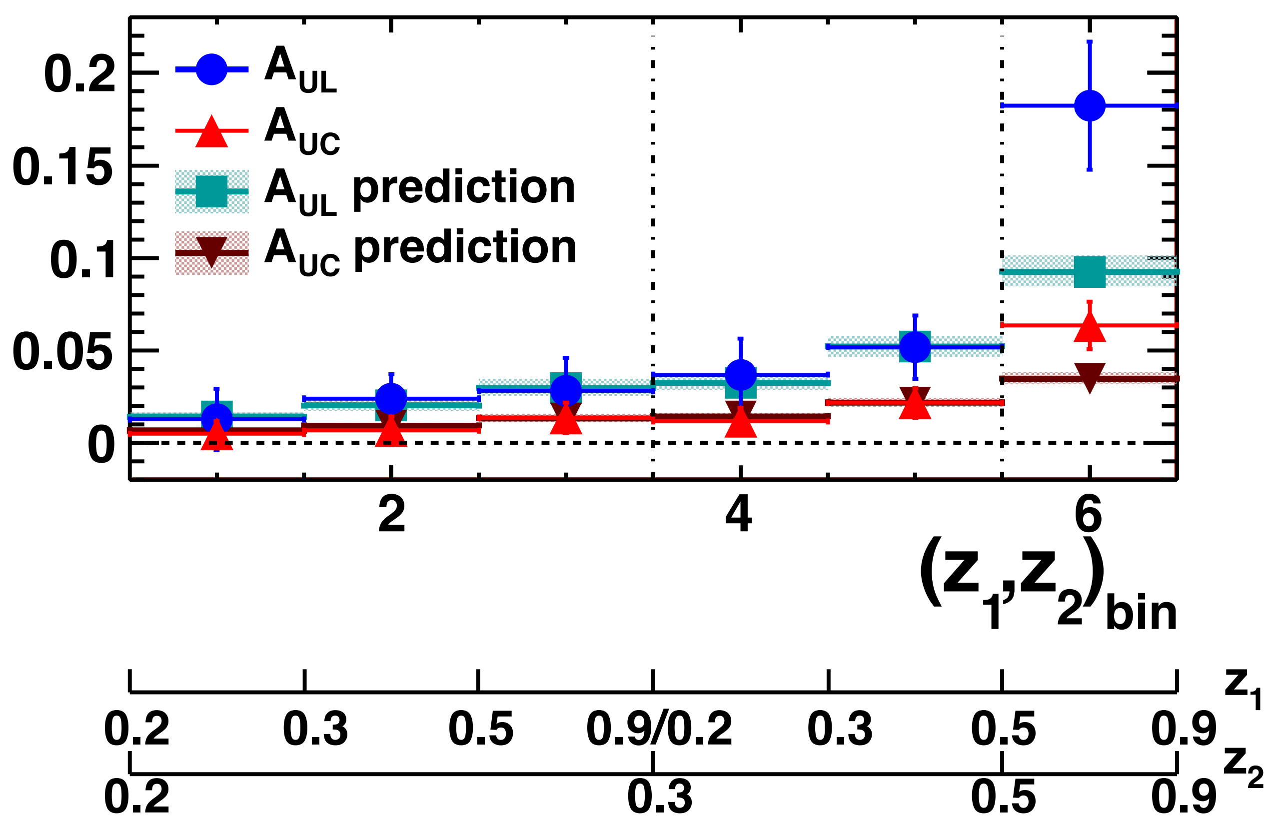


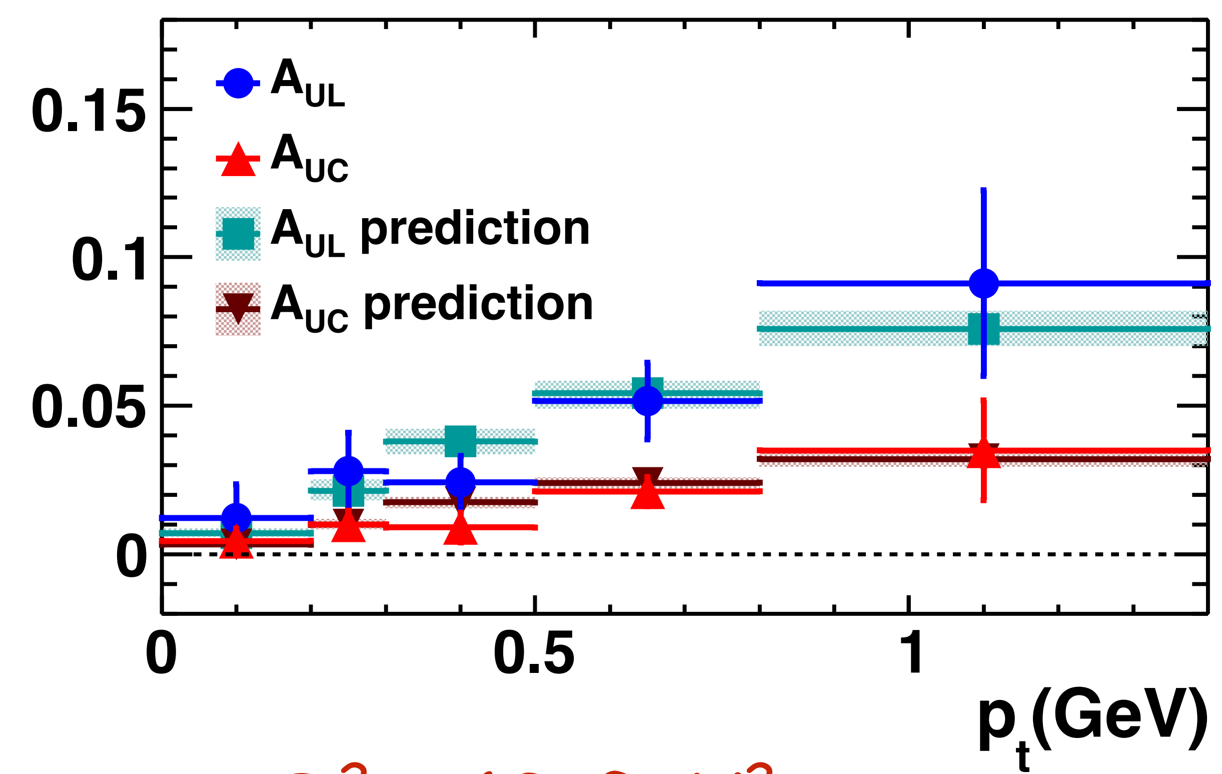
BaBar and Belle data on A_0

(I. Garzia talk at TMDe2015)

a similar asymmetry just measured by BES-III

(arXiv 1507:06824)





$Q^2 = 13\ GeV^2$

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

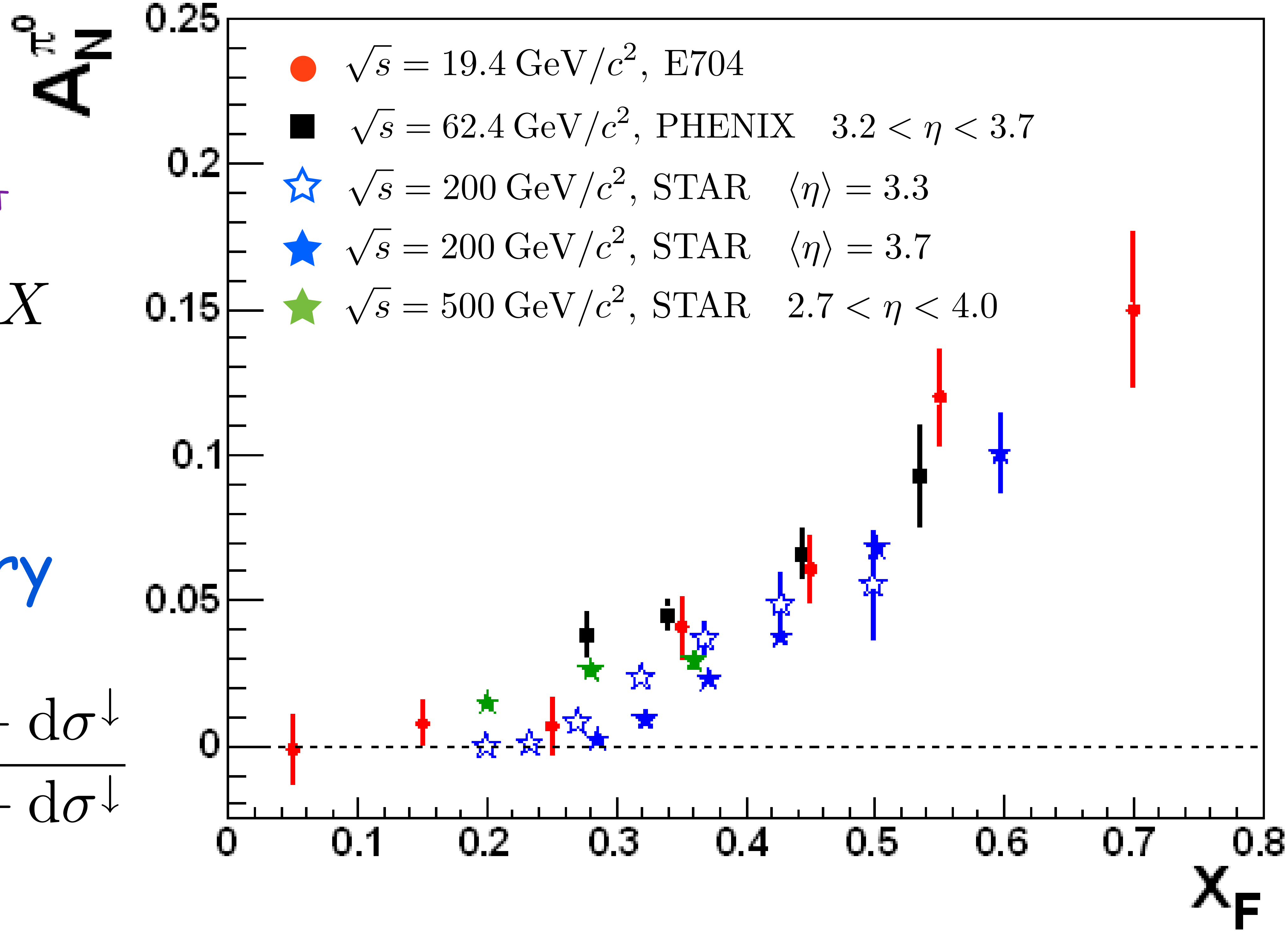
other experimental evidence of the Sivers and Collins effects

large P_T

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

Single Spin Asymmetry

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



TMD extraction from data - first phase

simple parameterisation, factorised $k_\perp$ and $p_\perp$ Gaussian dependences, no TMD evolution, limited number of parameters, ...

unpolarised TMDs - fit of SIDIS multiplicities

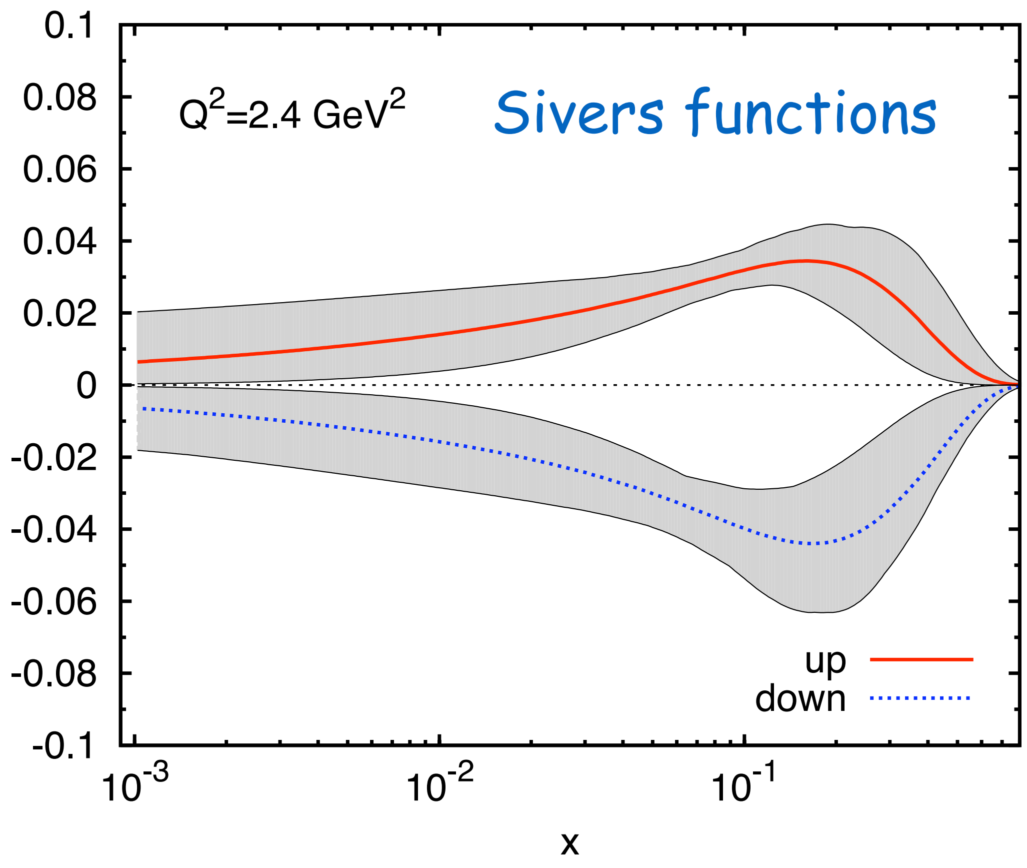
Sivers function - fit of SIDIS asymmetries

Collins function - fit of e+e- $\to h_1\, h_2$ azimuthal correlations

Collins function & Transversity distribution - combined fits of SIDIS asymmetries & e+e- $\to h_1\, h_2$ data

more and more precise data needed, larger kinematical ranges, multi dimensional binning, ...

talks by Schlegel, Puckett, Sbrizzai, Delcarro, Prokudin, Bradamante, Yoshida, Martin, Silva, Bedfer, Sirtl, Radici, Schnell, Xiao, van Daal, Avakian, Seidl, Anulli...



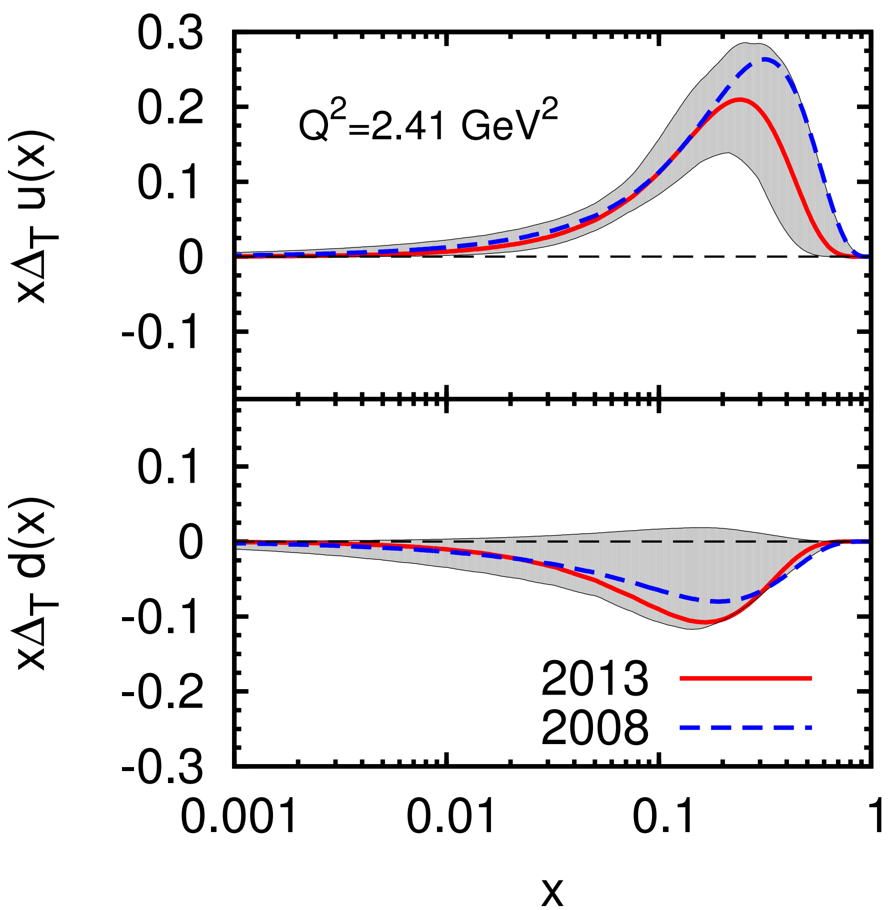
TO-CA-JLab, Bochum and PV groups

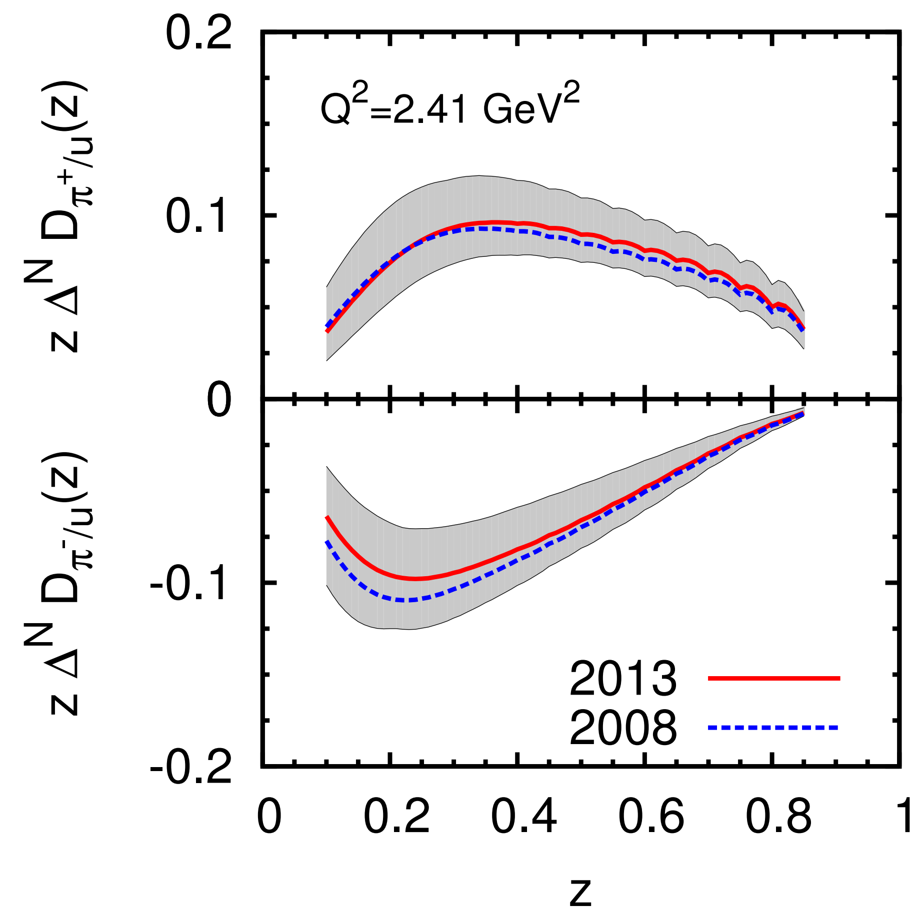
unpolarized TMD-PDFs
and TMD-FFs

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

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

$$\langle k_\perp^2\rangle = 0.57 \quad \langle p_\perp^2\rangle = 0.12 \quad \text{GeV}$$





transversity
(left) and
Collins functions

Sivers effects induces distortions in the parton distribution

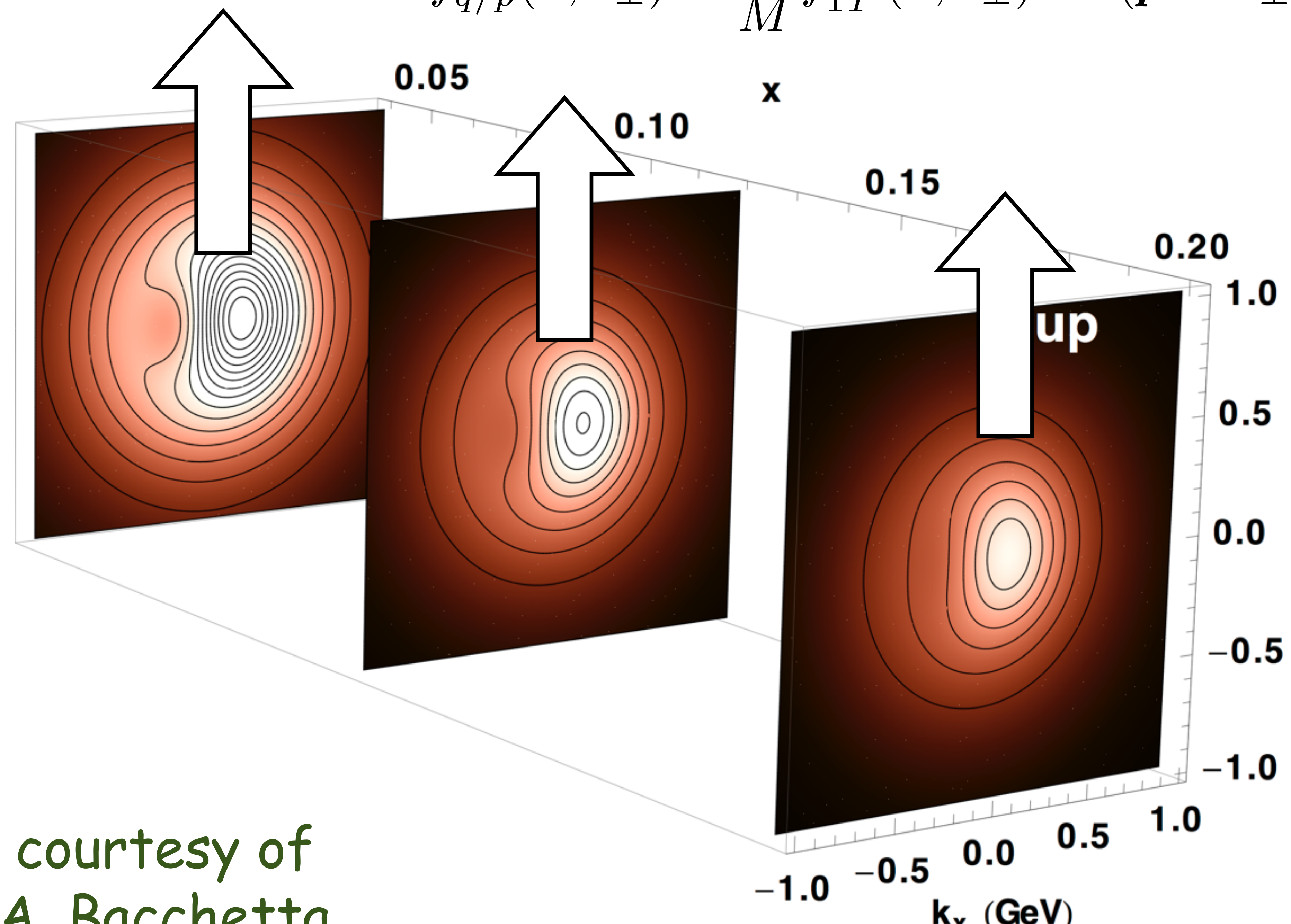
$$f_{q/p,\boldsymbol{S}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

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

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

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

u quark



courtesy of
A. Bacchetta

TMDs and QCD - TMD evolution

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

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

dedicated tools:

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

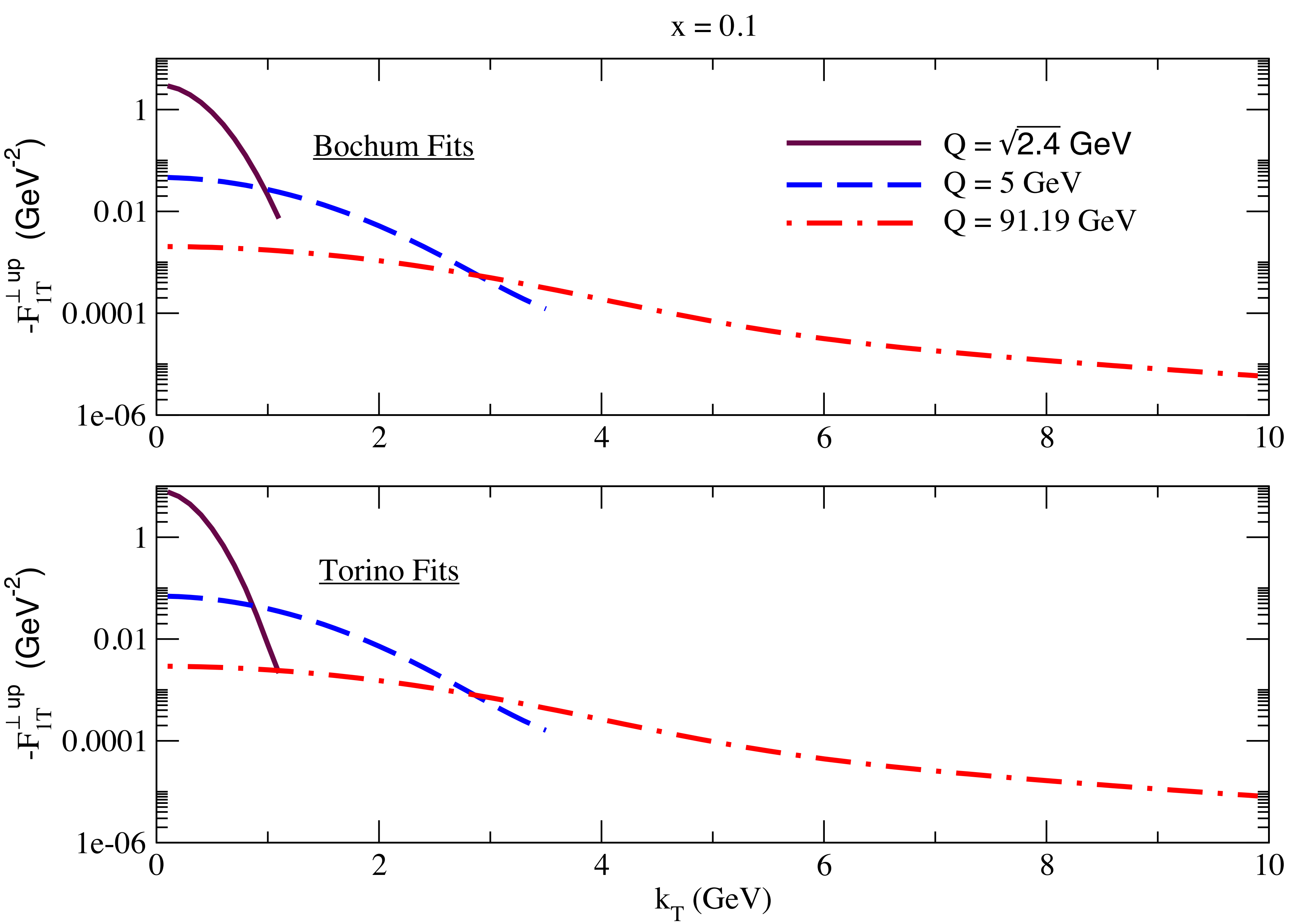
talks by Collins, Kang, Echevarria,...

TMD phenomenology - phase 2

how does gluon emission affect the transverse motion?

a few selected results

TMD evolution of up quark Sivers function

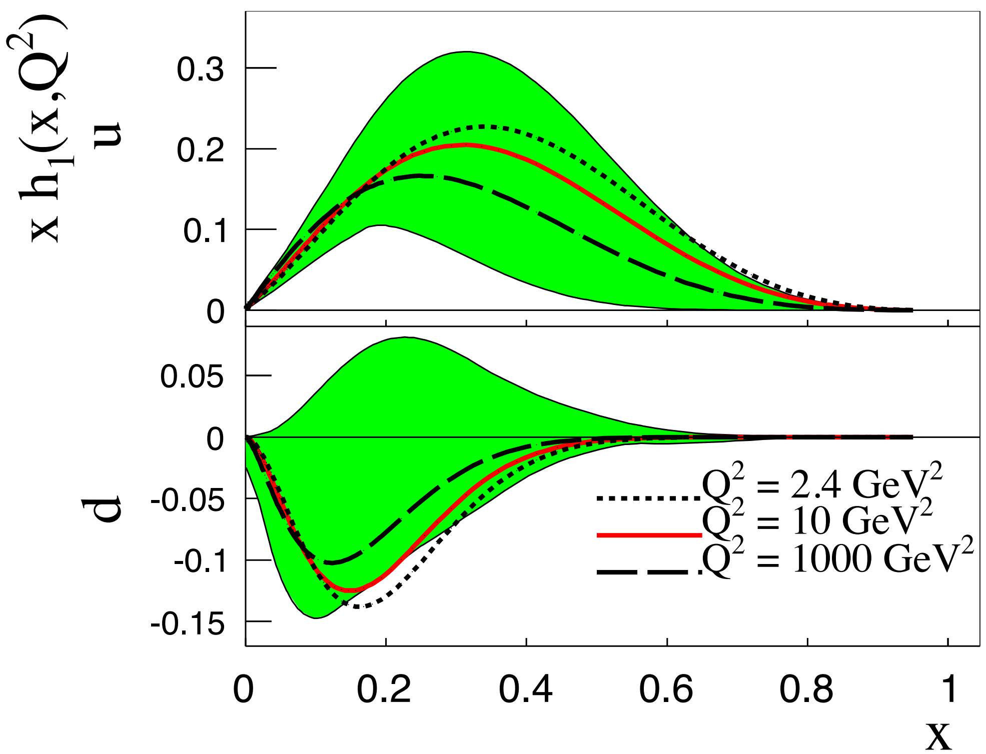


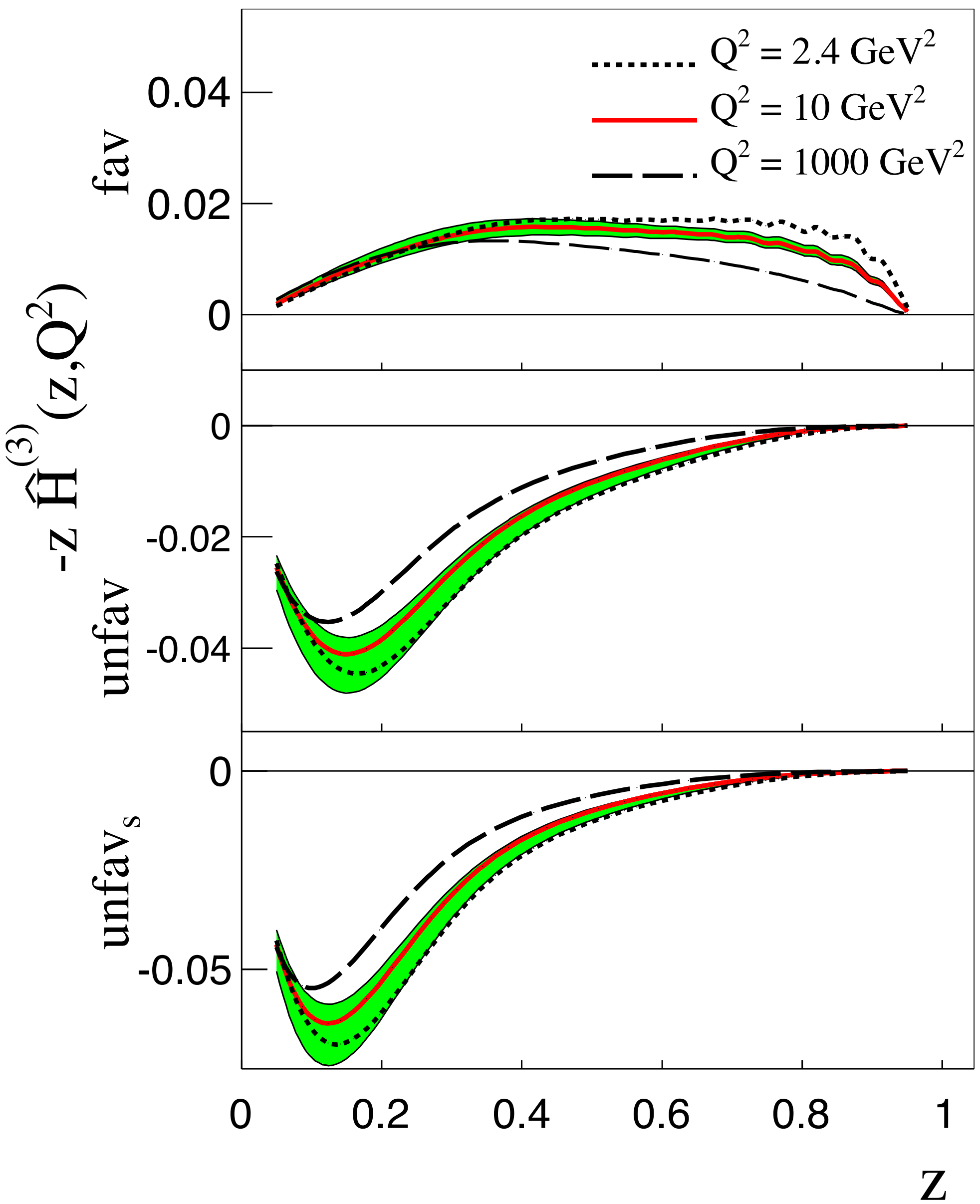
Aybat, Collins, Qiu, Rogers, Phys. Rev. D85 (2012) 034043

Extraction of transversity and Collins functions with TMD evolution

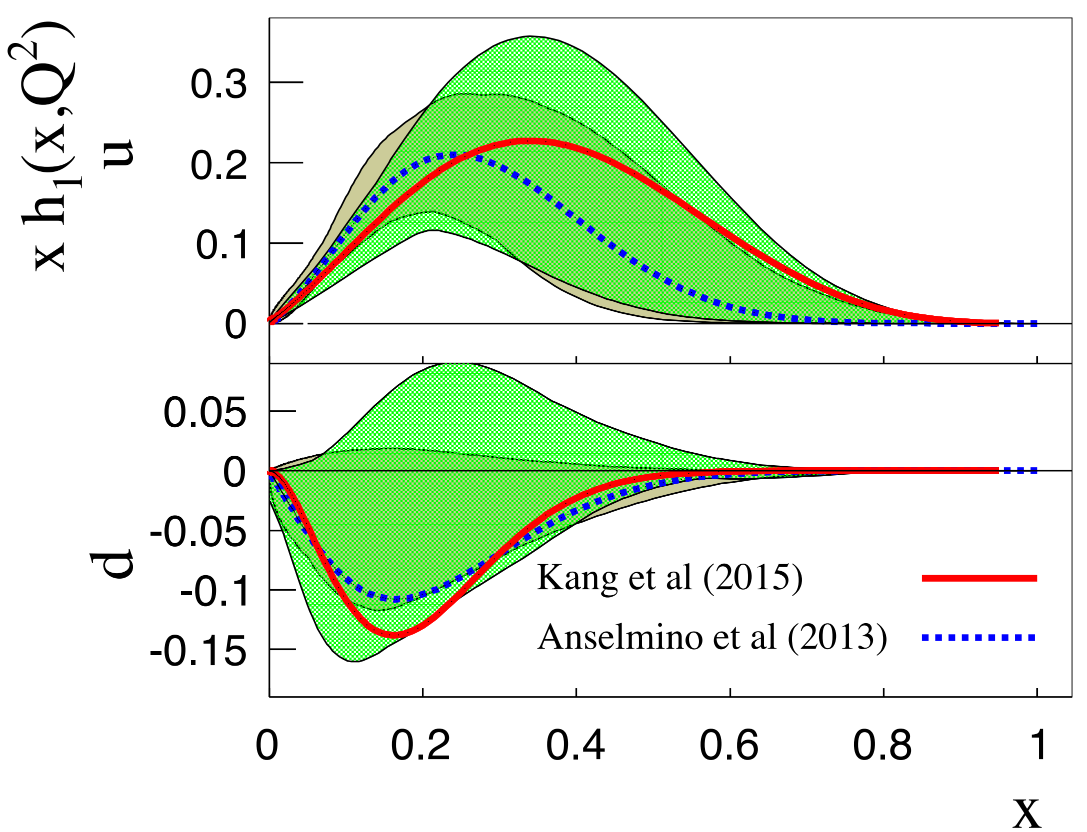
(Kang, Prokudin, Sun, Yuan, arXiv:1505.05589)

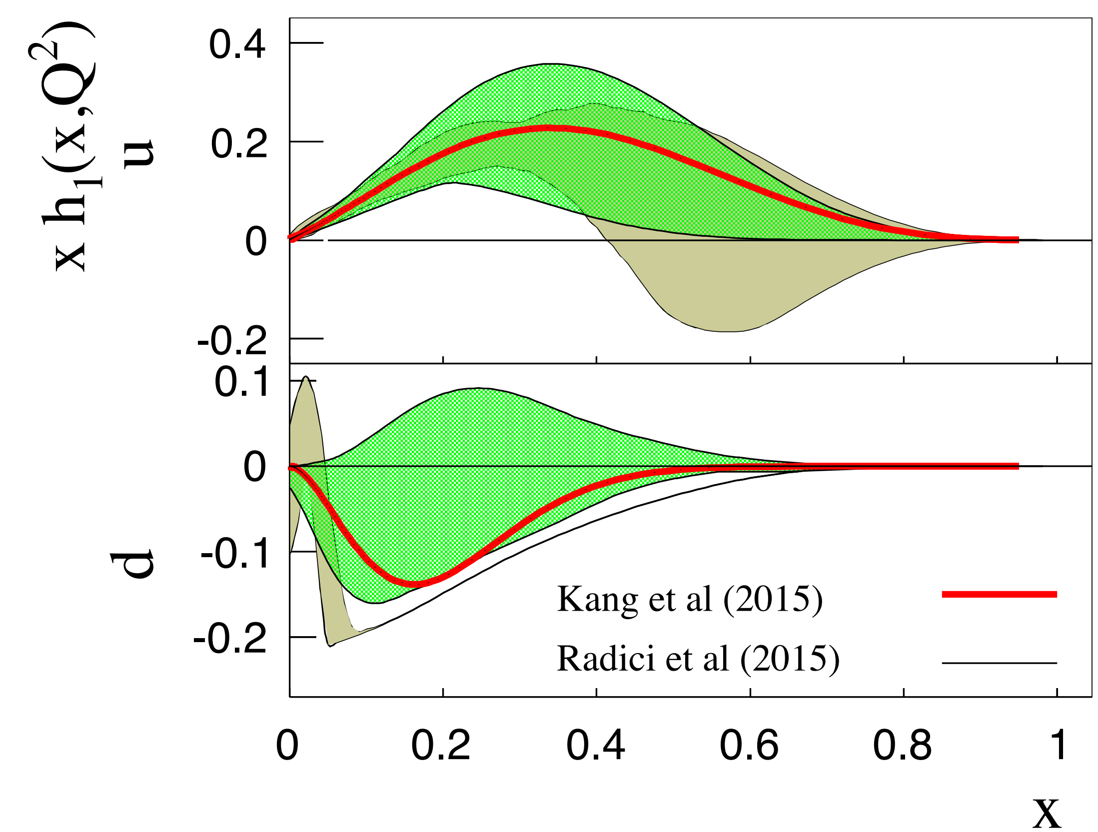
transversity distributions

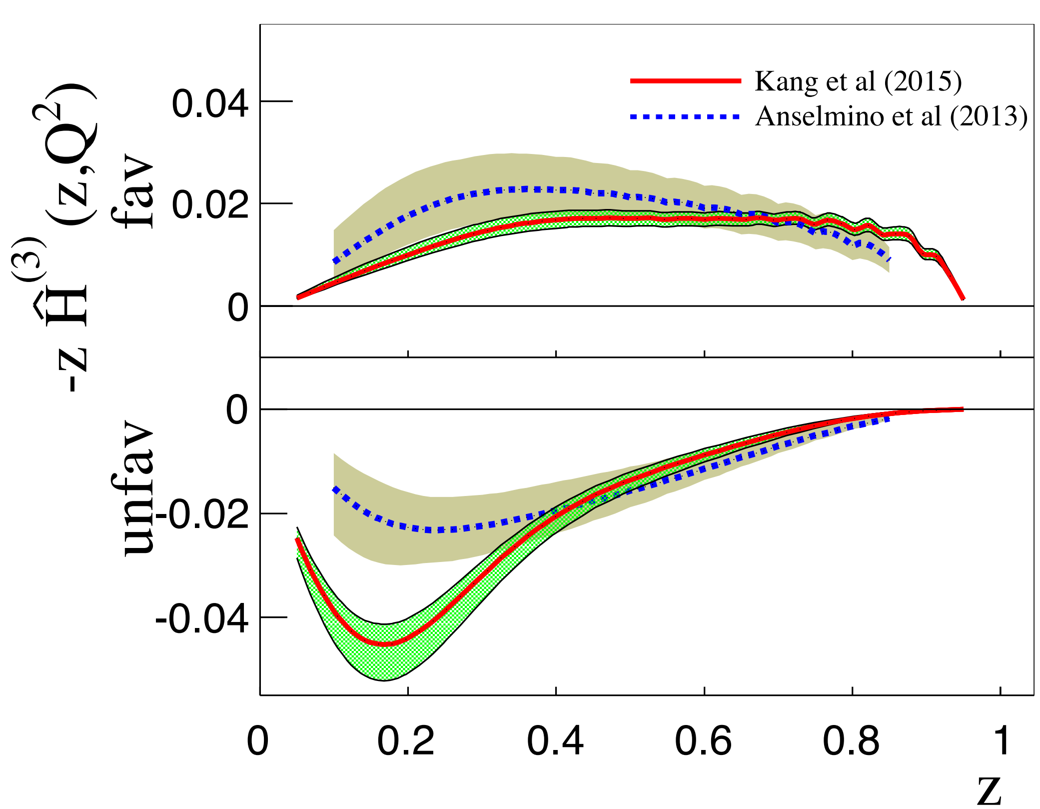




moment of Collins functions







comparison with phase 1 extraction, $Q^2 = 2.4\ \mathrm{GeV}^2$

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

no compelling evidence of TMD evolution yet

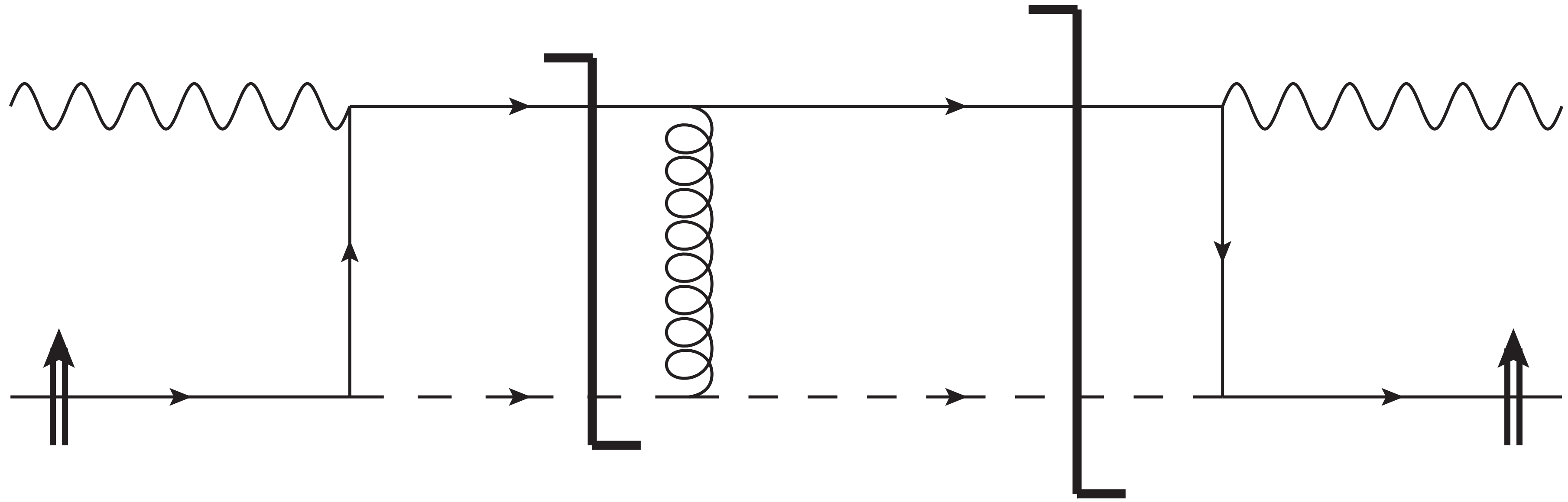
open issues in TMD phenomenology

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

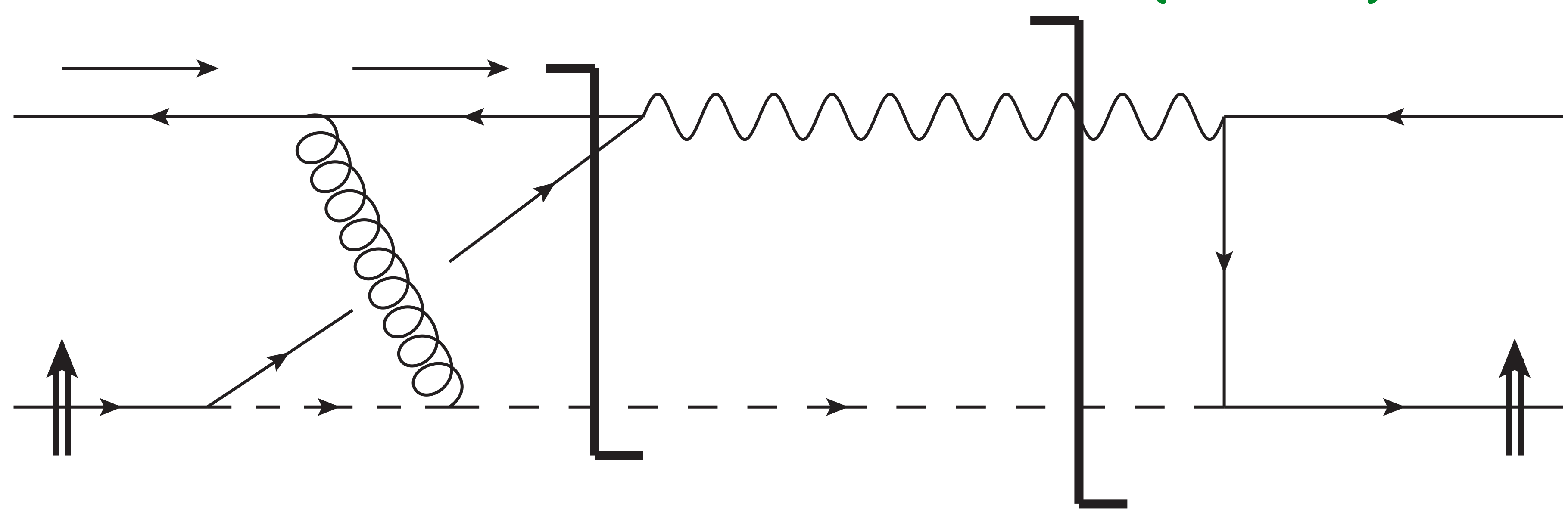
Collins, PL B536 (2002) 43

models of Sivers function and gauge links, process dependence

SIDIS final state interactions ($\Rightarrow A_N$)

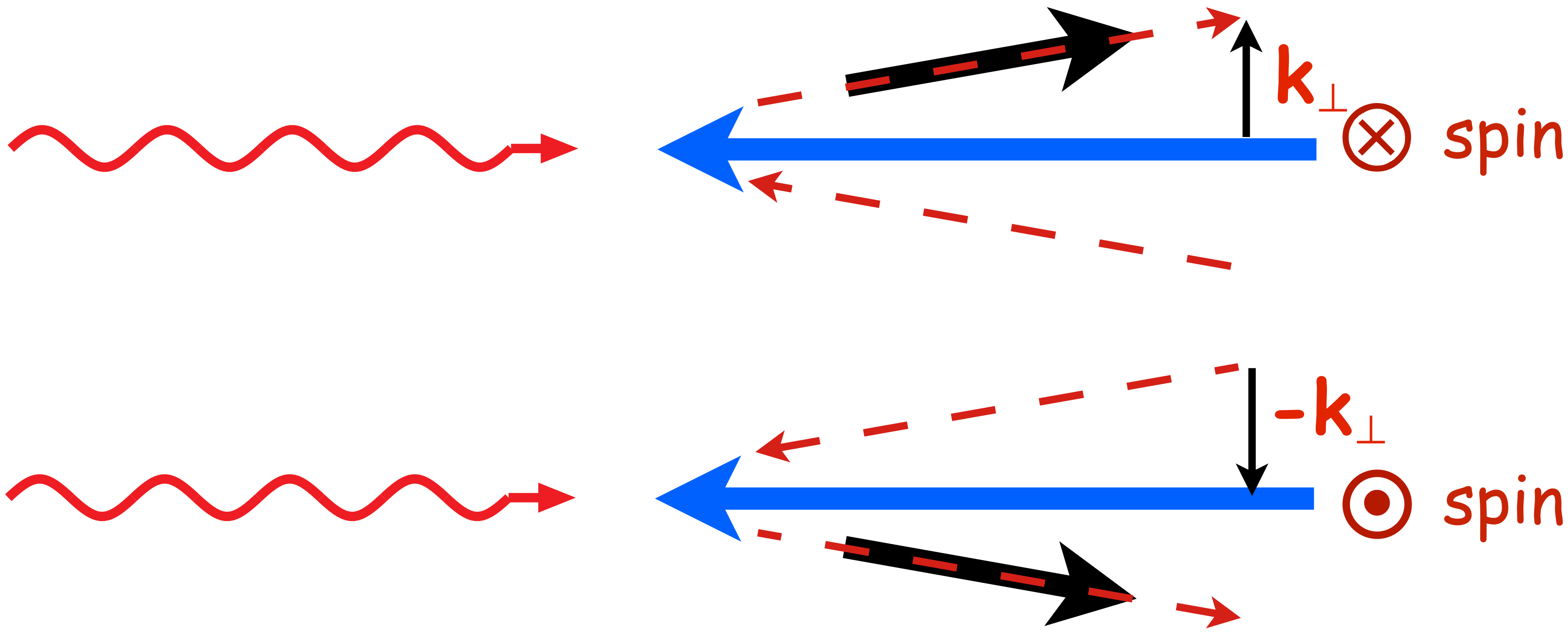


D-Y initial state interactions ($\Rightarrow -A_N$)



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...



$$P_T \sim k_\perp$$

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

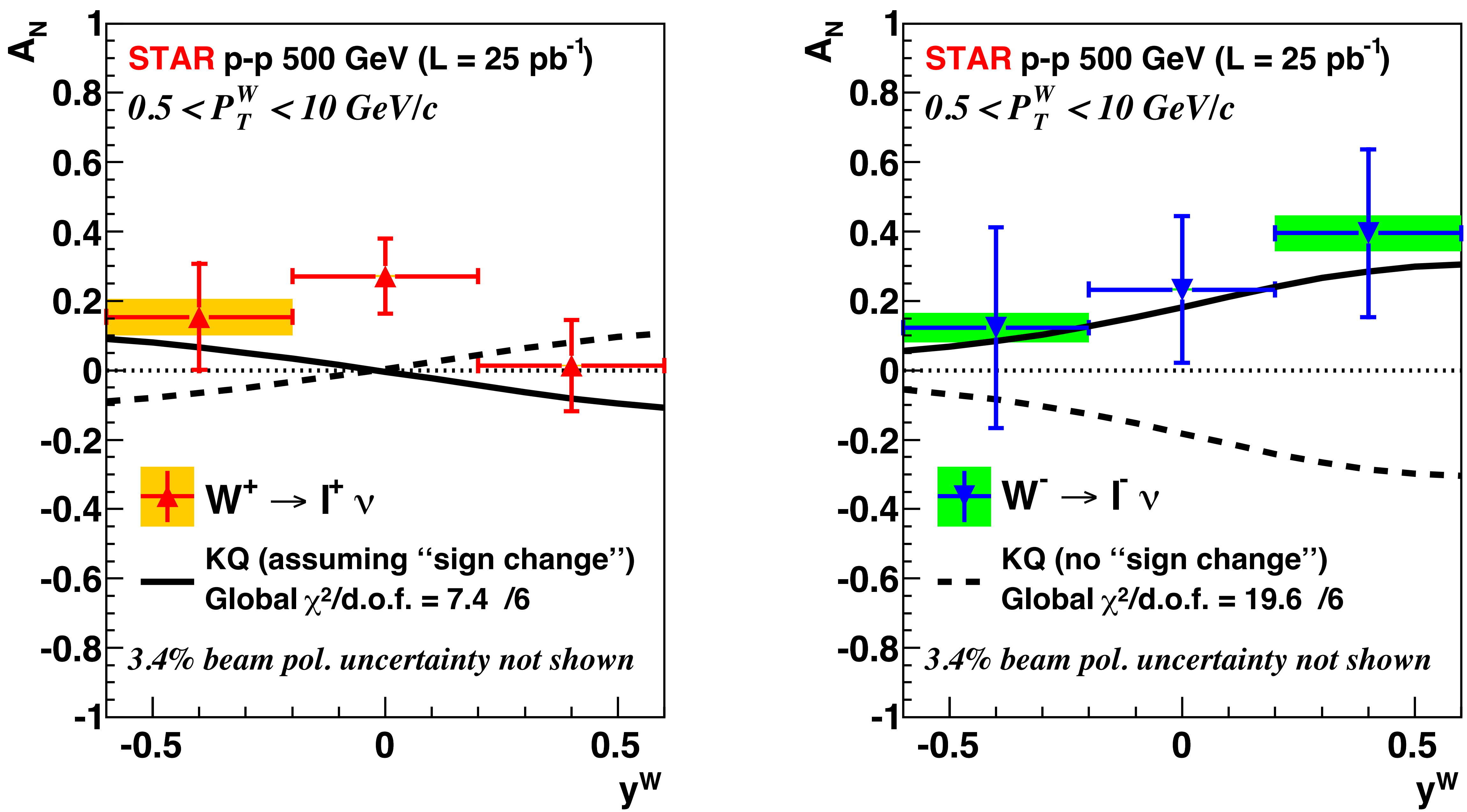
$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

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, $p^{\uparrow}p \to W^{\pm}X$

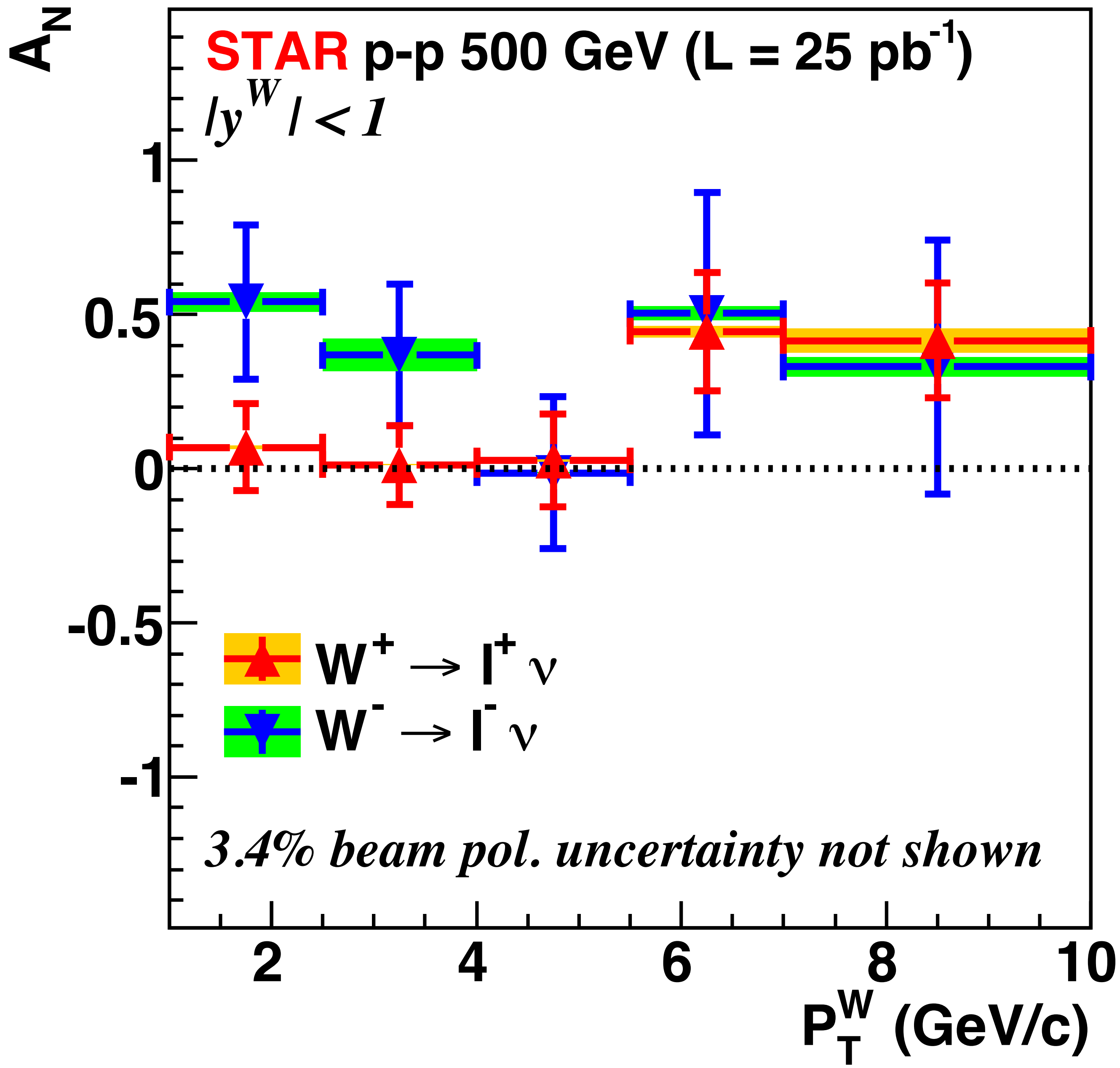
STAR Collaboration, PRL 116 (2016) 132301



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

(new results from COMPASS expected soon)

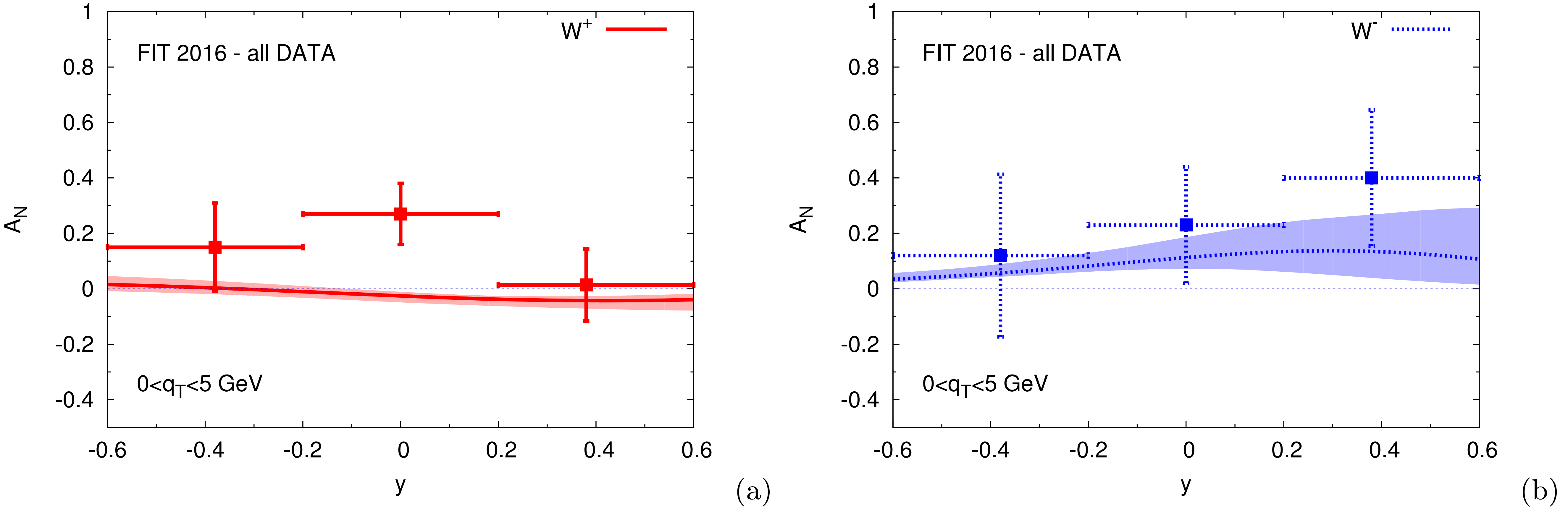
talks by Ogawa, Parsamyan, Huang, Yamazaki, Quintas....



experimental data up to large p_T values, beyond the validity of TMD factorization

analysis of data (in preparation):

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



$$\langle \chi^2/\mathrm{n.o.d.} \rangle = 1.63$$ with sign change

$$\langle \chi^2/\mathrm{n.o.d.} \rangle = 2.35$$ with no sign change

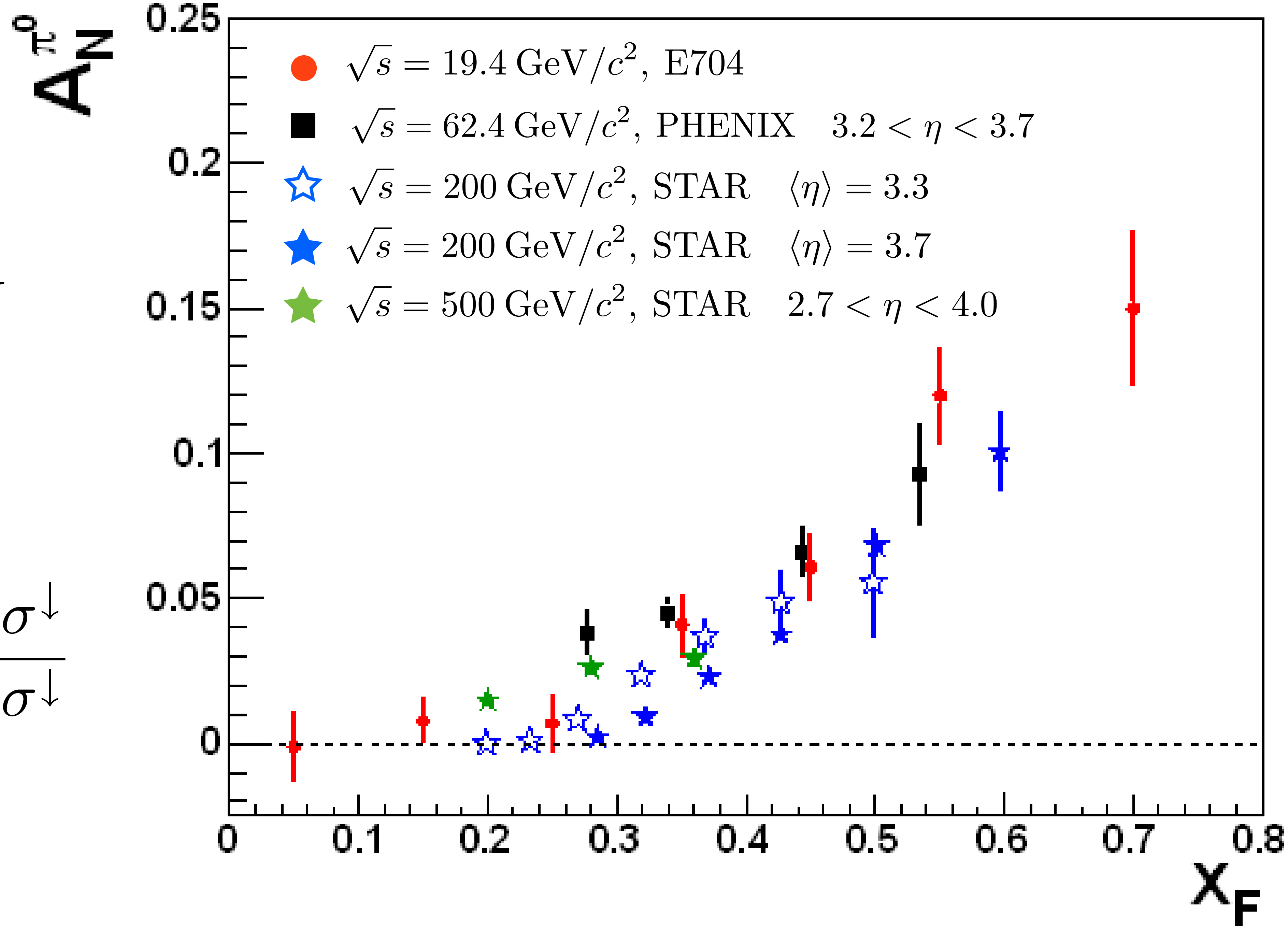
other experimental evidence of the Sivers and Collins effects

large P_T

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

Single Spin Asymmetry

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



talks by Pitonyak, Lajoie, Koike, Gamberg, Heppelman, Kim, Novitzky, ...

TMD contributions to A_N (assuming TMD factorisation)

$$
\begin{aligned}
d\sigma^{\uparrow} - d\sigma^{\uparrow} = \sum_{a,b,c} \Big\{ & \Delta^N f_{a/p^{\uparrow}}(\boldsymbol{k}_\perp) \otimes f_{b/p} \otimes d\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \\
+ \; & h_1^{a/p} \otimes f_{b/p} \otimes d\Delta\hat{\sigma}(\boldsymbol{k}_\perp) \otimes \Delta^N D_{\pi/c^{\uparrow}}(\boldsymbol{k}_\perp) \\
+ \; & h_1^{a/p} \otimes \Delta^N f_{b^{\uparrow}/p}(\boldsymbol{k}_\perp) \otimes d\Delta'\hat{\sigma}(\boldsymbol{k}_\perp) \otimes D_{\pi/c} \Big\}
\end{aligned}
$$

(1) Sivers effect

(2) transversity $\otimes$ Collins

(3) transversity $\otimes$ Boer - Mulders

main contribution from Sivers effect, can explain qualitatively most SIDIS and A_N data

(M.A. M. Boglione, D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, PRD86 (2012) 074032; PRD88 (2013) 054023)

possible higher-twist contributions to A_N
(collinear factorisation)

$$d\sigma(\vec{S}_\perp) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}$$

(1) Twist-3 contribution related to Sivers function

(2) Twist-3 contribution related to Boer-Mulders function

(3) Twist-3 fragmentation: has two contributions, one related to Collins function + a new one

the first contribution with a twist-3 quark-gluon-quark correlator was expected to be the dominant one, but ....

sign mismatch

(Kang, Qiu, Vogelsang, Yuan, PR D83 (2011) 094001)

using the SIDIS Sivers function to build the twist-3 q-g-q correlator $T_{q,F}$

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

leads to sizeable value of A_N, but with the wrong sign....

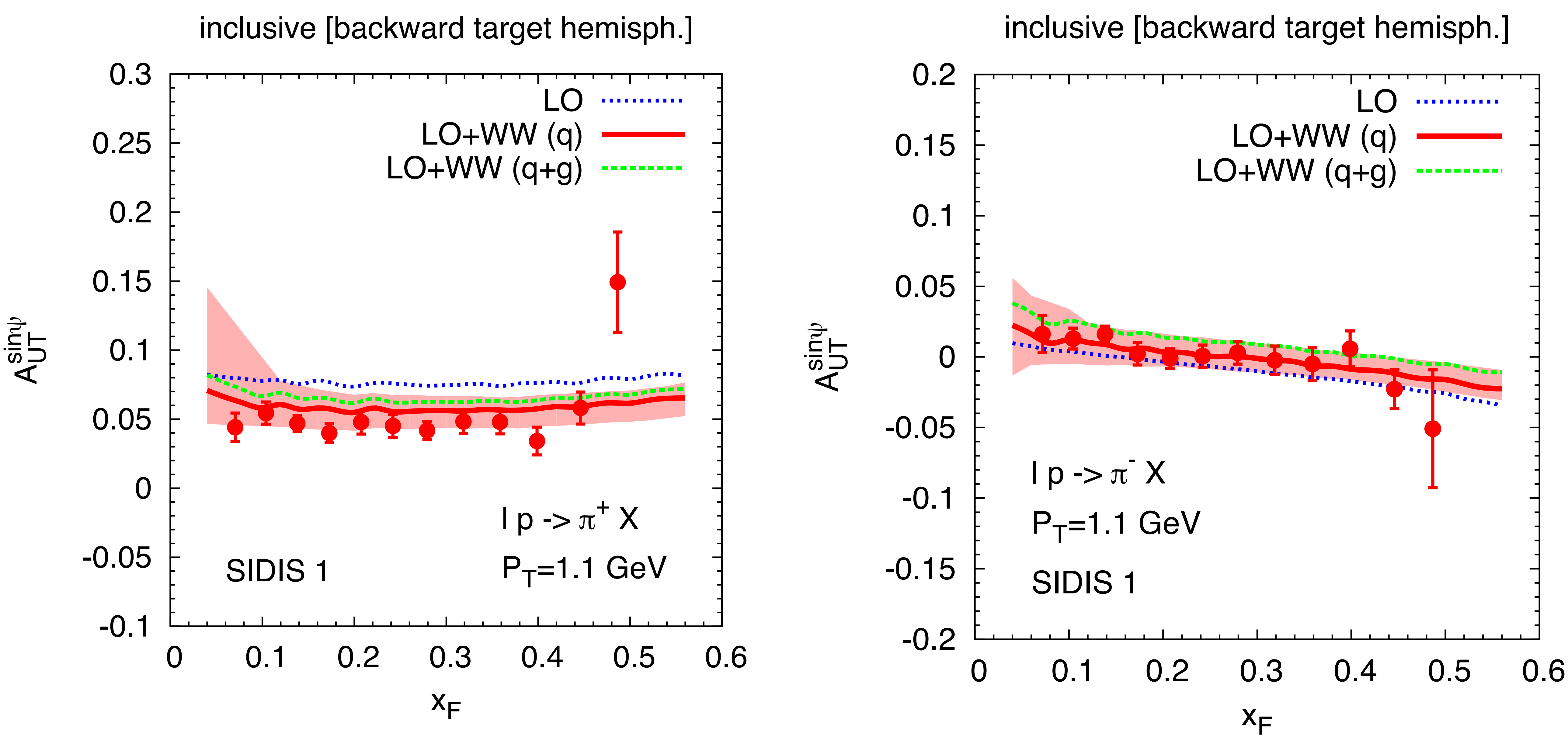
the same mismatch does not occur adopting TMD factorization; the reason is that the hard scattering part in higher-twist factorization is negative

A_N might be explained by new twist-3 fragmentation functions

(Kanazawa, Koike, Metz, Pitonyak, PRD 89 (2014) 111501)

but A_N in $lp \to \pi X$ can be well explained by TMD factorisation + Weizsäcker-Williams approximation

(U. D'Alesio, C. Flore, F. Murgia, in preparation - talk by U. D'Alesio at QCD evolution 2016)



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 (talk by Aschenauer)....

Thank you!