Introduction to orbital effects in hard scattering

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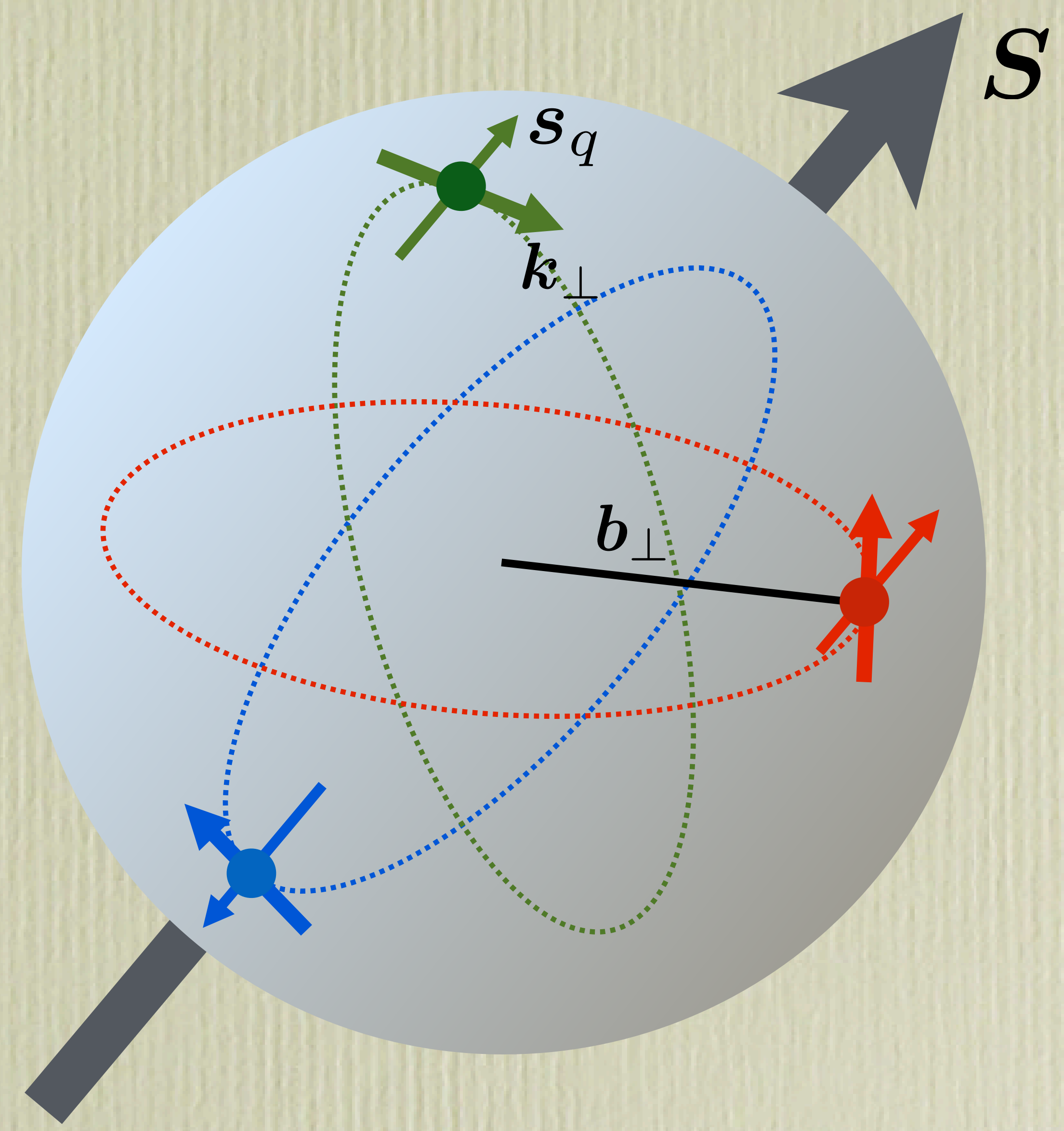
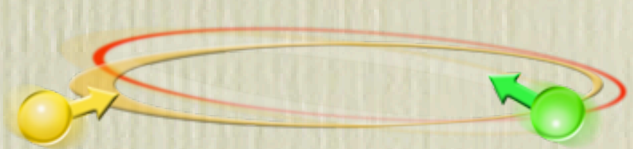
exploring the
3D nucleon
structure

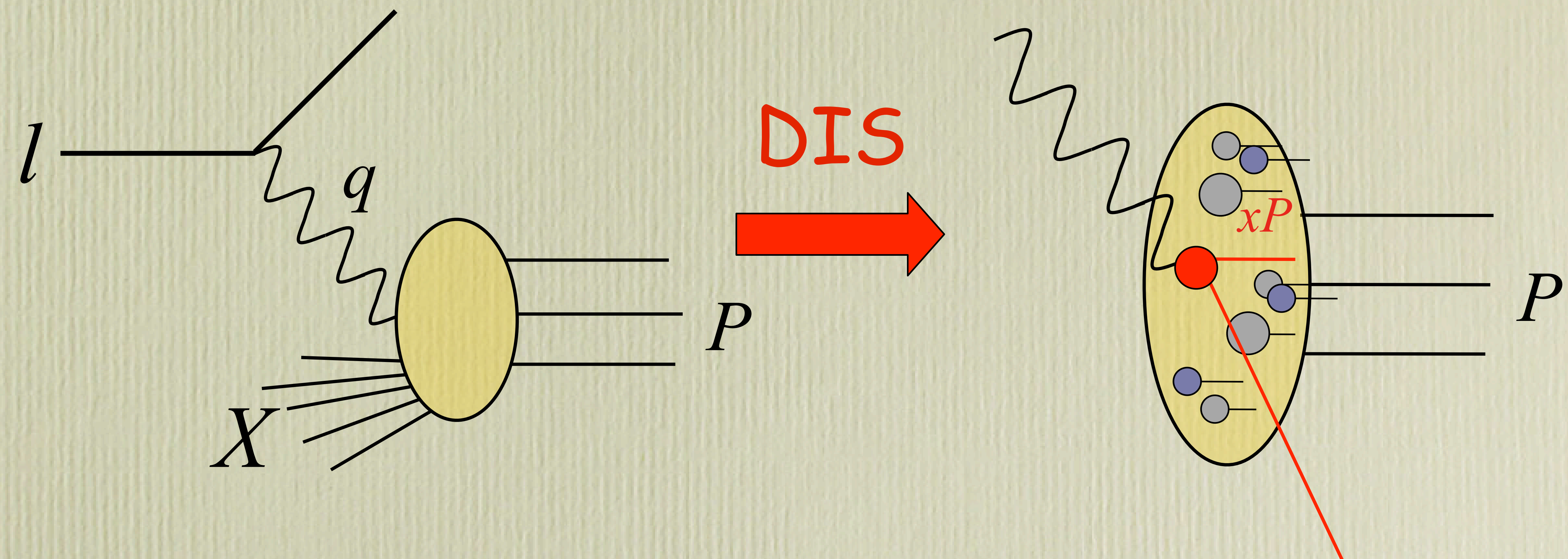




3D Parton Distributions: path to the LHC

LNF, 29/11 - 2/12, 2016

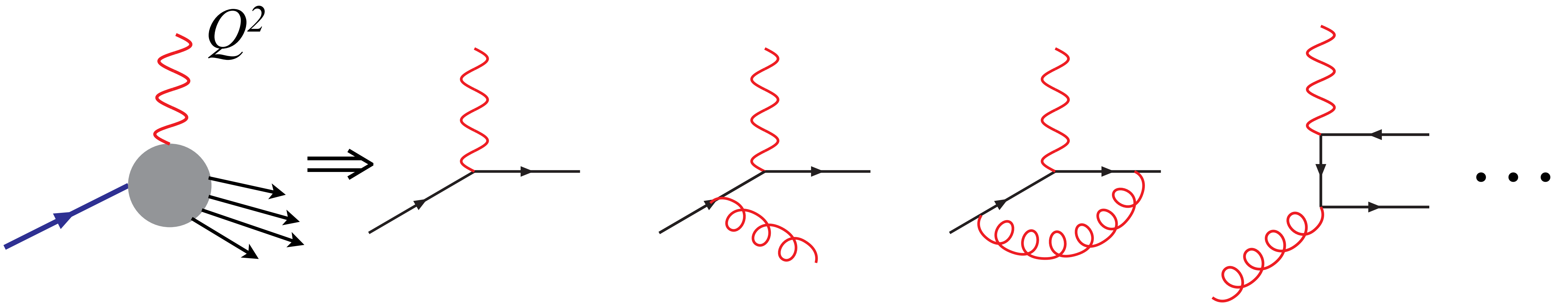
usual (successful) way of exploring the proton structure (collinear parton model)



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

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



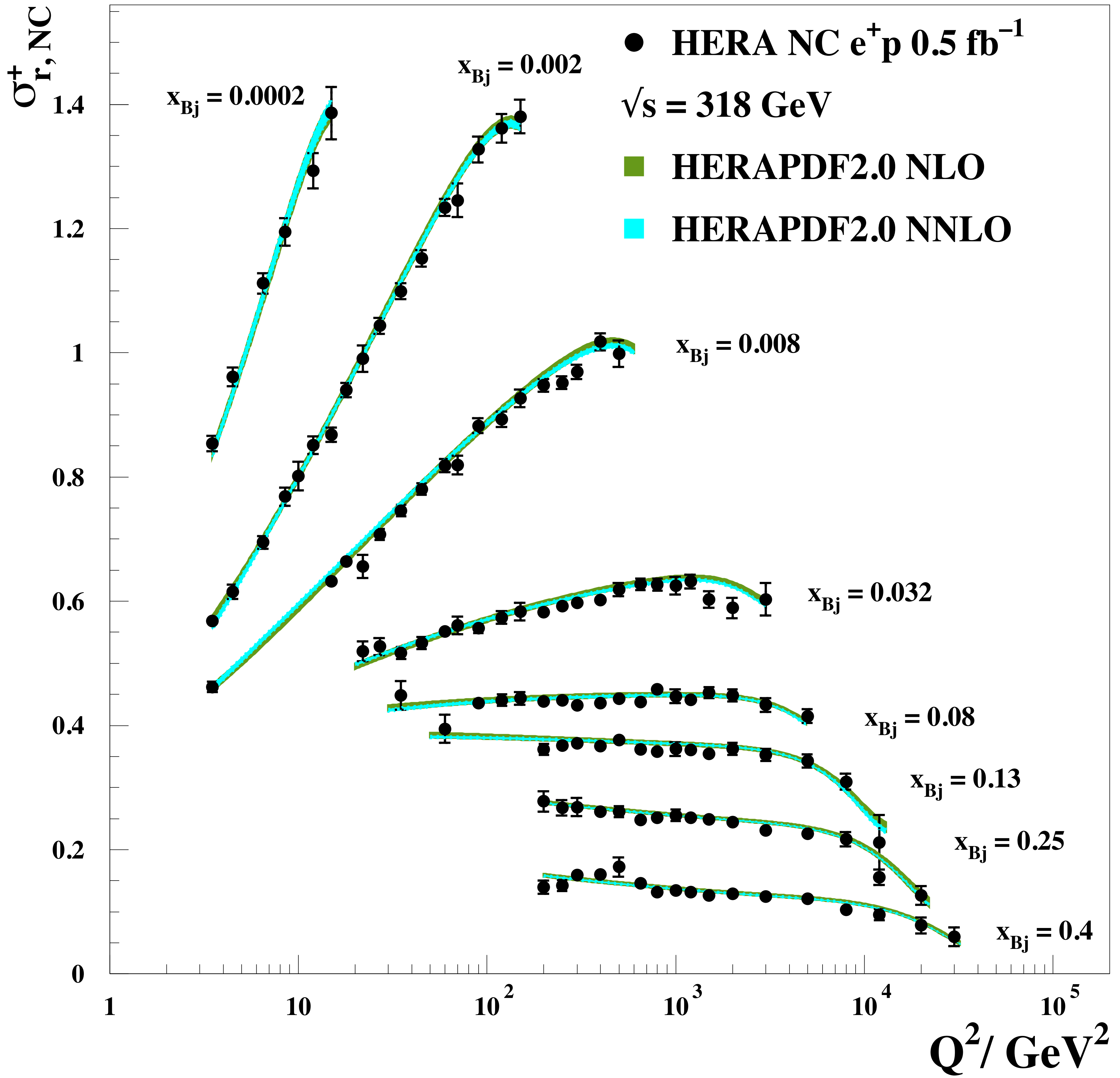
$$\mathrm{DIS} - \mathrm{pQCD}: \quad q(x) \Rightarrow \underbrace{q(x, Q^2)}_{\text{PDFs}}$$

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



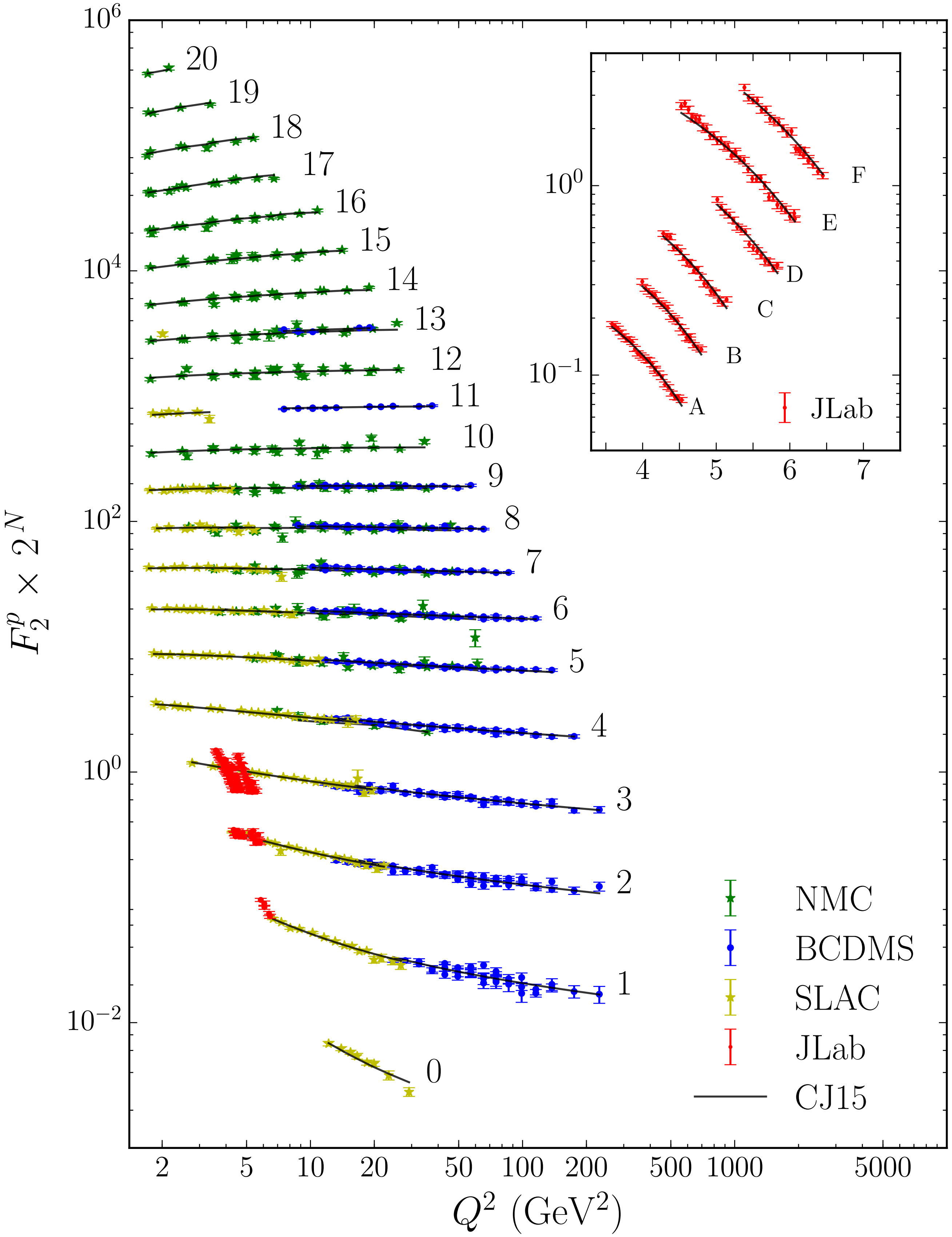
$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^\pm p}_{\mathrm{NC}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+}$$

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

Eur. Phys. J. C75 (2015) 580

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

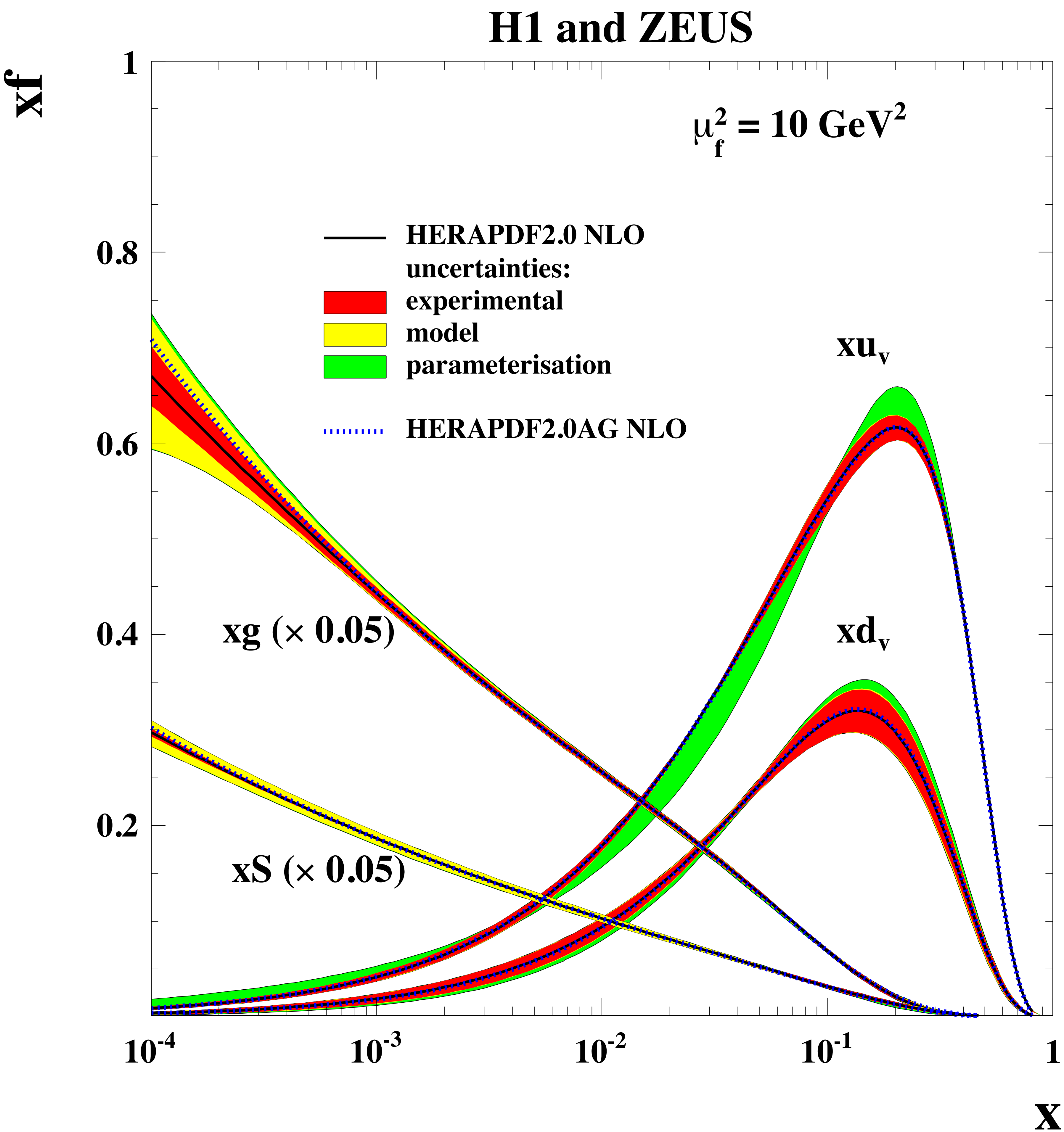
from M. Pennington, arXiv:1604.01441



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



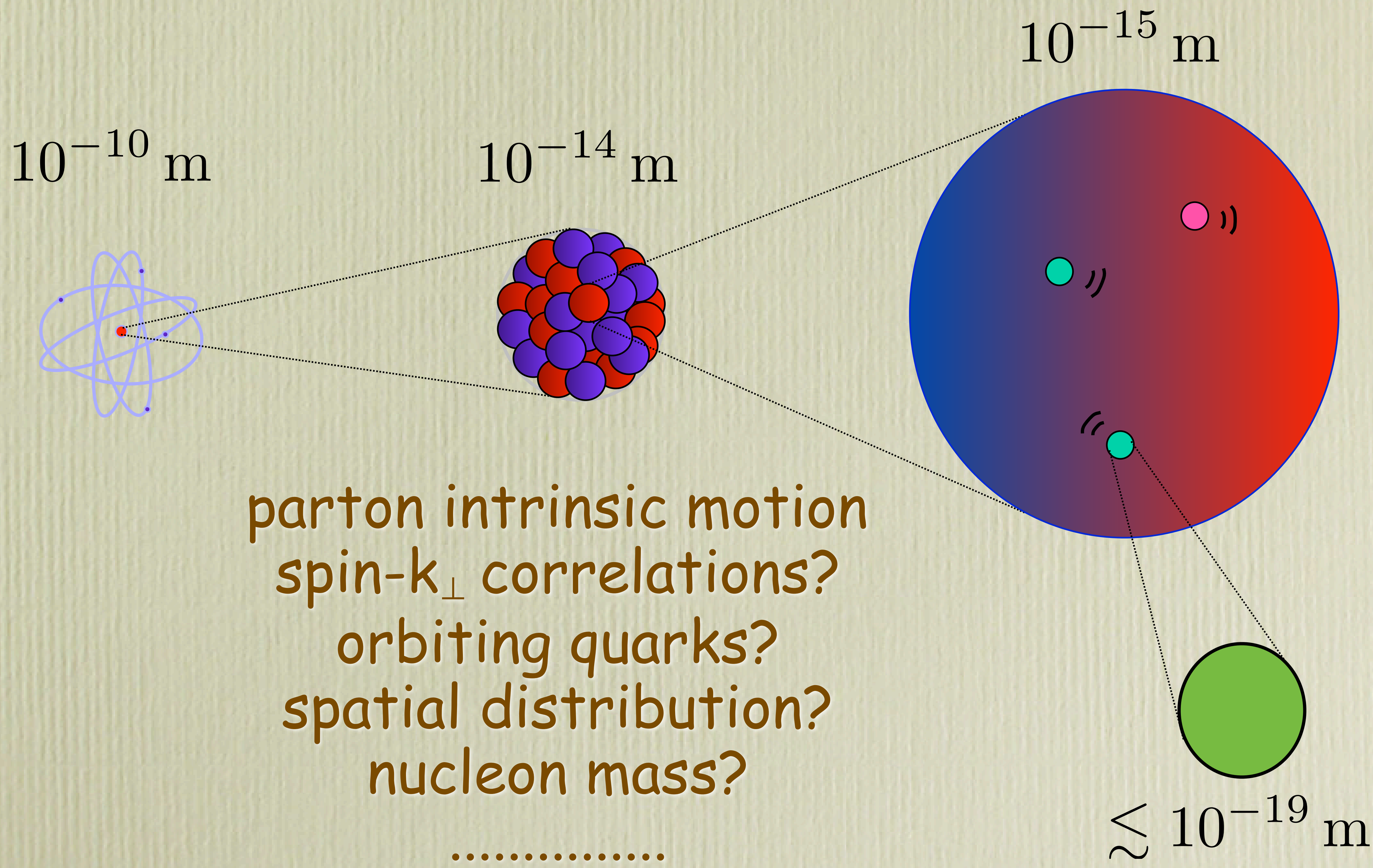
unpolarized distribution

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

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

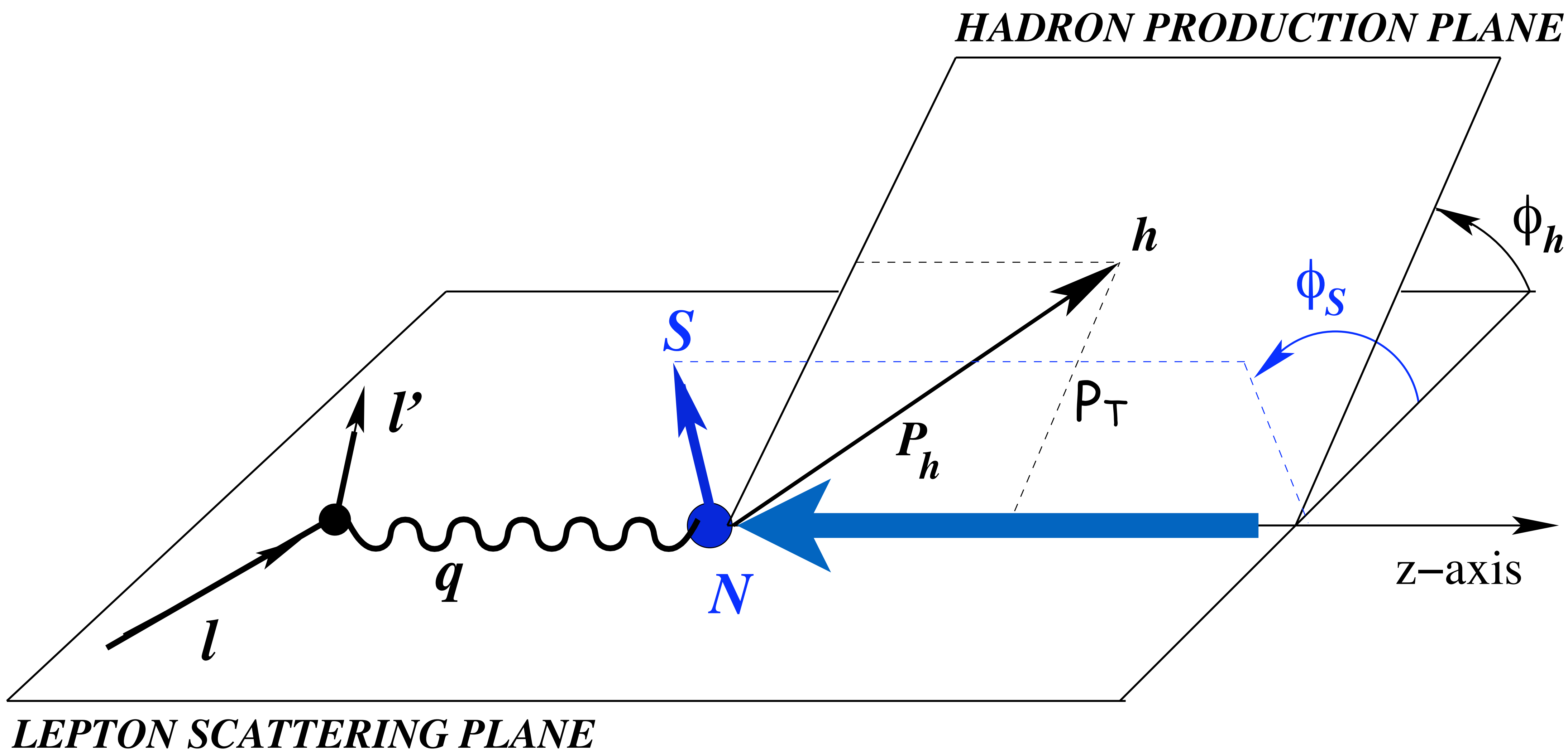


parton intrinsic motion
spin-$k_\perp$ correlations?
orbiting quarks?
spatial distribution?
nucleon mass?
....

which processes are sensitive to parton intrinsic motion?

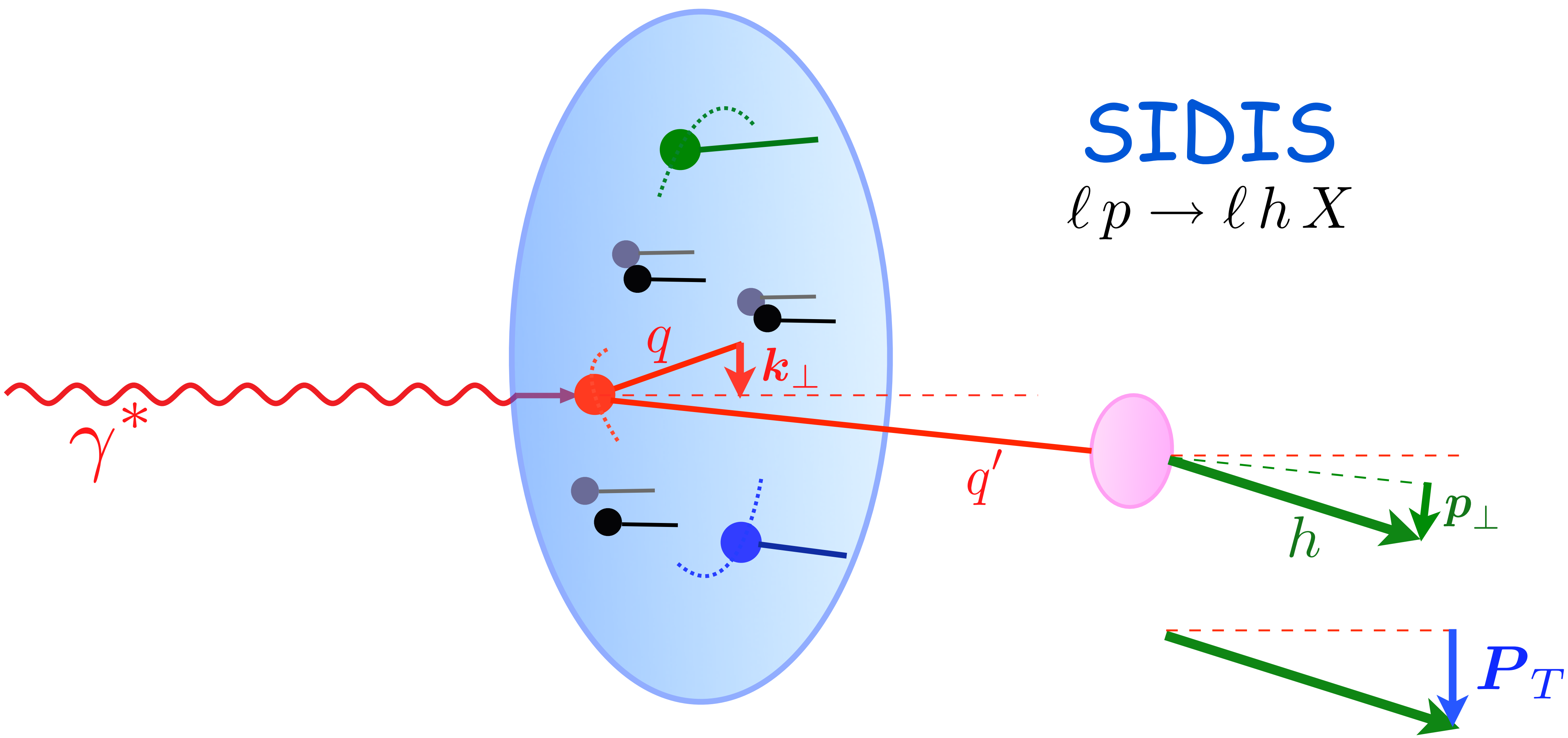
(polarised) semi-inclusive deep inelastic scattering (SIDIS)

$$\ell\, p^{\uparrow} \to \ell\, h\, X$$



P_T and azimuthal dependences generated by parton transverse (orbital) motion and spin and nucleon spin

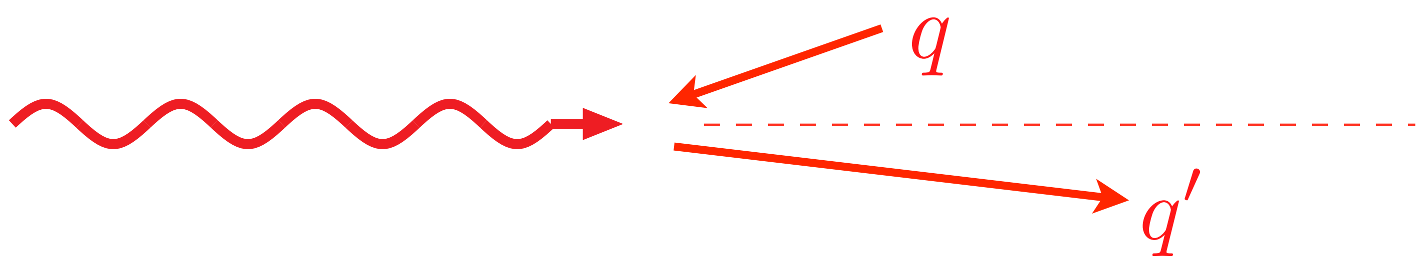
P_T dependence



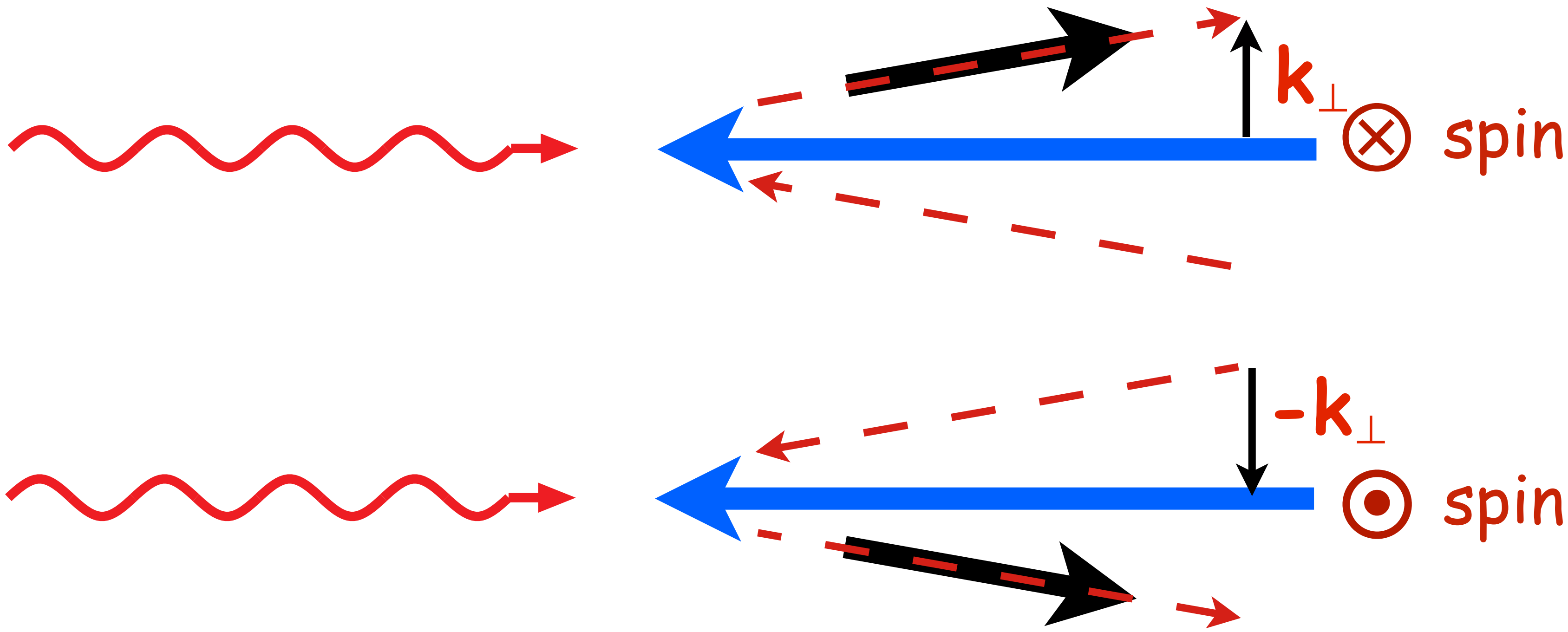
$\Lambda_{\rm QCD} \simeq k_\perp \simeq P_T \ll Q$

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

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



single spin asymmetry: the Sivers effect



$$P_T \sim k_\perp$$

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

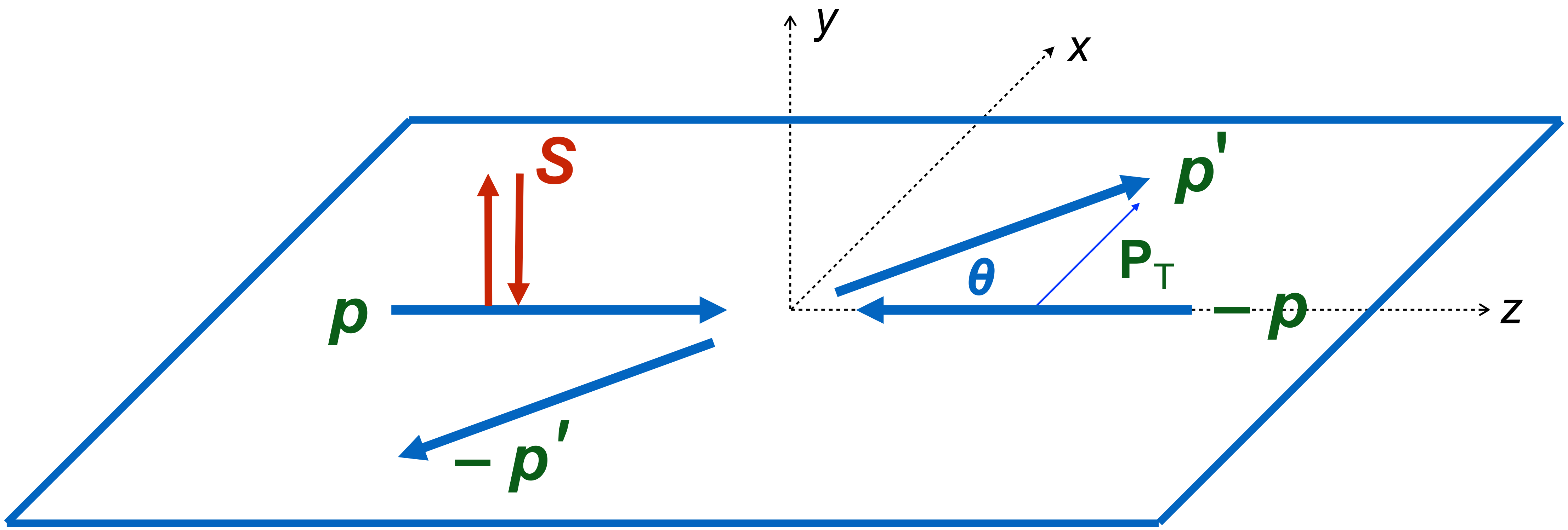
$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

single spin asymmetry for the process $\ell\, p^\uparrow \to \ell\, h\, X$

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

Single Spin Asymmetries from elementary dynamics?

Transverse single spin asymmetries in elastic scattering



$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto \sin\theta$$

Example: $p\, p \rightarrow p\, p$

$$\begin{cases} H_{++;++} \equiv \Phi_1 \\ H_{--;++} \equiv \Phi_2 \\ H_{+-;+-} \equiv \Phi_3 \\ H_{-+;+-} \equiv \Phi_4 \\ H_{-+;++} \equiv \Phi_5 \end{cases}$$

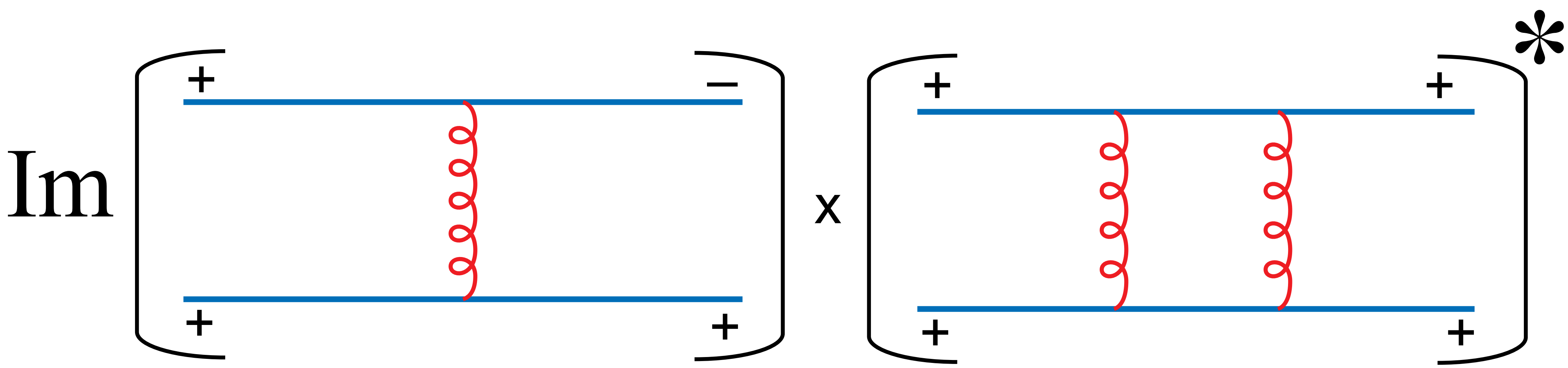
5 independent helicity amplitudes

$$A_N \propto \mathrm{Im}\left[\Phi_5 \left(\Phi_1 + \Phi_2 + \Phi_3 - \Phi_4\right)^*\right]$$

Single spin asymmetries at partonic level

$$(q\,q' \to q\,q' \qquad \ell\,q \to \ell\,q)$$

$A_N \neq 0$ needs helicity flip + relative phase

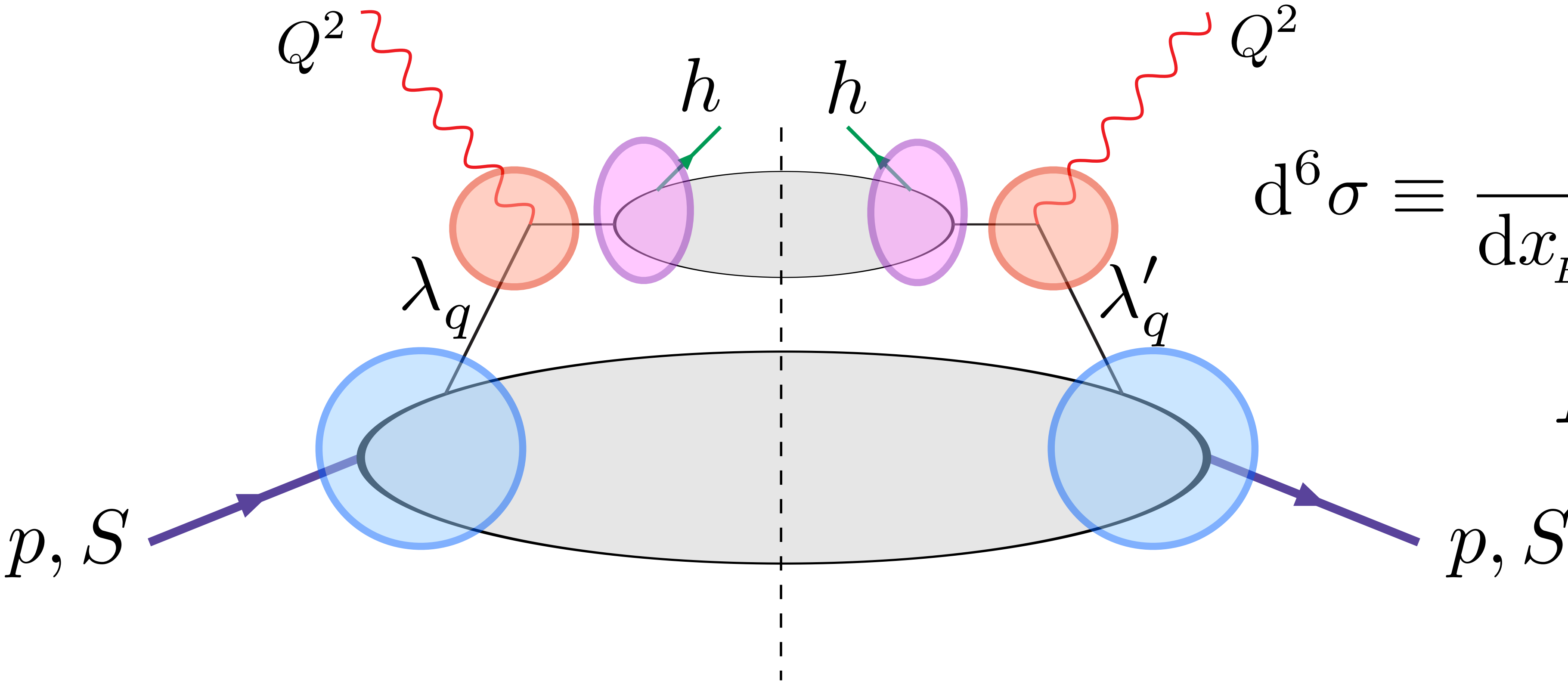


QED and QCD interactions conserve helicity, up to corrections $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

$$\Longrightarrow \quad A_N \propto \frac{m_q}{E_q}\,\alpha_s \quad \text{at quark level}$$

large SSA observed at hadron level are not generated in elementary QED or QCD interactions

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 $P_T \approx k_\perp \approx \Lambda_{\rm QCD}$

Two scales: $P_T \ll Q^2$

TMD-PDFs | hard scattering | TMD-FFs

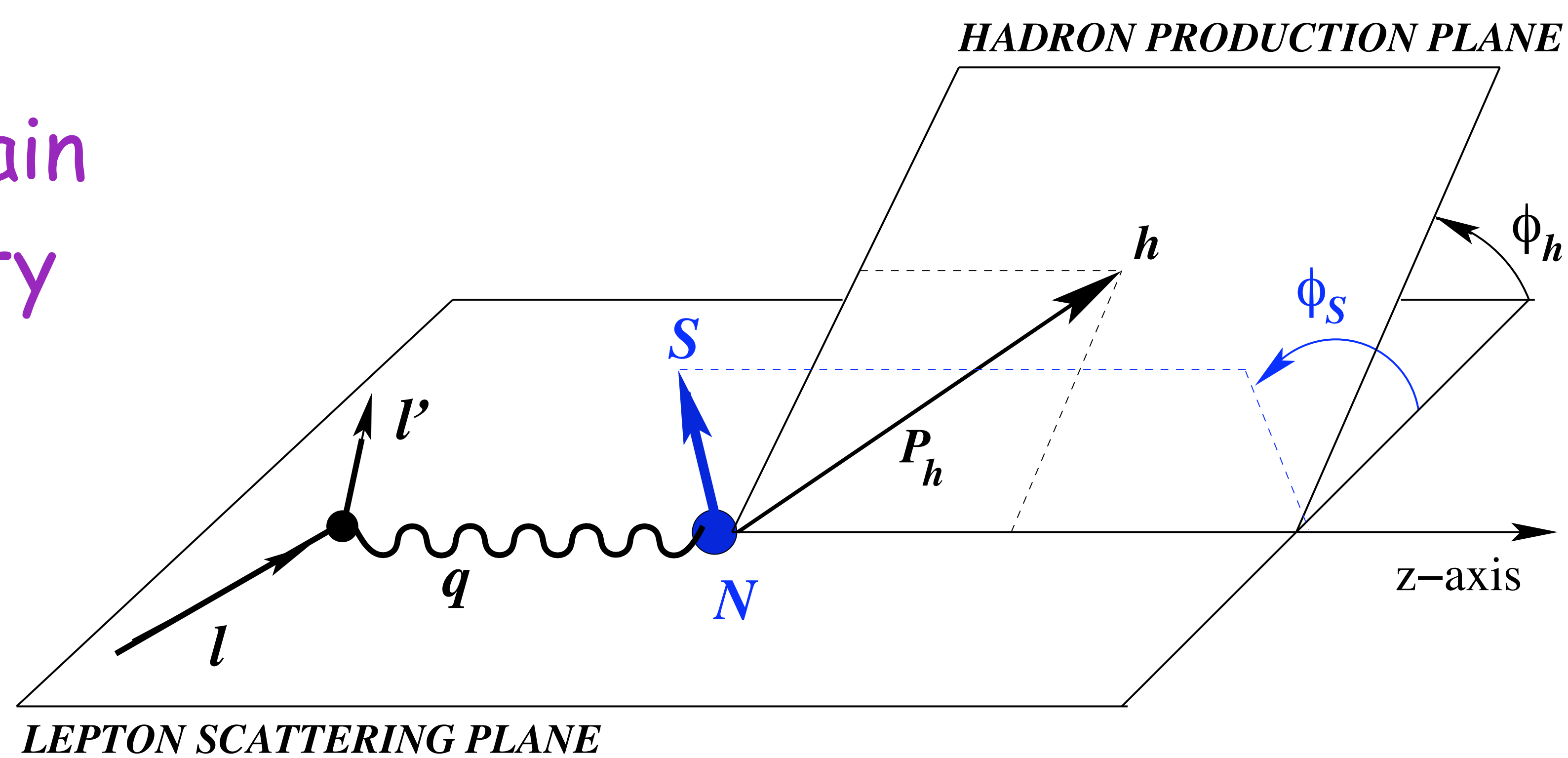
$$d\sigma^{\ell p \to \ell h X} = \sum_q f_q(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q \to \ell q}(y, \boldsymbol{k}_\perp; Q^2) \otimes D_q^h(z, \boldsymbol{p}_\perp; Q^2)$$

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

(talks by Bacchetta, Martin, D'Alesio, Gamberg, Schnell, Boer, ...)

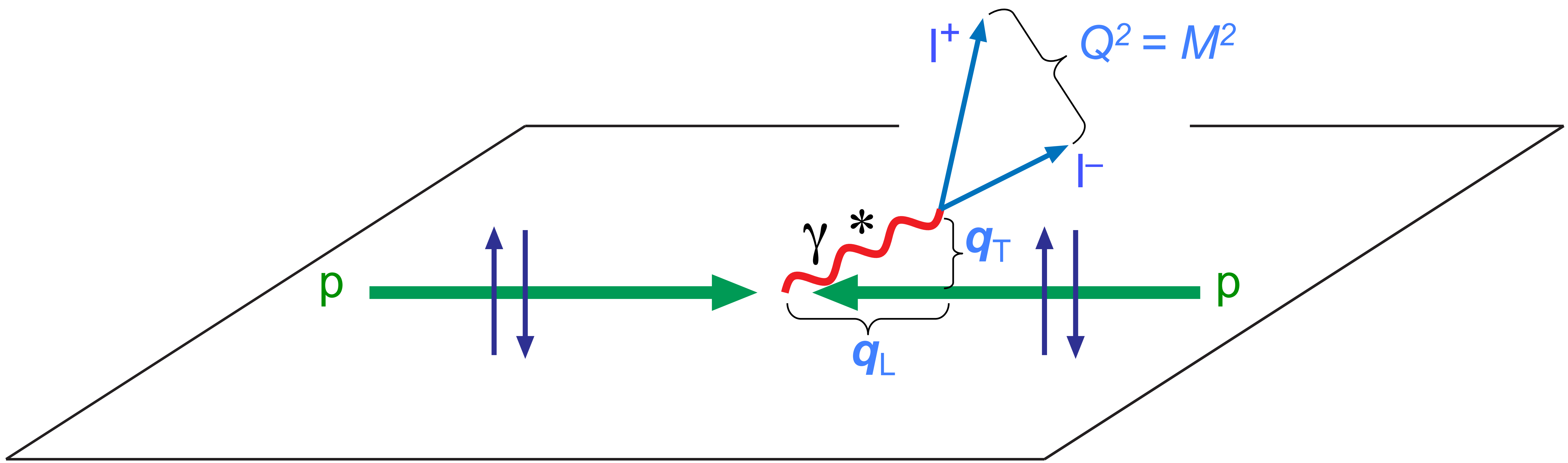
$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \;=\;& F_{UU} + \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \frac{1}{Q}\,\cos\phi\, F_{UU}^{\cos\phi} + \lambda\,\frac{1}{Q}\,\sin\phi\, F_{LU}^{\sin\phi} \\
&+\; S_L\left\{\sin(2\phi)\, F_{UL}^{\sin(2\phi)} + \frac{1}{Q}\,\sin\phi\, F_{UL}^{\sin\phi}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

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

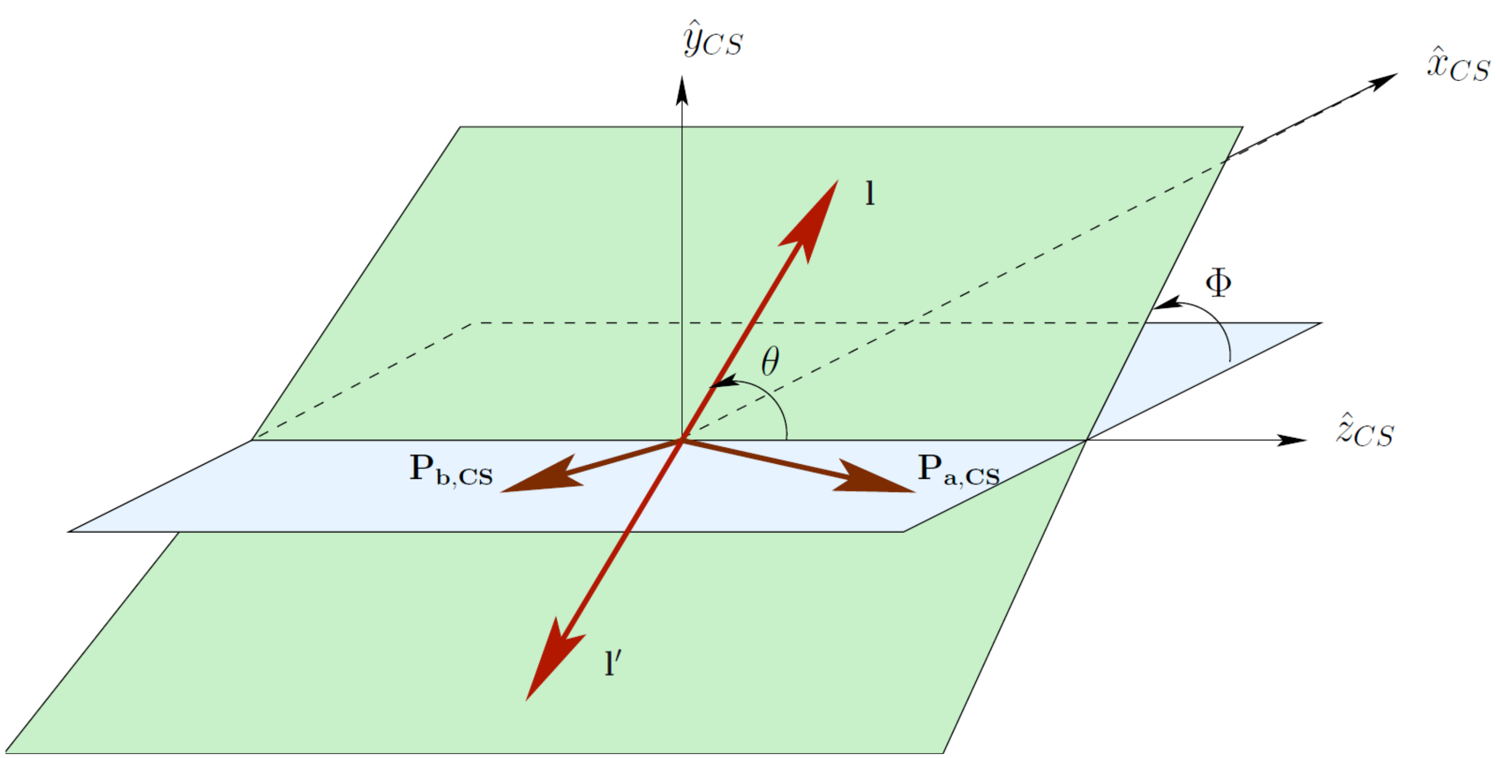
(talks by Peng, Lorenzon, Quintans, Vogelsang)

Case of one polarized nucleon only

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

B-M ⊗ B-M

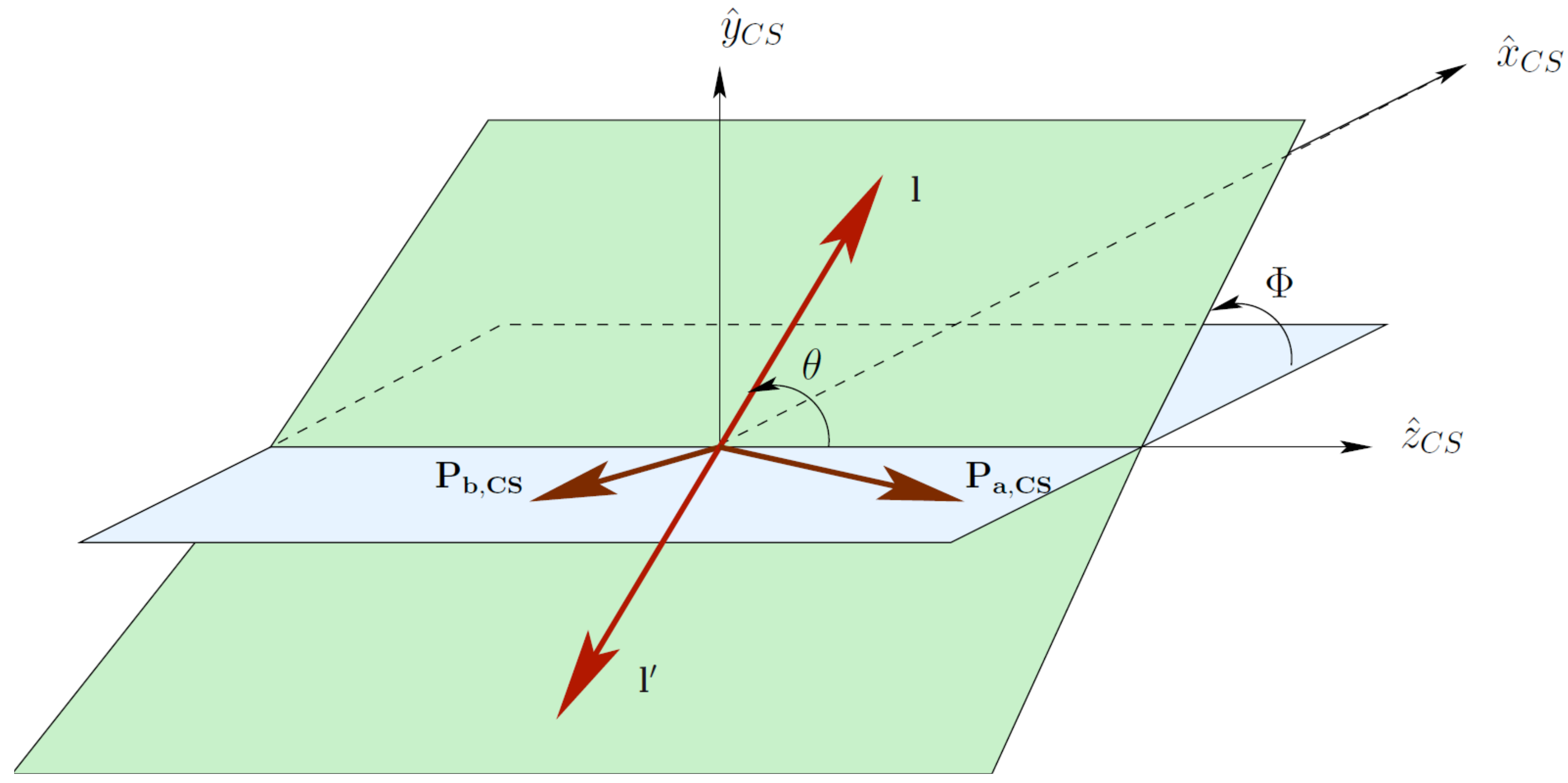
Sivers



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: $\lambda = 1 \quad \mu = \nu = 0$

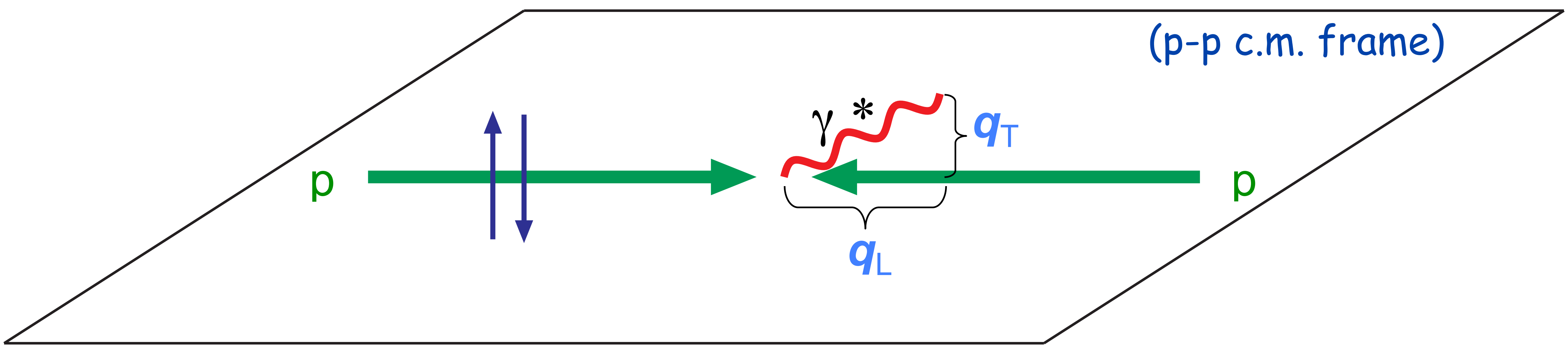
Sivers effect in D-Y processes

By looking at the $d^4\sigma/d^4q$ cross section one can single out the Sivers effect in D-Y processes

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto \sum_q \Delta^N f_{q/p^\uparrow}(x_1, \boldsymbol{k}_{\perp 1}) \otimes f_{\bar{q}/p}(x_2, k_{\perp 2}) \otimes \mathrm{d}\hat{\sigma}$$

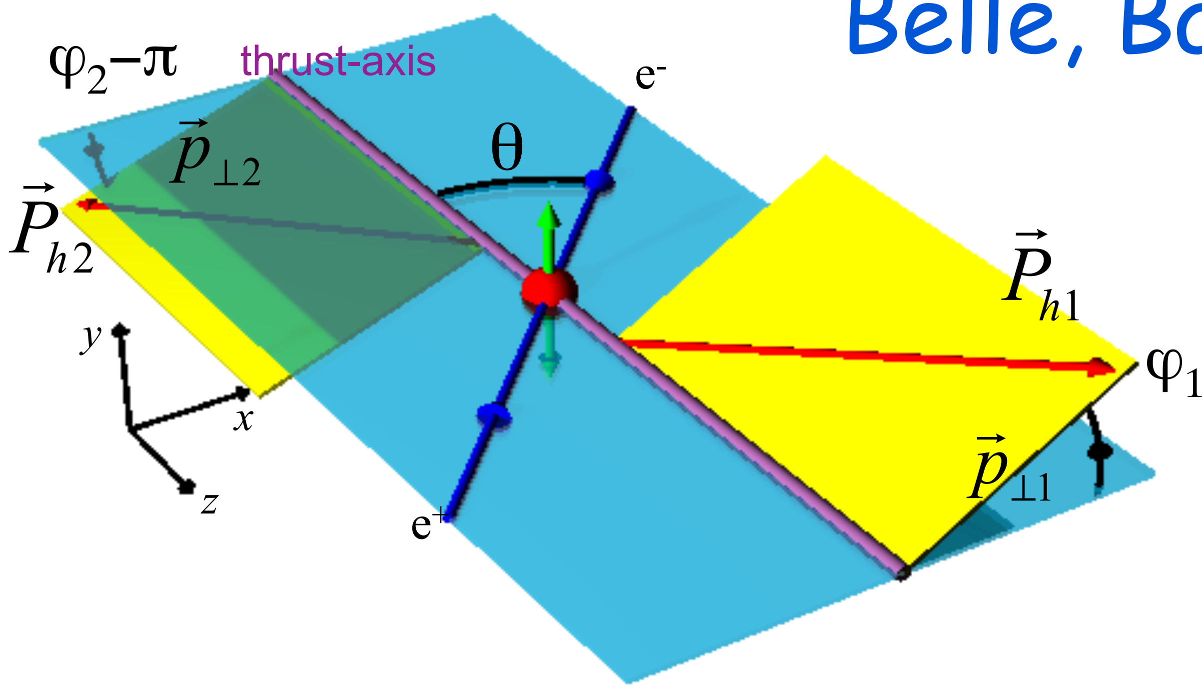
$$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$$

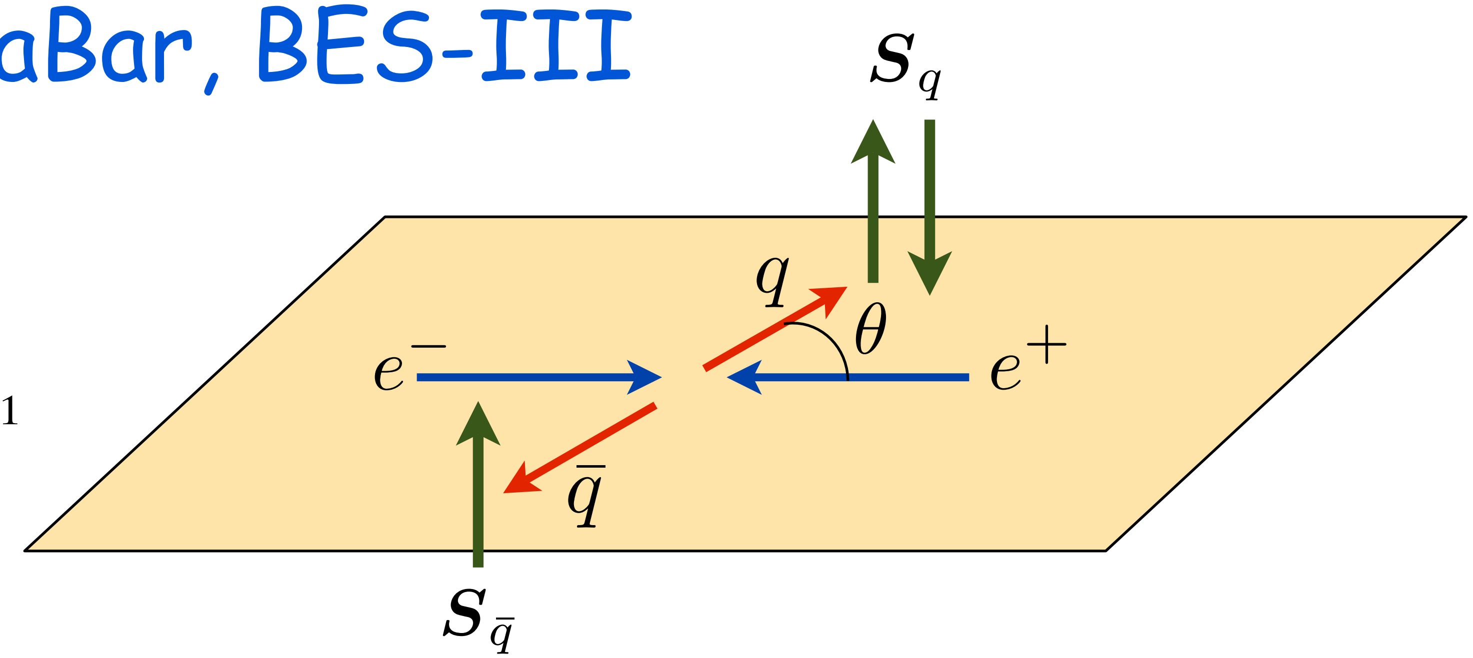
$$A_N^{\sin(\phi_S - \phi_\gamma)} \equiv \frac{2\int_0^{2\pi} \mathrm{d}\phi_\gamma \, [\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow] \, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} \mathrm{d}\phi_\gamma \, [\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$



Transverse motion of hadrons in fragmentation processes
Collins function from e^+e^- processes

Belle, BaBar, BES-III





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

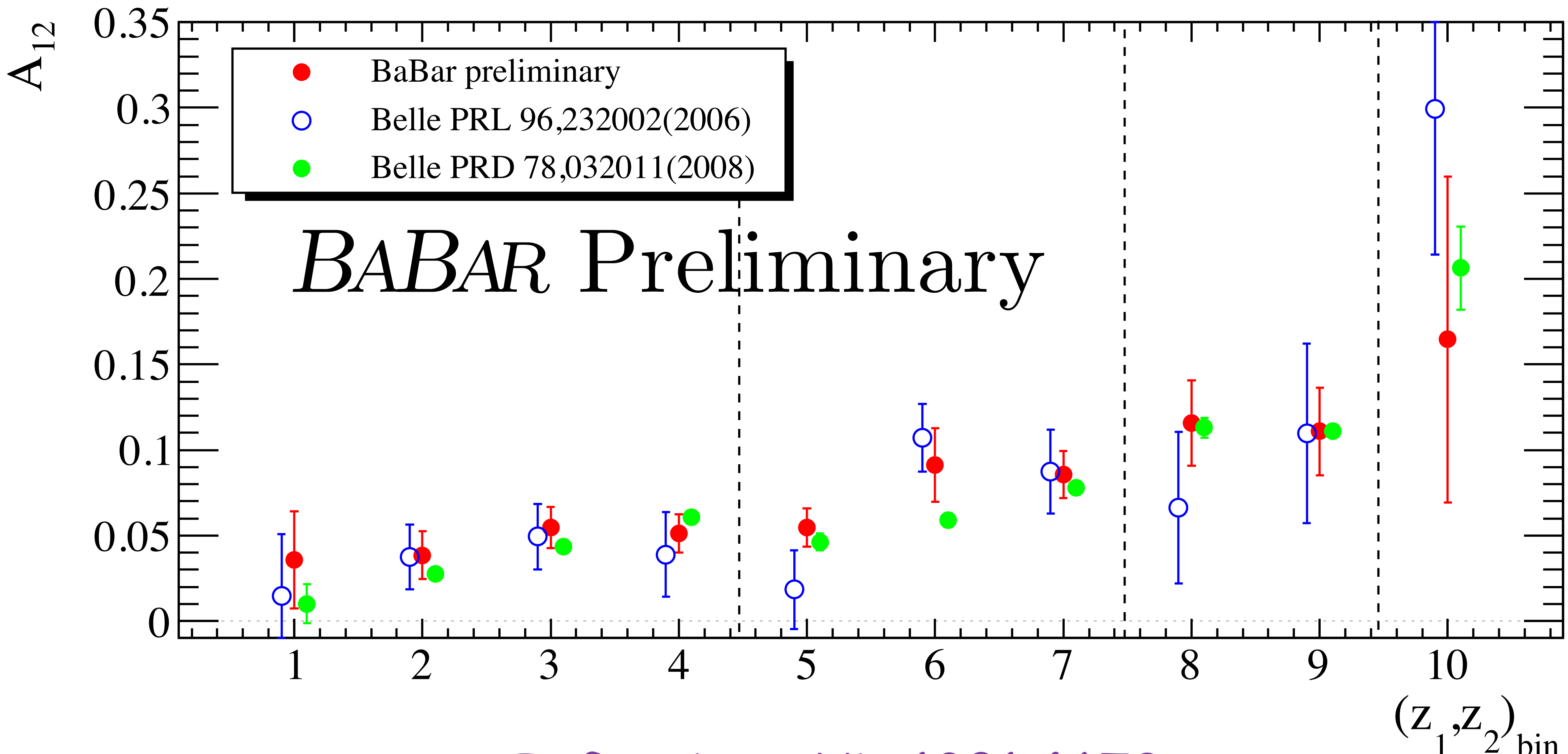
$$A_{12}(z_1, z_2, \theta, \varphi_1+\varphi_2) \equiv \frac{1}{\langle d\sigma\rangle}\, \frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\, dz_2\, d\cos\theta\, d(\varphi_1+\varphi_2)}$$

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

another similar asymmetry can be measured, A_0

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

(talks on FFs by Matevosyan, Radici, Liang, Goldstein, …)

Some (effects of) TMDs have been clearly measured, TMDs have been extracted from data ....

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

$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$ Sivers function: correlate $\mathbf{k}_\perp$ of quark with $\mathbf{S}_T$ of parent proton

$H_1^{\perp q}(z, \boldsymbol{p}_\perp^2)$ Collins function: correlate $\mathbf{p}_\perp$ of hadron and $\mathbf{s}_T$ of fragmenting quark

and even some first 3D nucleon imaging is available, but do we know better the orbital motion of quarks and gluons inside the nucleon?

Is there a direct access to parton angular momentum?
Sivers function and angular momentum

Ji's sum rule

forward limit of GPDs

$$J^q = \frac{1}{2}\int_0^1 dx\, x \left[H^q(x,0,0) + E^q(x,0,0)\right]$$

usual PDF $q(x)$

cannot be measured directly

anomalous magnetic moments

$$\kappa^p = \int_0^1 \frac{dx}{3}\left[2E^{u_v}(x,0,0) - E^{d_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

$$\kappa^n = \int_0^1 \frac{dx}{3}\left[2E^{d_v}(x,0,0) - E^{u_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

$$(E^{q_v} = E^q - E^{\bar{q}})$$

(talk on GPDs by Dupré)

Sivers function and angular momentum

assume

$$f_{1T}^{\perp(0)a}(x; Q_L^2) = -L(x) E^a(x, 0, 0; Q_L^2)$$

$$f_{1T}^{\perp(0)a}(x, Q) = \int d^2\boldsymbol{k}_\perp\, \widehat{f}_{1T}^{\perp a}(x, k_\perp; Q)$$

L(x) = lensing function
(unknown, can be computed in models)

parameterise Sivers and lensing functions

fit SIDIS and magnetic moment data

obtain E^q and estimate total angular momentum

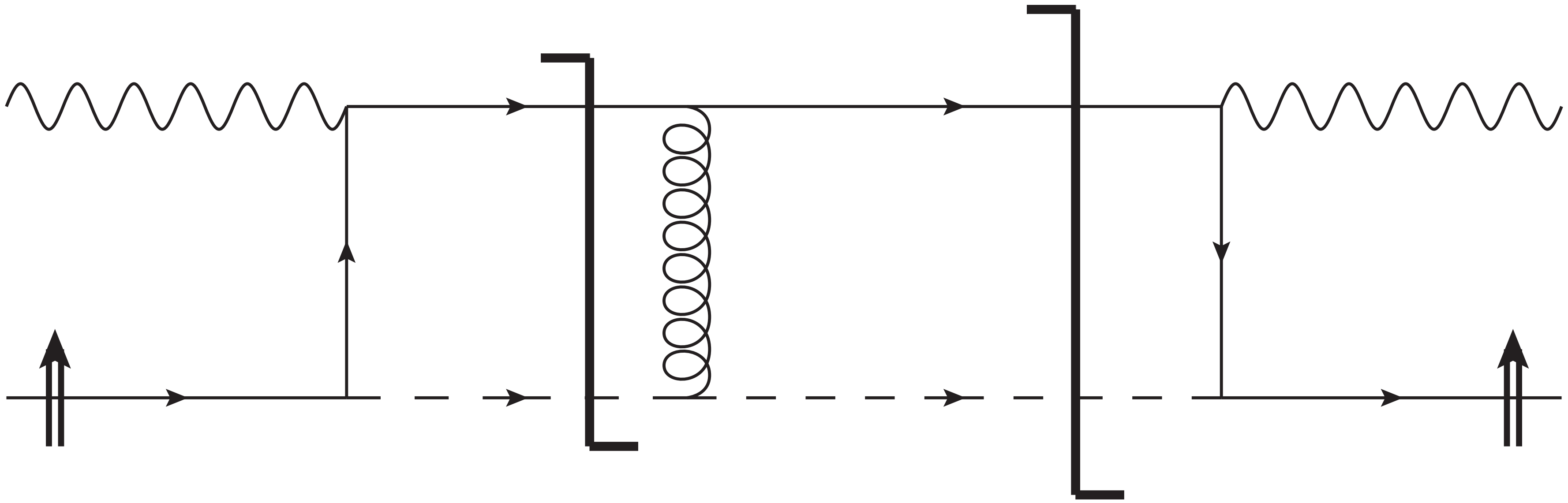
results at $Q^2 = 4$ GeV^2: $J^u \approx 0.23$, $J^{q \neq u} \approx 0$

Bacchetta, Radici, PRL 107 (2011) 212001

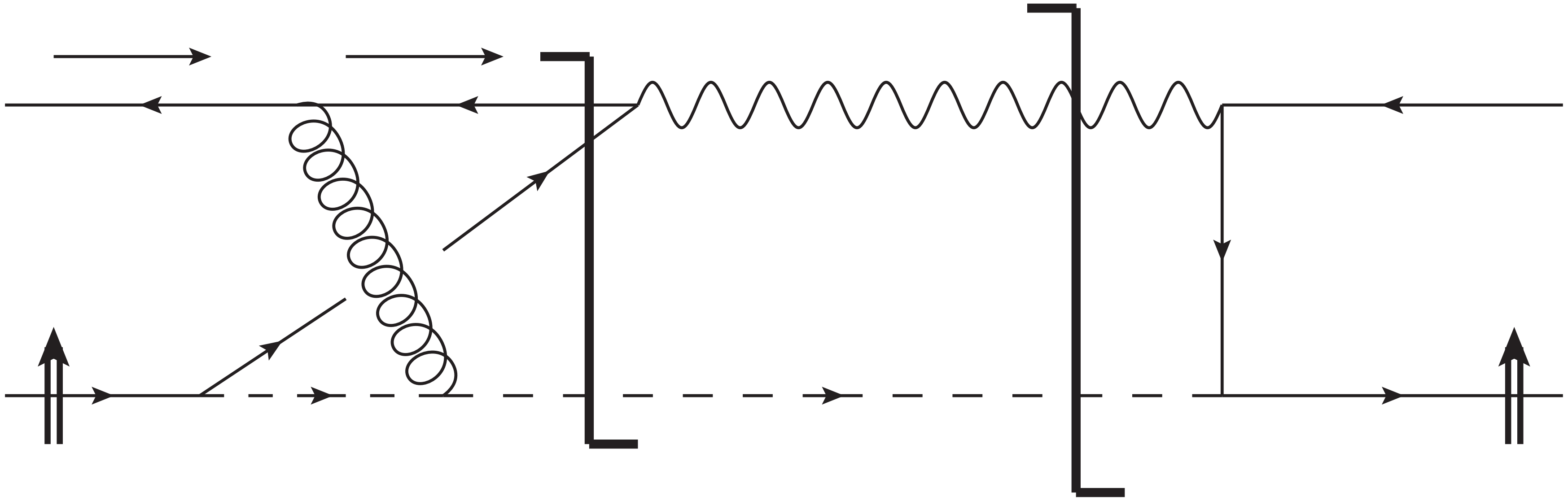
(talk by Burkardt)

Examples and interpretation of the Sivers function: simple quark-scalar diquark model of the proton

SIDIS final state interactions ($\Rightarrow A_N$)



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

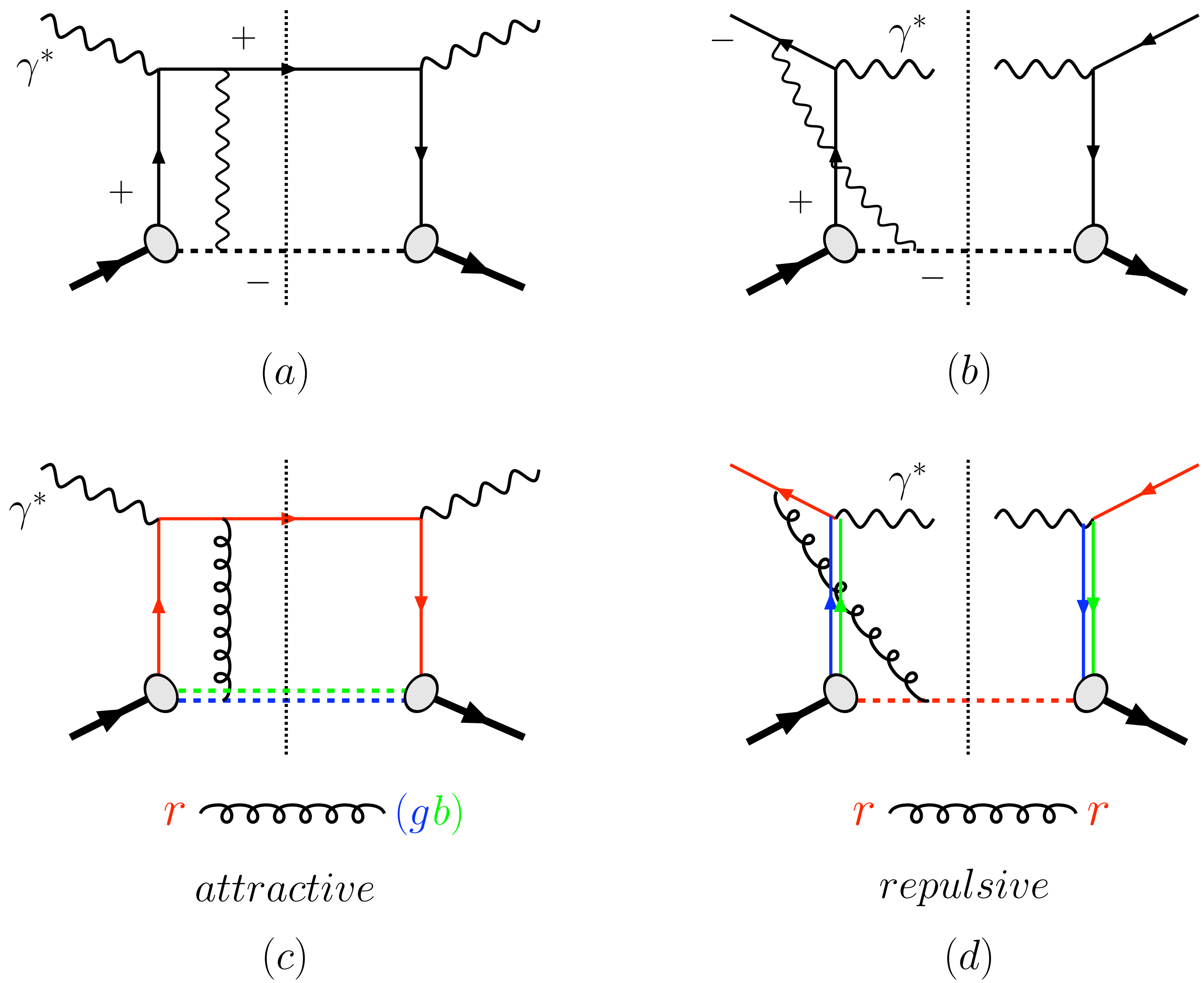


Brodsky, Hwang, Schmidt, PL B530 (2002) 99; NP B642 (2002) 344
Brodsky, Hwang, Kovchegov, Schmidt, Sievert, PR D88 (2013) 014032

process-dependence of Sivers functions

DIS: "attractive"

D-Y: "repulsive"

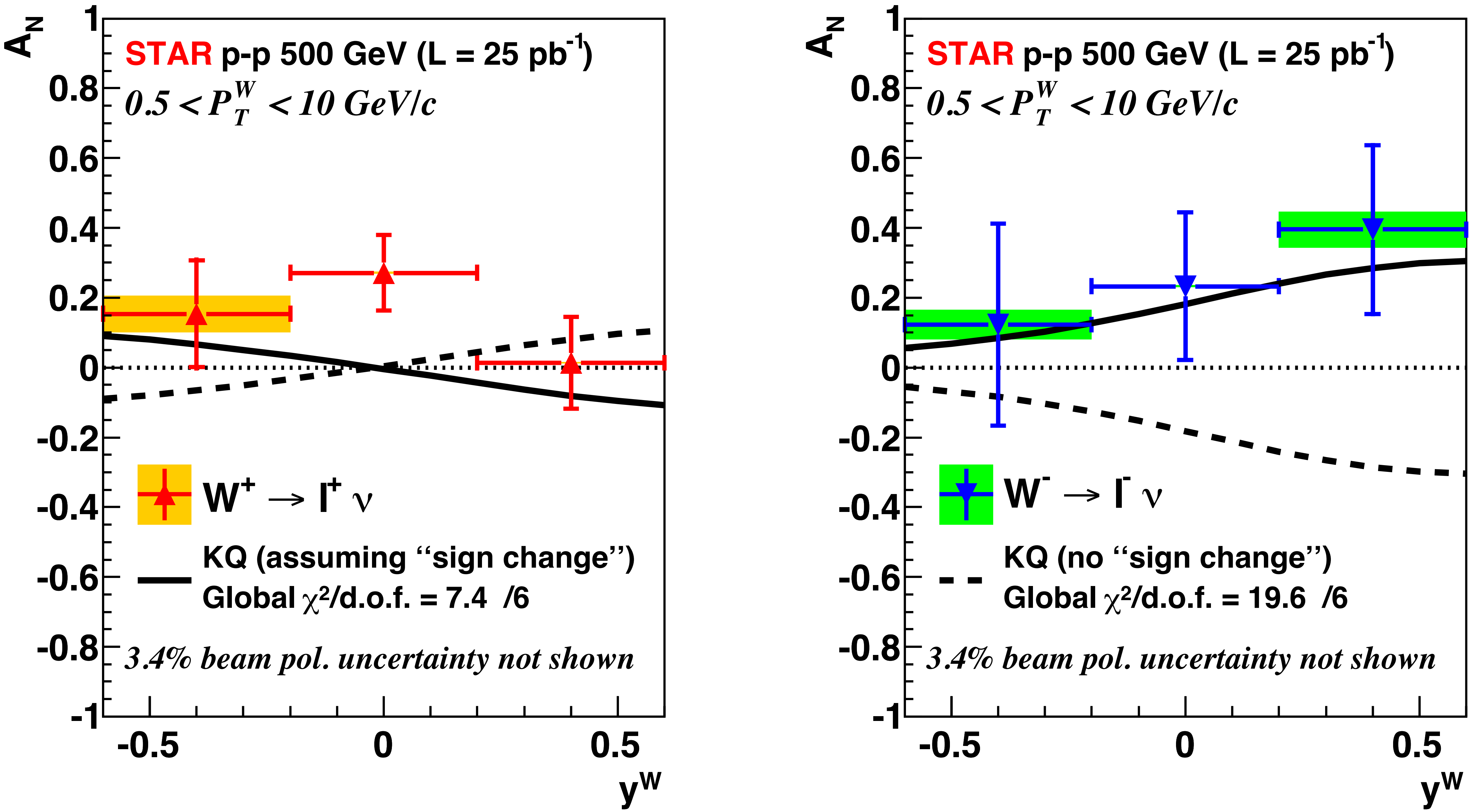


$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

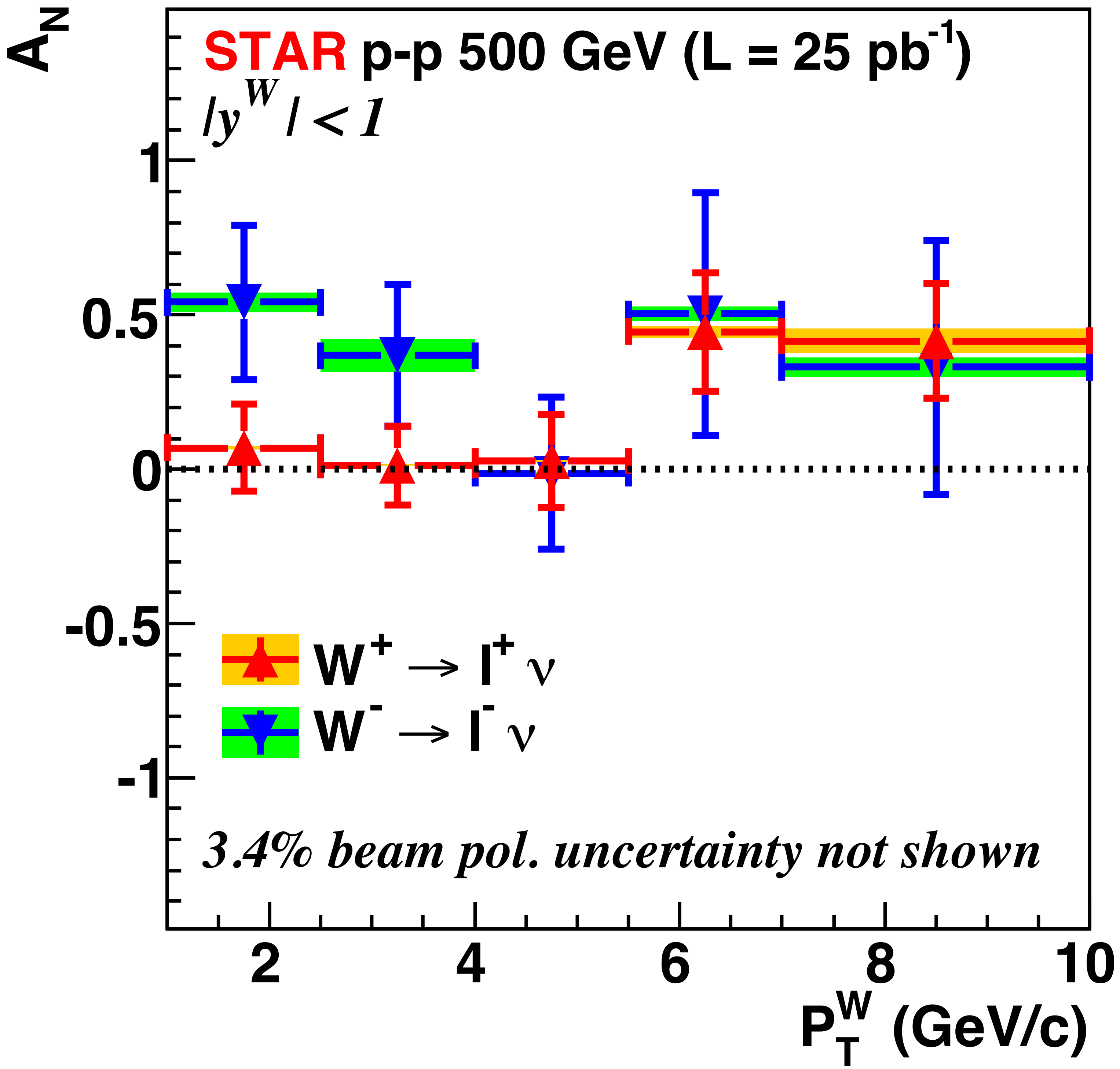
Collins, PL B536 (2002) 43

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

STAR Collaboration, arXiv:1511.06003



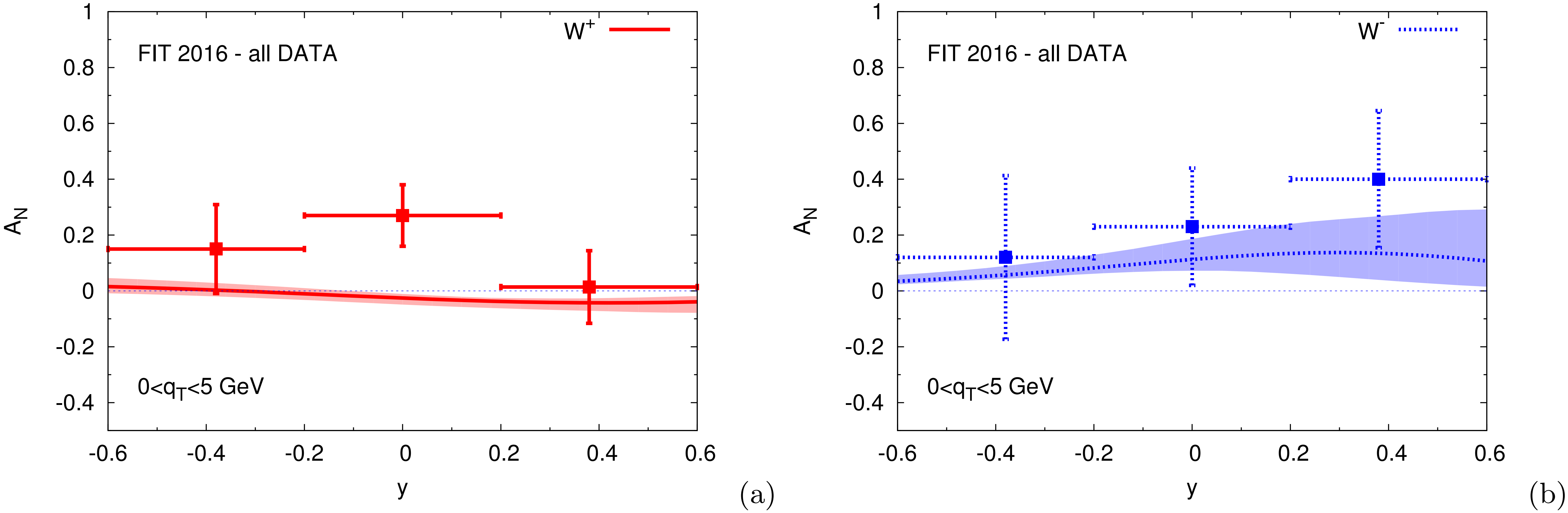
some hints at sign change .....



experimental data up to large p_T values....

analysis of data (in preparation):

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



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

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

(talk by D'Alesio)

TMDs in pp single inclusive processes?

The mysterious SSAs in large P_T single hadron inclusive production

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

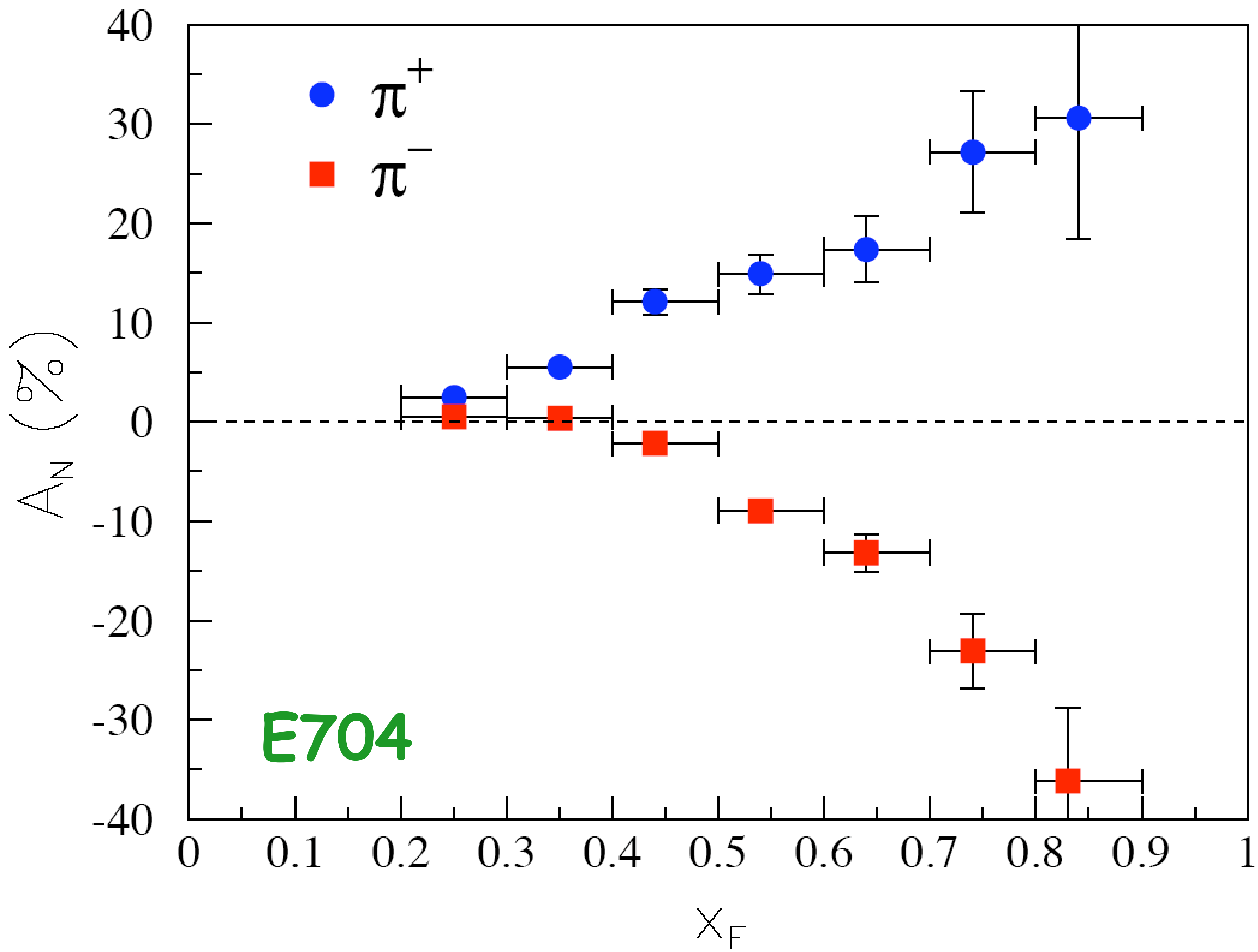
Single Spin Asymmetry

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

E704 (1991)

$\sqrt{s}$ = 20 GeV

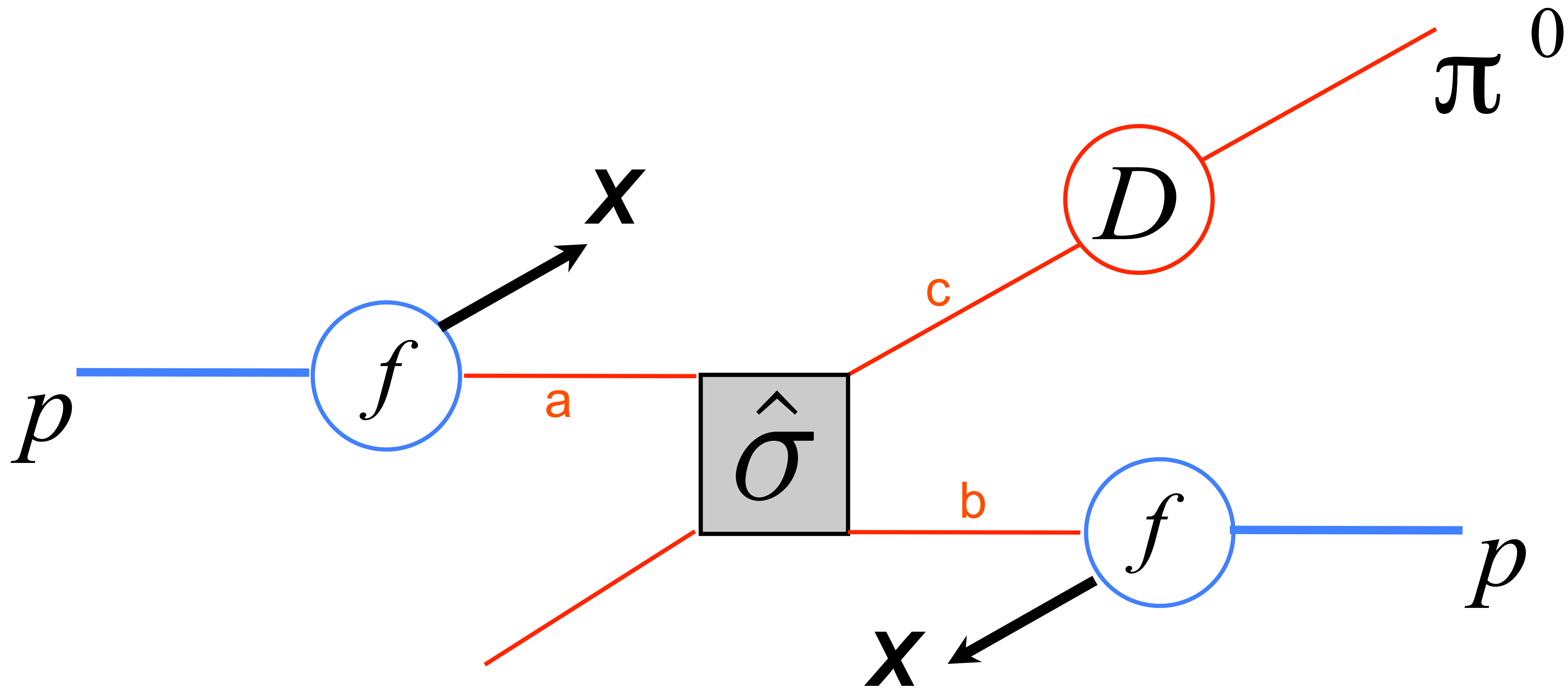
$0.7 < p_T < 2.0$



Cross section for $p\,p \to \pi^0\,X$ in pQCD, only one scale, P_T

based on factorization theorem

(in collinear configuration)

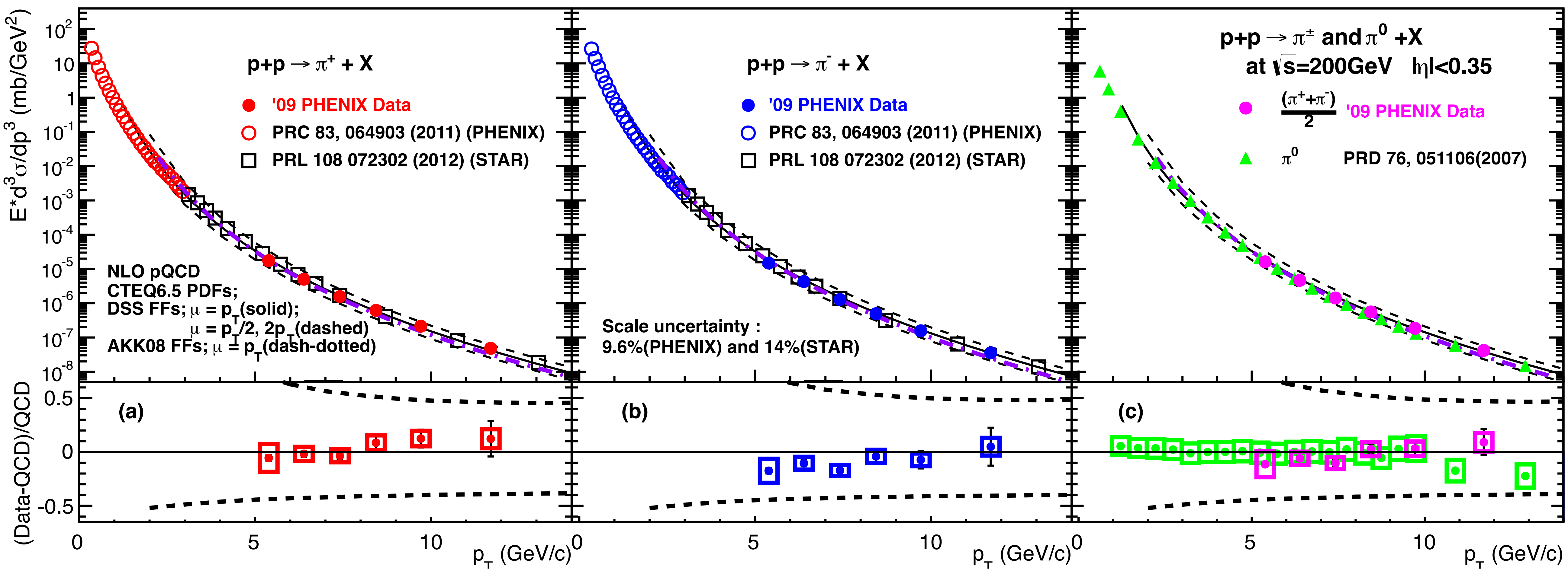


$$\mathrm{d}\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

pQCD elementary interactions

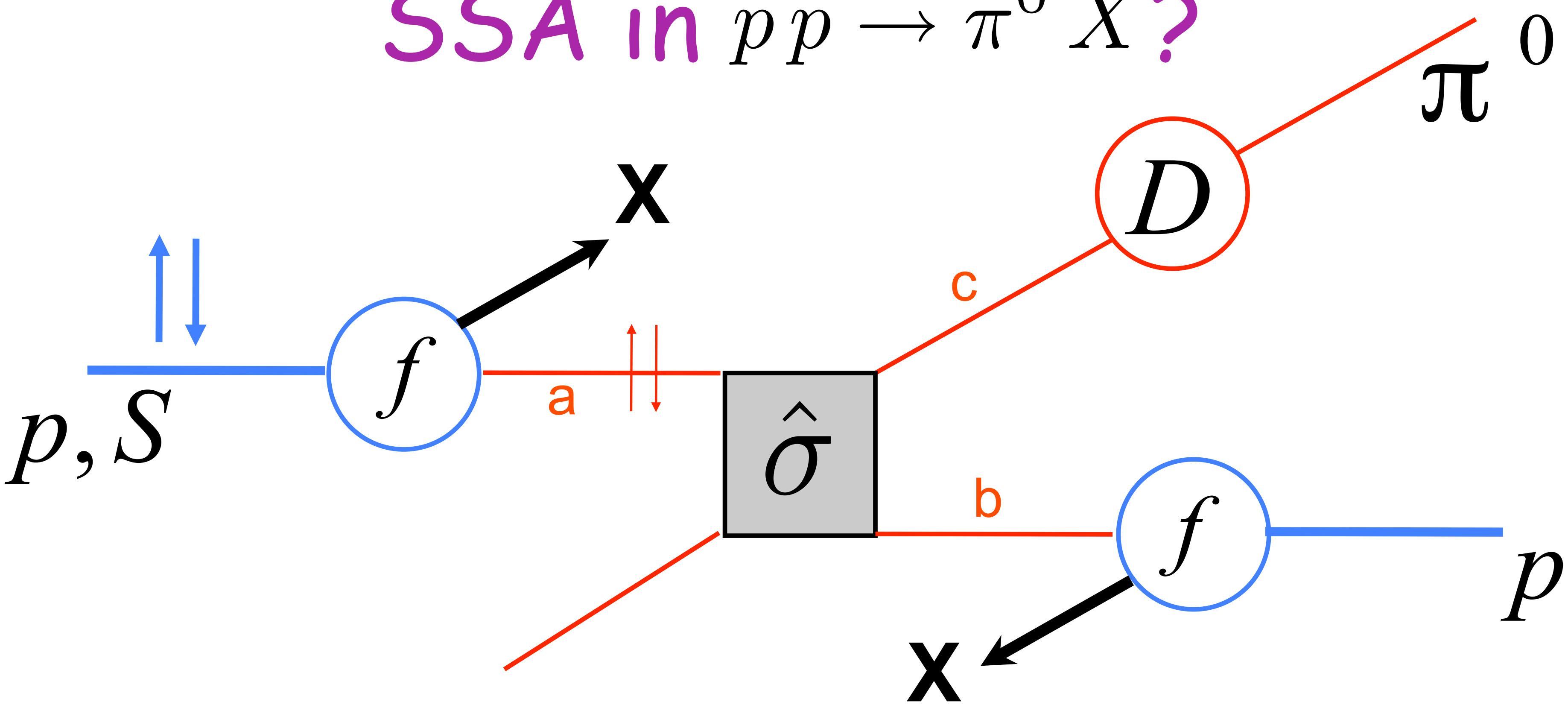
mid-rapidity RHIC data, unpolarised cross sections

(arXiv:1409.1907 [hep-ex], Phys. Rev. D91 (2015) 3, 032001)



good agreement between RHIC data and collinear pQCD calculations; similarly for jet production at LHC

SSA in $p\,p \to \pi^0\,X$?



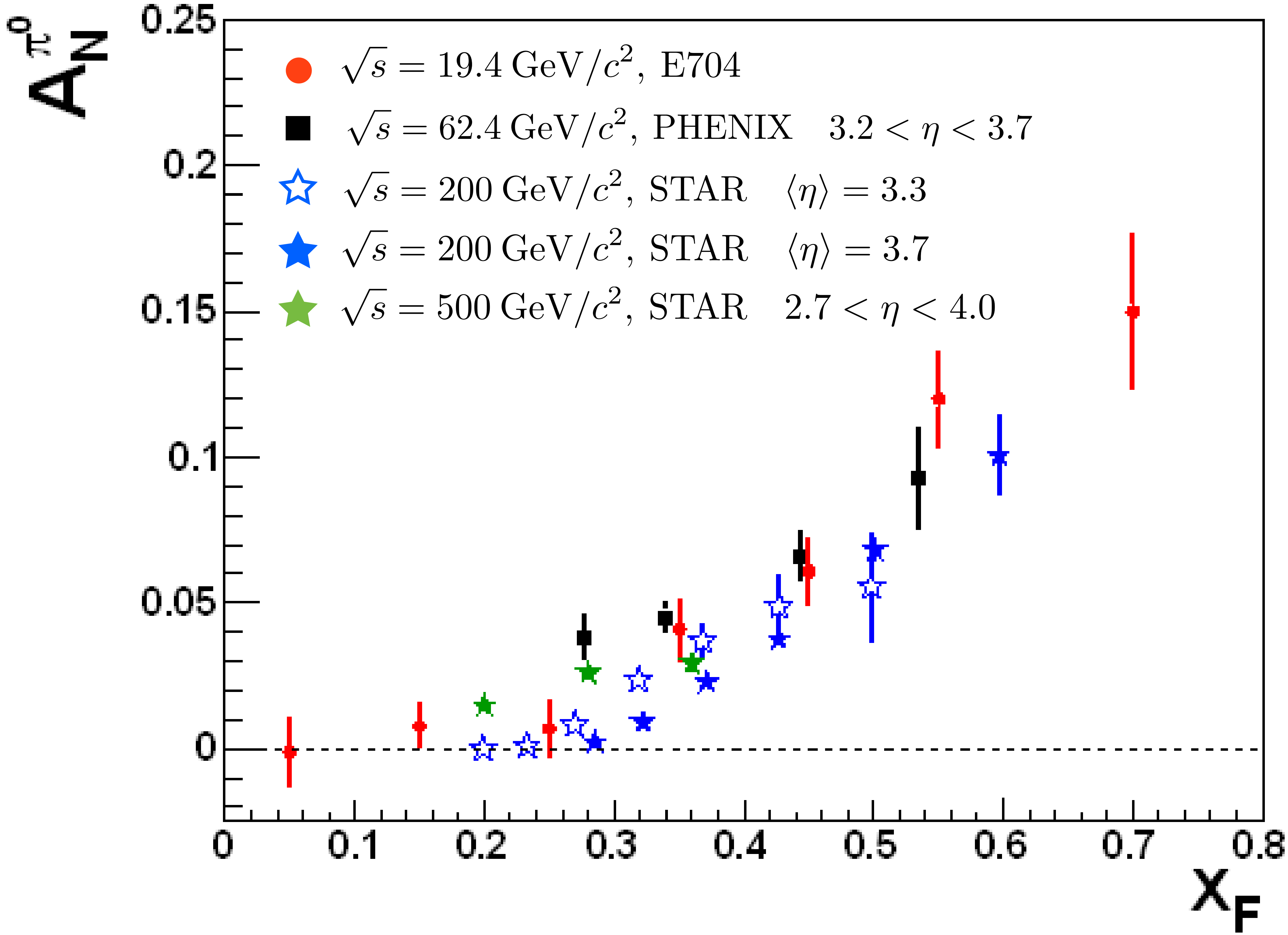
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{\Delta_T f_a}_{} \otimes f_b \otimes \underbrace{[d\hat{\sigma}^{\uparrow} - d\hat{\sigma}^{\downarrow}]}_{\text{pQCD elementary SSA}} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

transversity

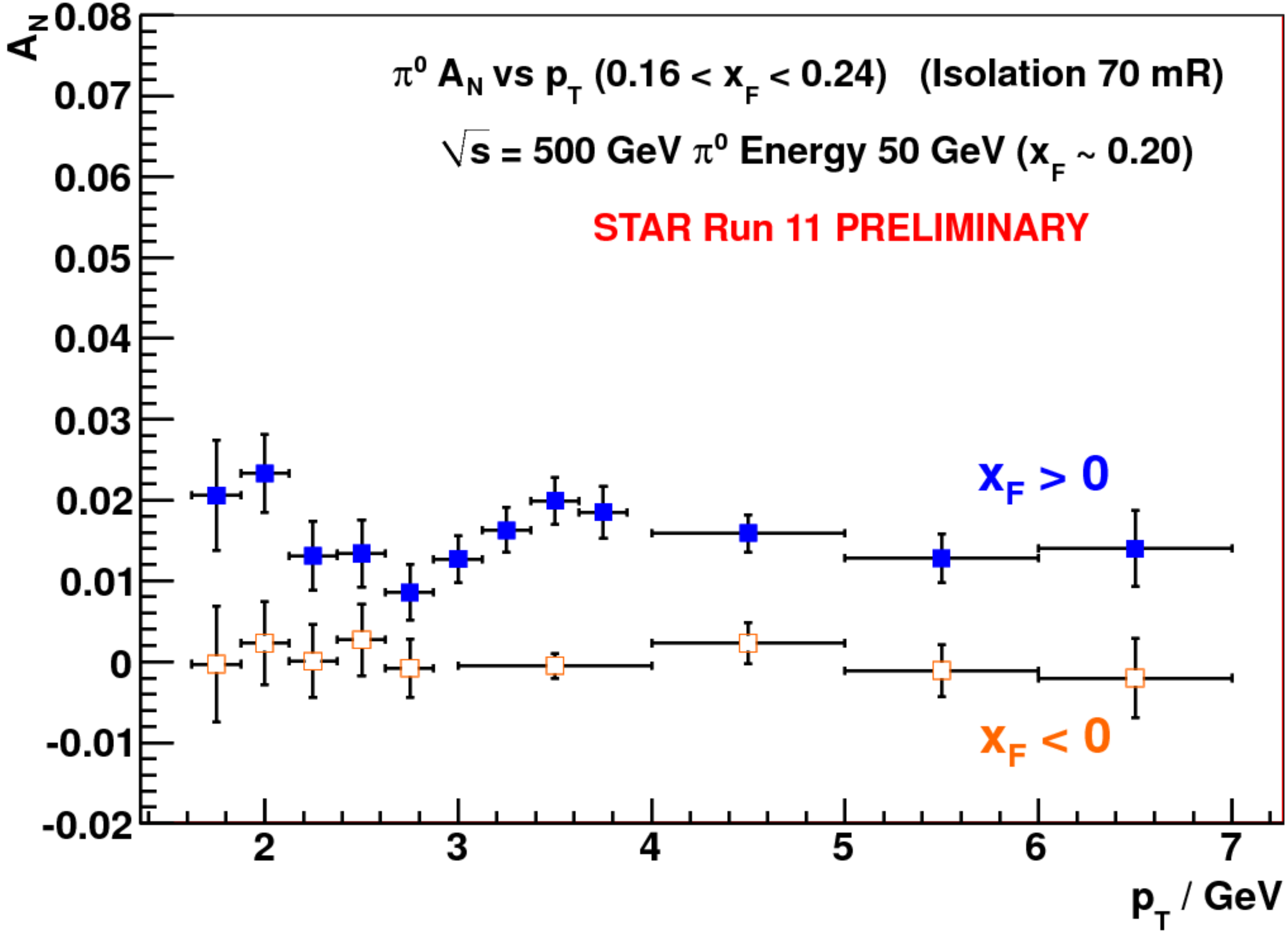
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \hat{a}_N \propto \frac{m_q}{E_q}\,\alpha_s$$

was considered almost a theorem

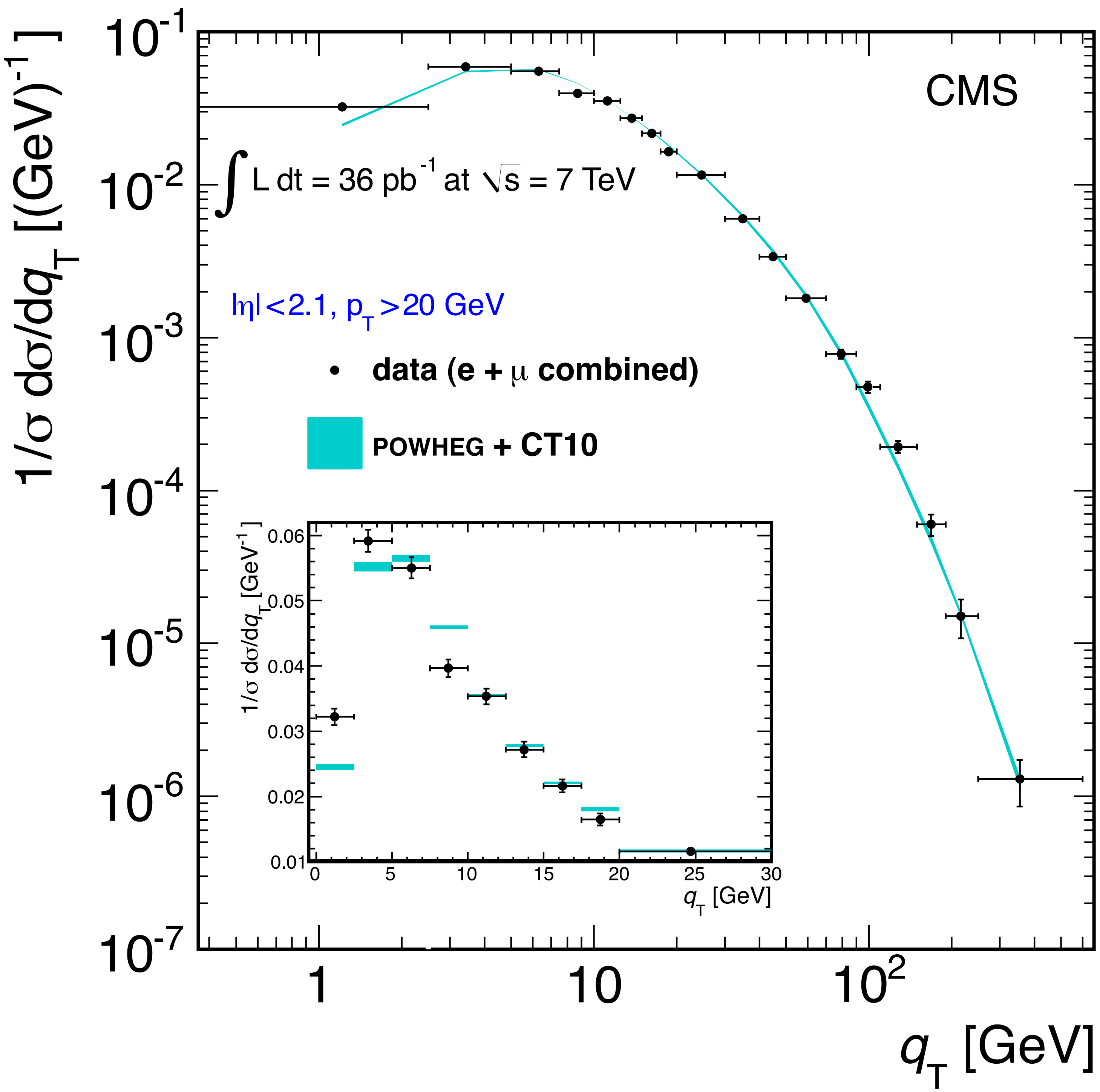
but $A_N \neq 0$ persists at high energies ....



…. and at large P_T



Z-boson transverse momentum q_T spectrum in pp collisions at the LHC



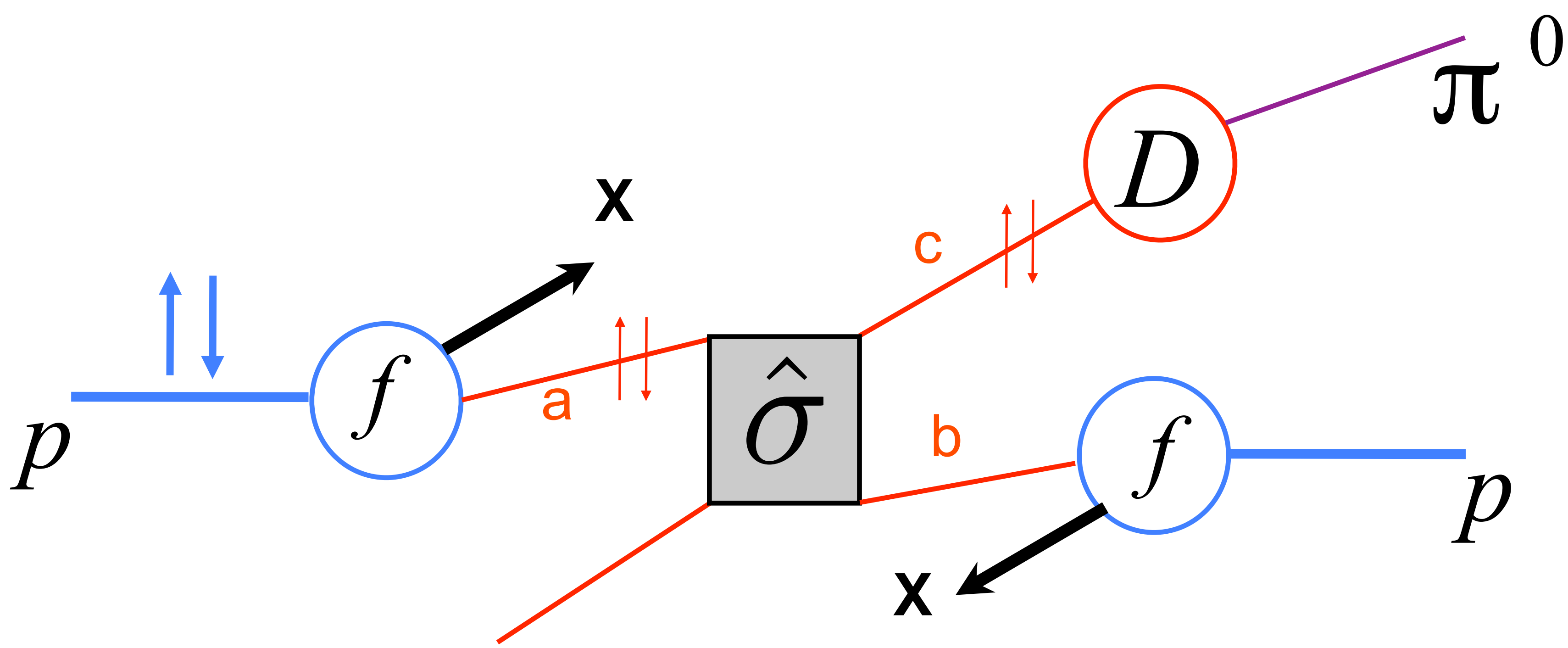
The small q_T region cannot be explained by usual collinear PDF factorization: needs TMD-PDFs

Phys. Rev. D85 (2012) 032002

SSA in hadronic processes: TMDs, higher-twist correlations?

Two main different (?) approaches

1. Generalization of collinear scheme (GPM)
(assuming factorization)



$$\mathrm{d}\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes \mathrm{d}\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes D_{\pi/c}(z, \boldsymbol{p}_{\perp\pi})$$

non perturbative single spin effects in TMDs

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, ...

Field-Feynman

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

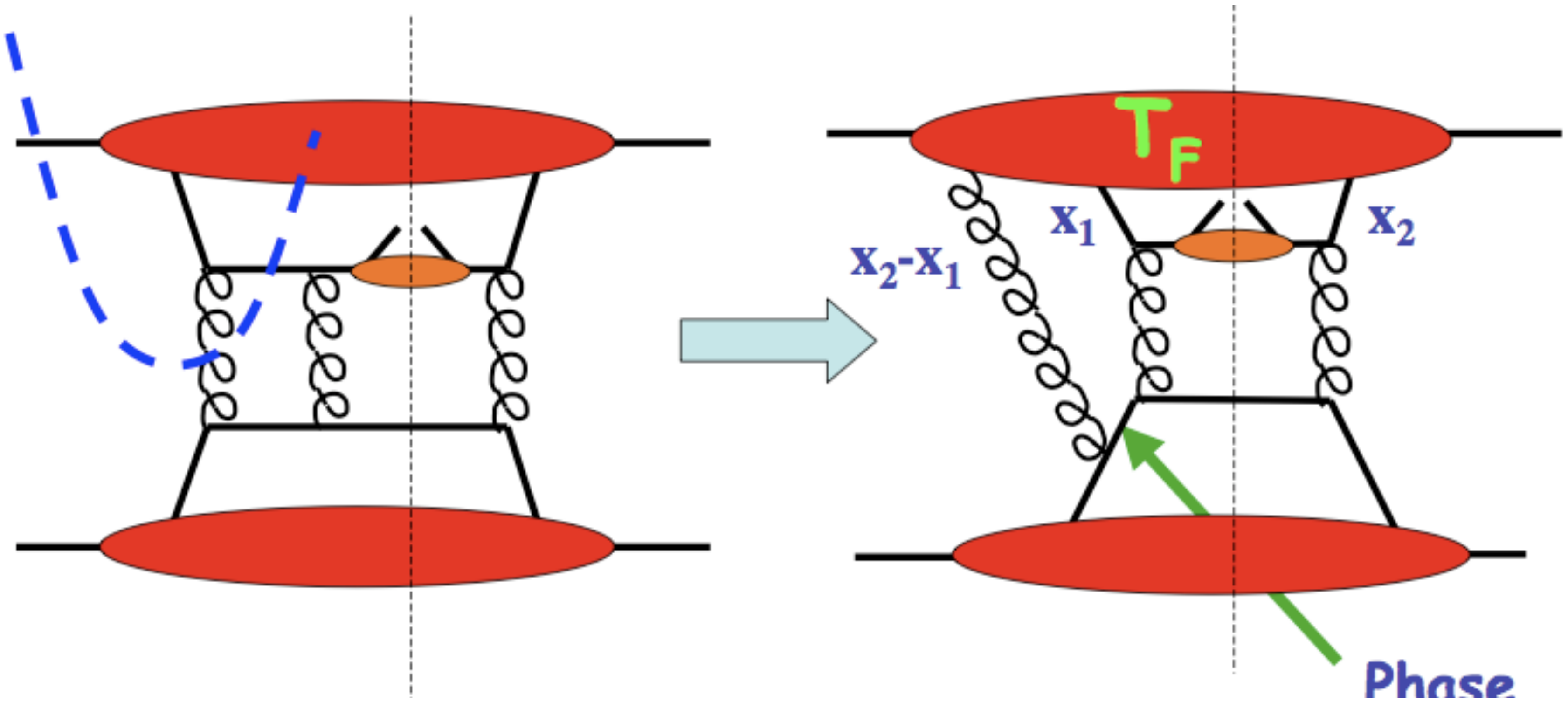
(M.A. M. Boglione, D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, PRD86 (2012) 074032; PRD88 (2013) 054023)

2. Higher-twist partonic correlations (ETQS)

(Efremov, Teryaev, Ratcliffe; Qiu, Sterman; Kouvaris, Vogelsang, Yuan; Bacchetta, Bomhof, Mulders, Pijlman; Koike; Gamberg, Kang...)

higher-twist partonic correlations - factorization OK

$$\mathrm{d}\Delta\sigma \propto \sum_{a,b,c} \underbrace{T_a(k_1, k_2, \boldsymbol{S}_\perp)}_{\text{twist-3 correlators}} \otimes f_{b/B}(x_b) \otimes \underbrace{H^{ab\to c}(k_1, k_2)}_{\text{product of hard amplitudes, not cross sections}} \otimes D_{h/c}(z)$$



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

possible higher-twist contributions to A_N

(collinear factorisation)

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

(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 $T_{q,F}$

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

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

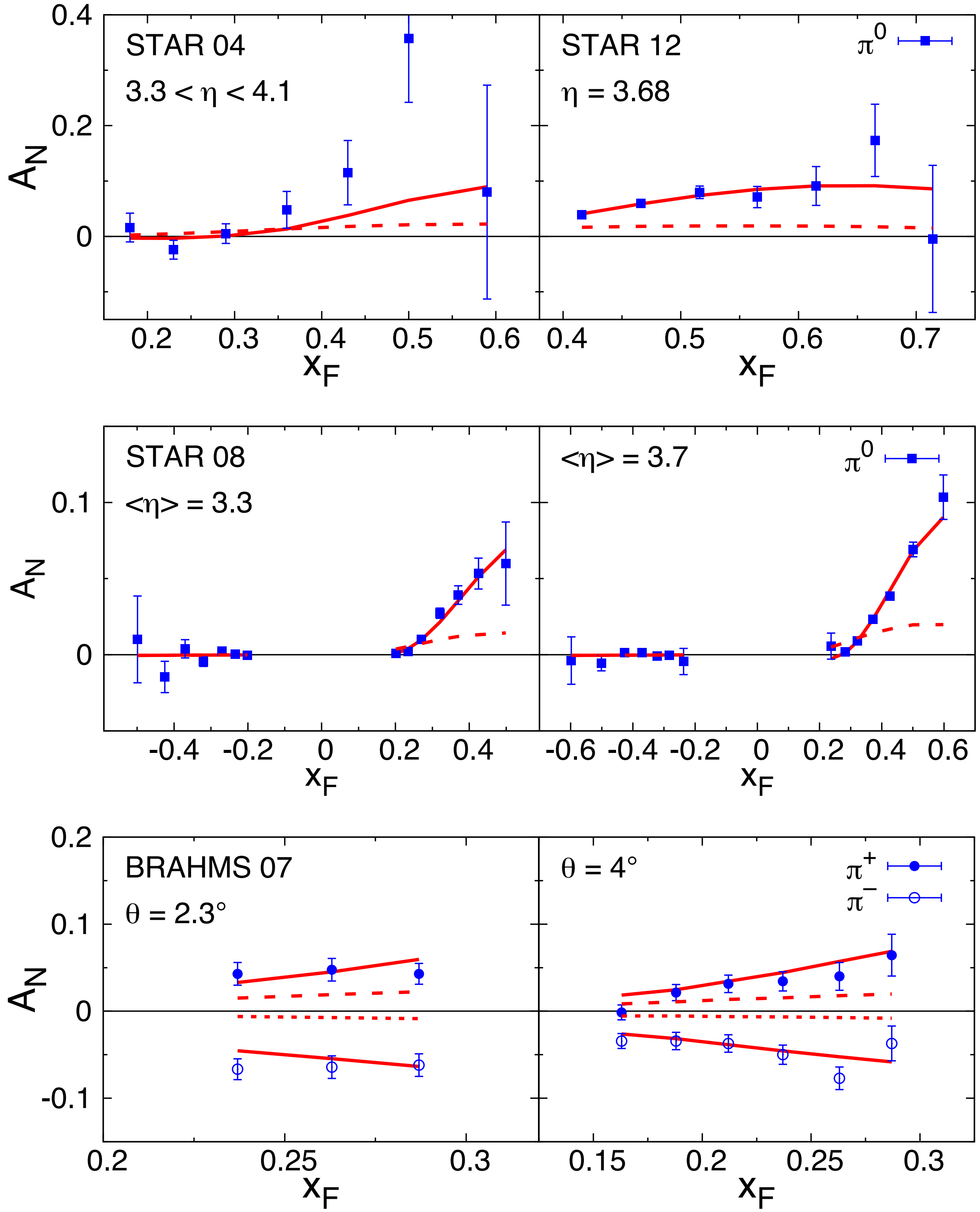
the same mismatch does not occur adopting TMD factorization; the reason is that the hard scattering part in higher-twist factorization is negative

A_N might be explained by new twist-3 fragmentation functions

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

A_N from twist-3 fragmentation functions

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



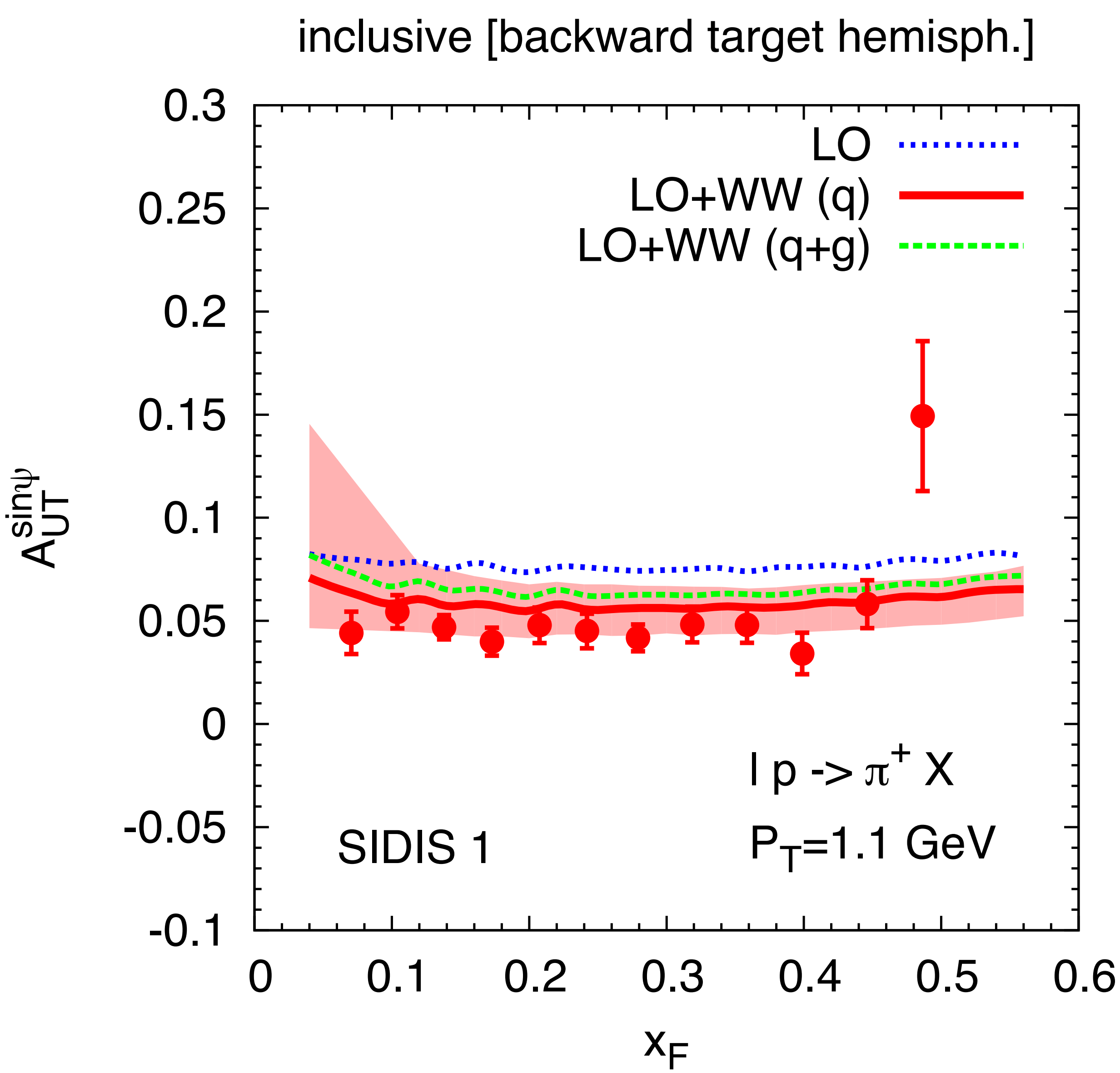
good fit of A_N mainly due to the new twist-3 fragmentation function

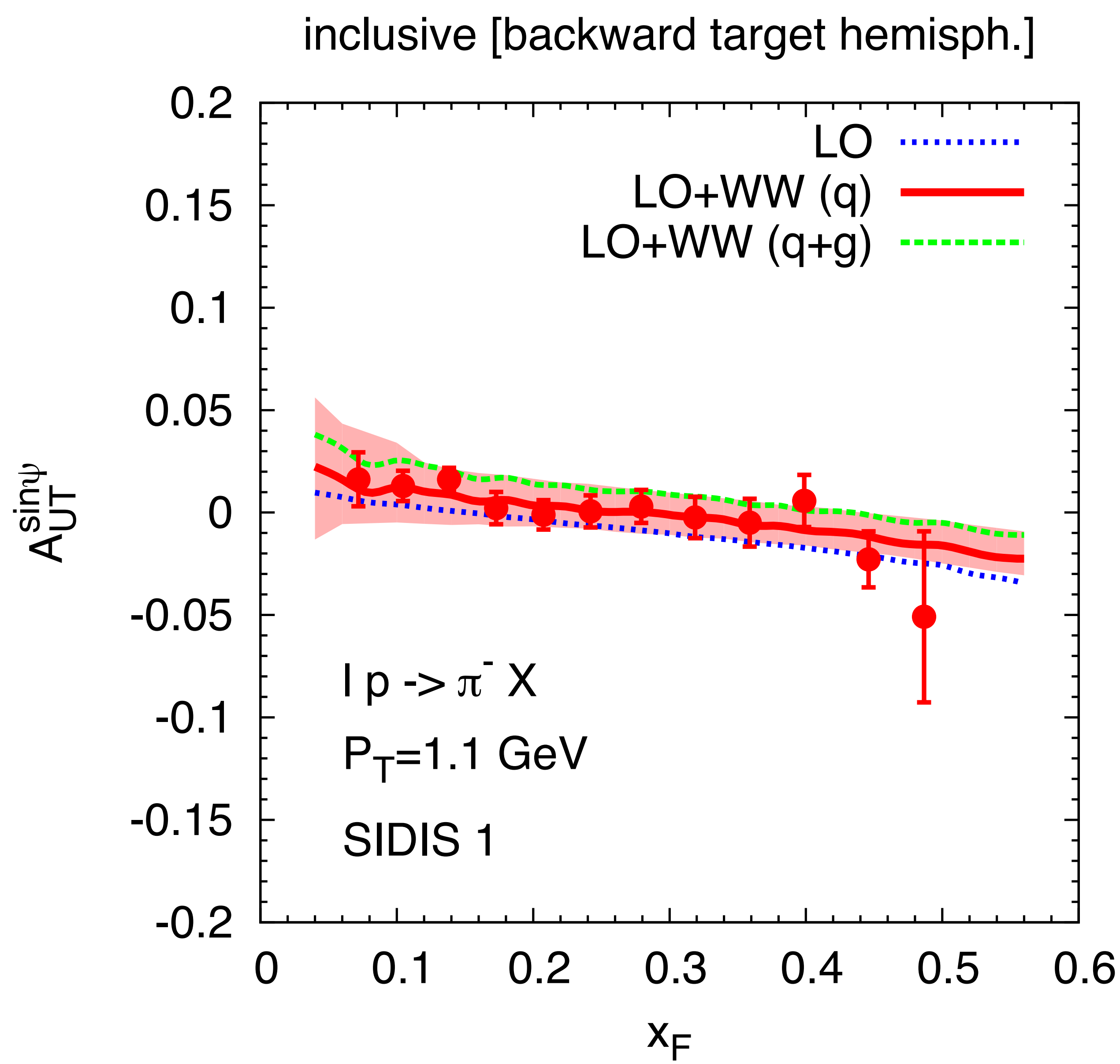
it gives too large values of A_N in $\ell p^\uparrow \to \pi X$ processes

Gamberg, Khang, Metz, Pitonyak, PRD 90 (2014) 074012

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)





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:

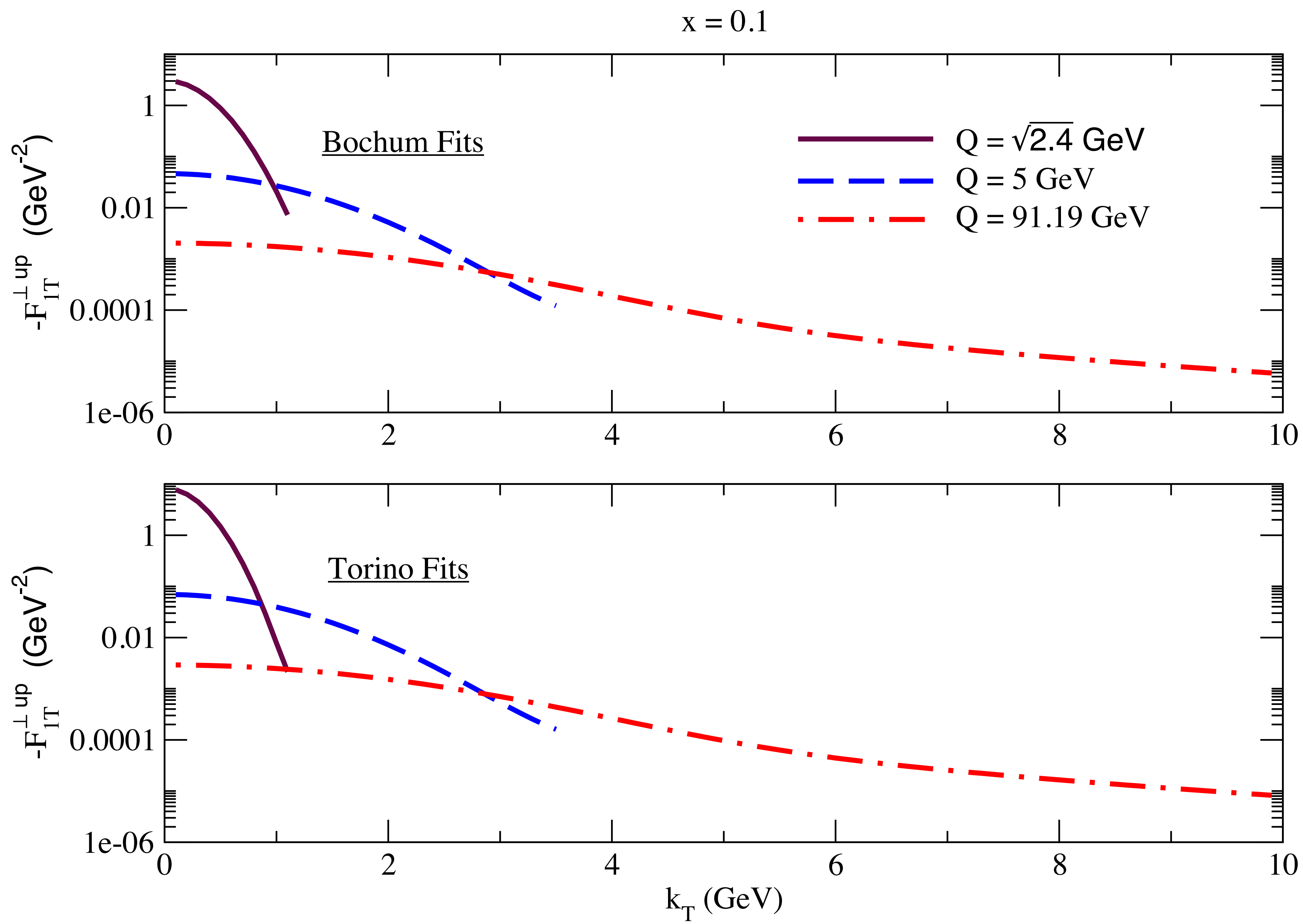
TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions

(talks by Bacchetta, Gamberg, Mulders, Cherednikov,...)

TMD phenomenology with QCD evolution

how does gluon emission affect the transverse motion?

example: TMD evolution of up quark Sivers function



Aybat, Collins, Qiu, Rogers, Phys. Rev. D85 (2012),
Kang, Prokudin, Sun, Yuan, arXiv:1505.05589), ...

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?
The analysis of TMDs and GPDs is 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!