(The mystery of) SSAs:
TMD vs collinear twist-3 vs GPM

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

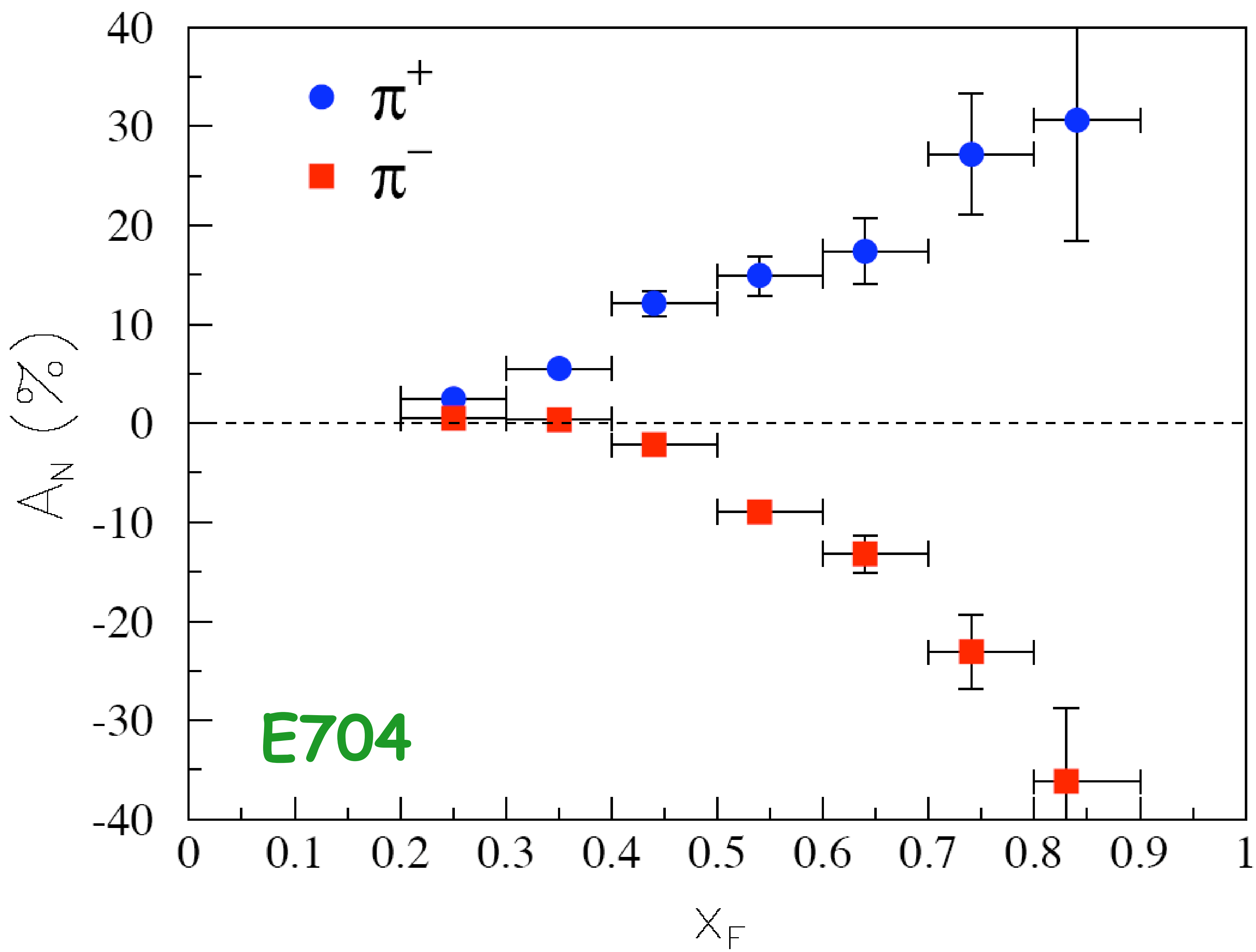
Single Spin Asymmetry

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

E704 (1991)

$\sqrt{s}$ = 20 GeV

$0.7 < p_T < 2.0$

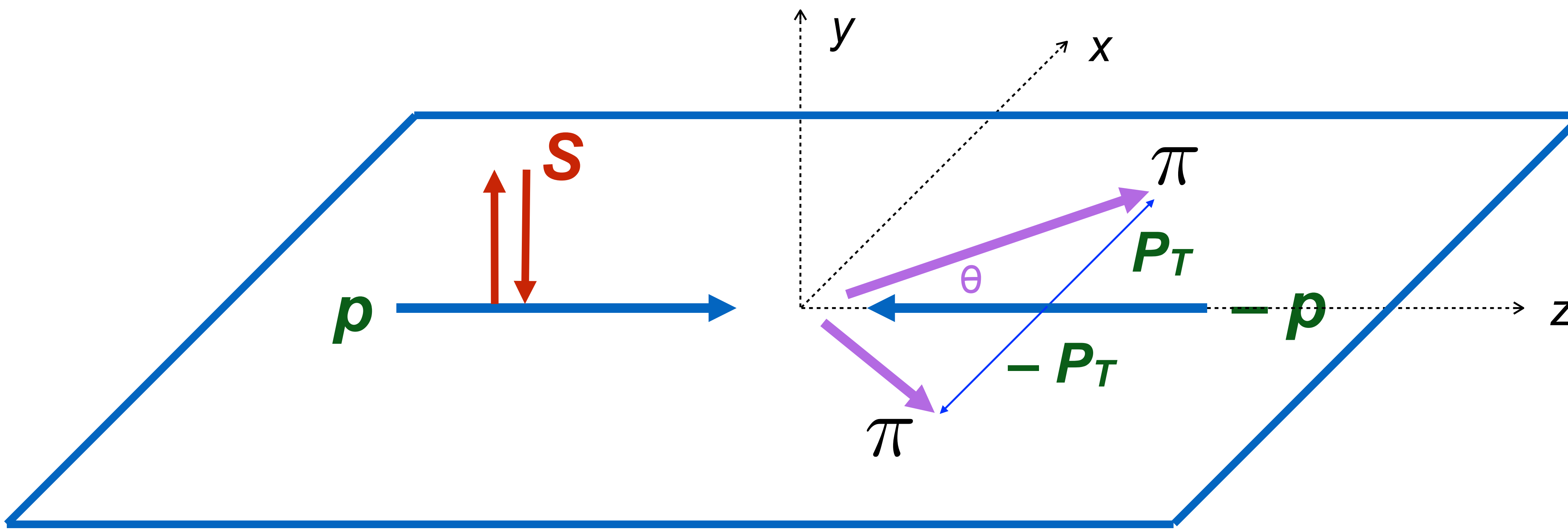


M. Anselmino, Torino University & INFN

New observables in quarkonium production,
ECT*, February 29 - March 4, 2016

A_N = simple left-right asymmetry

$$A_N = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\downarrow}(\boldsymbol{P}_T)}{d\sigma^{\uparrow}(\boldsymbol{P}_T) + d\sigma^{\downarrow}(\boldsymbol{P}_T)} = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\uparrow}(-\boldsymbol{P}_T)}{2\, d\sigma^{\text{unp}}(P_T)}$$

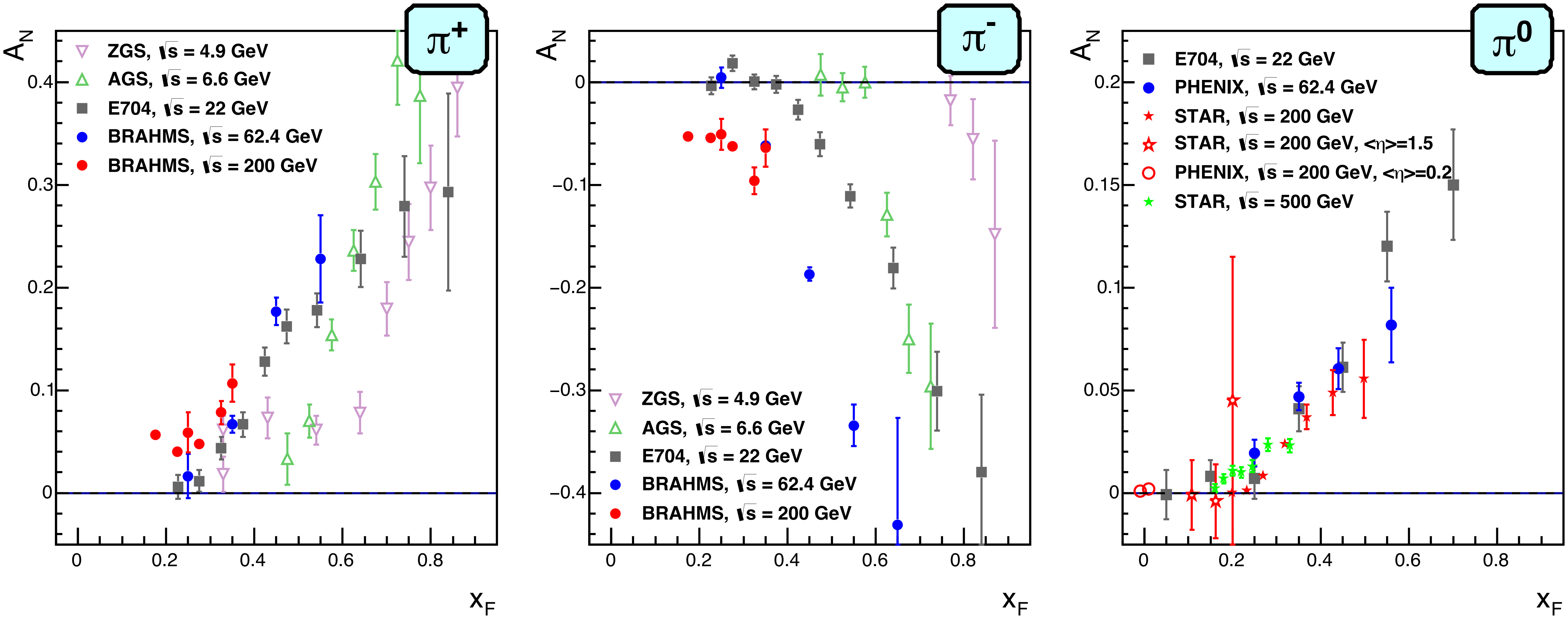


$$A_N \equiv \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}} \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto \sin\theta$$

transverse Single Spin Asymmetry (SSA)

Collections of results on A_N

The RHIC cold QCD Plan: A Portal to the EIC, arXiv 1602.03922
E. Aschenauer, U. D'Alesio, F. Murgia, arXiv:1512.05379 - EPJA

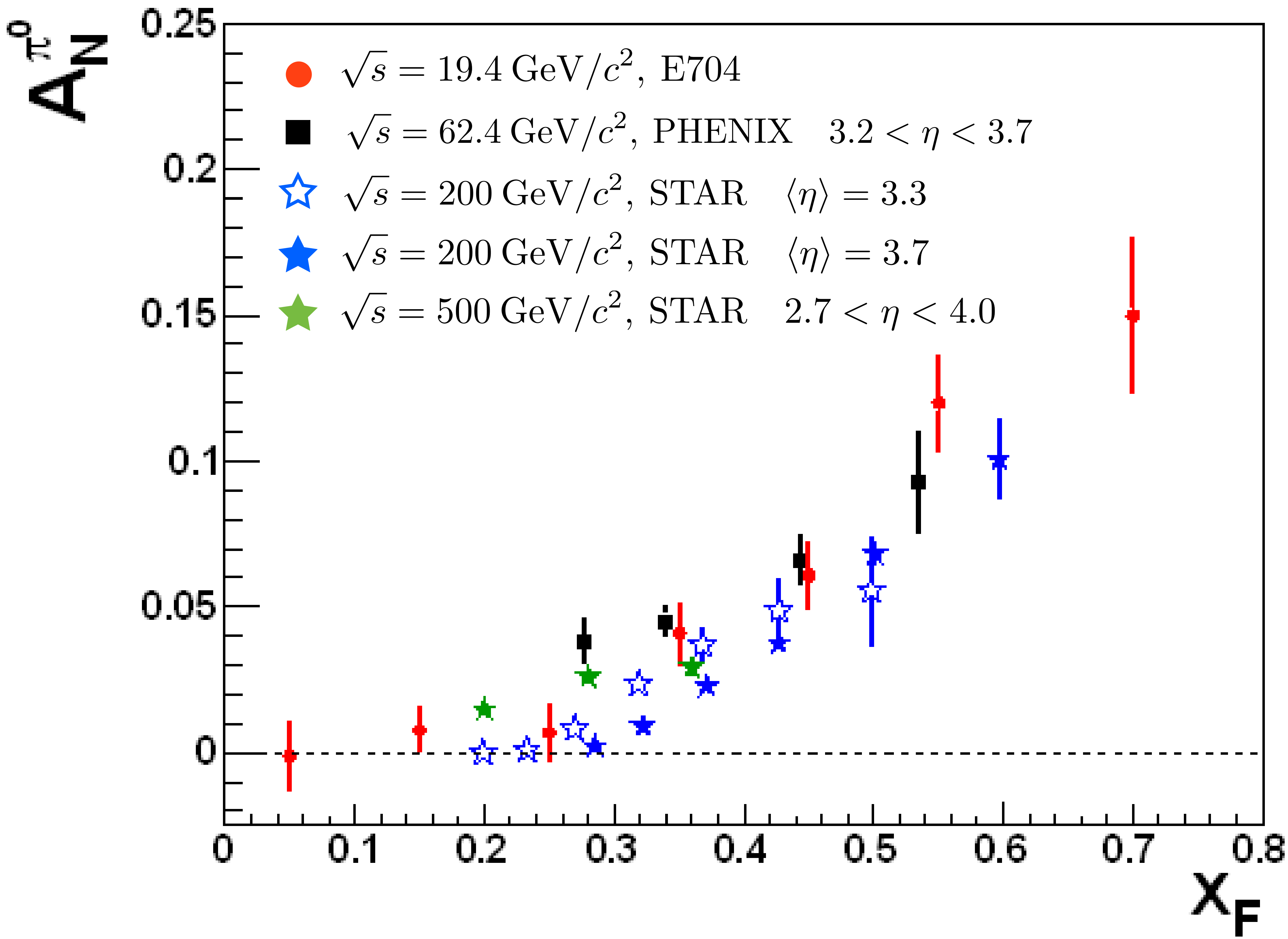


$$p^{\uparrow} p \rightarrow \pi X$$

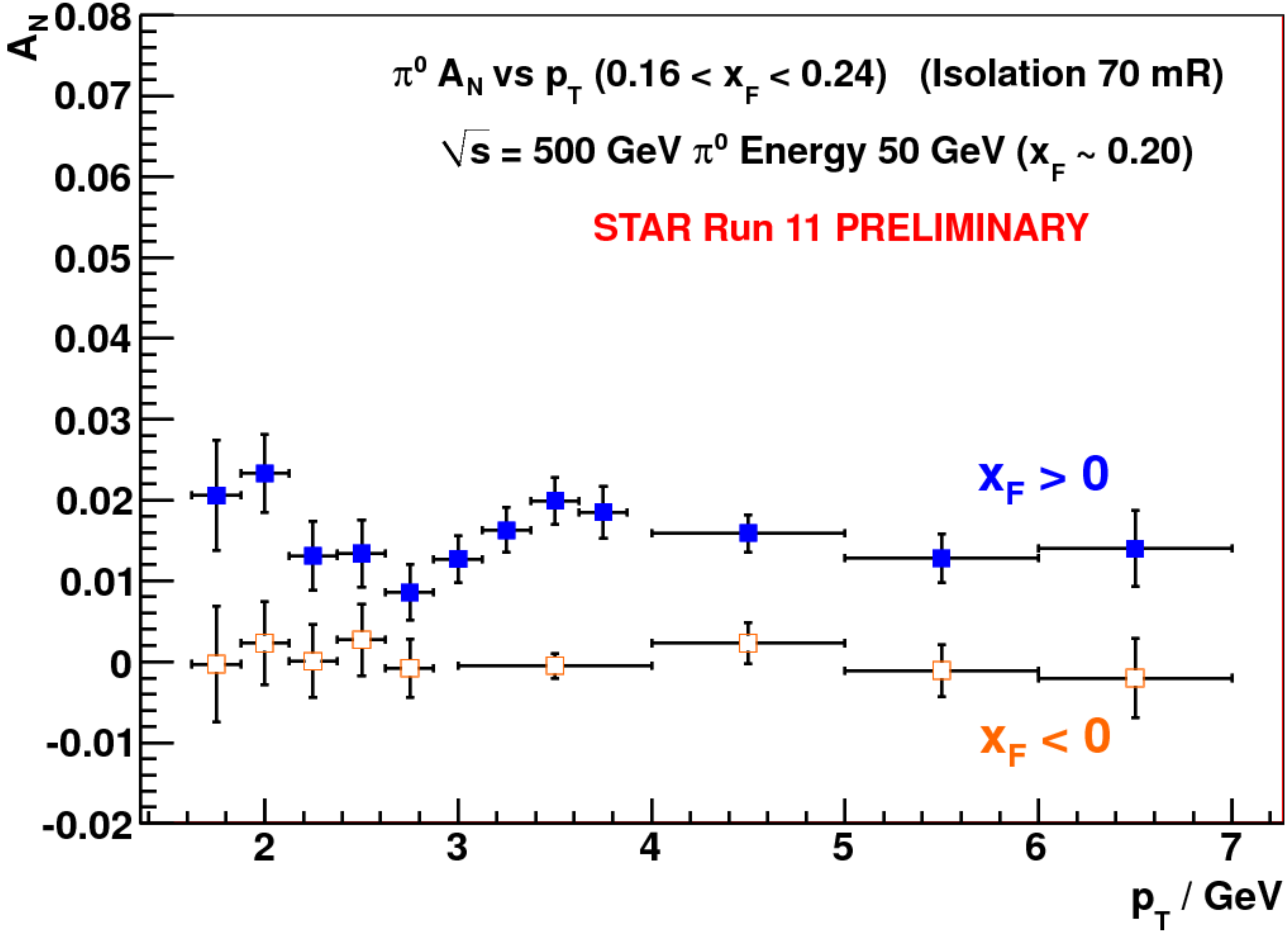
$x_F = x_1 - x_2$

A_N becomes large for large values of x_1,
positive effect for π+ (u quarks),
negative effect for π- (d quarks)

A_N persists at high energies ....

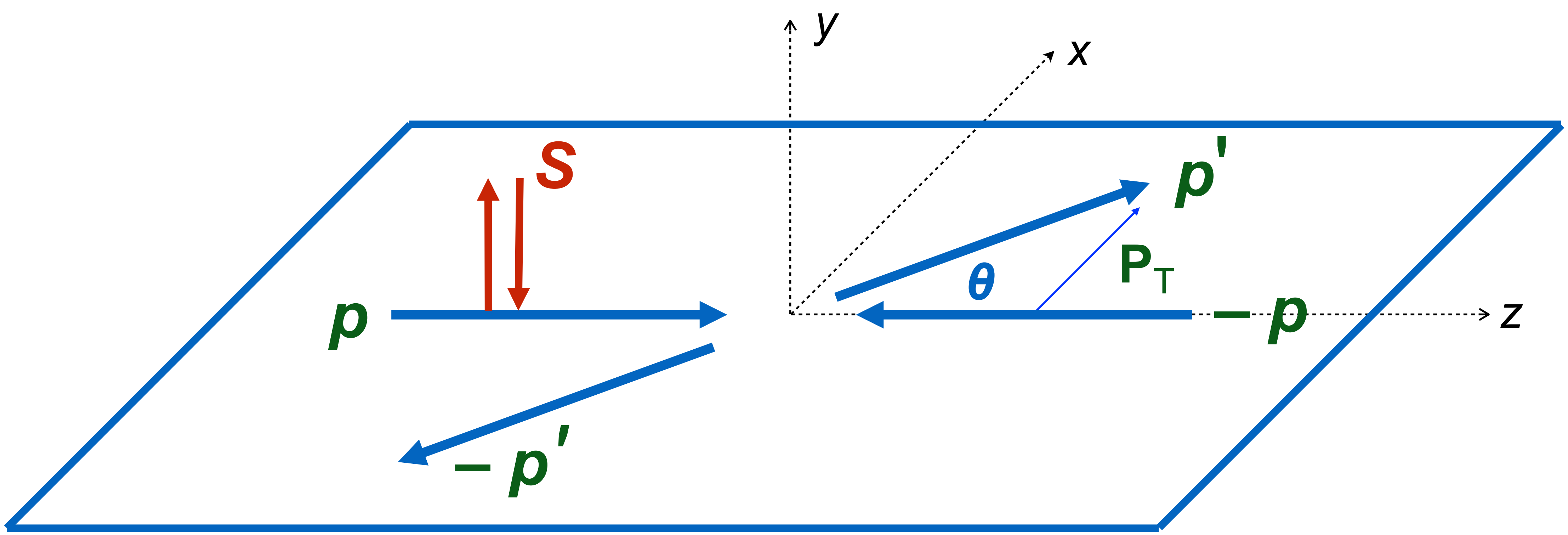


.... and at large P_T



How do we get Single Spin Asymmetries?

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: $p\,p \to p\,p$

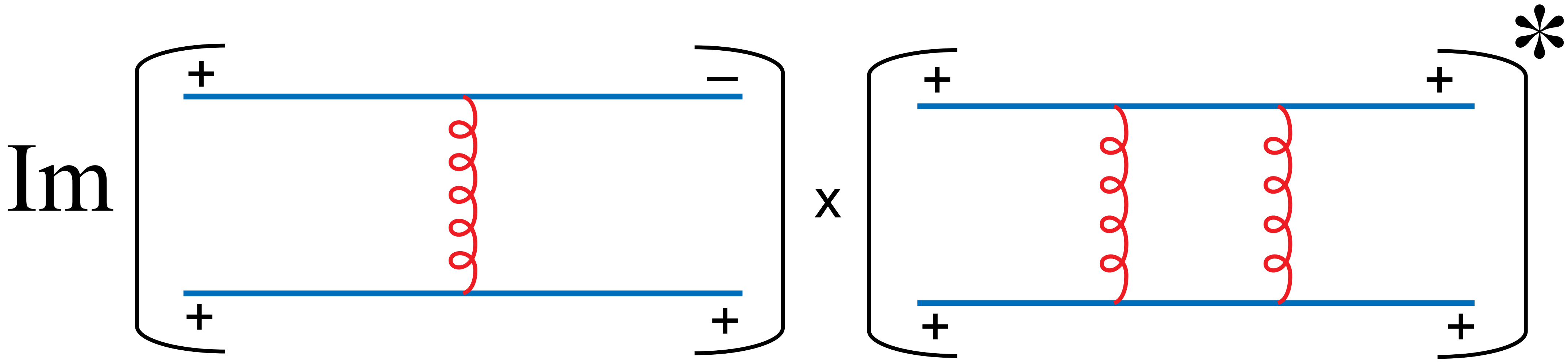
$$\left\{\begin{array}{l} H_{++;++} \equiv \Phi_1 \\ H_{--;++} \equiv \Phi_2 \\ H_{+-;+-} \equiv \Phi_3 \\ H_{-+;+-} \equiv \Phi_4 \\ H_{-+;++} \equiv \Phi_5 \end{array}\right.$$

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. Example: $q\,q' \to q\,q'$

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



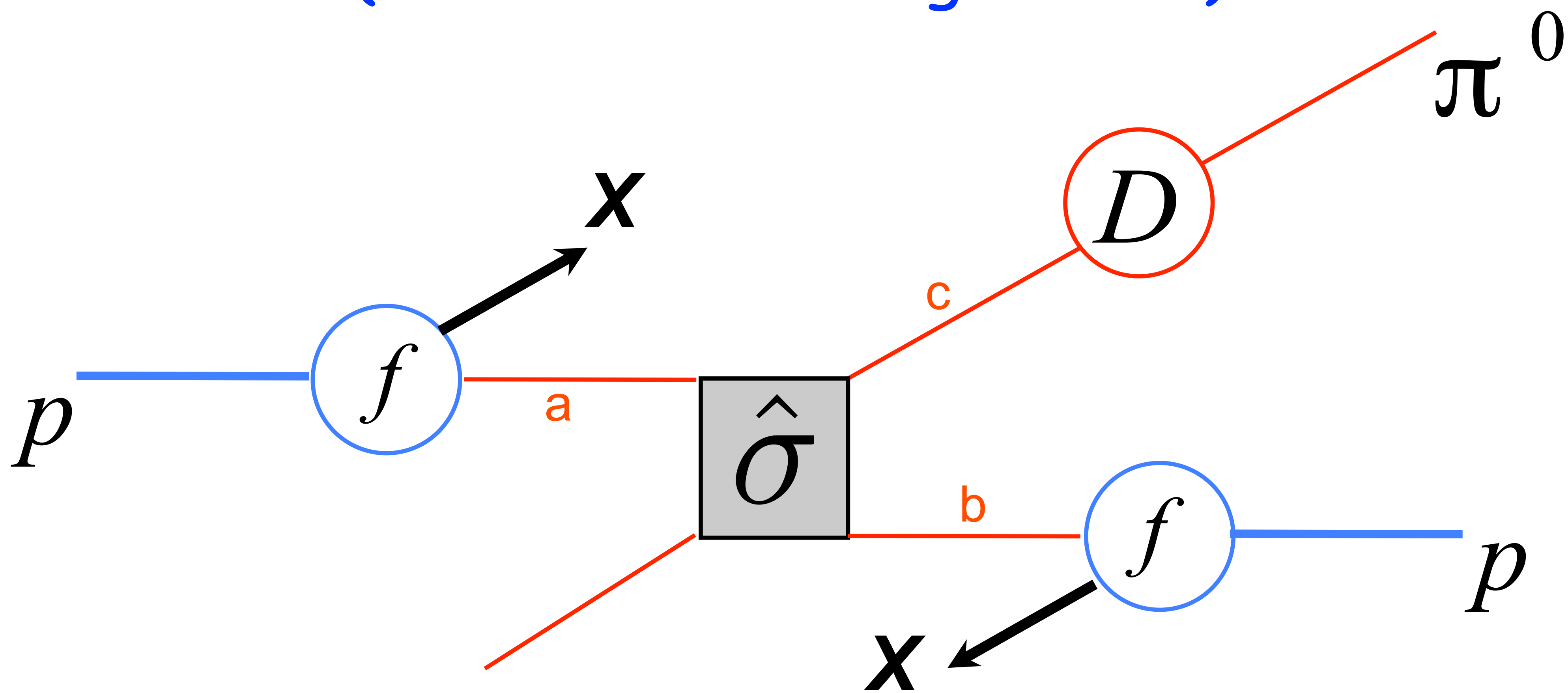
QED and QCD interactions conserve helicity, up to corrections $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

$\Rightarrow$ $A_N \propto \frac{m_q}{E_q}\,\alpha_s$ at quark level

but large SSA observed at hadron level!

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

based on factorization theorem
(in collinear configuration)

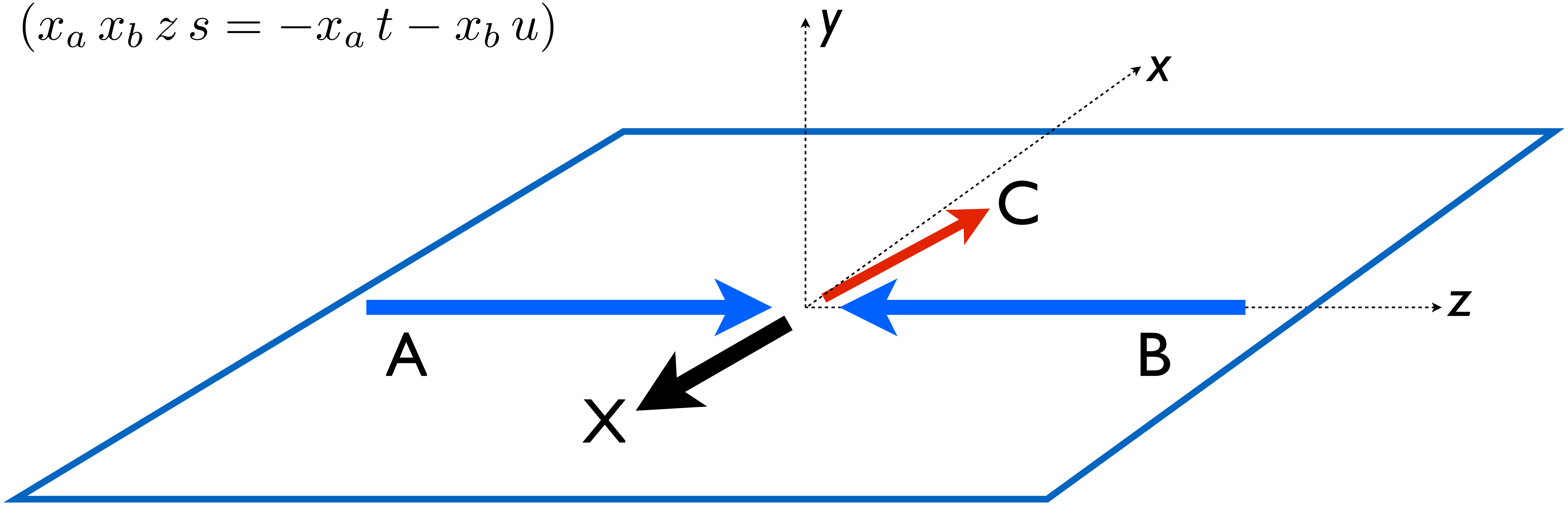


$$\mathrm{d}\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

pQCD elementary interactions

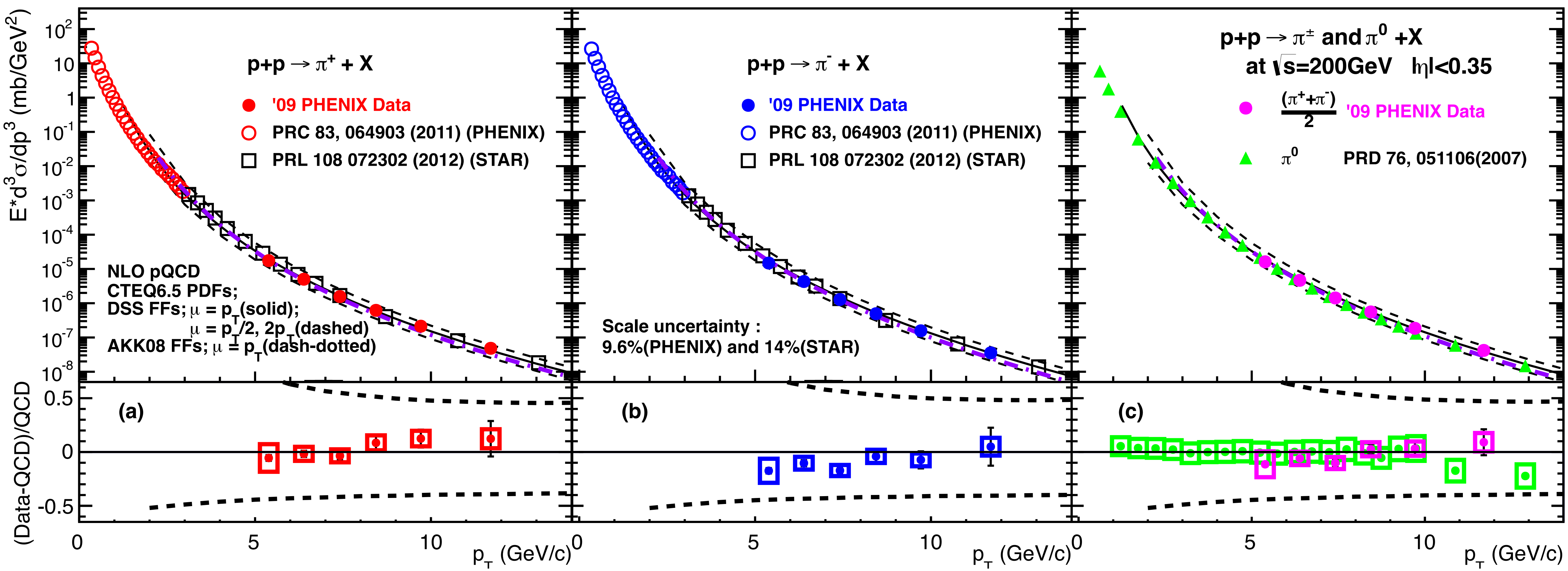
$$\begin{aligned}\frac{E_C\, d\sigma^{AB\to CX}}{d^3\boldsymbol{p}_C} &= \sum_{a,b,c,d}\int dx_a\, dx_b\, dz\, f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)\\ &\times \frac{\hat{s}}{\pi z^2}\,\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s},\hat{t},\hat{u},x_a,x_b)\,\delta(\hat{s}+\hat{t}+\hat{u})\,D_{C/c}(z,Q^2)\\ &= \sum_{a,b,c,d}\int dx_a\, dx_b\, f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)\\ &\times \frac{1}{\pi z}\,\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s},\hat{t},\hat{u},x_a,x_b)\,D_{C/c}(z,Q^2)\end{aligned}$$

$$(x_a\, x_b\, z\, s = -x_a\, t - x_b\, u)$$



mid-rapidity RHIC data, unpolarised cross sections

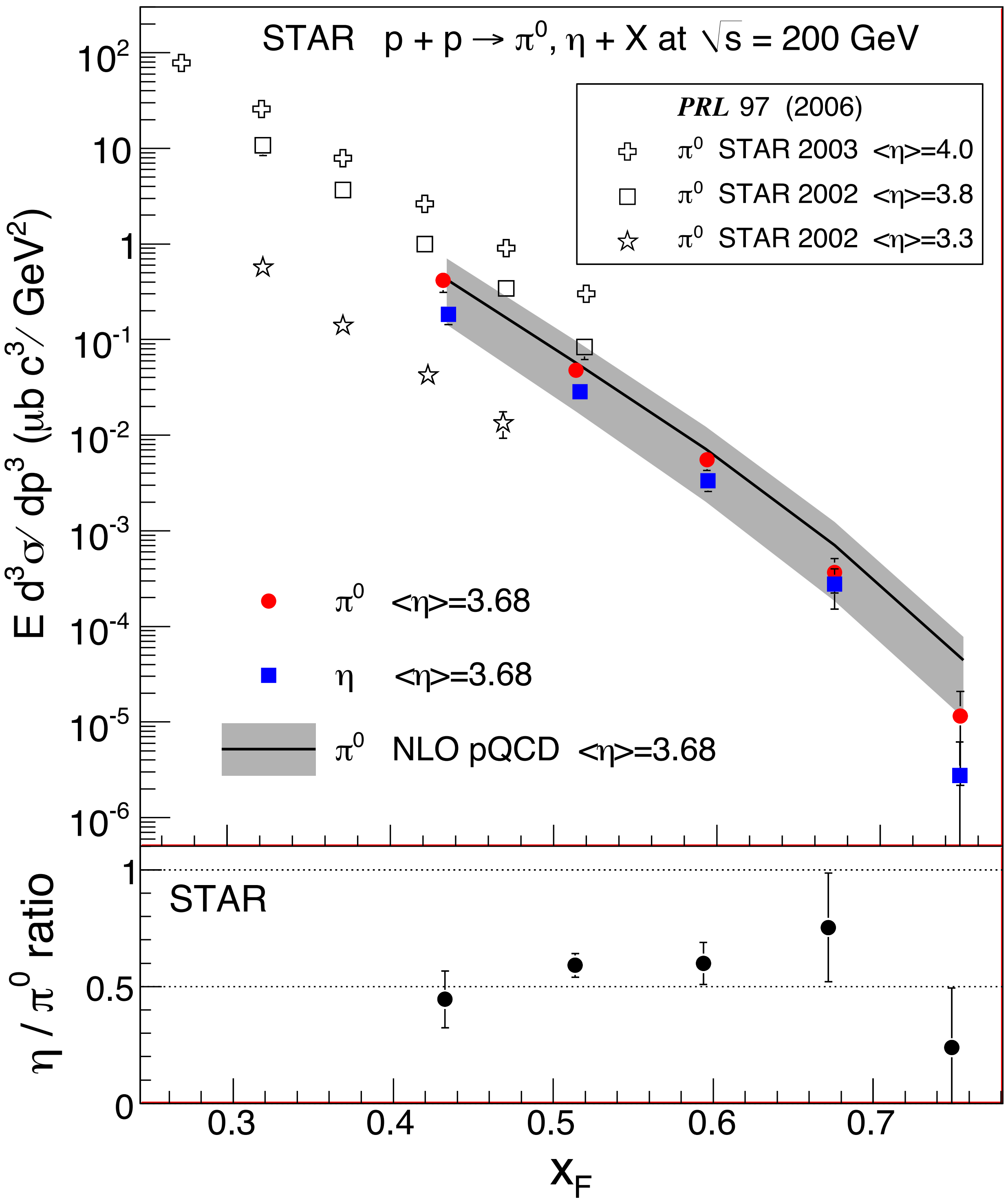
(arXiv:1409.1907 [hep-ex], Phys. Rev. D91 (2015) 3, 032001)



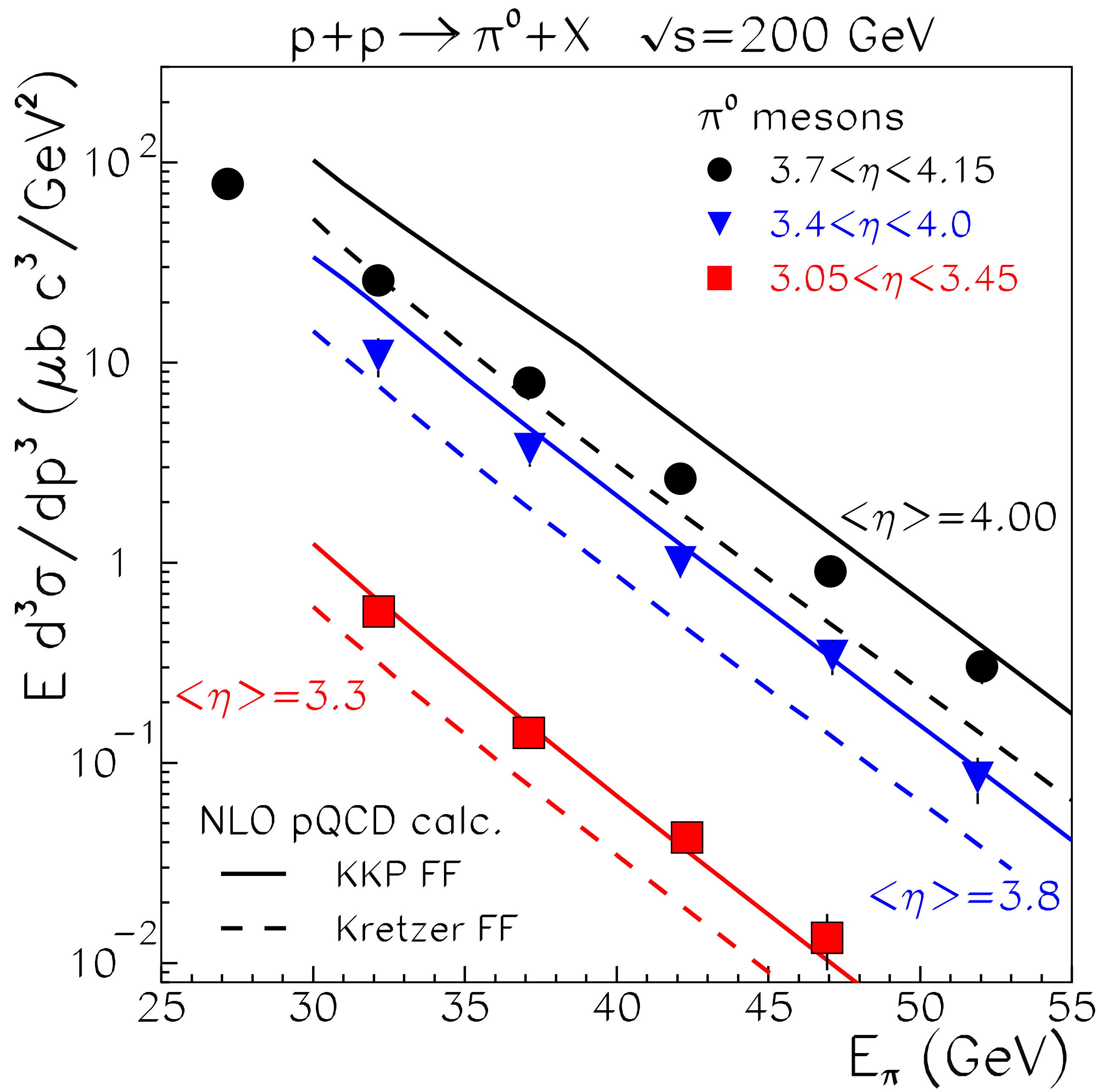
good agreement between RHIC data and collinear pQCD calculations

good agreement also at large rapidity

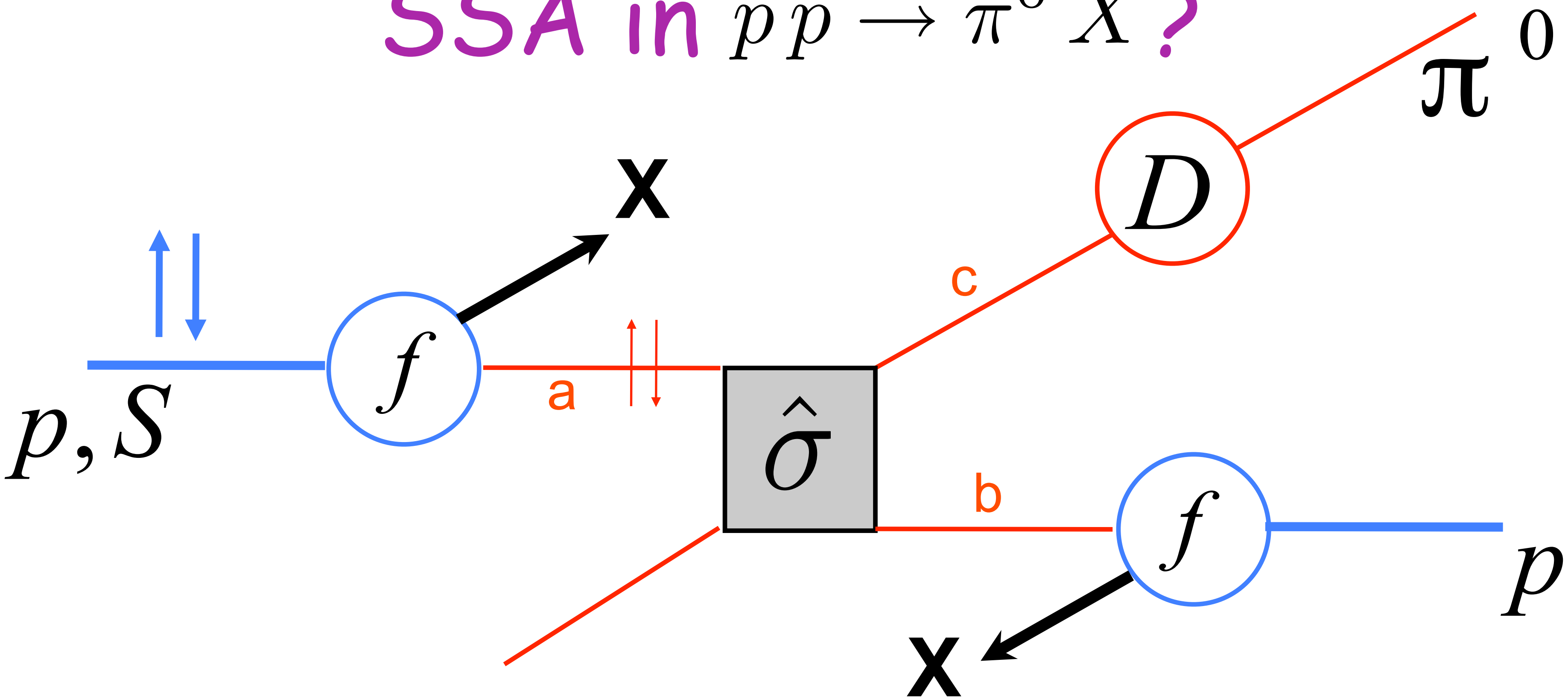
Phys. Rev. D86 (2012) 051101



Phys. Rev. Lett. 97 (2006) 152302



SSA in $pp \to \pi^0 X$?



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

transversity

pQCD elementary SSA

FF

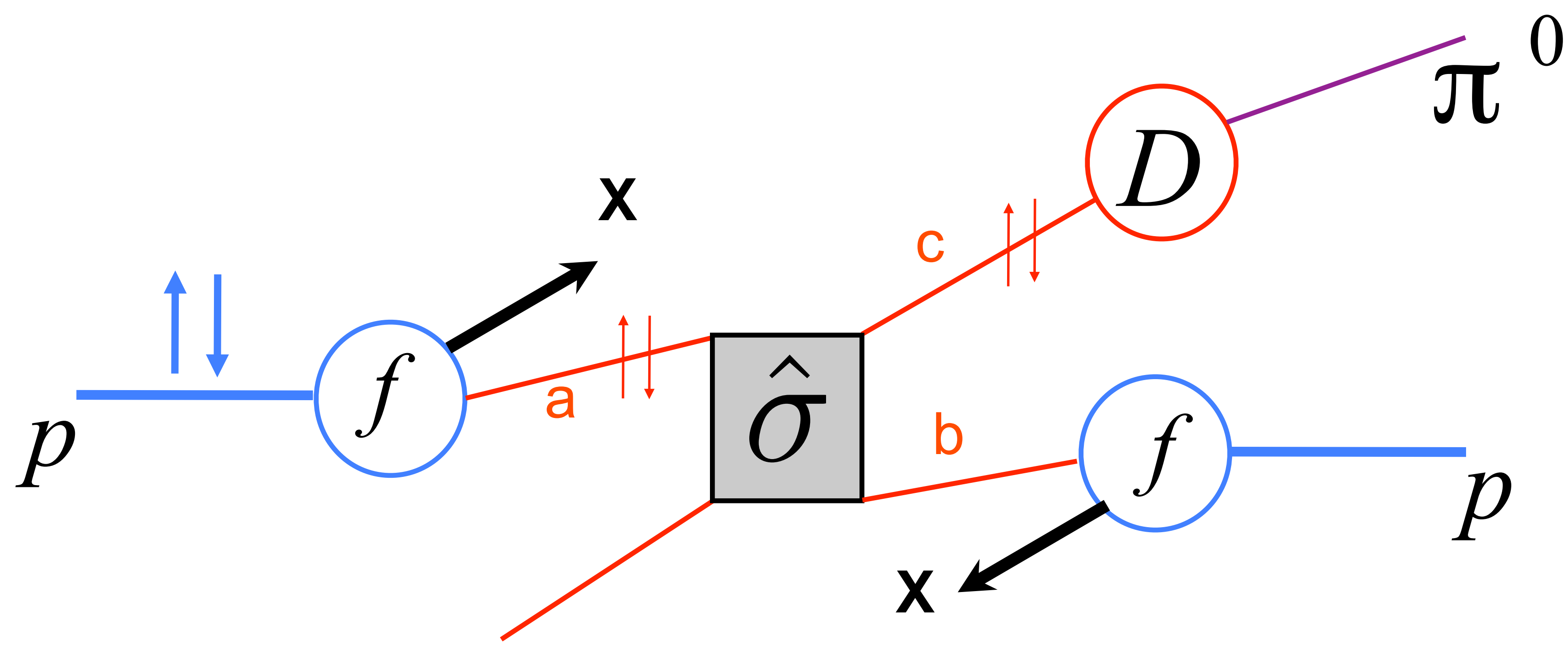
$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \hat{a}_N \propto \frac{m_q}{E_q}\,\alpha_s$$

was considered almost a theorem

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

Two main different (?) approaches

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



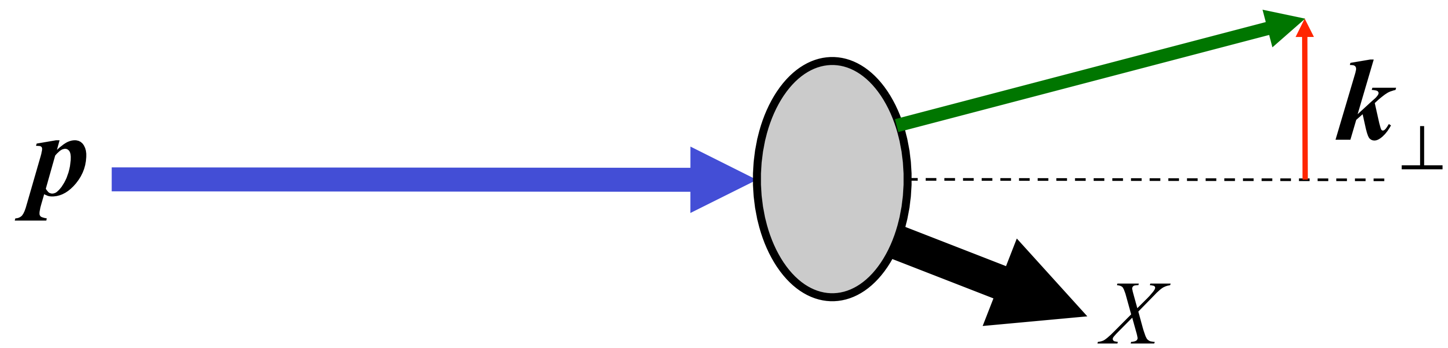
$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma}^{ab \to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes D_{\pi/c}(z, \boldsymbol{p}_{\perp \pi})$$

non perturbative single spin effects in TMDs

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

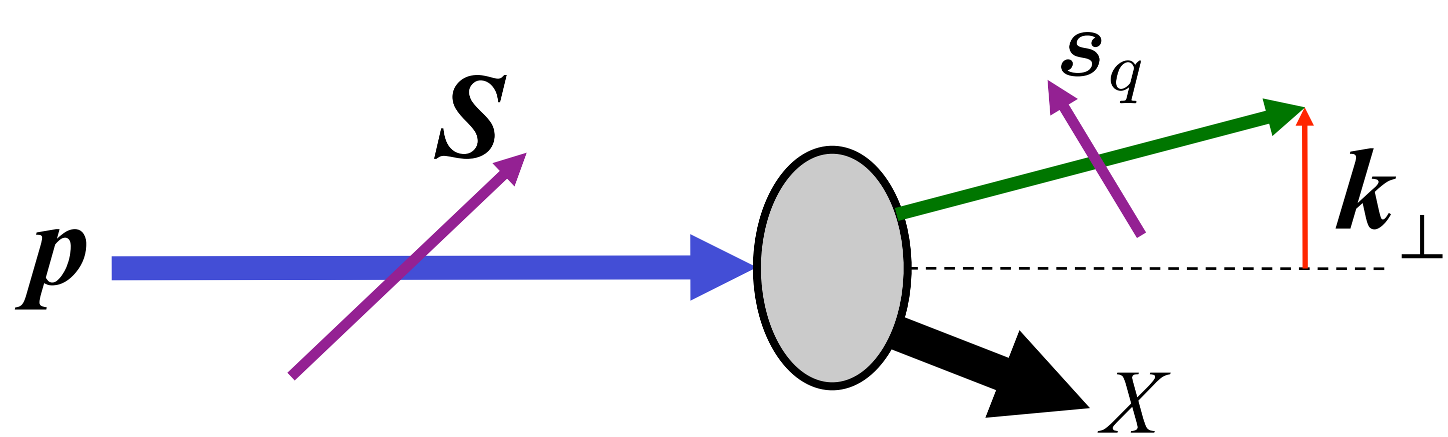
Field-Feynman

TMD - PDFs



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

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

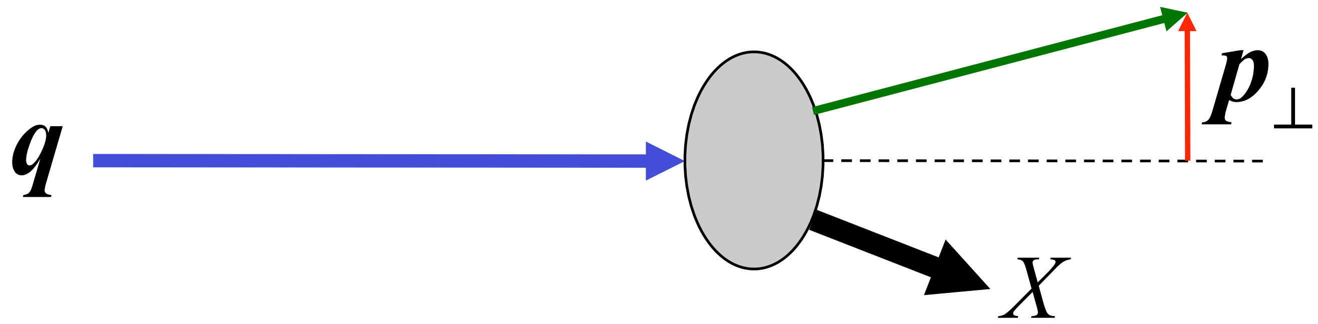


$$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp) \qquad \boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp) \qquad \boldsymbol{S} \cdot \boldsymbol{s}_q \qquad \cdots$$

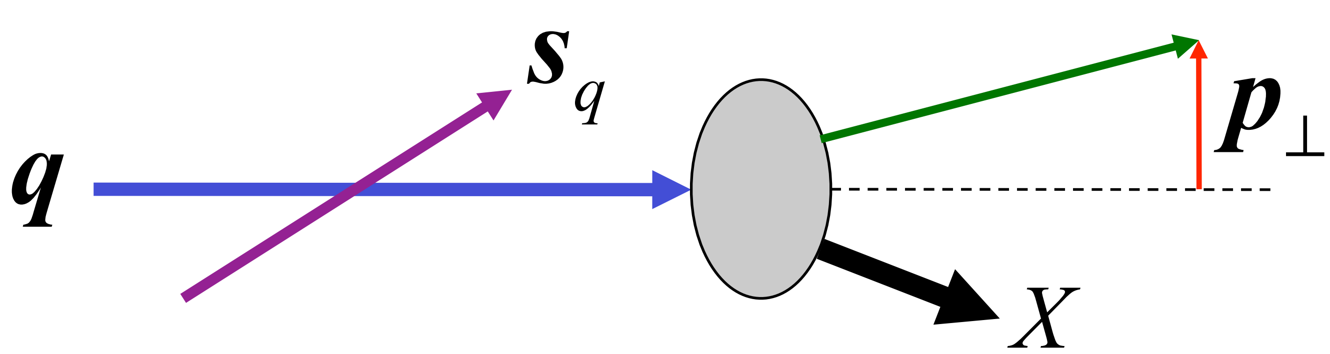
"Sivers effect" "Boer-Mulders effect"

TMD - FFs

similar spin-$\mathbf{p}_\perp$ correlations in fragmentation process
(case of final spinless hadron)



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



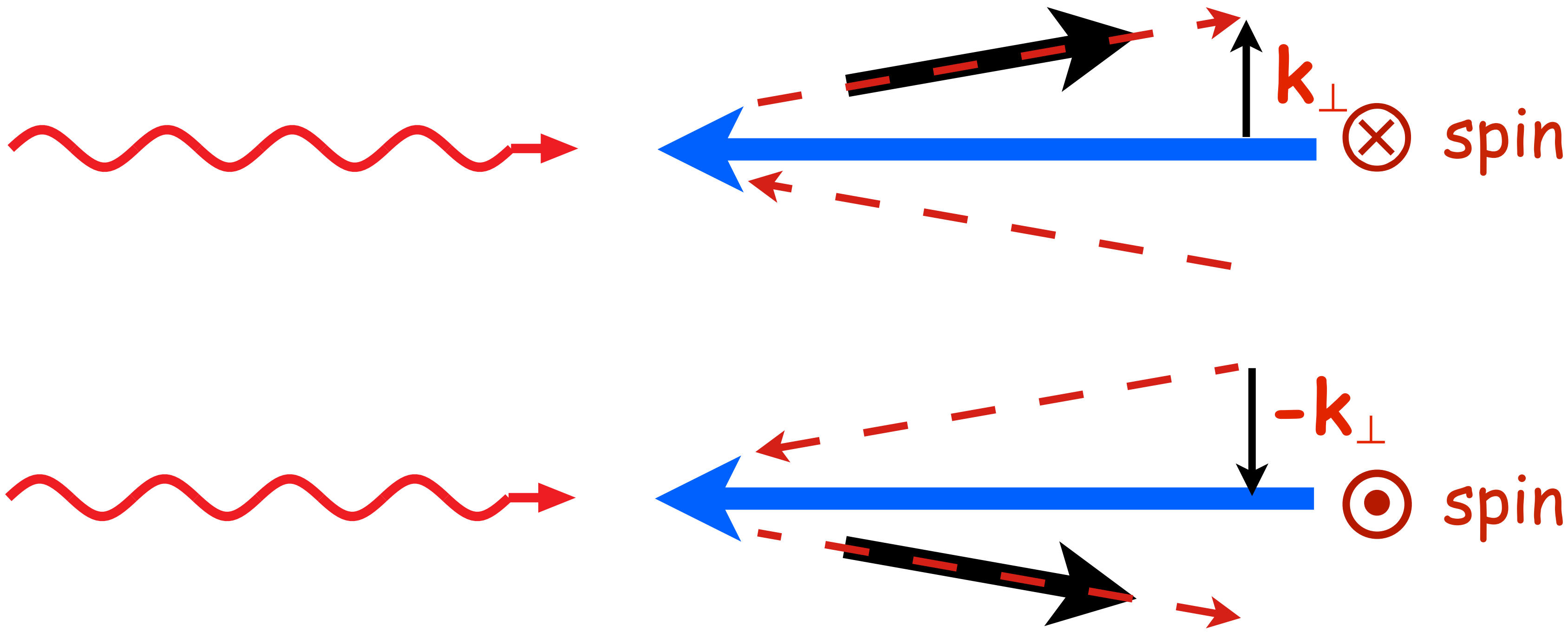
$$H_1^{\perp q}(x, \boldsymbol{p}_\perp^2)$$

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

"Collins effect"

$$\begin{aligned} D_{h/q,\boldsymbol{s}_q}(z, \boldsymbol{p}_\perp) &= D_{h/q}(z, p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z, p_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp) \\ &= D_1^q(z, p_\perp) + \frac{p_\perp}{z M_h} H_1^{\perp q}(z, p_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{p}}_\perp) \end{aligned}$$

simple physical picture for the Sivers effect



$P_T \sim k_\perp$

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

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

Phenomenology - TMD factorization

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

main contribution from Sivers and Collins effects

$$d\sigma^\uparrow - d\sigma^\downarrow \equiv \frac{E_\pi\, d\sigma^{\,p^\uparrow \to \pi\, X}}{d^3\boldsymbol{p}_\pi} - \frac{E_\pi\, d\sigma^{\,p^\downarrow \to \pi\, X}}{d^3\boldsymbol{p}_\pi} = [d\sigma^\uparrow - d\sigma^\downarrow]_{\rm Sivers} + [d\sigma^\uparrow - d\sigma^\downarrow]_{\rm Collins}$$

$$\begin{aligned}[d\sigma^\uparrow - d\sigma^\downarrow]_{\rm Sivers} = & \sum_{q_a,b,q_c,d} \int \frac{dx_a\, dx_b\, dz}{16\,\pi^2\, x_a\, x_b\, z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u}) \\ & \times \Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}) \cos\phi_a \\ & \times f_{b/p}(x_b, k_{\perp b})\, \frac{1}{2}\left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 + |\hat{M}_3^0|^2\right]_{ab\to cd} D_{\pi/c}(z, p_\perp)\end{aligned}$$

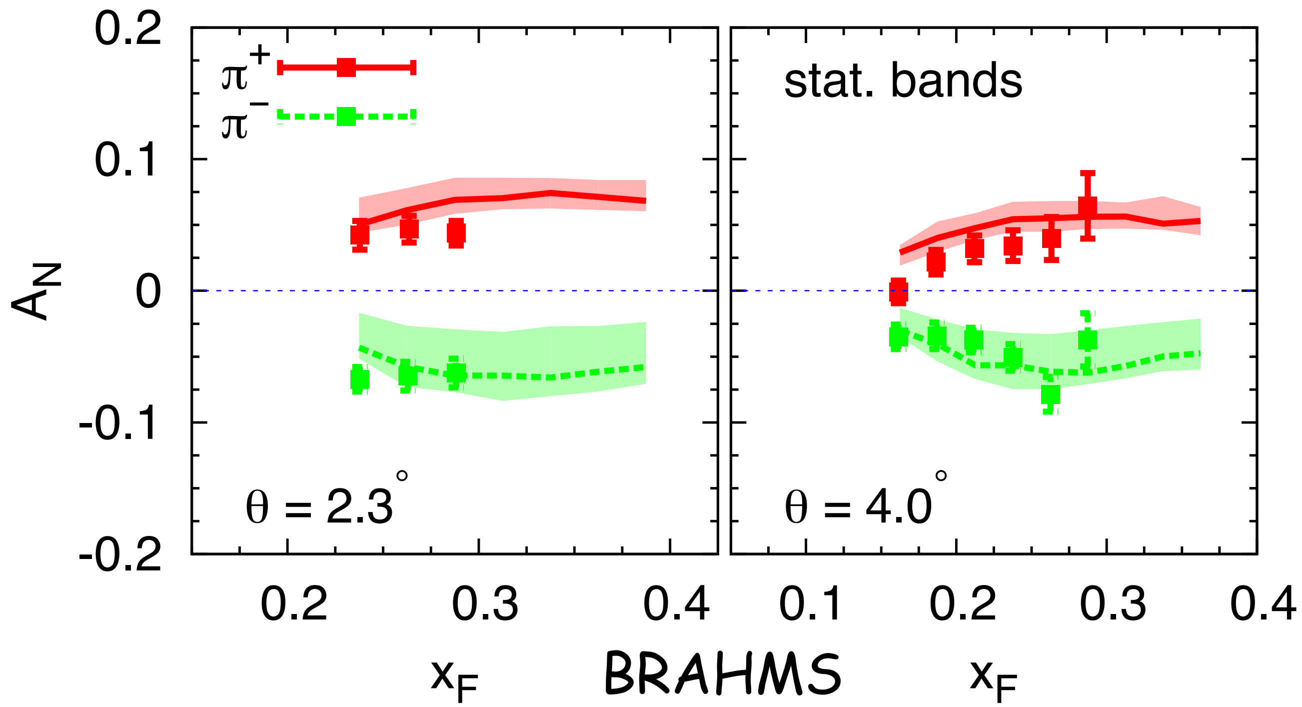
$\longrightarrow$ Sivers phase

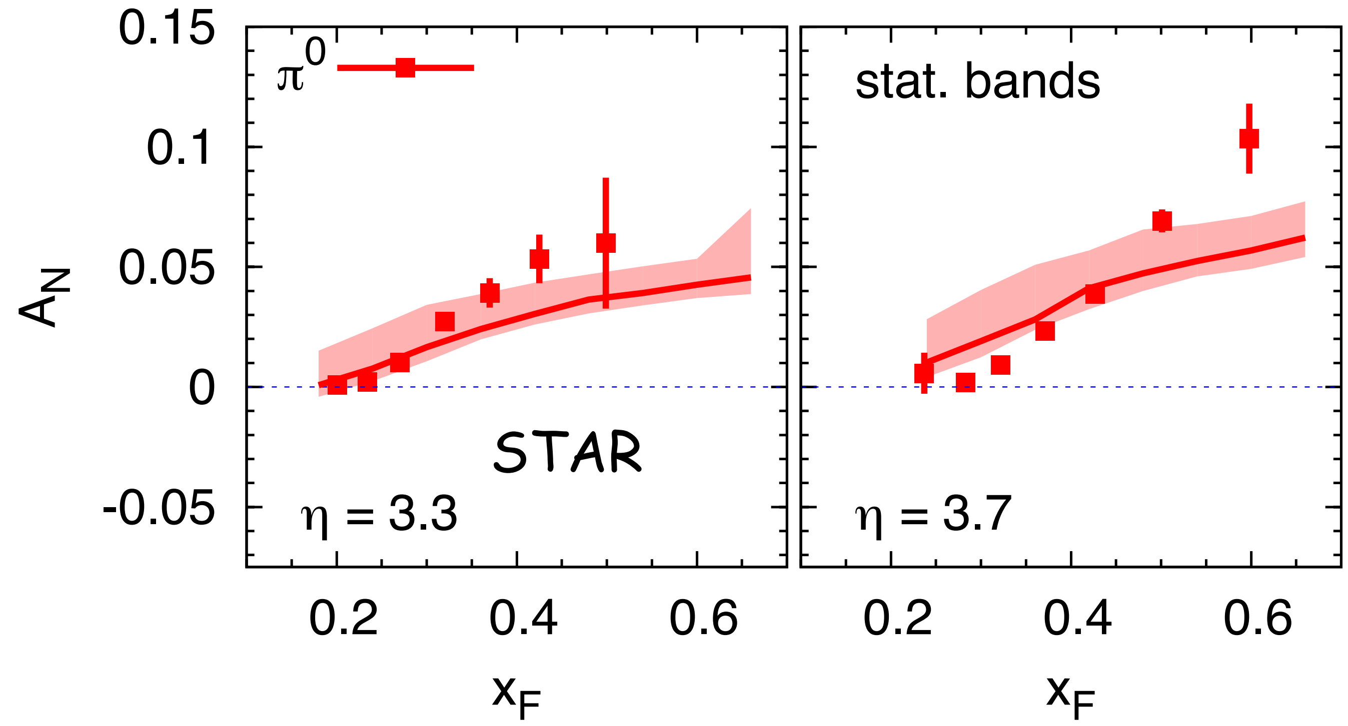
$$\begin{aligned}[d\sigma^\uparrow - d\sigma^\downarrow]_{\rm Collins} = & \sum_{q_a,b,q_c,d} \int \frac{dx_a\, dx_b\, dz}{16\,\pi^2\, x_a\, x_b\, z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u}) \\ & \times \Delta_T q_a(x_a, k_{\perp a}) \cos(\phi_a + \varphi_1 - \varphi_2 + \phi_\pi^H) \\ & \times f_{b/p}(x_b, k_{\perp b}) \left[\hat{M}_1^0\, \hat{M}_2^0\right]_{q_a b\to q_c d} \Delta^N D_{\pi/q_c^\uparrow}(z, p_\perp)\end{aligned}$$

$\longrightarrow$ Collins + scattering phases

negligible contributions from other TMDs

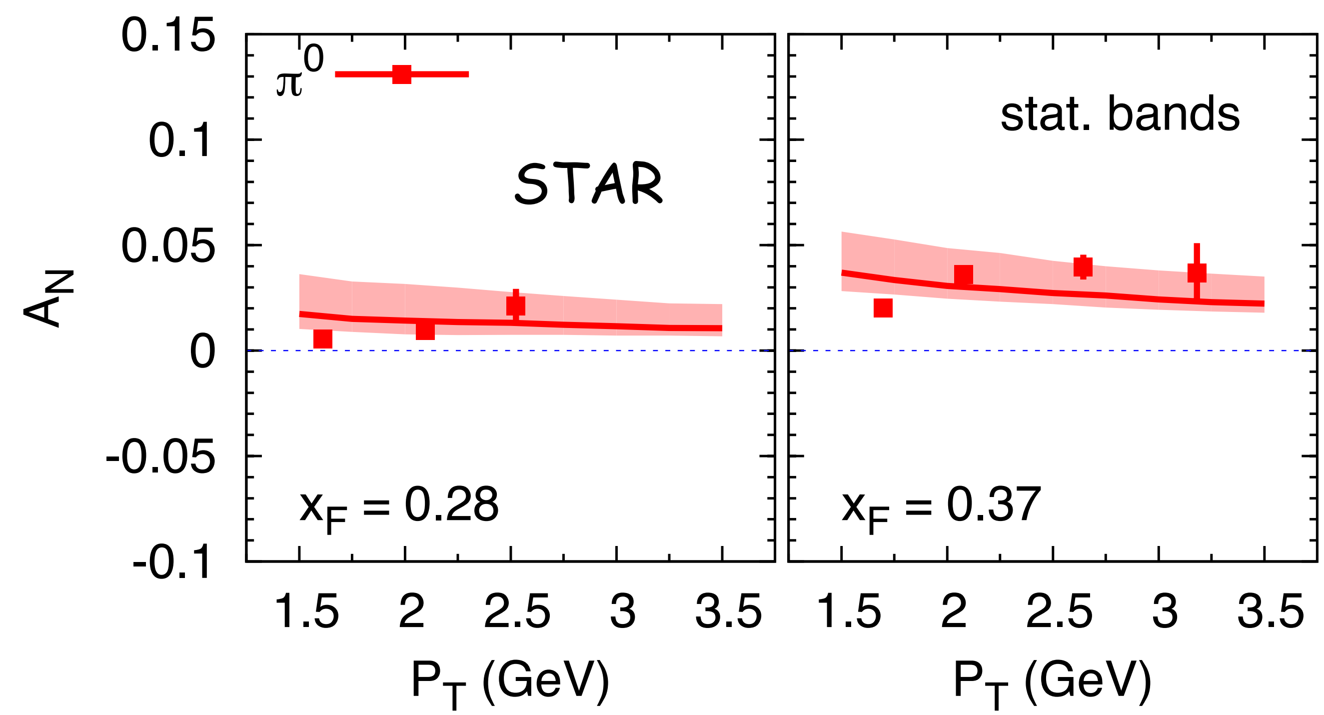
M. A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia , A. Prokudin,
Phys. Rev. D88 (2013) 054023





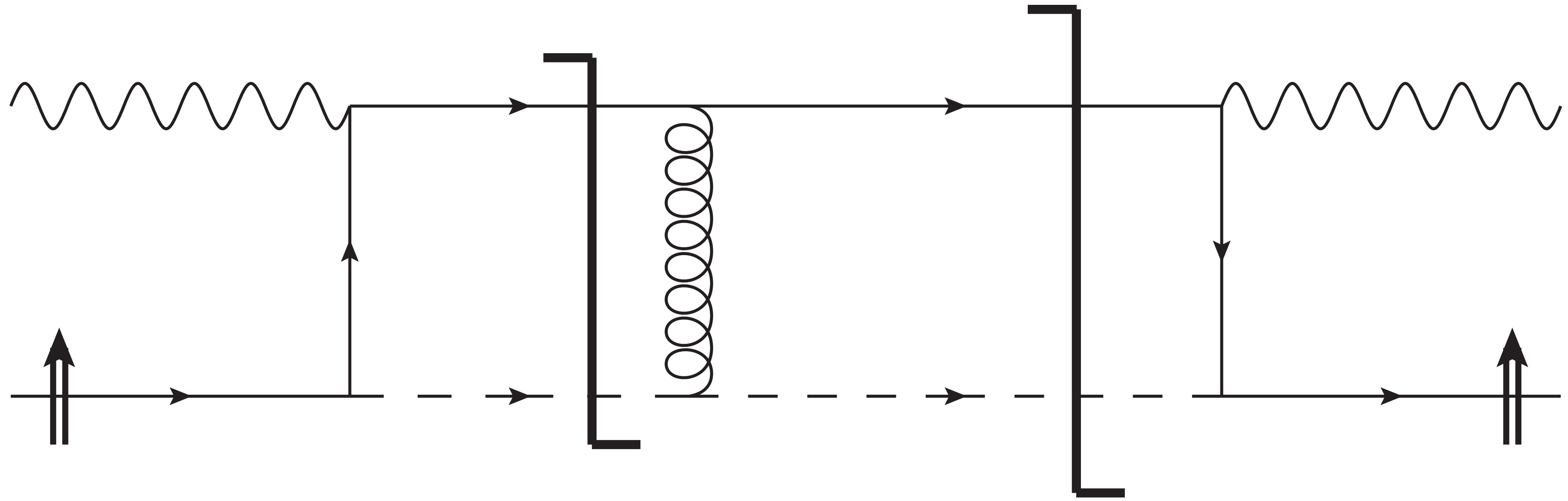
A_N, as obtained in the GPM scheme with the SIDIS extracted Sivers functions, compared with some RHIC data.

The SIDIS data leave great uncertainty in the large x values of the Sivers functions.

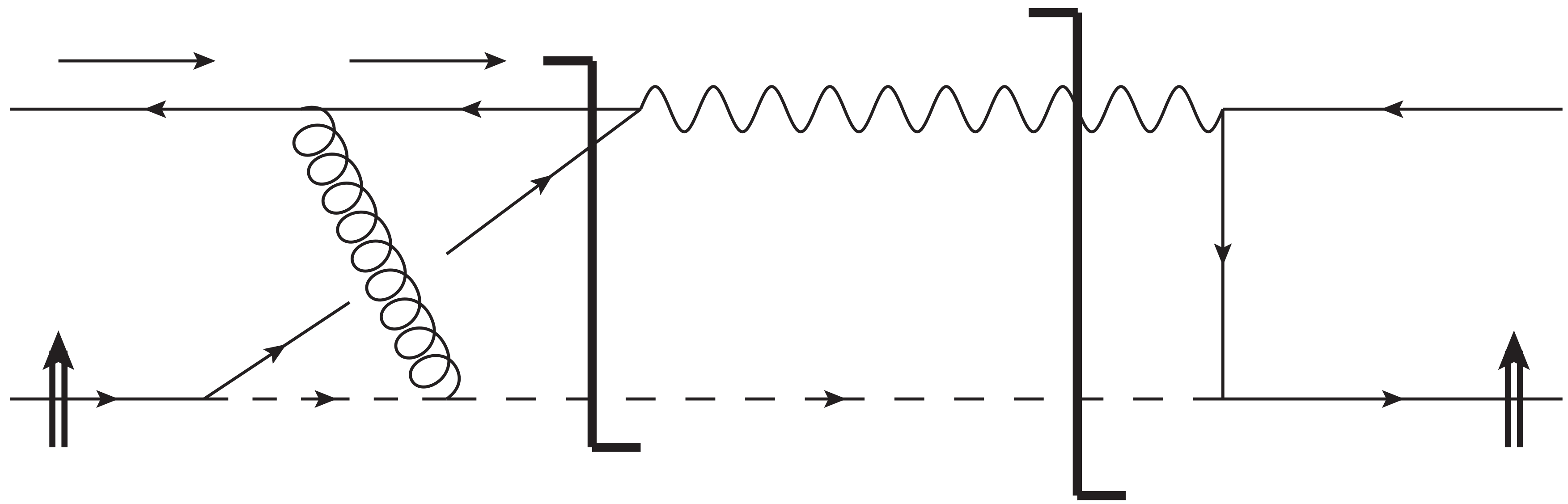


examples of non vanishing Sivers function - simple quark-scalar diquark model of the proton

SIDIS final state interactions ($\Rightarrow A_N$)



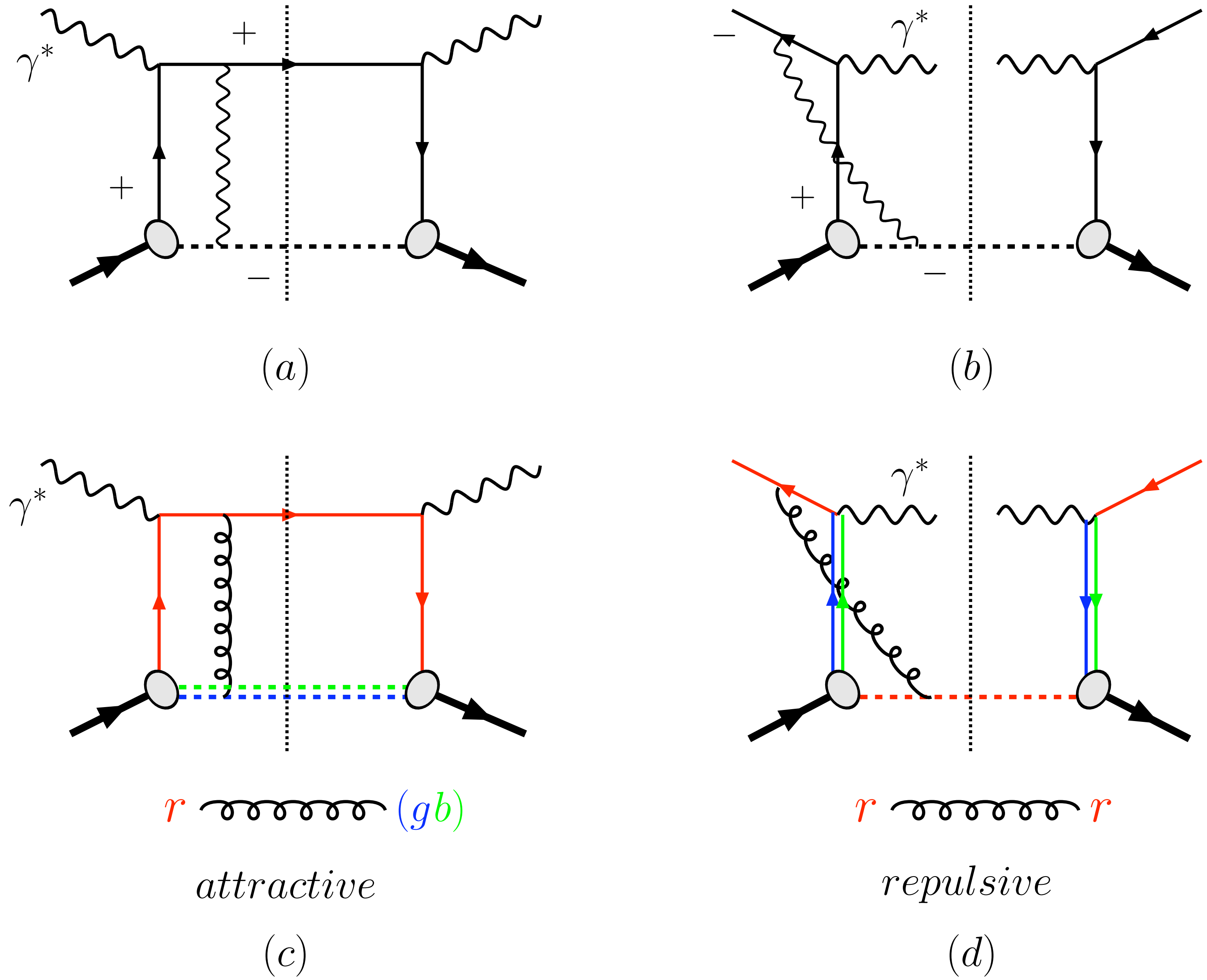
D-Y initial state interactions ($\Rightarrow -A_N$)



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

2. Higher-twist partonic correlations (ETQS)

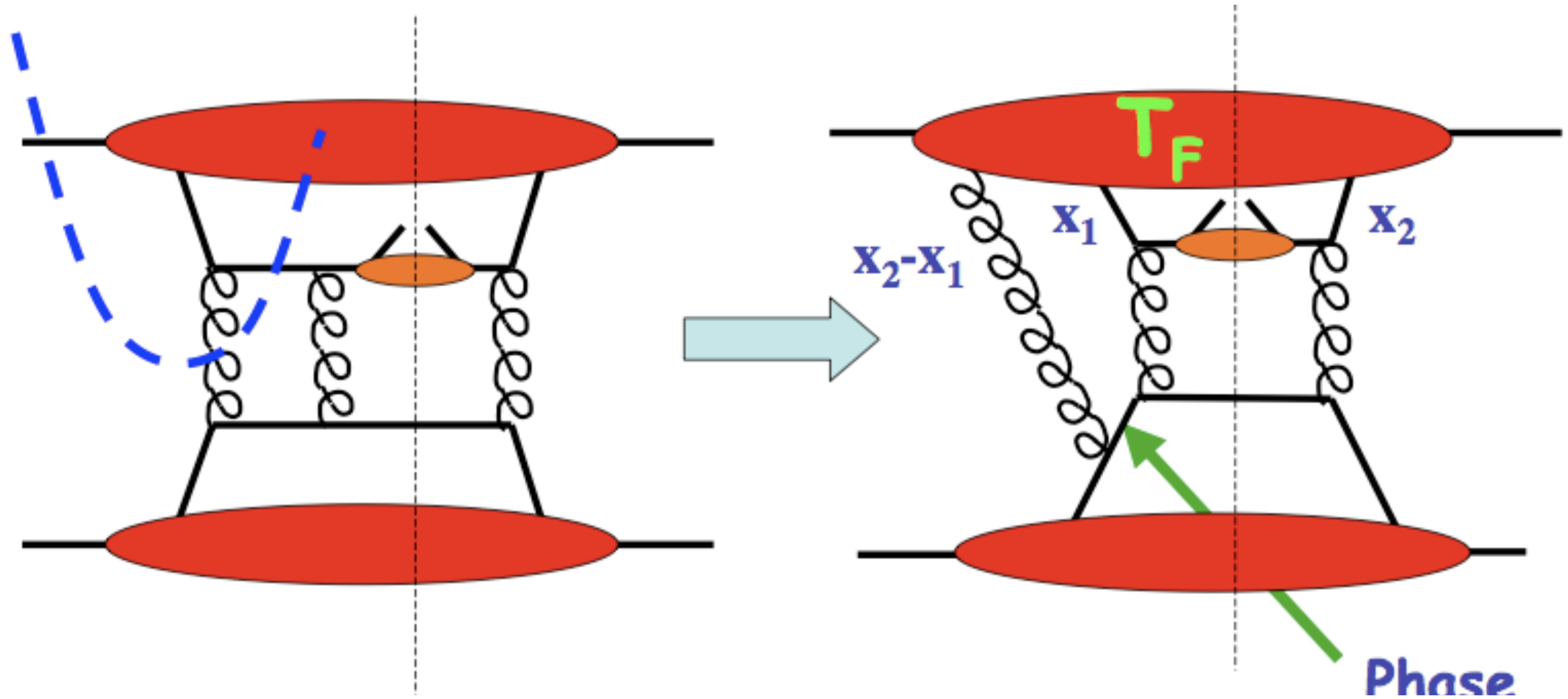
(Efremov, Teryaev, Ratcliffe; Qiu, Sterman; Kouvaris, Vogelsang, Yuan; Bacchetta, Bomhof, Mulders, Pijlman; Koike; Gamberg, Kang...)

higher-twist partonic correlations - factorization OK

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

twist-3 correlators

product of hard amplitudes, not cross sections



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

Phenomenology - higher-twist, ETQS functions

Kouvaris, Qiu, Vogelsang, Yuan, PRD 74 (2006) 114013
Kang, Qiu, Vogelsang, Yuan, PRD83 (2011) 094001

$$E_h \frac{d\Delta\sigma(s_\perp)}{d^3 P_h} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{b/B}(x') \int \frac{dx}{x} \sqrt{4\pi\alpha_s} \left(\frac{\epsilon^{P_{h\perp} s_\perp n \bar{n}}}{z\hat{u}} \right)$$
$$\times \left[T_{a,F}(x,x) - x\frac{d}{dx} T_{a,F}(x,x) \right] H_{ab\to c}(\hat{s},\hat{t},\hat{u}) \delta\left(\hat{s}+\hat{t}+\hat{u}\right),$$

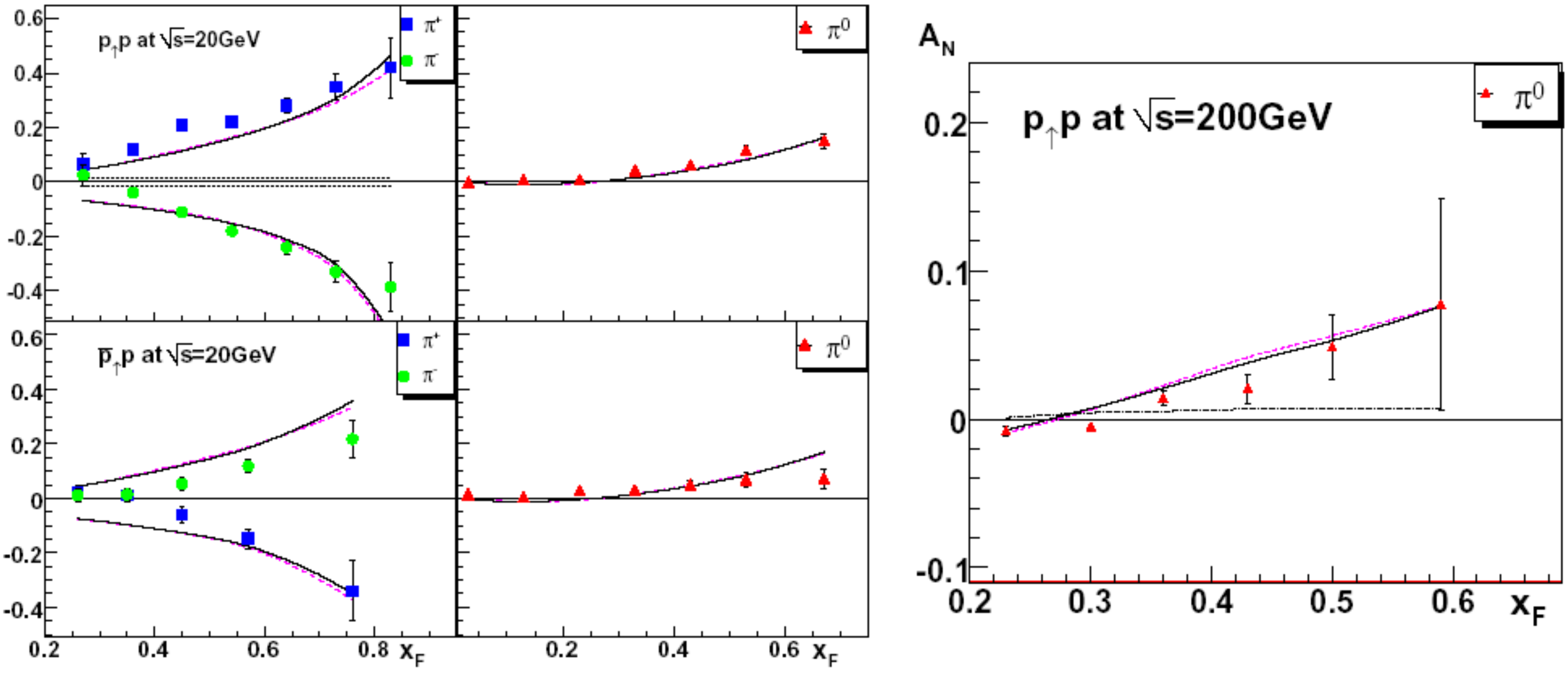
$$H_{ab\to c}(\hat{s},\hat{t},\hat{u}) = H^I_{ab\to c}(\hat{s},\hat{t},\hat{u}) + H^F_{ab\to c}(\hat{s},\hat{t},\hat{u}) \left(1 + \frac{\hat{u}}{\hat{t}}\right)$$

products of hard scattering amplitudes

$qg \to qg$ is the dominant partonic channel

$$H^I_{qg\to qg} = \frac{1}{2(N_c^2-1)} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} \right] \left[1 - N_c^2 \frac{\hat{u}^2}{\hat{t}^2} \right] \xrightarrow{|\hat{t}| \ll \hat{s} \sim |\hat{u}|} \left[-\frac{N_c^2}{2(N_c^2-1)} \right] \left[\frac{2\hat{s}^2}{\hat{t}^2} \right],$$
$$H^F_{qg\to qg} = \frac{1}{2N_c^2(N_c^2-1)} \left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}} \right] \left[1 + 2N_c^2 \frac{\hat{s}\hat{u}}{\hat{t}^2} \right] \xrightarrow{|\hat{t}| \ll \hat{s} \sim |\hat{u}|} \left[-\frac{1}{N_c^2-1} \right] \left[\frac{2\hat{s}^2}{\hat{t}^2} \right]$$

both contributions are negative



fits of E704 and STAR data

Kouvaris, Qiu, Vogelsang, Yuan

sign mismatch

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

compare

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

as extracted from fitting A_N data, with that obtained by inserting in the above relation the SIDIS extracted Sivers functions

similar magnitude, but opposite sign!

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

other higher-twist contributions to A_N

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

(1) Twist-3 contribution related to Sivers function

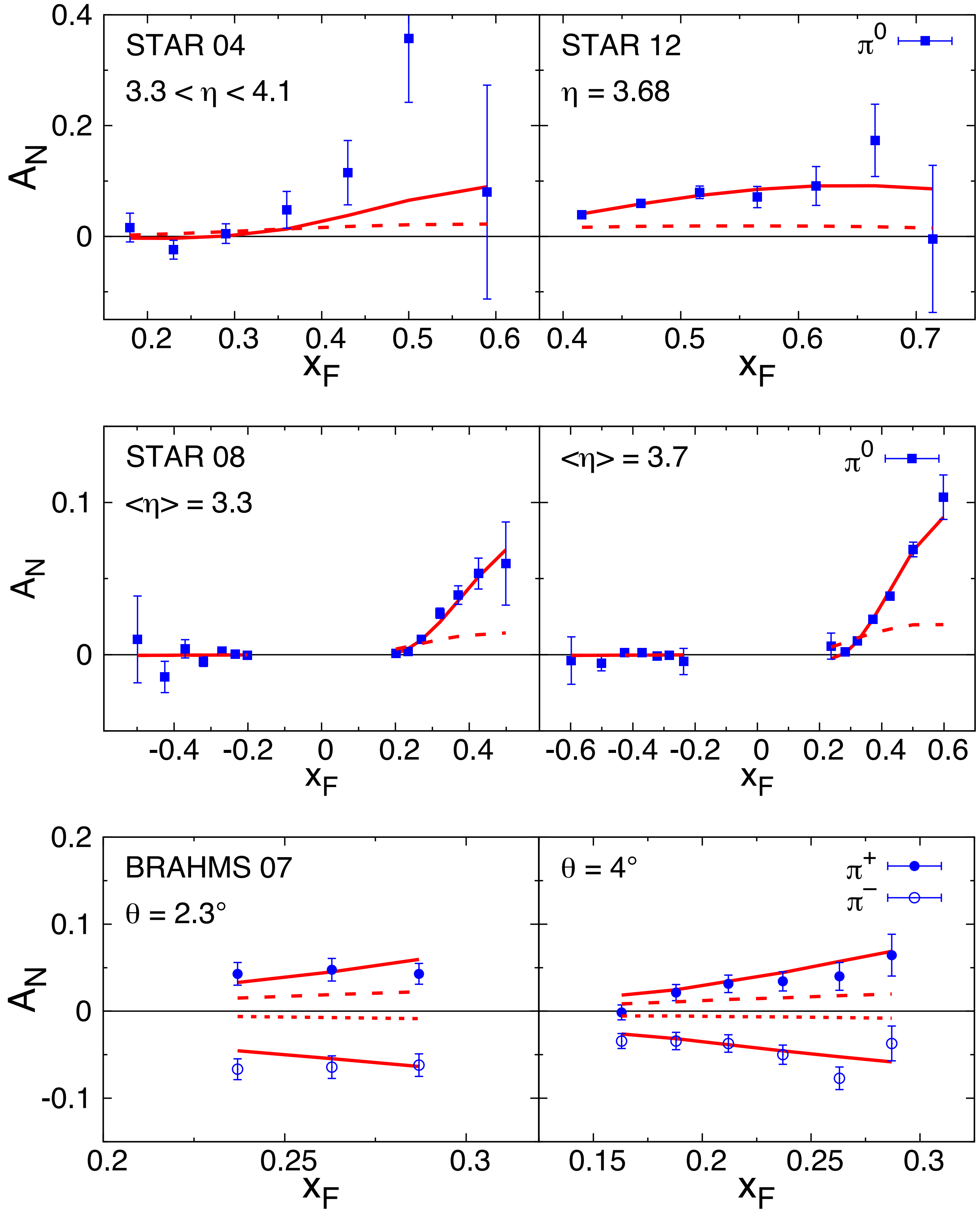
(2) Twist-3 contribution related to Boer-Mulders function

(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 gives a wrong sign ....

A_N from twist-3 fragmentation functions

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

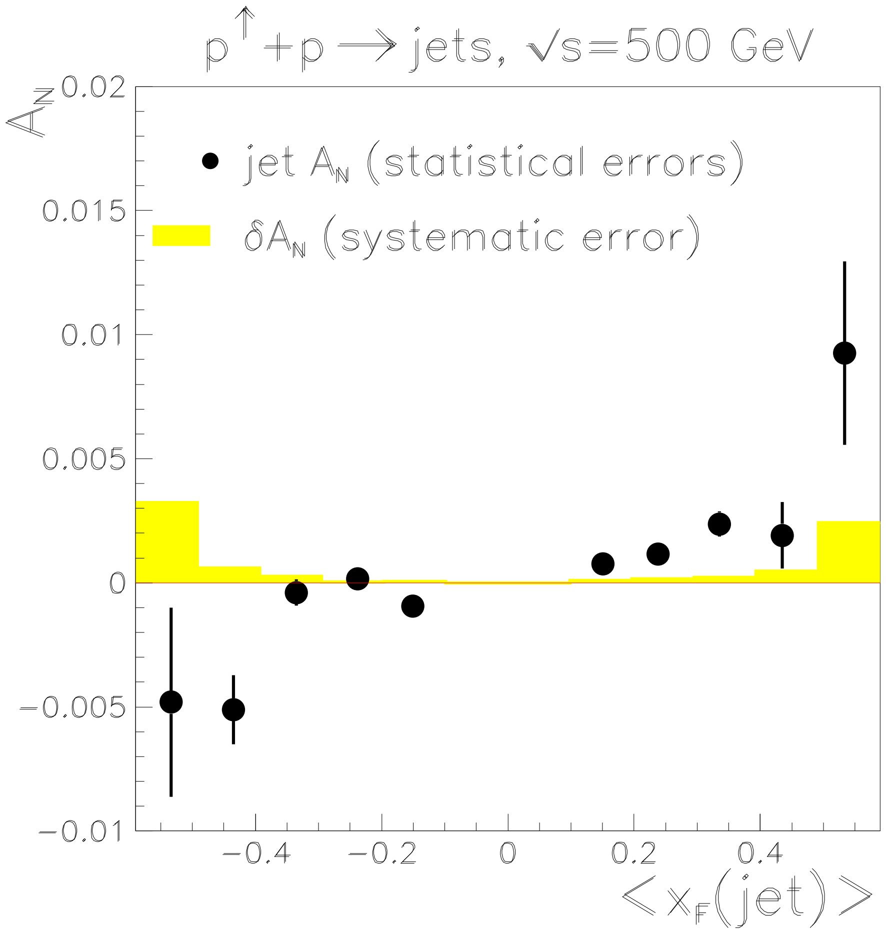


good fit of A_N mainly due to the new twist-3 fragmentation function

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

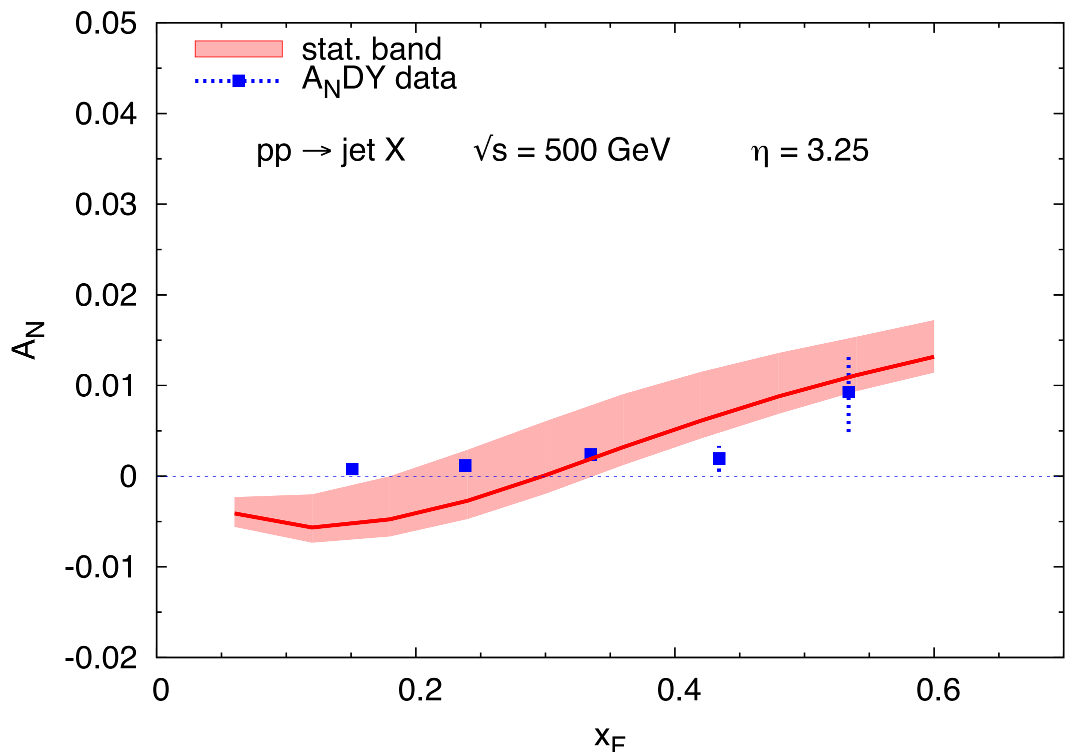
Gamberg, Khang, Metz, Pitonyak, PRD 90 (2014) 074012

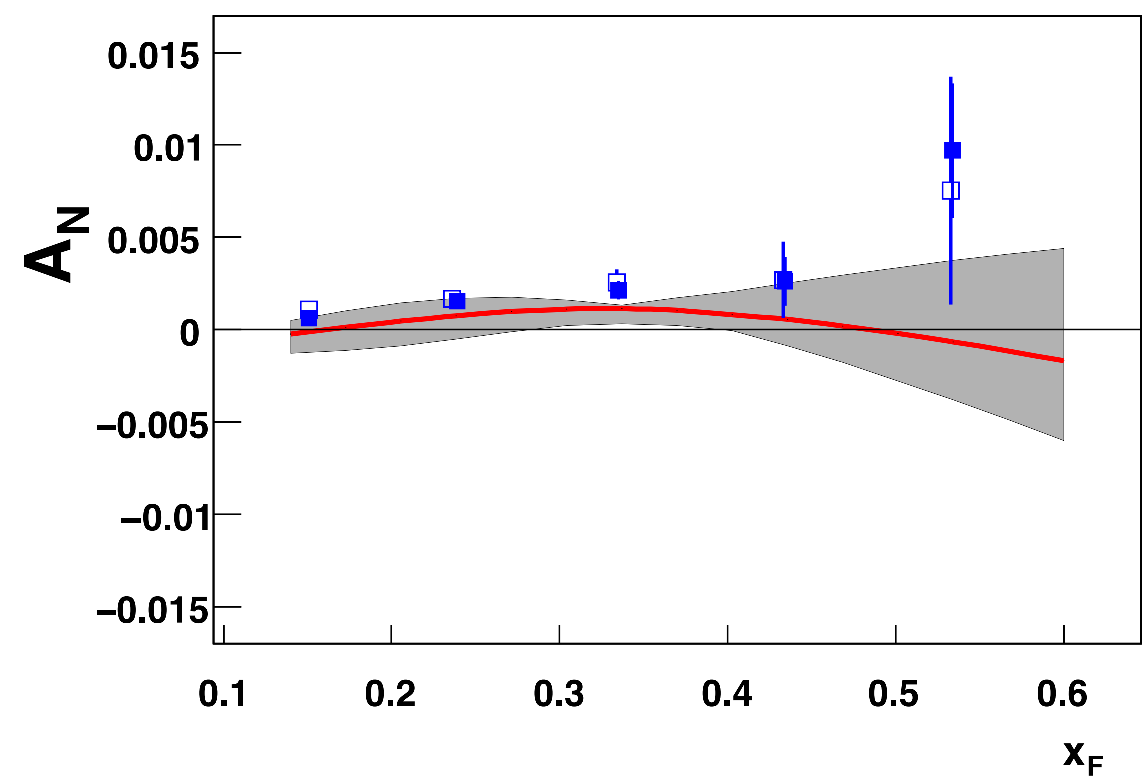
A_N for jet production at A_NDY
Phys. Lett. B750 (2015) 660



lower left plot: A_N assuming TMD factorization, PRD 88 (2013) 054023

lower right plot: A_N with twist-3 correlation function, Gamberg, Kang, Prokudin, PRL 110 (2013) 232301

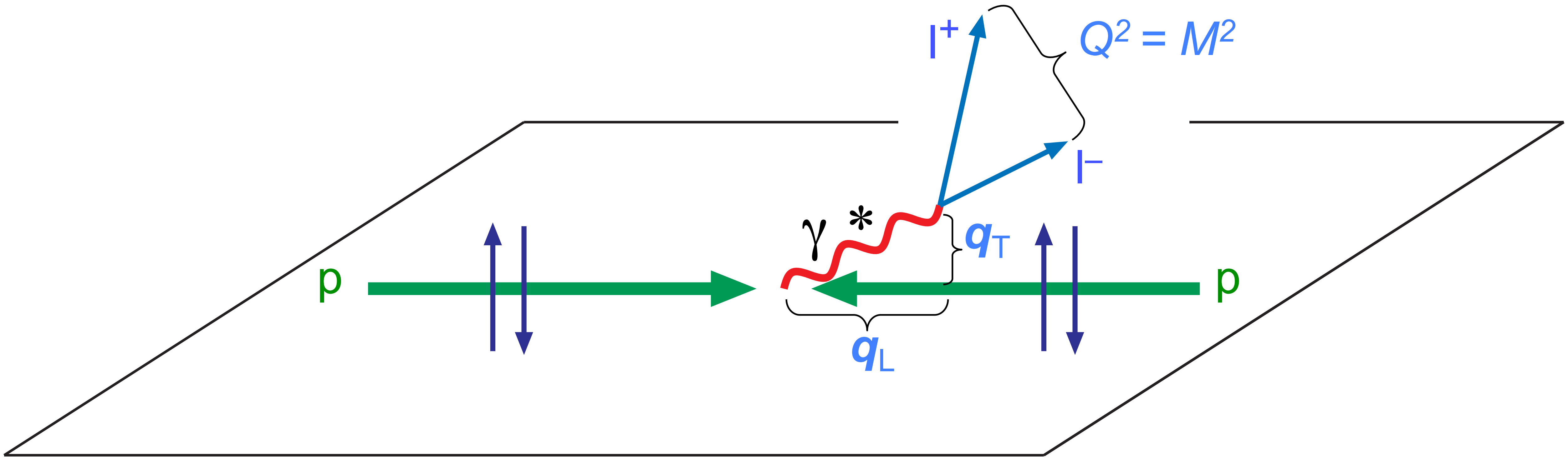




measuring A_N for prompt photon production might help

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

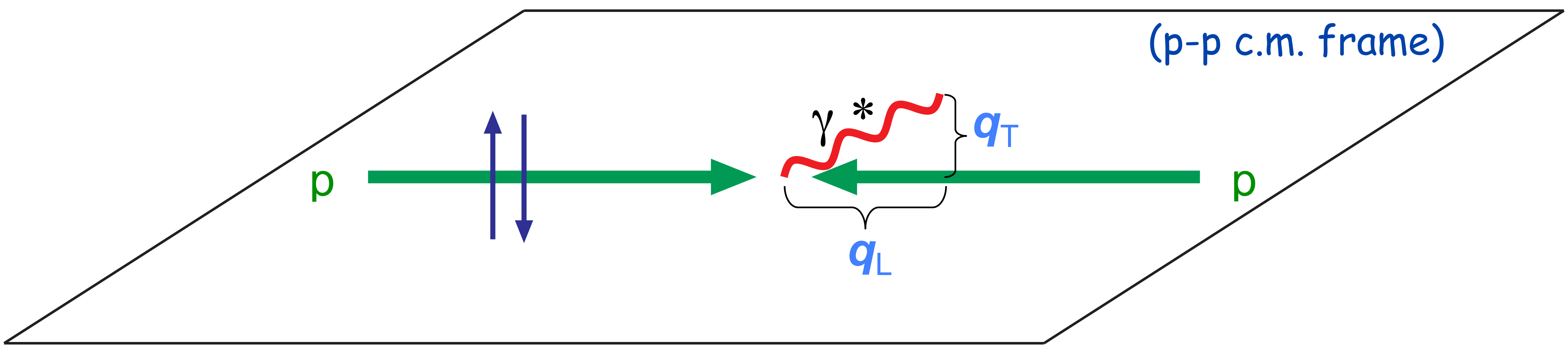
Sivers effect in D-Y processes

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

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

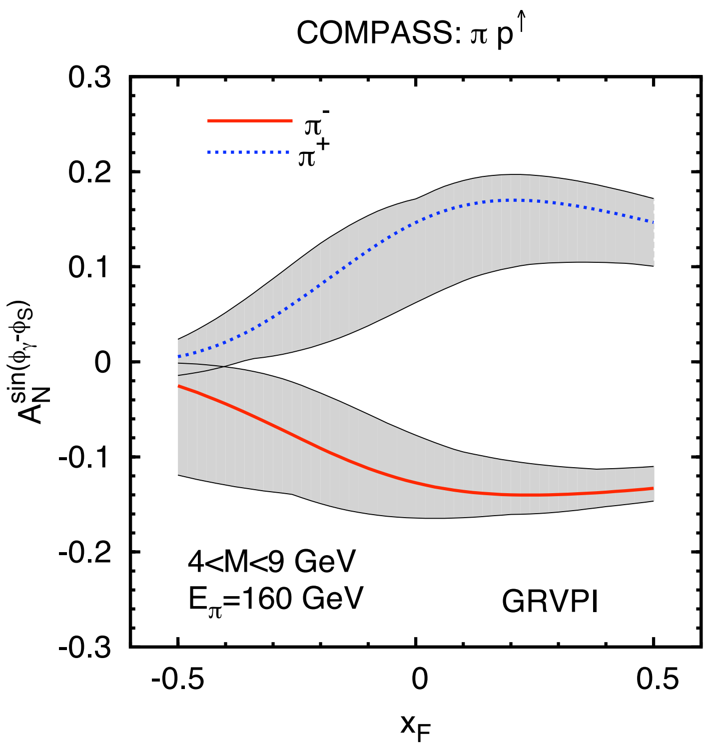
$$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$$

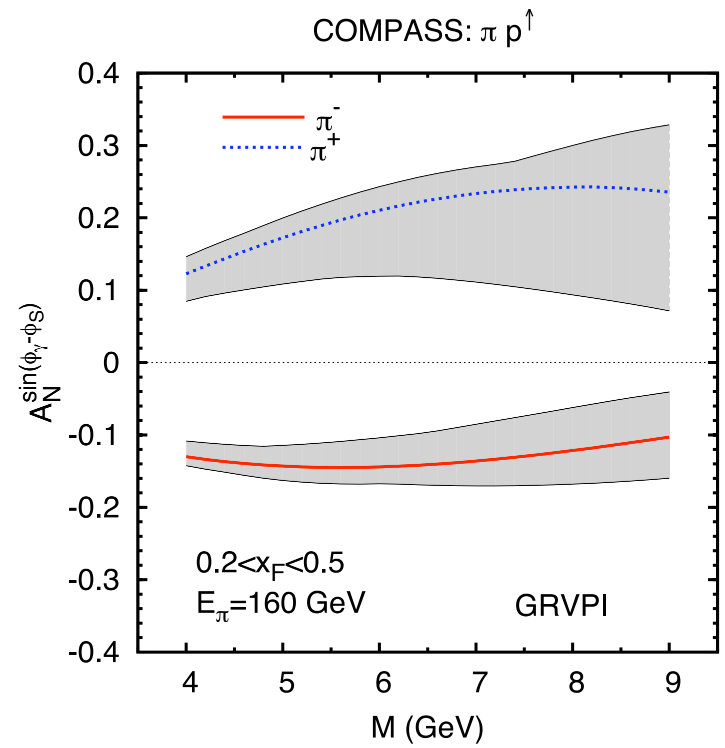
$$A_N^{\sin(\phi_S - \phi_\gamma)} \equiv \frac{2\int_0^{2\pi} d\phi_\gamma \, [d\sigma^\uparrow - d\sigma^\downarrow] \, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} d\phi_\gamma \, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

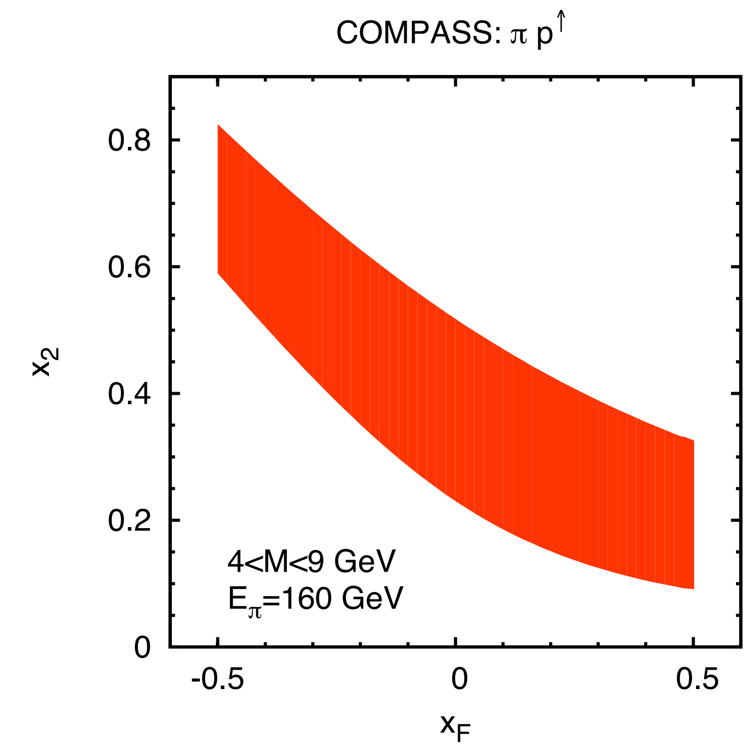


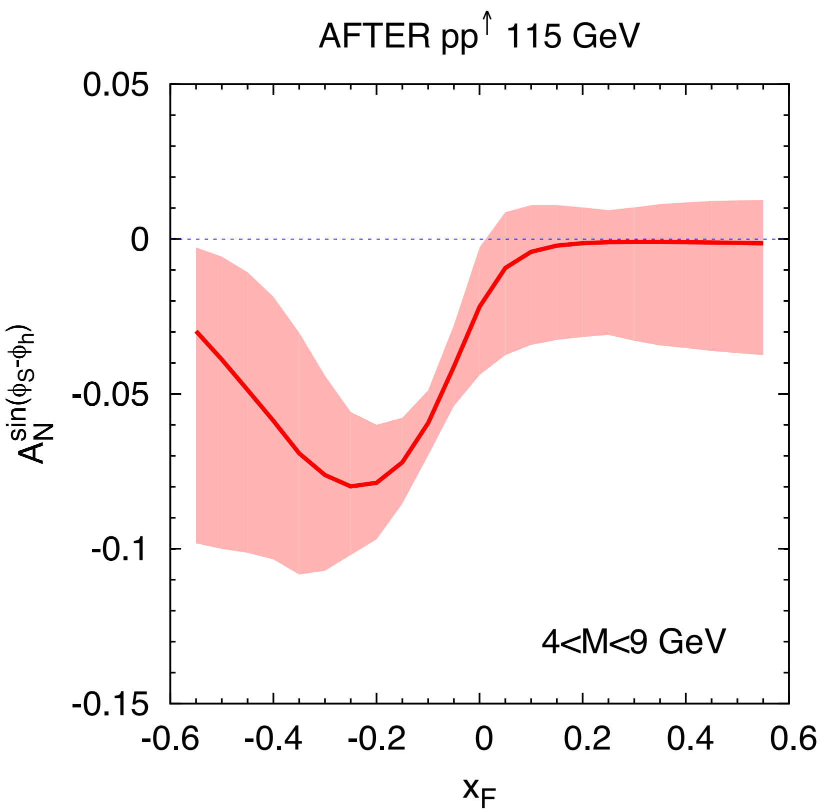
Predictions for A_N - no TMD evolution

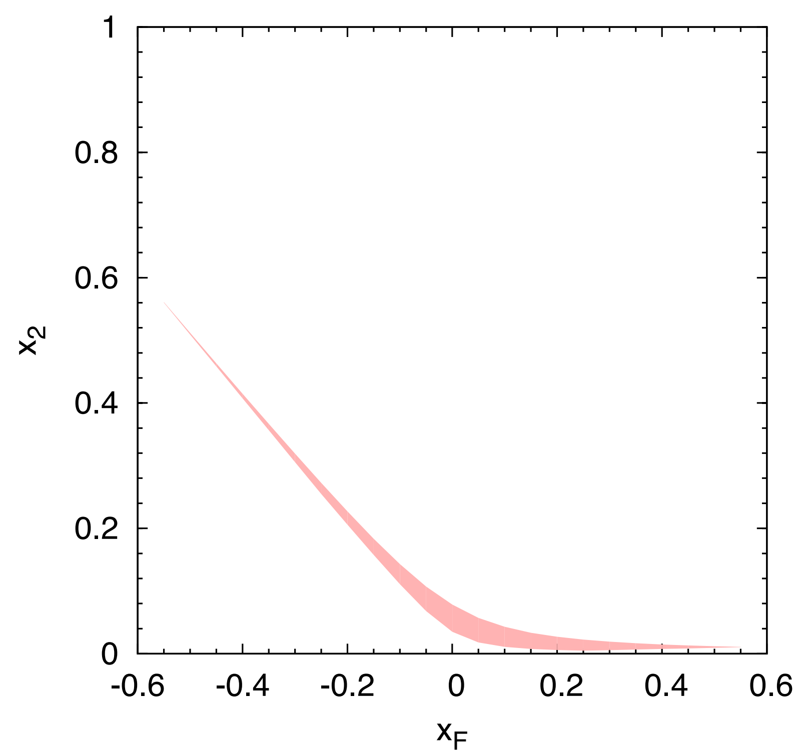
Sivers functions from SIDIS, with sign change









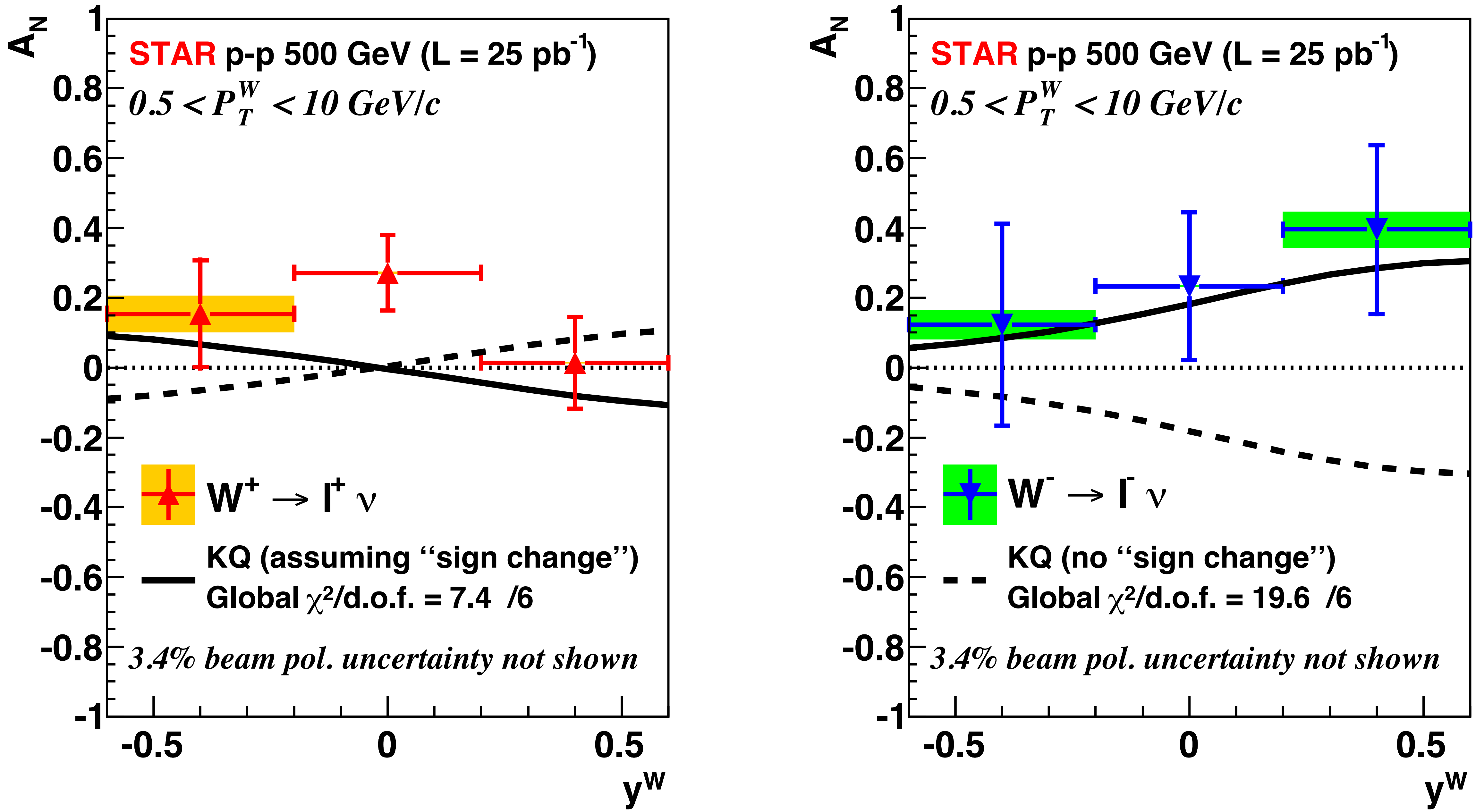


expected Sivers asymmetry in D-Y @AFTER, with sign change

M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, PR D79 (2009) 054010

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

STAR Collaboration, arXiv:1511.06003



some hints at sign change .....

Conclusions

SSAs (A_N) are experimentally very well established; common features from medium to high energy, up to rather large P_T values. Originate in valence quark region.
They cannot be originated by collinear pQCD spin effects.

GPM with assumed TMD factorisation relates A_N to intrinsic nucleon properties (Sivers distribution) or hadronisation properties (Collins FF). Same mechanisms in SIDIS, e+e- and, possibly, D-Y interactions.

Higher-twist approach is factorised; generates A_N from pQCD + non perturbative correlators; indirectly related to TMDs (with problems). In models, it predicts opposite values of A_N in SIDIS and D-Y (general argument based on gauge links ?).

keep measuring A_N ....