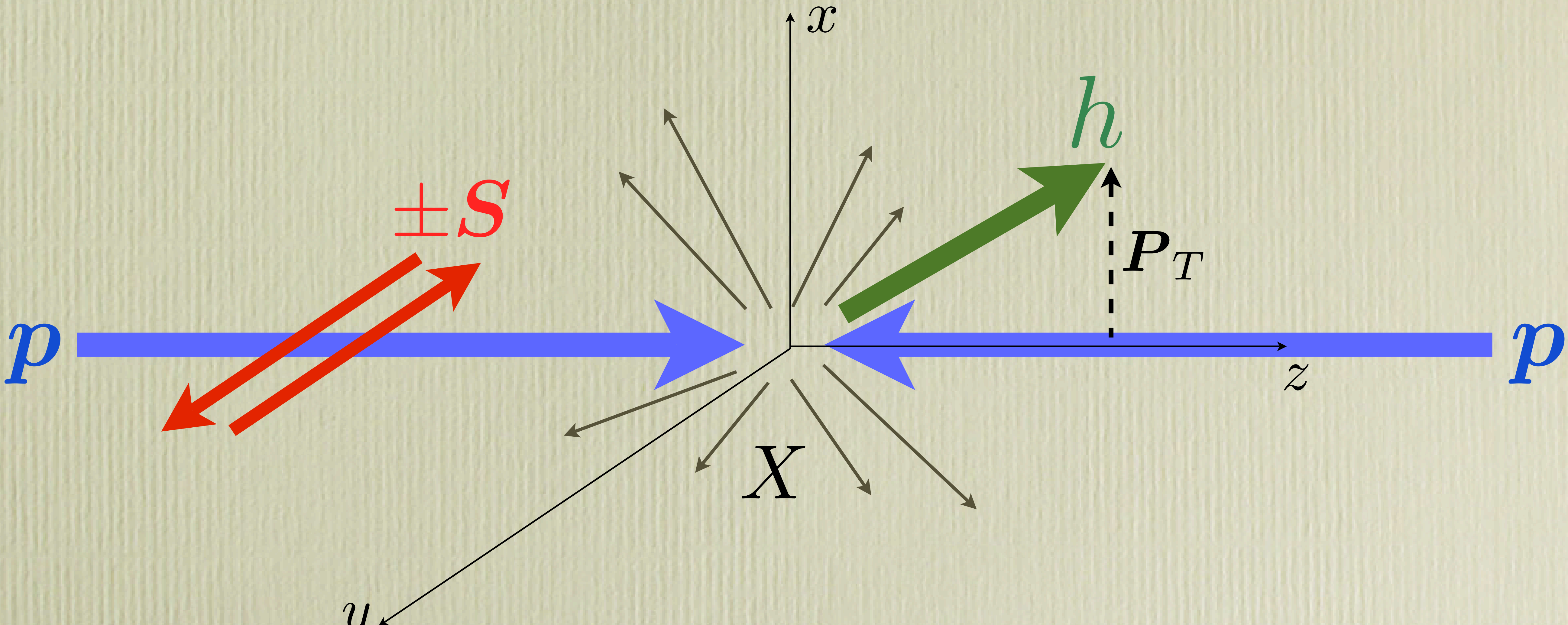
Single Spin Asymmetries (in inclusive hadronic interactions)

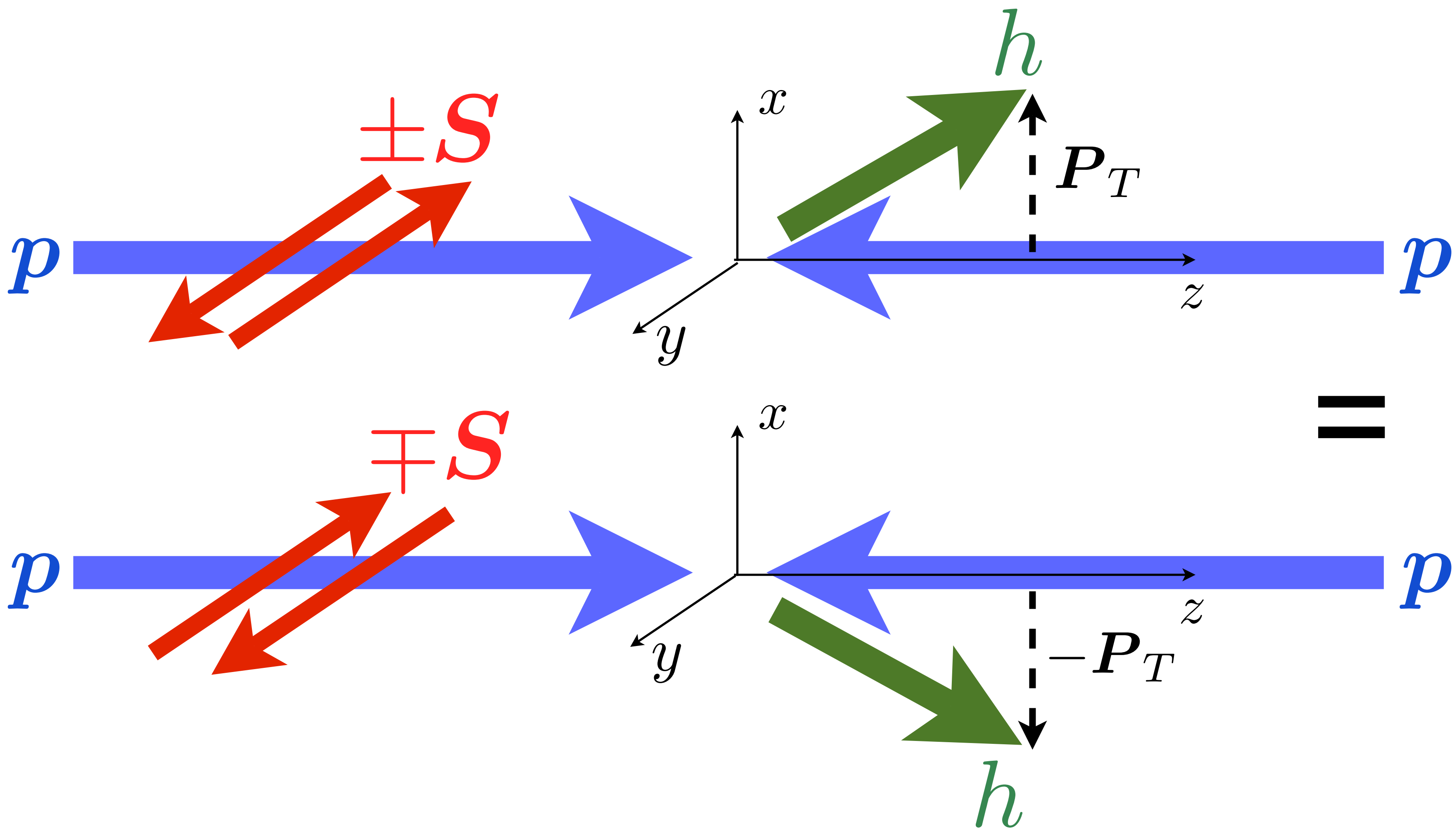
$$p^{\uparrow} p \to h\, X$$



Mauro Anselmino,
Torino University and INFN

ECT*, February 6, 2013

A_N = simple left-right asymmetry



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

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

transverse Single Spin Asymmetry (SSA) $\pm \boldsymbol{S} = \uparrow, \downarrow$

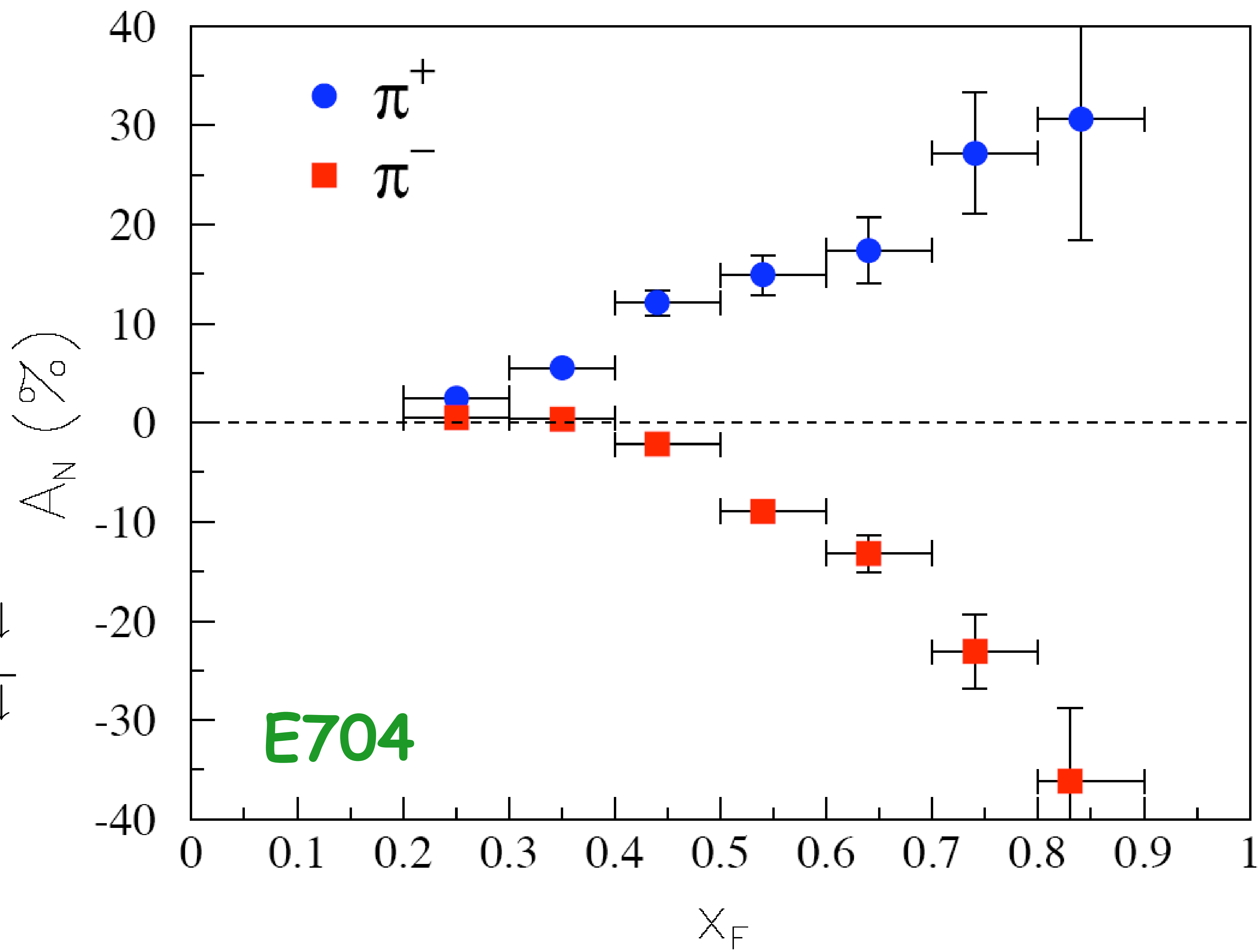
where it all started from ... (~1991)

large P_T

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

Single Spin Asymmetry

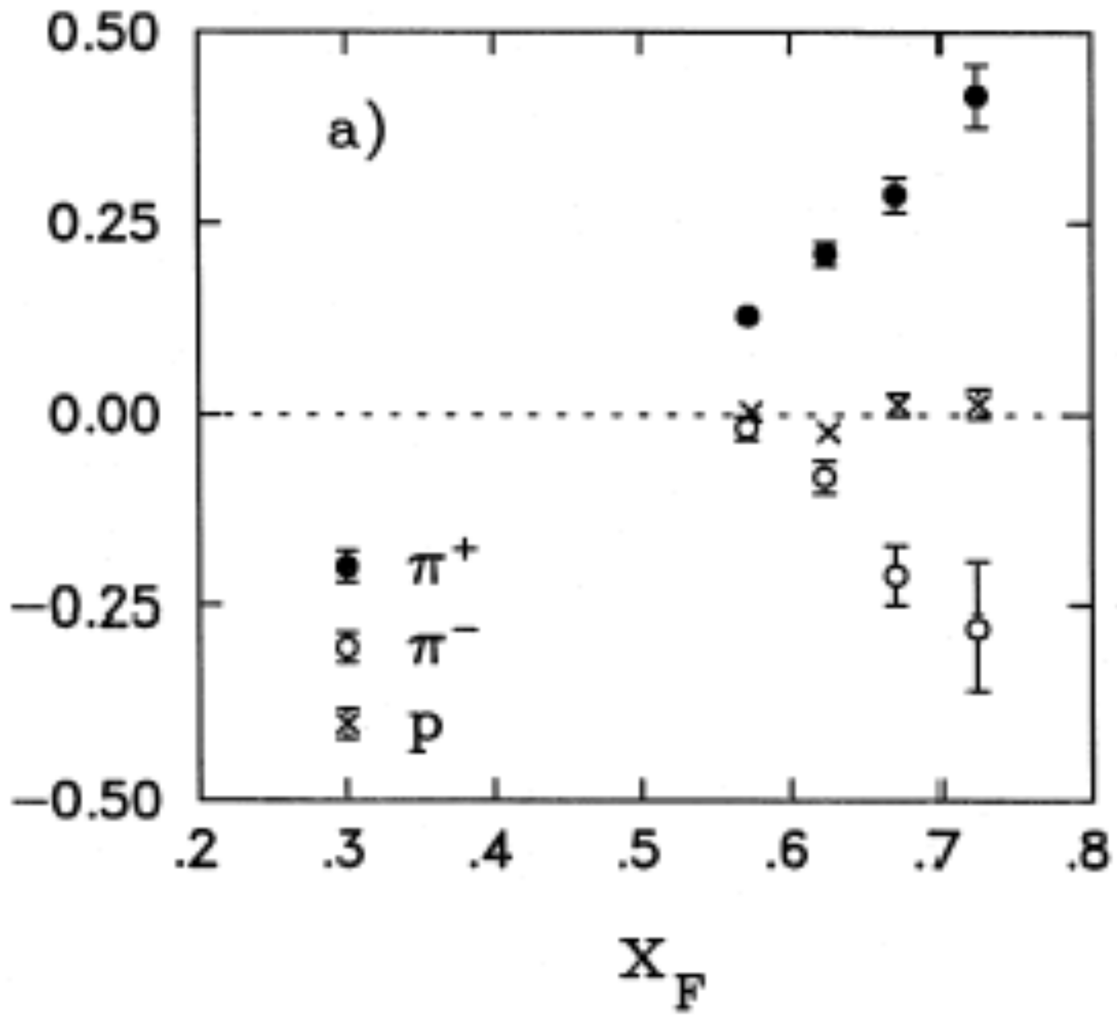
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



E704 $\sqrt{s}$ = 20 GeV $0.7 < p_T < 2.0$

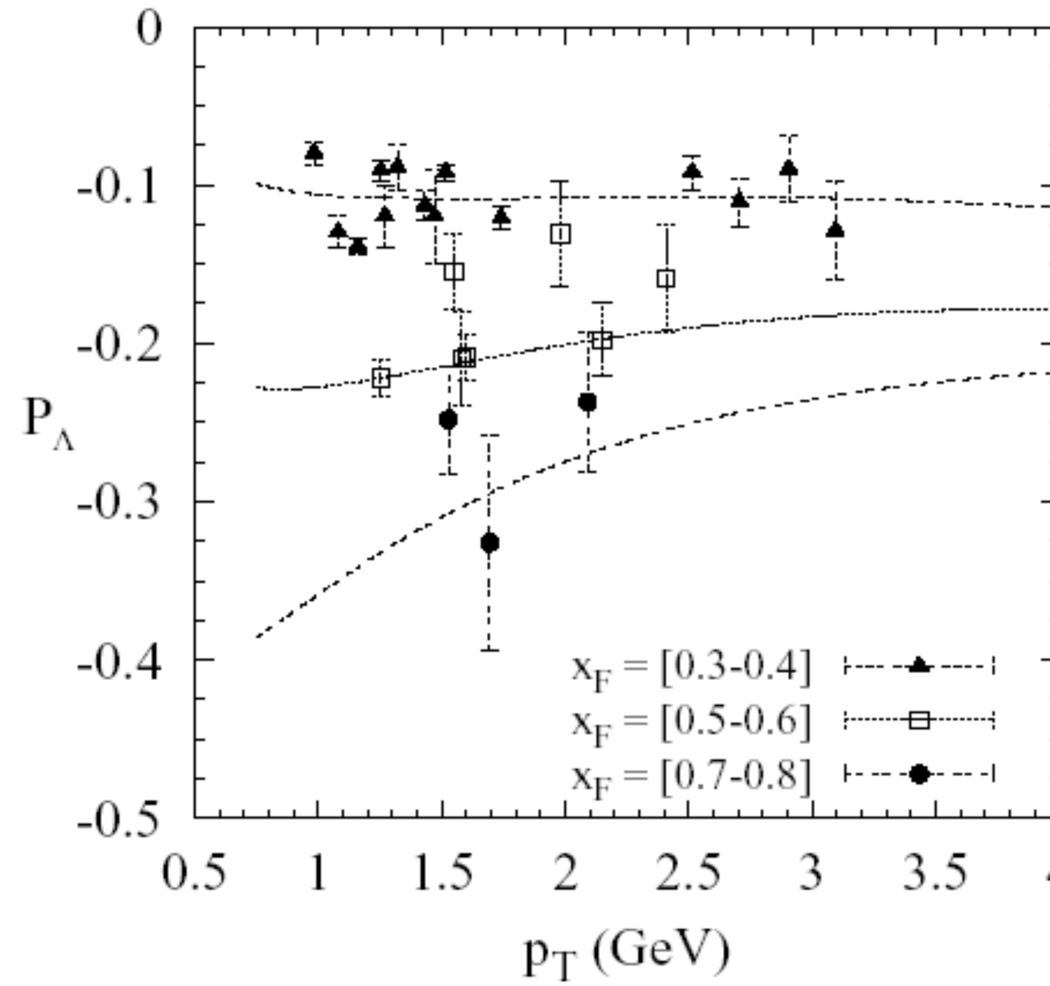
and even before ...

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

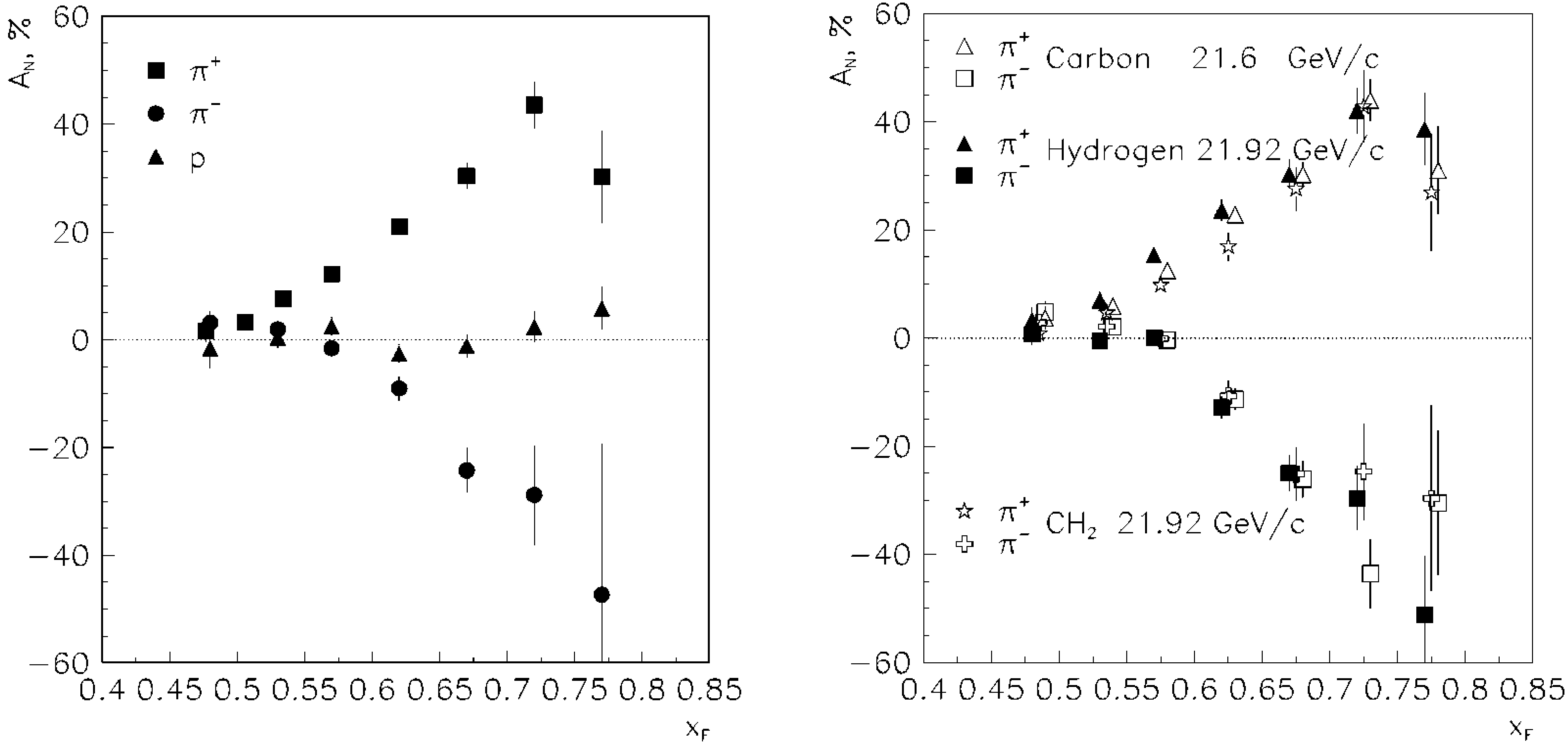


BNL-AGS
$\sqrt{s}$ = 6.6 GeV
0.6 < p_T < 1.2

$p N \to \Lambda^{\uparrow} X$



Transverse Λ polarization in unpolarized p-Be scattering at Fermilab



$$P_T \leq 1\,\mathrm{GeV}$$

E925, BNL AGS, 22 GeV

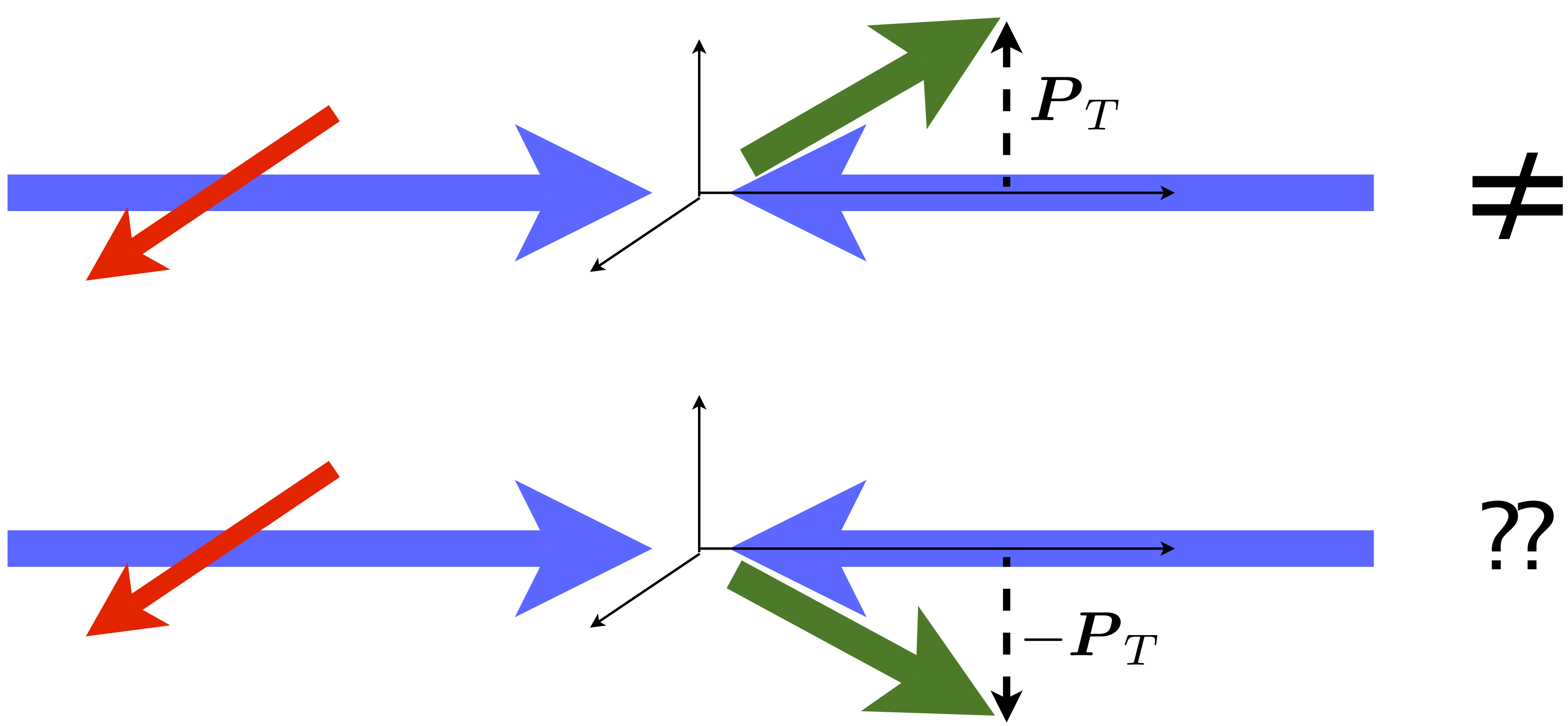
PRD 65 (2002) 092008

large SSAs observed in several experiments (but not such a high energy so far...)

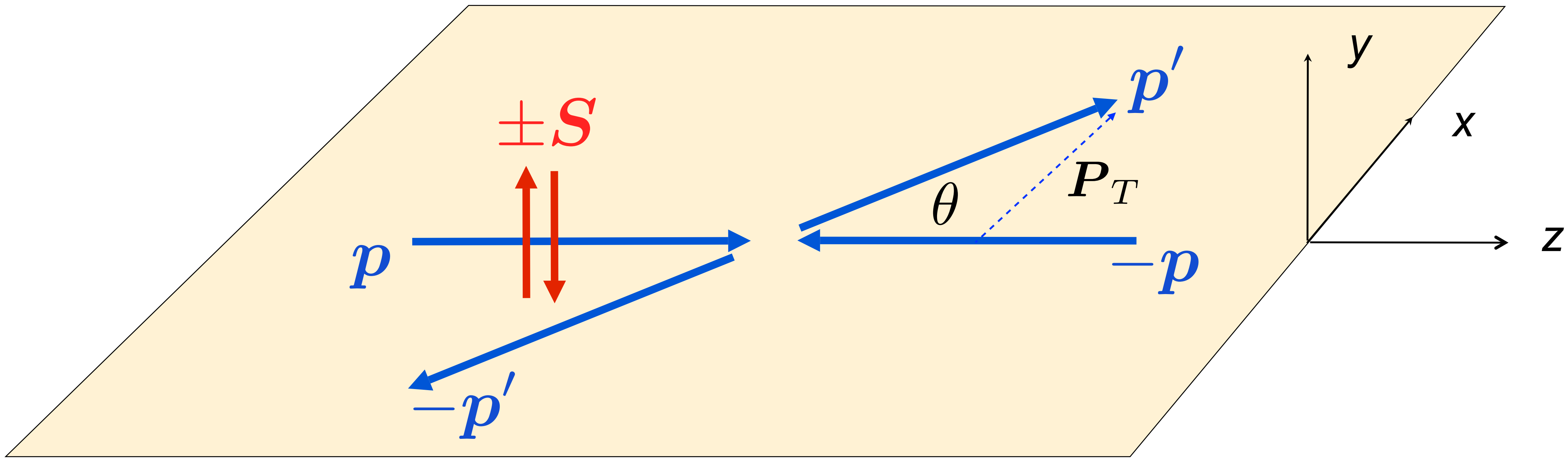
same trend: A_N increases with x_F, is positive for π^+, negative for π^- (getting into the valence quark region?)

could A_N be related to elementary QCD dynamics?

could it persist at higher energies?



Transverse single spin asymmetries in elastic scattering



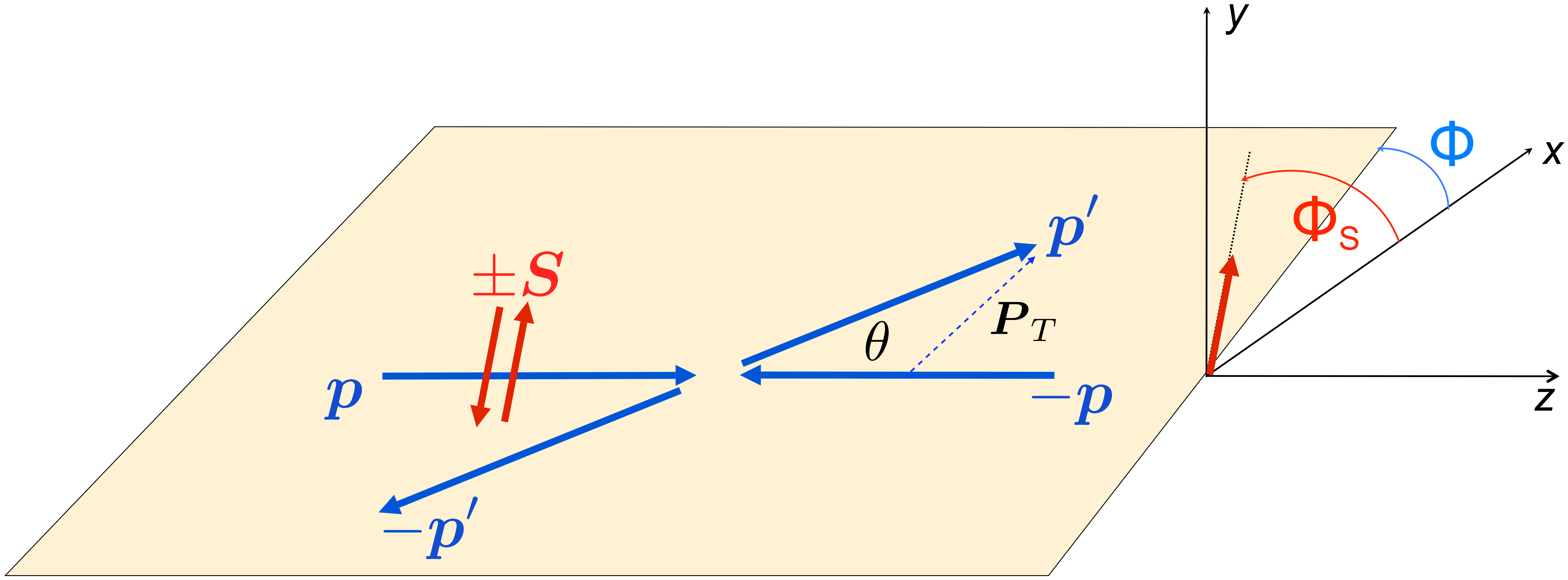
$$A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto \sin\theta$$

Example: $p\,p \longrightarrow p\,p$

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

5 independent helicity amplitudes

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



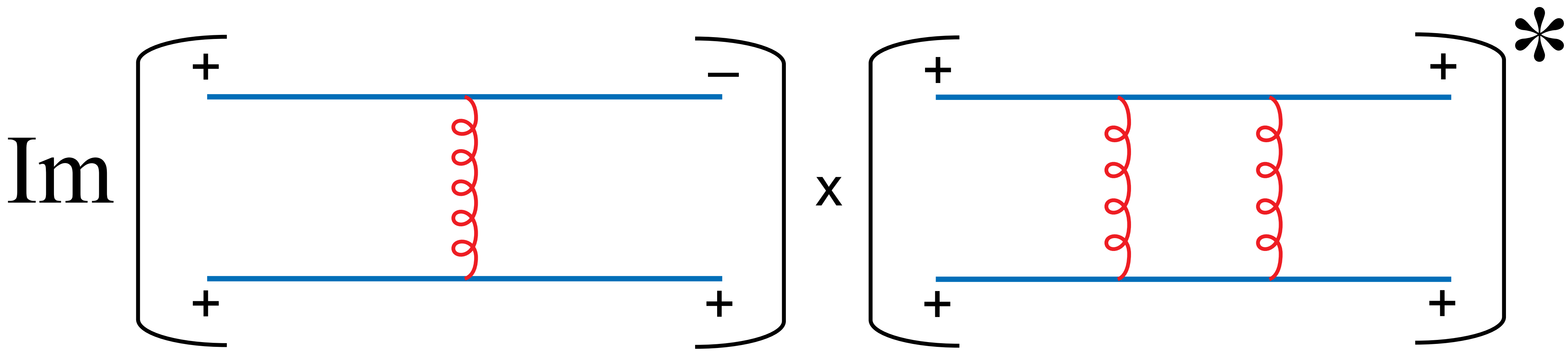
for a generic configuration:

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

A_N is zero for longitudinal spin

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 $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

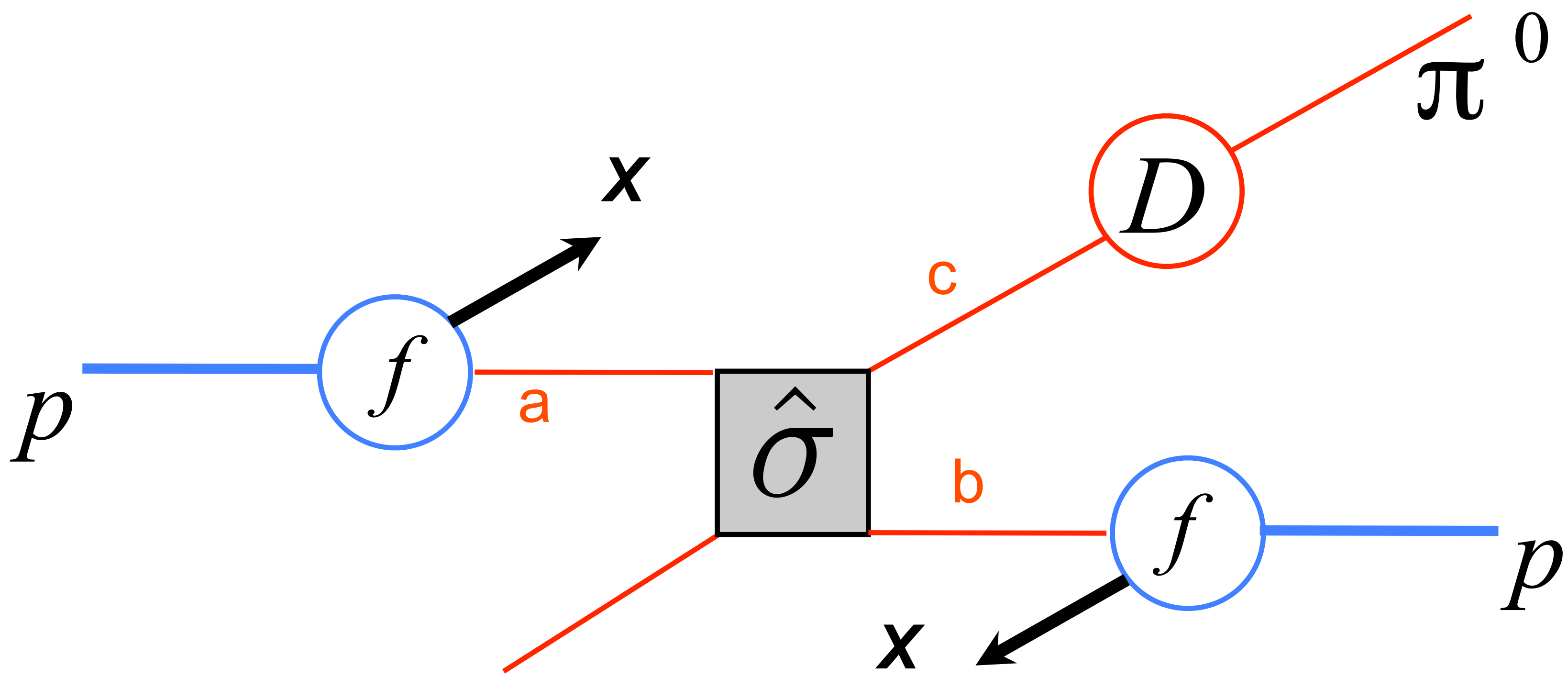
$$\Longrightarrow \quad A_N \propto \frac{m_q}{E_q}\,\alpha_s \quad \text{at quark level}$$

(Kane, Pumplin, Repko, 1978)

but large SSA observed at hadron level!

Cross section for $p\,p \rightarrow \pi^0\,X$ in pQCD

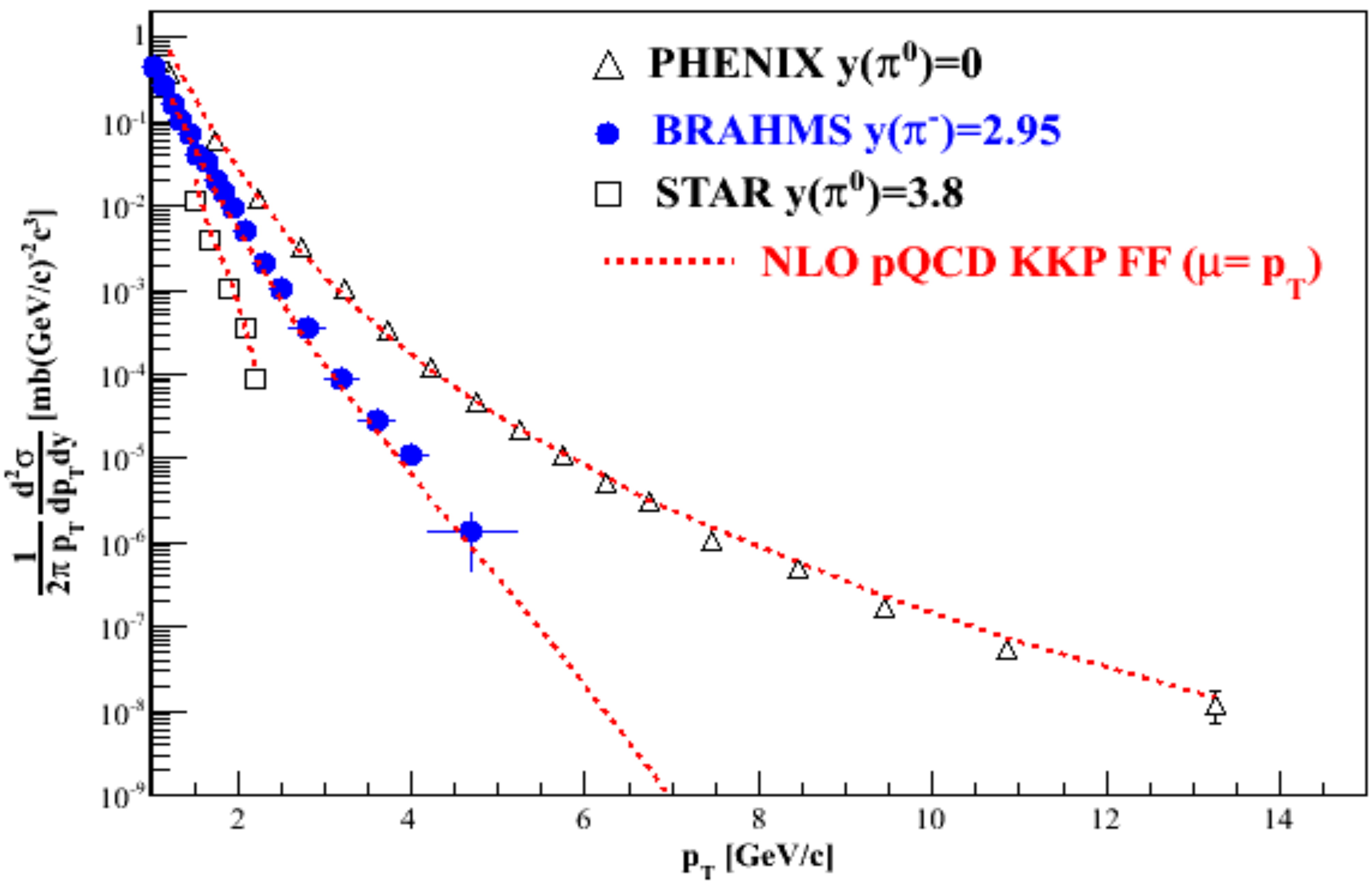
based on factorization theorem
(in collinear configuration)



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

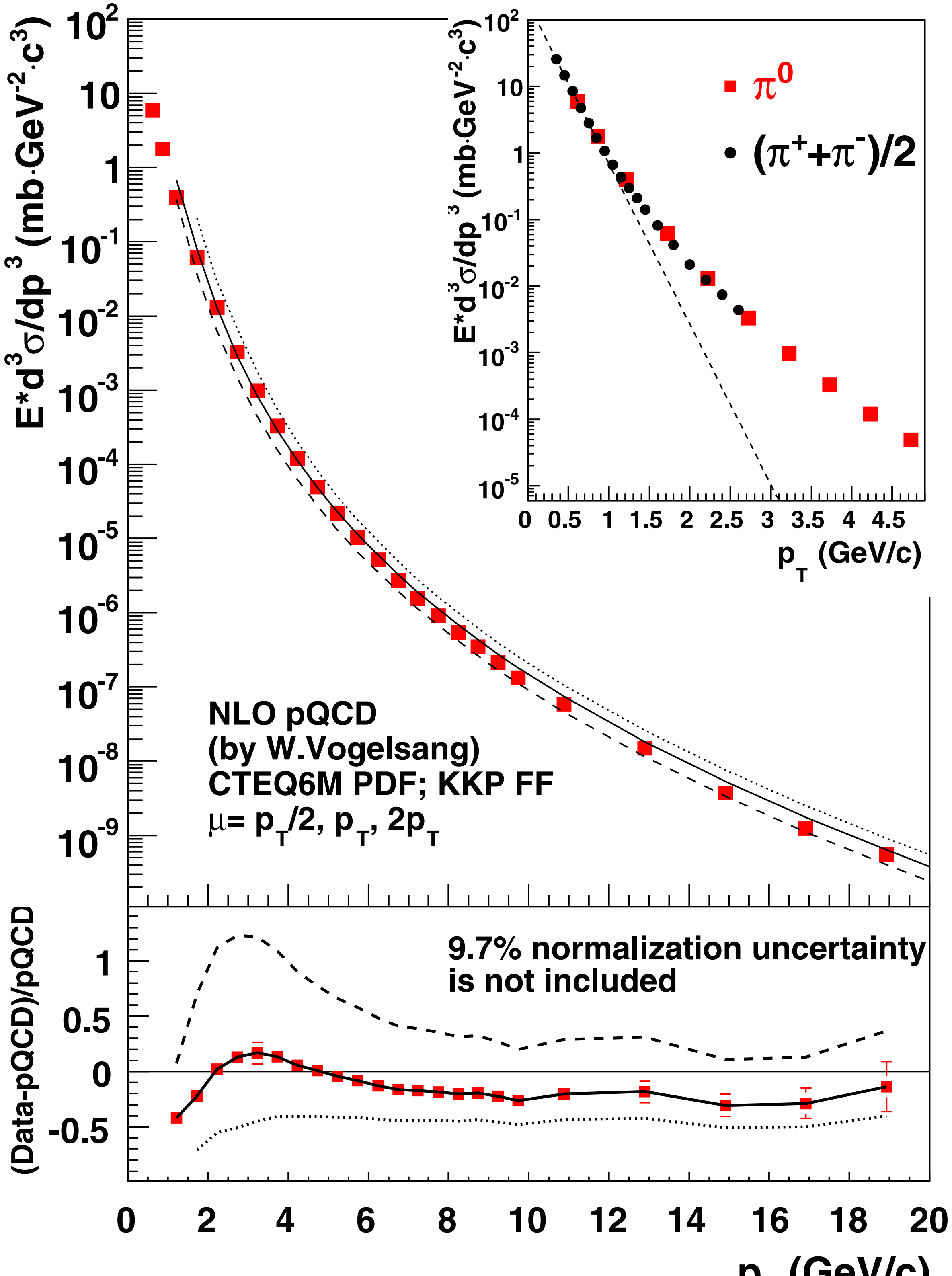
$d\hat{\sigma}^{ab\rightarrow cd}$ → pQCD elementary interactions

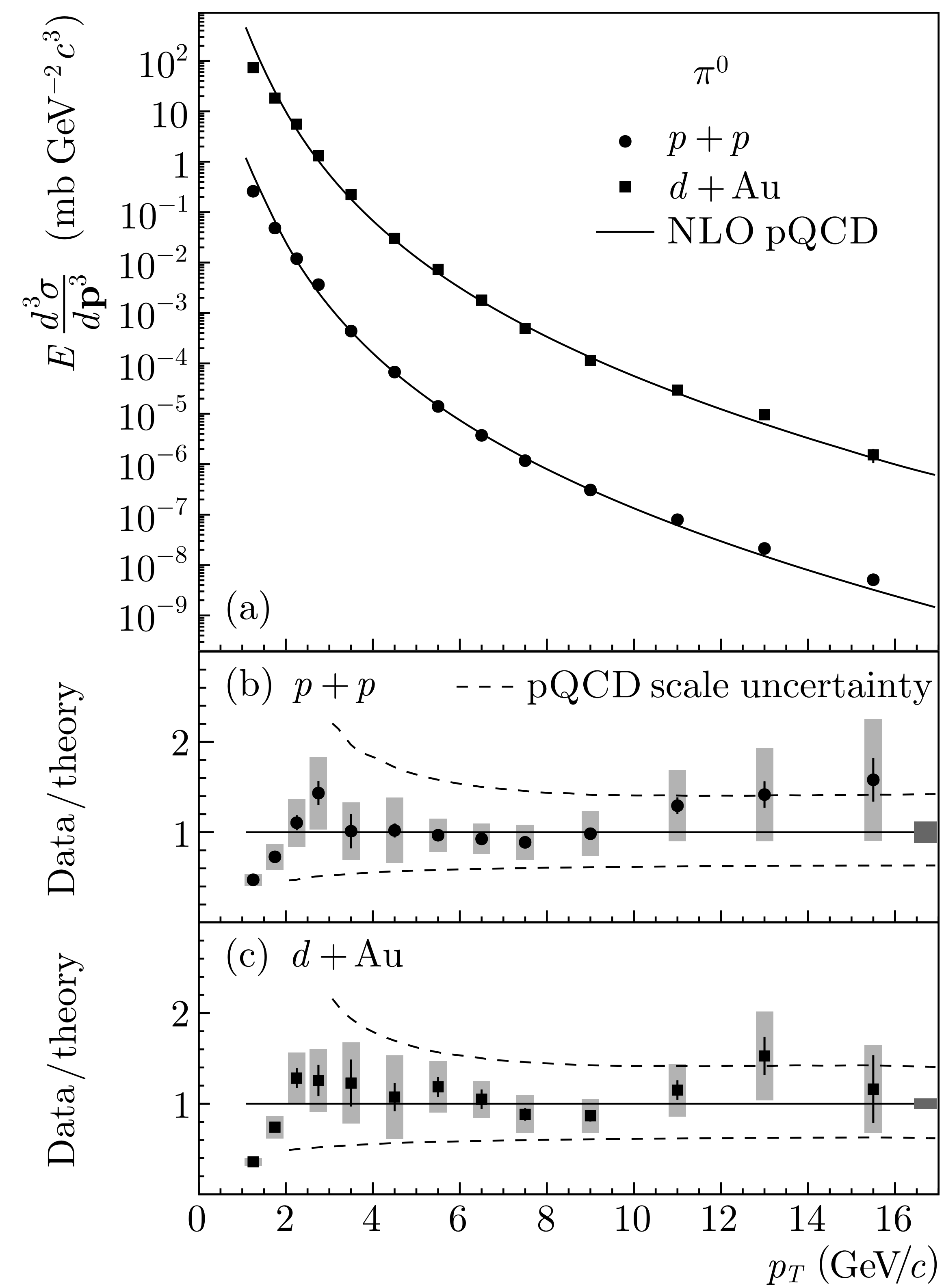
Polarization-averaged cross sections at $\sqrt{s}$=200 GeV



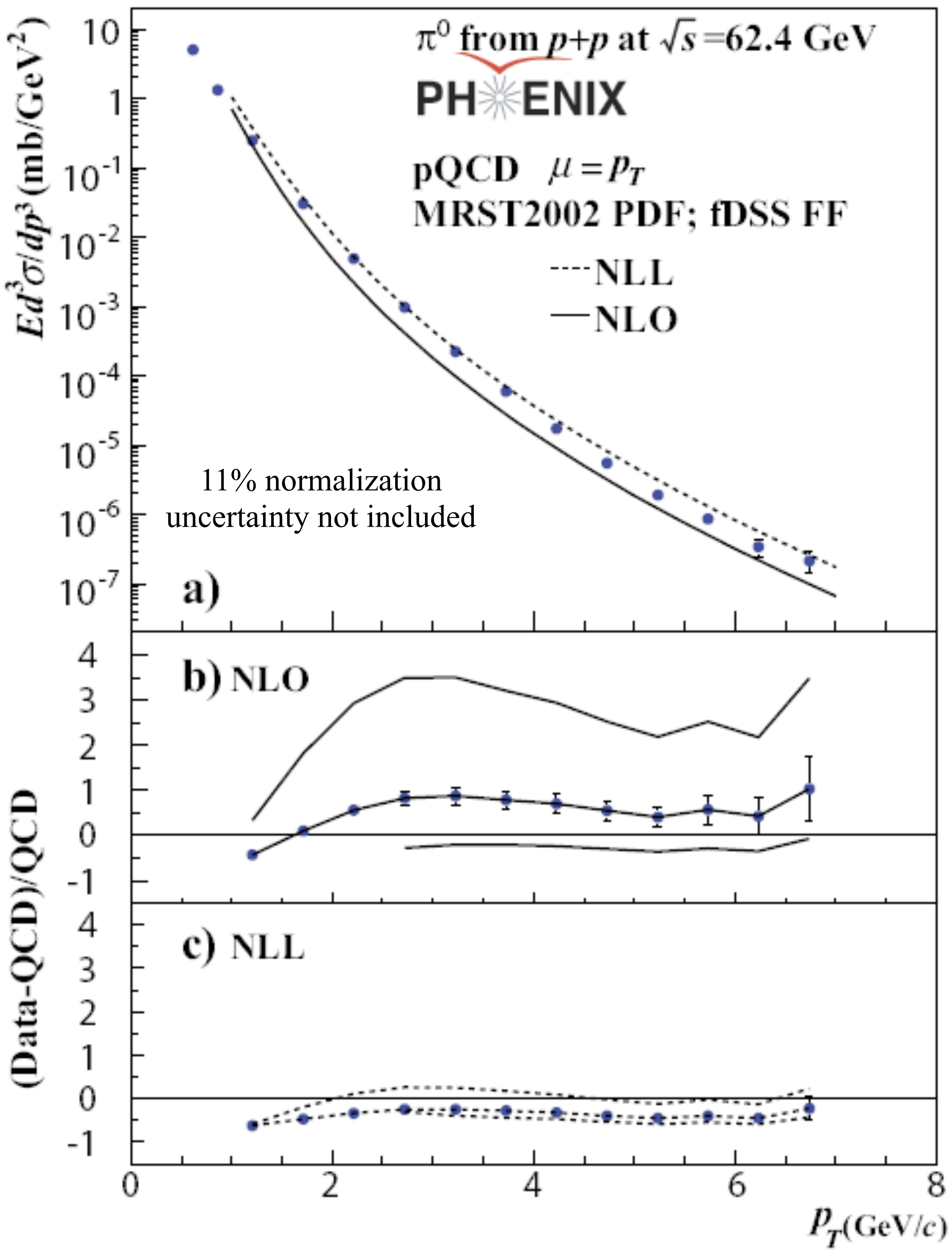
good pQCD description of data at 200 GeV, at all rapidities, down to p_T of 1-2 GeV/c

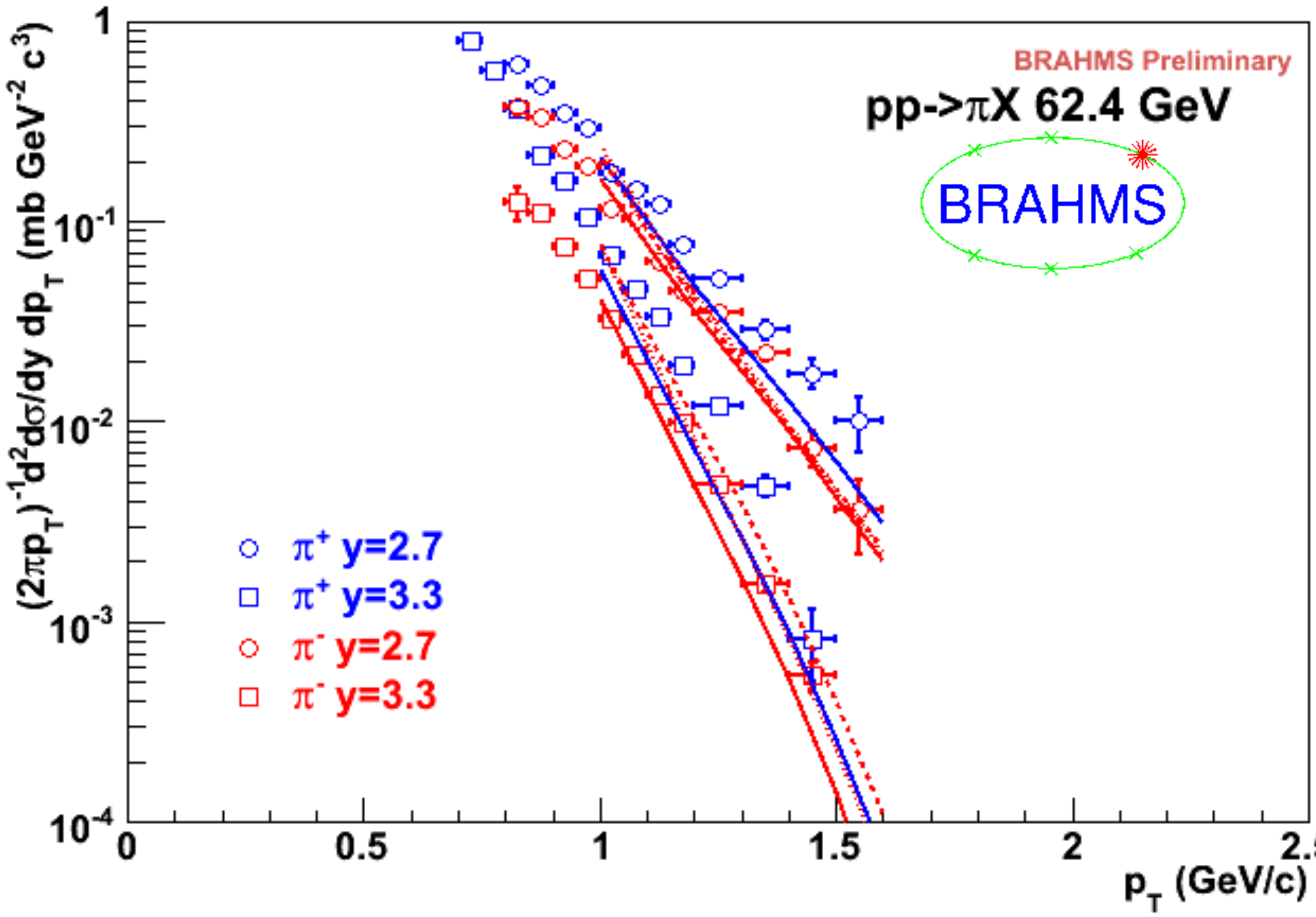
Phenix data $\sqrt{s}$ = 200 GeV STAR data arXiv:0912.2838





rather good agreement even at at √s=62.4 GeV



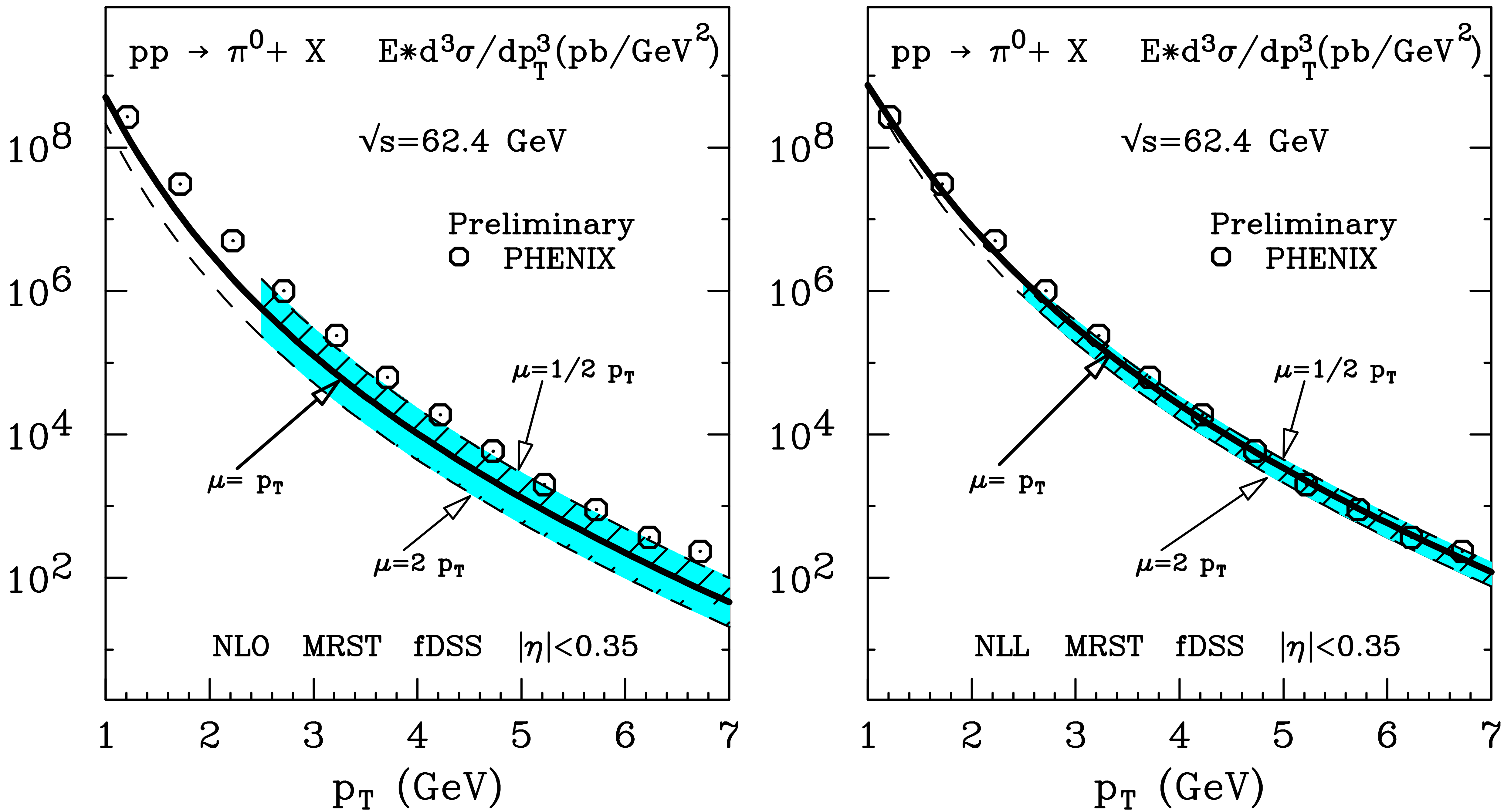


Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of μ=p_T, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

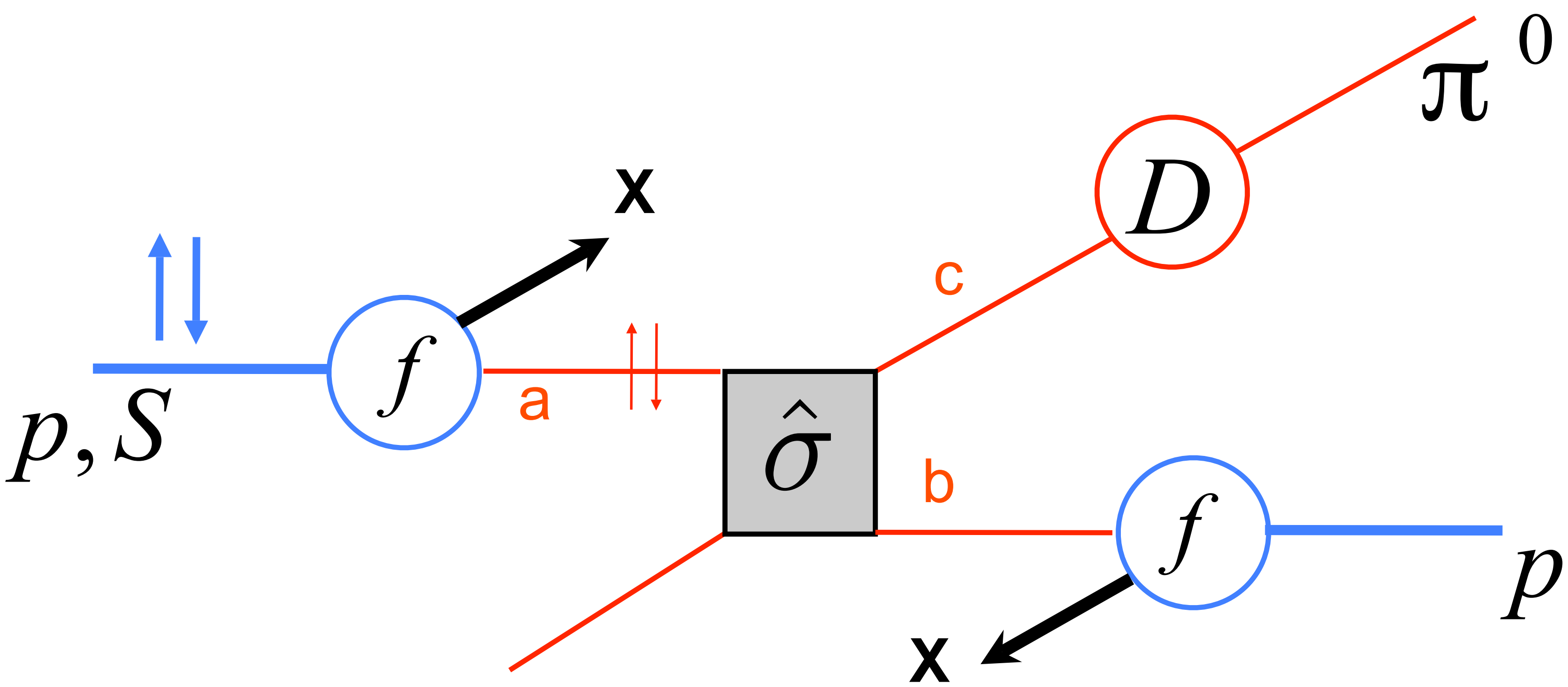
mid-rapidity pions

de Florian, Vogelsang, Wagner

PRD **76**, 094021 (2007)



SSA?



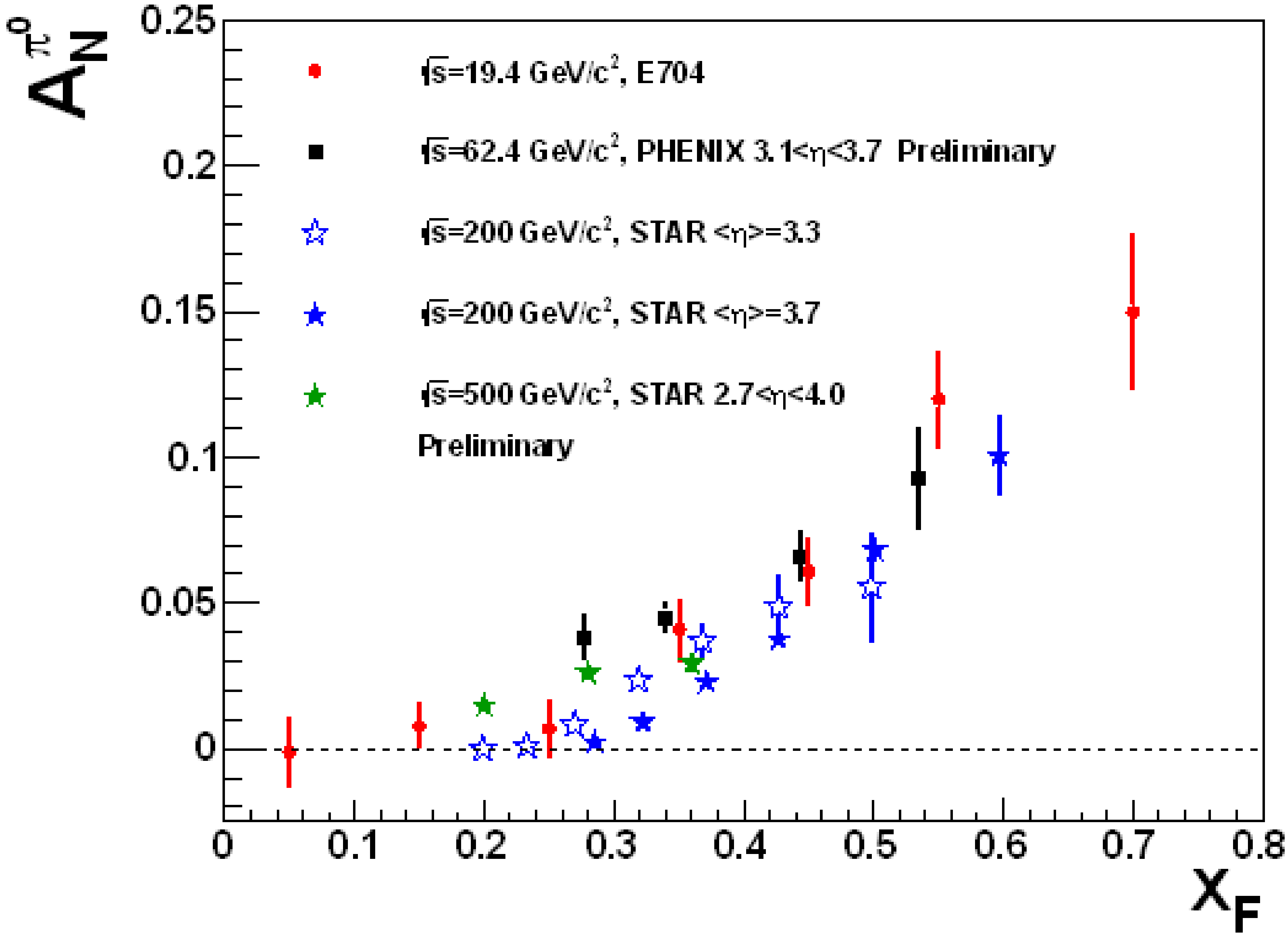
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{\Delta_T f_a}_{\text{transversity}} \otimes f_b \otimes \underbrace{[d\hat{\sigma}^{\uparrow} - d\hat{\sigma}^{\downarrow}]}_{\text{pQCD elementary SSA}} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

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

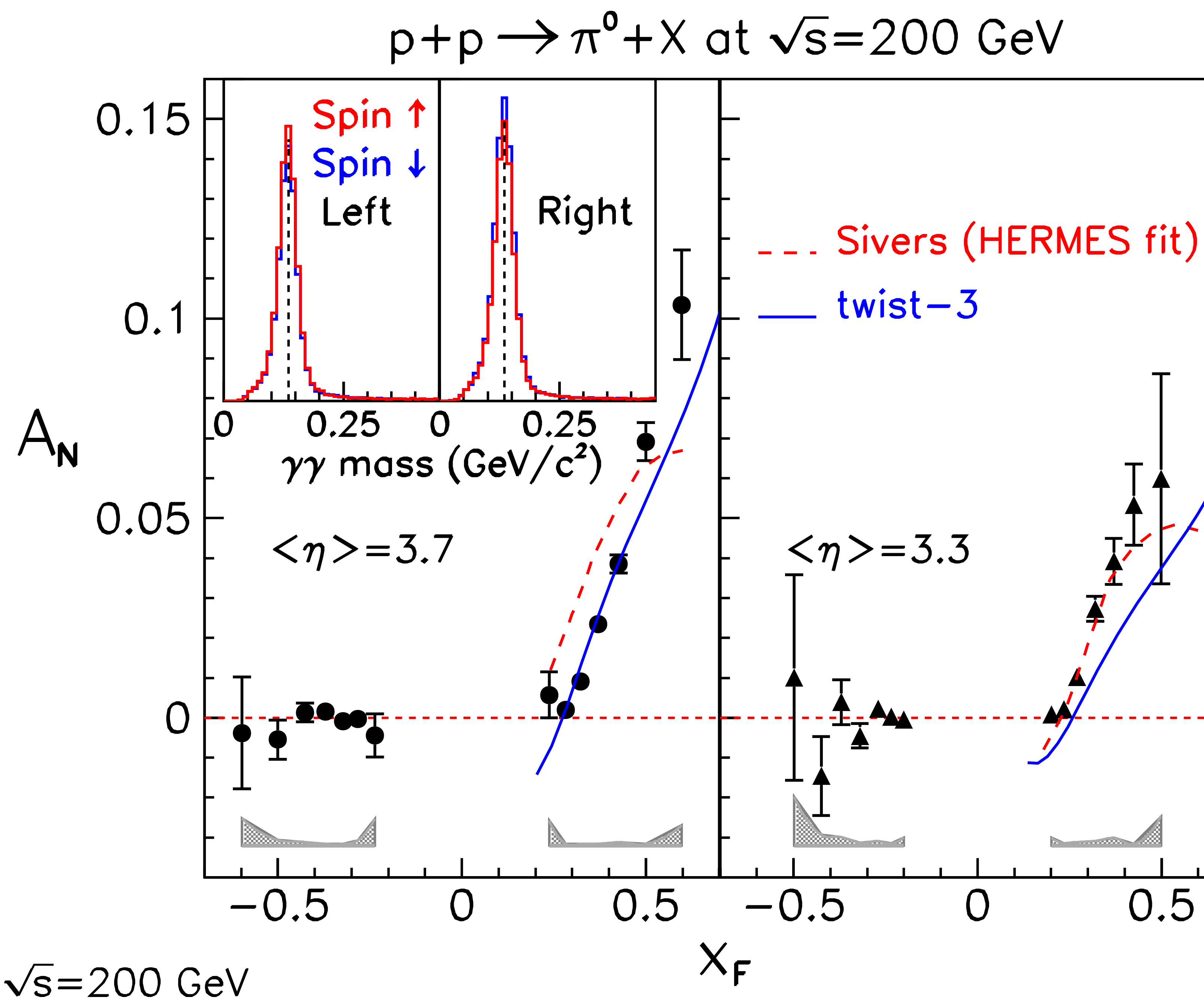
was considered almost a theorem

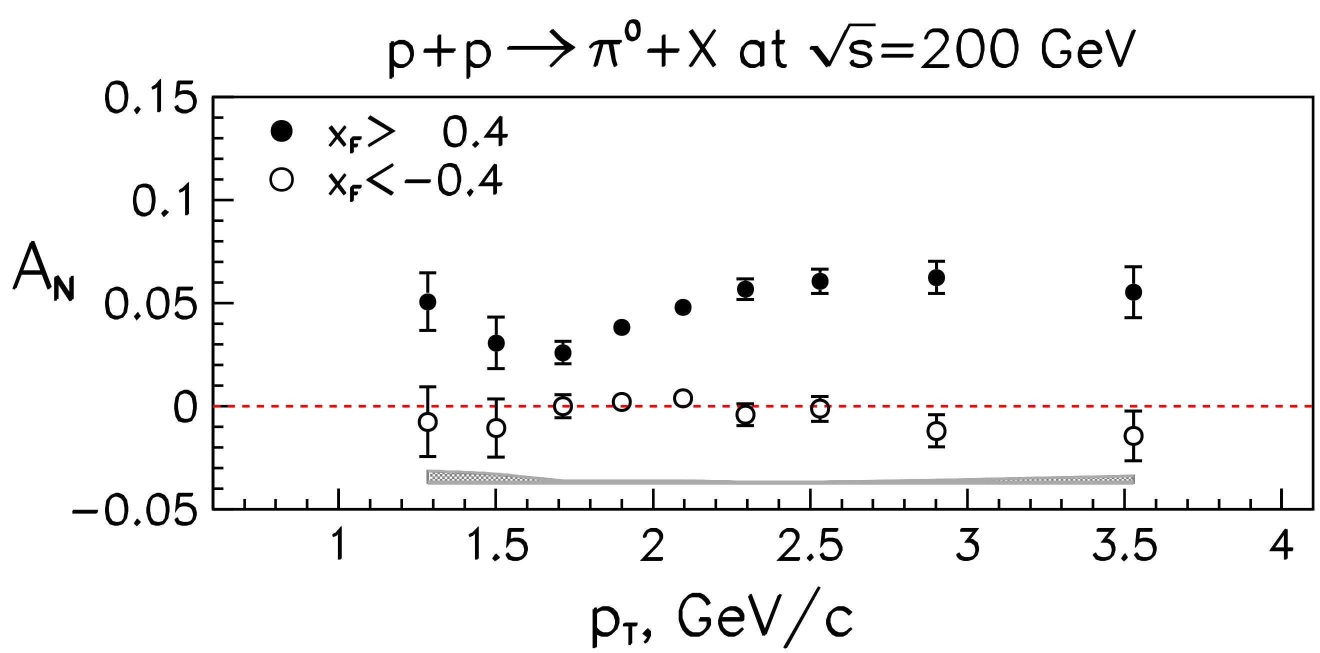
(Kane, Pumplin, Repko, 1978)

Good description of unpolarized cross-section, with collinear factorization. But A_N is not zero ...

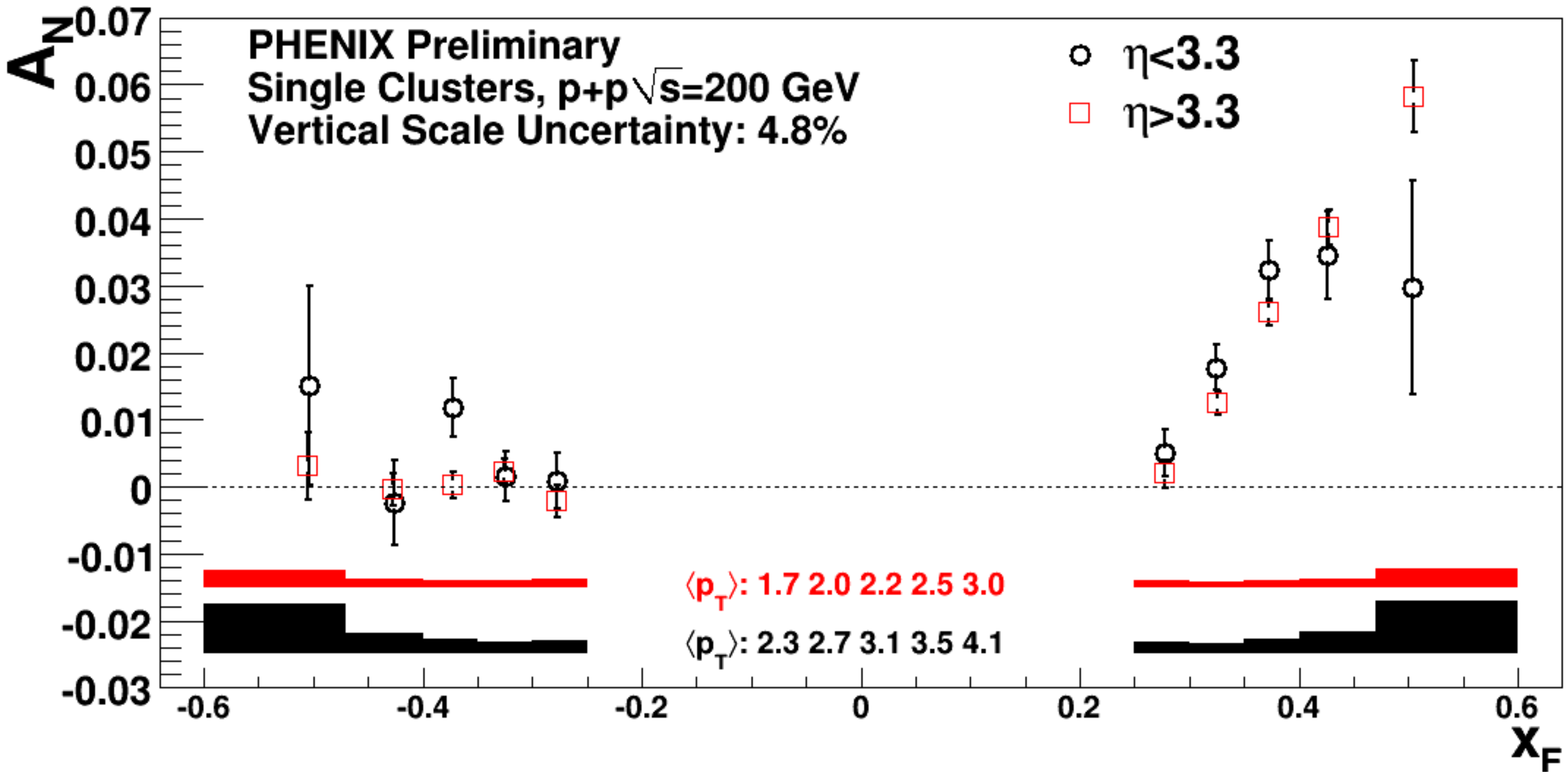


STAR data



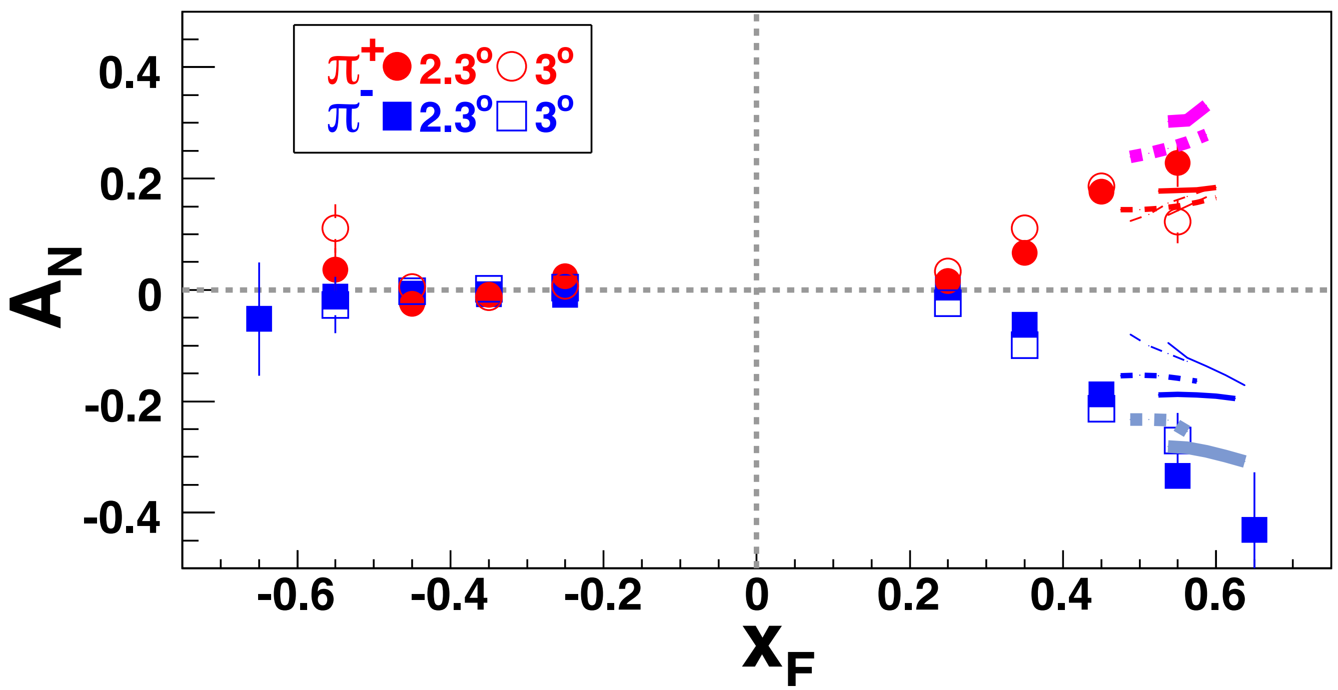


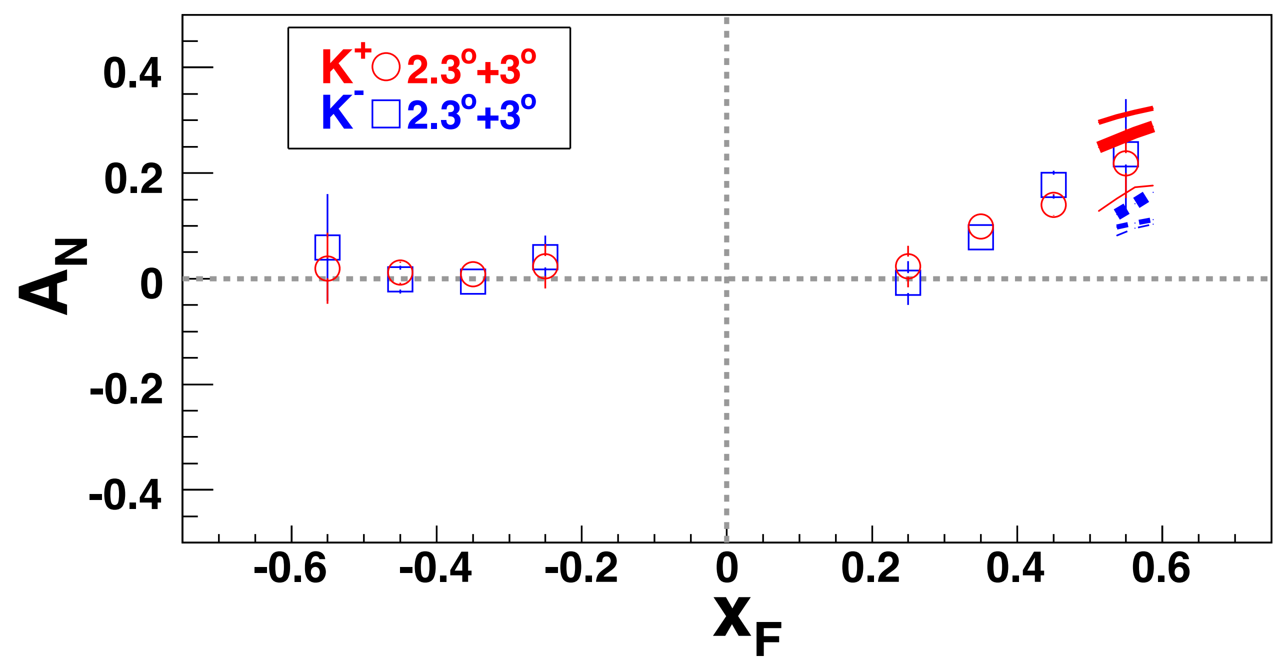
PRL 101, 222001 (2008)

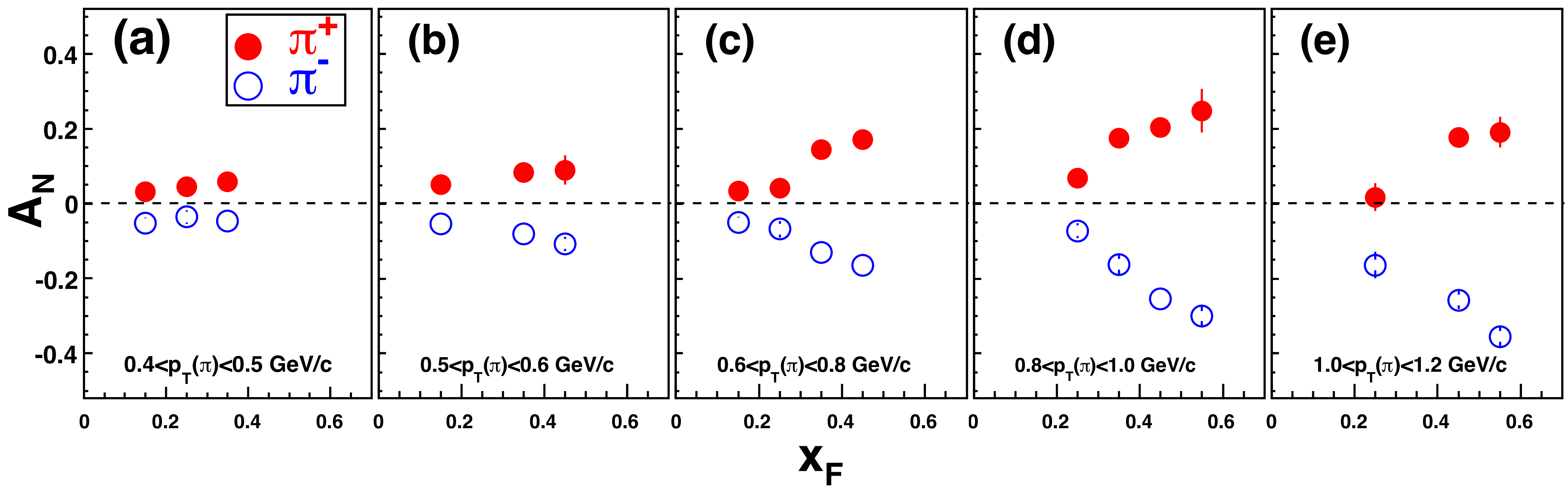


PHENIX Preliminary
Single Clusters, p+p √s=200 GeV
Vertical Scale Uncertainty: 4.8%
η<3.3
η>3.3
⟨pT⟩: 1.7 2.0 2.2 2.5 3.0
⟨pT⟩: 2.3 2.7 3.1 3.5 4.1
A_N
x_F
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

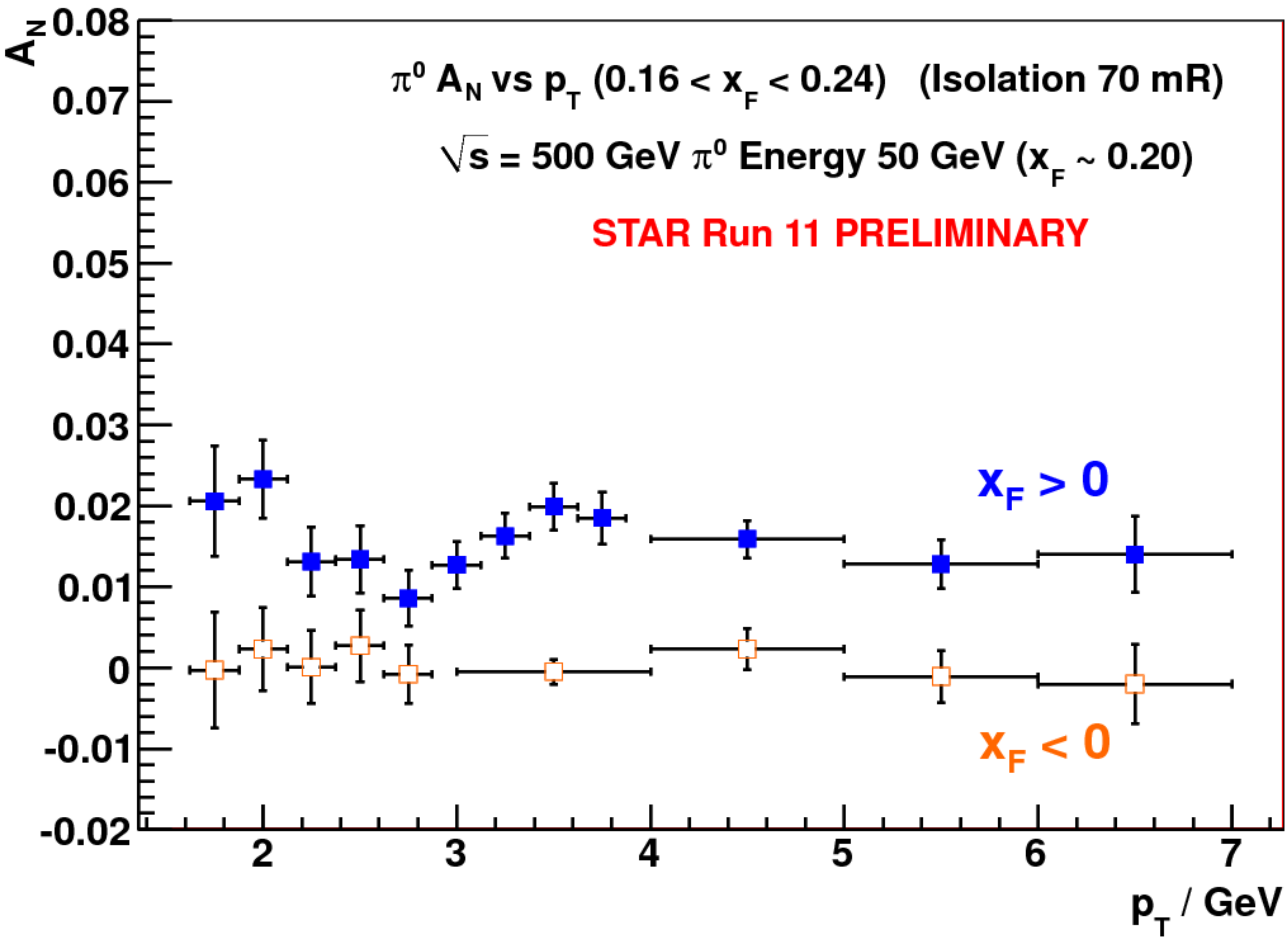
BRAHMS, arXiv:0801.1078



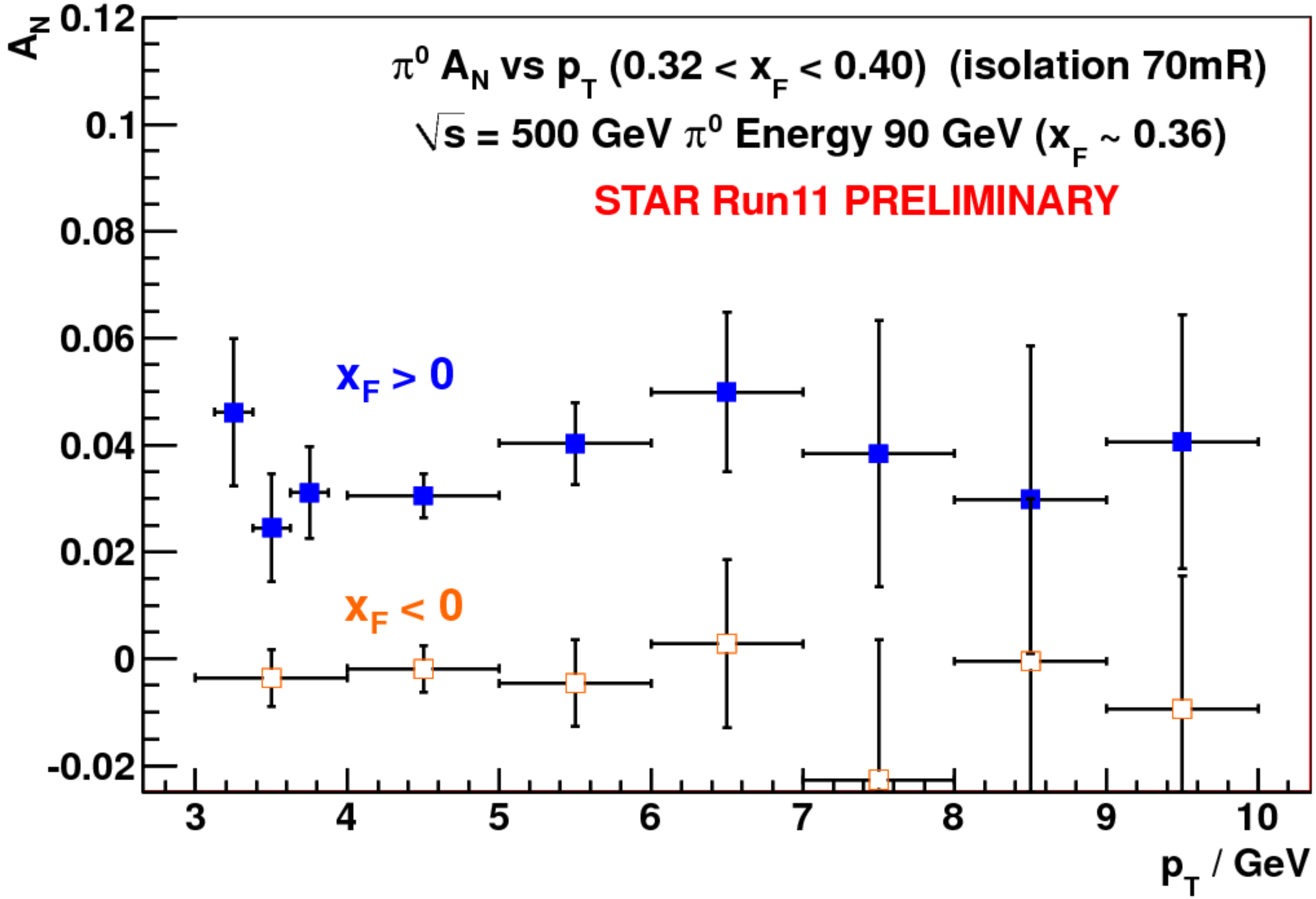




$$\sqrt{s} = 62.4 \text{ GeV}$$

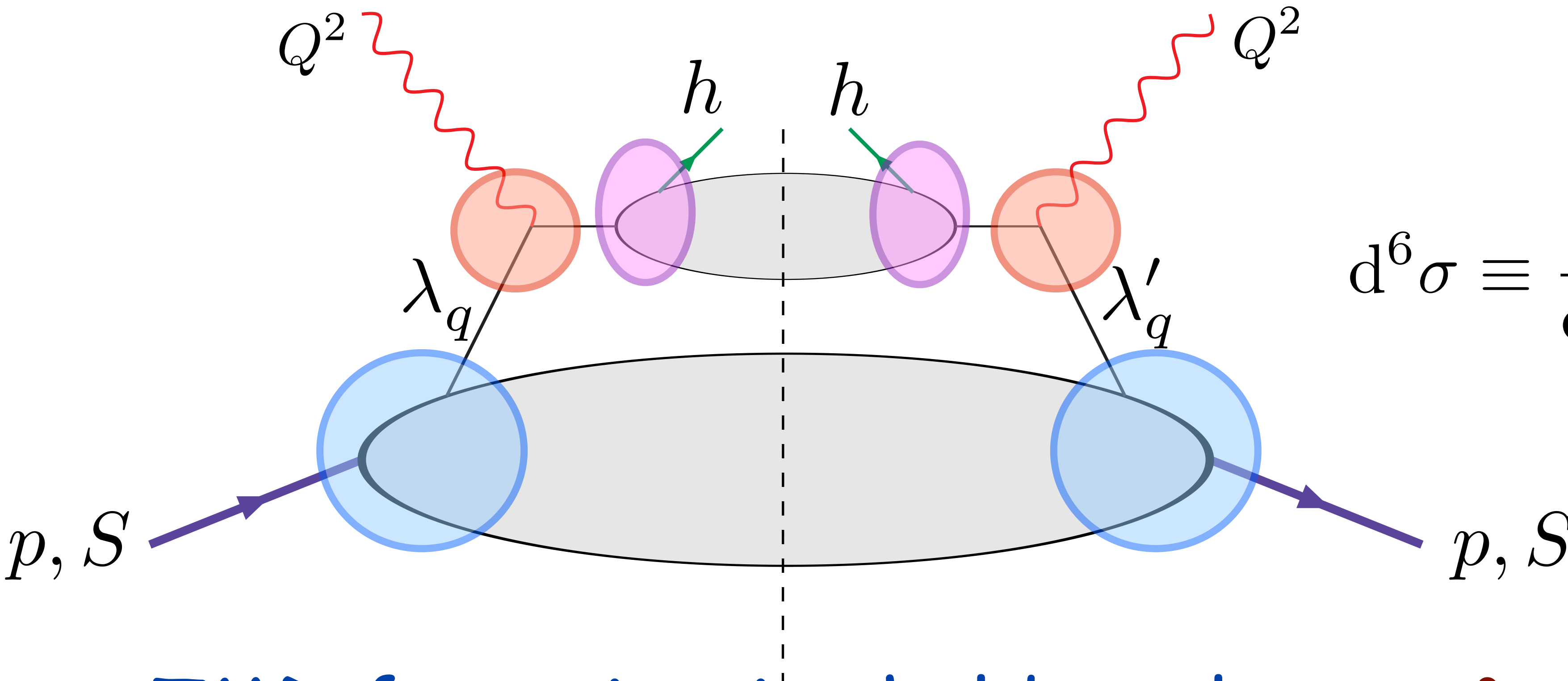


π^0 A_N vs p_T (0.16 < x_F < 0.24) (Isolation 70 mR)
$\sqrt{s}$ = 500 GeV π^0 Energy 50 GeV (x_F ~ 0.20)
STAR Run 11 PRELIMINARY
$x_F > 0$
$x_F < 0$
A_N
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
2
3
4
5
6
7
p_T / GeV



are there SSAs in other processes?

SSAs and TMDs in SIDIS



talks by S. Melis and G. Schnell

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

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

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

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

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

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

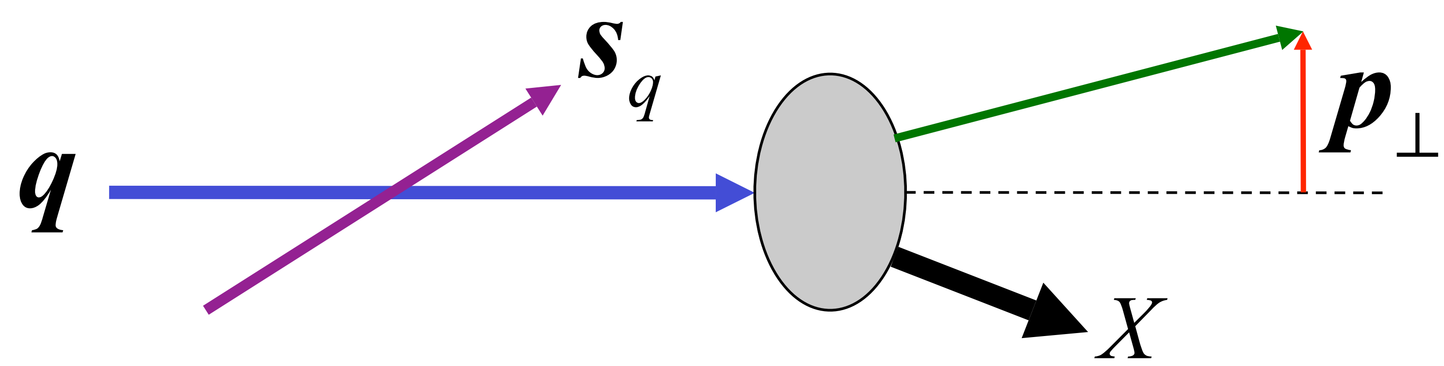
$f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$ correlate $k_\perp$ of quark with S_T of proton (Sivers)

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

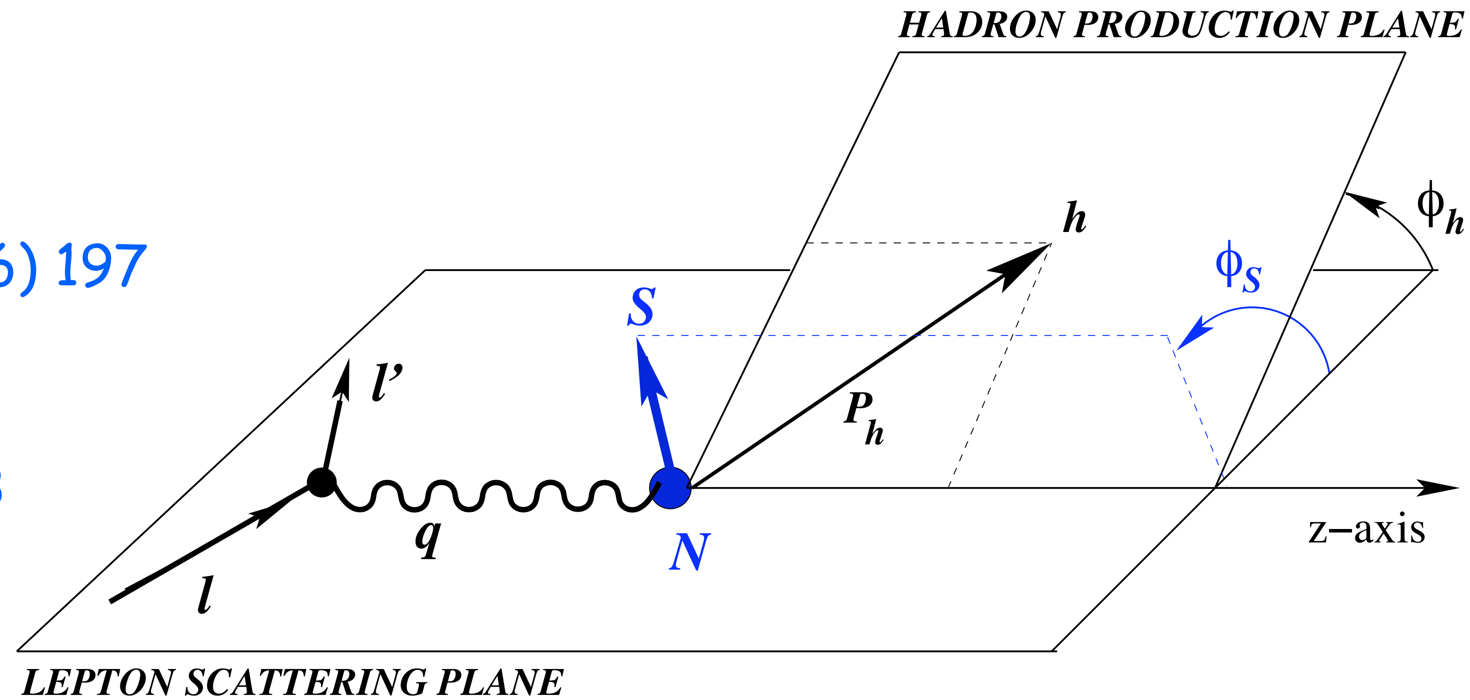
there are 2 independent TMD-FFs for spinless hadrons

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

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

Kotzinian, **NP B441** (1995) 234
Mulders and Tangermann, **NP B461** (1996) 197
Boer and Mulders, **PR D57** (1998) 5780
Bacchetta et al., **PL B595** (2004) 309
Bacchetta et al., **JHEP 0702** (2007) 093
Anselmino et al., **PR D83** (2011) 114019

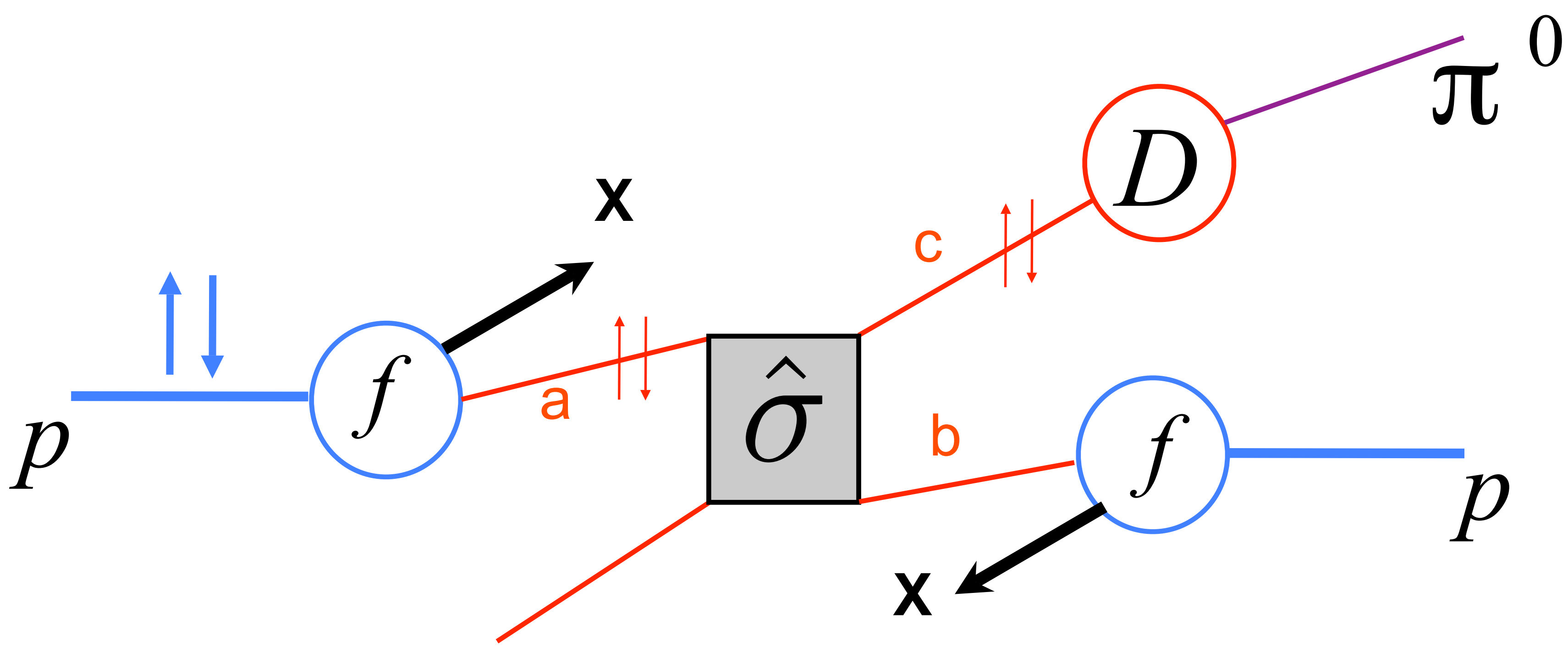


the $F^{(\cdots)}_{S_B\, S_T}$ contain the TMDs; plenty of Spin Asymmetries

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

Two main different (?) approaches

1. Generalization of collinear scheme (assuming factorization)

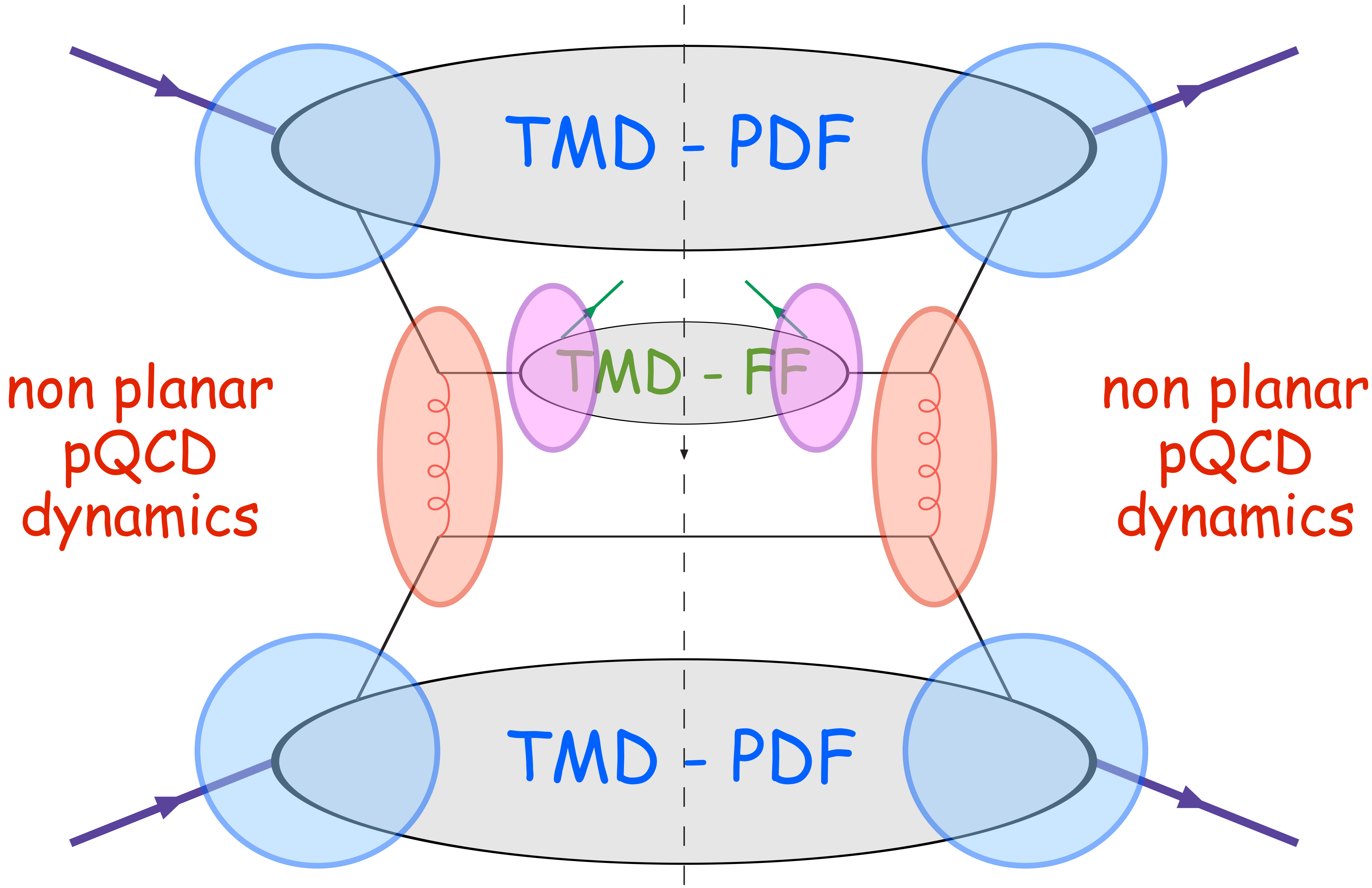


$$\mathrm{d}\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z,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

single spin effects in TMDs

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

TMD factorization



factorization assumed

(talk by C. Pisano for way of probing TMDs through azimuthal distribution of pions inside a jet)

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

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

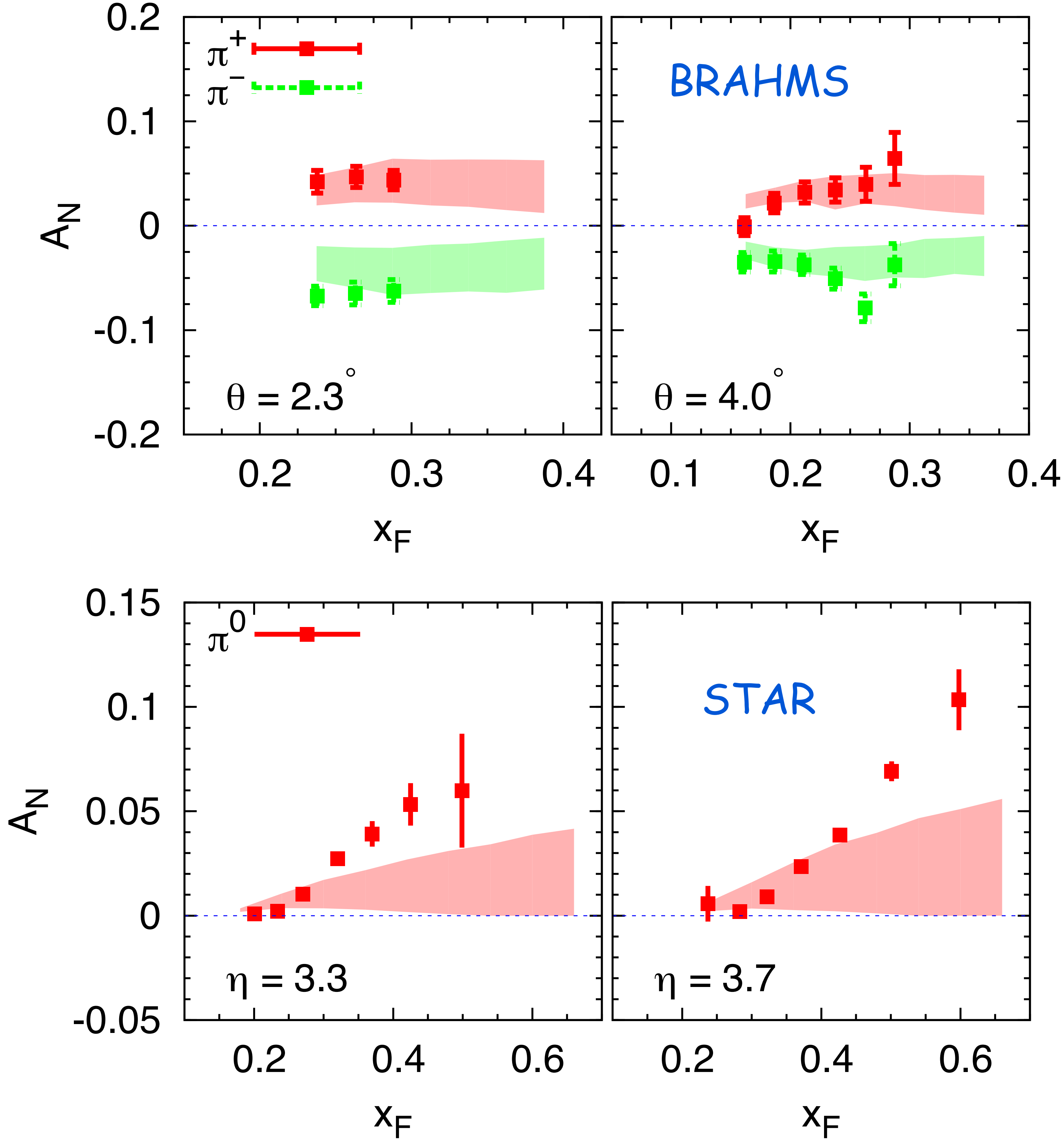
$$\begin{aligned}
[d\sigma^\uparrow - d\sigma^\downarrow]_{\rm Sivers} = & \sum_{q_a, b, q_c, d} \int \frac{dx_a \, dx_b \, dz}{16\,\pi^2 \, x_a \, x_b \, z^2 s} \, d^2\boldsymbol{k}_{\perp a} \, d^2\boldsymbol{k}_{\perp b} \, d^3\boldsymbol{p}_\perp \, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c)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

$\longrightarrow$ 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

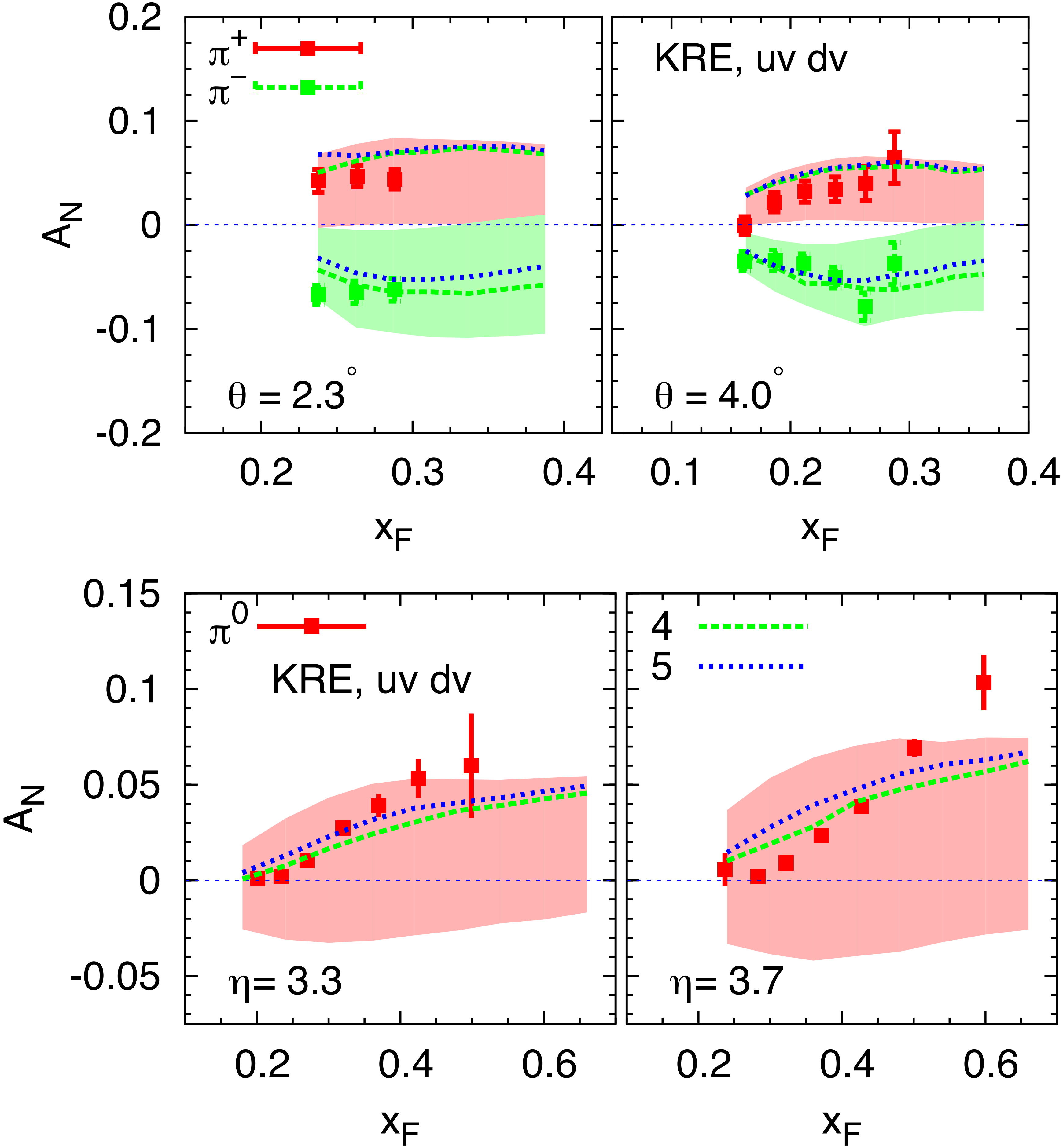


A_N and Collins effect alone

Collins contribution to A_N, according to extration from SIDIS and e+e- data.

Problems at $x_F \gtrsim 0.3$

M.A, M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, PR D86 (2012) 074032

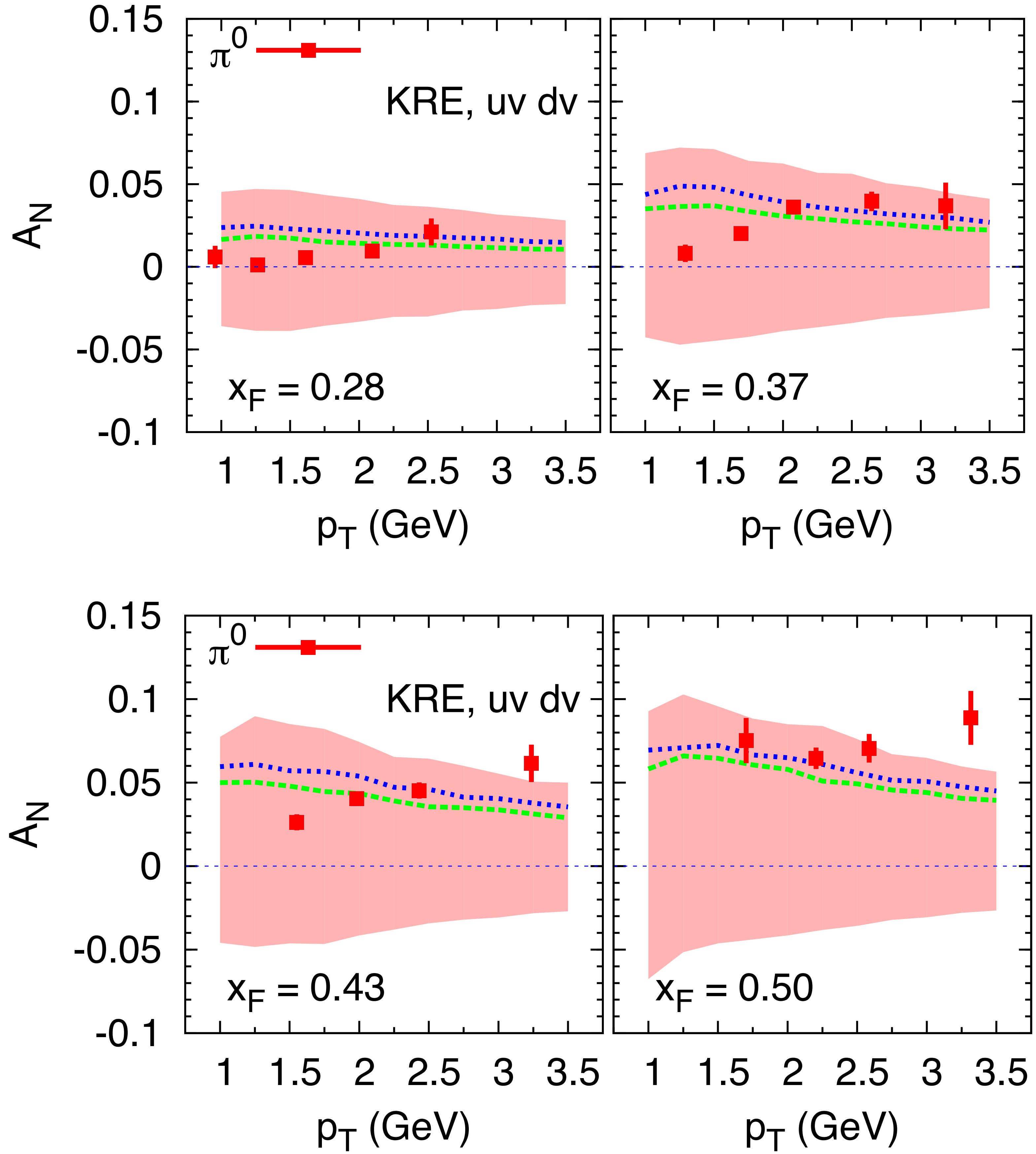


A_N vs. x_F and Sivers effect alone

Sivers contribution to A_N, according to extration from SIDIS data.

can be large enough

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



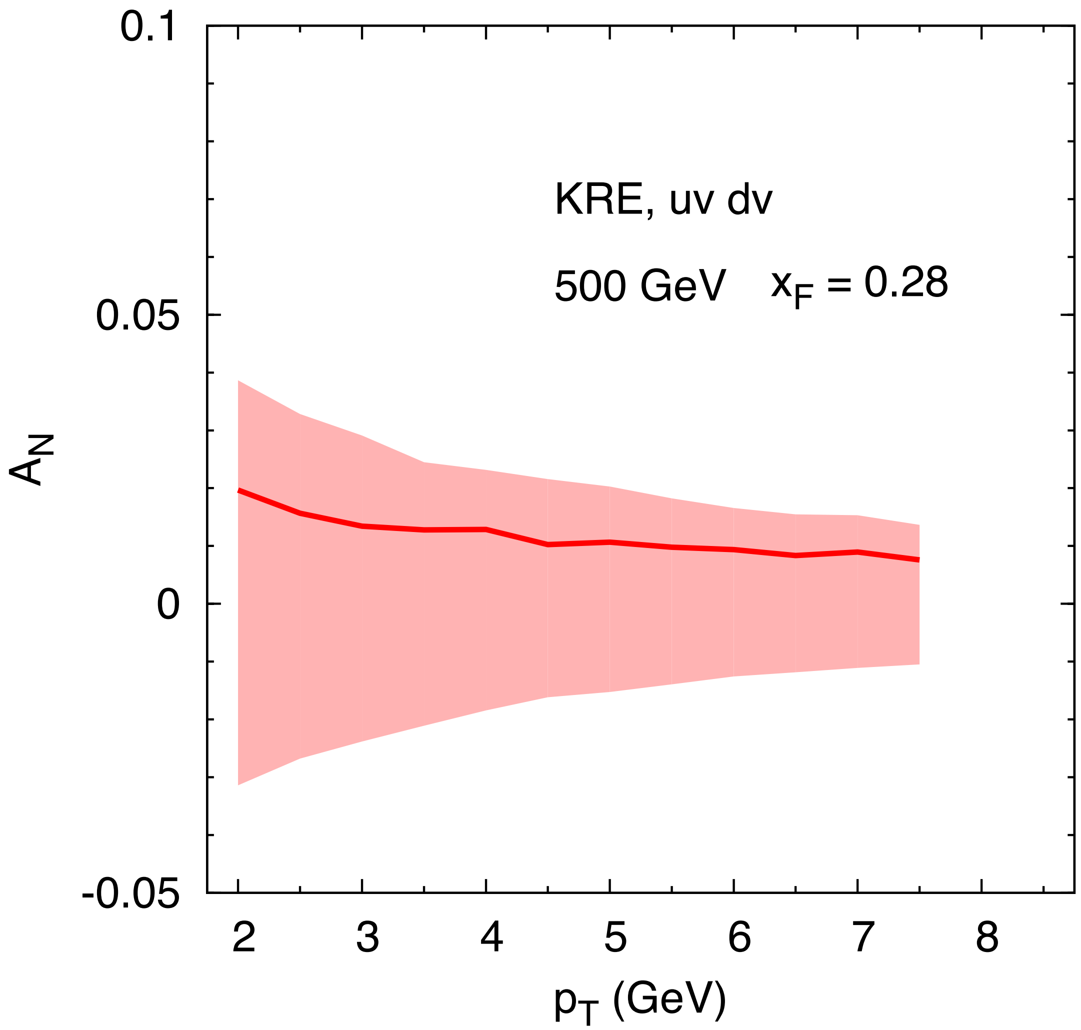
A_N vs. P_T and Sivers effect alone

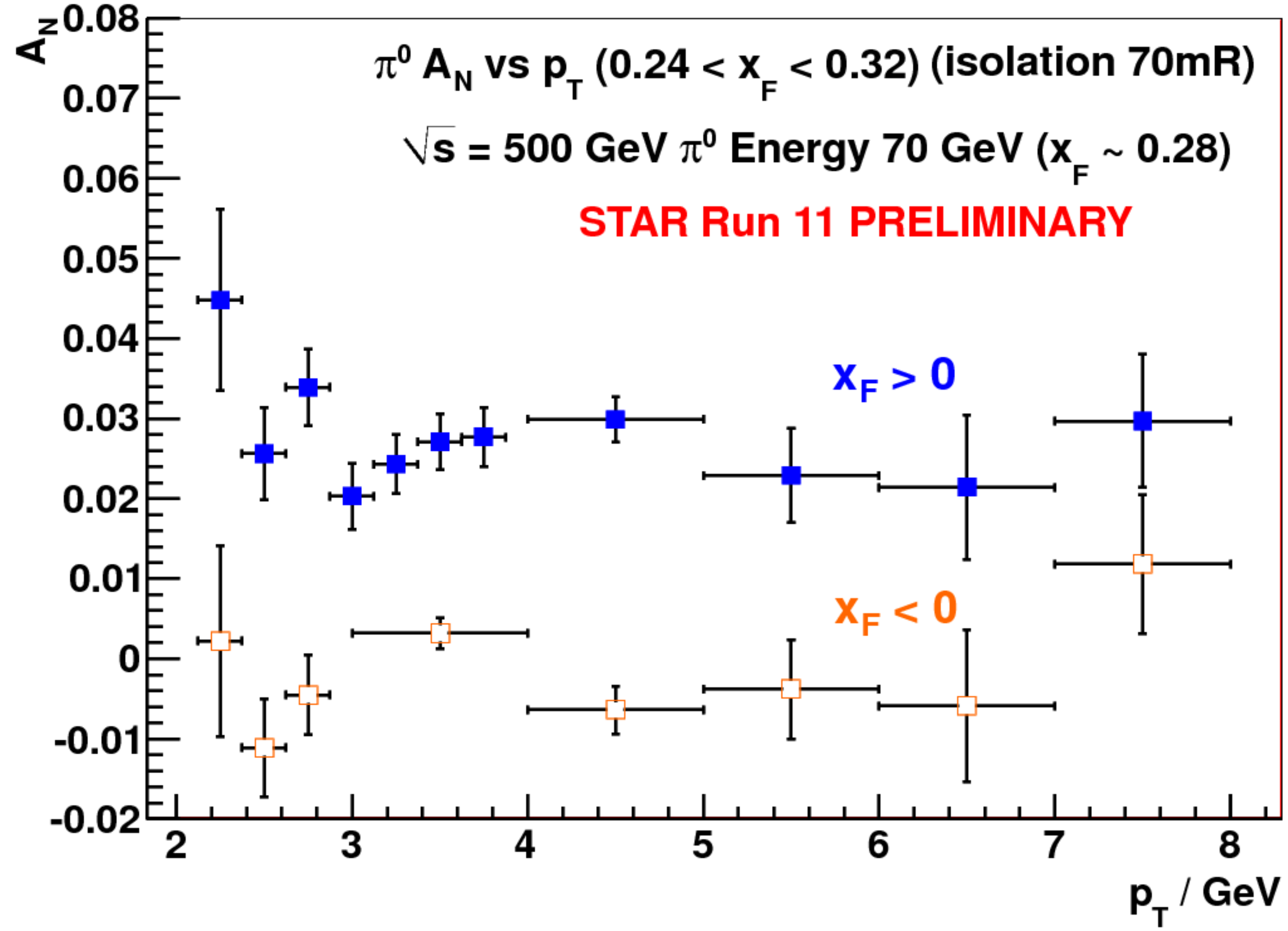
Sivers contribution to A_N, according to extration from SIDIS data.

can be large enough

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

U. D'Alesio





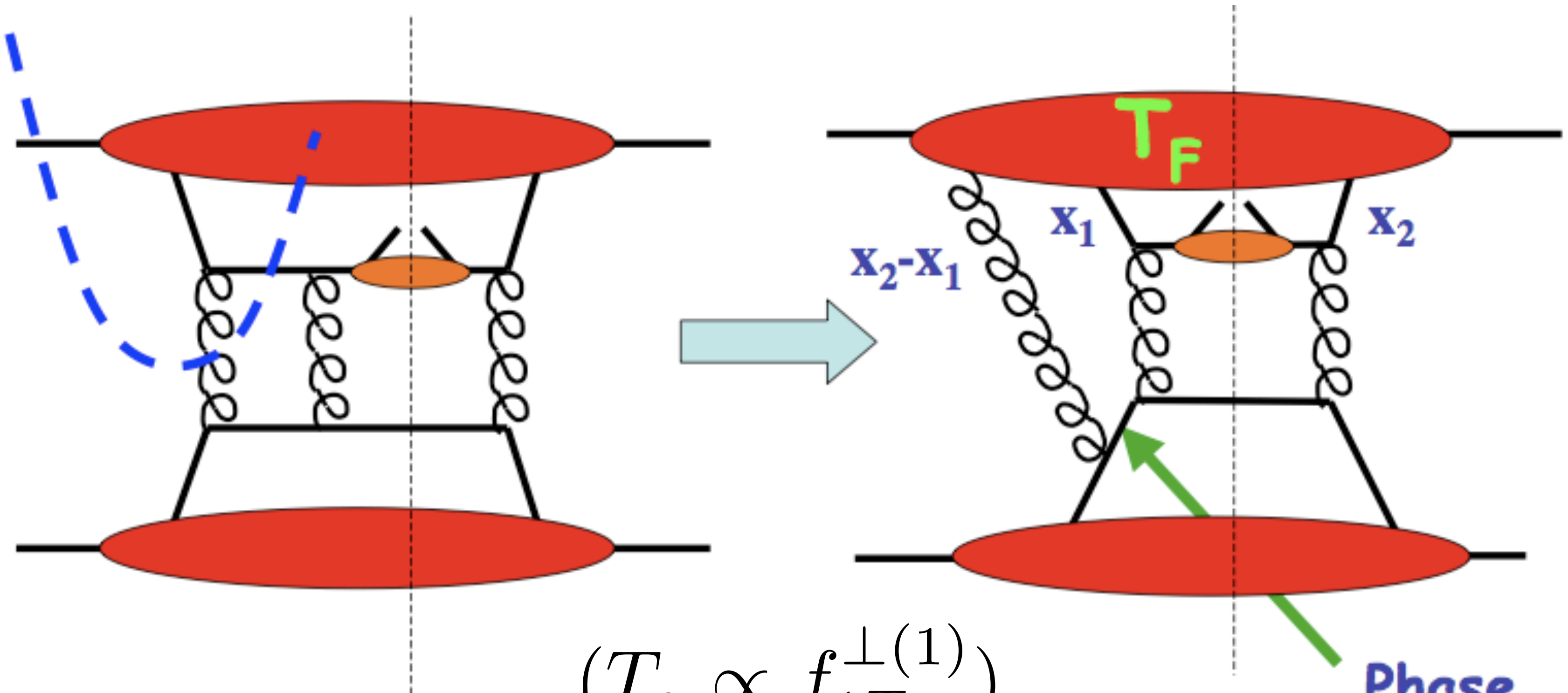
even P_T dependence of latest STAR data could be explained

2. Higher-twist partonic correlations

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

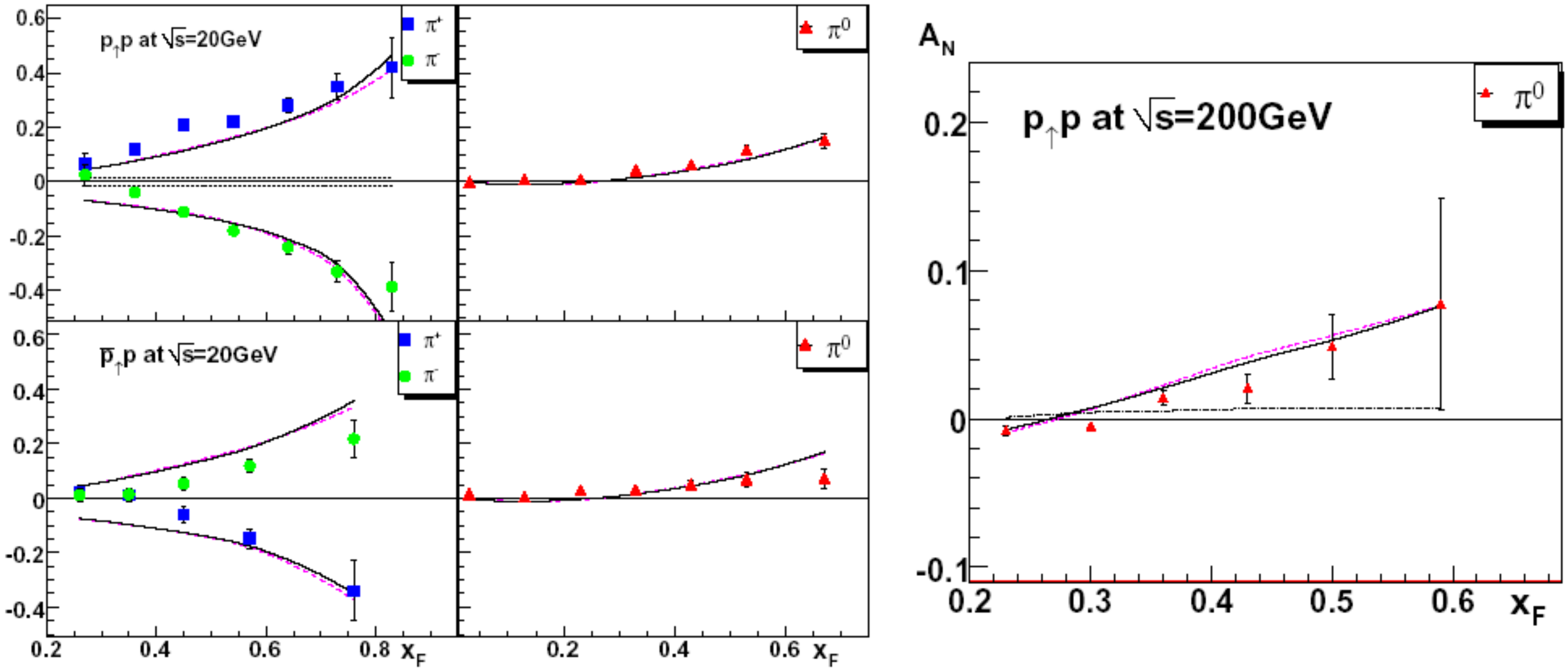
higher-twist partonic correlations - factorization OK

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



$(T_a \propto f_{1T}^{\perp(1)})$

possible project: compute T_a using SIDIS extracted Sivers functions



fits of E704 and STAR data

Kouvaris, Qiu, Vogelsang, Yuan

sign mismatch

(Kang, Qiu, Vogelsang, Yuan)

compare

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

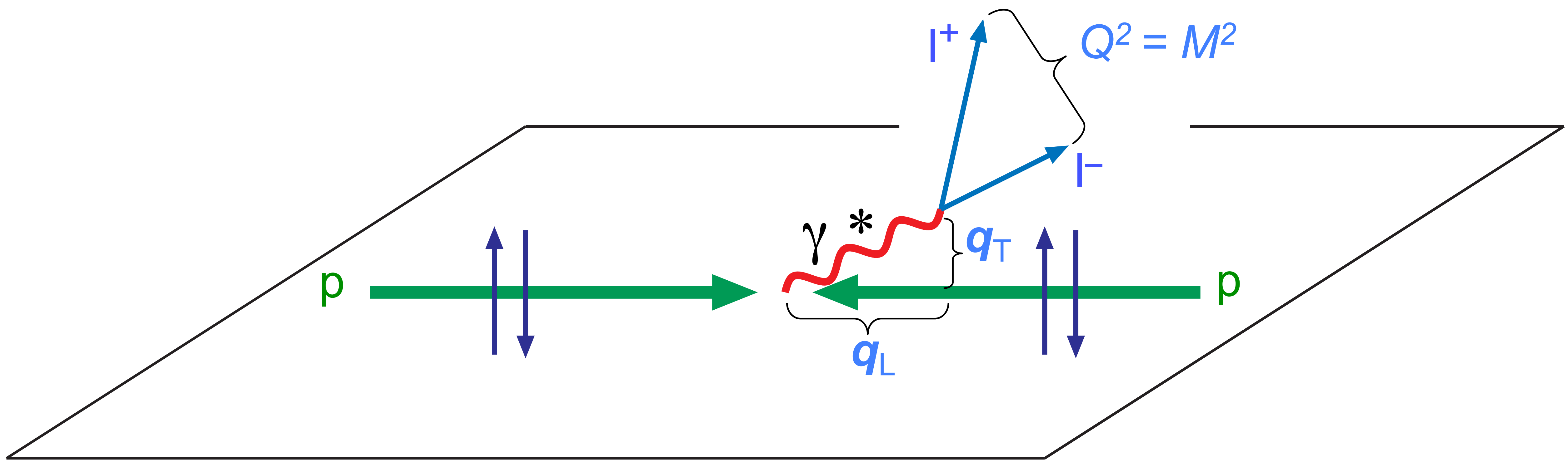
as extracted from fitting A_N data, with that obtained by inserting in the the above relation the SIDIS extracted Sivers functions

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

node in the Sivers function (Boer, Kang, Prokudin...)?
Study it at large x values

Drell-Yan processes - TMDs



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

cross-section: most general pp leading-twist expression

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\times$$

S. Arnold, A. Metz and M. Schlegel, arXiv:0809.2262 [hep-ph]

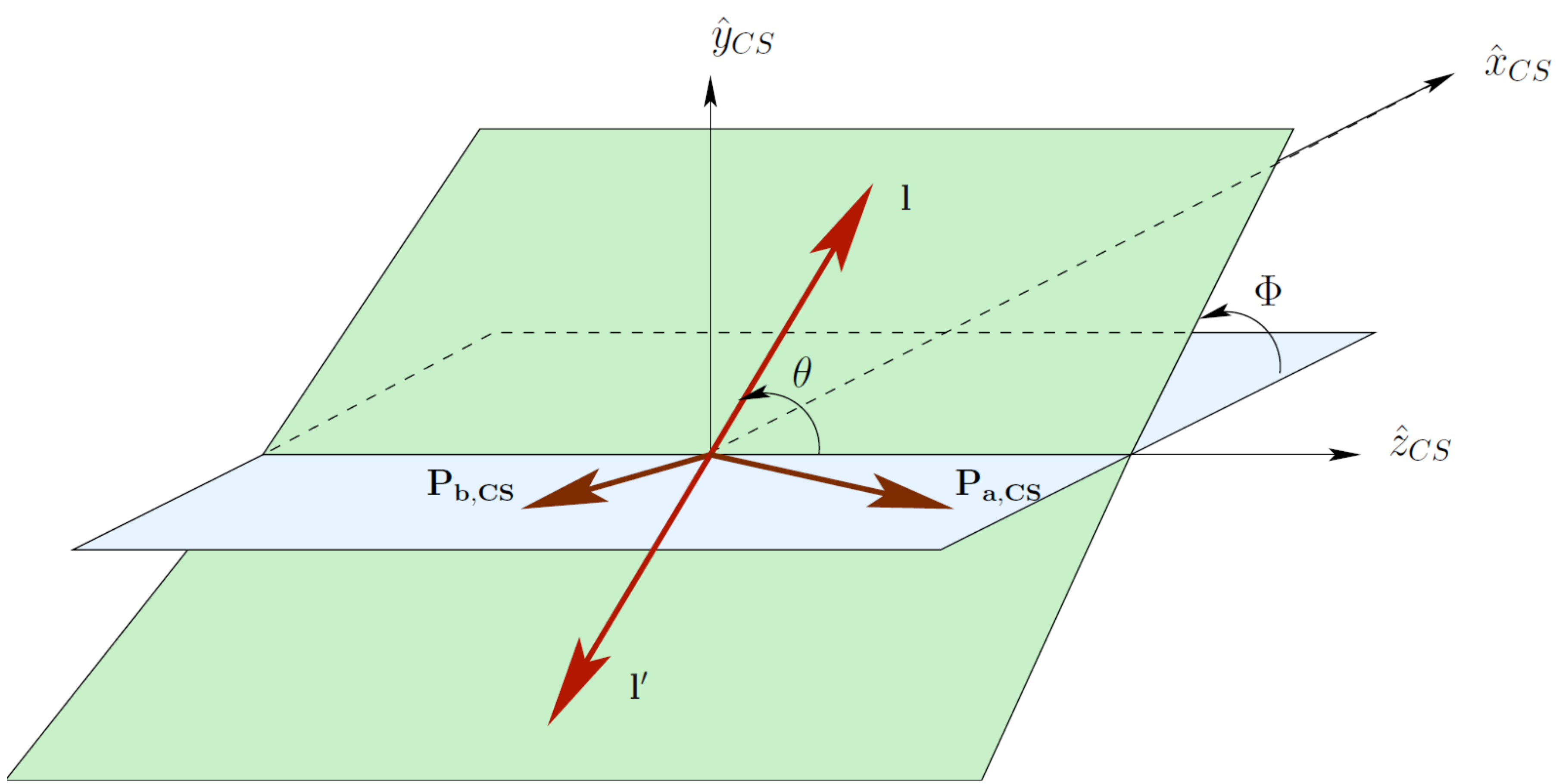
$$\begin{aligned}
&\Big\{\Big((1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi}\Big)\\
&+\ S_{aL}\Big(\sin 2\theta\sin\phi\,F_{LU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LU}^{\sin 2\phi}\Big)\\
&+\ S_{bL}\Big(\sin 2\theta\sin\phi\,F_{UL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UL}^{\sin 2\phi}\Big)\\
&+\ |\vec{S}_{aT}|\Big[\sin\phi_a\Big((1+\cos^2\theta)\,F_{TU}^1 + (1-\cos^2\theta)\,F_{TU}^2 + \sin 2\theta\cos\phi\,F_{TU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TU}^{\cos 2\phi}\Big)\\
&\qquad + \cos\phi_a\Big(\sin 2\theta\sin\phi\,F_{TU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TU}^{\sin 2\phi}\Big)\Big]\\
&+\ |\vec{S}_{bT}|\Big[\sin\phi_b\Big((1+\cos^2\theta)\,F_{UT}^1 + (1-\cos^2\theta)\,F_{UT}^2 + \sin 2\theta\cos\phi\,F_{UT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UT}^{\cos 2\phi}\Big)\\
&\qquad + \cos\phi_b\Big(\sin 2\theta\sin\phi\,F_{UT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{UT}^{\sin 2\phi}\Big)\Big]\\
&+\ S_{aL}\,S_{bL}\Big((1+\cos^2\theta)\,F_{LL}^1 + (1-\cos^2\theta)\,F_{LL}^2 + \sin 2\theta\cos\phi\,F_{LL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LL}^{\cos 2\phi}\Big)\\
&+\ S_{aL}\,|\vec{S}_{bT}|\Big[\cos\phi_b\Big((1+\cos^2\theta)\,F_{LT}^1 + (1-\cos^2\theta)\,F_{LT}^2 + \sin 2\theta\cos\phi\,F_{LT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{LT}^{\cos 2\phi}\Big)\\
&\qquad\quad + \sin\phi_b\Big(\sin 2\theta\sin\phi\,F_{LT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LT}^{\sin 2\phi}\Big)\Big]\\
&+\ |\vec{S}_{aT}|\,S_{bL}\Big[\cos\phi_a\Big((1+\cos^2\theta)\,F_{TL}^1 + (1-\cos^2\theta)\,F_{TL}^2 + \sin 2\theta\cos\phi\,F_{TL}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TL}^{\cos 2\phi}\Big)\\
&\qquad\quad + \sin\phi_a\Big(\sin 2\theta\sin\phi\,F_{TL}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TL}^{\sin 2\phi}\Big)\Big]\\
&+\ |\vec{S}_{aT}|\,|\vec{S}_{bT}|\Big[\cos(\phi_a+\phi_b)\Big((1+\cos^2\theta)\,F_{TT}^1 + (1-\cos^2\theta)\,F_{TT}^2 + \sin 2\theta\cos\phi\,F_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TT}^{\cos 2\phi}\Big)\\
&\qquad\quad + \cos(\phi_a-\phi_b)\Big((1+\cos^2\theta)\,\bar{F}_{TT}^1 + (1-\cos^2\theta)\,\bar{F}_{TT}^2 + \sin 2\theta\cos\phi\,\bar{F}_{TT}^{\cos\phi} + \sin^2\theta\cos 2\phi\,\bar{F}_{TT}^{\cos 2\phi}\Big)\\
&\qquad\quad + \sin(\phi_a+\phi_b)\Big(\sin 2\theta\sin\phi\,F_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TT}^{\sin 2\phi}\Big)\\
&\qquad\quad + \sin(\phi_a-\phi_b)\Big(\sin 2\theta\sin\phi\,\bar{F}_{TT}^{\sin\phi} + \sin^2\theta\sin 2\phi\,\bar{F}_{TT}^{\sin 2\phi}\Big)\Big]\Big\}
\end{aligned}$$

Drell-Yan

48 structure functions ...

Case of one polarized nucleon only

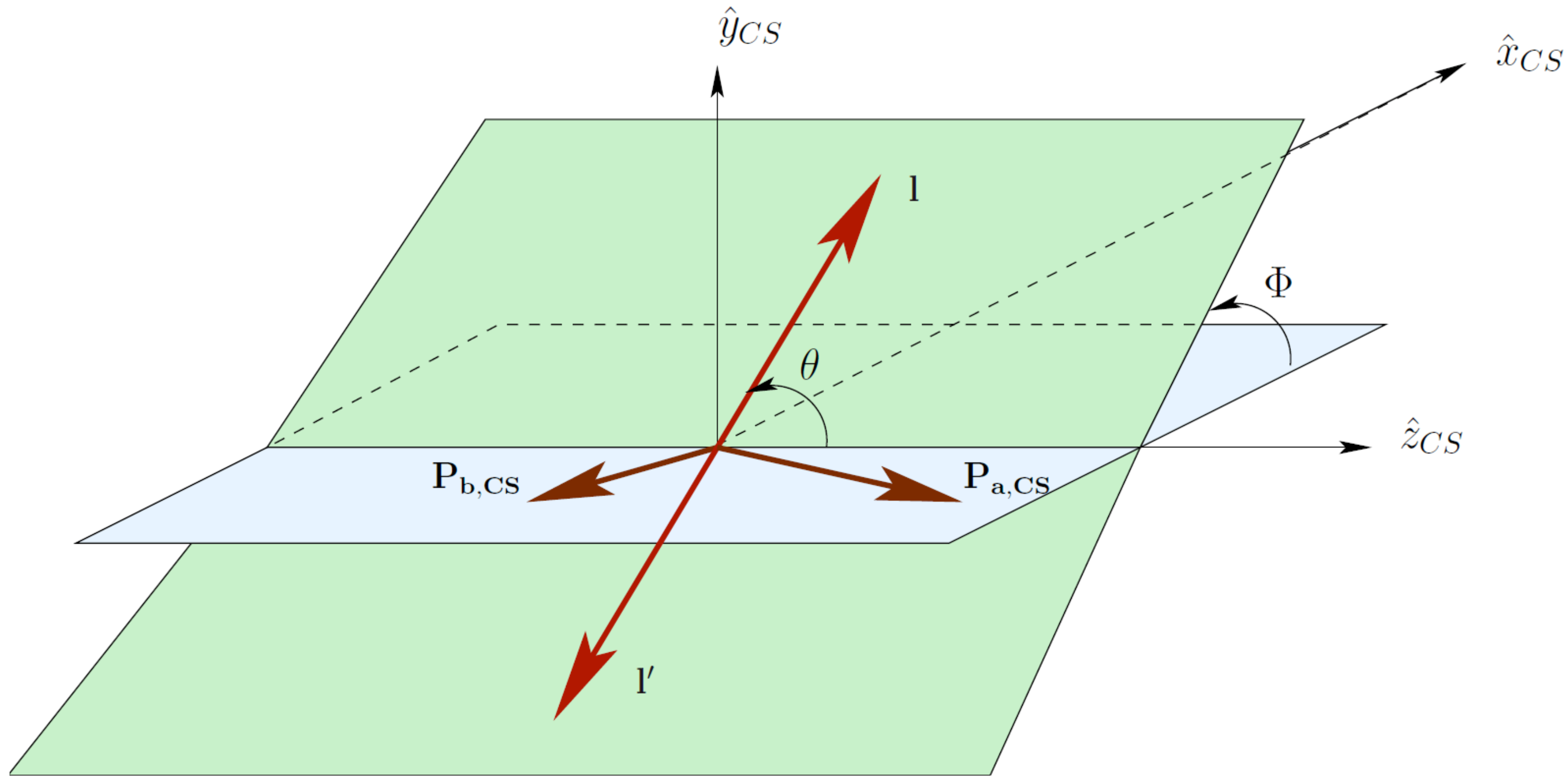
$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} \;=\; & \frac{\alpha^2}{\Phi\,q^2}\Big\{(1+\cos^2\theta)\,F_U^1 + (1-\cos^2\theta)\,F_U^2 + \sin 2\theta\cos\phi\,F_U^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_U^{\cos 2\phi} \\
& + S_L\left(\sin 2\theta\sin\phi\,F_L^{\sin\phi}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



Collins-Soper frame

Unpolarized cross section already very interesting

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

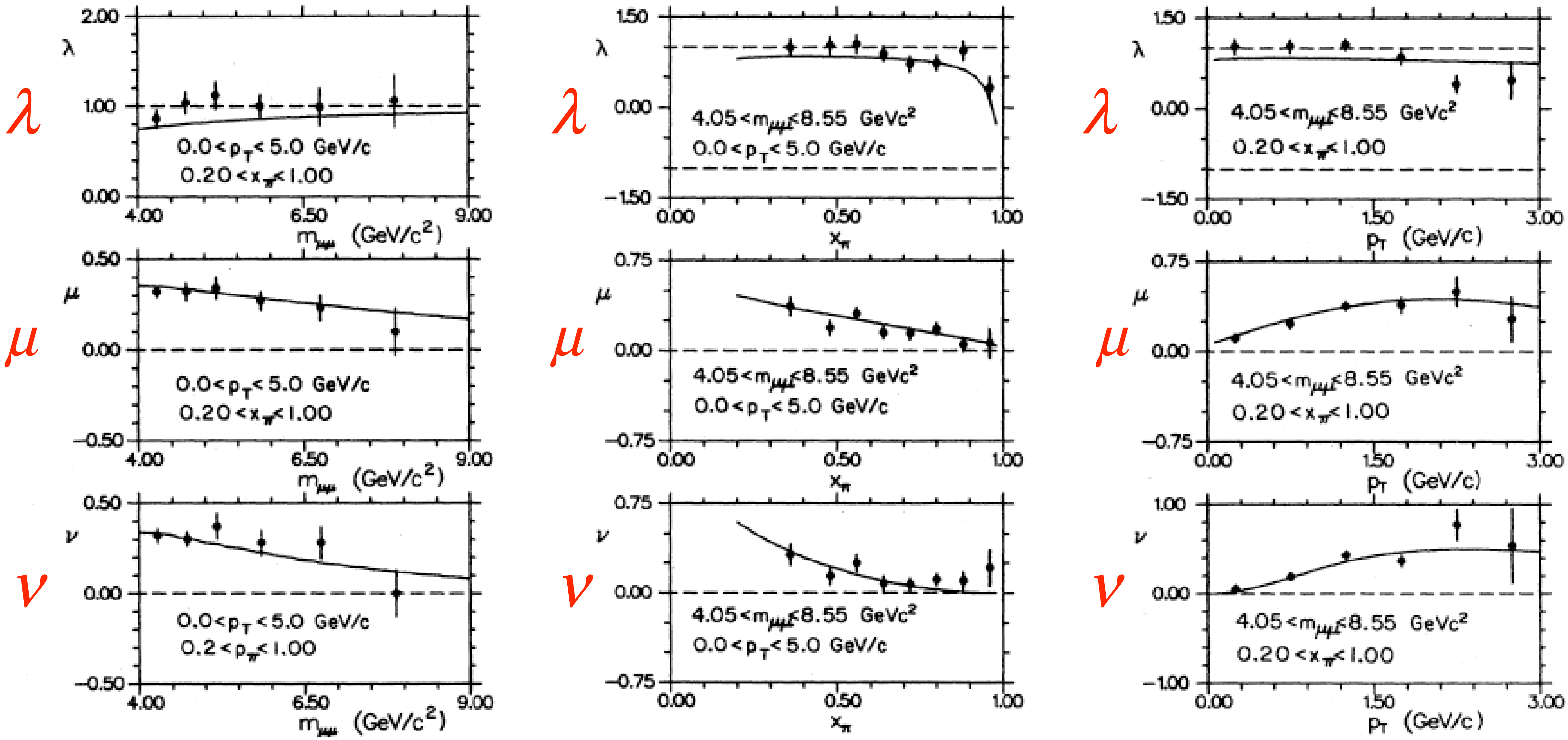


Collins-Soper frame

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

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ — Phys. Rev. D 39 (1989) 92



$m_{\mu\mu}$ (GeV/c^2) $\quad x_\pi \quad p_T$ (GeV/c)

$$\lambda \neq 1 \quad \mu, \nu \neq 0 \quad 1 - \lambda - 2\nu \neq 0$$

(valence quarks ?)

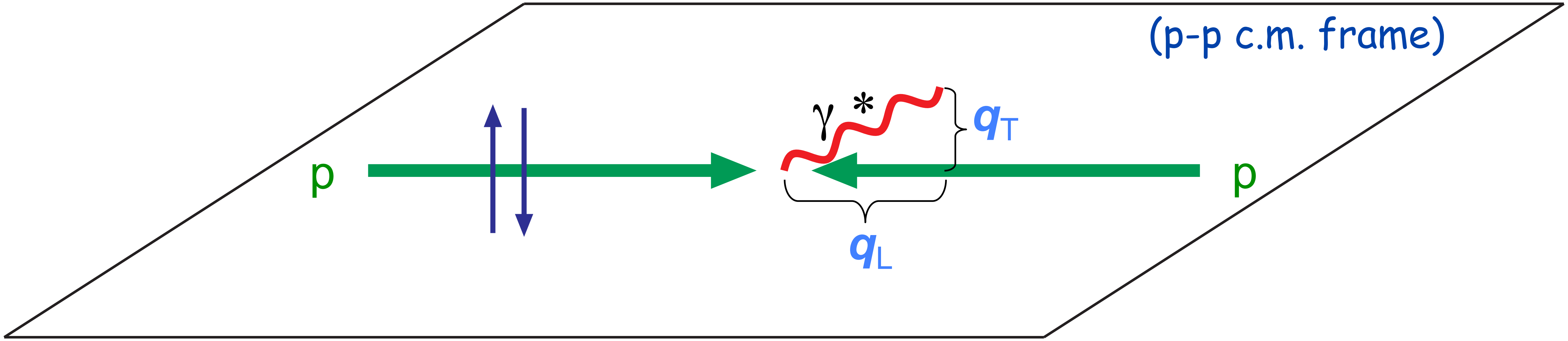
Sivers effect in D-Y processes

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

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

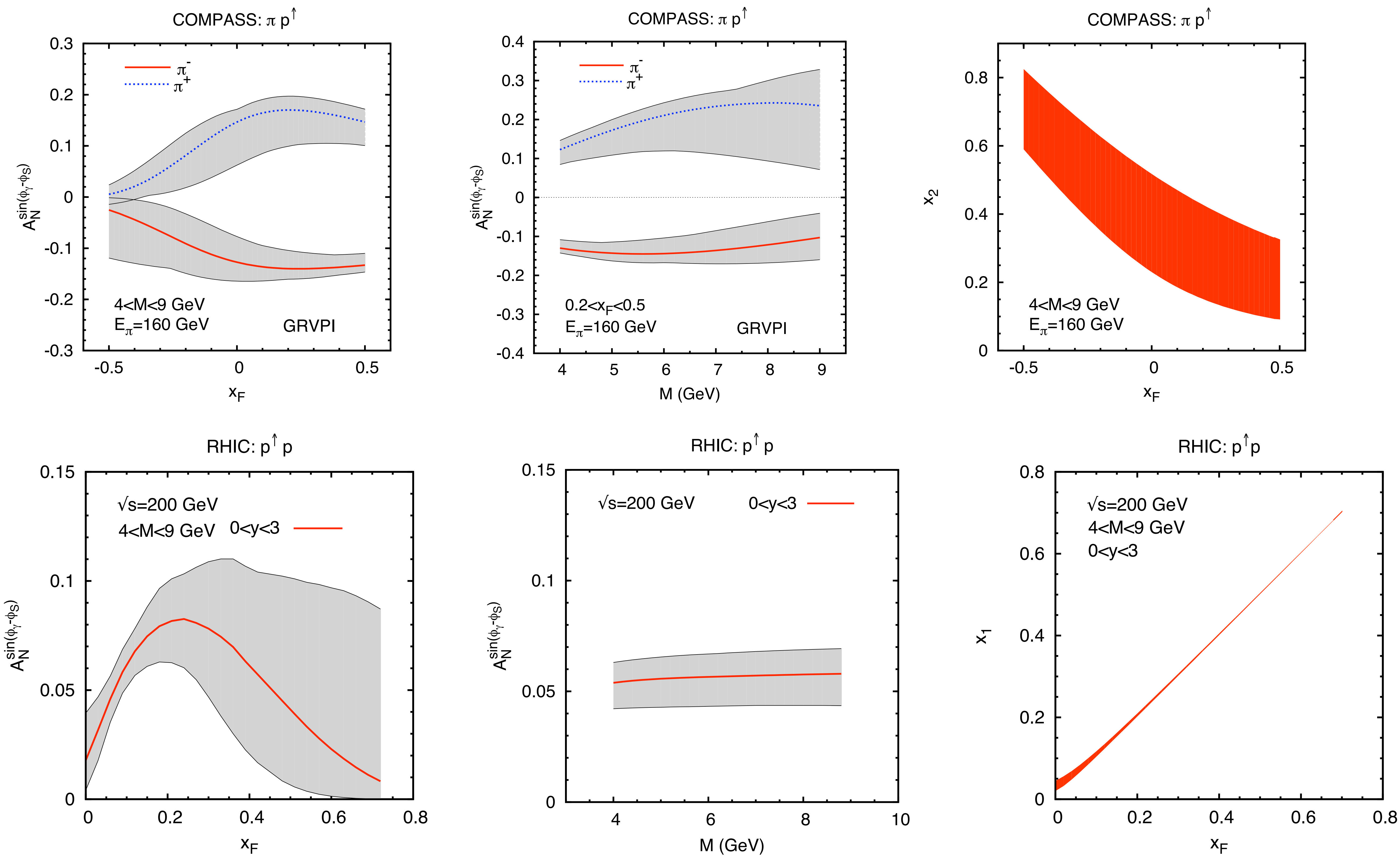
$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$

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



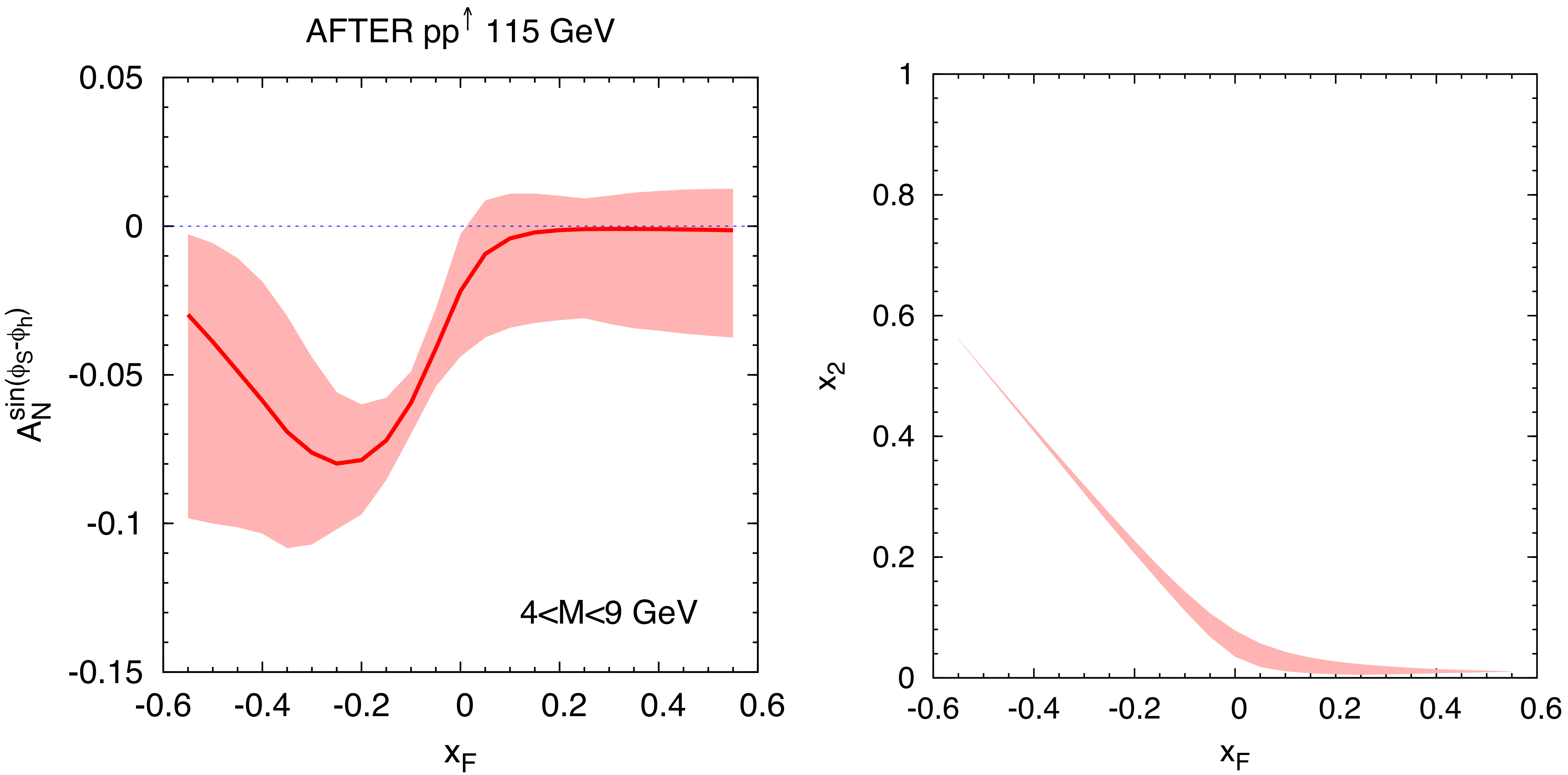
Predictions for A_N

Sivers functions as extracted from SIDIS data, **with opposite sign**



M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, e-Print: arXiv:0901.3078

expected Sivers asymmetry in D-Y@AFTER, sign change, no TMD evolution



A_N: a simple, unexpected, single spin asymmetry measured in many experiments

its understanding is not easy and reveals subtle aspects of QCD dynamics

a global study of transverse spin asymmetries in SIDIS, large P_T and D-Y processes should lead to a better knowledge of the 3-dimensional nucleon structure

THANK YOU!