Transverse Momentum Dependent **distributions:Theory...Phenomenology, future**

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Outline

- Motivations:
  Understanding transverse degrees of freedom in a hadron: $\boldsymbol{s}_\perp$ and $\boldsymbol{k}_\perp$.
  h_1: wanted!
  TMD's: tool to SSA; window on partonic orbital angular momentum?
- Help from:
  $f_{1T}^\perp$ (Sivers), $H_1^\perp$ (Collins), $h_1^\perp$ (Boer-Mulders), $D_{1T}^\perp$ (polarizing ff).
  (Other leading twist TMD's not considered here)
- Strategy: TMD $\otimes$ process $\otimes$ kinematics(set-ups)
- SSA and DSA: clear vs. involved cases (SIDIS, DY, e^+e^-, $pp \to CX$)
  present vs. future
- Summary

- Formal issues of TMD's and their still open problems (gauge invariant definitions, universality, factorization, evolution, resummation, soft factor, models...) accounted in Bacchetta and Metz's talks.

- Focus on TMD's within a phenomenological approach:
which, where and how.

1. Processes
2. kinematics (role of phases)

- Short overview on "standard" cases;
- Deeper insight in cases where there is a not clear access to TMD's.

Hadronic Processes

SIDIS $\ell p^{\uparrow} \to \ell' h X$**:** A_{UT}

- ok $k_\perp$ factorization (Ji, Ma, Yuan '04, '05)
- LO: partons≡ quarks
- azimuthal dependences:
- $\phi_S - \phi_h \to f_{1T}^{\perp}$ (Sivers: direct access),
- $\phi_S + \phi_h \to h_1 \otimes H_1^{\perp}$ (transversity - Collins)

a) $h = \pi$: basic case

b) $h = K^+(u\bar{s}), K^-(\bar{u}s)$ same but
access to strange $f_{1T}^{\perp}$: $D_s(K)$
different flavour weighting even in the ud sector:
i.e. $D_u(\pi^-)/D_{\bar{u}}(\pi^-) < D_u(K^-)/D_{\bar{u}}(K^-) \to$ complementary role

- experim. data from: HERMES, COMPASS, CLAS

- analysis: Collins et al. '05 , Efremov et al. '05, Vogelsang and Yuan '05 , Anselmino et al. '05
accounted in Schweitzer, Boglione, Elschenbroich talks

$e^+e^- \to \pi\pi X$

- ok $k_\perp$ factorization
- LO: partons $\equiv$ quarks
- azimuthal dependences:

$\cos(2\phi)$: $H_1^\perp H_1^\perp$ (Collins: direct access)

data from BELLE

analysis: Efremov et al. ’06, Anselmino et al. (in progress)

accounted in Schweitzer, Boglione, Seidl talks

DY: $pp \rightarrow \ell^+\ell^- X$ **:** A_{TT}**,** A_N

$p^\uparrow p^\uparrow \rightarrow \ell^+\ell^- X$ $[A_{TT}]$:

- azimuthal dependence:

$cos(2\phi)$: $h_1 h_1$ (transversity: direct access)

but

- pp case at large $\sqrt{s}$ (RHIC): sea region and $h_{1\bar{q}} \rightarrow$ small values (statistics)
- $p\bar{p}$ case at moderate $\sqrt{s}$ (PAX): valence and quadratic $h_{1q} \rightarrow$ large values (resummation ?)

estimates: Martin et al. ’98, ’99, Anselmino et al. ’05, Shimizu et al. ’05, Barone et al. ’06

accounted in Metz talk

$p^{\uparrow}p \rightarrow \ell^+\ell^- X \; [A_N]$

- ok $k_\perp$ factorization (Ji, Ma, Yuan '04, '05)
- LO: partons $\equiv$ quarks
- azimuthal dependence:
- $\int d\phi_{e^+e^-} \rightarrow f_{1T}^{\perp}$ (Sivers: direct access)
- $\phi_{e^+e^-} \rightarrow h_1 \otimes h_1^{\perp}$ (transversity - Boer-Mulders)

estimates: Efremov et al. '05, Anselmino et al '03, '05

Unpolarized SIDIS and DY

- azimuthal dependences:

$\cos(2\phi) :\rightarrow h_1^{\perp} \otimes H_1^{\perp}$ (mixed with Cahn effect)
$\cos(2\phi) :\rightarrow h_1^{\perp} \otimes h_1^{\perp}$

estimates: Boer '99, Gamberg et al. '03, Anselmino et al. '05
data: EMC, FNAL-E665

accounted in Boglione, Gamberg, Goldstein talks

$p^{\uparrow}p \to CX$ **:** A_N

- the “dirty” case
- $k_\perp$ factorization still UNKNOWN, but:

1. first data on SSA and more are coming
2. if universality is broken in a stronger way (not simply a change of sign), possible well defined prescription and/or channel selection

- LO: partons $\equiv$ quarks and gluons
- no azimuthal dependences...not really true (see below)
- many effects at work...but help from $C(=\pi, D, \Lambda, \gamma)$ and kinematics (Anselmino et al. ’05, ’06)

a) $p^{\uparrow} p \to \pi X$: $\int$ phases

$f_{1T}^{\perp}$ (Sivers) *****

$h_1 \otimes H_1^{\perp}$ (transversity - Collins) **

$h_1 \otimes h_1^{\perp}$ (transversity - Boer-Mulders) *

$f_{1T}^{\perp} \otimes h_1^{\perp} \otimes H_1^{\perp}$ (Sivers - Boer-Mulders - Collins) -

Phenomenological *ansatz*, Anselmino et al. 05, '06

$$d\sigma^{A,S_A+B,S_B\to C+X} = \sum_{a,b,c,d,\{\lambda\}} \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \otimes \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b})$$
$$\otimes\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\, \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \otimes \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

non-planar partonic scattering: relative azimuthal phases at work!

b) $p^\uparrow p \to DX$: $\int$ phases

$f_{1T}^\perp$ (Sivers) *****

partonic subprocesses: $q\bar{q} \to c\bar{c}$, $gg \to c\bar{c} \Longrightarrow d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow} = 0$

Anselmino et al. 05

c) $pp \to \Lambda^\uparrow X$: P_T $\int$ phases

$D_{1T}^\perp$ (polarizing ff) *****

$h_1^\perp \otimes H_1$ (Boer-Mulders - transversity ff) **

$h_1^\perp \otimes h_1^\perp \otimes D_{1T}^\perp$ (Boer-Mulders - polar. ff) *

UD et al. in progress

$p^{\uparrow}p \rightarrow \gamma X$: A_N $\int$ phases

$f_{1T}^{\perp}$ (Sivers) *****

$h_1 \otimes h_1^{\perp}$ (transversity - Boer-Mulders) ***

- partonic subprocesses: $q\bar{q} \rightarrow \gamma g$, $qg \rightarrow \gamma q$
- one vertex is QED $\rightarrow e_q^2$

$p^{\uparrow}p \rightarrow jetX$: A_N

$f_{1T}^{\perp}$ (Sivers)

$h_1 \otimes h_1^{\perp}$ (transversity - Boer-Mulders)

$p^{\uparrow} p \rightarrow C_1 C_2 X$ **:** A_N

$p^{\uparrow} p \rightarrow jet\, jet\, X$ nearly back-to-back
$f_{1T}^{\perp}$ gluon, Boer and Vogelsang '04

$p^{\uparrow} p \rightarrow \pi\, jet X$
separation of contributions:
$f_{1T}^{\perp}$
$h_1 \otimes H_1^{\perp}$

help from kinematics

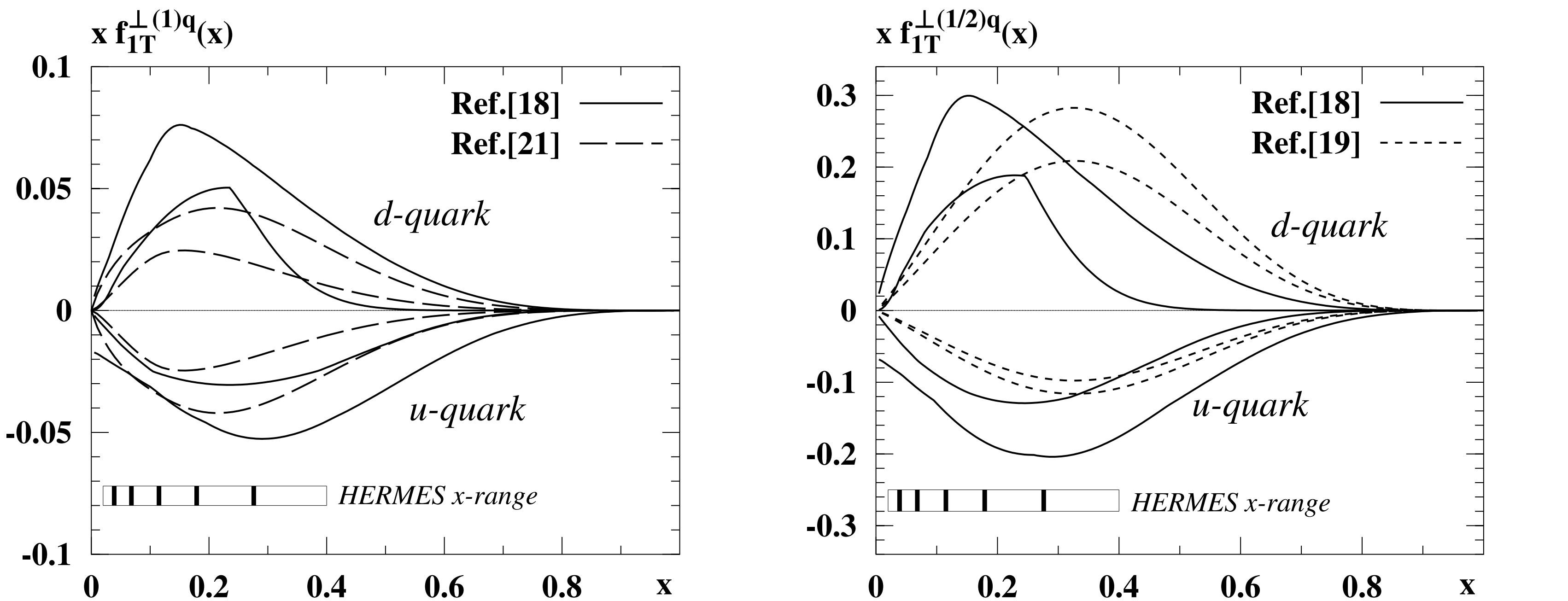
SIDIS and e^+e^-: ok

- a combined analysis $\rightarrow h_1$ and $H_1^\perp$;
- universality of $H_1^\perp$

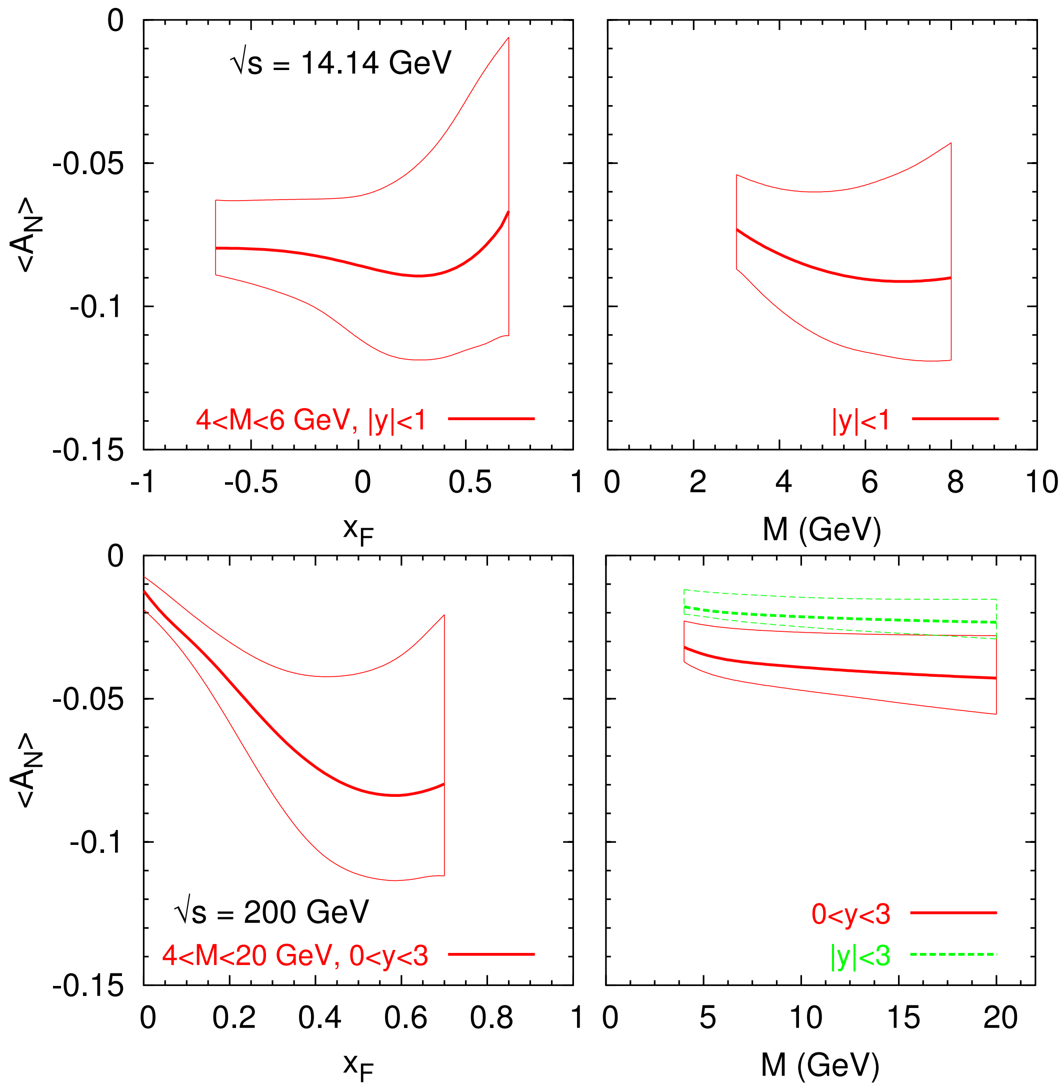
SIDIS and DY: ok

- $f_{1T}^\perp$ for quarks;
- universality (sign change) of $f_{1T}^\perp$: a crucial test.

- new data from COMPASS on H targets and CLAS relevant to cover different and complementary x regions;
- estimates for RHIC, JPARC, PAX;



Comparison of different extractions of the Sivers function (1-σ). [18] Anselmino et al., [19] Vogelsang and Yuan, [21] Collins et al., ’05



Predictions for A_N in DY at PAX and RHIC (Anselmino et al. '05)

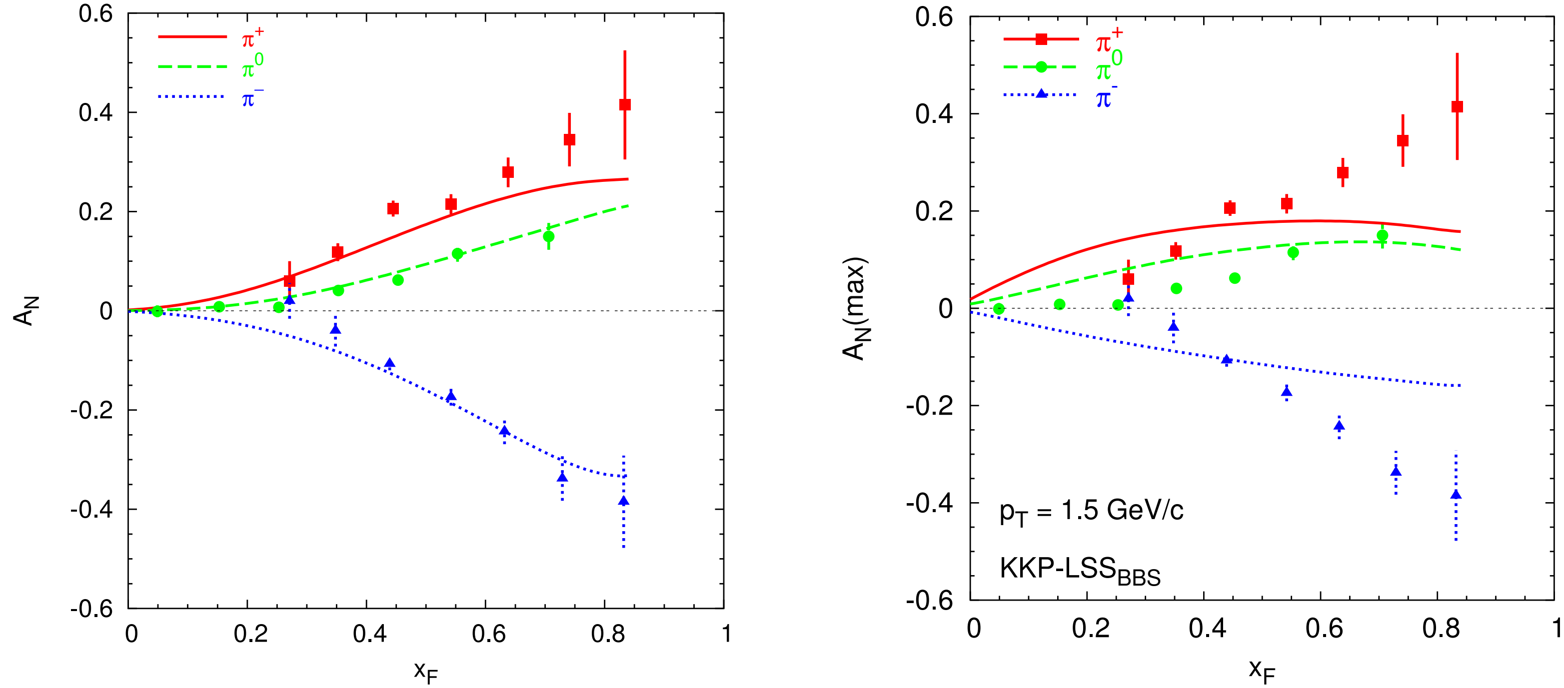
$pp \to \pi X$: high vs. moderate energies, forward, backward and central rapidity

many contributions to A_N, BUT

- Sivers effect alone can describe E704 data (UD and Murgia ’04).
- Collins effect suppressed (other contrib.s vanishing) Anselmino et al. ’05.
- STAR, PHENIX data on π^0 and BRAHMS data on $K^\pm$ can be explained in terms of the Sivers effect (as extracted from E704).
- Forward rapidities: valence dominated;
- Sensitivity to the gluon Sivers function?

a) high energies (RHIC): midrapidity (PHENIX): gluon dominated [backward rapidities less useful due to phases cancellation]

b) moderate energies (PAX, JPARC): backward rapidities gluon dominated and large [mid rap. valence contaminated]



A_N at E = 200 GeV vs. x_F at p_T = 1.5 GeV/c. Data are from [E704] PLB261-264 (1991).

Sivers effect [left] (valence-like).

Collins effect [right](full saturated).

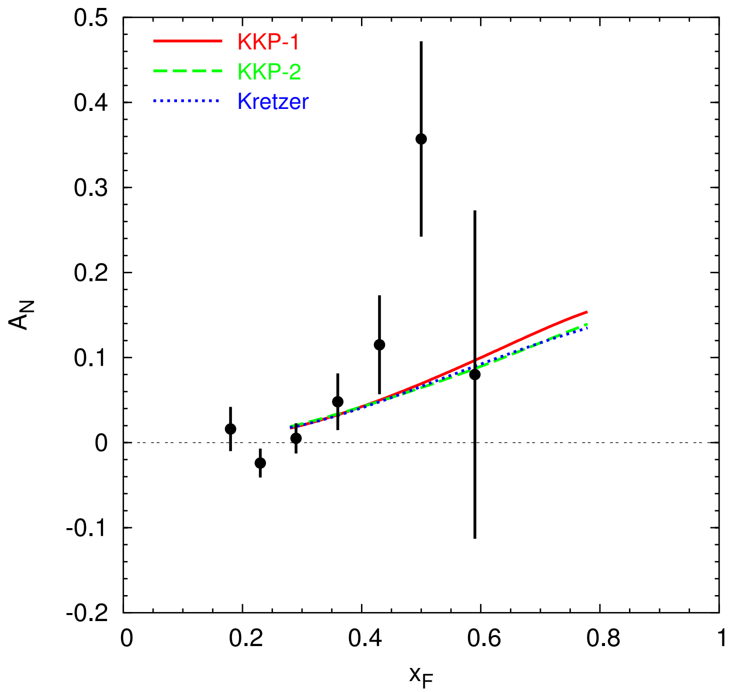
$N_u = +0.40 \; a_u = 2.0 \; b_u = 0.3$

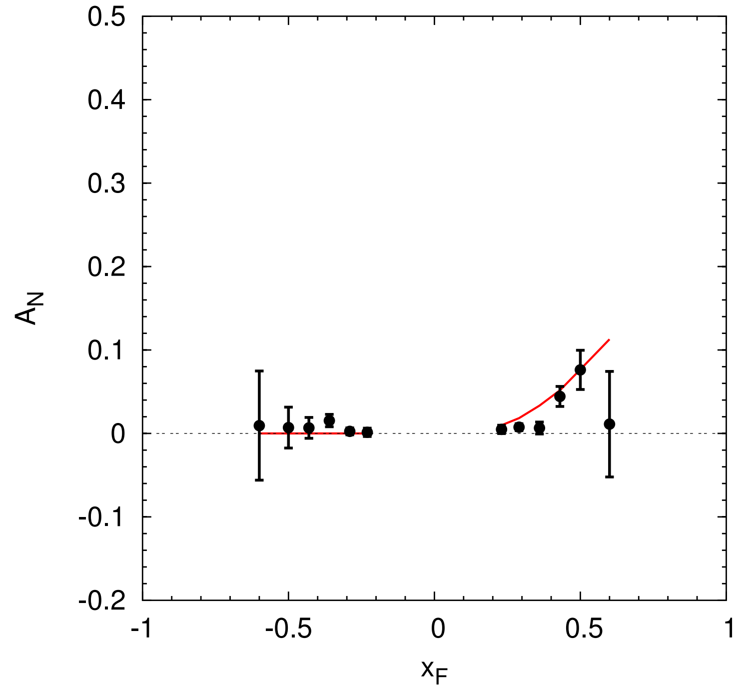
$N_d = -0.90 \; a_d = 2.0 \; b_d = 0.2$

$\simeq$ CONSISTENCY with SIDIS

Transversity funct. and

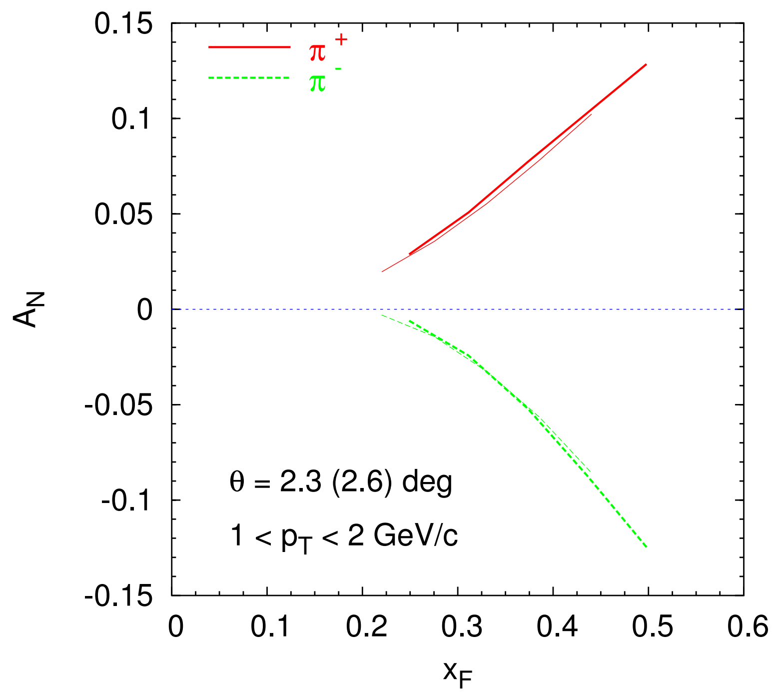
Collins funct. full saturated

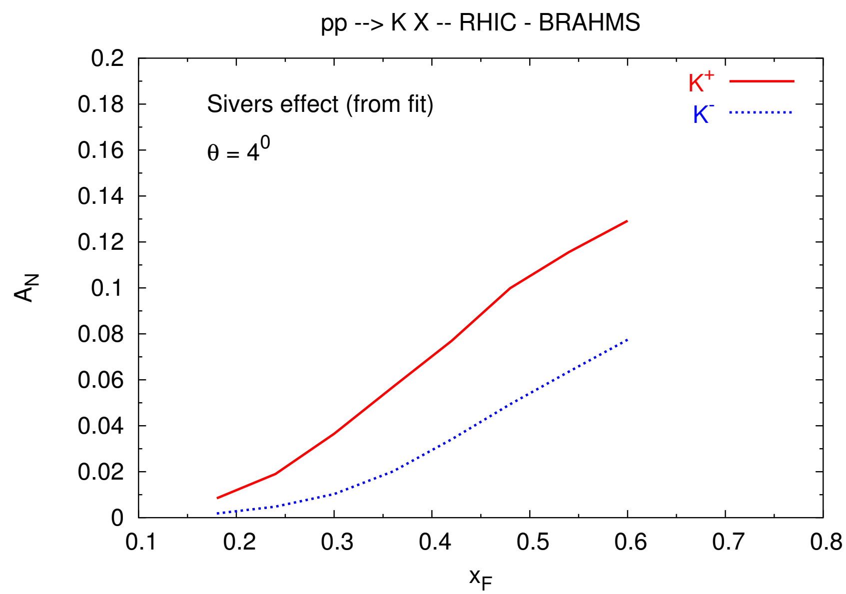




Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone [U.D. and F. Murgia PRD70 (05)] at $\sqrt{s}$ = 200 GeV and $\eta = 3.8$ vs. x_F Data are from [STAR] PRL92 (04).

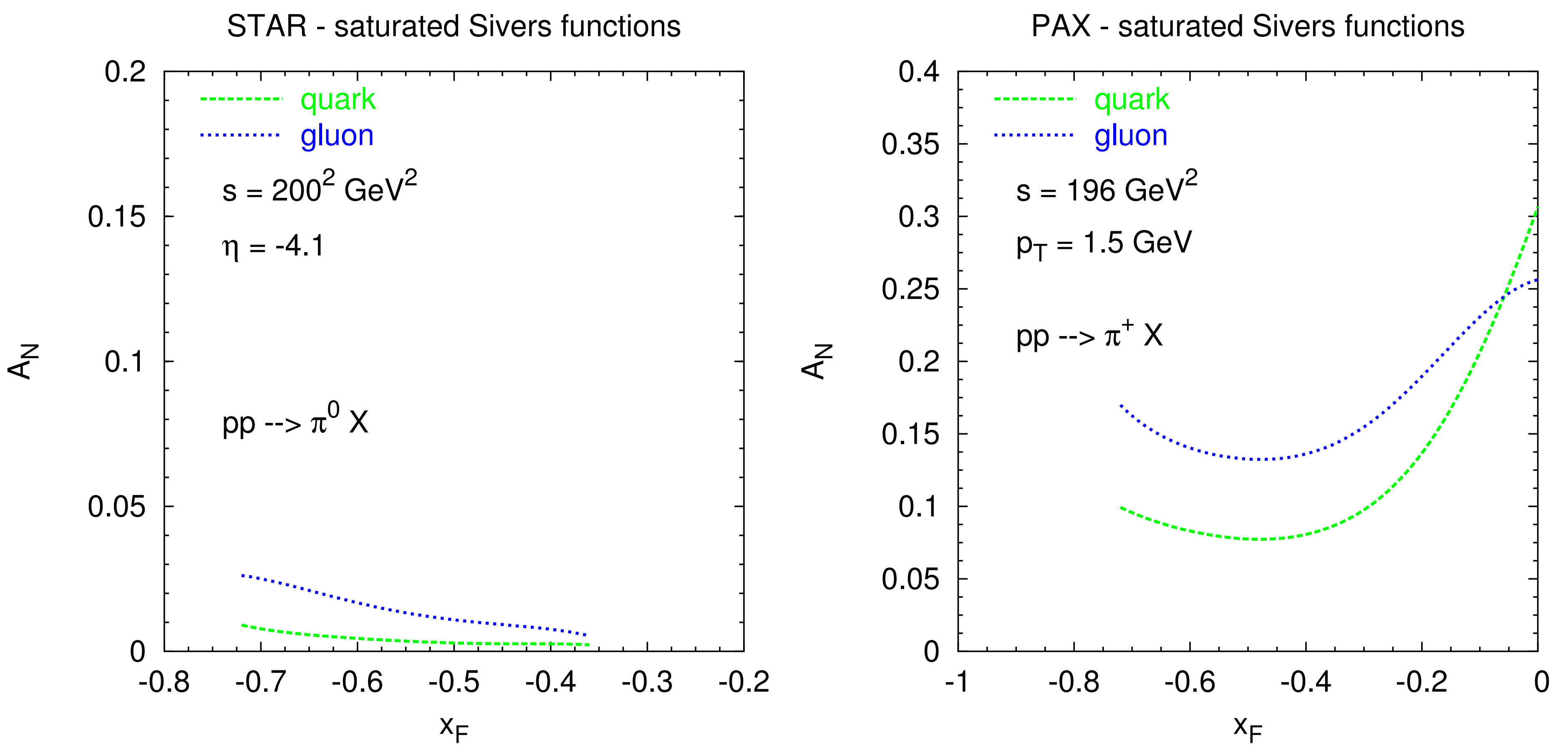
Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 200 GeV and $\eta = 4.1$ vs. x_F. STAR preliminary data.





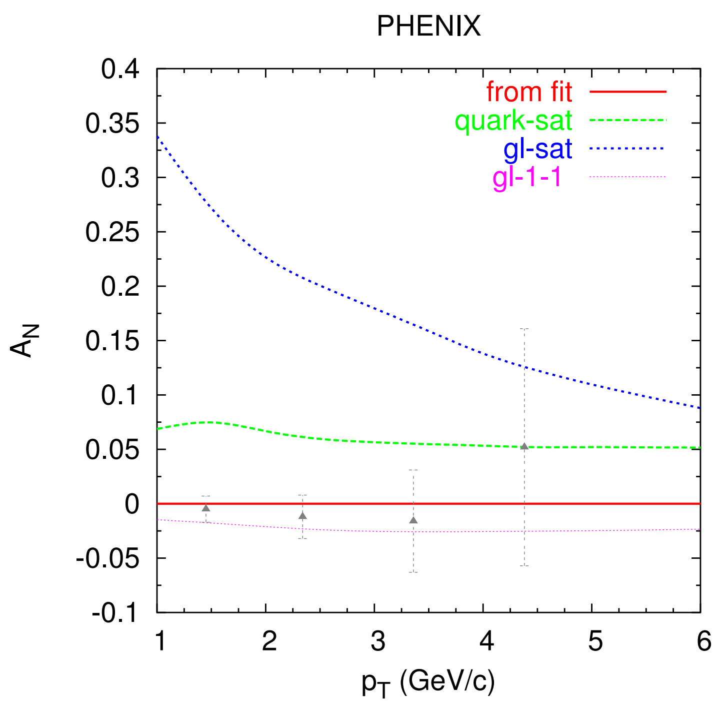
Estimates for $A_N(\pi^{\pm})$ (left) and $A_N(K^{\pm})$ (right) at RHIC.

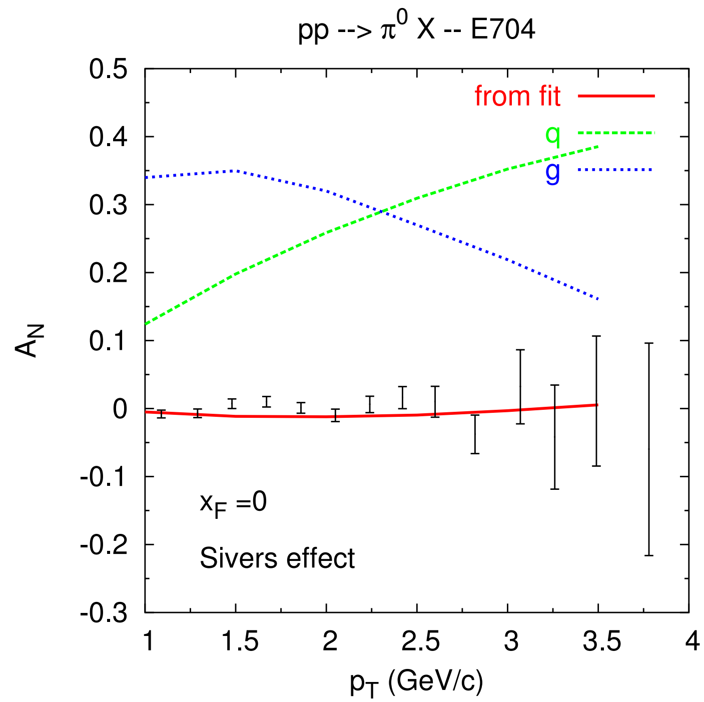
Notice: $K^-(\bar{u}s)$ positive: large non leading ff and no strange Sivers function (as in Anselmino, Murgia '98).



Test of relevance of contributions:

$\frac{2k_\perp}{M}|f_{1T}^{\perp a}| = 2f_{a/p}$ (positivity bound)





PHENIX data (left): Constraint on the gluon $f_{1T}^{\perp}$ at $x < 0.1$:
$\simeq 10^{-3}$-10^{-1} its positivity bound. Anselmino et al., in preparation.
(E704, right)

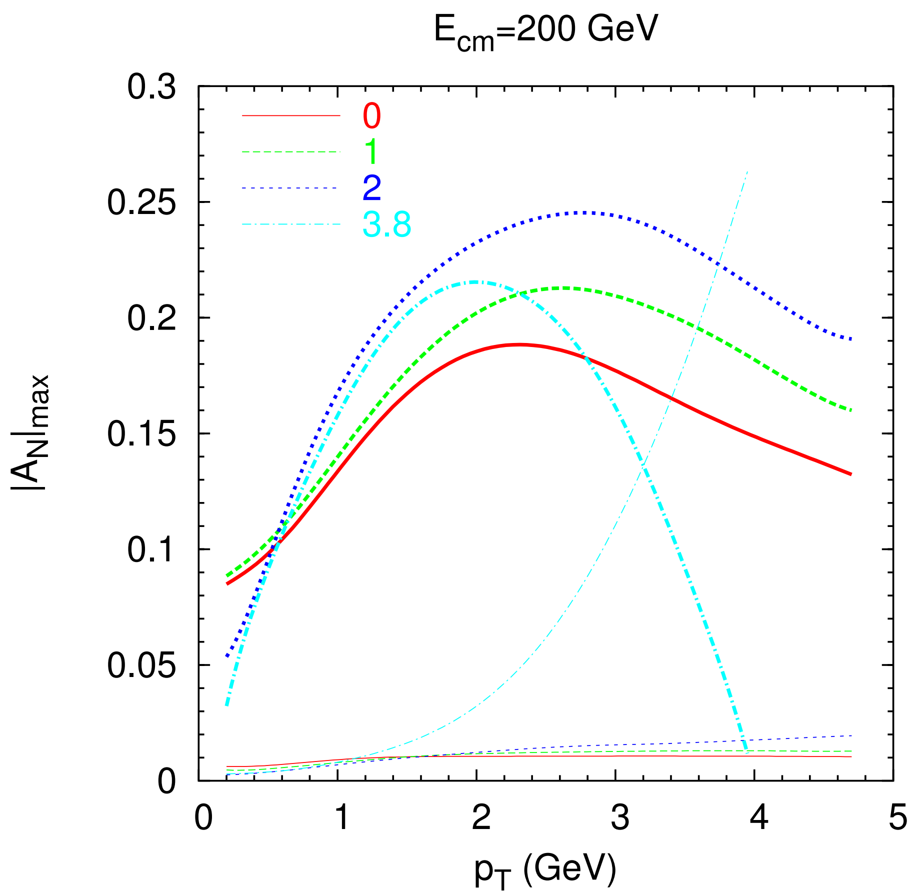
ther (future) measurements:

$p^{\uparrow}p \rightarrow DX$: high vs. moderate energies, pp vs. $p\bar{p}$

Remember:

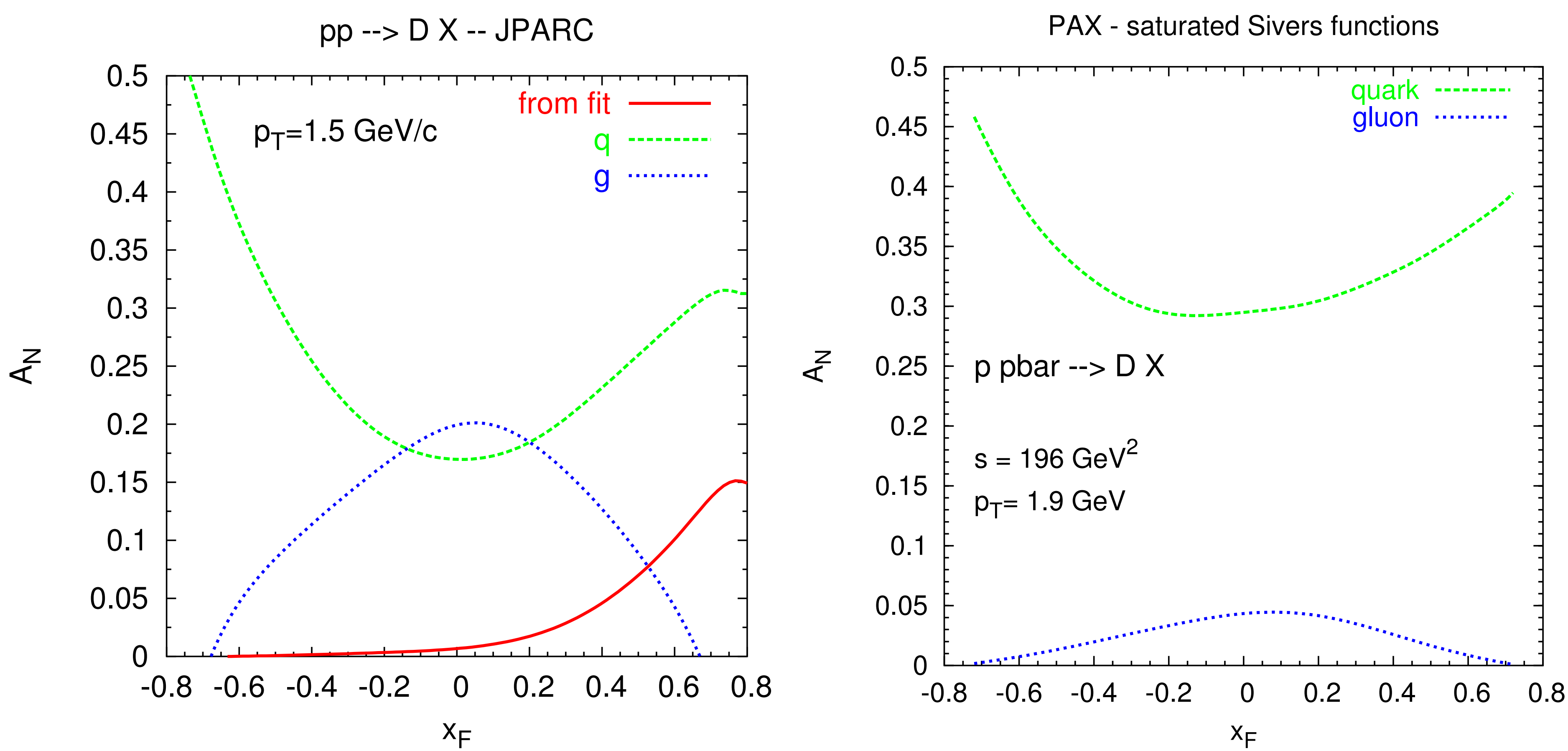
for D: $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$

Test of the relevance of different contributions: saturation of positivity bounds



Maximized $A_N(D)$ at RHIC, $\sqrt{s} = 200$ GeV.

Sivers effect, saturated: g (thick lines), q (thin lines).



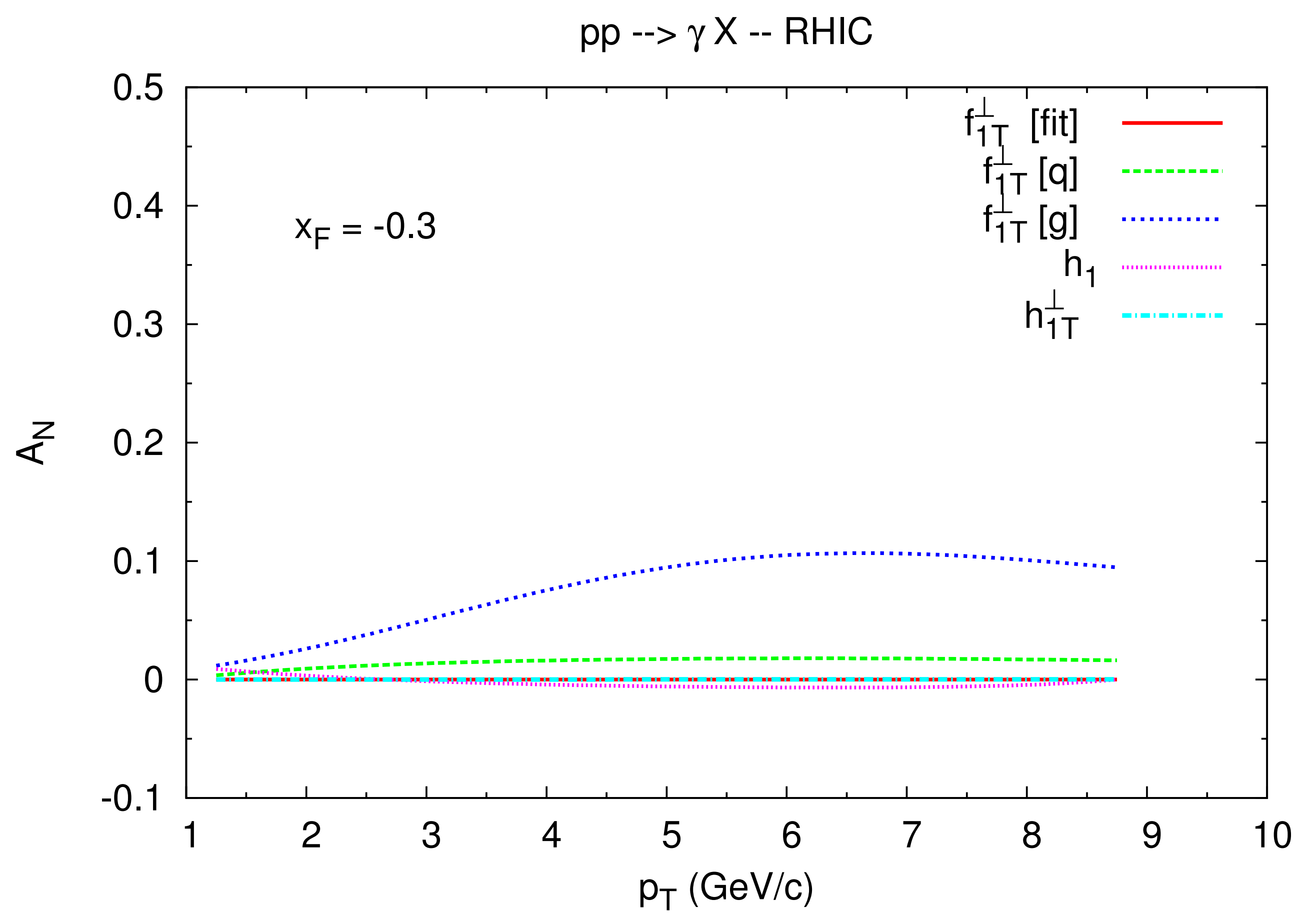
Maximized $A_N(D)$ at JPARC, $\sqrt{s} = 10$ GeV and PAX $\sqrt{s} = 14$ GeV.

$pp \to \gamma X$: high vs. moderate energies, pp vs. $p\bar{p}$

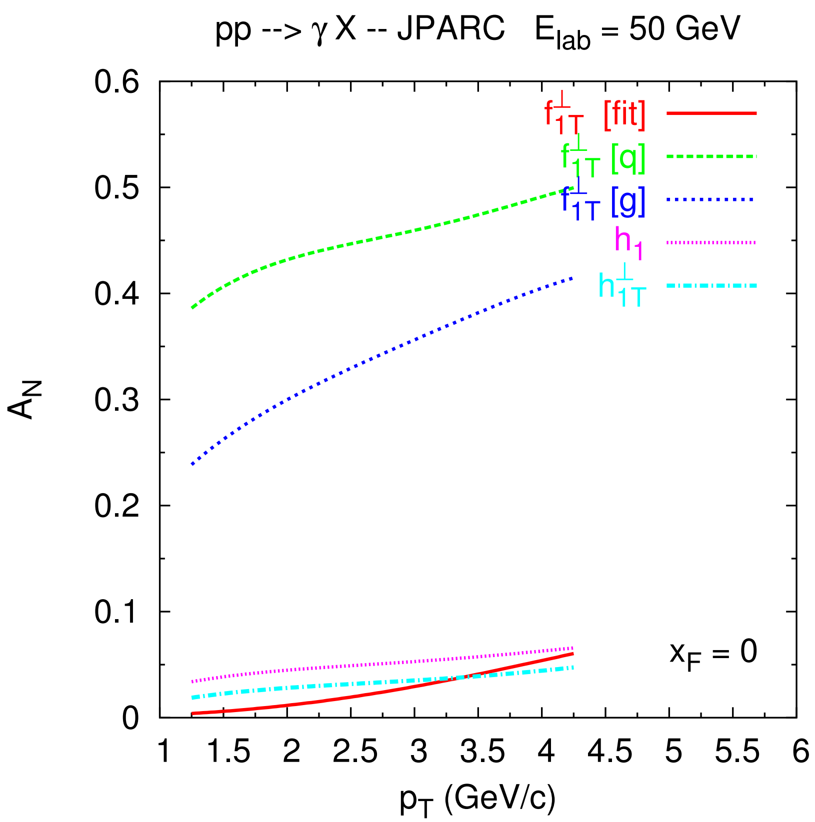
- Sivers effect dominance
- sensitivity to gluon Sivers function
- sensitivity to h_1 (and $h_1^\perp$) ?!?!

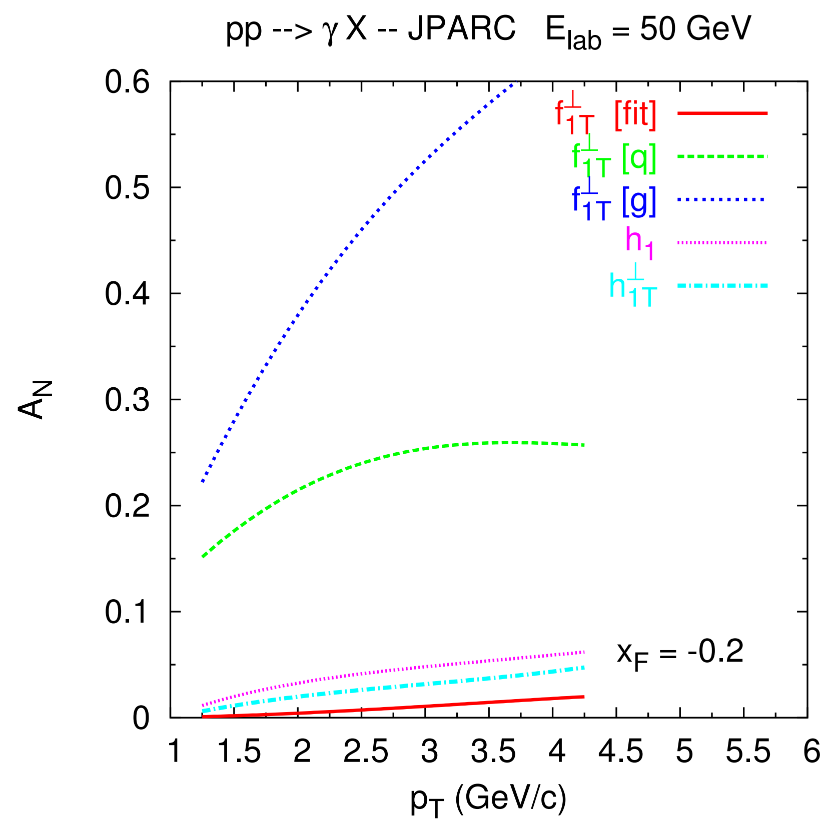
$q\bar{q}$: $\sum_q e_q^2 f_q f_{\bar{q}}$
qg: $\sum_q e_q^2 f_q f_g$

Notice: easier case (w.r.t $pp \to hX$) to check $k_\perp$-factorization;

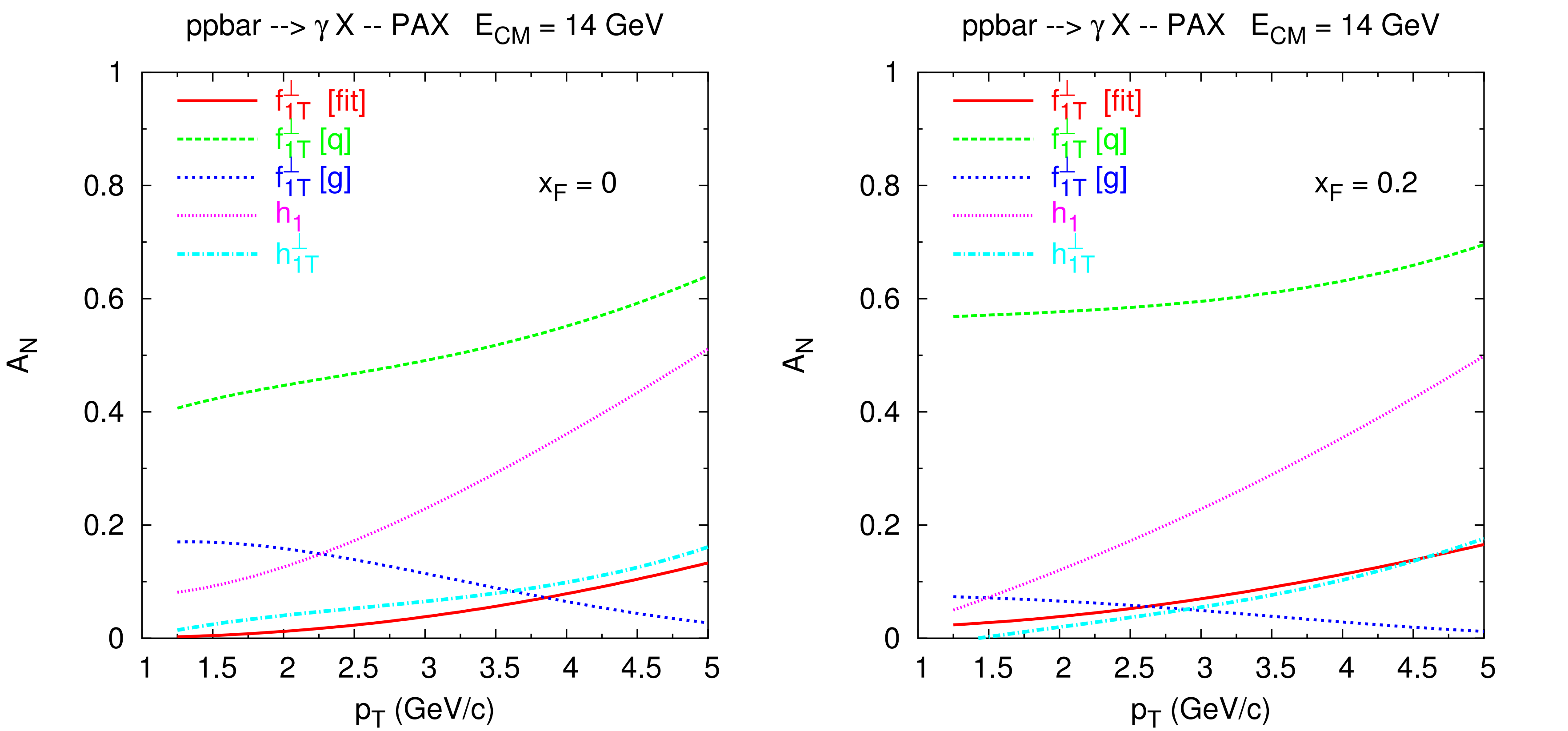


gluon $f_{1T}^{\perp}$ dominance at large energies, $x_F > 0$ and moderate p_T (cfr. Schmidt et al. '05)





Maximized $A_N(\gamma)$ at JPARC, $\sqrt{s} = 10$ GeV, $x_F = 0$ (left) and $x_F = -0.2$ (right).



Maximized $A_N(\gamma)$ at PAX, $\sqrt{s} = 14$ GeV, $x_F = 0$ (left) and $x_F = 0.2$ (right).

Summary

TMD's: a new window into the QCD hadron structure

h_1: fundamental quantity:

a) direct access through A_{TT} in DY ($\bar{p}$ enhancement of valence region)

b) help from TMD's: SIDIS and $e^+e^- \rightarrow H_1^\perp$

$f_{1T}^\perp$:

a) direct access through A_N in SIDIS and DY (quark)

b) role in $pp \rightarrow CX$ ($C = \pi, D, \gamma$) (quark and gluon)

- Interplay of different processes and different kinem. set-ups:

- high vs. moderate energies, forward, backward and mid-rapididy, pp vs. $p\bar{p}$

$h_1^\perp$:

a) direct access through A_N in DY (quark)

b) role in (un)polarized hadronic processes

- QCD vs. phenomenological models
- physical interpretation (OAM...)
- $k_\perp$- factorization in $pp \to CX$
- Twist-three vs. TMD's phenomenology
- evolution...

TMD's: a more and more exciting field ...