SSA and partonic intrinsic motion

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Outline

- Generalized pQCD approach with spin and $\boldsymbol{k}_\perp$-effects in distribution and fragmentation functions and elementary dynamics for $pp \to hX$;
- SSA - theory: helicity formalism;
- SSA - phenomenology (1): Sivers and Collins effects vs. data;
- SSA - phenomenology (2): $x_F < 0$: the gluon Sivers function;
- SSA - phenomenology (3): D meson production and Drell-Yan processes;
- Conclusions and outlook

Polarized cross sections: Helicity formalism

◇ **Helicity density matrices** within a $\boldsymbol{k}_\perp$-factorization scheme to describe parton spin states for a polarized cross section:

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

$$\otimes\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\ \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \otimes \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

- $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}$: helicity density matrix of parton a inside hadron A with spin S_A
- $\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}} \simeq \sum_{\lambda_a,\lambda_b,\lambda_c,\lambda_d} |\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}|^2$ (scattering amplitudes)
- $\hat{D}^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c} \equiv \sum\!\!\!\!\!\!\int_{X,\lambda_X} \hat{\mathcal{D}}_{\lambda_C,\lambda_X;\lambda_c}\ \hat{\mathcal{D}}^*_{\lambda'_C,\lambda_X;\lambda'_c}$

  i.e. the product of *fragmentation amplitudes* for $c \to C + X$

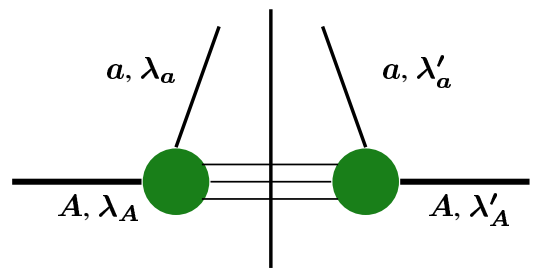
Helicity density matrices: phases from soft parts

◇ PDF at L.O. (and twist two) as the inclusive cross section for $A \to a + X$.

Helicity density matrix of parton $a \leftrightarrow$ to the hel. density matrix of hadron A.

$$\rho^{a/A,S_A}_{\lambda_a,\lambda'_a} \quad \hat{f}_{a/A,S_A}(x_a, \boldsymbol{k}_{\perp a}) = \sum_{\lambda_A,\lambda'_A} \rho^{A,S_A}_{\lambda_A,\lambda'_A} \hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}$$

$$\hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A} \equiv \sum\!\!\!\!\!\!\int_{X_A,\lambda_X} \hat{\mathcal{F}}_{\lambda_a,\lambda_X;\lambda_A} \hat{\mathcal{F}}^*_{\lambda'_a,\lambda_X;\lambda'_A}$$



$$\hat{\mathcal{F}}_{\lambda_a,\lambda_X;\lambda_A}(x_a, \boldsymbol{k}_{\perp a}) = \mathcal{F}_{\lambda_a,\lambda_X;\lambda_A}(x_a, k_{\perp a}) \exp[i\lambda_A \phi_a]$$

$$\Rightarrow \hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a, \boldsymbol{k}_{\perp a}) = F^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a, k_{\perp a}) \exp[i(\lambda_A - \lambda'_A)\phi_a]$$

◇ same for FF (pion case): $\hat{D}^{\pi}_{\lambda_c,\lambda'_c} = D^{\pi}_{\lambda_c,\lambda'_c} \exp[i(\lambda_c - \lambda'_c)\phi^H_\pi]$

Partonic interpretation: notations

Spin and $k_\perp$-dependent quark distributions of leading twist (8):

$$\Delta\hat{f}_{s_x/\uparrow} \equiv \hat{f}_{s_x/\uparrow} - \hat{f}_{-s_x/\uparrow} = [F_{+-}^{+-} + F_{+-}^{-+}]\sin\phi_a \qquad [h_{1T},\ h_{1T}^\perp]$$

$$\Delta\hat{f}_{s_y/\uparrow} = -2\,\mathrm{Im}F_{++}^{+-} + [F_{+-}^{+-} - F_{+-}^{-+}]\cos\phi_a \qquad [h_1^\perp,\ h_{1T},\ h_{1T}^\perp]$$

$$\Delta\hat{f}_{s_z/\uparrow} = 2\,\mathrm{Re}F_{+-}^{++}\sin\phi_a \qquad [g_{1T}^\perp]$$

$$\Delta\hat{f}_{s_x/+} = 2\,\mathrm{Re}F_{++}^{+-} \qquad [h_{1L}^\perp]$$

$$\Delta\hat{f}_{s_y/+} = \Delta\hat{f}_{s_y/A} = -2\,\mathrm{Im}F_{++}^{+-} \qquad [h_1^\perp]$$

$$\Delta\hat{f}_{s_z/+} = [F_{++}^{++} - F_{--}^{++}] \qquad [g_1(\Delta f_a)]$$

$$\hat{f}_{a/\uparrow} = \hat{f}_{a/A} + \frac{1}{2}\Delta^N\hat{f}_{a/\uparrow} = [F_{++}^{++} + F_{--}^{++}] + 2\,\mathrm{Im}F_{+-}^{++}\cos\phi_a\,.$$

$$[f_1,\ f_{1T}^\perp]$$

Single Spin Asymmetries: $A^{\uparrow}B \to \pi X$

- Configuration ($AB \equiv pp$):
  AB center of mass frame - A along $+Z$-axis, π in the XZ plane with $\boldsymbol{p}_T$ parallel to $+X$-axis. $S_A = \uparrow$ or $\downarrow$ along Y-axis, $S_B = 0$.

- $\boldsymbol{k}_\perp$'s imply: non-planar $ab \to cd$ scattering; different $\perp$ directions.

Parton helicity amplitudes in pp c.o.m frame in terms of hel. amplitudes in partonic c.o.m. frame.

boost + rotations: $\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} = \hat{M}^0_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}(\hat{s},\hat{t})\, \mathrm{e}^{i\lambda_m \xi_m}\, \mathrm{e}^{i(\lambda_a-\lambda_b)\phi''_c}$

Various combinations of "T-odd" effects in (un)polarized cross sections but

by including proper phases + numerical (8-dim., VEGAS) integration:

$$d\sigma^{\rm unp} \simeq f_{a/p} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c}$$

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \simeq \Delta^N f_{a/p^\uparrow} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \qquad \text{“Sivers effect”}$$
$$+ \; h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^\uparrow} \qquad \text{“Collins effect”}$$

Notice: the explicit phases entering the convolutions are

$$\Delta^N f_{a/p^\uparrow} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \to \sin(\phi_{S_A} - \phi_a) \equiv \cos\phi_a$$

$$h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^\uparrow} \to \sin[\phi_{S_A} - (\phi_a + \phi_c'' - \xi_a - \tilde{\xi}_a + \xi_c + \tilde{\xi}_c + \phi_\pi^H)]$$

M. Anselmino, M. Boglione, U.D., E. Leader, F. Murgia PRD71 (05)

Parameterization of the Sivers function

For each VALENCE quark $q = u, d$ we adopt the factorized form

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x, k_\perp)$$

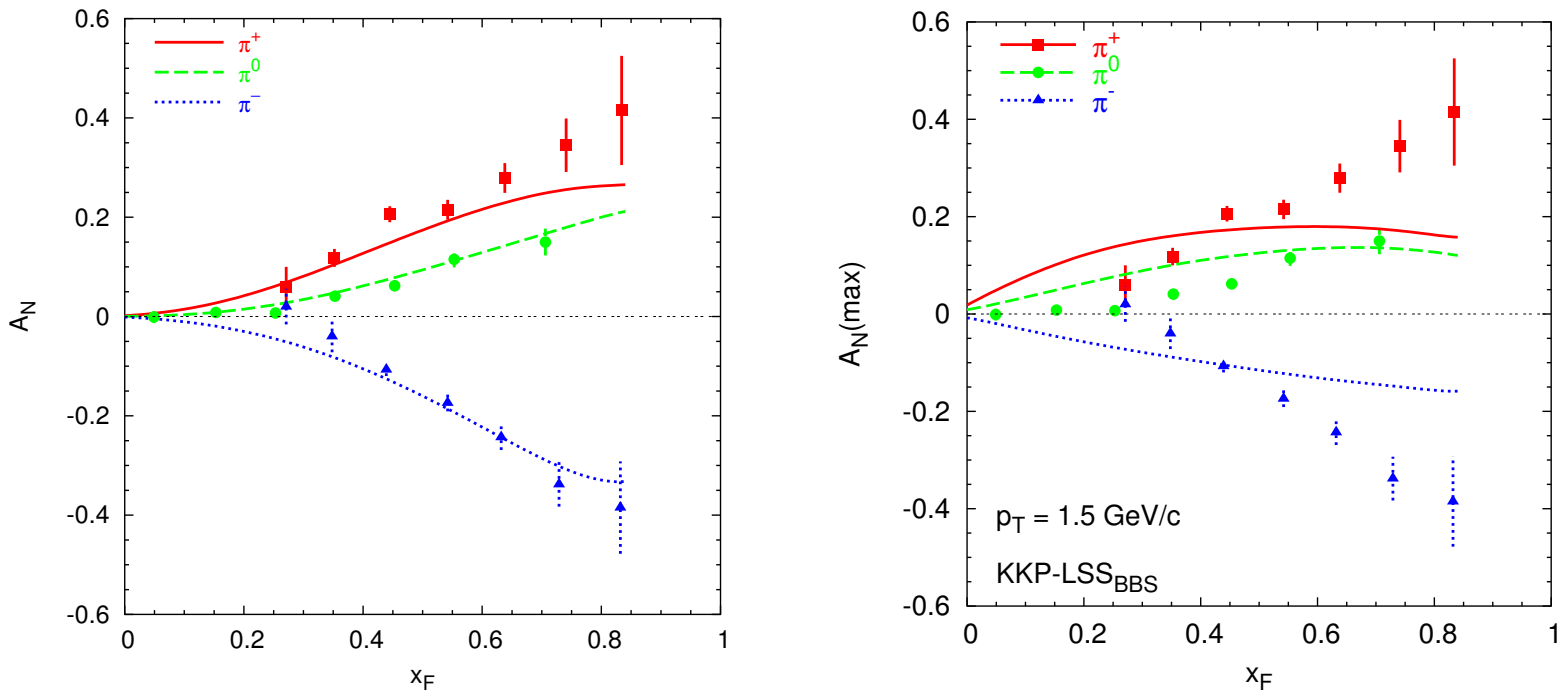
where

$$\mathcal{N}_q(x) = N_q\,x^{a_q}(1-x)^{b_q}\,\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\,b_q^{b_q}}$$

$$h(k_\perp) = \frac{2k_\perp\,M}{k_\perp^2 + M^2}$$

alternative $k_\perp$ depend. : $\quad h'(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M'}\,e^{-k_\perp^2/M'^2}$

$\rightarrow$ 7 parameters



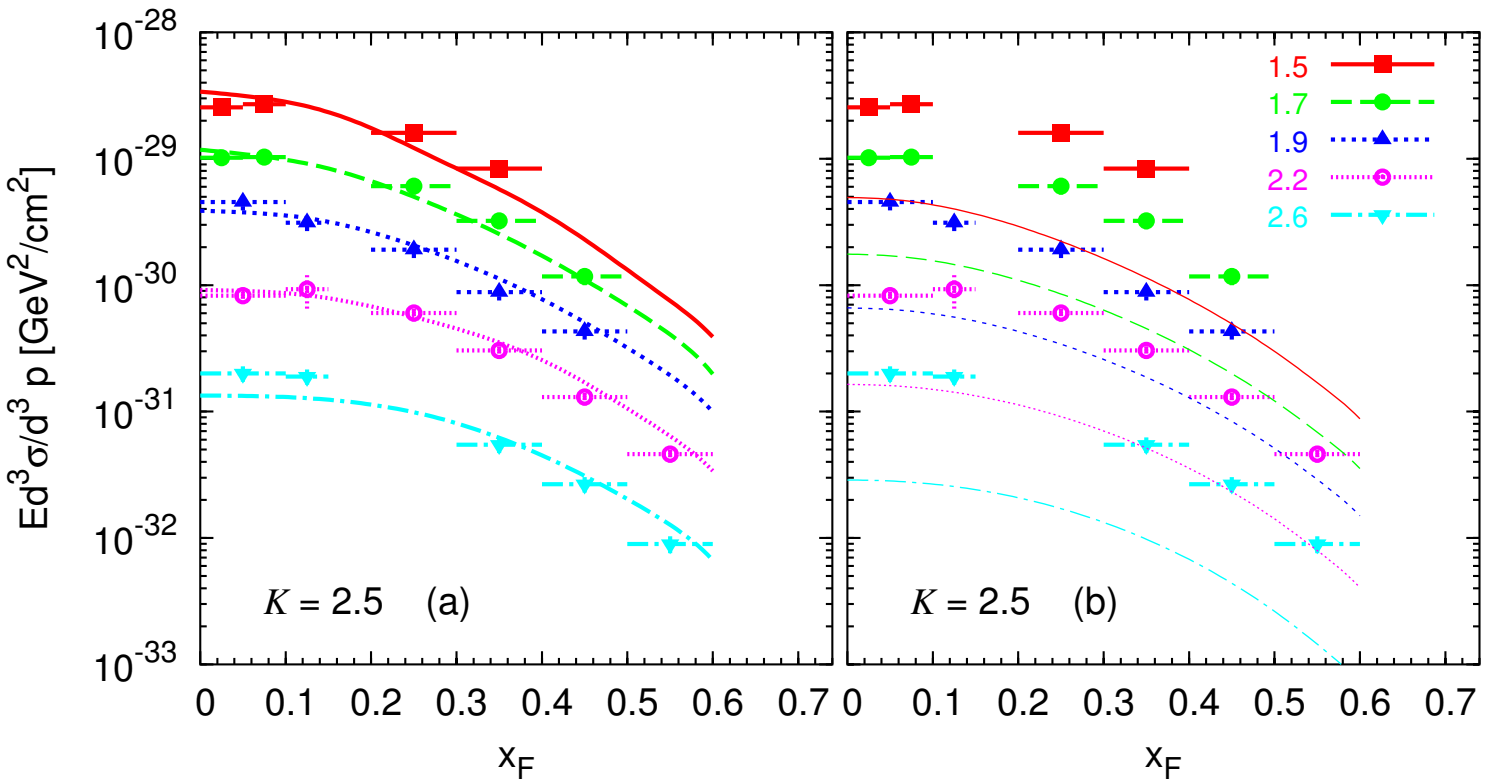
A_N at E = 200 GeV vs. x_F at p_T = 1.5 GeV/c. Data are from [E704] PLB261-264 (1991).

Sivers effect [left] (valence-like). Collins effect [right](full saturated).

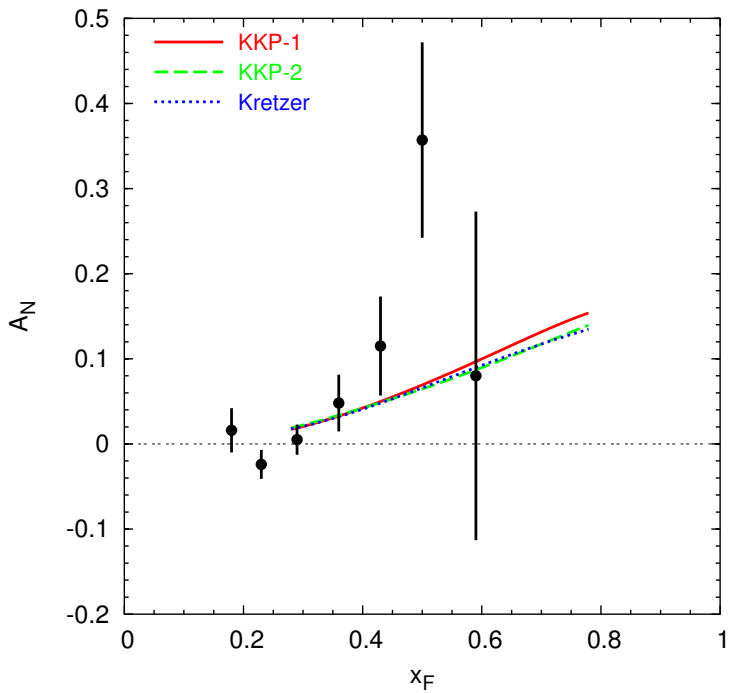
$N_u = +0.40 \; a_u = 2.0 \; b_u = 0.3$ Transversity funct. and

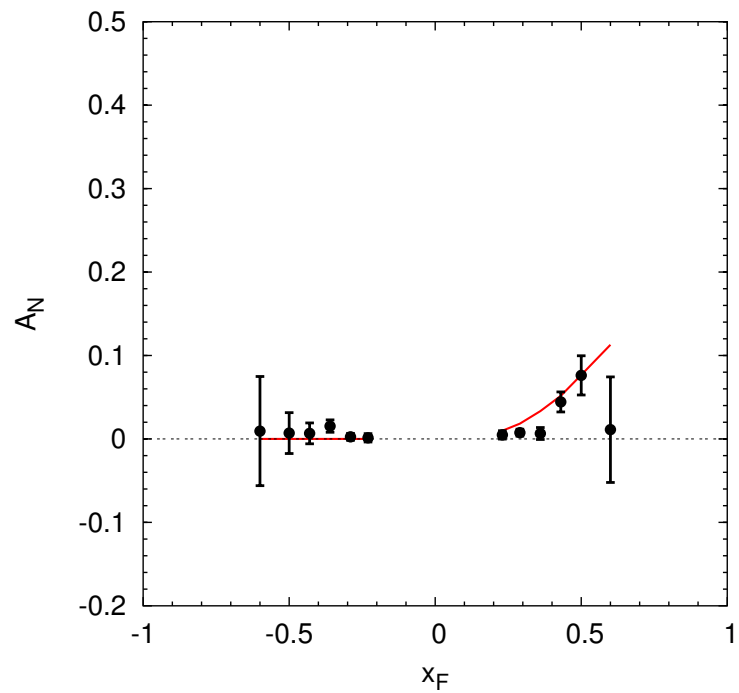
$N_d = -0.90 \; a_d = 2.0 \; b_d = 0.2$ Collins funct. full saturated

$\simeq$ CONSISTENCY with SIDIS



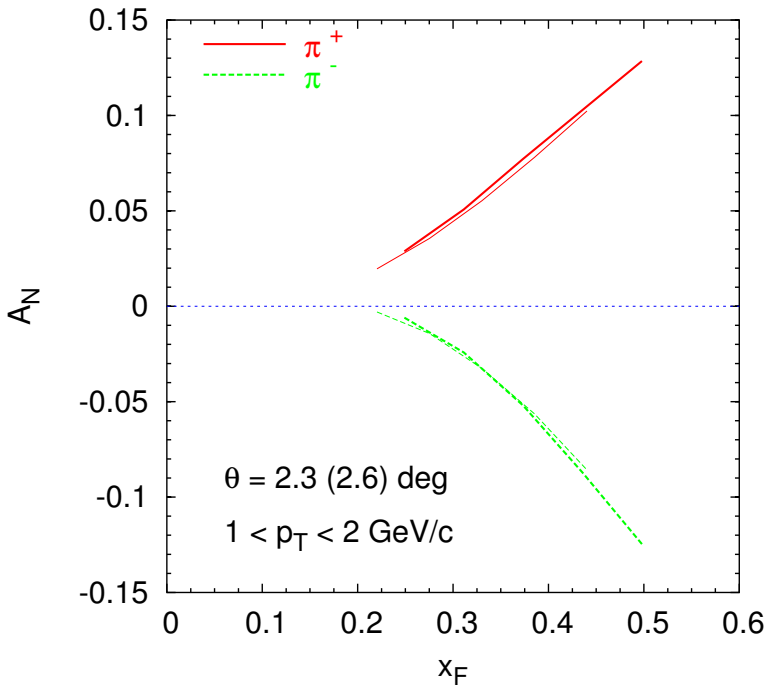
Estimates of π^0 invariant cross sections **with (left) and without (right)** $\boldsymbol{k}_\perp$ **effects** at E= 200 GeV vs. x_F for different p_T values. U.D. & F. Murgia PRD70 [05]. Data are from [BNL] Donaldson *et al.* PLB 73 (1978).

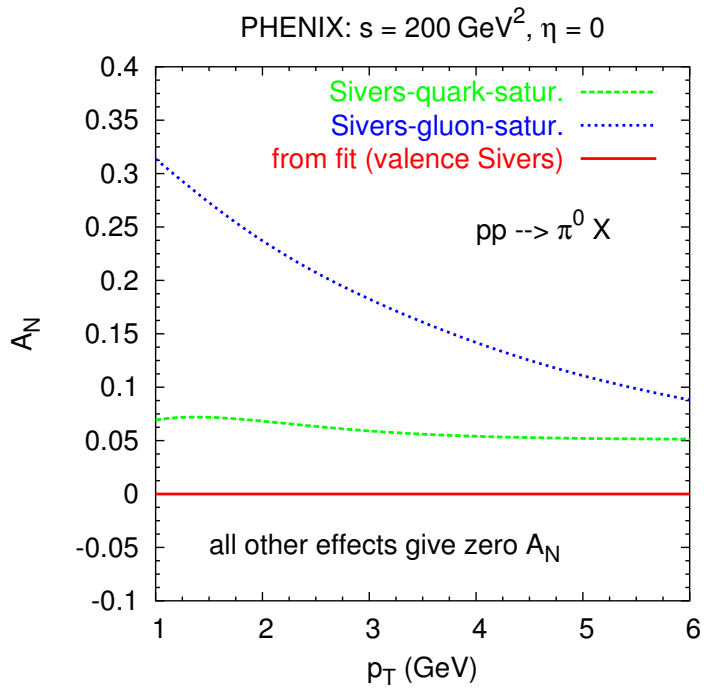




Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone [U.D. and F. Murgia PRD70 (05)] at $\sqrt{s}$ = 200 GeV and $\eta = 3.8$ vs. x_F Data are from [STAR] PRL92 (04).

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.





Predictions of $A_N(pp \to \pi^{\pm} X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 200 GeV and $\theta = 2.3(2.6)$ deg. vs. x_F [BRAHMS kinematics].

Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 200 GeV and $\eta = 0$ vs. p_T [PHENIX kinematics]. Consistent with preliminary data.
Maximized effects are also shown.
Collins effect suppressed!

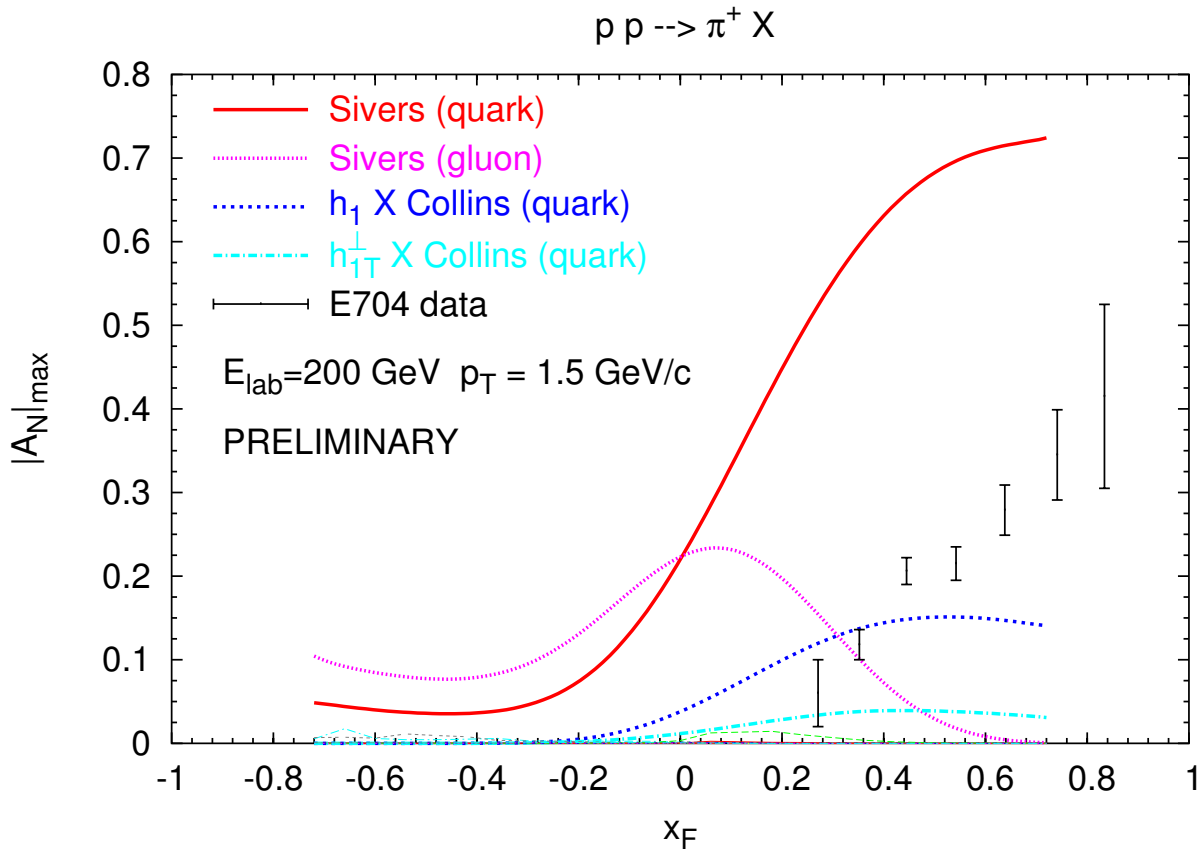
Consistency between Sivers functions from $p^{\uparrow}p \to \pi X$ and $\ell p^{\uparrow} \to \ell' \pi X$

• $\ell p \to \ell' \pi X$ (HERMES): moderately small $x_B(x) \Rightarrow$ explore "sea region" and No gluons at LO;

• $pp \to \pi X$ (E704, STAR), large A_N at large $x_F \Rightarrow$ constraint to the valence behaviour of TMD pdf's. [U.D. and F. Murgia PRD70 (04)]
gluon-sea cancelation at work at $x_F \simeq 0$?

• Interplay of Collins effect ?
New analysis [M.Anselmino et al. PRD71 (05)] with full microscopic dynamics $\Rightarrow$ suppression of the Collins effect;

All mechanisms at work in $p^{\uparrow}p \to \pi X$



Contributions to A_N at $\sqrt{s} = 20$ GeV, **keeping only proper phases:** $\Delta f(x, k_\perp) = (2) f(x, k_\perp)$**.**

SSA at $x_F < 0$ and the gluon Sivers function

$p^\uparrow p \to \pi X$ in terms of $ab \to cd$ [c fragments into π]

$x_F > 0$ ($x_1 > x_F$) $\to$ valence region of $p^\uparrow$ and sea region for p
$x_F < 0$ (x_1 low) $\to$ sea region of $p^\uparrow$ and valence region of p

in particular

$x_F \to 1 \Rightarrow \hat{t} \to 0$ and $x_1 \to 1$:

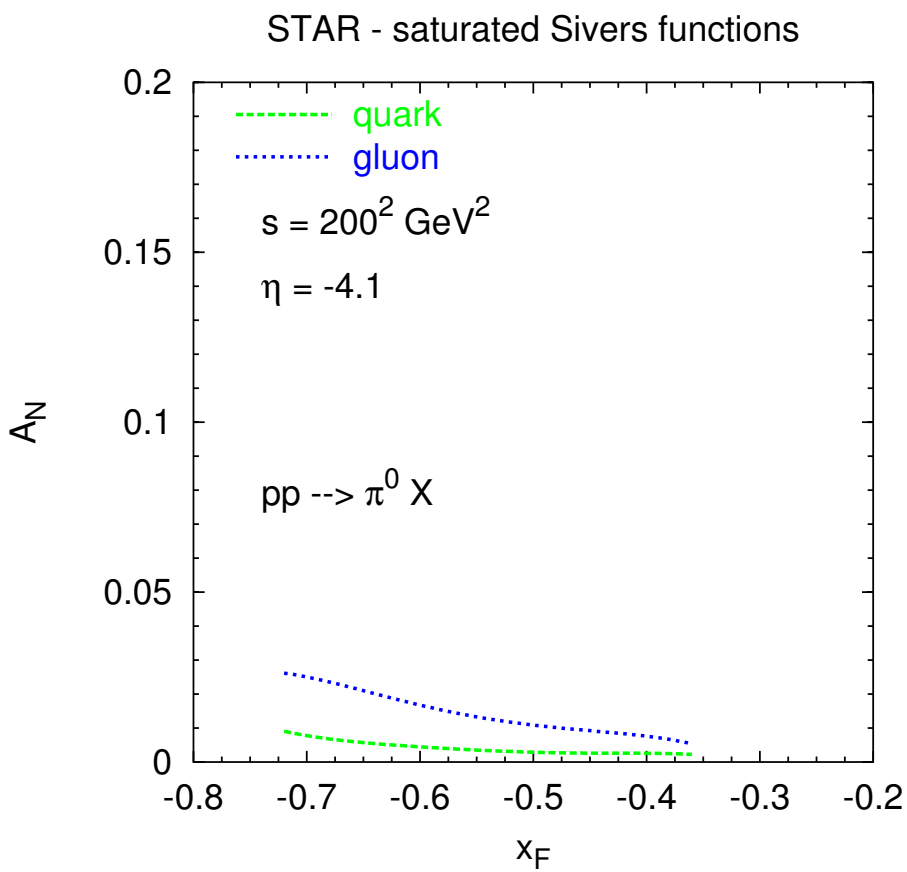
$i)$ $\hat{s}^2/\hat{t}^2$ terms dominate the partonic cross section

$ii)$ $qb \to qb$ (larger PDF and FF) enhanced

$x_F \to -1 \Rightarrow \hat{u} \to 0$ and $x_1 \to 0$:

$i)$ $\hat{s}^2/\hat{u}^2$ terms dominate the partonic cross section

$ii)$ $gq \to qg$ (larger PDF and FF) enhanced



Estimates of A_N (Sivers effect), saturating the positivity bounds $\left[\Delta^N f_{a/p^\uparrow}(x,k_\perp) = 2 f_{a/p}(x,k_\perp)\right]$, at $\sqrt{s}$ = 200 GeV and fixed $\eta = 4.1$. 5 times smaller than at $\sqrt{s}$ = 20 GeV!!!

Phases and partonic dynamics [Sivers effect: $\cos\phi_a$]

partonic process: $ab \to cd$

$$\hat{t} = (p_a - p_c)^2 = -2E_aE_c(1-\cos\theta_{ac})$$
$$\hat{u} = (p_b - p_c)^2 = -2E_bE_c(1-\cos\theta_{bc})$$

$$\boldsymbol{p}_c = E_c(\sin\theta_c, 0, \cos\theta_c) = E_c(\sin\theta_h, 0, \cos\theta_h) \quad [\boldsymbol{p}_c\,//\boldsymbol{p}_h]$$
$$\boldsymbol{p}_a = (k_{\perp a}\cos\phi_a, k_{\perp a}\sin\phi_a, E_a\cos\theta_a) \qquad \boldsymbol{p}_b = (k_{\perp b}\cos\phi_b, k_{\perp b}\sin\phi_b, E_b\cos\theta_b)$$

with

$$\cos\theta_a \simeq 1 + \mathcal{O}(k_\perp^2/s) \qquad \cos\theta_b \simeq -1 + \mathcal{O}(k_\perp^2/s)$$

$$\cos\theta_{ac} = k_{\perp a}/E_a\cos\phi_a\sin\theta_h + \cos\theta_h$$
$$\cos\theta_{bc} = k_{\perp b}/E_b\cos\phi_b\sin\theta_h - \cos\theta_h$$

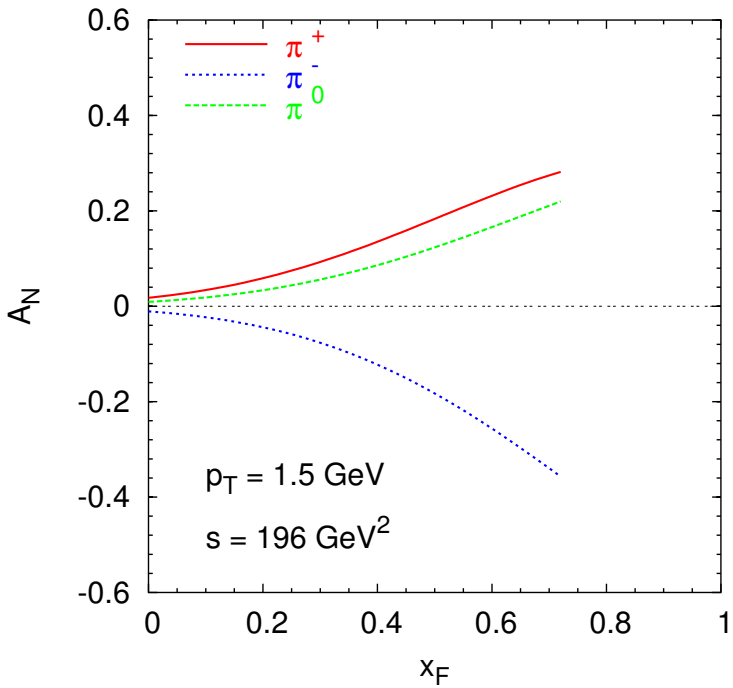
$\theta_h \to 0 (x_F > 0)$: $\hat{t} \to 0$ enforced for $\phi_a \to 0$ almost independent of ϕ_b

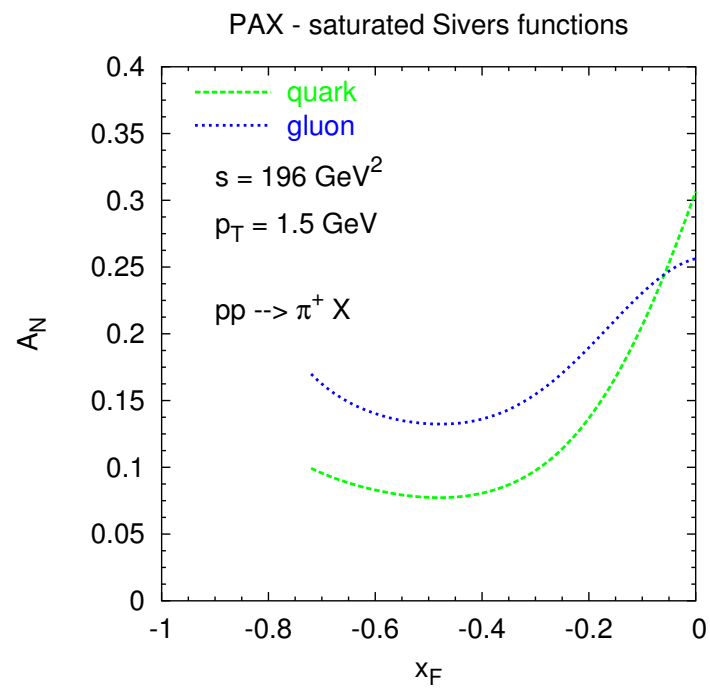
$\theta_h \to \pi (x_F < 0)$: $\hat{u} \to 0$ enforced for $\phi_b \to 0$ almost independent of ϕ_a

• at STAR $|\eta| \approx 4$ i.e. $\theta_h \approx 2(178)$ degrees
$\Rightarrow$ at $x_F < 0$ (all range) $\hat{u}$ dominance and almost no $\hat{t}$ contamination
$\Rightarrow$ $d\hat{\sigma}$ almost independent of ϕ_a: strong suppression from the integration of the $\cos\phi_a$ Sivers factor;
$x_F < 0$ data seem not able to constrain the gluon Sivers pdf

• at E704, $\sqrt{s}$ = 20 GeV with $p_T > 1 - 1.5$ GeV
$\Rightarrow$ $10(20) < \theta_h < 170(160)$ degrees (depending on x_F)
$\Rightarrow$ also at $x_F \to -1$ still a contamination from $\hat{t}$, i.e. dependence on ϕ_a, in $d\hat{\sigma}$ and therefore a less severe suppression;
but No data

• at PAX A_N in the negative x_F region: a potential tool.





Predictions of $A_N(pp \to \pi X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 14 GeV and $p_T = 1.5$ GeV vs. x_F [PAX kinematics].

Estimates of $A_N(pp \to \pi^+ X)$ in terms of Sivers effect alone, saturating the positivity bounds, at $\sqrt{s}$ = 14 GeV and $p_T = 1.5$ GeV vs. x_F [PAX kinematics].

Gluon Sivers function from $p^\uparrow p \to DX$ at RHIC

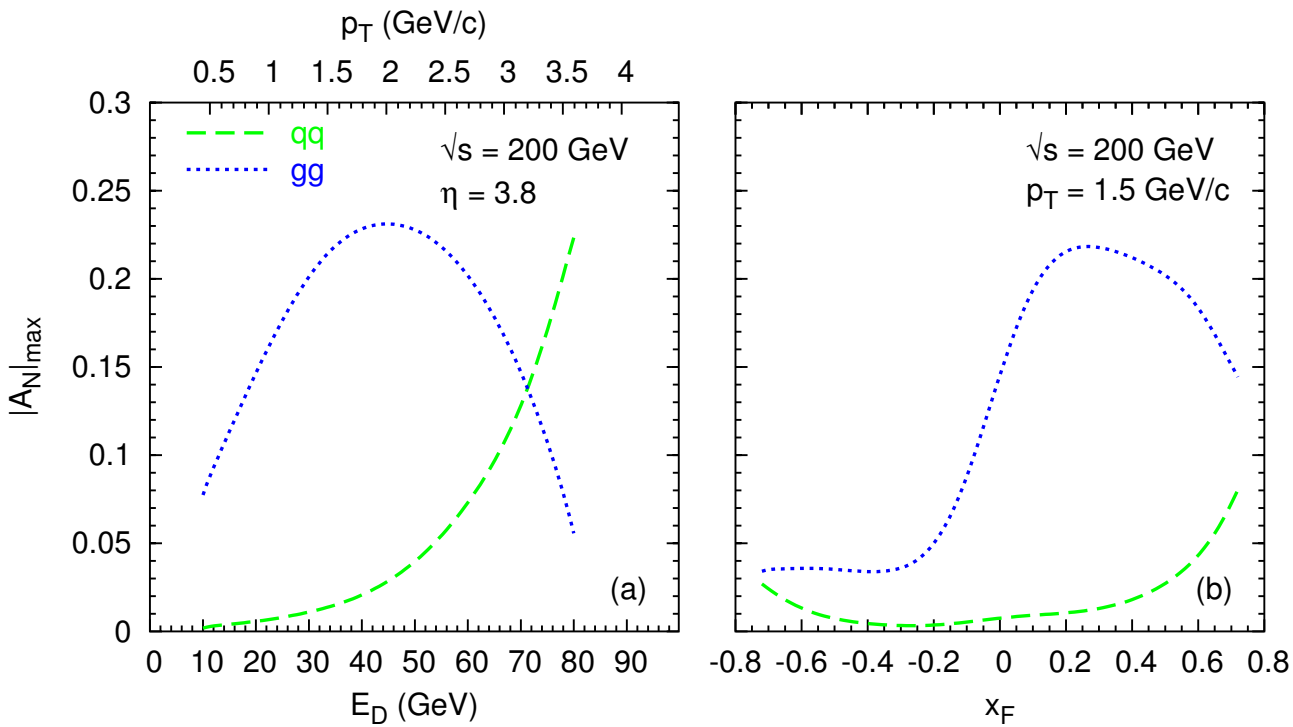
M. Anselmino, M. Boglione, U.D., E. Leader, F. Murgia PRD70 (04)

- unpol. cross-sections: $q\bar{q} \to c\bar{c}$ + $gg \to c\bar{c}$ (dominant: up to 10 times)
- helicity formalism with full $\boldsymbol{k}_\perp$: $d\sigma^\uparrow - d\sigma^\downarrow$ develops various "'T-odd" combinations

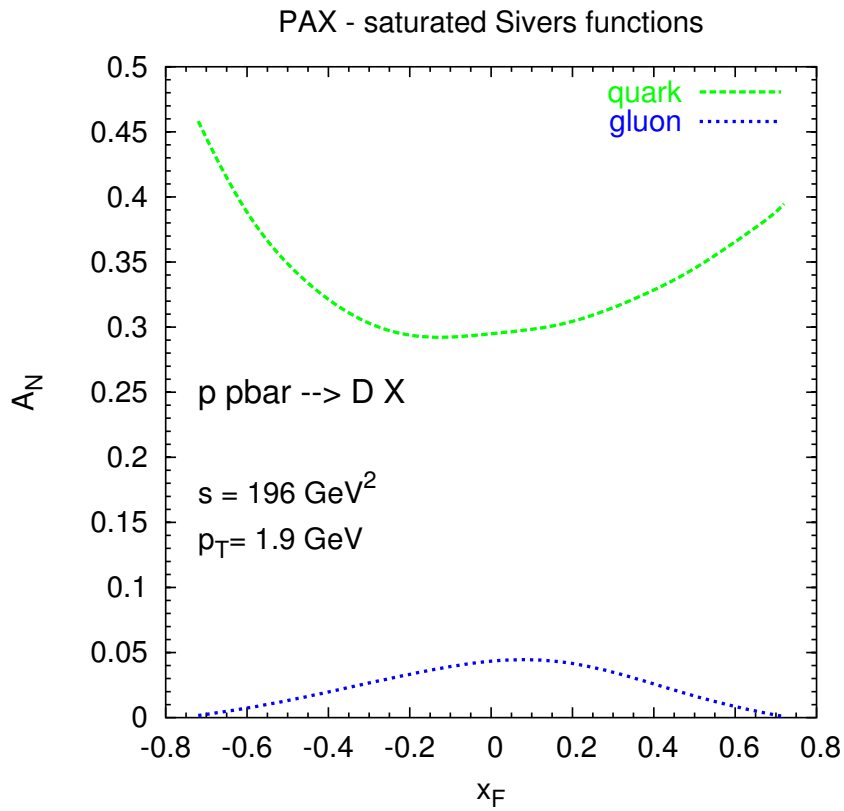
  NO $h_1 \Delta^N D_{D/c^\uparrow}$ (zero transverse single spin transfer)
- proper phases: integration washes out all terms BUT Sivers effect
- gluon dominance up to $x_F = 0.5$ ($x-$saturated):

$A_N \neq 0 \Rightarrow$ gluon Sivers effect

Also from jet correlations in $p^\uparrow p$ reactions (D. Boer, W. Vogelsang PRD69 [04]).



Estimates for A_N in terms of Sivers effect, $x-$ saturated from quarks or gluons at $\sqrt{s}$ = 200 GeV vs. x_F at fixed $\eta = 3.8$ (left) and at fixed p_T = 1.5 GeV/c (right).
FF set: Cacciari *et al.* PRD55 (1997).



Estimates of A_N for $p^{\uparrow}p \to DX$ at PAX, collider mode, $\sqrt{s}$ = 14 GeV, at fixed p_T = 1.9 GeV. Access to the quark Sivers function. NO Collins effect!!

Access to the Sivers effect and universality: SSA in $p^\uparrow p \to \ell^+\ell^- X$ processes

[M. Anselmino, U.D., F. Murgia, PRD67 (03)]

Differential cross sections in the variables: M^2, y, $\boldsymbol{q}_T$ $\quad [q_T^2 \ll M^2]$

Angular distribution of the lepton pair production plane: integrated over.

$$d\sigma^\uparrow - d\sigma^\downarrow \simeq \Delta^N f_{q/A^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) \otimes \hat{f}_{\bar{q}/B}(x_b, \boldsymbol{k}_{\perp b})\, d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}$$

Other mechanisms for SSA in Drell-Yan processes:

$\sum_q h_1(x_a, \boldsymbol{k}_{\perp a}) \otimes \Delta^N f_{\bar{q}^\uparrow/B}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\Delta\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}$ [D. Boer PRD60 (99)]

$d\Delta\hat{\sigma} = d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow} \simeq \cos 2\phi \quad [\phi = \widehat{\boldsymbol{P}_A \boldsymbol{N}}_{\ell^+\ell^-}] \quad \int d\phi \Rightarrow 0$

Universality [J. Collins PLB536 (02)]:

$$\Delta^N f_{q/A^\uparrow}(x, k_\perp)|_{DY} = -\Delta^N f_{q/A^\uparrow}(x, k_\perp)|_{DIS} ???...$$

Conclusions and outlook

- A generalized pQCD approach to SSA and unpol. cross sections:
  LO–pQCD + spin and new $\boldsymbol{k}_\perp$-dependent PDF and FF;
- $A_N(p^\uparrow p \to \pi X)$: Complete $\boldsymbol{k}_\perp$-helicity formalism + phenomenology.
  True detailed microscopic dynamics (proper phases) $\Rightarrow$
  Sivers effect results confirmed;
  Collins effect suppressed (against former claims!);
- good agreement with recent STAR data on A_N both at $x_F > 0$ and $x_F < 0$ in terms of Sivers effect alone and valence like behaviour.
- $A_N(p^\uparrow p \to \pi X)$ at $x_F < 0$: strong suppression (of all mechanisms!!) by phase conspiracy;
  - at large energies (RHIC) and $\theta \to \pi$ all contributions, even saturated, give almost zero SSA.
  - at intermediate energies (PAX) the $x_F < 0$ region may constrain the gluon Sivers function;

- $A_N(p^\uparrow p \to \pi X)$ at $x_F = 0$ vs. p_T [PHENIX]: strong suppression; ONLY SIVERS effect (gluon and/or sea quark) at work!
- SSA with D meson production as a tool to extract the gluon Sivers function (RHIC) and the quark Sivers function (PAX).
- SSA in Drell-Yan: a tool to extract the quark Sivers function and to test the universality condition on TMD pdf.
- Combined analysis of different processes and in different kinematical configurations to map the TMD structure of hadrons.