T M D distributions in hadronic collisions: $p^{\uparrow}p \to D + X$ and $p^{\uparrow}p \to \gamma + X$

Umberto D'Alesio
Physics Department and INFN
University of Cagliari, Italy

SPIN2006 *17th International Spin Physics Symposium*
October 2-7, 2006 Kyoto, Japan

[*U.D., S. Melis, F. Murgia in progress*;
and coll. with M. Anselmino, M. Boglione, E. Leader]

Outline

1. $A^{\uparrow}B \to C + X$
   TMD's + helicity formalism in SSA $\Rightarrow$
   many effects at work: role of phases and kinematics;

2. $p^{\uparrow}p \to D + X$ high vs. moderate $\sqrt{s}$
   RHIC: gluon Sivers function
   J-PARC and PAX ($p^{\uparrow}\bar{p}$): quark Sivers function

3. $p^{\uparrow}p \to \gamma + X$ high vs. moderate $\sqrt{s}$
   RHIC: gluon Sivers function
   J-PARC and PAX ($p^{\uparrow}\bar{p}$): quark Sivers function, transversity

Conclusions and outlook

Polarized cross sections: Helicity formalism with $\boldsymbol{k}_\perp$

For the inclusive process $A(S_A)\,B \to C + X$ in a generalized factorization scheme with inclusion of $\boldsymbol{k}_\perp$:

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

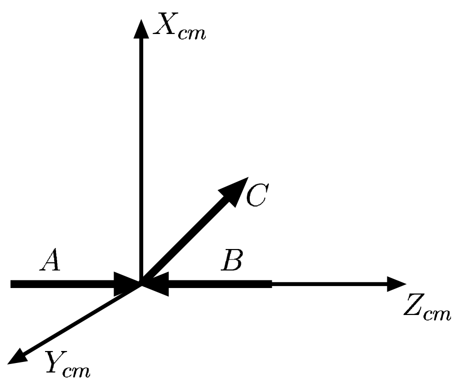
$$\otimes\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\,\hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \otimes \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

- $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}$: 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)
- $\hat{D}^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c}$ generalized ff $\Rightarrow D_{C/c}(z,\boldsymbol{k}_{\perp C}) = 1/2\sum_{\lambda_C,\lambda_c}\hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda_c}$

- $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})$ gives the 8 twist-2 spin and TMD distributions.

By summing over $\{\lambda\}$: many effects (from the soft parts) appear together: Sivers, Collins($\otimes h_1$), Boer-Mulders($\otimes h_1$), linear gluon polarizations...

Hard (if not impossible) extraction !... But



Whereas the hadronic process $(A,S_A)+B\to C+X$ takes place in the (XZ) plane, the partonic sub-processes (soft and hard) are not planar any more $(\boldsymbol{k}_{\perp a},\,\boldsymbol{k}_{\perp b},\,\boldsymbol{k}_{\perp C})$

$\Rightarrow$ partonic azimuthal phases

- Each mechanism (or combination of mechanisms) appear with a specific azimuthal dependence and must be integrated over the partonic phase space and over some specific experimental region.

It has been shown that in $p^{\uparrow}p \to \pi X$ (A_N at large x_F):
- Sivers effect alone allows a good description of E704 (and STAR) data;
- Collins effect is suppressed and not able alone to describe E704 data (preventing also the access to the transversity distribution);
- all other effects are negligible.

UD, Murgia '04, Anselmino, Boglione, UD, Leader, Melis, Murgia '05, '06.

Strategy to access different mechanisms in *pp* collisions:

- choice of the final state (selection of partonic channels)
- choice of kinematics to control the role of the azimuthal phases

Exercise:

study of maximized A_N by using (trivial positivity bounds):

$\Delta^N f(x, k_\perp) = (2) f(x, k_\perp)$

$\Delta^N D(z, k_\perp) = (2) D(z, k_\perp)$

Two examples: heavy meson and direct photon production.

$p^\uparrow p \to DX$

RHIC: $\sqrt{s} = 200$ GeV

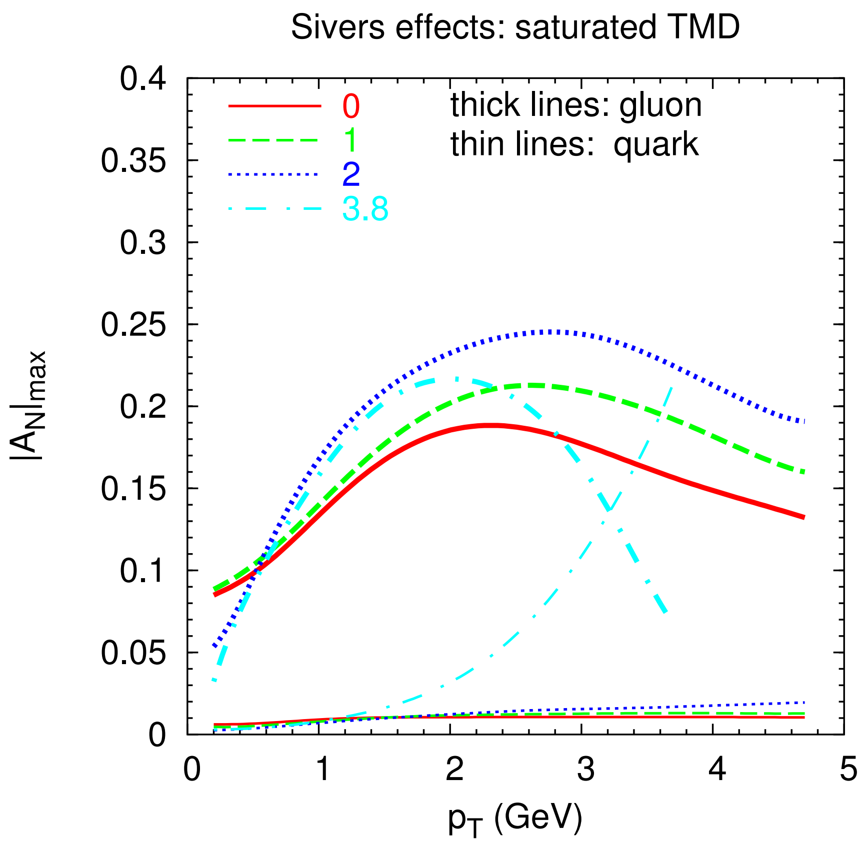
- unpolarized cross-sections:

$q\bar{q} \to c\bar{c}$ ($\hat{s}$-channel) + $gg \to c\bar{c}$ (dominant: up to 10 times)

A_N contains various spin-TMD contributions:

- $M_{++;+-} \neq 0$: heavy quark mass!
- NO $h_1 \otimes f_{b/p} \otimes \Delta\hat{D}_{D/c^\uparrow}$ ($h_{1g} = 0$ and no $\perp$ spin transfer in $\hat{s}$- channel);
- proper phases: integration washes out all terms other than the Sivers effect

Anselmino, Boglione, UD, Leader, Murgia '04.



Maximized $A_N(D)$ at RHIC, $\sqrt{s} = 200$ GeV for various pseudo-rapidities.

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

Access to the gluon Sivers function.

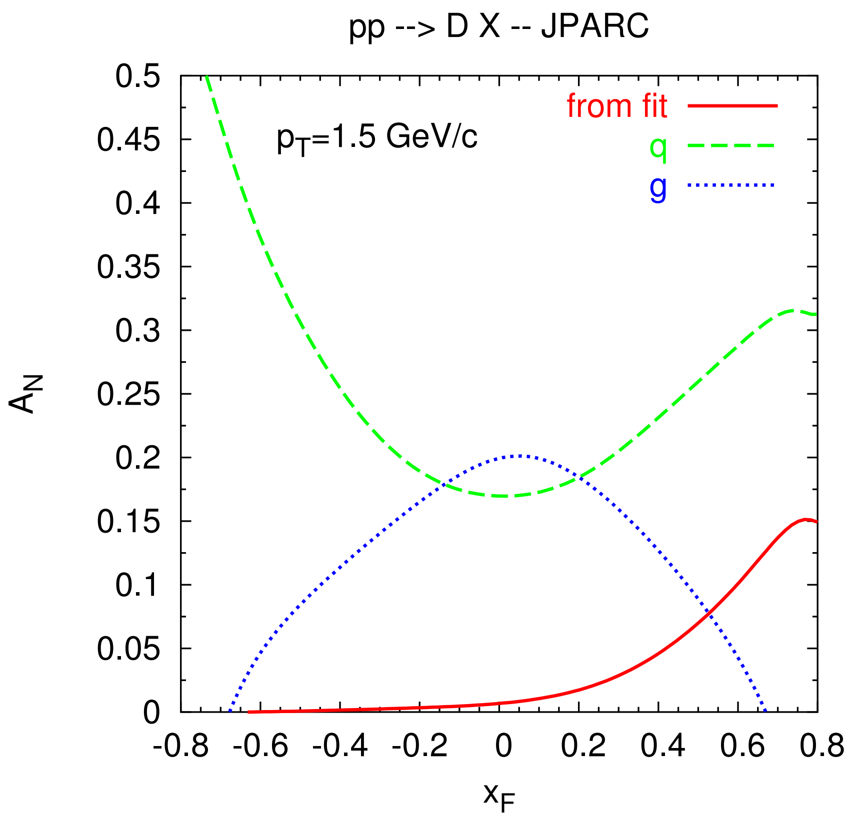
What happens at lower energies?

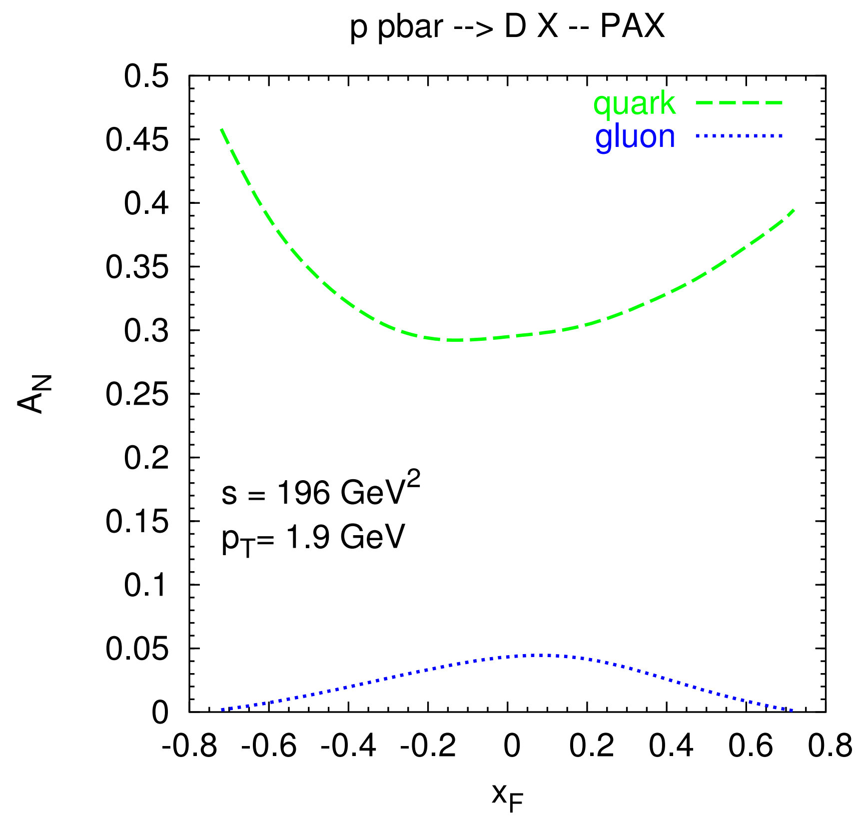
- in $p^{\uparrow}p \to DX$ at J-PARC ($\sqrt{s}$ = 10 GeV)
- in $p^{\uparrow}\bar{p} \to DX$ at PAX ($\sqrt{s}$ = 14 GeV)

In both cases we probe larger x values (at $x_F > 0$).

In the second case ($\bar{p}$) we enhance the $q\bar{q} \to c\bar{c}$ subprocess.

Low energies implies enhanced threshold effects, resummation...
expected (likely true) to be less important in A_N (ratio of cross-sections).





Maximized $A_N(D)$ at J-PARC, $\sqrt{s}$ = 10 GeV in terms of the Sivers effect:
q dominance at large $|x_F|$.

Maximized $A_N(D)$ at PAX $\sqrt{s}$ = 14 GeV in terms of the Sivers effect [$q\bar{q}$ dominance over all x_F values: $\bar{q}$ in $\bar{p}$].

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

- 2 elementary processes: $qg \to \gamma q$ and $q\bar{q} \to \gamma g$
- only Sivers effect in qg (no transverse spin transfer);

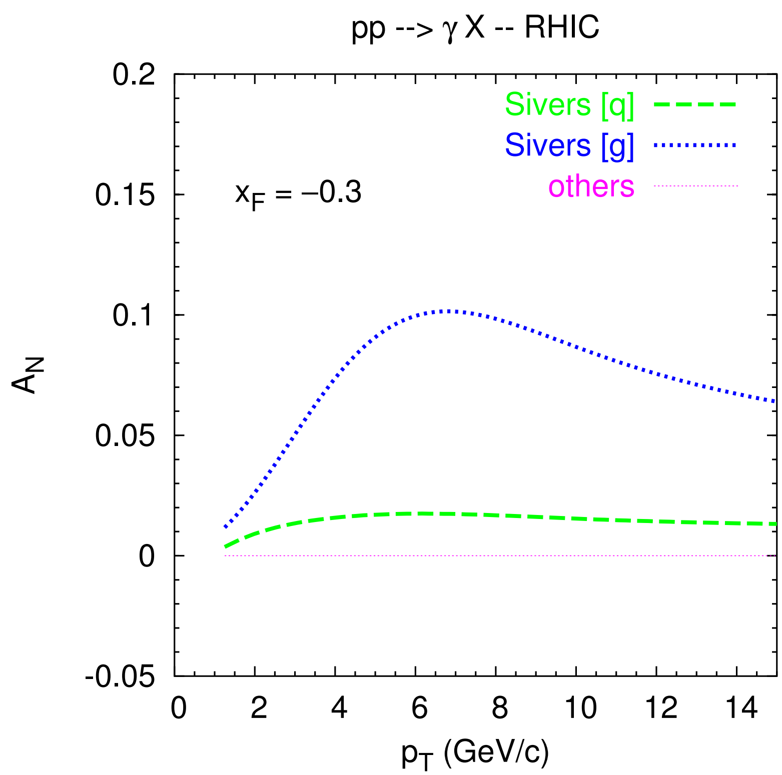
$$\Delta\hat{f}_{q/A^{\uparrow}} \otimes \hat{f}_{g/B} \qquad \Delta\hat{f}_{g/A^{\uparrow}} \otimes \hat{f}_{q/B}$$

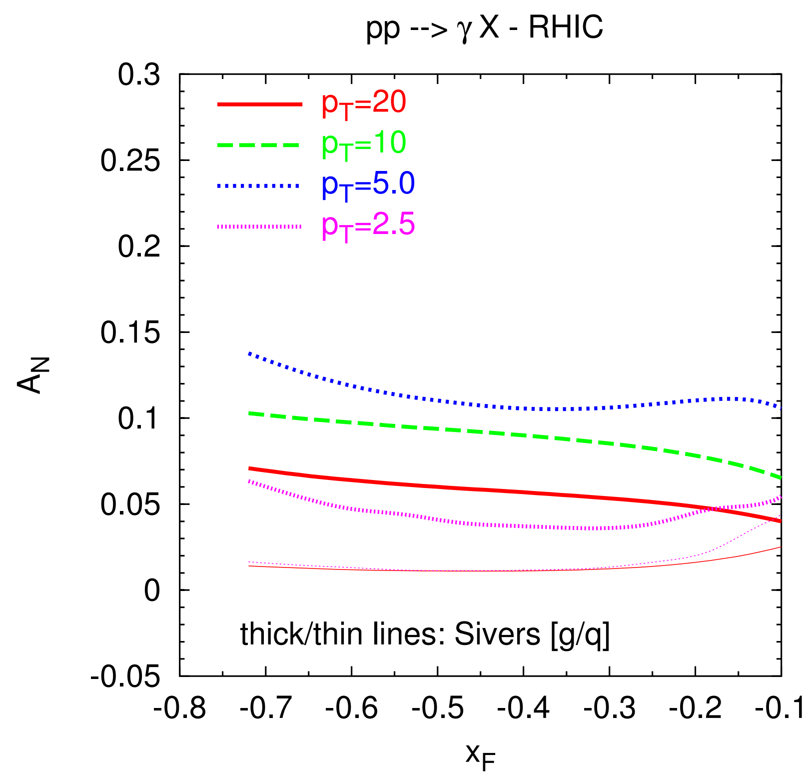
- Sivers effect and transversity $\otimes$ Boer-Mulders in $q\bar{q}$:

$$\Delta\hat{f}_{q/A^{\uparrow}} \otimes \hat{f}_{\bar{q}/B} \qquad \Delta\hat{f}_{q^{\uparrow}/A^{\uparrow}} \otimes \Delta\hat{f}_{\bar{q}^{\uparrow}/B}$$

- coupling to $\gamma \Rightarrow \sum_q e_q^2 ...$: u flavour dominance

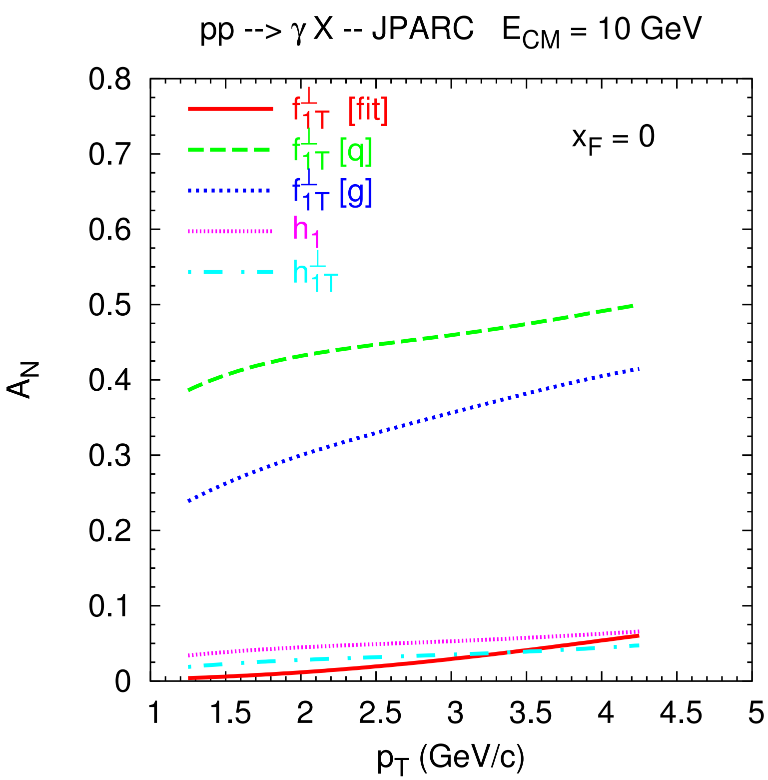
Which mechanisms are really active and where?

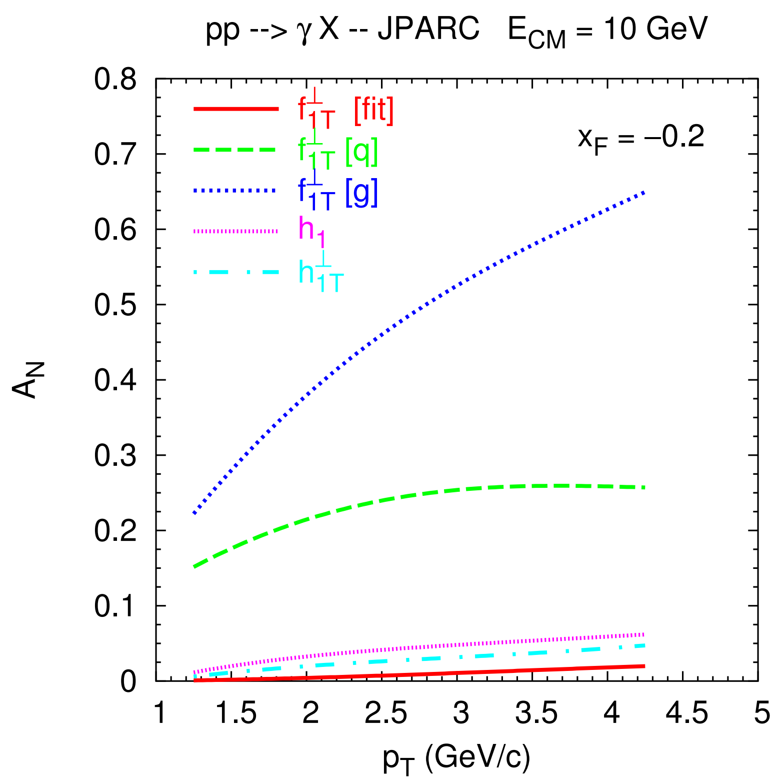




Maximized $A_N(\gamma)$ at RHIC, $\sqrt{s} = 200$ GeV at $x_F = -0.3$: gq ($\simeq 1/\hat{u}$) larger than qg ($\simeq 1/\hat{t}$), larger than $q\bar{q}$ (low x).

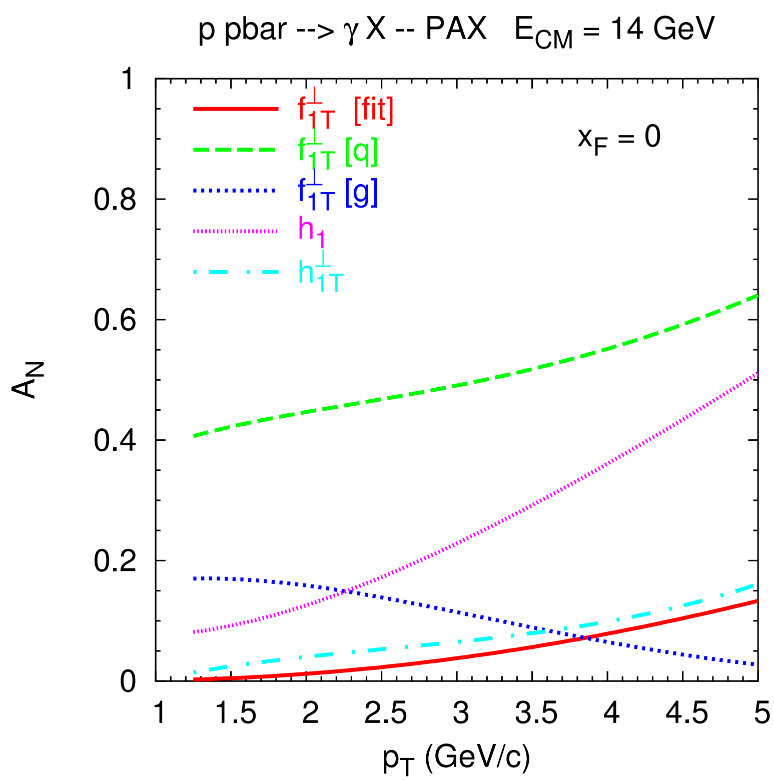
Maximized $A_N(\gamma)$ at RHIC, $\sqrt{s} = 200$ GeV in terms of the Sivers effect. (cfr. Schmidt, Soffer, Yang '05).

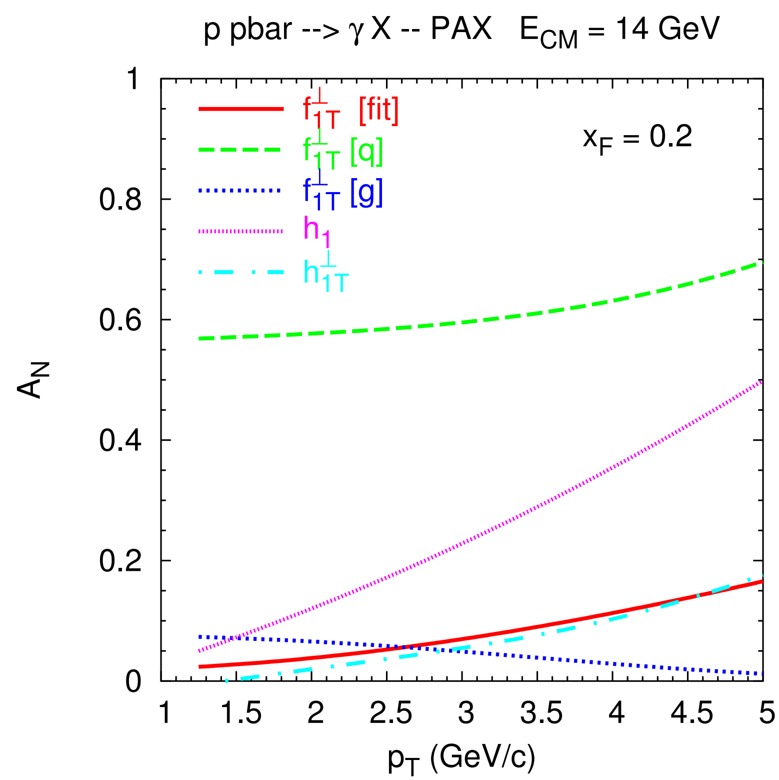




Maximized $A_N(\gamma)$ at J-PARC, $\sqrt{s} = 10$ GeV at $x_F = 0$: dominance of the quark Sivers effect. Same at $x_F > 0$.

Maximized $A_N(\gamma)$ at J-PARC, $\sqrt{s} = 10$ GeV at $x_F = -0.2$: dominance of the gluon Sivers effect.





Maximized $A_N(\gamma)$ at PAX, $\sqrt{s} =$ 14 GeV, at $x_F = 0$: dominance of the quark Sivers effect. Access to the transversity distributions?

Maximized $A_N(\gamma)$ at PAX, $\sqrt{s} =$ 14 GeV at $x_F = 0.2$: same at $x_F = 0$. [$x > 0.1$ and $\bar{q}$ in $\bar{p}$]. Notice u flavour enhanced by e_q^2.

Conclusions

1. Generalized $\boldsymbol{k}_\perp$ factorization scheme within the helicity formalism for one-particle inclusive pp collisions;

2. role and relevance of the azimuthal phases: suppression of the Collins effect in $p^\uparrow p \to \pi X$;

3. $p^\uparrow p \to C X$: choice of C to select partonic channels
   - high vs. moderate energies
   - kinematics (forward/backward rapidities)
   - crucial interplay of the azimuthal phases

4. $p^\uparrow p \to D + X$: access to quark (low $\sqrt{s}$) / gluon (high $\sqrt{s}$) Sivers TMD;
   $p^\uparrow p \to \gamma + X$: access to quark (low $\sqrt{s}$) / gluon (high $\sqrt{s}$) Sivers TMD;
   $p^\uparrow \bar{p} \to \gamma + X$: (low $\sqrt{s}$) access to the transversity distribution.
   ...