Constraints on gluon Sivers distribution from RHIC results

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Outline

1. A_N in $pp \to \pi + X$:
   TMD's + helicity formalism $\Rightarrow$ role of phases and kinematics;
2. Gluon Sivers mechanism at RHIC: STAR vs. PHENIX
3. Constraints from the Burkardt sum rule
4. Conclusions and outlook

Helicity formalism in a $\boldsymbol{k}_\perp$-scheme for the process $A^\uparrow B \to CX$:

- many spin-TMD effects at work
- partonic azimuthal phases.

For instance in $p^\uparrow p \to \pi X$:

- Sivers effect appears only with a $\cos\phi_a$ (a parton in $p^\uparrow$) dependence (unpol. partonic cross section, unpol. ff.)
- Collins effect appears with a complex azimuthal phase dependence (from transversity distributions, partonic double transverse spin asymmetry, Collins angle) $\to$ suppression

$$A_N^{\rm Sivers} \sim \sum_{abcd} \int dx_a\, dx_b\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^2\boldsymbol{k}_{\perp \pi}$$
$$\left\{ \Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}) \cos\phi_a\, \hat{f}_{b/p}(x_b, k_{\perp b})\, \frac{d\hat{\sigma}}{d\hat{t}}(\hat{t}, \hat{u}) \hat{D}_{\pi/c}(z, k_{\perp \pi}) \right\}$$

in the subprocess $ab \to cd$: $\hat{t} = (p_a - p_c)^2 \quad \hat{u} = (p_b - p_c)^2$

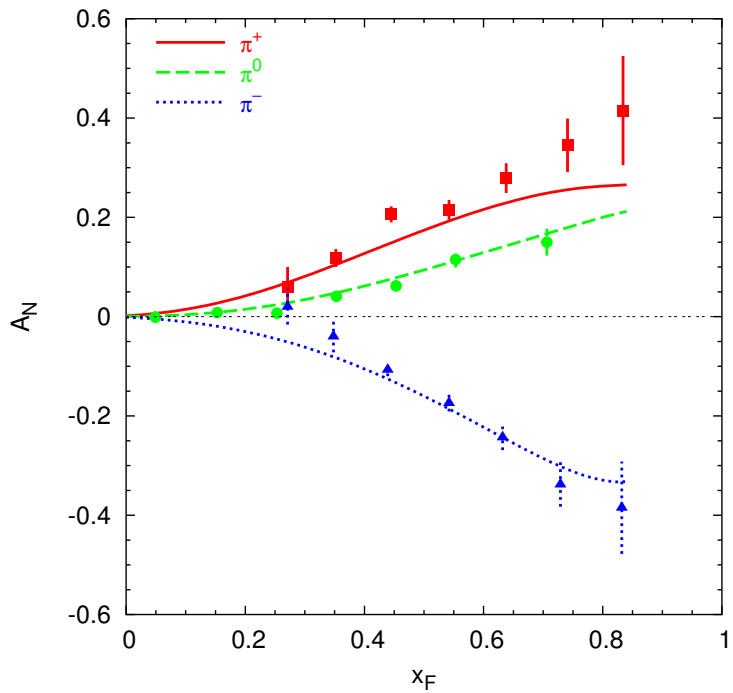
Moreover, the pion pseudo-rapidity selects:

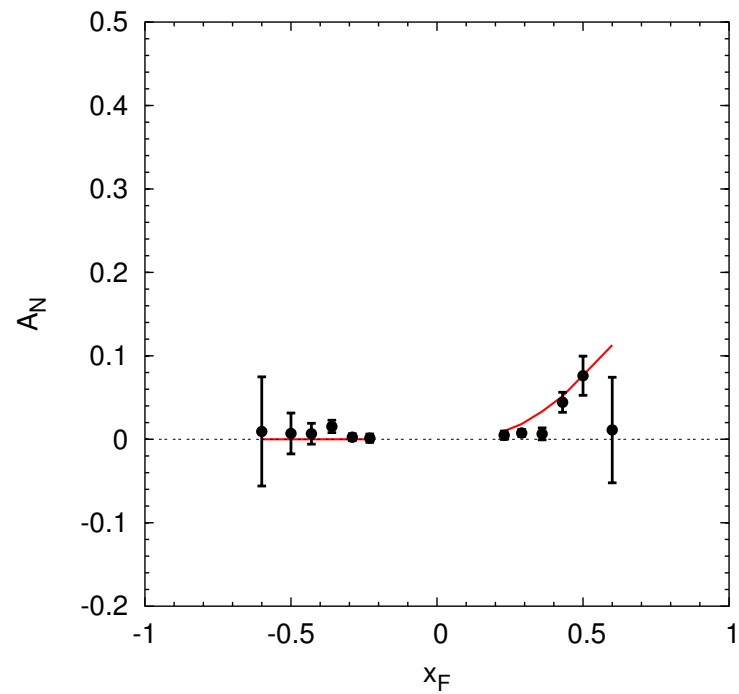
1. valence or sea (gluon) region (control at pdf level...well known)
2. backward, central, forward angles (control of phases entering $\hat{t}$, $\hat{u}$).

From 1: data at large negative x_F at RHIC might be sensitive to the gluon Sivers function.

2 prevents this: whereas at large positive x_F, the $\hat{t}$ - channel dominance implies a strong dependence on ϕ_a in $d\hat{\sigma}$, at STAR ($\eta \simeq -4$), $\hat{u}$ dominance $\Rightarrow$ $d\hat{\sigma}$ does not depend on ϕ_a and even Sivers effect is almost washed out $[\int d\phi_a \cos\phi_a ...]$!

Notice: this would not happen at lower energies (J-PARC, PAX) where the backward scattering angles, at moderate p_T, are still far from 180 degrees.





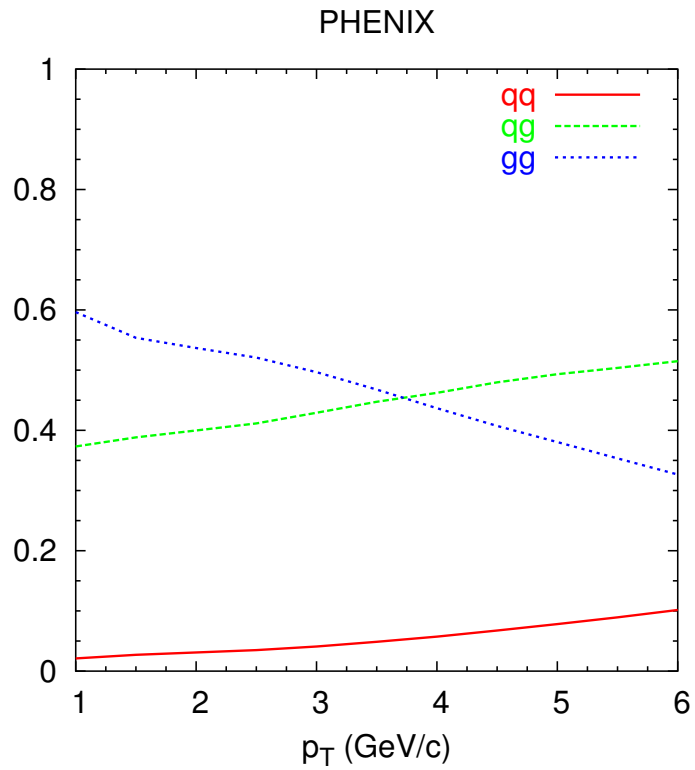
Estimates of A_N with Sivers effect at $E = 200$ GeV vs. x_F at $p_T = 1.5$ GeV/c. Distribution function set: MRST01; fragmentation function set: KKP. Data are from Adams et al. [E704] PL B261 (1991).

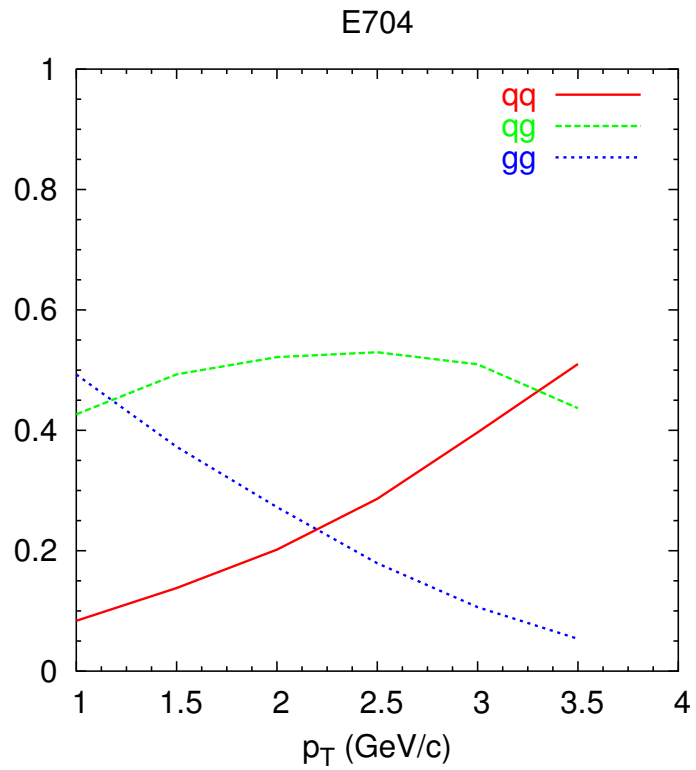
Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 200 GeV and $\eta = 4.1$ vs. x_F. STAR preliminary data.

Mid-rapidity data at RHIC

A_N for the $p^\uparrow p \to \pi^0 X$ process at RHIC
$\sqrt{s}$ = 200 GeV, with $1 < p_T < 5$ GeV/c and $|\eta| < 0.35$.
In our approach:
- Vanishing of all possible contributions to A_N other than the Sivers effect;
- $x_a^{\min} \simeq 0.005$: gluon dominance in the transversely polarized proton
$\Rightarrow$ constraint (upper bound) on the gluon Sivers function.

What about E704 data collected, at comparable rapidity and p_T ranges, at ($\sqrt{s} \simeq 20$ GeV)?
- too large $x_a^{\min}$





Ratios of partonic contributions to $Ed^3\sigma/d^3p$ for $pp \to \pi X$ at mid-rapidity, at $\sqrt{s} = 200$ GeV.

Ratios of partonic contributions to $Ed^3\sigma/d^3p$ for $pp \to \pi X$ at mid-rapidity, at $\sqrt{s} = 20$ GeV.

Notice:

- The valence u and d Sivers functions alone, so far extracted, predict an almost vanishing SSA, compatible with the PHENIX and E704 data.

$\Rightarrow$ No need to introduce sea/gluon Sivers contributions.

On the other hand, a large gluon Sivers function would
- not affect the analysis of the E704 and STAR data at large positive x_F;
- strongly affect the description of the mid-rapidity PHENIX data.

Small value of A_N *measured* by PHENIX vs. the gluon Sivers function.

A_N with different conditions on the gluon Sivers function.

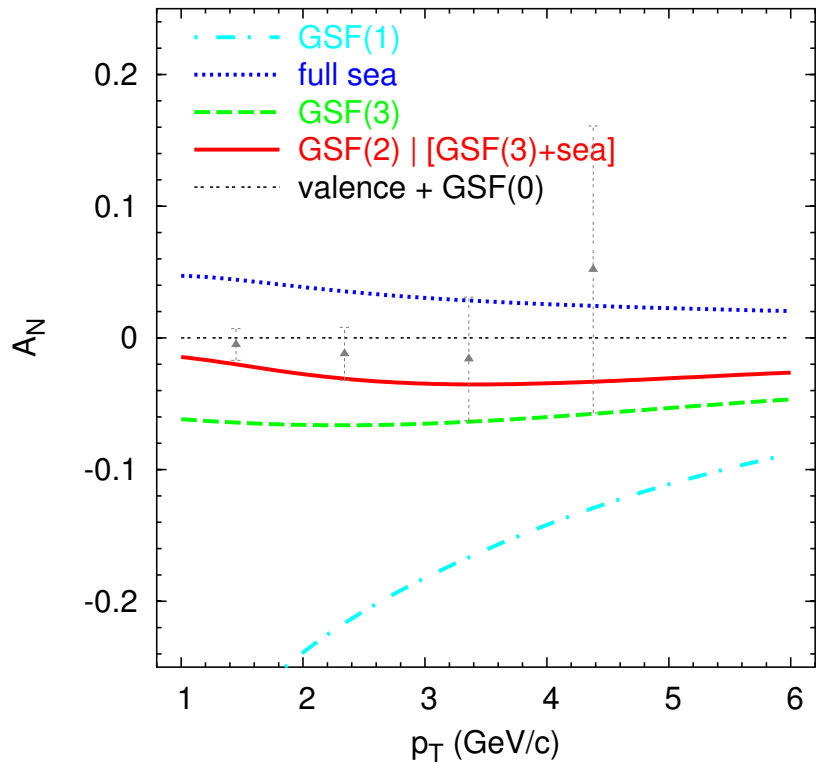
1. Largest (in magnitude) gluon Sivers distribution, [GSF(1)],

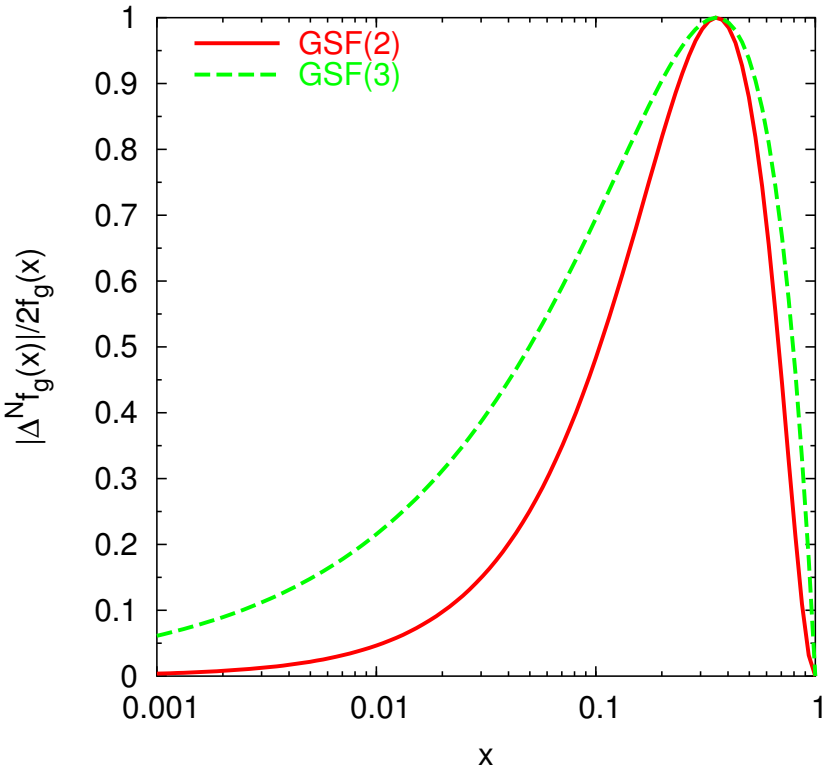
$$\Delta^N \hat{f}_{g/p^\uparrow}(x, k_\perp) = -2\hat{f}_{g/p}(x, k_\perp) \,. \tag{1}$$

2. Use of a parameterization of $\Delta^N \hat{f}_{g/p^\uparrow}$ [GSF(2)] yielding values of A_N falling, approximately, within 1-σ deviation below the lowest p_T data.

In both cases the sea-quark Sivers functions are assumed to vanish.

3. Inclusion of all sea-quarks with the largest *positive* Sivers functions [$\Delta^N \hat{f}_{q_s/p^\uparrow}(x, k_\perp) \equiv 2\hat{f}_{q_s/p}(x, k_\perp)$].
   A (largest) negative GSF [GSF(3)] which, together with this positive sea-quark contribution, gives a SSA compatible with data.





$A_N(pp \to \pi^0 + X)$ at mid-rapidity for different gluon Sivers function scenarios compared with PHENIX data [PRL95 '05].

Normalized GSF(2,3) vs. x.

Notice:

- The same $\langle k_\perp^2 \rangle$ has been used for all partons (quarks and gluons).

Using smaller values of $\langle k_\perp^2 \rangle_q$ and, *e.g.*, $\langle k_\perp^2 \rangle_g \simeq 2 \langle k_\perp^2 \rangle_q$ would lead to a more stringent bound on the GSF.

- Use of different sets for unpol pdf (CTEQ6 vs. MRST01) and ff (Kretzer vs. KKP) gives similar results (all well within the overall uncertainty).

Constraints from the Burkardt sum rule (BSR)

The BSR (Burkardt '04) states that

$$\langle \boldsymbol{k}_\perp \rangle = \sum_a \langle \boldsymbol{k}_\perp \rangle_a = \int dx \int d^2\boldsymbol{k}_\perp \, \boldsymbol{k}_\perp \sum_a \Delta \hat{f}_{a/p^\uparrow}(x, \boldsymbol{k}_\perp) = 0 \, .$$

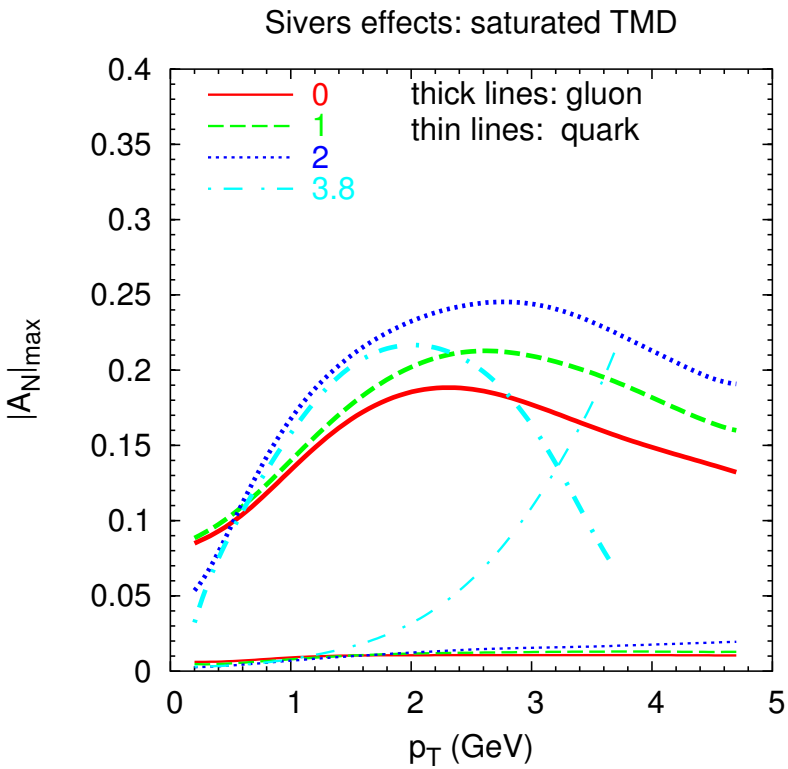
In our approach, this corresponds to total (transverse) momentum conservation, inside a transversely polarized proton:

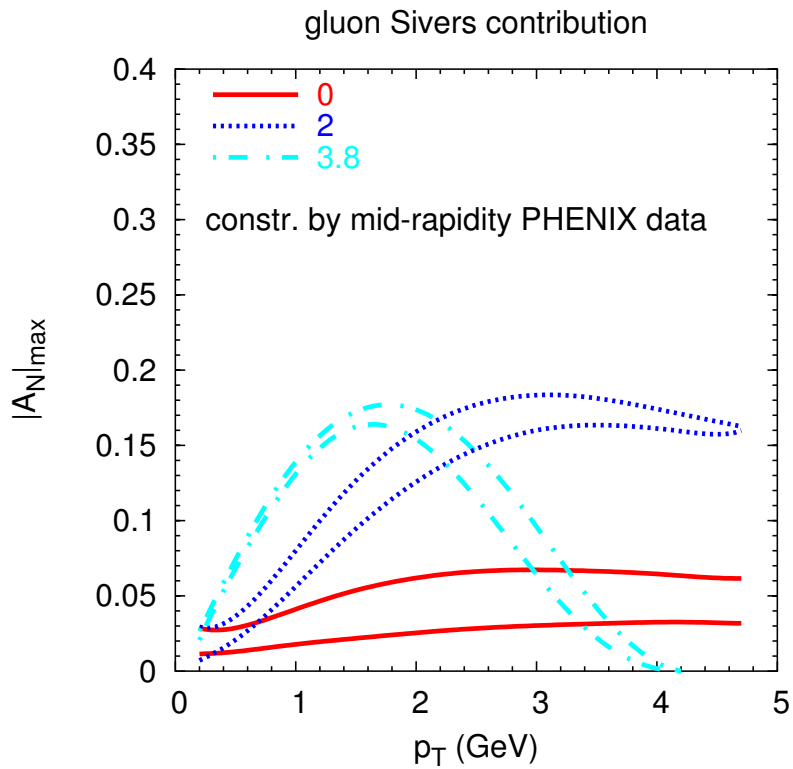
$$\hat{f}_{a/p^\uparrow}\left(x_a, \boldsymbol{k}_{\perp a}\right) = \hat{f}_{a/p}\left(x_a, k_{\perp a}\right) + \frac{1}{2} \Delta \hat{f}_{a/p^\uparrow}\left(x_a, \boldsymbol{k}_{\perp a}\right) \, ,$$

The BSR ensures this non-trivial result also including (the crucial) initial/final state interactions.

Problem: BSR requires an integration over the full x range ($x \to 0$???)

[Valence and no GSF] or [full sea + GSF(3)]: 10% accuracy;
GSF(1) or GSF(2) both without sea: strong violation.





Maximized $A_N(pp \to DX)$ at $\sqrt{s} = 200$ GeV and various η in terms of quark and gluon Sivers effects.

$A_N(pp \to DX)$ at $\sqrt{s} = 200$ GeV and various η in terms of the gluon Sivers effect as constrained by PHENIX mid-rapidity data.

Conclusions and outlook

1. All available data are compatible with valence-like quark Sivers distributions and vanishing sea-quark and gluon contributions.
2. PHENIX data on A_N allow to reach quantitative conclusions on the magnitude of the GSF.
3. Useful and related processes are:
   $p^\uparrow p \to$ jet jet $+X$ (Boer, Vogelsang '04), $p^\uparrow p \to D + X$ (Anselmino et al. '05), $p^\uparrow p \to \gamma + X$ (Schmidt et al. '05; UD, Melis, Murgia in progress)
4. Open and fundamental issues: GSF and the gluon orbital angular momentum (Brodsky, Gardner '06; Sivers '06).