Learning on transverse SSA in hadronic collisions

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

Workshop on Transverse momentum, spin, and position distributions of partons in hadrons

June 10-15, 2007 Trento, Italy

Outline

- Status of SSA phenomenology in $pp \to \pi + X$: Twist-3 vs. TMD approach;
- $pp \to \pi + X$ at mid-rapidity: access to the gluon Sivers function;
- $pp \to \gamma + X$ and $pp \to \gamma$ jet $+X$: disentangling theoretical approaches;
- $pp \to \pi$ jet $+X$: access to the f Collins mechanism;
- TMD effects in A_{LL} in pp collisions ?
- Conclusions

$$pp \longrightarrow \pi + X$$

based on works with

M.Anselmino, M.Boglione, E.Leader, S.Melis, F.Murgia

Namely 2 pQCD approaches:

Twist-3 formalism and Generalized parton model with $k_\perp$

Twist-3 **collinear** factorization (Qiu-Sterman 90s, Kouvaris et al. 06):

- 3 valence contributions: (one from each hadron in $p^\uparrow p \to \pi + X$)
- the chiral-even function, $T_{a,F}(x,x)$ (polarized proton), largely considered
- competing chiral-odd term in the fragmentation (not negligible: Koike et al. '03)
- no twist-3 gluon function considered (up to now)
- pQCD at NLO able to describe unpol. cross sections at large energies (200 GeV, RHIC) but fails at moderate energies (20 GeV, E704)
- GLOBAL fit of A_N data (high and low energy data): GOOD description
    - using LO unpol. cross sections
    - rescaling E704 calculation of A_N
    - neglecting the potentially large contribution from chiral-odd FF.

Summarizing:

- low energy data cause some problems both for the unpolarized cross section and SSA description

- fitting all available data a simple parametrization of the twist-3 chiral-even function allows a good description of them

$T_{a,F}(x,x) = N_a(x) f_{a/p}(x)$

with positive (negative) twist-3 function for $u(d)$ quark.

Generalized parton model with $\boldsymbol{k}_\perp$ (Anselmino et al. 95-06):

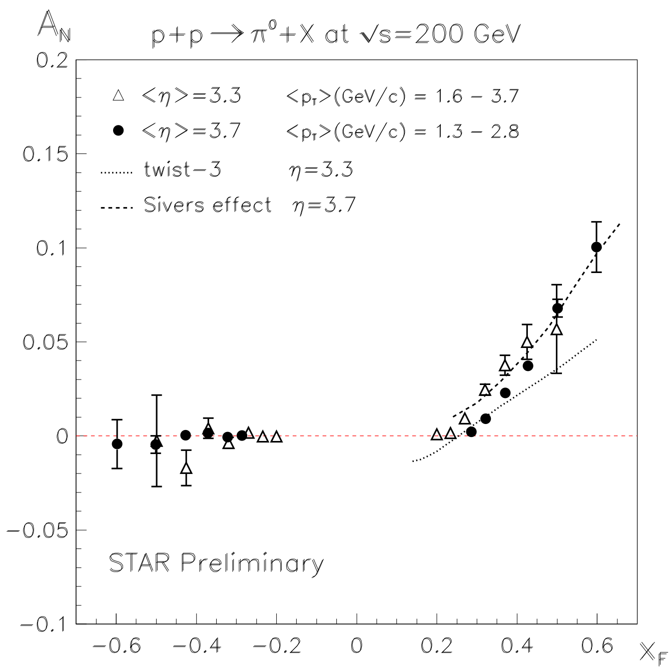
$$d\sigma^{A,S_A+B,S_B\to C+X} = \sum_{a,b,c,d,\{\lambda\}} \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \otimes \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b}) \otimes \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\,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

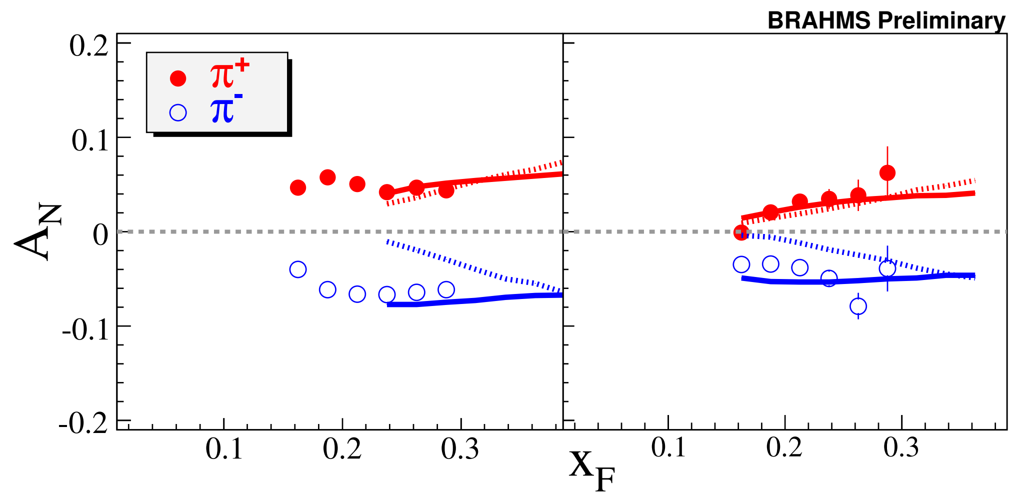
- no factorization proof
- all possible contributions: Sivers, Boer-Mulders, Collins mechanisms for quarks and gluons and all possible combinations
- only the Sivers effect able alone to describe the large x_F E704 data
- other effects suppressed (role of phases and proper $k_\perp$ kinematics)
- fair description of low and high-energy unpol. cross section data at LO
- fit on E704 A_N data: GOOD description
- predictions for RHIC in terms of Sivers effect:

GOOD for neutral pions (STAR), problems for charged pions (BRAHMS)

$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = N_a(x) f_{a/p}(x)\, h(k_\perp)$$

Positive (negative) Sivers function for $u(d)$ quark (remember $\Delta^N f_{a/p^\uparrow} \simeq -f_{1T}^\perp$).





Left: $A_N(p^\uparrow p \to \pi^0 + X)$ at $\sqrt{s} = 200$ GeV: Sivers effect (GPM approach, dashed line) and twist-3 calculations (dotted line).

Right: $A_N(p^\uparrow p \to \pi^\pm + X)$ at $\sqrt{s} = 200$ GeV for two scattering angles 2.3^0 (left) and 4^0 (right). Dotted line: Sivers effect; solid line: twist-three approach.

It seems that:

Twist-3 can describe all data; Sivers effect fails in describing high energy data.

but

TMD approach: Sivers effect from low energy data PREDICTS high energy SSA

Twist-3 function is fitted on ALL data (handling with the low energy data)

So, can the Sivers effect do a better job for high energy SSA data?

Need of a global fit: in progress...

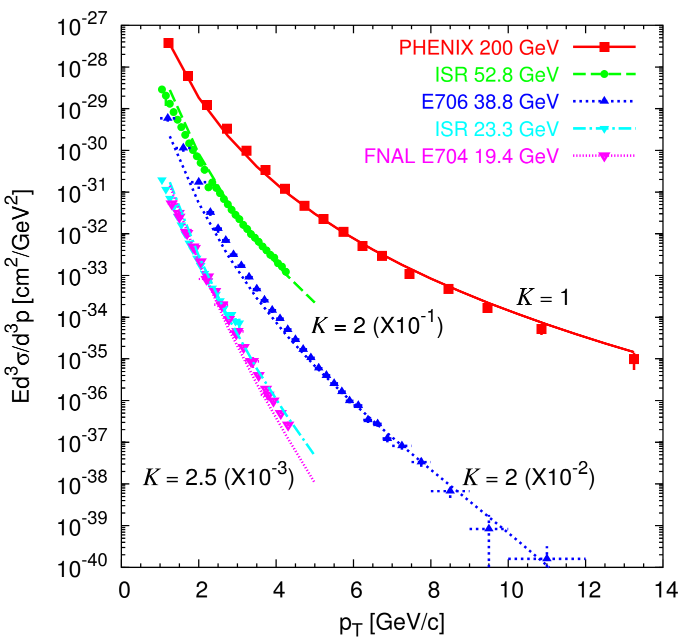
in the meantime:

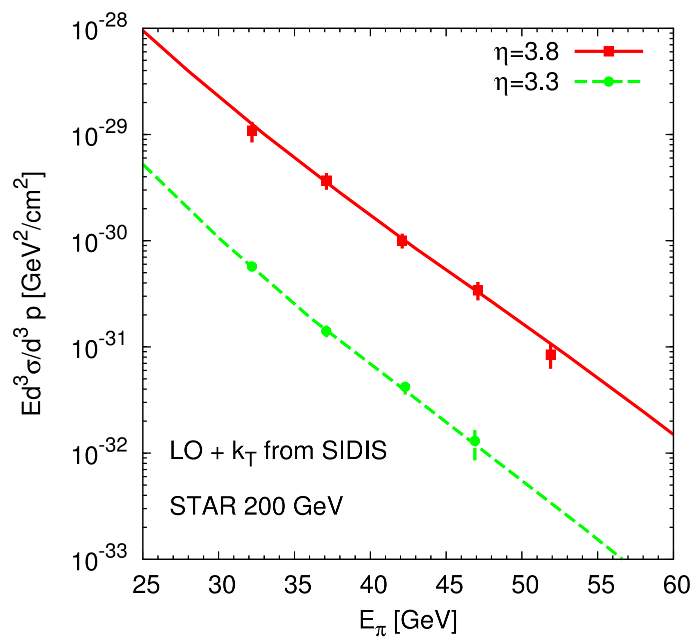
SIDIS $\ell p^{\uparrow} \to \ell' \pi + X$ $A_{UT}^{\sin(\phi-\phi_S)}$: a clean access to the Sivers effect

Can we use it into the process under study?

Plenty of issues: universality, modified universality, sign change or, even more, jungle of gauge links...Let us see what happens.

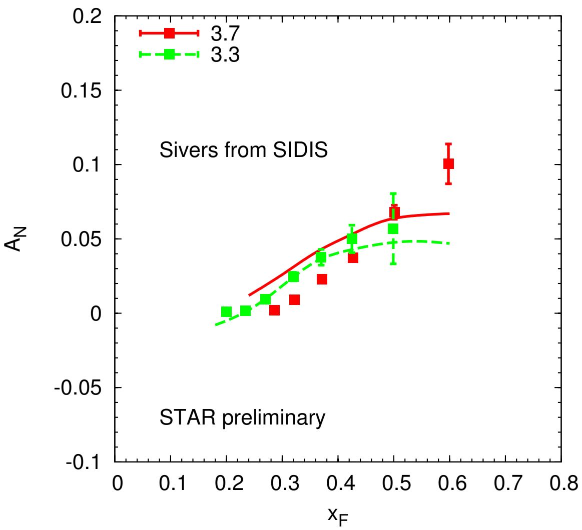
Remember: SIDIS extraction of Sivers funct. is performed in the region $x < 0.4$ (Anselmino et al. '05). [Prokudin talk]



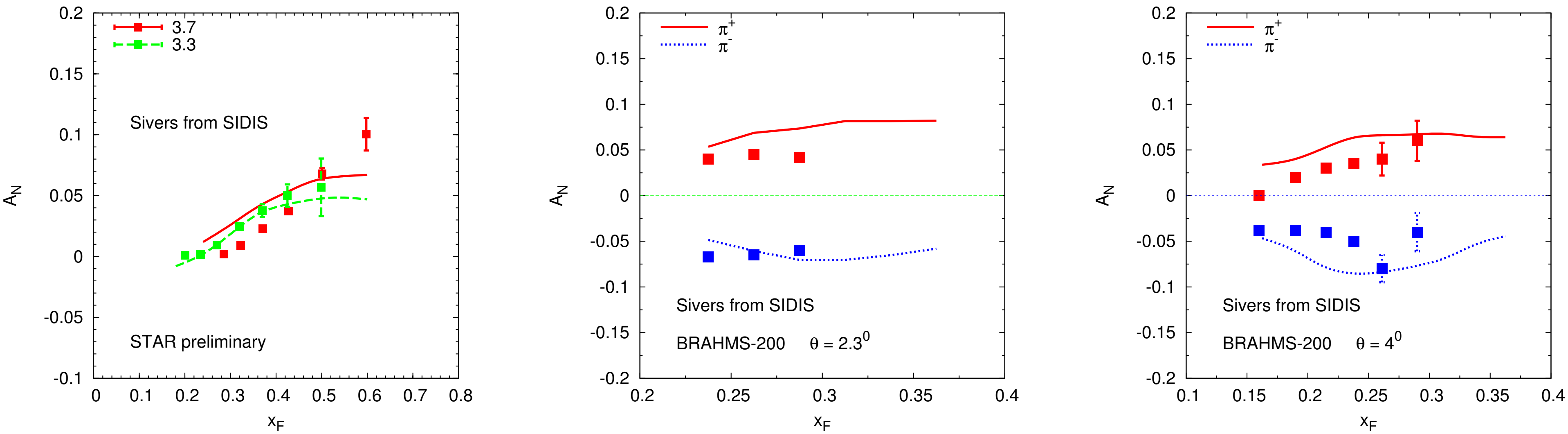


Estimates of unpolarized cross sections for $pp \to \pi X$ at LO with $k_\perp$ at mid- and forward-rapidity.

$k_\perp$ as extracted from SIDIS (Cahn effect) [Anselmino et al. 05]



Predictions of Sivers effect (from SIDIS) compared to A_N from STAR



Predictions of Sivers effect (from SIDIS) compared to A_N from STAR and BRAHMS.

Conclusions:

- Sivers effect can, in principle, describe SSA observed at RHIC as well as (or as bad as) the twist-3 approach does

- Sivers effect as extracted from SSA in SIDIS predicts A_N for $pp \to \pi X$ in fair agreement with data

  - Universality breaking does not yet come out from this comparison

- From a phenomenological point of view $pp \to \pi X$ processes cannot distinguish between the 2 approaches (same for $pp \to$ jet X).

Notice:

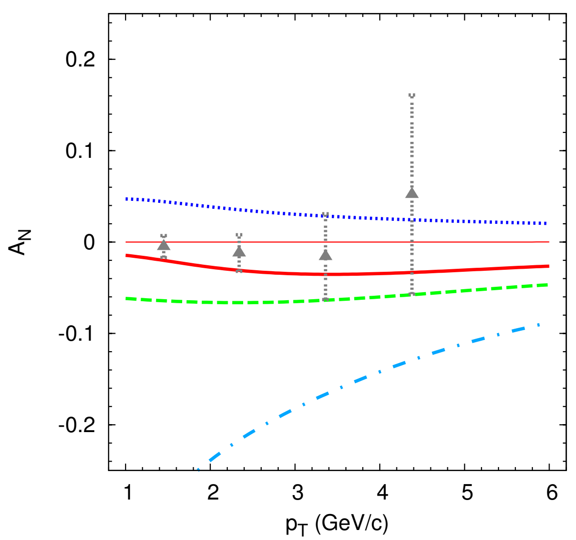
Collins effect (and transversity) as extracted from SIDIS and e^+e^- [Anselmino et al. '07] gives a completely negligible contribution in $pp \to \pi X$. No contamination!

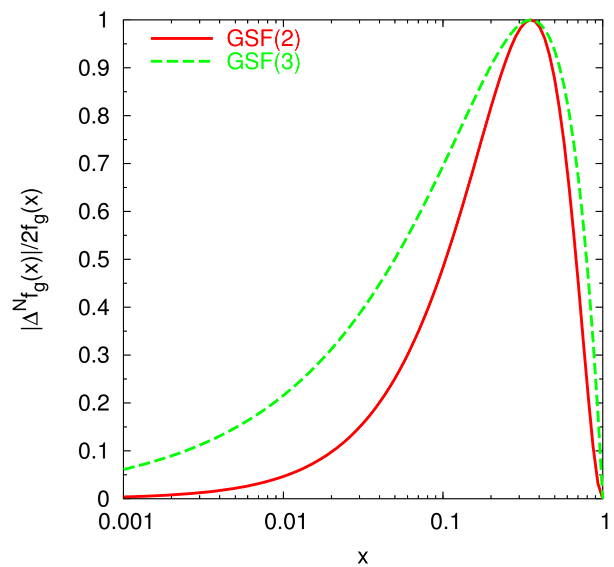
Gluon Sivers effect in $pp \longrightarrow \pi + X$

M.Anselmino, UD, S.Melis, F.Murgia '06

Generalized parton model with $k_\perp$:

- mid-rapidity $\longrightarrow$ only Sivers effect survives
- large energies (RHIC) $\longrightarrow$ dominance of gluons
- $A_N \approx 0$ at PHENIX $\longrightarrow$ constraints on the gluon Sivers function





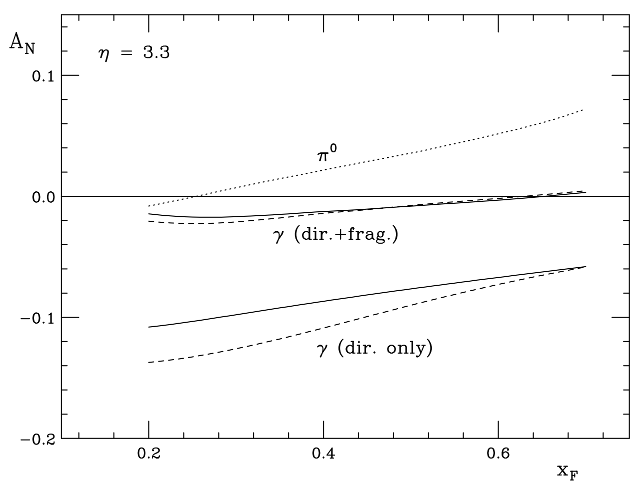
Left: Different contributions to A_N at $\eta = 0$ compared to PHENIX data.

Right: upper bounds on the gluon Sivers function.

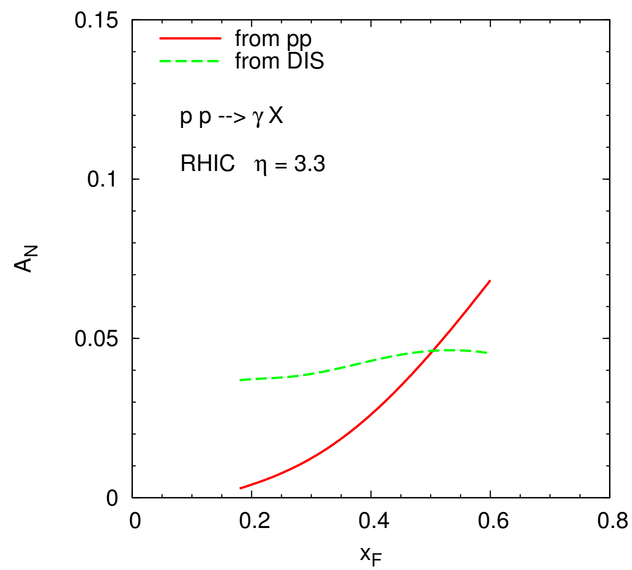
$$pp \longrightarrow \gamma + X$$

Twist-3 vs. generalized parton model with $k_\perp$:

Twist-3 function enters with an opposite hard scattering part w.r.t. the Sivers function, coupled with unpolarized partonic cross section.



Twist-3 calculation (Kouvaris et al. ’06)



Sivers effect (UD, Murgia ’04)

$$pp \to \gamma\, jet + X$$

A.Bacchetta, C.Bomhof, UD, P.Mulders, F.Murgia ’07

Comparison between the generalized parton model with $k_\perp$ and the color-gauge-invariant approach. [Bacchetta, Bomhof, Mulders, Pijlman, '04 '05]

Both assume $k_\perp$ factorization.

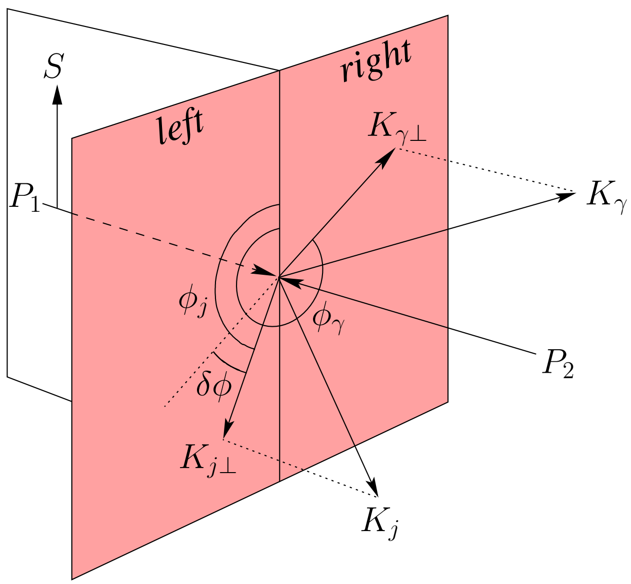
Color-gauge-invariant approach: [Mulders talk]

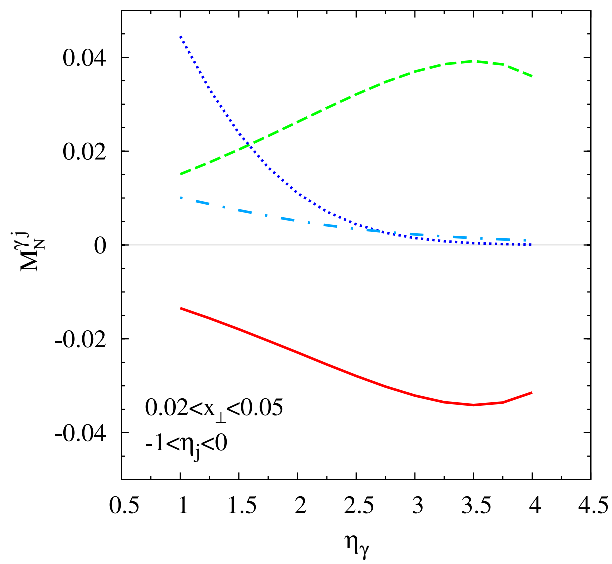
- gauge links (Wilson lines) as initial- final- state color interactions
- process dependence of T-odd functions (phases)
  - Sivers function: opposite sign from SIDIS to DY
- $pp \to$ hadrons: Wilson line structure highly intricate (many colored partons)
- photons: colorless $\to$ simplified treatment, i.e. gluonic pole cross sections as ordinary cross sections multiplied by color prefactors
- in particular the $qg \to \gamma q$ process gets a minus sign

$p^{\uparrow}(P_1) + p(P_2) \to \gamma(K_\gamma) + \text{jet}(K_j) + X$ at RHIC: Sivers and BM effects at work

$$M_N^{\gamma j}(\eta_\gamma, \eta_j, x_\perp) = \frac{\int d\phi_j\, d\phi_\gamma\, \frac{2|\boldsymbol{K}_{\gamma\perp}|}{M} \sin(\delta\phi)\cos(\phi_\gamma)\, \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}{\int d\phi_j\, d\phi_\gamma\, \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}$$

to emphasize the differences $\to$ enhance the gluon contr. in the unpolarized proton: large η_γ and small η_{jet} and $0.01 < x_\perp < 0.05$





q Sivers q Sivers gl. Sivers BM

$pp \longrightarrow \pi\, jet + X$

P.Contu, UD, M.Melis, F.Murgia, in progress

$p^{\uparrow}p$ collision along the Z axis in the pp c.m. frame
$\boldsymbol{S}$ along the Y axis
jet-axis on the XZ plane; pion around the jet: $\boldsymbol{p}_\pi = z\boldsymbol{p}_{\rm jet} + \boldsymbol{k}_{\perp\pi}$

spin-jet-pion correlation ($\boldsymbol{x}_H, \boldsymbol{y}_H, \boldsymbol{z}_H$: parton helicity frame)

$\boldsymbol{S}\cdot(\boldsymbol{p}_{\rm jet}\times\boldsymbol{p}_\pi) = \boldsymbol{Y}\cdot(\boldsymbol{p}_{\rm jet}\times\boldsymbol{p}_\pi) = \boldsymbol{y}_H\cdot(\boldsymbol{z}_H\times\boldsymbol{p}_\pi) = \boldsymbol{x}_H\cdot\boldsymbol{p}_\pi = k_{\perp\pi}\cos\phi_\pi^H$

and this coincides with the Collins phase:

$\boldsymbol{s}_{q'}\cdot(\boldsymbol{p}_{\rm jet}\times\boldsymbol{k}_{\perp\pi})$

the fragmenting parton q' staying on the plane orthogonal to the proton polarization
$\rightarrow$ it can be polarized only along the proton polarization, i.e. along the Y axis.

Schematically we have (helicity formalism + $\boldsymbol{k}_\perp$):

$d\sigma^{\mathrm{UNP}} = a + b\,\cos\phi_\pi^H$ where

$a = f \otimes f \otimes D\ +\ \mathrm{BM} \otimes \mathrm{BM} \simeq f \otimes f \otimes D$

$b = \mathrm{BM} \otimes \mathrm{Collins}$

$d\sigma^\uparrow - d\sigma^\downarrow = c + d\cos\phi_\pi^H$ where

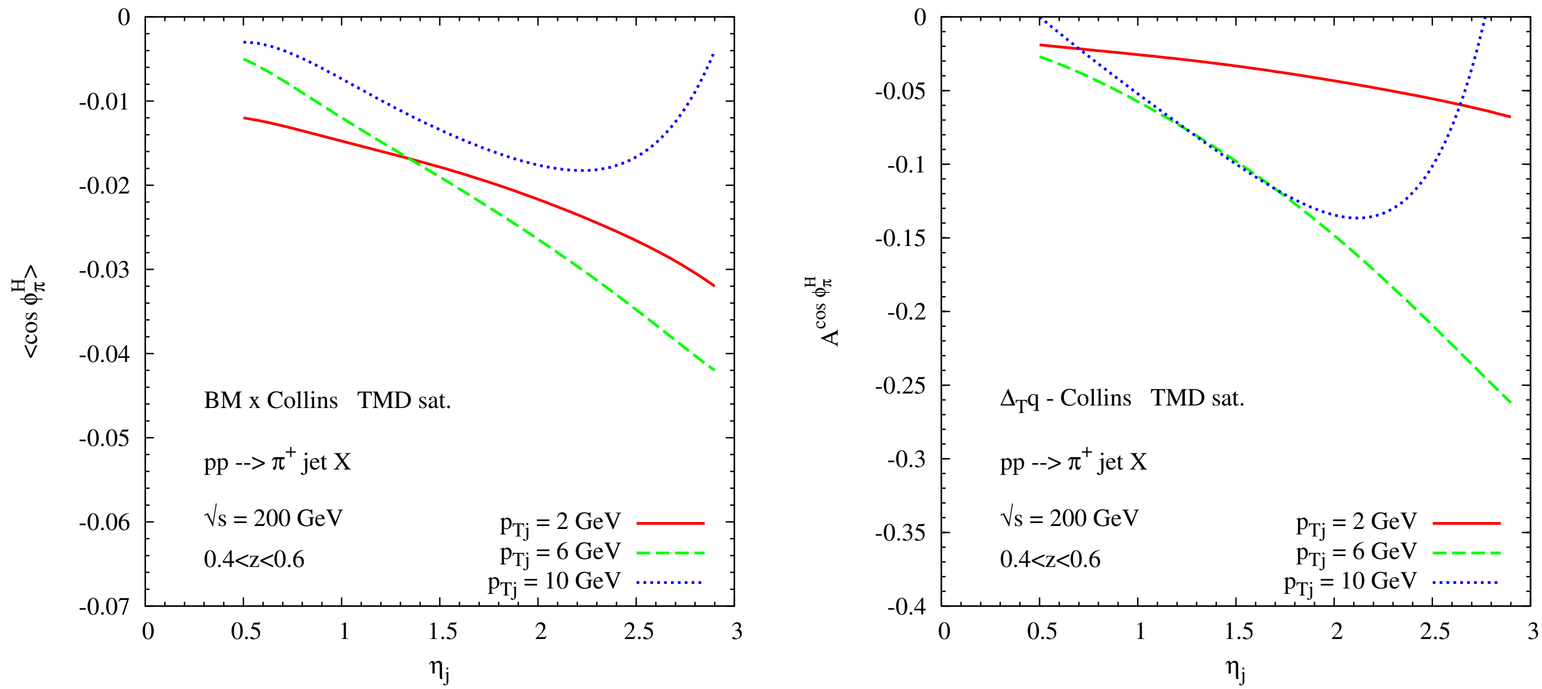
$c = \mathrm{Sivers}\ +\ \mathrm{transversity} \otimes \mathrm{BM} \simeq \mathrm{Sivers}$

$d = \mathrm{transversity} \otimes \mathrm{Collins}\ +\ \mathrm{Sivers} \otimes \mathrm{BM} \otimes \mathrm{Collins} \simeq \mathrm{transversity} \otimes \mathrm{Collins}$

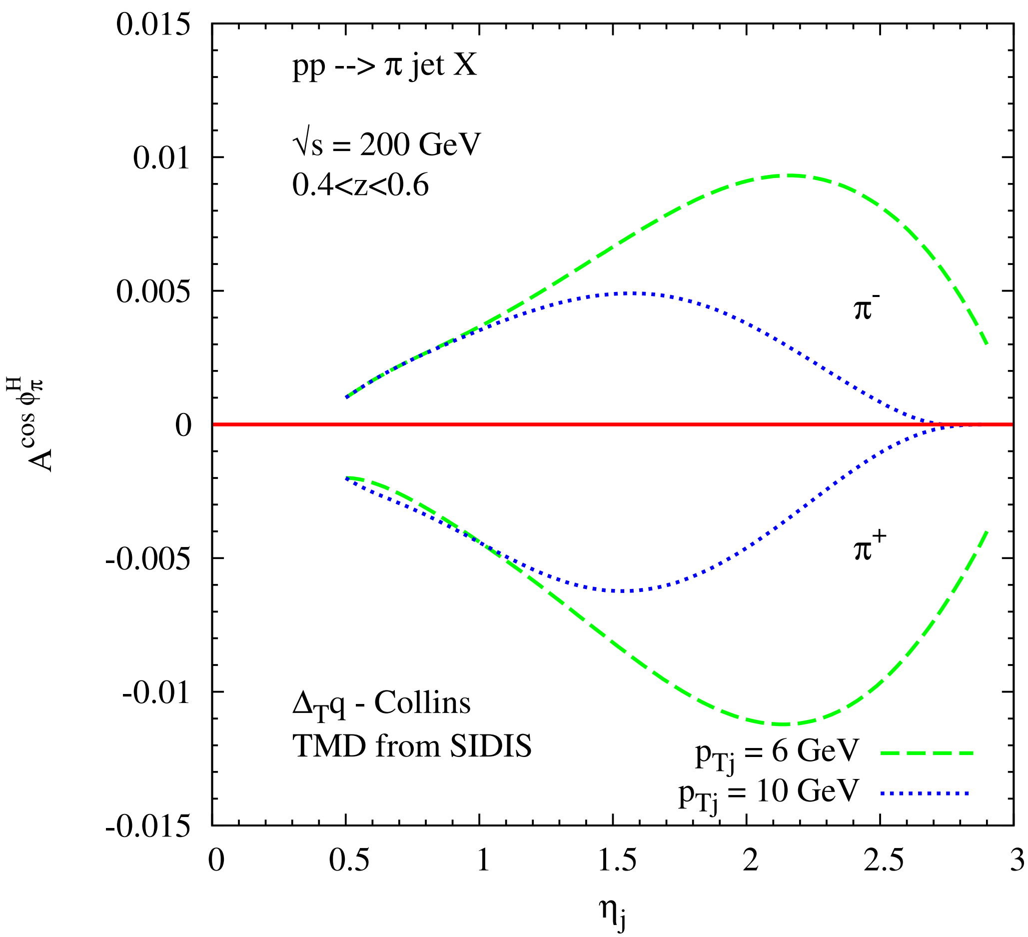
Therefore

$$\langle\cos\phi_\pi^H\rangle \simeq b/a \simeq \mathrm{BM} \otimes \mathrm{Collins}$$

$$A_N^{\cos\phi_\pi^H} = \frac{\int d\phi_\pi^H \cos\phi_\pi^H\,(d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi_\pi^H\,(d\sigma^\uparrow + d\sigma^\downarrow)} \simeq d/a \simeq \mathrm{transversity} \otimes \mathrm{Collins}$$



Estimates for $\langle \cos\phi_\pi^H \rangle$ (left) and $A_N^{\cos\phi_\pi^H}$ (right), with spin and TMD functions saturated to their bounds.



Predictions for $A_N^{\cos\phi_\pi^H}$ for charged pions, adopting the transversity and Collins functions as extracted from SIDIS and e^+e^- data [Anselmino et al. 07.].

TMD effects in $A_{LL}(pp \rightarrow \pi X)$

M.Anselmino, M.Boglione, UD, E.Leader, S.Melis, F.Murgia, in progress

Motivations: negative low p_T data at mid-rapidity observed by PHENIX (first Runs).

Generalized parton model with $k_\perp$:

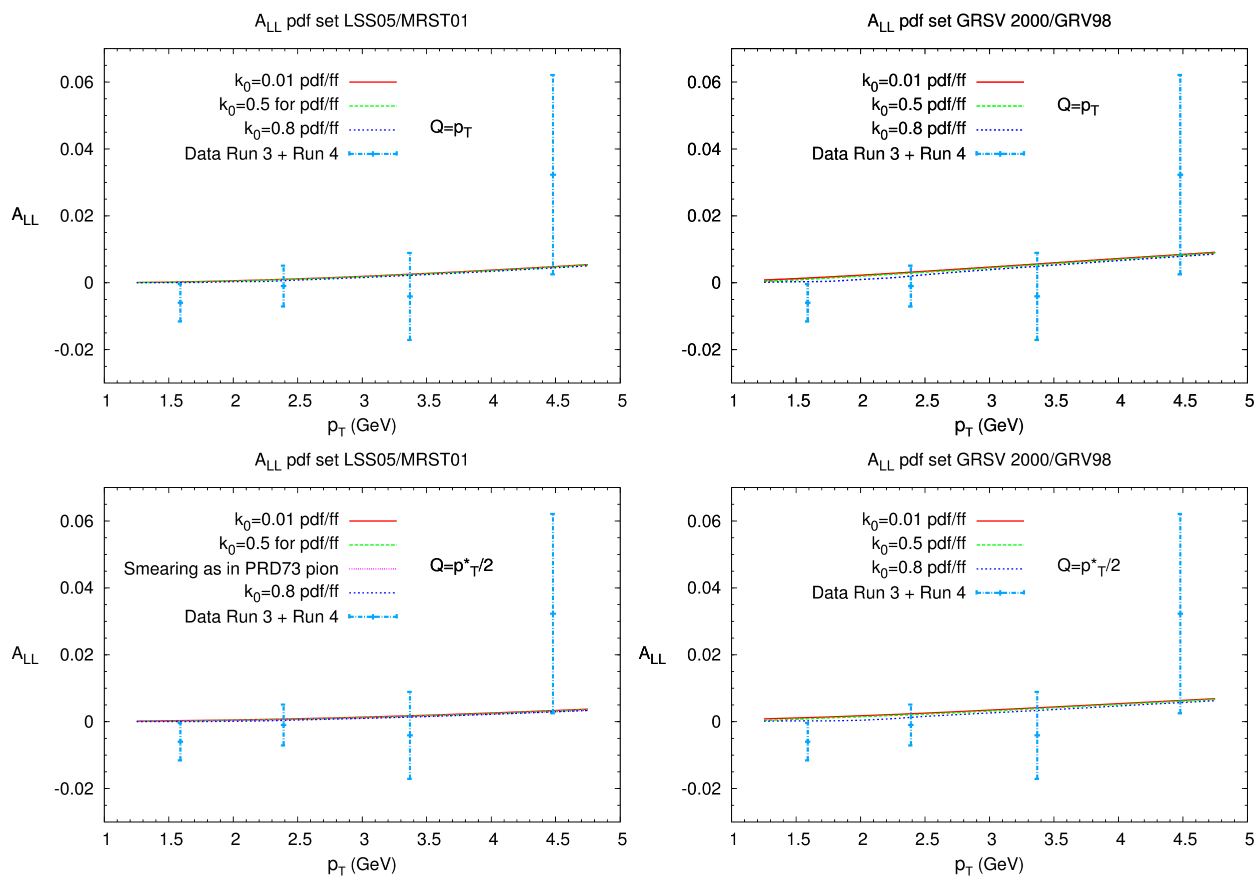
Num[A_{LL}], $q_a q_b \to q_c q_d$ contribution

$$
\begin{aligned}
&[\Sigma(+,+) - \Sigma(+,-)]^{q_a q_b \to q_c q_d} = \\
&\quad \Delta \hat{f}^a_{s_z/+}(x_a, k_{\perp a})\, \Delta \hat{f}^b_{s_z/+}(x_b, k_{\perp b}) \left[|\hat{M}_1^0|^2 - |\hat{M}_2^0|^2 - |\hat{M}_3^0|^2 \right] \hat{D}_{C/c}(z, k_{\perp C}) \\
&+ \quad 2 \hat{M}_2^0\, \hat{M}_3^0\, \hat{D}_{C/c}(z, k_{\perp C}) \times \\
&\qquad \Big[\Delta \hat{f}^a_{s_x/+}(x_a, k_{\perp a})\, \Delta \hat{f}^b_{s_x/+}(x_b, k_{\perp b}) \cos(\varphi_3 - \varphi_2) \\
&\qquad + \boxed{\Delta \hat{f}^a_{s_y/A}(x_a, k_{\perp a})\, \Delta \hat{f}^b_{s_x/+}(x_b, k_{\perp b}) \sin(\varphi_3 - \varphi_2)} \Big] \\
&- \quad \boxed{\hat{f}_{a/A}(x_a, k_{\perp a})\, \Delta \hat{f}^b_{s_x/+}(x_b, k_{\perp b})\, \hat{M}_1^0\, \hat{M}_3^0 \sin(\varphi_1 - \varphi_3 + \phi_C^H)\, \Delta^N \hat{D}_{C/c^\uparrow}(z, k_{\perp C})} \,.
\end{aligned}
$$

- some terms appearing in the kernels (those entering also A_L) vanish identically after integration over the parton momenta
- the T-odd terms (i.e. $h_{1L}^{\perp}$) give a negligible contribution at mid-rapidity
- the usual contributions (helicity PDF's) even with different choices of $k_\perp$ widths cannot change the results obtained in the collinear picture.

TMD effects cannot give negative contributions to A_{LL}.

The complete calculation in the TMD approach is not in contradiction with data.



Comparisons of TMD approach results for A_{LL} at mid-rapidity (PHENIX data).

Conclusions

- SSA in $pp \to \pi + X$

  description in terms of twist-3 formalism or Sivers effect

  Sivers effect from SIDIS compatible with data: universality?

  mid-rapidity: constraints on the gluon Sivers function

- $pp \to \gamma + X$: opposite sign between twist-3 and Sivers effect
- $pp \to \gamma$ jet $+X$: opposite sign between color-gauge-invariant approach and generalized parton model
- $pp \to \pi$ jet $+X$: access to the Collins effect
- No TMD effects in A_{LL} at mid-rapidity: consistency with data