Transverse Single Spin Asymmetries in hard scattering processes

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

Symmetries and Spin SPIN-PRAHA-2008

July 20-26, 2008 Prague

based on collaboration with

M. Anselmino, M. Boglione, A. Kotzinian, E. Leader, S. Melis, F. Murgia, A. Prokudin, C. Turk

UD, F.Murgia (2007) 0712.4328, Prog. in Part. and Nucl. Phys. (in press)

Outline

- Motivations: experimental evidence of SSAs.

From $p^{\uparrow}p \to hX$ to $\ell p^{\uparrow} \to \ell' hX$

- Theoretical approaches to SSAs:

Transverse Moment Dependent approach vs. Higher-Twist formalism

- TMD approach in a parton model and in QCD

- TMD functions and their role in azimuthal and SSAs: Phenomenology

- Extraction of Sivers, Collins and transversity functions

- SSAs: From SIDIS to pp collisions

- Conclusions and outlook

SSAs: QCD expectations vs. data

SSAs in pQCD

Kane, Pumplin, Repko 1978

$$\hat{a}_N = \frac{d\hat{\sigma}^{a^\uparrow b \to cd} - d\hat{\sigma}^{a^\downarrow b \to cd}}{d\hat{\sigma}^{a^\uparrow b \to cd} + d\hat{\sigma}^{a^\downarrow b \to cd}} \sim \mathrm{Im}[A_{\rm flip}\, A^*_{\rm no-flip}]$$

requires:

- helicity flip at the partonic level but helicity is conserved in massless QCD

- relative phase between helicity amplitudes but Born amplitudes are real.

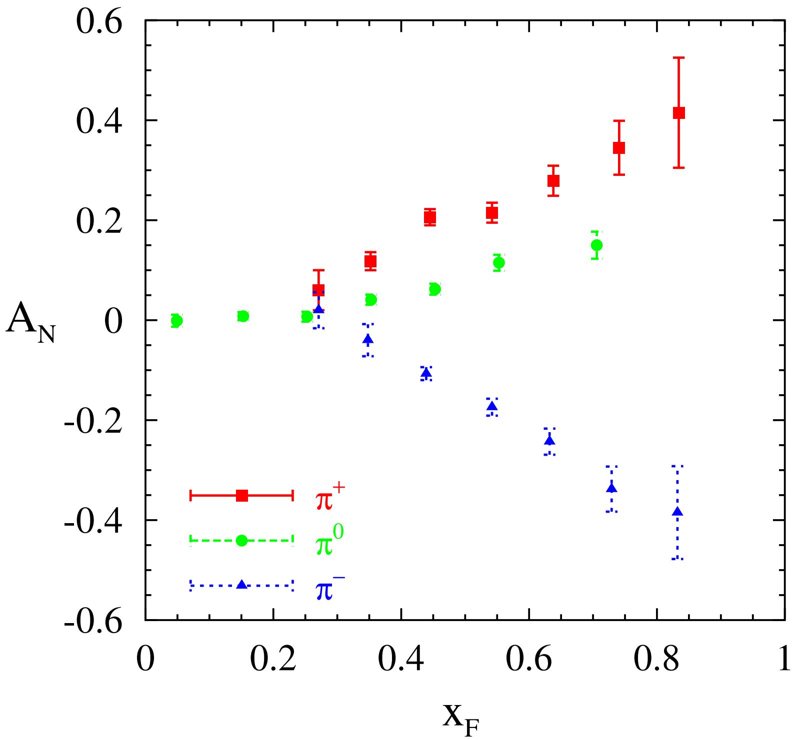
$$\Rightarrow \hat{a}_N \propto \alpha_s \frac{m}{\sqrt{s}}$$

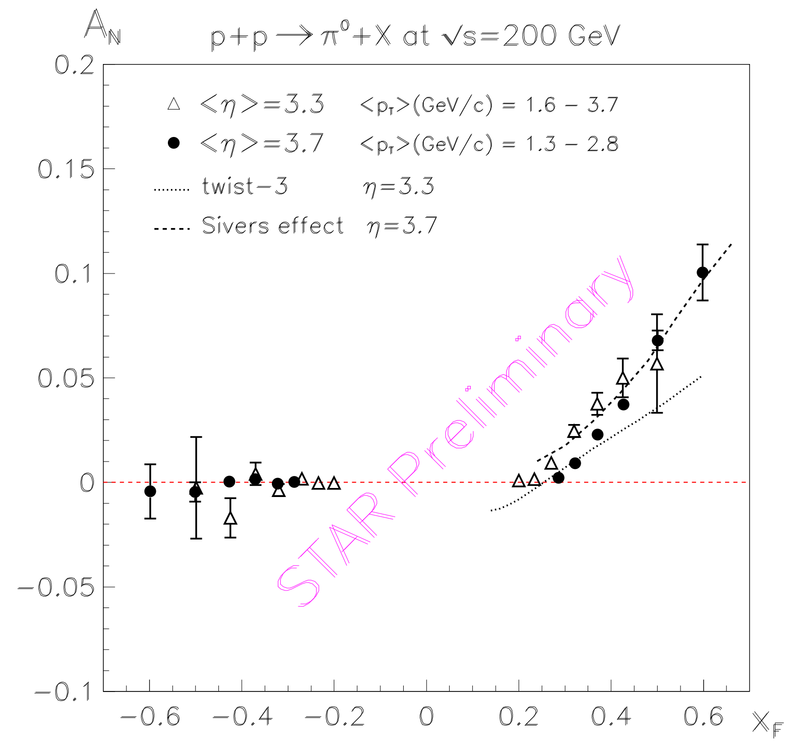
$p^\uparrow p \to hX$: $A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$ [transverse w.r.t. production plane]

$\hat{a}_N \to A_N$: further dilution

pQCD: $A_N \simeq$ few % at large energy scales!

What do experimental data say?

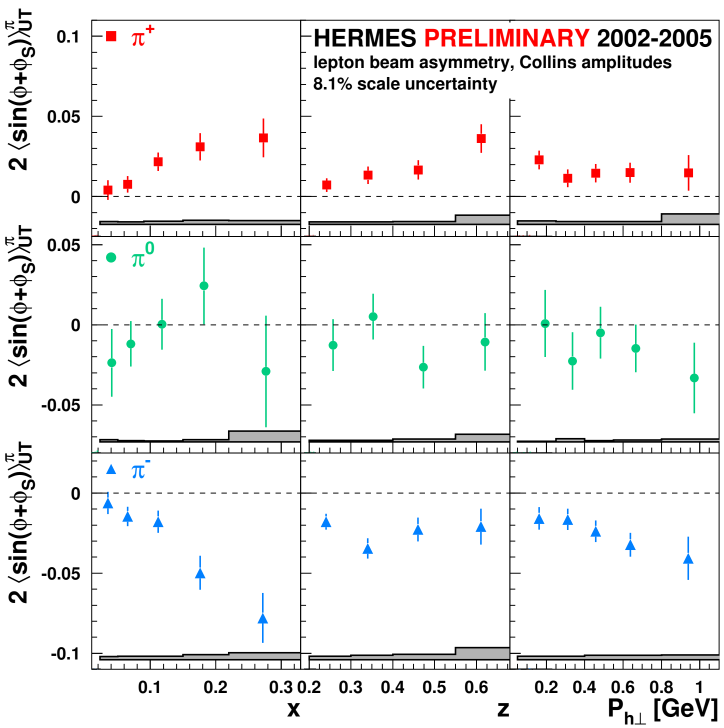


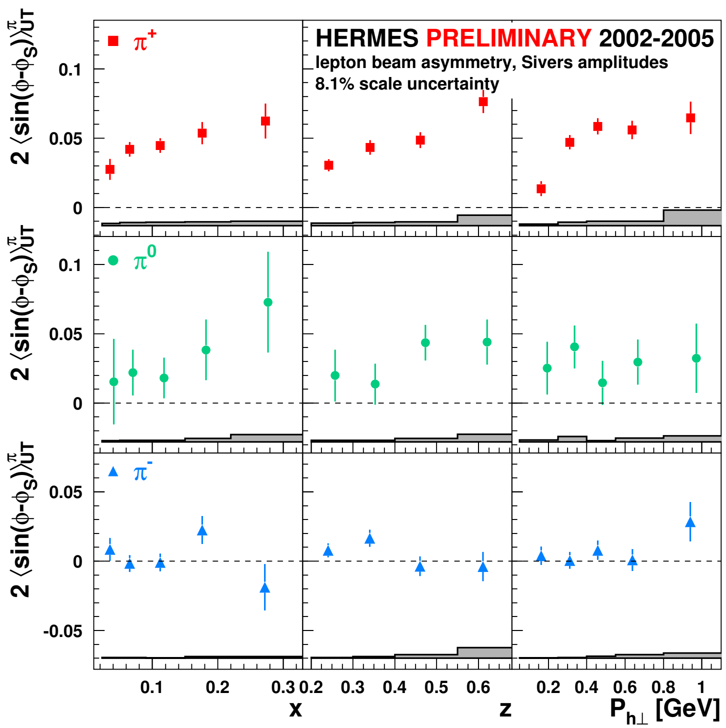


A_N data for $pp \to \pi X$:

(left) at $\sqrt{s} = 20$ GeV [*E704 coll. (1991)*], (right) at $\sqrt{s} = 200$ GeV [*STAR coll. (2004)*]

$\ell p^{\uparrow} \to \ell' \pi X$: A_{UT} [*HERMES coll. 2006*]





Experimental observation: large SSAs!

Theoretical approaches in QCD

1. Spin and transverse momentum dependent (TMD) distributions:
   azimuthal asymmetries in the soft part

2. Higher-twist functions in collinear pQCD

...a brief overview

TMD approach

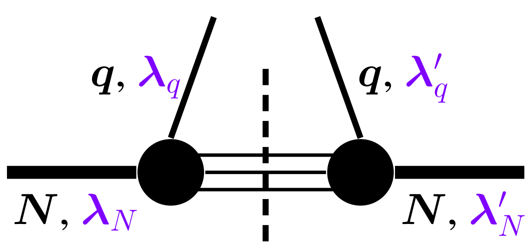
Nucleon structure in a collinear picture: $p_q = xP_N$ and $S = 0, (+), (\uparrow)$

three leading twist quantities $\Rightarrow$ complete description of quark momentum and spin:

- unpolarized parton distribution: $q(x) = q_{+/+} + q_{-/+}$
- longitudinally polarized distribution: $\Delta q(x) = q_{+/+} - q_{-/+}$
- transversely polarized distribution: $\Delta_T q(x) = q_{\uparrow/\uparrow} - q_{\downarrow/\uparrow}$ $\qquad [h_1^q, \delta q]$

Three independent forward quark-nucleon amplitudes ($N \to qX$):

$$F^{\lambda_q \lambda'_q}_{\lambda_N \lambda'_N}$$



$$q(x) = F^{++}_{++} + F^{--}_{++} \qquad \text{helicity average}$$

$$\Delta q(x) = F^{++}_{++} - F^{--}_{++} \qquad \text{helicity difference}$$

$$\Delta_T q(x) = F^{+-}_{+-} \qquad \text{helicity flip}$$

$\hat{F}^{\lambda_q,\lambda'_q}_{\lambda_N,\lambda'_N}(x,\boldsymbol{k}_\perp)$ Helicity conservation, Parity, Rotational invariance

$\longrightarrow$ 3 + 5 independent amplitudes i.e. $\longrightarrow$ 3 + 5 spin and TMD distributions

Helicity formalism (each direction refers to the particle helicity frame)

$$
\begin{aligned}
f_q(x,\boldsymbol{k}_\perp) &= \left(F^{++}_{++} + F^{--}_{++}\right) && \text{unpolarized} \\
\Delta f_{s_z/+}(x,\boldsymbol{k}_\perp) &= \left(F^{++}_{++} - F^{--}_{++}\right) && \text{helicity} \\
\Delta f_{s_x/+}(x,\boldsymbol{k}_\perp) &= 2\,\mathrm{Re}F^{+-}_{++} \\
\Delta' \hat{f}_{s_y/\uparrow}(x,\boldsymbol{k}_\perp) &= \left(F^{+-}_{+-} - F^{-+}_{+-}\right)\,\sin(\phi_\uparrow - \phi_q) \Rightarrow && \text{transversity} \\
\Delta \hat{f}_{s_x/\uparrow}(x,\boldsymbol{k}_\perp) &= \left(F^{+-}_{+-} + F^{-+}_{+-}\right)\,\cos(\phi_\uparrow - \phi_q) \\
\Delta \hat{f}_{s_z/\uparrow}(x,\boldsymbol{k}_\perp) &= 2\,\mathrm{Re}F^{++}_{+-}\,\cos(\phi_\uparrow - \phi_q)\,, \\
\Delta \hat{f}_{q/\uparrow}(x,\boldsymbol{k}_\perp) &= 4\,\mathrm{Im}F^{++}_{+-}\,\sin(\phi_\uparrow - \phi_q) && \text{Sivers} \\
\Delta f_{s_y/N}(x,\boldsymbol{k}_\perp) &= -2\,\mathrm{Im}F^{+-}_{++} && \text{Boer – Mulders}
\end{aligned}
$$

NOTICE: $\Delta \equiv$ difference of quark spin directions [except for Sivers funct.]

Other notation (Amsterdam group): $f_1, g_{1L}, h^\perp_{1L}, h_{1T}, h^\perp_{1T}, g_{1T}, f^\perp_{1T}, h^\perp_1$

• Sivers function [ImF^{++}_{+-}] $f_{1T}^{\perp}$ *Sivers 1990*

$$\Delta\hat{f}_{q/\uparrow}(x,\boldsymbol{k}_\perp) \equiv \hat{f}_{q/\uparrow} - \hat{f}_{q/\downarrow} = \Delta^N f_{q/\uparrow}(x,k_\perp)\; \boldsymbol{S}\cdot(\hat{\boldsymbol{P}}\times\hat{\boldsymbol{k}}_\perp)$$

$\Delta\hat{f}_{q/\uparrow}(x,\boldsymbol{k}_\perp)$
"T-odd",
chiral-even

• Boer-Mulders function [ImF^{+-}_{++}] $h_1^{\perp}$ *Boer, Mulders 1998*

$$\Delta\hat{f}_{\uparrow/N}(x,\boldsymbol{k}_\perp) \equiv \hat{f}_{\uparrow/N} - \hat{f}_{\downarrow/N} = \Delta^N f_{\uparrow/N}(x,k_\perp)\; \boldsymbol{s}_q\cdot(\hat{\boldsymbol{P}}\times\hat{\boldsymbol{k}}_\perp)$$

$\Delta\hat{f}_{\uparrow/N}(x,\boldsymbol{k}_\perp)$
"T-odd",
chiral-odd

(*Sivers '90, Anselmino, Boglione, Murgia '95*): parton model with $k_\perp$ effects *assuming* TMD factorization

$$A_N(pp \to \pi X) = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{2d\sigma^{\rm unp}}$$

$$d\Delta\sigma^{\rm Sivers} \propto \sum_{a,b,c} \Delta\hat{f}_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma}^{ab\to cd}(x, \boldsymbol{k}_\perp) \otimes D_{\pi/c}(z, \boldsymbol{k}_{\perp\pi})$$

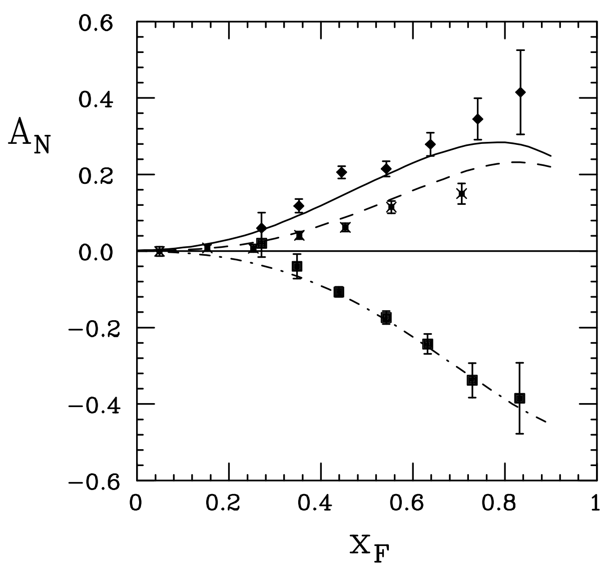
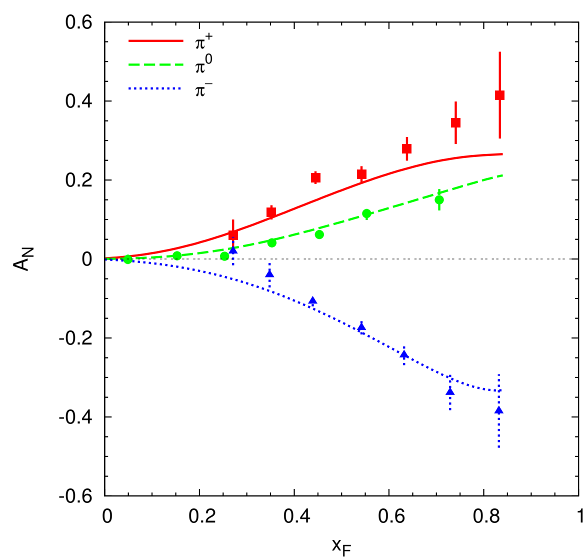


FIG. 1



Fit of E704 data: (left) leading $k_\perp$ (ABM), (right) full $k_\perp$ [*UD & F.Murgia 2004*]

- TMD in the fragmentation sector ($P_h = z p_q + \boldsymbol{k}_\perp$)

spin-0 (or unpolarized): 1 + 1 FFs spin-1/2: 3 + 5 FFs (as for PDFs)

unpolarized hadron:

$D_{h/q}$ probability for $q \to h + X$ unpolarized FF

$$\Delta \hat{D}_{h/q^\uparrow} \equiv \hat{D}_{h/q^\uparrow} - \hat{D}_{h/q^\downarrow} = \Delta^N D_{h/q^\uparrow}(z, p_\perp)\, \boldsymbol{s_q} \cdot (\hat{\boldsymbol{p}}_q \times \hat{\boldsymbol{k}}_\perp)$$

Collins '93

$\Delta \hat{D}_{h/q^\uparrow}(z, \boldsymbol{k}_\perp)$
"T-odd",
chiral-odd

T-odd but safe: final state interactions between h X

SSAs in $pp \to CX$: generalized parton model (TMD approach)

$$
\begin{aligned}
d\sigma^{\uparrow} - d\sigma^{\downarrow} \; = & \sum_{a,b,c} \Big\{ \Delta \hat{f}_{a/p^{\uparrow}} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} & \text{Sivers} \\
& + \; h_1^{a/p} \otimes f_{b/p} \otimes \Delta\hat{\sigma} \otimes \Delta \hat{D}_{\pi/c^{\uparrow}} & \text{Collins} \\
& + \; h_1^{a/p} \otimes \Delta \hat{f}_{b^{\uparrow}/p} \otimes \Delta'\hat{\sigma} \otimes D_{\pi/c} \Big\} & \text{Boer} - \text{Mulders}
\end{aligned}
$$

Complete structure and full $k_\perp$- kinematics in the helicity formalism

[*Anselmino et al. 06*].

Higher-Twist approach

Alternative approach to SSAs in $A^{\uparrow}B \to CX$: $A_N \simeq m/\sqrt{s}$

Twist-three formalism [*Efremov-Terayev '82, Qiu-Sterman '91, Koike et al. 2000*]

$$\begin{aligned} d\sigma^{\uparrow} - d\sigma^{\downarrow} &= \sum_{abc} \phi^{(3)}_{a/A^{\uparrow}}(x_1, x_2) \otimes \phi_{b/B}(x') \otimes \hat{H} \otimes D_{c\to C}(z) \\ &+ \sum_{abc} h_1^{a/A}(x) \otimes \phi_{b/B}(x') \otimes \hat{H}' \otimes D^{(3)}_{c\to C}(z_1, z_2) \\ &+ \sum_{abc} h_1^{a/A}(x) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{H}'' \otimes D_{c\to C}(z) \end{aligned}$$

$\Phi^{(3)}$, $D^{(3)}$: higher-twist partonic correlations (rather than PDFs or FFs)
$\hat{H}$: elementary interactions for $ab \to cd$ process

Strong analogy to A_N in terms of TMD distributions.

$$\Phi^{(3)}_{a/p^\uparrow}(x_1,x_2) \sim \int \frac{dy^-}{4\pi}\, e^{ixp^+y^-}\langle P,\boldsymbol{S}_T|\,\overline{\psi}_a(0)\gamma^+$$
$$\times\left[\int dy_2^-\,\epsilon_{\rho\sigma\alpha\beta}\,S_T^\rho\,p_1^\alpha\,p_2^\beta\,F^{\sigma+}(y_2)\right]\psi_a(y^-)\,|P,\boldsymbol{S}_T\rangle$$

• *TWO* parton momentum fractions, x_1, x_2, and an external gluonic field $F^{\mu\nu}$;
$\Phi^{(3)} \to T(x_1,x_2)$ (in the twist-three factorization proof)

• $\hat{H}$ involves two terms

- $\delta(x_1 - x_2)$: gluon momentum set to zero $\to$ *Soft Gluon Pole* ($\to x_1 = x_2 = x$)
- $\delta(x_i)$: quark momentum set to zero $\to$ *Soft Fermion Pole*

A_N is large at large x_F (valence region of $p^\uparrow$)
Only SGP enters with $dT(x,x)/dx$: leading effect if $T(x,x) \simeq (1-x)^\beta$ at large x

Recent developments [*Kouvaris et al. '06, Koike et al. '07*].

Phenomenology of Twist-three vs. TMD approach in $pp \to \pi X$

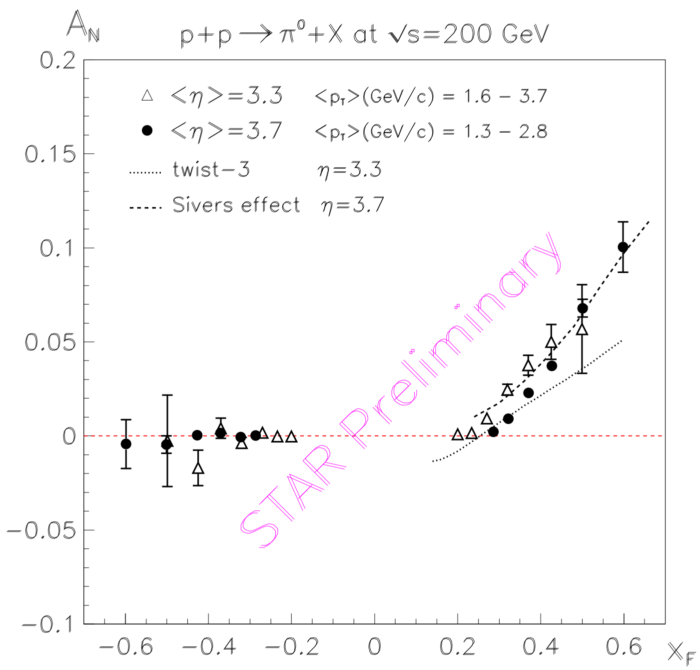
Twist-3 **collinear** factorization:

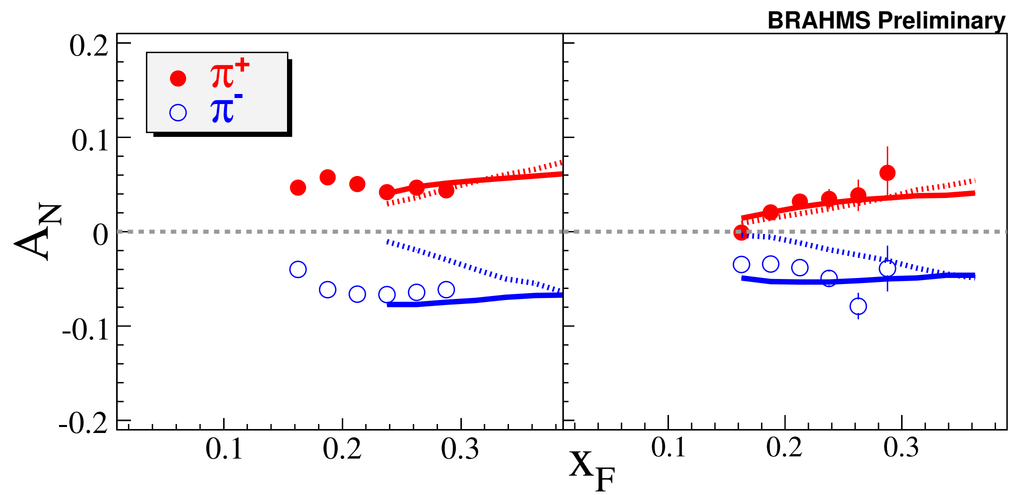
- 3 valence contributions: (one from each hadron in $p^{\uparrow}p \to \pi + X$)
- pQCD at NLO describes unpol. cross sections at large energies (200 GeV, RHIC), fails at moderate energies (20 GeV, E704)
- GLOBAL fit of A_N data (high and low energy data): GOOD description
    - using LO unpol. cross sections
    - rescaling E704 calculation of A_N
    - neglecting the potentially large contribution from chiral-odd FF.
- low energy data: problems both for the unpol. cross section and SSA description
- fit of all available data by a simple parametrization of $T(x, x)$

Generalized parton model with $\boldsymbol{k}_\perp$

- no factorization proof
- Sivers effect able to describe the large x_F E704 data
- 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)





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 to PREDICT high energy SSA

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

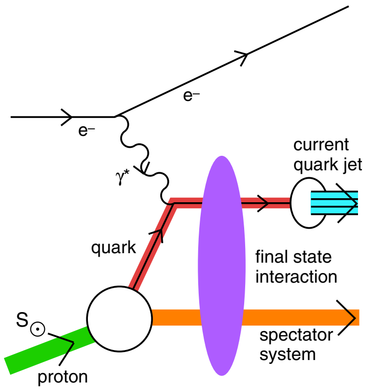
So, can the Sivers effect do a better job for high energy SSA data?

Need of a global fit: in progress...

Back on it later on

TMD approach in QCD

“T-odd” distributions: T-reversal invariance $\Rightarrow \Delta f_{\uparrow} = -\Delta f_{\uparrow} \rightarrow \mathbf{0}$ ($A^{+} = 0$ gauge)



Brodsky, Hwang, Schmidt 2001

final state interactions in DIS through soft gluon rescattering: leading twist effect.

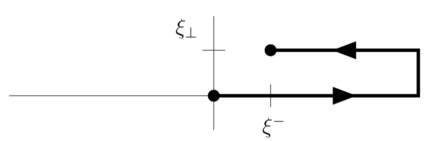
- Model for the Sivers asymmetry
- Need of quark orbital angular momentum.

Soft gluons $\leftrightarrow$ gauge link for gauge-invariant parton density [*Collins, Ji, Yuan, ...*]

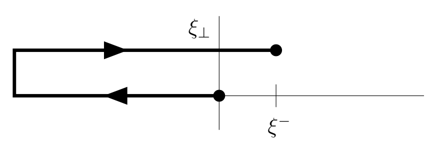
$$\mathcal{P}\exp\left(-ig_s\int_{\xi^-}^{\infty} dz^- \,\hat{A}^+(z^-,\xi_\perp)\right)$$

T-reversal invariance implies [*modified universality*]

$$\Delta f_{\uparrow}|_{\rm future} = -\Delta f_{\uparrow}|_{\rm past} \implies \Delta f_{\uparrow}|_{\rm DIS} = -\Delta f_{\uparrow}|_{\rm DY}$$



DIS



DY

• TMD factorization proved for
DY, SIDIS, [and e^+e^- annihilation] processes in the two-scale regime:
- large Q^2 (i.e. boson virtuality)
- small q_T (lepton-pair or final hadron transverse momentum)
[*Collins, Ji, Ma, Yuan, Belitsky '04*]

• gauge links $\longrightarrow$ universality of Collins function (*Collins & Metz '04, Yuan '08*)

• $\int d\boldsymbol{k}_\perp k_\perp^2/(2M^2) f_{1T}^\perp(x, k_\perp) = T(x, x)$ [*Boer, Mulders, Piljman '03*]
- a step forward: equivalence of Twist-three and TMD approach for SIDIS and DY in the region where both apply: $\Lambda_{\rm QCD} \ll q_T \ll Q$ (*Ji, Qiu, Vogelsang ,Yuan '06*)

• Universality breaking effects in TMD approach for $pp \rightarrow hh + X$
(*Collins-Qiu, Vogelsang-Yuan, Mulders et al. '07*) [disappearing for $\int dk_\perp$!!!]
$pp \rightarrow h + X$ still under debate

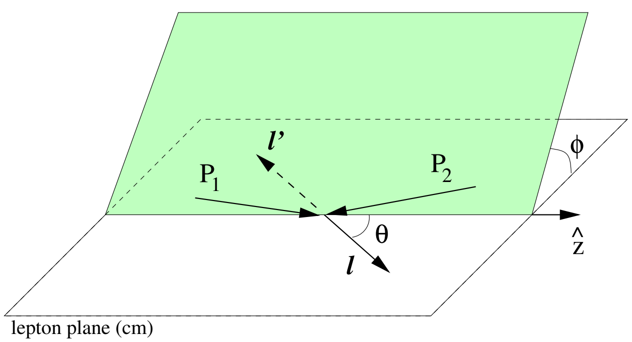
TMD approach and SSAs: phenomenology

• DY processes, $pp \to \ell^+\ell^- + X$:

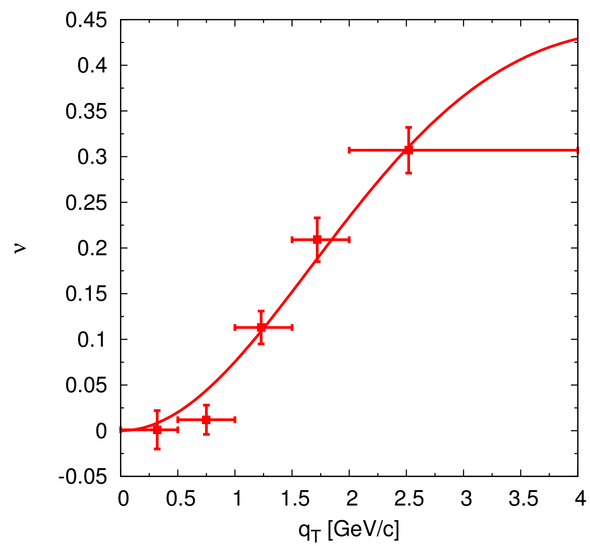
$$d\sigma \simeq 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

puzzling in LO and NLO collinear pQCD, explained in TMD approach:

$d\sigma \simeq$ Boer-Mulders$\otimes$Boer-Mulders $\cos 2\phi$



DY process in the lepton c.o.m. frame (CS).



Boer 1999

• SSA in $p^\uparrow p \to \ell^+\ell^- + X$:

$A_N \simeq \Delta^N f_{q/p^\uparrow} \otimes f_{\bar{q}/p} \sin(\phi - \phi_\uparrow) + \hat{a}_{TT} \boldsymbol{\Delta_T q} \otimes \Delta^N f_{\bar{q}^\uparrow/p} \sin(\phi + \phi_\uparrow)$

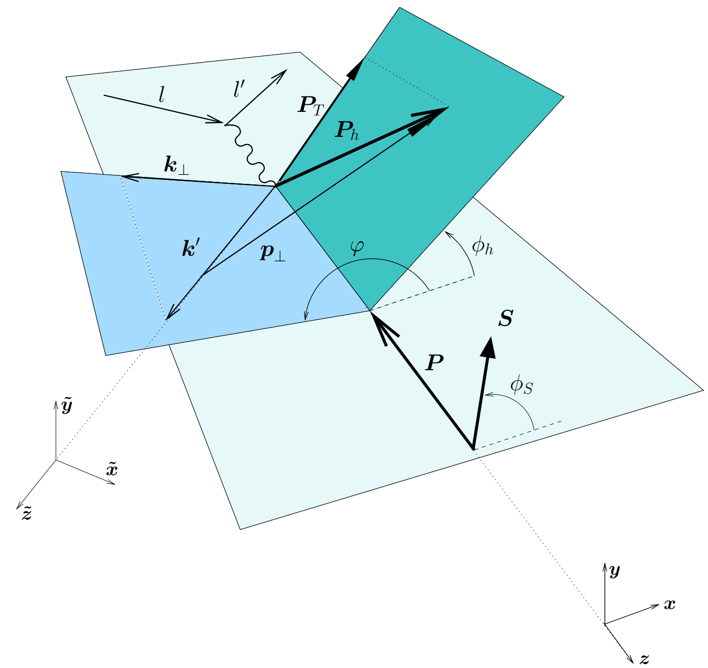
(different azimuthal dependences $\to$ separable) NO DATA

SIDIS

- azimuthal dependence in $\ell p \to \ell' h + X$

$d\sigma \simeq \Delta^N f_{q^\uparrow/p} \otimes \Delta^N D_{h/q^\uparrow} d\Delta\hat{\sigma} \cos 2\phi_h$

$+ f_{q/p} \otimes D_{h/q}\, d\hat{\sigma} \cos\phi_h$ [Cahn effect]



- SSA in $\ell p^\uparrow \to \ell' h + X$

$A_{UT} \simeq d\sigma(\phi_S) - d\sigma(\phi_S + \pi)$

$\simeq \Delta^N f_{q/p^\uparrow} \otimes D_{h/q} \sin(\phi_h - \phi_S) + \hat{d}_{NN}\, \boldsymbol{\Delta_T q} \otimes \Delta^N D_{h/q^\uparrow} \sin(\phi_h + \phi_S) + \cdots$

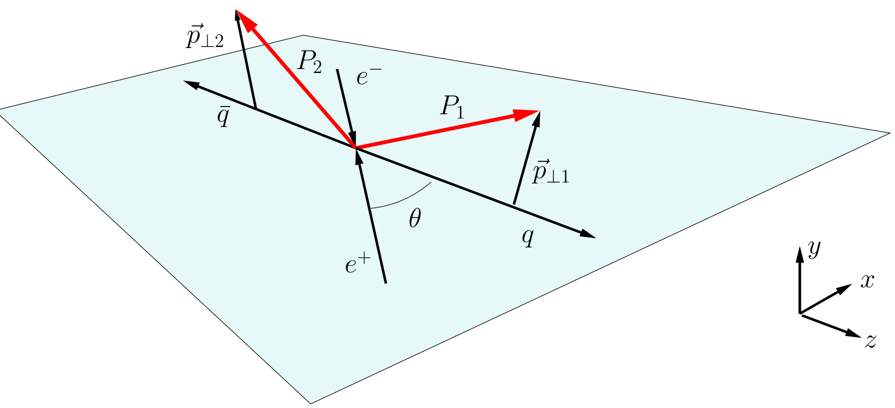
different azimuthal dependences $\longrightarrow$ separation of Sivers and Collins effects

$$A_{UT}^{\sin(\phi_h \pm \phi_S)} = 2\,\frac{\int d\phi_S\, d\phi_h\, [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi_h \pm \phi_S)}{\int d\phi_S\, d\phi_h\, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

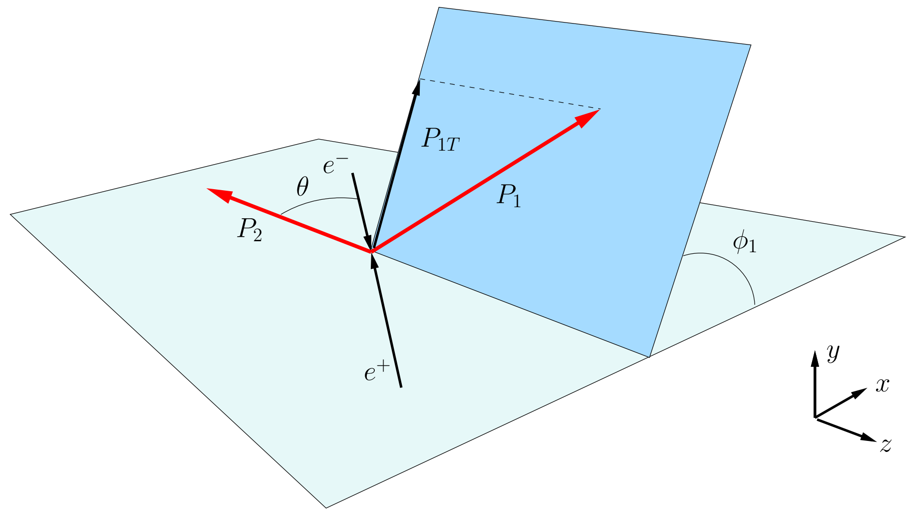
- Azimuthal correlations in $e^+e^- \to h_1 h_1 + X$: Collins effect

$$d\sigma \simeq (1+\cos^2\theta)\, D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2) + \sin^2\theta \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)$$

$\times \cos(\varphi_1 + \varphi_2)$ $\times \cos(2\phi_1)$



Reconstruction of the thrust axis



Experimental Program: Belle @ KEK [FIRST EVIDENCE]

Extraction of Sivers, Collins and transversity functions

Sivers function: u, d and sea (latest analysis) quarks

Collins function: favoured and unfavoured FFs: $u \to \pi^+$ and $d \to \pi^+$

Transversity: u and d quarks

simple ansatz: $N x^a (1-x)^b \times$ [Gaussian] $\boldsymbol{k}_\perp$ dependence

Other similar analysis from *Vogelsang & Yuan, Efremov et al.*

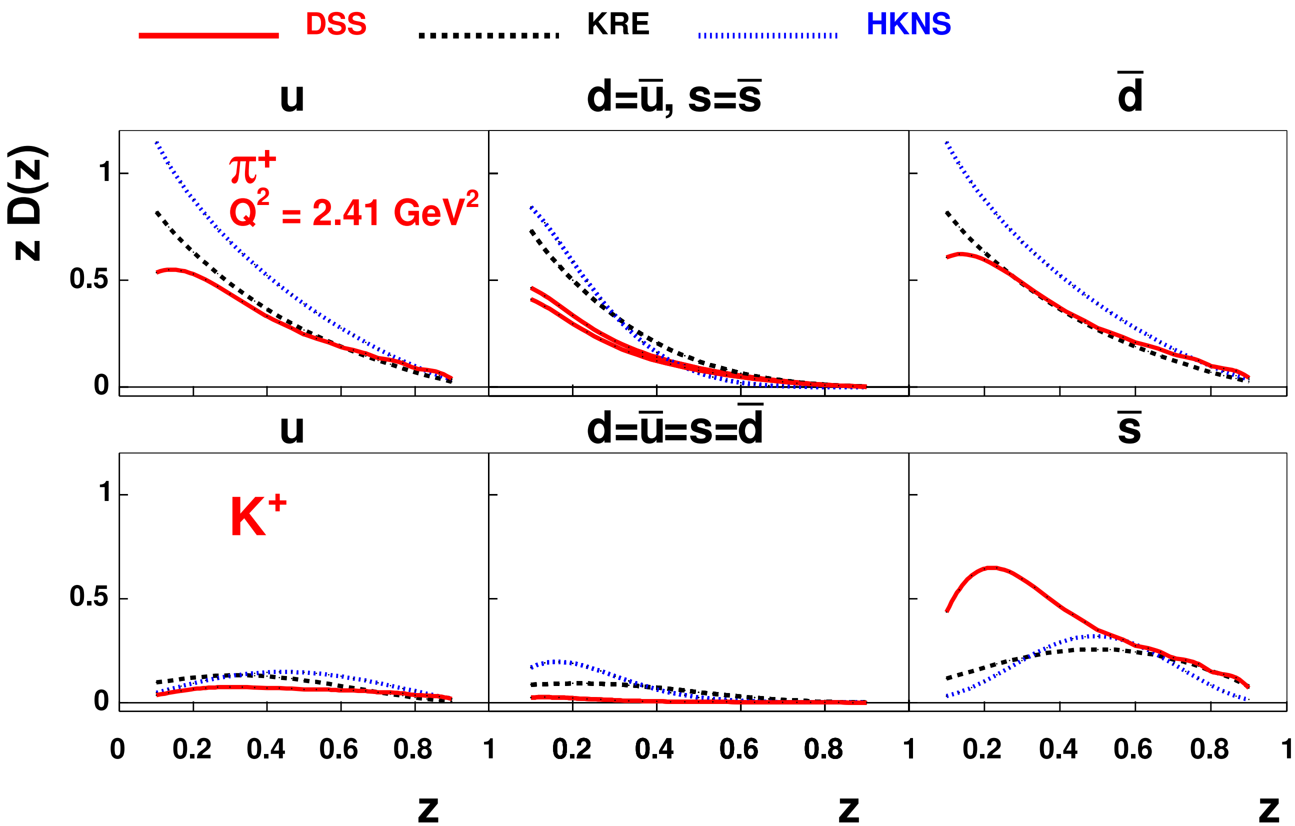
New (*Anselmino et al. '08*) vs. Old (*Anselmino et al. 05*) fits

- larger data set and more accurate data both for Collins and Sivers asymmetries
- new FF set: from KRE (*Kretzer 2000*) to DSS (*De Florian, Sassot, Stratman '07*)

in particular for the Sivers effect:

- old fit: up and down Sivers functions & independent large x behaviour
- new fit: up, down and sea [$A_{UT}^{K^+} > A_{UT}^{\pi^+}$] & same large x behaviour

Notice: *covered experimental region:* $\boldsymbol{x < 0.3}$

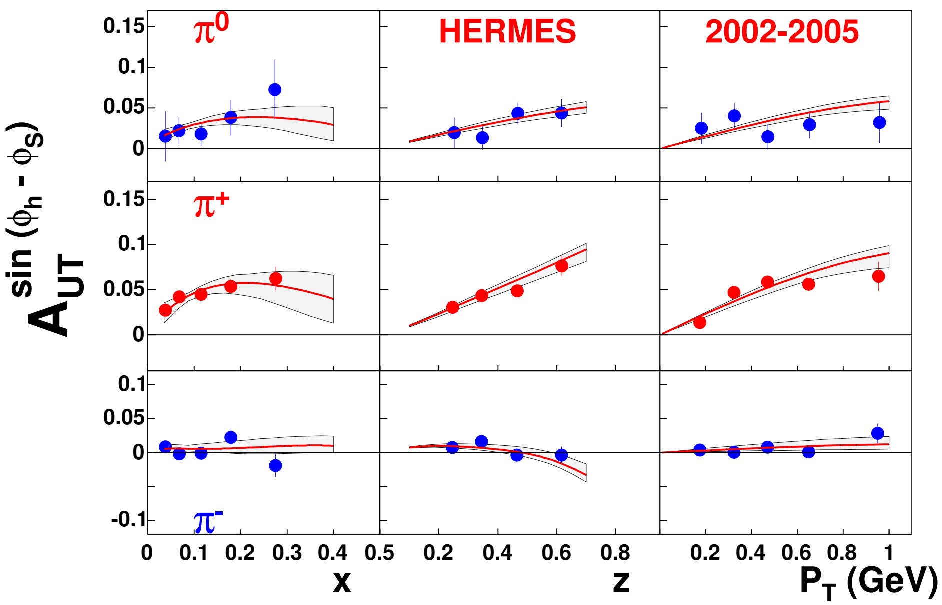


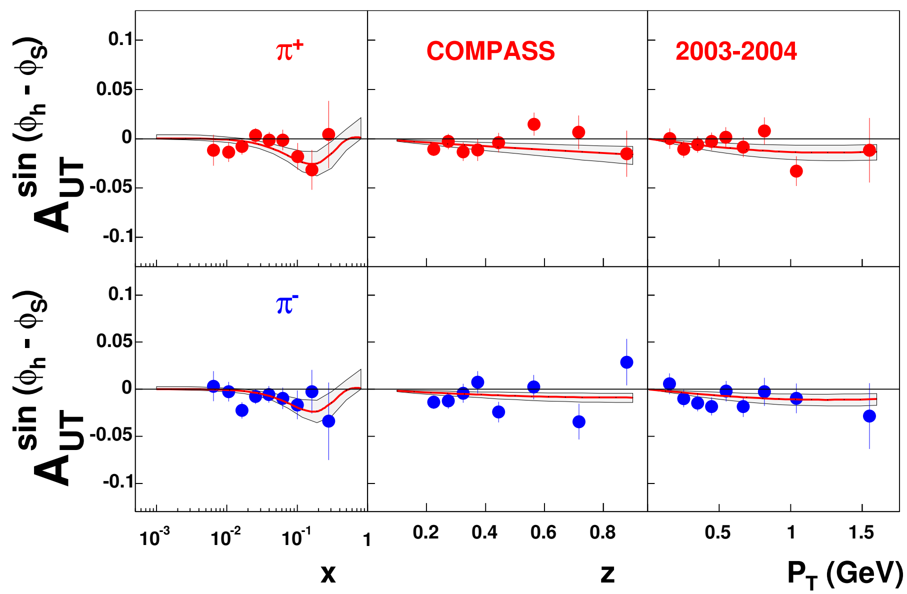
Comparison of three FF sets.

● Sivers effect in SIDIS:

NEW analysis [completed]

Anselmino et al. 2008

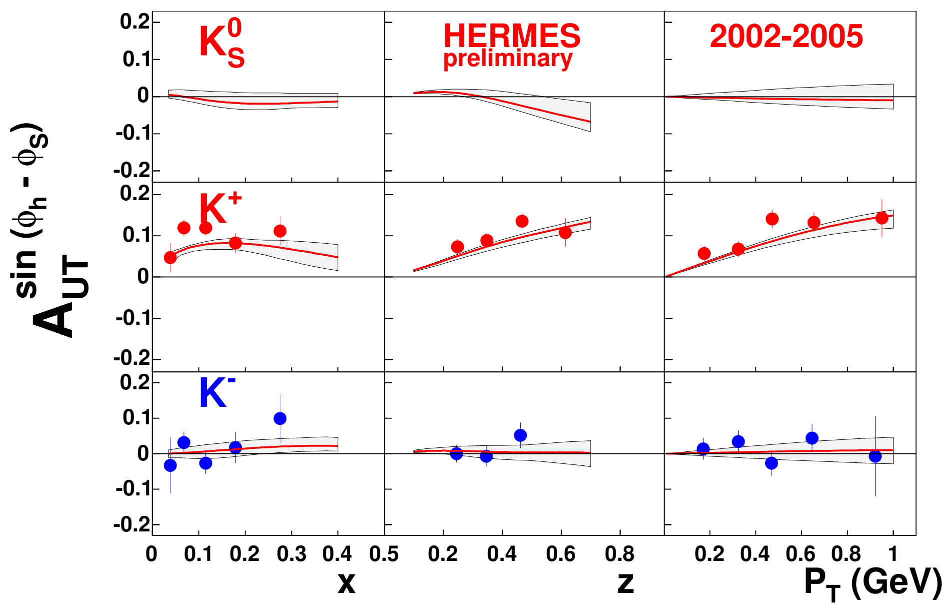


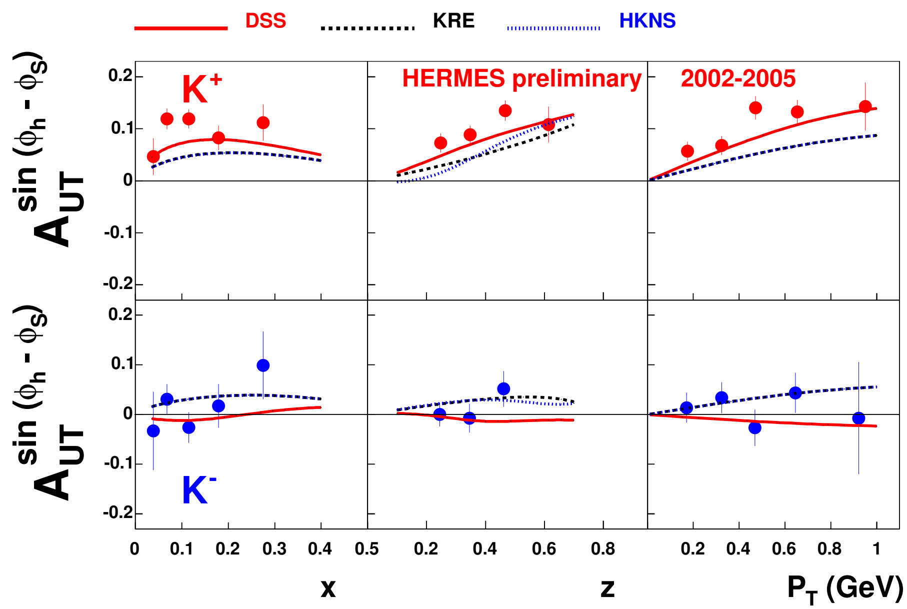


Fit of HERMES data [*Diefenthaler et al. 2006*], and COMPASS data [*Martin et al. 2006*]

(deuterium target)

KAON SSAs



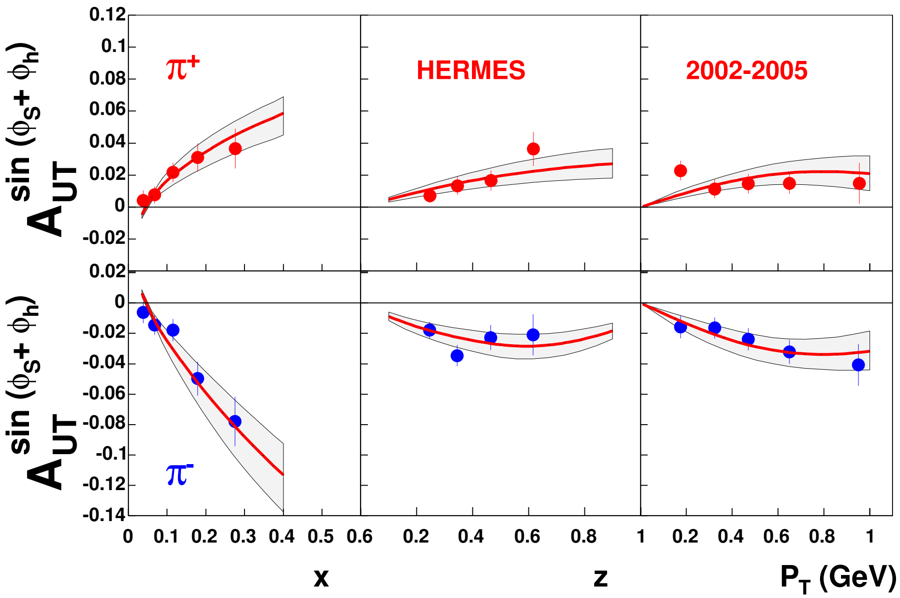


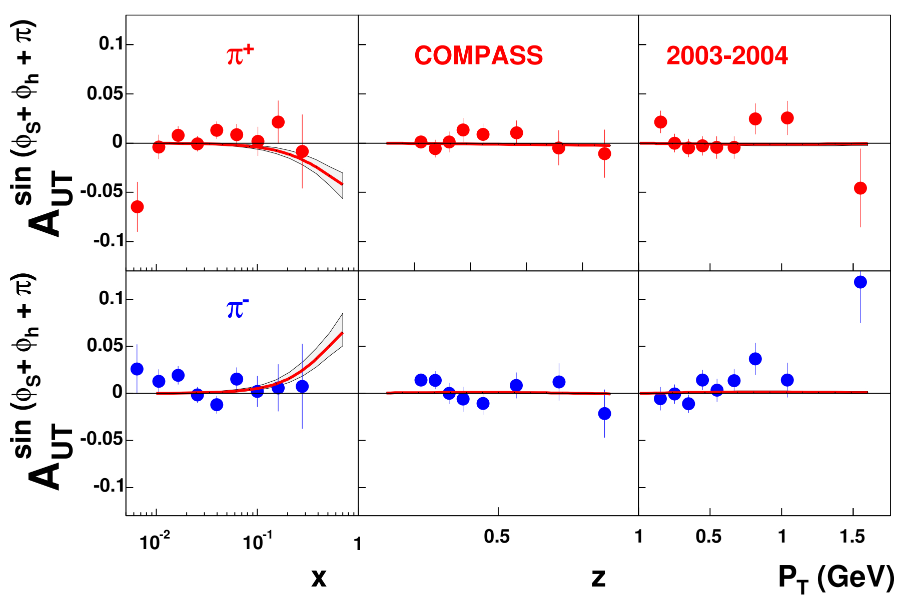
Fit of HERMES data [*Diefenthaler et al. 2006*], Comparison of fits adopting different FFs

• Collins effect in SIDIS:

NEW analysis [preliminary]

Anselmino et al. 2008

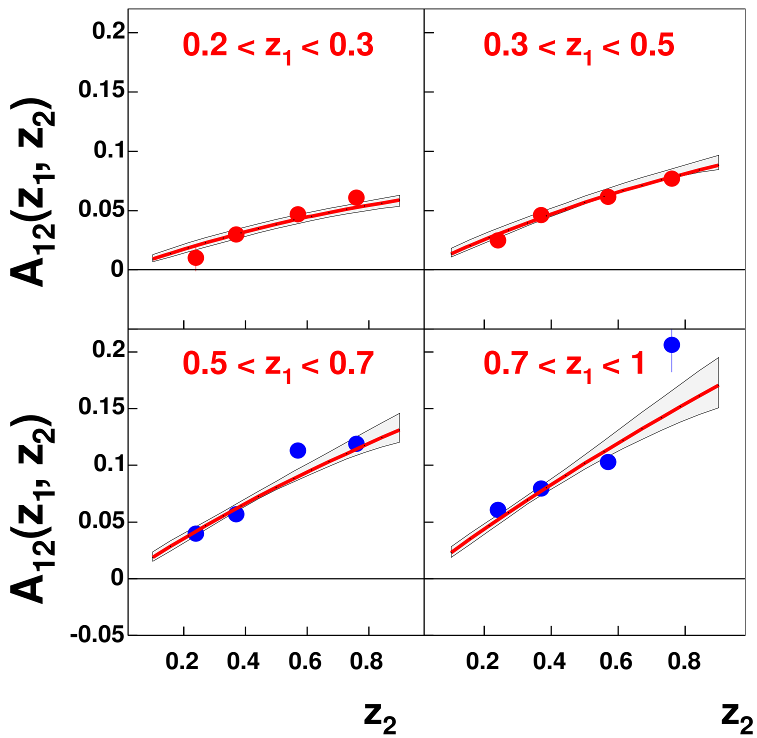


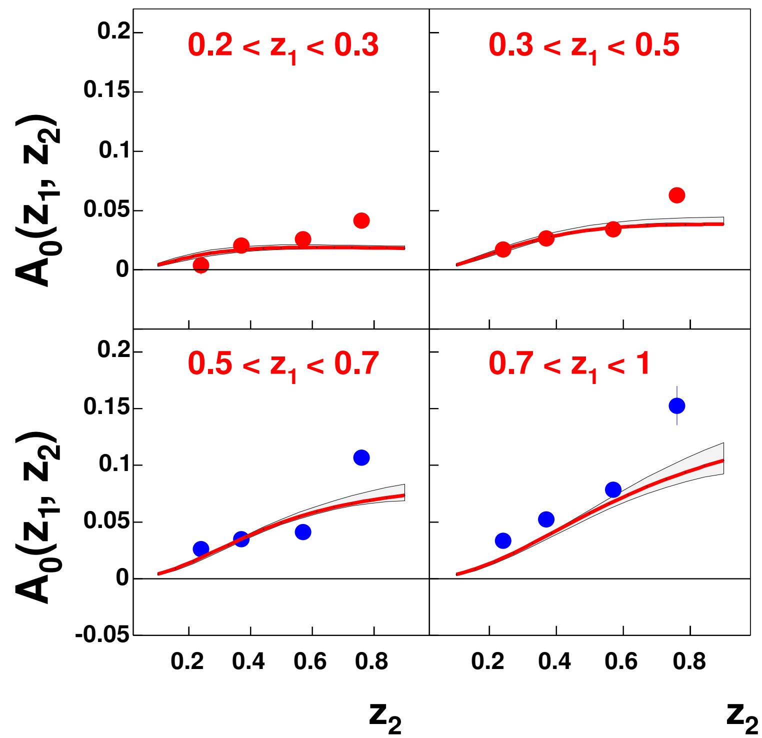


Preliminary fit of [left] HERMES data [*Diefenthaler et al. 2007*] (hydrogen target) and [right] COMPASS data [*Alekseev et al. 2008*] (deuterium target).

• Collins effect in $e^+e^- \to \pi\pi + X$

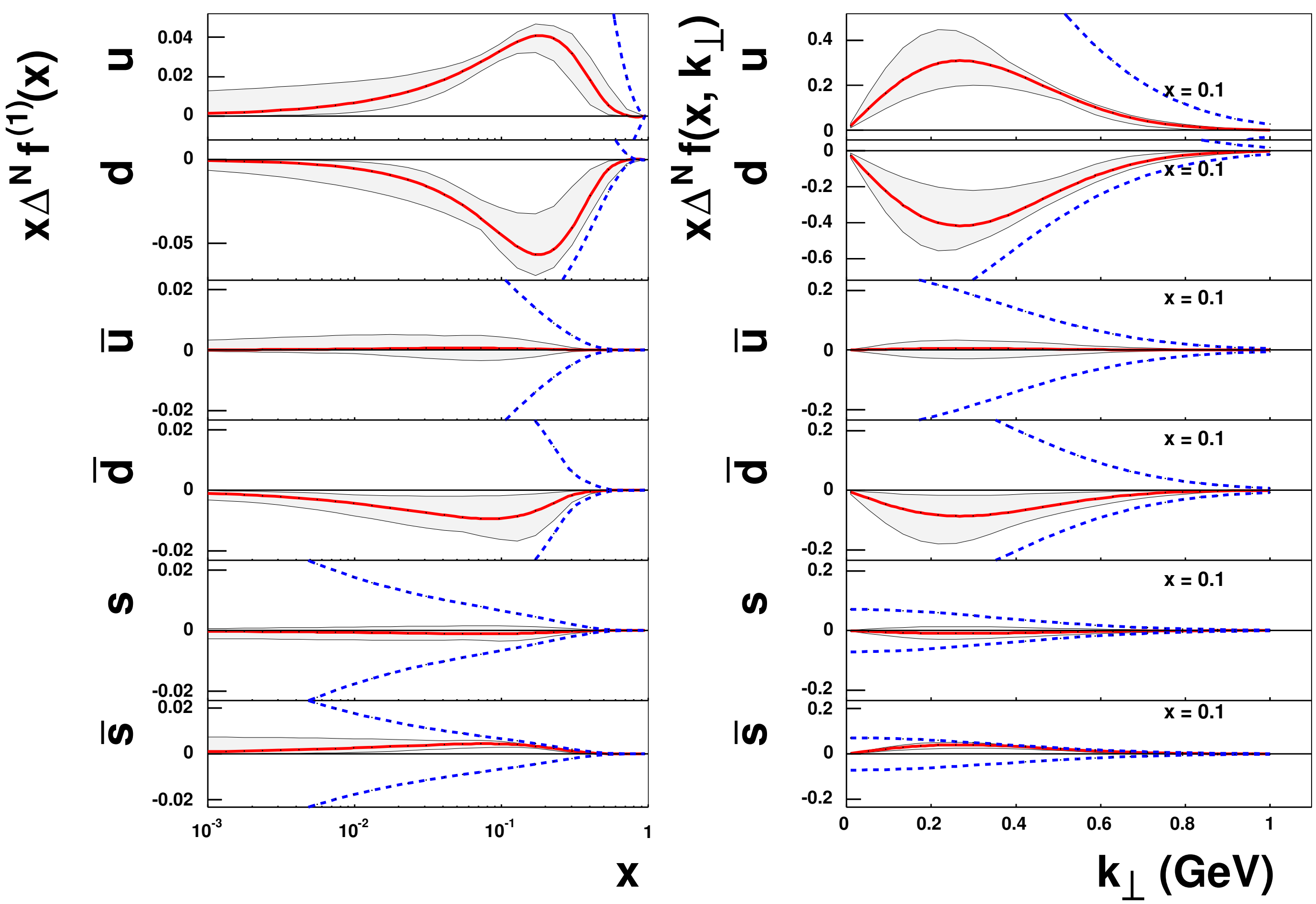
NEW analysis [preliminary] *Anselmino et al. 2008*



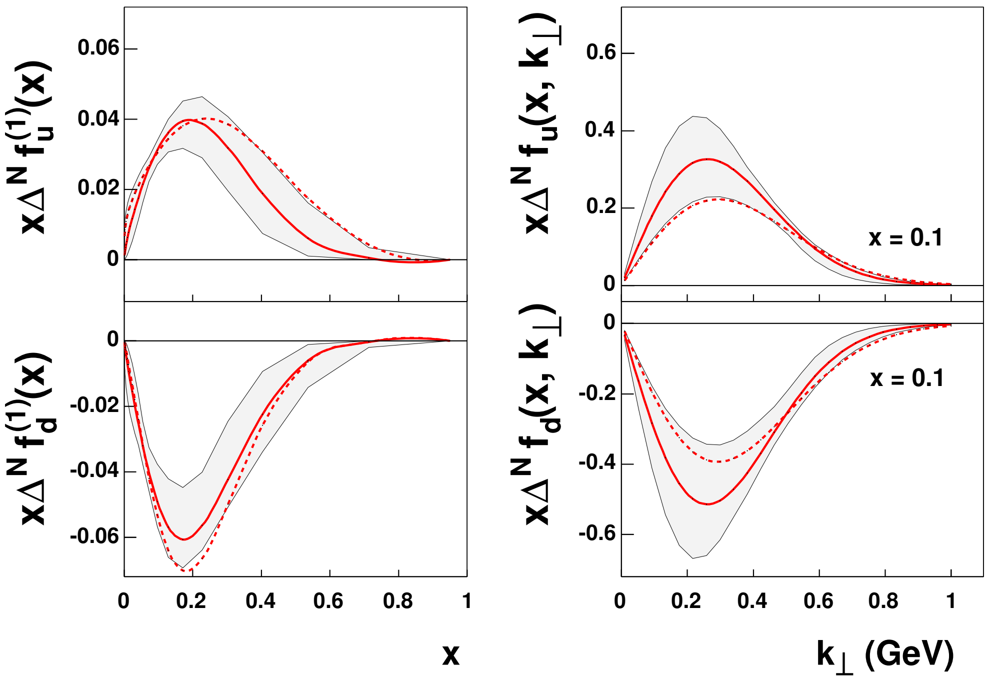


Preliminary fit of data on $e^+e^- \to h_1 h_2\, X$ from Belle Collaboration. [*Ogawa et al. 2007*].

New extraction of the Sivers function (π and $K^{\pm}$ data) *Anselmino et al. 2008*



Sivers function: valence quarks



Notice:

$A_{UT}^{\pi^+}(p^\uparrow) > 0$ (HERMES)

$A_{UT}^{\pi}(D^\uparrow) \simeq 0$ (COMPASS)

$A_{UT}(D^\uparrow) \simeq (\Delta^N f_u + \Delta^N f_d)(4D_u + D_d)$

$\Rightarrow \Delta^N f_u > 0,\ \Delta^N f_d < 0$

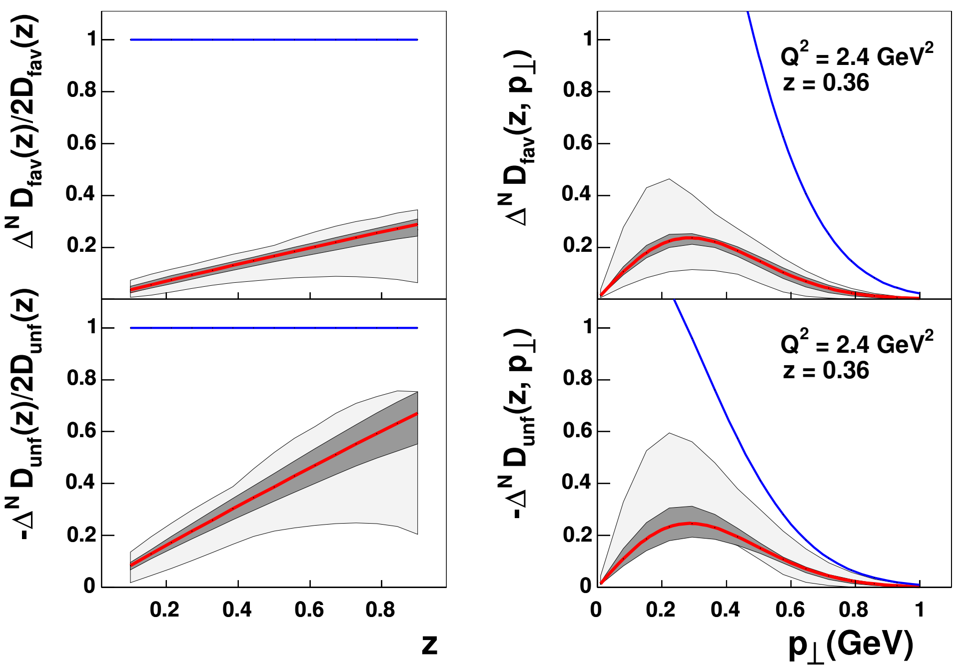
and similar size

Burkardt sum rule [*Burkardt '04*]: $\sum_a \langle k_\perp^a \rangle = 0 \quad \langle \boldsymbol{k}_\perp^a \rangle \equiv \int d^2 k_\perp \boldsymbol{k}_\perp \hat{f}_{a/p^\uparrow}$

$\langle k_\perp^u \rangle = 96$ MeV $\langle k_\perp^d \rangle = -113$ MeV $\langle k_\perp^{\rm sea} \rangle = -14$ MeV

$\Rightarrow$ little room for the gluon Sivers function

Collins function [NEW preliminary analysis] *Anselmino et al. 2008*



Consistent with other extractions [*Efremov et al. 2006, Vogelsang & Yuan 2005*]

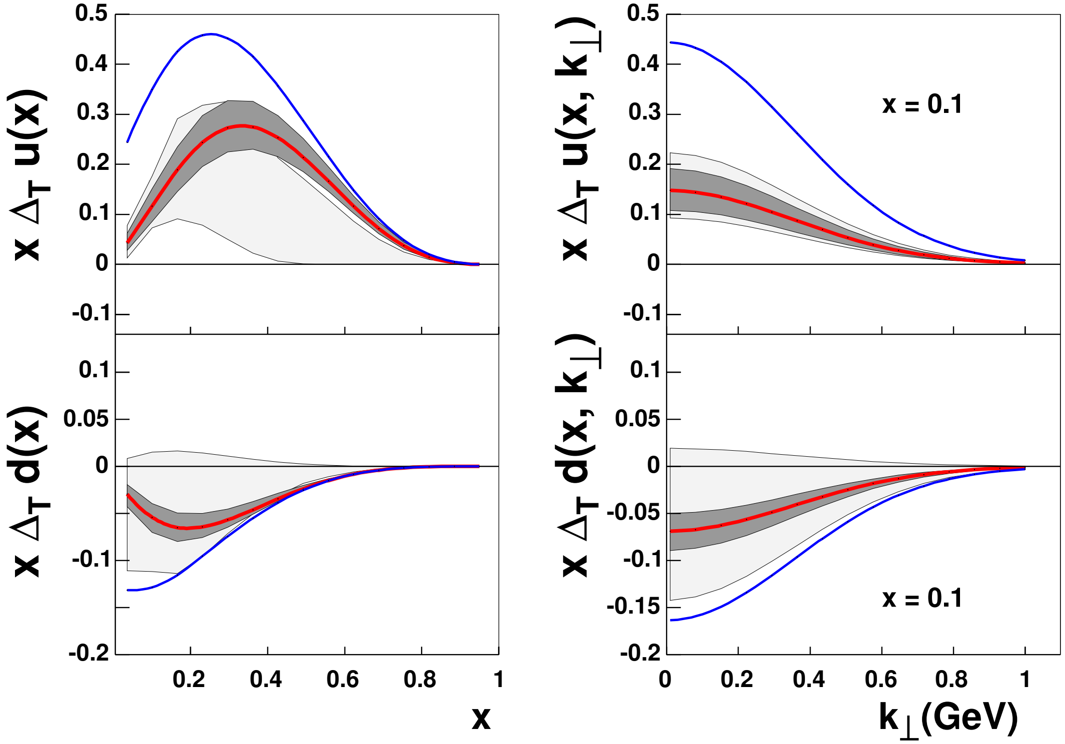
$A_{UT}^{\pi^+}(p) \simeq 4\Delta_T u\, \Delta^N D_{\rm fav} + \Delta_T d\, \Delta^N D_{\rm unf}$

$A_{UT}^{\pi^-}(p) \simeq 4\Delta_T u\, \Delta^N D_{\rm unf} + \Delta_T d\, \Delta^N D_{\rm fav}$

larger $|A_{UT}^{\pi^-}| \Rightarrow$ large and negative unfav. FF

Transversity function [NEW analysis: upgrade of 2007 **First extraction**]

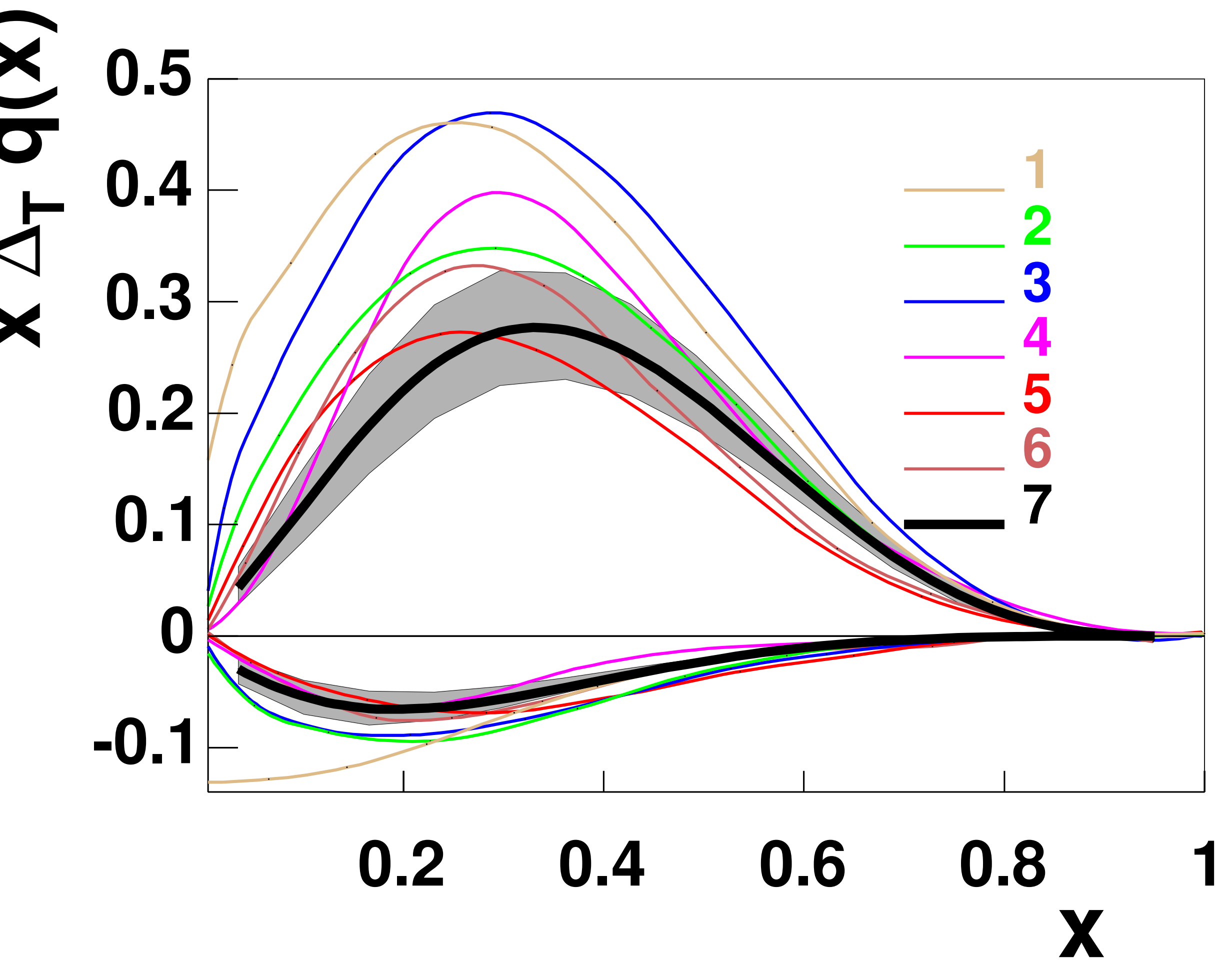
Anselmino et al. 2008



Errors strongly reduced! $\Delta_T u$: larger;

Tensor charge: $\delta u = 0.59^{+0.14}_{-0.13}$ $\delta d = -0.20^{+0.05}_{-0.07}$ at $Q^2 = 0.8$ GeV^2

Transversity: Comparison with models



1 *Soffer et al. 2002*

2 *Korotkov et al. 2001*

3 *Schweitzer et al. 2001*

4 *Wakamatzu 2007*

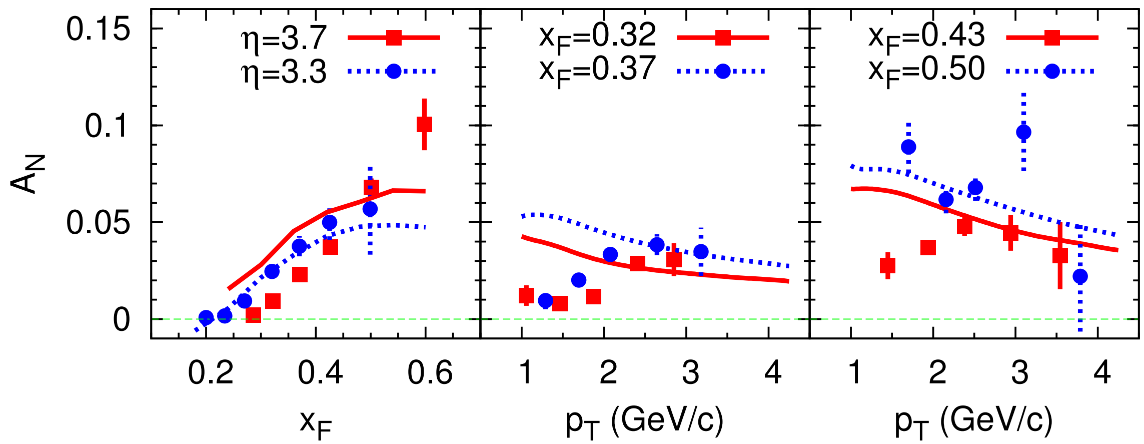
5 *Pasquini et al. 2005*

6 *Cloet et al. 2008*

7 Our improved analysis

SSAs: from SIDIS to pp collisions

Adopting Sivers & Collins functions as in the old fits with KRE set
(*Boglione, UD, Murgia '08*)

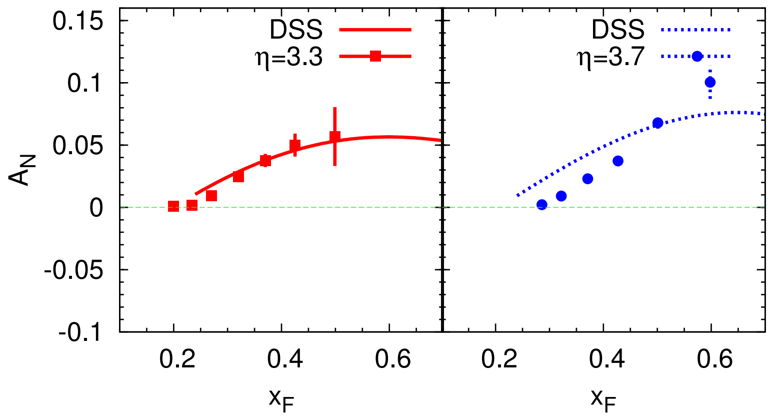


PREDICTIONS and comparison to STAR $A_N(\pi^0)$ data.

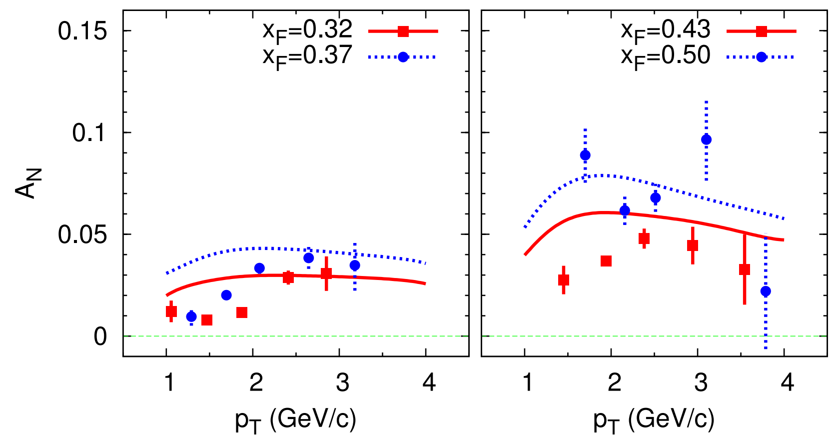
Notice: extrapolation to large x region (uncovered in SIDIS).

A better strategy: use of *pp* data and fit to SIDIS data.

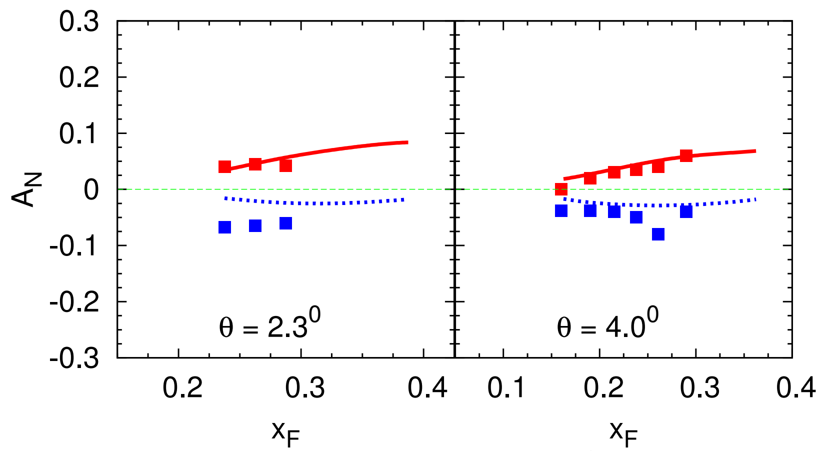
Sivers effect from SIDIS + *pp* scan ($\chi_{\rm dof} \simeq 1.2$)



STAR π^0



STAR π^0



BRAHMS $\pi^{\pm}$

- A global description of A_{UT}^{Sivers} and A_N (in terms of Sivers effect) seems possible.

- Collins effect (reassessed!: *Yuan '08*): in progress (new fit and scan)

- GOAL (future): a complete global analysis of Sivers and Collins effects in SIDIS, e^+e^- and $pp \to hX$.
A guidance to look for universality breaking effects (future)

- intermediate goal: disentangling Sivers and Collins effect in pp collisions

$pp \to \mathrm{jet}(\gamma) + X$ or $pp \to \mathrm{jet}\ \gamma + X$ (Sivers effect)
$pp \to \mathrm{jet}\ \pi + X$ (Collins effect) [*Yuan '08, UD-Murgia '08 (in progress)*]

and naturally

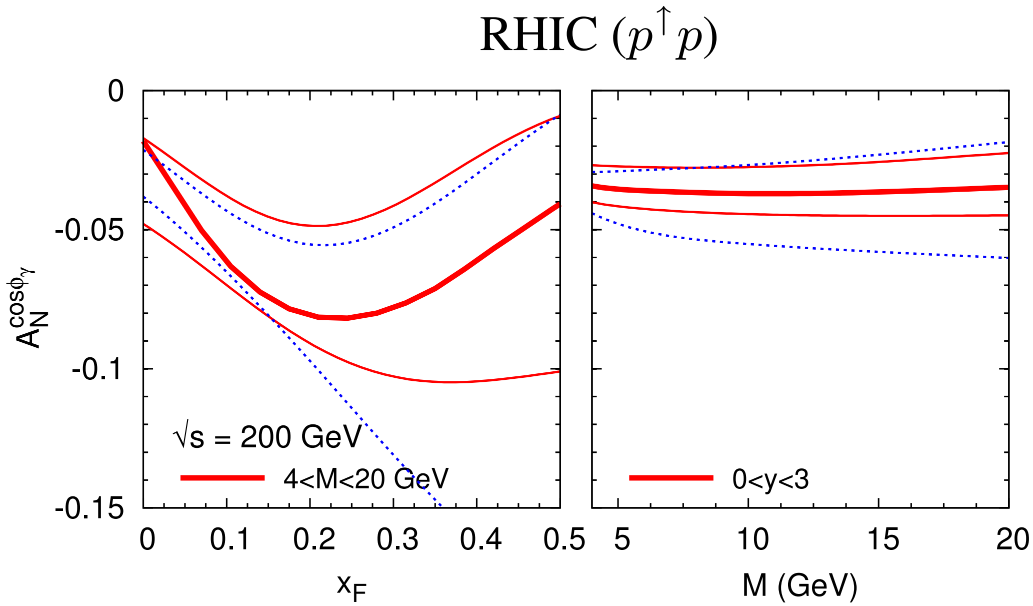
$pp \to \ell^+\ell^- + X$ (safe process)

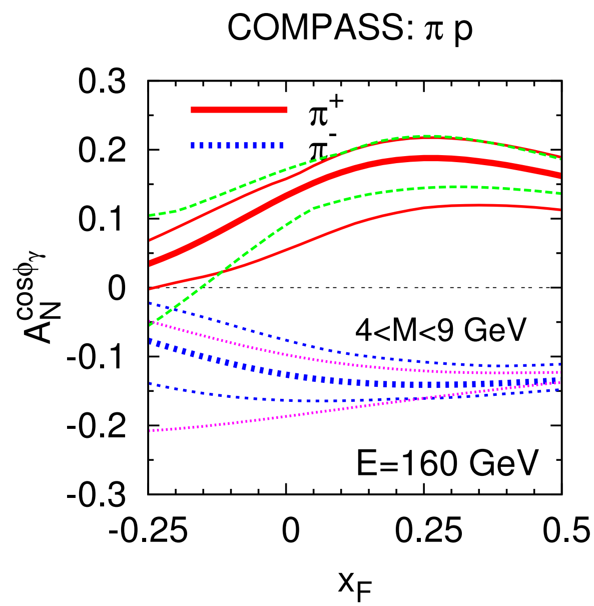
Importance of A_N in DY integrated over lepton angular variables

clean access to Sivers effect: *Anselmino, UD, Murgia '03, Efremov et al. '05, Vogelsang-Yuan '05, Anselmino et al. '05*

- modified universality (change of sign w.r.t. SIDIS): crucial test (*Collins '02*)

- small and intermediate x region at RHIC
- large x region at COMPASS (uncovered in SIDIS)





$A_N^{\sin(\phi_S-\phi_\gamma)}$ for DY from fits to SIDIS (free and pp-scan fit). [$\phi_S = \pi/2$]

COMPASS: $\pi^- p^\uparrow$: $\bar{u}u \to \ell^+\ell^-$

- Sign: definite !
- access to large x region.

Conclusions

- Azimuthal and transverse SSAs: powerful tool, recent and important progress
- extractions of Sivers, transversity and Collins functions from SIDIS and e^+e^-:
- Collins effect as a polarimeter to access $\Delta_T q$. Large (negative) unfavoured FF.
- First extraction of transversity distribution: u and d smaller than their Soffer bounds
- Sizeable Sivers function for valence quarks; little room for gluon Sivers function;

Conclusions

- Azimuthal and transverse SSAs: powerful tool, recent and important progress
- extractions of Sivers, transversity and Collins functions from SIDIS and e^+e^-:
- Collins effect as a polarimeter to access $\Delta_T q$. Large (negative) unfavoured FF.
- First extraction of transversity distribution: u and d smaller than their Soffer bounds
- Sizeable Sivers function for valence quarks; little room for gluon Sivers function;

Open issues:

- Q^2-evolution of TMDs
- modified universality: to be checked $[\Delta f_{\uparrow}|_{\rm DIS} = -\Delta f_{\uparrow}|_{\rm DY}]$
- SSAs in SIDIS: binning in x, z, $P_\perp$ and error correlation matrix
  large (low) x region still uncovered [JLAB(COMPASS)]
- SSAs in $p^\uparrow p \to CX$: disentangling TMD approach and Twist-3 formalism
- SSAs in $p^\uparrow p \to$ jet πX: universality and separation of Sivers and Collins effects