The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

**1942-53**

**Sixth International Conference on Perspectives in Hadronic Physics**

***12 - 16 May 2008***

# Exploring the transverse spin structure of the nucleon.

U. D'Alesio

*Physics Department and INFN*
*University of Cagliari*
*Italy*

---

based on the collaboration with:
Anselmino, Boglione, Kotzinian, Melis, Murgia, Prokudin, Turk

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

# Exploring the transverse spin structure of the nucleon

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

*Sixth International Conference on Perspectives in Hadronic Physics*

*May 12-16, 2008 Trieste, Italy*

based on collaboration with *Anselmino, Boglione, Kotzinian, Melis, Murgia, Prokudin, Turk*

# Outline

- Nucleon spin structure: collinear picture
- Transversity: few remarks
- Access to transversity (collinear framework): double spin asymmetries ...mainly
- Transverse Momentum Dependent (TMD) distributions: transversity friends
- Access to transversity and related TMDs: azimuthal and single spin asymmetries
- Phenomenology: overview and present status
- Conclusions and outlook

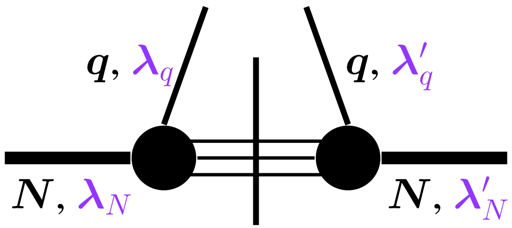
Nucleon structure in a collinear picture: $p_q = xP_N$ and $S = 0, (+), (\uparrow)$

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: $\Delta_T q(x) = q_{\uparrow/\uparrow} - q_{\downarrow/\uparrow}$ $[h_1^q, \delta q]$

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

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




$F^{++}_{++}$ $F^{--}_{++}$ (diagonal) $F^{+-}_{+-}$ (off$-$diagonal)

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

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

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

## Theory side (equally well known)

- pQCD evolution (NLO, NNLO); QCD sum rules

- vector charge — axial charge — tensor charge

$\int dx(q-\bar{q})$ — $\int dx(\Delta q+\Delta\bar{q})$ — $\int dx(\Delta_T q-\Delta_T\bar{q})$

- $|\Delta_T q| \leq (q+\Delta q)/2$ (Soffer bound)

- $\Delta_T q = \Delta q$ for non relativistic quarks

- No gluon transversity $\to$ Non-singlet $Q^2$-evolution

- Angular momentum sum rules:

$$\frac{1}{2} = \frac{1}{2}\int dx(\Delta q+\Delta\bar{q}) + \int dx \Delta g + L_z^q + L_z^g \quad \text{established}$$

$$\frac{1}{2} = \frac{1}{2}\int dx(\Delta_T q+\Delta_T\bar{q}) \qquad + L_T^q + L_T^g \quad \text{“controversial”}$$

*Bakker, Leader, Trueman 04*

Phenomenology [big differences]

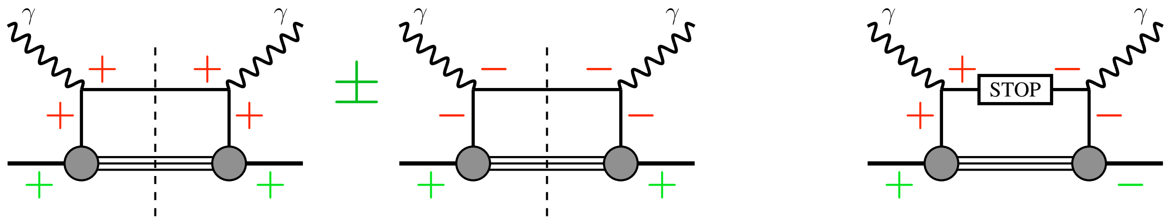
- $q$, $\bar{q}$ and $g$: very well known (extended $x, Q^2$ coverage)

- $\Delta q$ quite well known; $\Delta\bar{q}$ and $\Delta g$ known with large uncertainties but fast improving

- $\Delta_T q$ [escaped for long time] just started !

why?

$\Delta_T q$ is chirally-odd (off-diagonal amplitude: helicity flip)




$$F_{++}^{++} \quad \pm \quad F_{++}^{--} \qquad\qquad F_{+-}^{+-} \text{NO}$$

$\Delta_T q$: $\chi$-odd

$\Rightarrow$ needs a $\chi$-odd partner

**$\chi$-odd partner in INITIAL hadron**:

- $A_{TT}$ in Drell-Yan processes: $p^\uparrow p^\uparrow \to \ell^+\ell^-$ *Ralston, Soper 1979*

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \sim \sum_q e_q^2 \left[h_1^q(x_1)\, h_1^{\bar q}(x_2) + h_1^{\bar q}(x_1)\, h_1^q(x_2)\right]$$

feasible @ RHIC [large $\sqrt{s}$ (200 GeV)], small NLO QCD corrections

small $x$ (no gluon in evolution), small $h_1$ for antiquark $\Rightarrow A_{TT} \sim$ 1-2%

- IDEA, (PAX @ GSI): $p^\uparrow \bar p^\uparrow \to \ell^+\ell^- + X$

$$A_{TT}^{p\bar p} \sim \sum_q e_q^2 \left[h_1^q(x_1)\, h_1^q(x_2) + h_1^{\bar q}(x_1)\, h_1^{\bar q}(x_2)\right]$$

- product of two quark $h_1$, valence region [moderate $\sqrt{s}$]
- small resummation corrections in $A_{TT}$ [*Shimizu et al. 2005*]
- polarization of antiprotons, low rates

$A_{TT} \sim$ 20-40%

- Higher rates: $J/\psi$ peak (gain 2 order of magnitudes) [*Anselmino et al. 2004*]

• $p^\uparrow p^\uparrow \to \gamma(\pi) + X$ high rates but gluon dominance in $d\sigma^{\rm unp} \to$ small $A_{TT}$

## $\chi$-odd partner in FINAL hadron

• $\ell p^\uparrow \to \ell' \Lambda^\uparrow + X$ (SIDIS) or $pp^\uparrow \to \Lambda^\uparrow + X$

$\Lambda$ self-analyzing through parity violating decay

$P_\Lambda \simeq \Delta_T q(x) \Delta_T D_\Lambda(z)$, unknown twist-two transversely polarized FF

$u$ quark dominated (charge and nucleon content) but $s^\uparrow \to \Lambda^\uparrow$

• $\ell p^\uparrow \to \pi\pi + X$ [SSA, *Jaffe et al. 1998, Bacchetta, Bianconi, Boffi, Jakob, Radici*]

$A_{UT} \simeq \Delta_T q \otimes \delta q_I$

$\delta q_I \equiv$ interference FF: $q \to \pi\pi$ [collinear factorization]

unknown $\delta q_I$ (extraction from $e^+e^-$: promising)

Help from TMDs: $p_q = xP + \boldsymbol{k}_\perp$

$\hat{F}^{\lambda_q,\lambda'_q}_{\lambda_N,\lambda'_N}(x,\boldsymbol{k}_\perp)$ 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 common notation: $f_1, g_{1L}, h^\perp_{1L}, h_{1T}, h^\perp_{1T}, g_{1T}, f^\perp_{1T}, h^\perp_1$

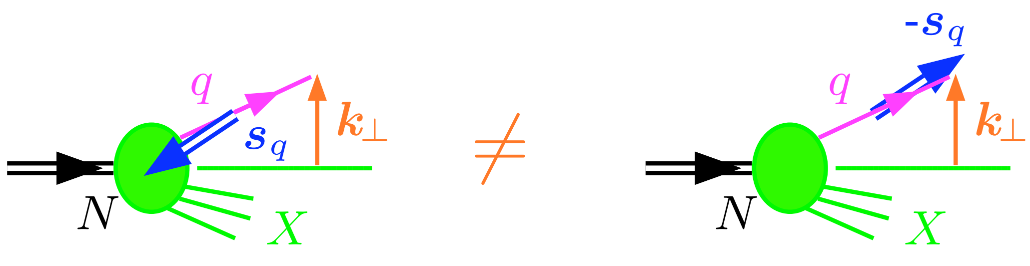
• Sivers function [Im$F^{++}_{+-}$] *Sivers 1990*

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


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

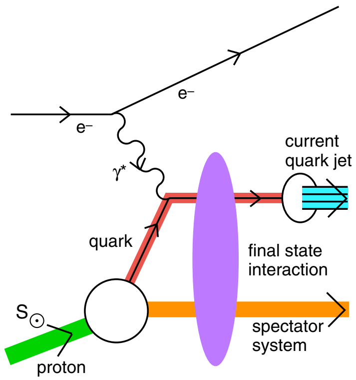
• Boer-Mulders function [Im$F^{+-}_{++}$] *Boer, Mulders 1998*

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




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

"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.

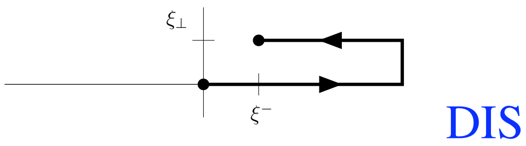
- Model for the Sivers asymmetry
- Need of quark orbital angular momentum.

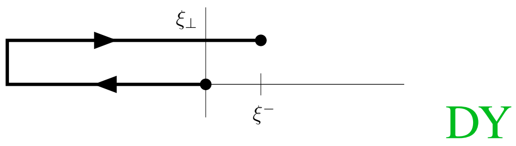
Soft gluons $\leftrightarrow$ gauge link for gauge-invariant parton density [*Collins, Ji, Yuan, ...*]

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

T-reversal invariance implies [*modified universality*]

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



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

spin-0 (or unpolarized): 1 + 1 FFs spin-1/2: 3 + 5 FFs (as 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 $h\ X$

gauge links $\to$ universality (*Collins & Metz 2004, Yuan 2008*) same function in
$e^+e^- \to hh + X \quad \ell p^\uparrow \to \ell' h + X$ and $p^\uparrow p \to h$ jet $+ X$

More functions $\rightarrow$ more difficulties??? Not exactly!

- Sivers function: link to Orbital Angular Momentum
- Boer-Mulders and Collins functions: ($\chi$-odd): friends of transversity
- Deeper understanding of color interaction [modified universality]
- Role in Azimuthal and Single Spin Asymmetries: beginning of TMDs

A quick look into SSAs

pQCD: vanishing SSA at large energy scales!

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

requires:

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

- relative phase between helicity amplitudes but real Born amplitudes.

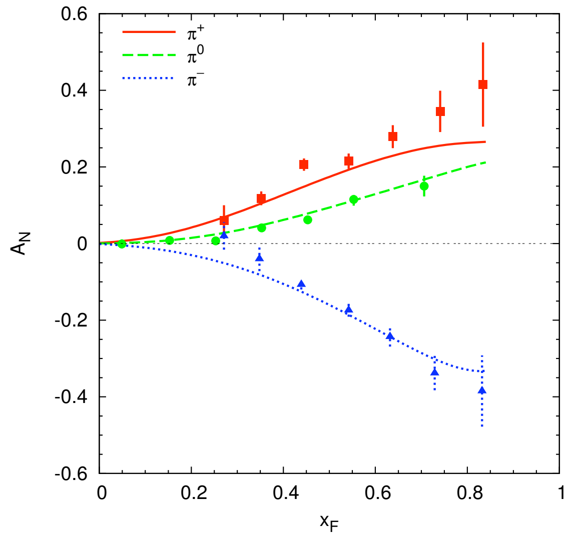
$$\Rightarrow \hat{a}_N \propto \alpha_s \frac{m}{\sqrt{s}} \qquad\qquad Kane\ et\ al.\ 1978$$

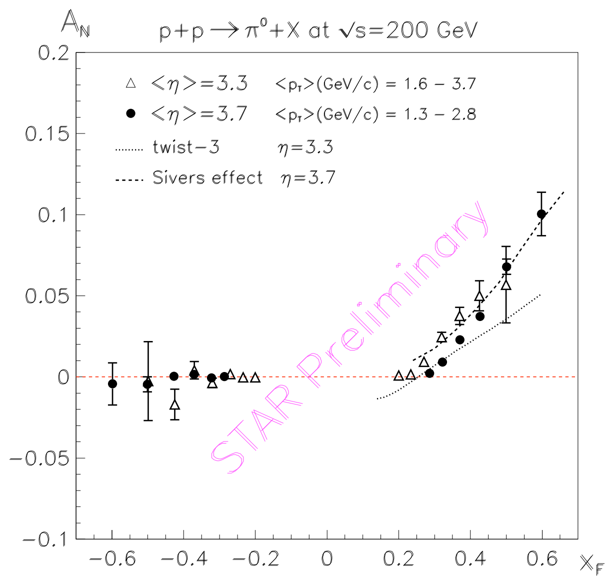
Contrary to observation: E704 data (90s) $p^\uparrow p \to \pi + X$ at $\sqrt{2}0$ GeV $\to$ large $A_N$
(transverse w.r.t. production plane)

TMD approach to SSAs (*Sivers, Anselmino, Boglione, UD, Leader, Melis, Murgia*):
model: not proved not disproved [alternative: Twist-3 approach, *Qiu & Sterman*]

$A_N \simeq$ Sivers + Transversity$\otimes$Collins + Boer-Mulders$\otimes$transversity (not separable)

Rich phenomenology [to the latest **RHIC** data at $\sqrt{s} = 200$ GeV,
**intense programme** @ BRAHMS, STAR, PHENIX]




E704(left), STAR(right) data, *UD, Murgia 04* (Sivers effect), *Kouvaris et al. 06* (Twist-3 mech.)

TMDs vs. Azimuthal and SSAs: QCD developments

• 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, Yuan, Ma, Belitsky*

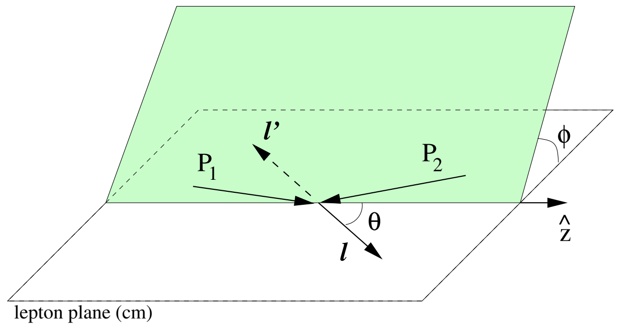
Opening of a new and exciting phenomenology

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

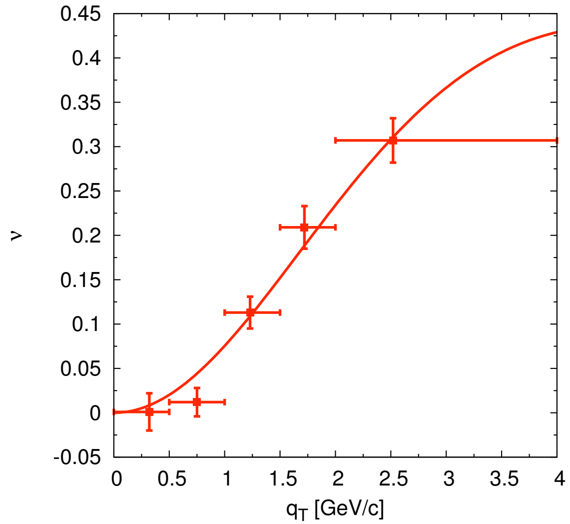
$$d\sigma \simeq 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

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 $p^\uparrow p \to \ell^+\ell^- + X$:

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

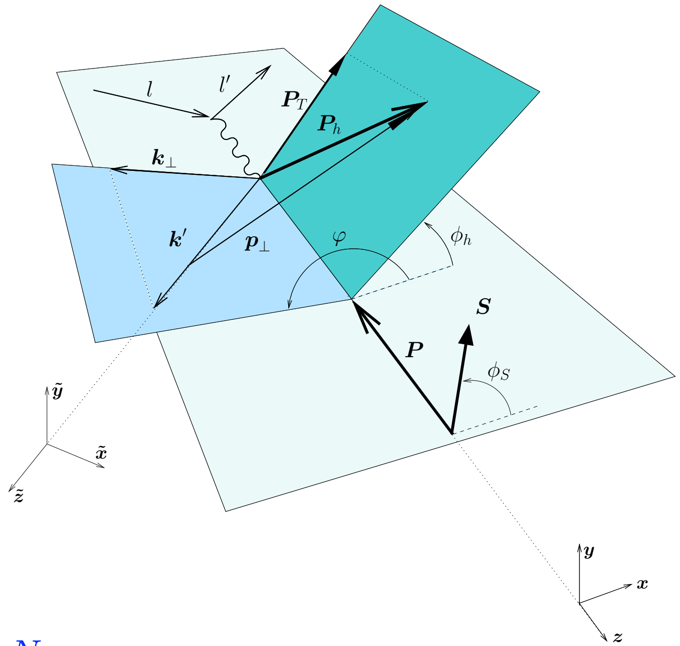
(different azimuthal dependences $\to$ separable) NO DATA

# SIDIS

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

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

+ Cahn effect



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

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

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

(different azimuthal dependences → separation of Sivers and Collins effects)

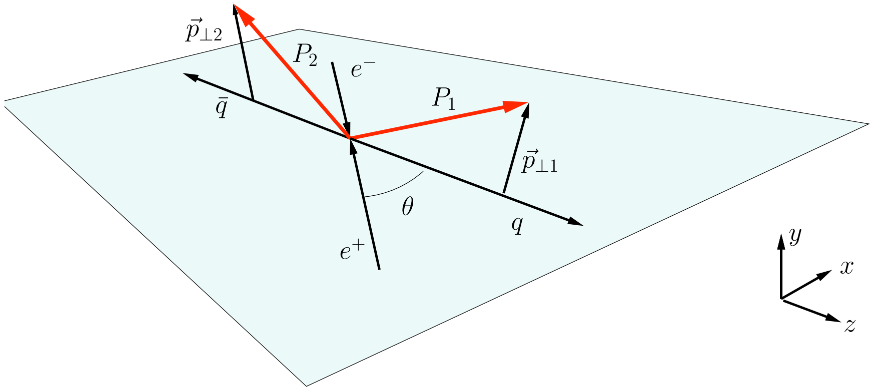
Experimental Programmes:

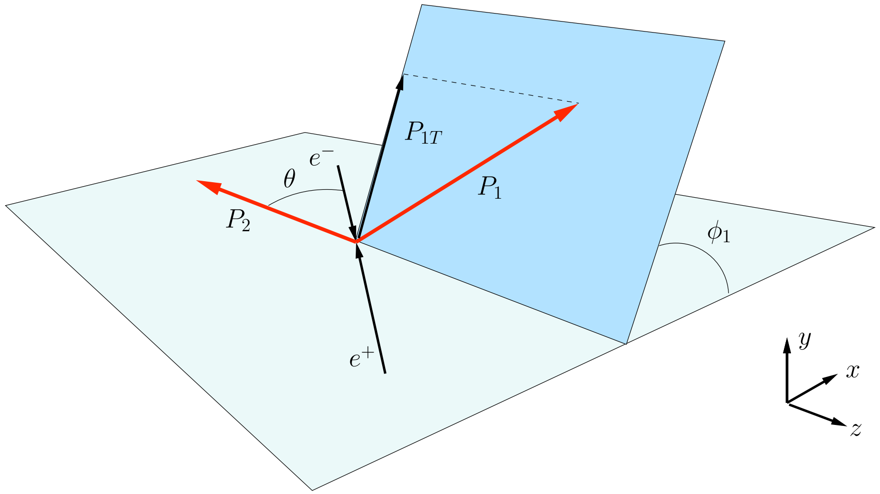
HERMES @ HERA [FIRST EVIDENCE], COMPASS @ CERN, CLAS @ JLAB

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

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

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




Reconstruction of the thrust axis

Experimental Program: Belle @ KEK [FIRST EVIDENCE]

# Phenomenology of:

## Sivers function
## Collins function & transversity function

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

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

Transversity: $u$ and $d$ quarks

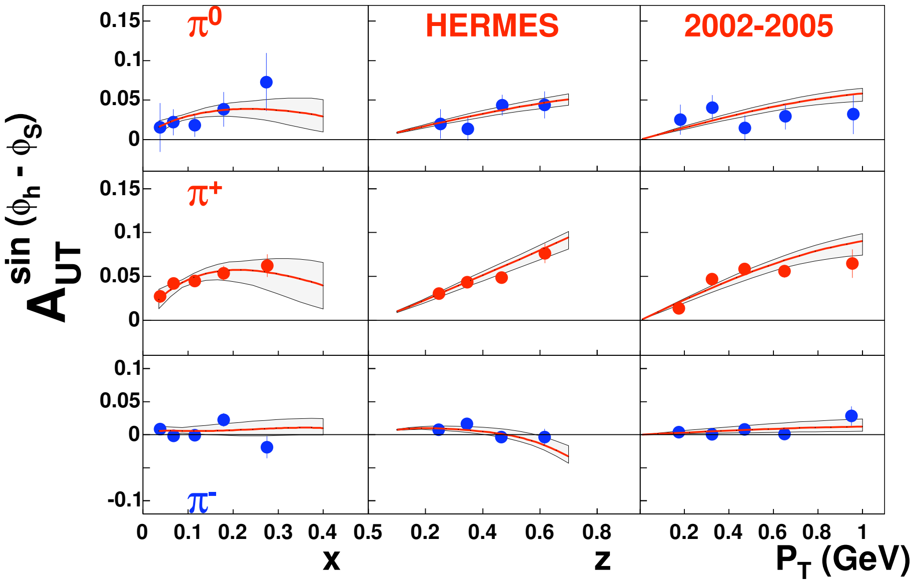
simple ansatz: $N x^a (1-x)^b \times$ [Gaussian] $\boldsymbol{k}_\perp$ dependence

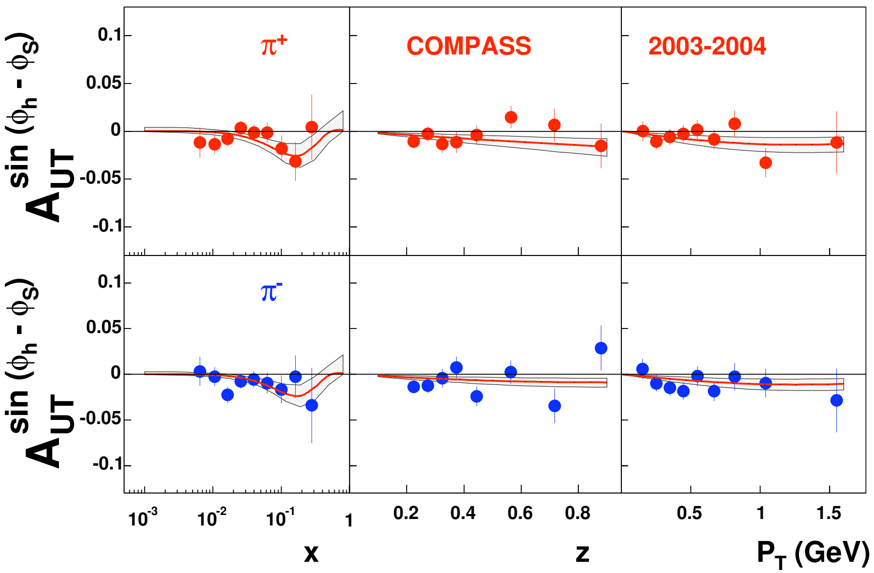
Other similar analyses from *Vogelsang & Yuan, Efremov et al.*

- Sivers effect in SIDIS:

NEW analysis [completed]

*Anselmino et al. 2008*



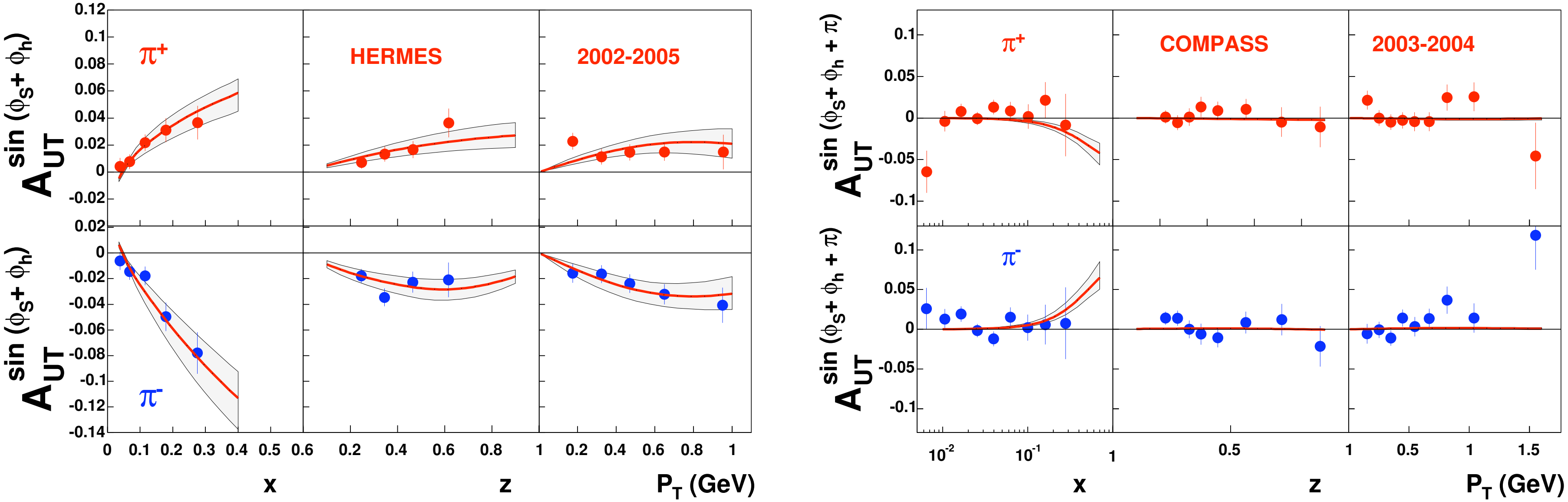




Fit of HERMES data [*Diefenthaler et al. 2006*], and COMPASS data [*Martin et al. 2006*]

(deuterium target)

• Collins effect in SIDIS:

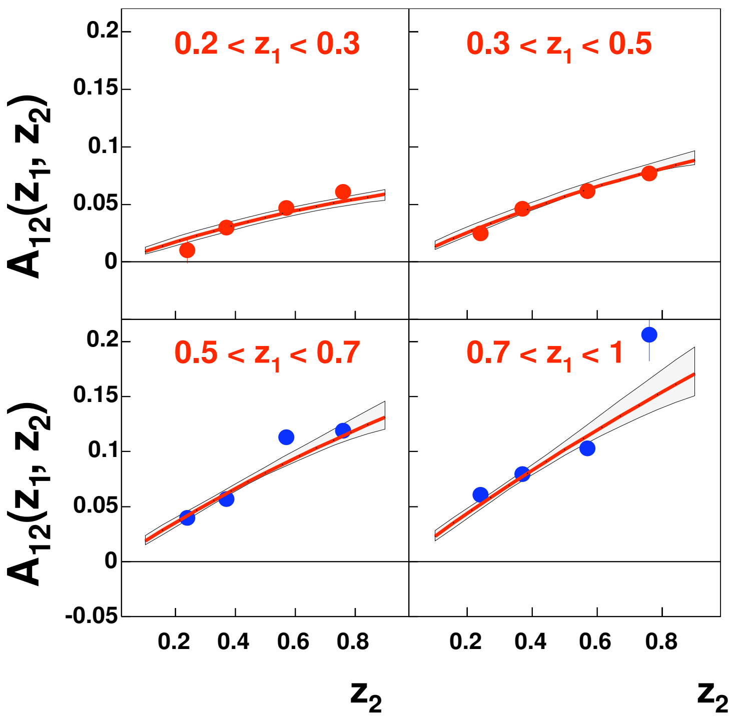
NEW analysis [preliminary]   *Anselmino et al. 2008*

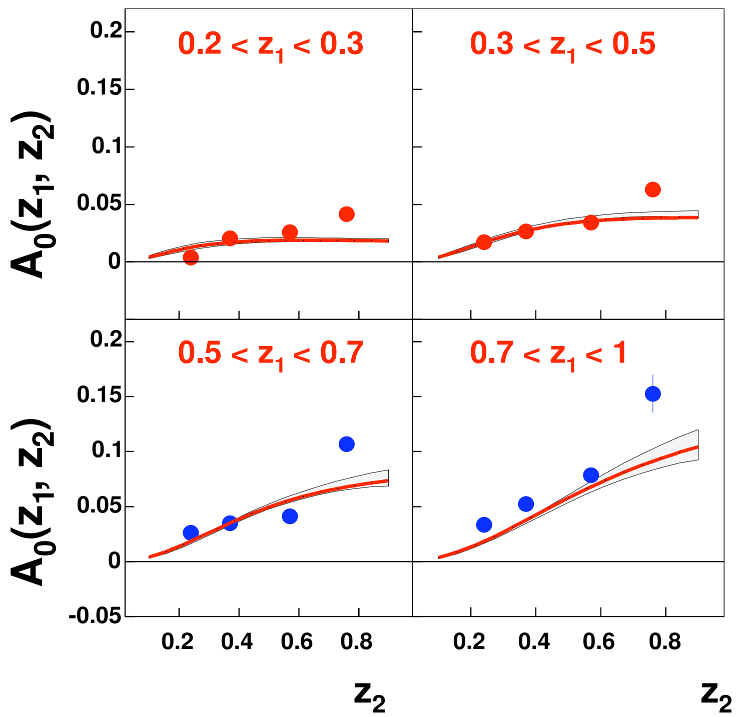



Preliminary fit of [left] HERMES data [*Diefenthaler et al. 2007*] (hydrogen target) and [right] COMPASS data [*Alekseev et al. 2008*] (deuterium target).

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

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

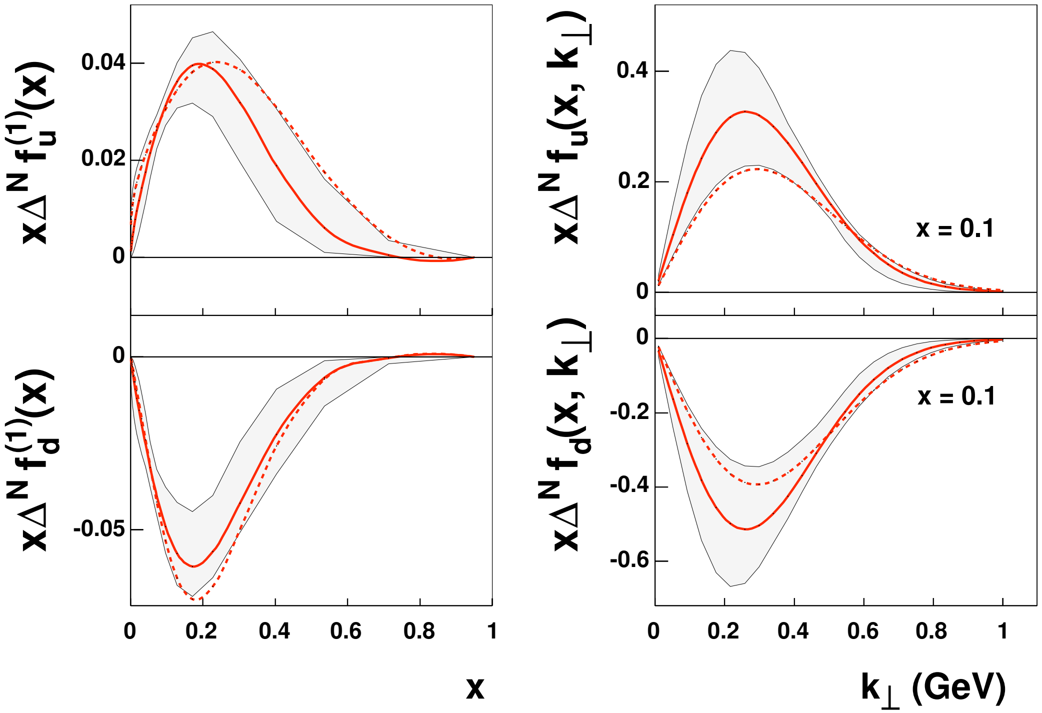



Preliminary fit of data on $e^+e^- \to h_1 h_2 \, X$ from Belle Collaboration. [*Ogawa et al. 2007*].

Sivers function: valence quarks

New analysis (on $\pi$ and $K^{\pm}$) *Anselmino et al. 2008*




Remember:

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

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

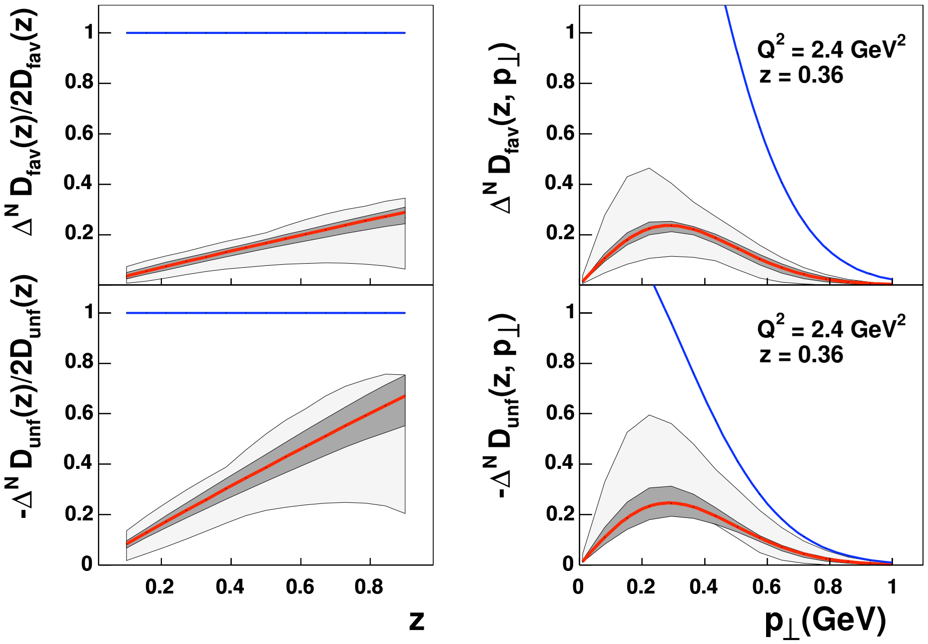
$\Rightarrow \Delta^N f_u > 0, \Delta^N f_d < 0$

and similar size

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

$\Rightarrow$ [via Burkardt Sum Rule] little room for gluon Sivers function

Collins function [NEW analysis: upgrade of 2007] *Anselmino et al. 2008*



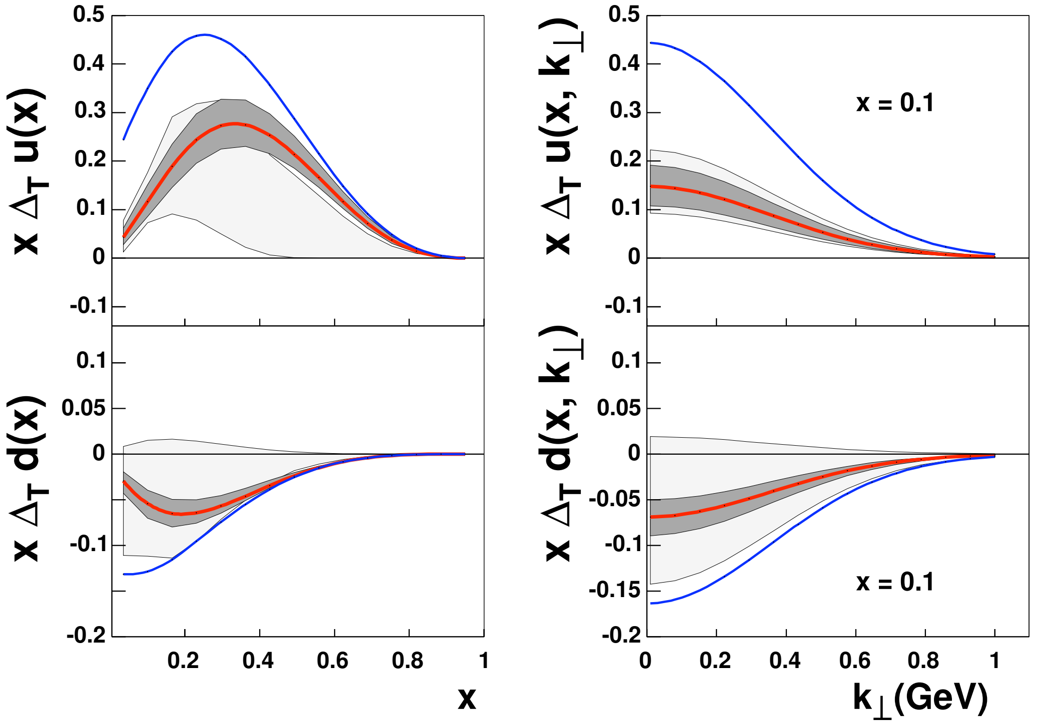

Consistent with other extractions [*Efremov et al. 2006, Vogelsang & Yuan 2005*]

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

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

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

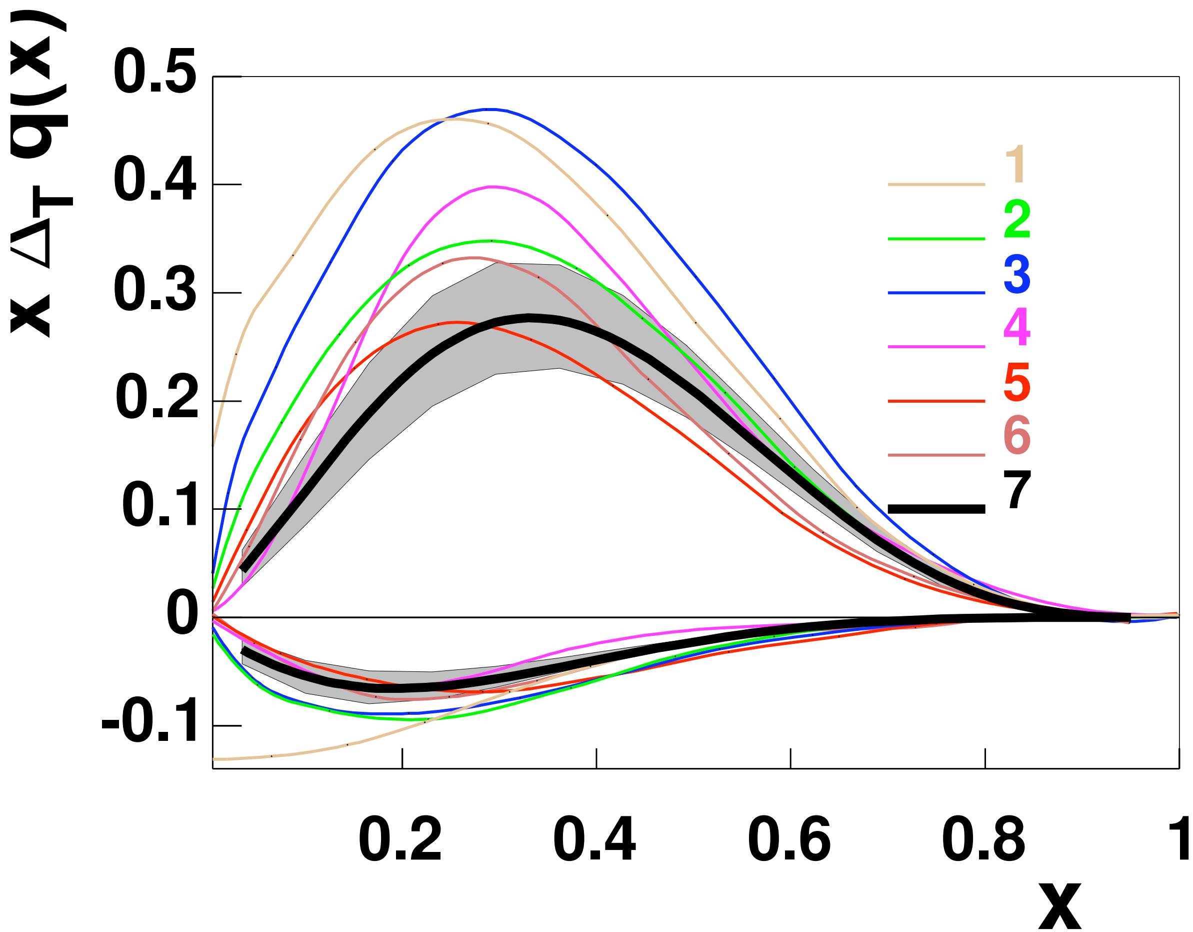
*Anselmino et al. 2008*




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 $Q^2 = 0.8\ \mathrm{GeV}^2$

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**

## Conclusions

- Transverse spin structure of nucleons: recent and important progresses
- Sivers effect: in a transversely polarized nucleon quarks are left-right asymmetric around the spin direction; $\boldsymbol{L \neq 0}$
- 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

# Conclusions

- Transverse spin structure of nucleons: recent and important progresses
- Sivers effect: in a transversely polarized nucleon quarks are left-right asymmetric around the spin direction; $\boldsymbol{L} \neq 0$
- 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

## **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 $\pi X$: universality and separation of Sivers and Collins effects

**THE TRANSVERSE SPIN ERA HAS JUST STARTED**

Let's enjoy it

*THANK YOU*