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Exploring the transverse spin structure of the nucleon

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

Outline

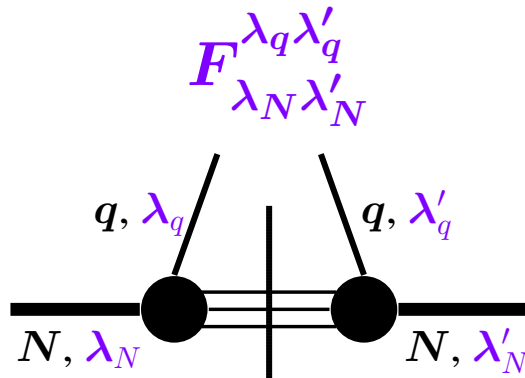
- Nucleon spin structure: **collinear picture**
- **Transversity**: few remarks
- Access to transversity (collinear framework): **double spin asymmetries** ...mainly
- **Transverse Momentum Dependent (TMD)** distributions: transversity friends
- Access to transversity and related TMDs: **azimuthal and 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 ($N \rightarrow qX$):



$$F_{++}^{++} \quad F_{++}^{--} \text{ (diagonal)} \quad F_{+-}^{+-} \text{ (off-diagonal)}$$

$$q(x) = F_{++}^{++} + F_{++}^{--} \quad \text{helicity average}$$

$$\Delta q(x) = F_{++}^{++} - F_{++}^{--} \quad \text{helicity difference}$$

$$\Delta_T q(x) = F_{+-}^{+-} \quad \text{helicity flip}$$

Theory side (equally well known)

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

- vector charge axial charge tensor charge

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

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

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

- No gluon transversity \rightarrow Non-singlet Q^2 -evolution

- Angular momentum sum rules:

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

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

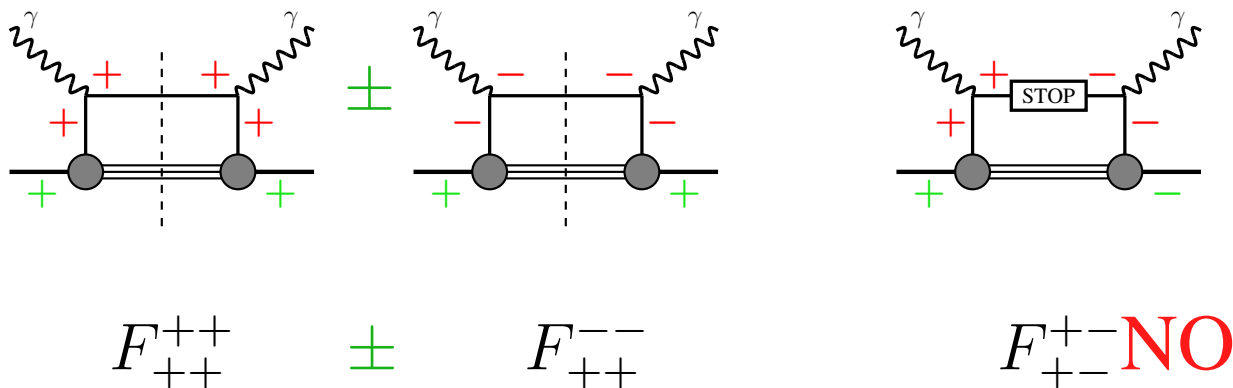
Bakker, Leader, Trueman 04

Phenomenology [big differences]

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



$\Delta_T q$: χ -odd
 \Rightarrow needs a χ -odd partner

χ -odd partner in INITIAL hadron:

- A_{TT} in Drell-Yan processes: $p^\uparrow p^\uparrow \rightarrow \ell^+ \ell^-$

Ralston, Soper 1979

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

feasible @ RHIC [large \sqrt{s} (200 GeV)], small NLO QCD correctionssmall x (no gluon in evolution), small h_1 for antiquark $\Rightarrow A_{TT} \sim 1\text{-}2\%$

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

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

- 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

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

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

- $p^\uparrow p^\uparrow \rightarrow \gamma(\pi) + X$ **high rates** but **gluon dominance** in $d\sigma^{\text{unp}} \rightarrow$ small A_{TT}

χ -odd partner in FINAL hadron

- $\ell p^\uparrow \rightarrow \ell' \Lambda^\uparrow + X$ (SIDIS) or $pp^\uparrow \rightarrow \Lambda^\uparrow + X$

Λ **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 $s^\uparrow \rightarrow \Lambda^\uparrow$

- $\ell p^\uparrow \rightarrow \pi\pi + X$ [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: $q \rightarrow \pi\pi$ [collinear factorization]

unknown δq_I (extraction from e^+e^- : **promising**)

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

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

→ 3 + 5 independent amplitudes i.e. → 3 + 5 spin and TMD distributions

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

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

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

Other common notation: $f_1, g_{1L}, h_{1L}^\perp, h_{1T}, h_{1T}^\perp, g_{1T}, f_{1T}^\perp, h_1^\perp$

• Siverts function [$\text{Im}F_{+-}^{++}$]

Sivers 1990

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



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

• Boer-Mulders function [$\text{Im}F_{++}^{+-}$]

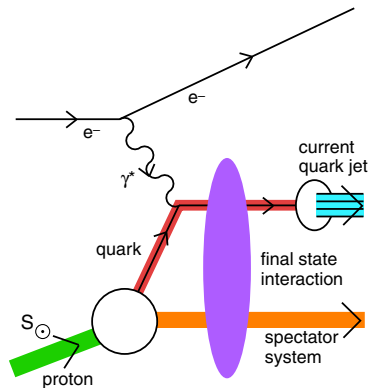
Boer, Mulders 1998

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



$\Delta \hat{f}_{\uparrow/N}(x, \mathbf{k}_\perp)$
 “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.

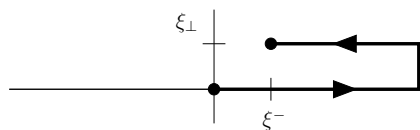
- Model for the Sivers asymmetry
- Need of quark orbital angular momentum.

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

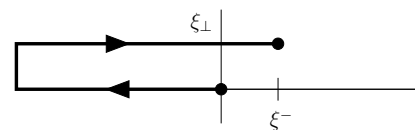
$$\mathcal{P} \exp \left(-ig_s \int_{\xi^-}^{\infty} dz^- \hat{A}^+(z^-, \xi_{\perp}) \right)$$

T-reversal invariance implies [*modified universality*]

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



DIS



DY

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

spin-0 (or unpolarized): 1 + 1 FFs

spin-1/2: 3 + 5 FFs (as PDFs)

unpolarized hadron:

$D_{h/q}$ probability for $q \rightarrow h + X$

unpolarized FF

$$\Delta \hat{D}_{h/q\uparrow} \equiv \hat{D}_{h/q\uparrow} - \hat{D}_{h/q\downarrow} = \Delta^N D_{h/q\uparrow}(z, p_\perp) \mathbf{s}_q \cdot (\hat{\mathbf{p}}_q \times \hat{\mathbf{k}}_\perp) \quad \text{Collins '93}$$



$\Delta \hat{D}_{h/q\uparrow}(z, \mathbf{k}_\perp)$
 “T-odd”,
 chiral-odd

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

gauge links \rightarrow universality (Collins & Metz 2004, Yuan 2008) same function in $e^+e^- \rightarrow hh + X$ $lp^\uparrow \rightarrow l'h + X$ and $p^\uparrow p \rightarrow h \text{ jet} + X$

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

- **Sivers function: link to Orbital Angular Momentum**
- **Boer-Mulders and Collins functions: (χ -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!

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

requires:

- **helicity flip** at the partonic level but **helicity conserved in massless QCD**
- **relative phase** between helicity amplitudes but **real Born amplitudes**.

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

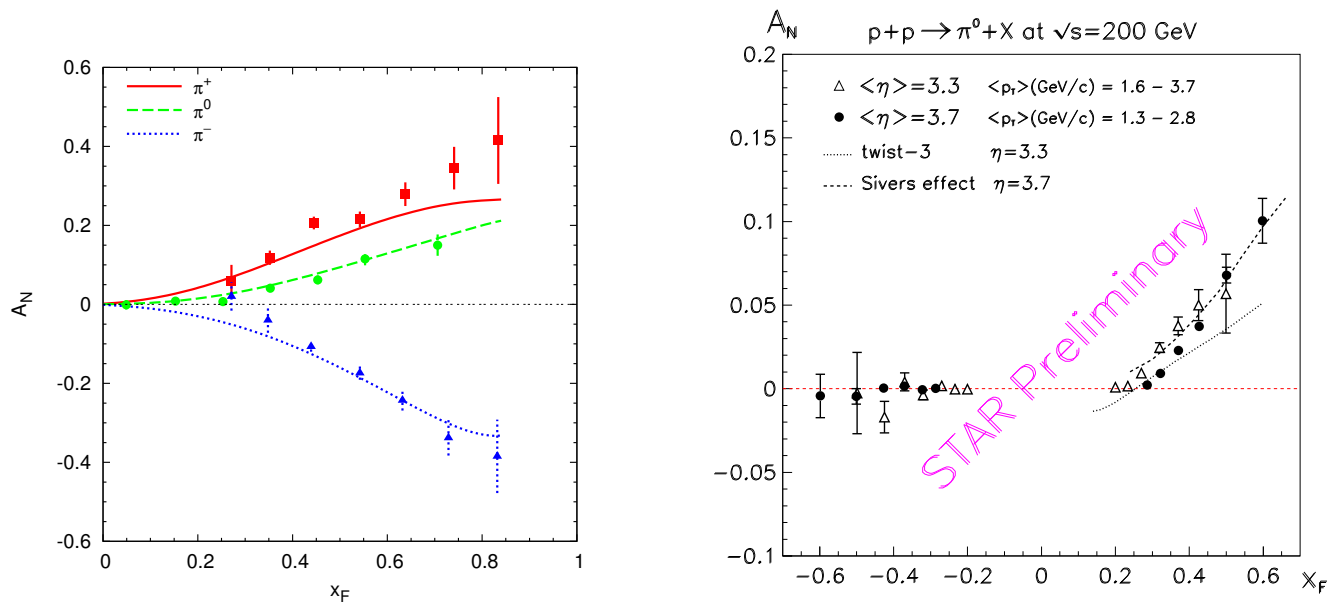
Kane et al. 1978

Contrary to observation: E704 data (90s) $p^\uparrow p \rightarrow \pi + X$ at $\sqrt{20}$ GeV \rightarrow **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*]

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

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

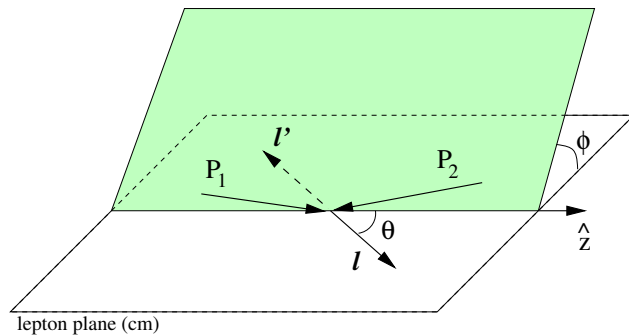
Opening of a new and exciting phenomenology

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

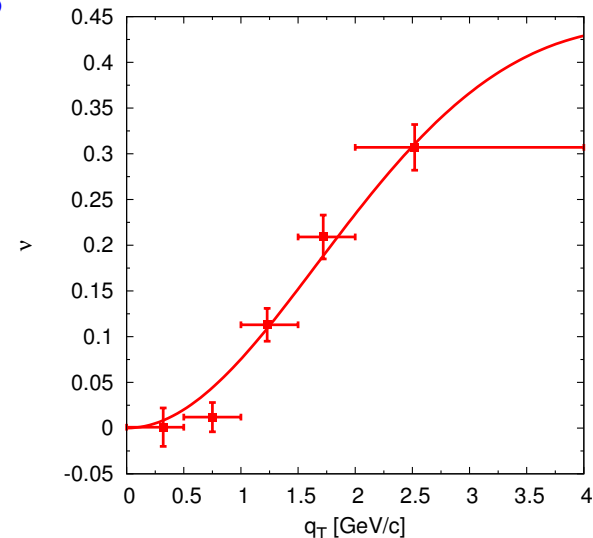
$$d\sigma \simeq 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

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

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



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



Boer 1999

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

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

(different azimuthal dependences \rightarrow separable)

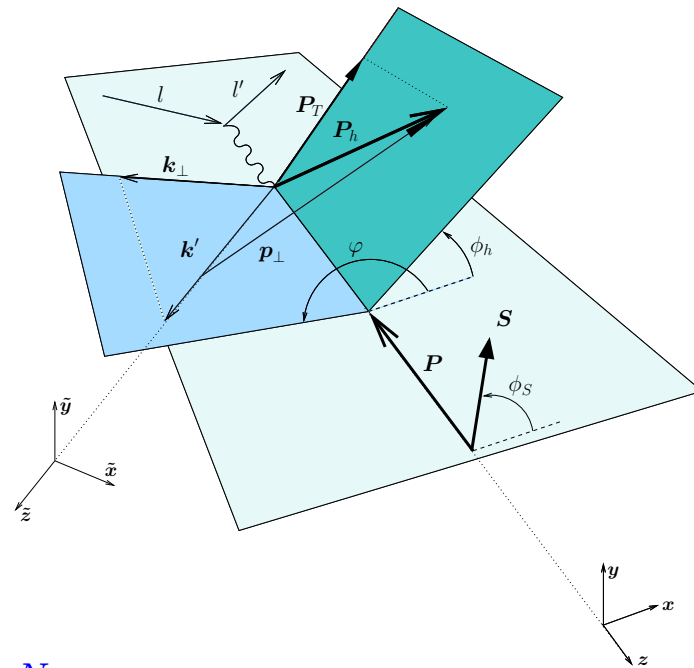
NO DATA

SIDIS

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

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

+ Cahn effect



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

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

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

(different azimuthal dependences \rightarrow separation of **Sivers** and **Collins** effects)

Experimental Programmes:

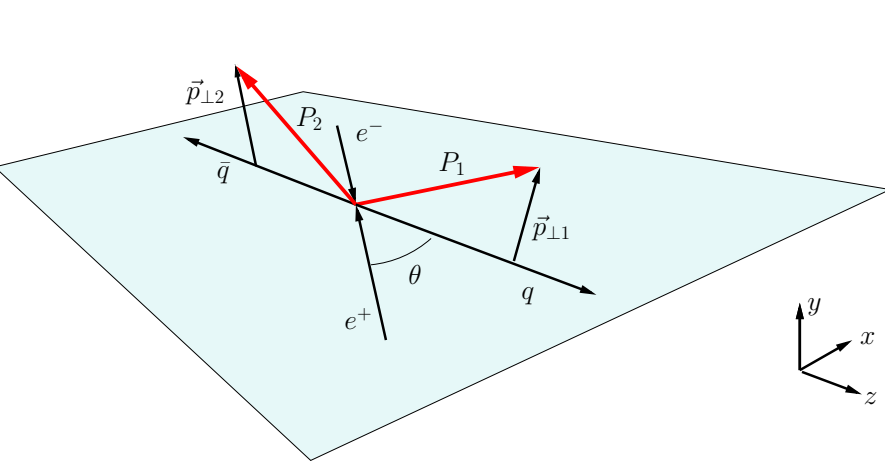
HERMES @ HERA [FIRST EVIDENCE], COMPASS @ CERN, CLAS @ JLAB

- Azimuthal correlations in $e^+e^- \rightarrow h_1h_1 + X$: Collins effect

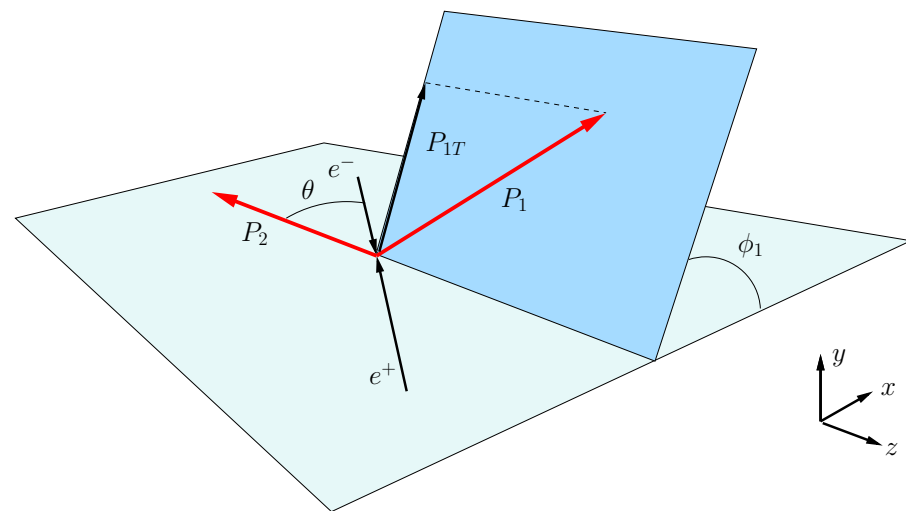
$$d\sigma \simeq (1 + \cos^2 \theta) D_{h_1/q} D_{h_2/\bar{q}} + \sin^2 \theta \Delta^N D_{h_1/q\uparrow} \Delta^N D_{h_2/\bar{q}\uparrow}$$

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

$$\times \cos(2\phi_1)$$



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: $u \rightarrow \pi^+$ and $d \rightarrow \pi^+$

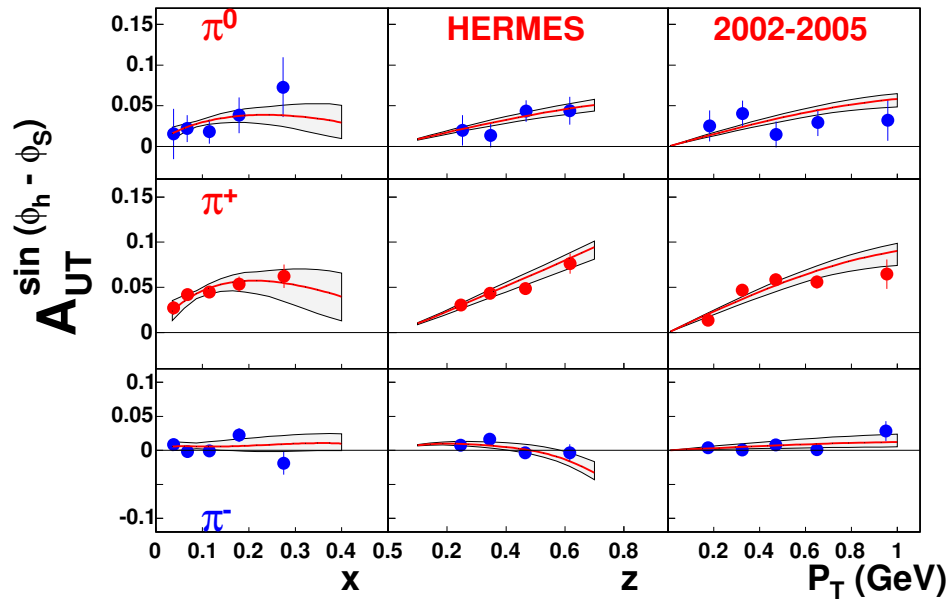
Transversity: u and d quarks

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

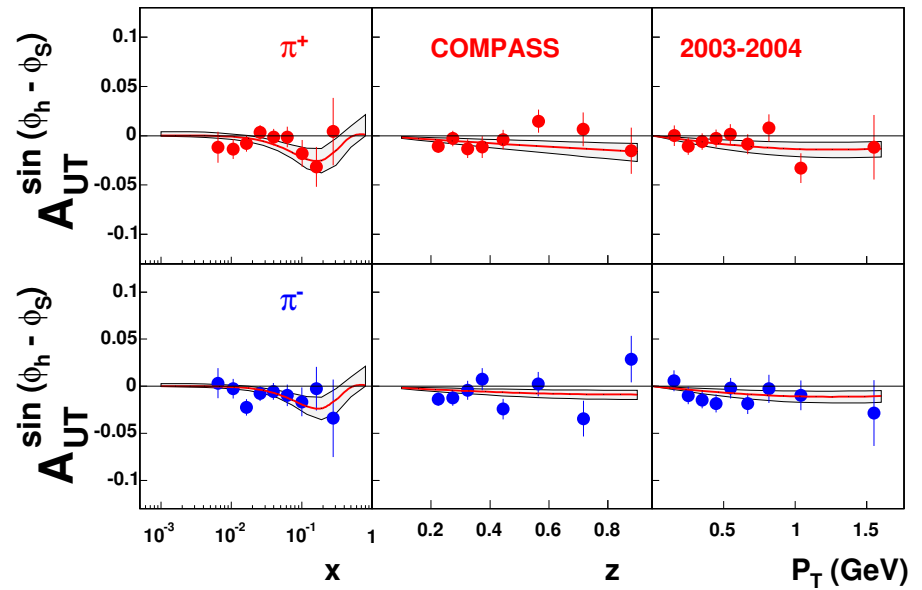
Other similar analyses from *Vogelsang & Yuan, Efremov et al.*

- Siverson effect in SIDIS:
NEW analysis [completed]

Anselmino et al. 2008



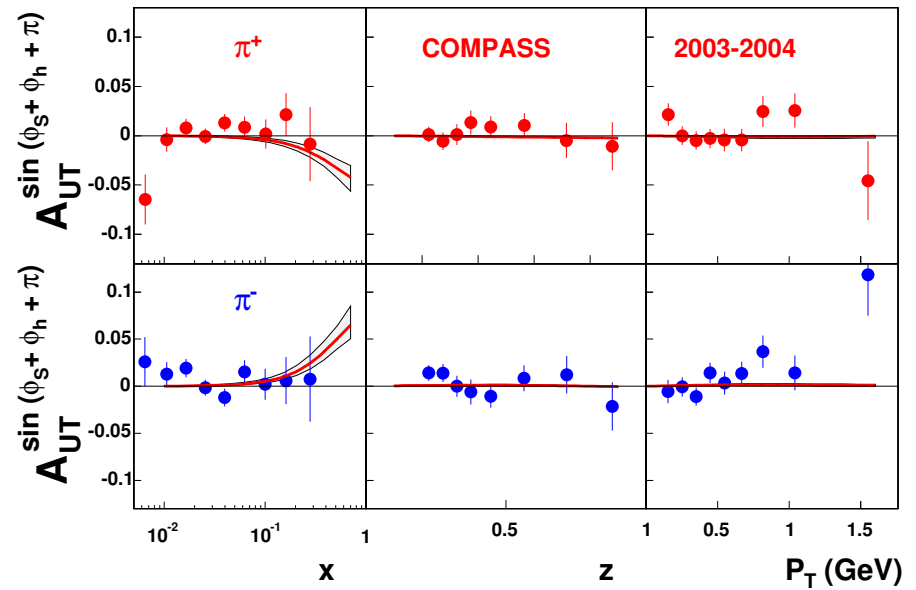
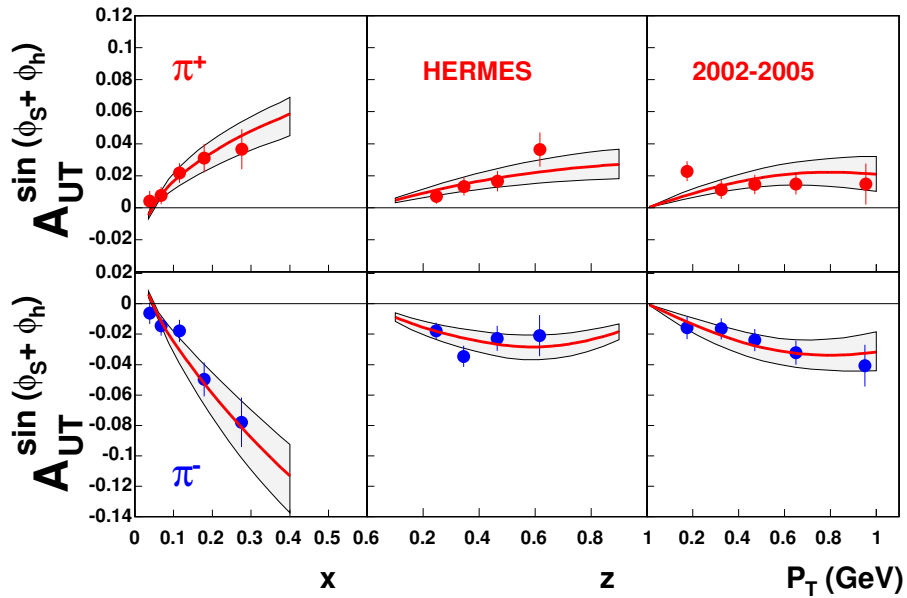
Fit of HERMES data [Diefenthaler et al. 2006],



and COMPASS data [Martin et al. 2006]
(deuterium target)

- Collins effect in SIDIS:
NEW analysis [preliminary]

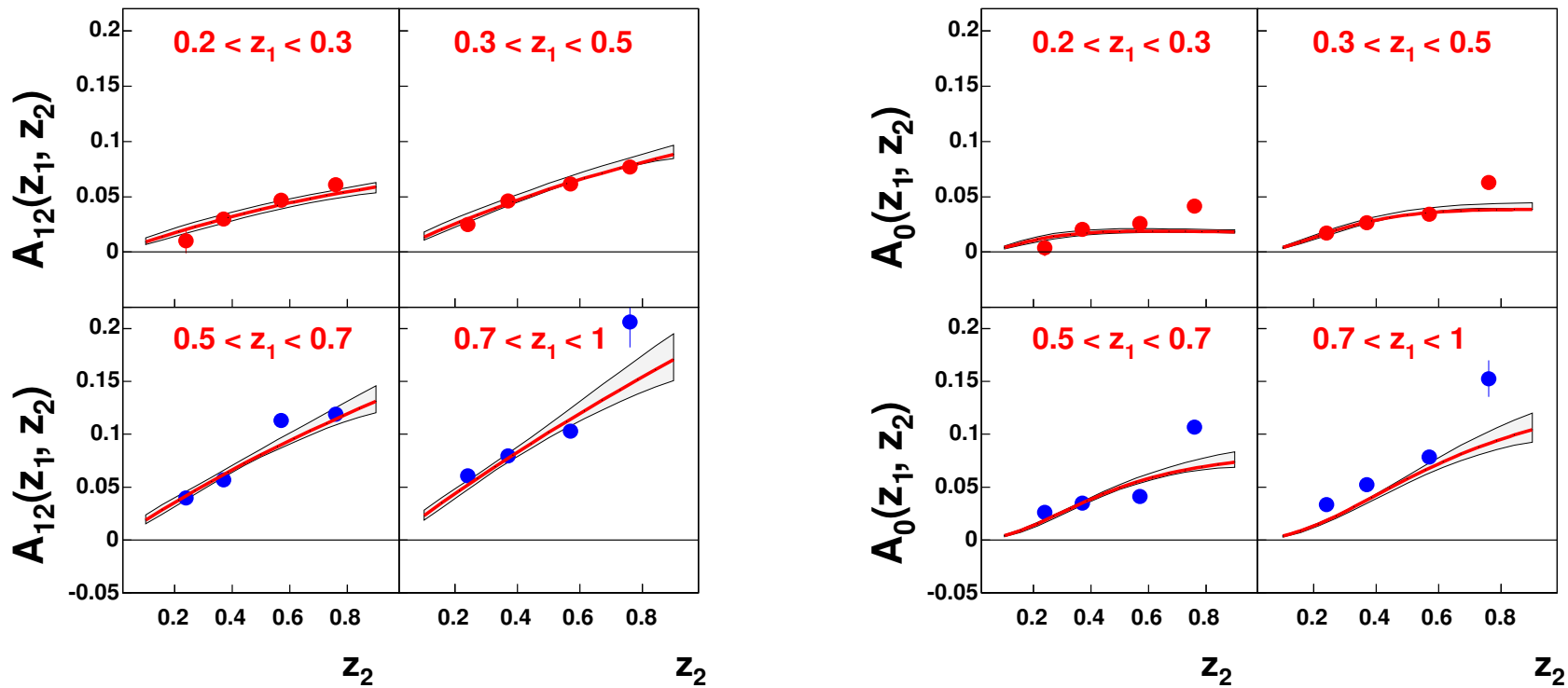
Anselmino et al. 2008



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 $e^+e^- \rightarrow \pi\pi + X$
NEW analysis [preliminary]

Anselmino *et al.* 2008

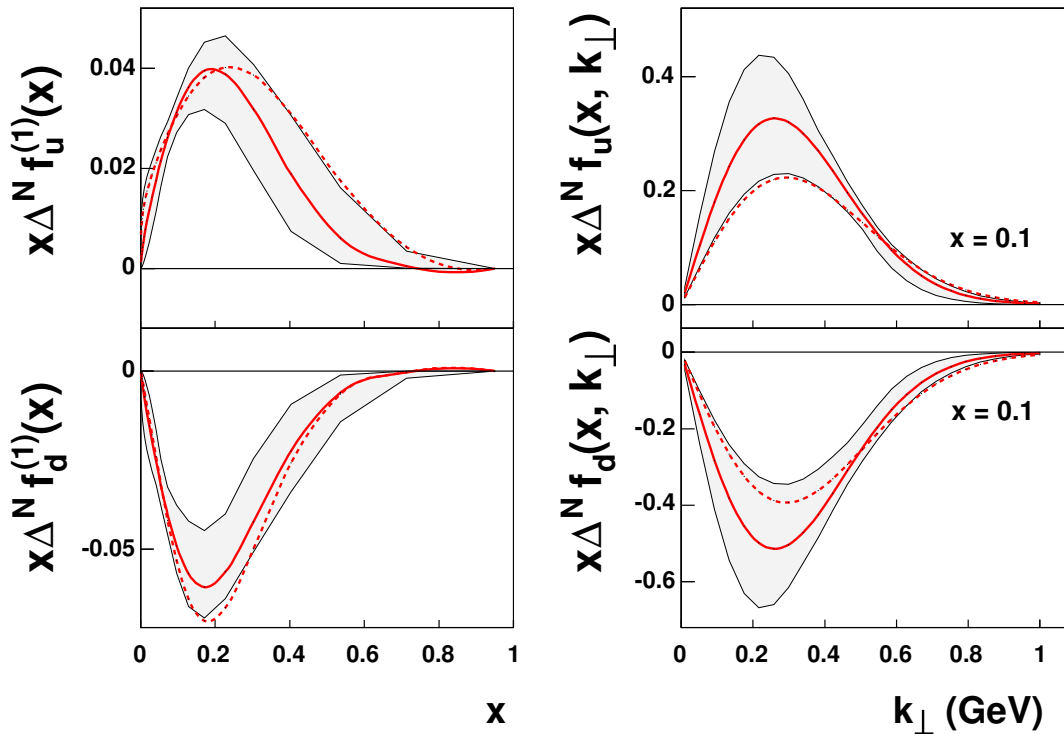


Preliminary fit of data on $e^+e^- \rightarrow h_1 h_2 X$ from Belle Collaboration. [Ogawa *et al.* 2007].

Sivers function: valence quarks

New analysis (on π and K^\pm)

Anselmino et al. 2008



Remember:

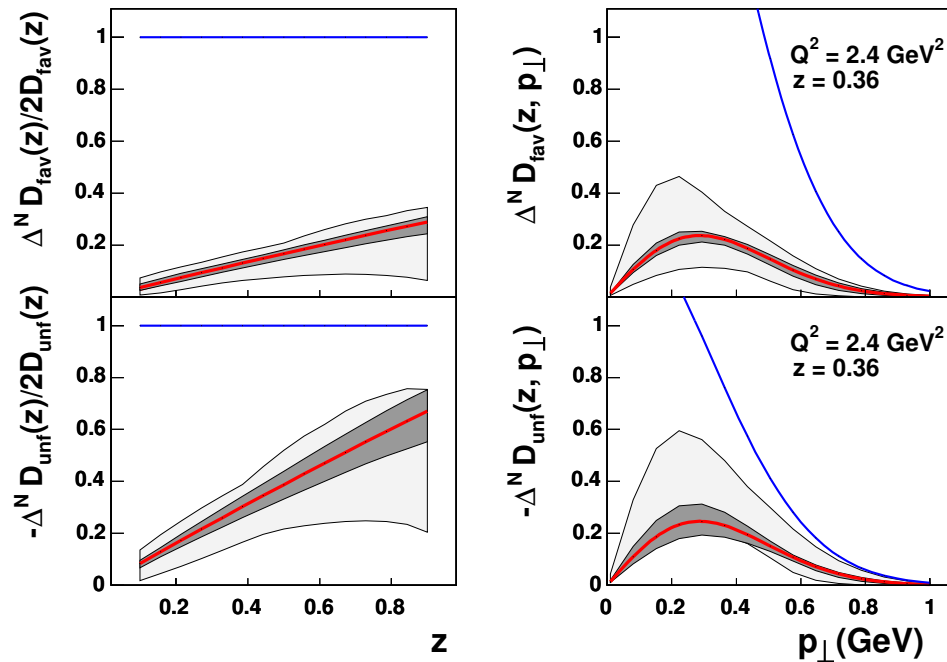
$A_{UT}^{\pi^+}(p^\uparrow) > 0$ (HERMES)
 $A_{UT}^{\pi}(D^\uparrow) \simeq 0$ (COMPASS)
 $\Rightarrow \Delta^N f_u > 0, \Delta^N f_d < 0$
 and similar size

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

\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]

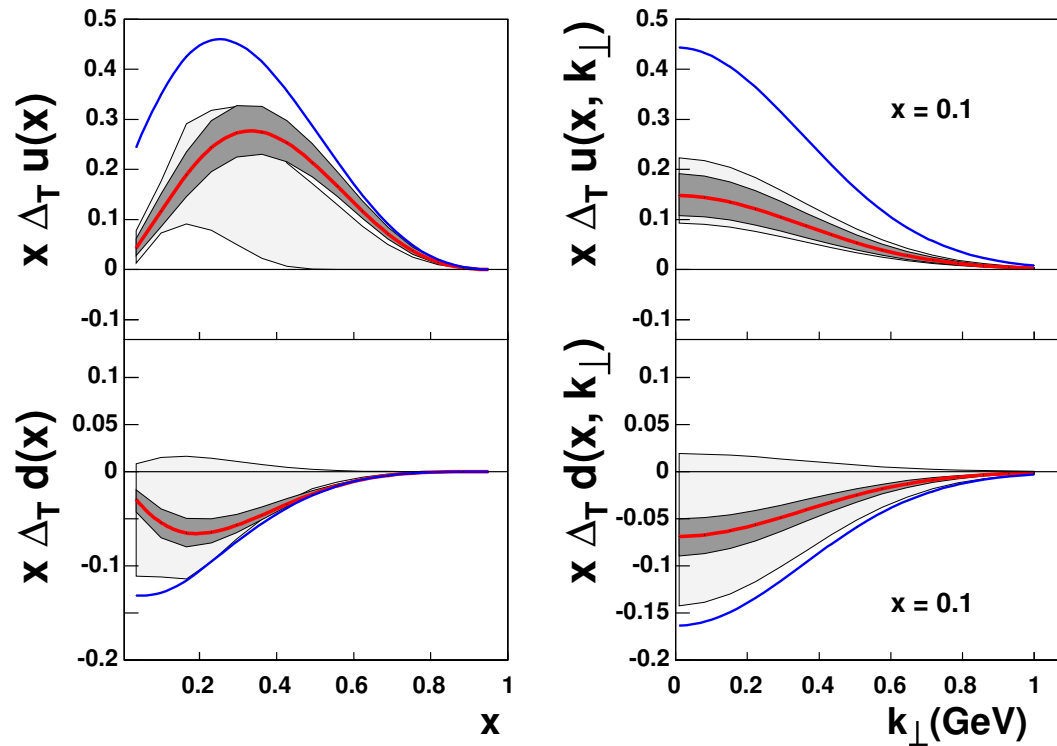
$$A_{UT}^{\pi^+}(p) \simeq 4\Delta_T u \Delta^N D_{\text{fav}} + \Delta_T d \Delta^N D_{\text{unf}}$$

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

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

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

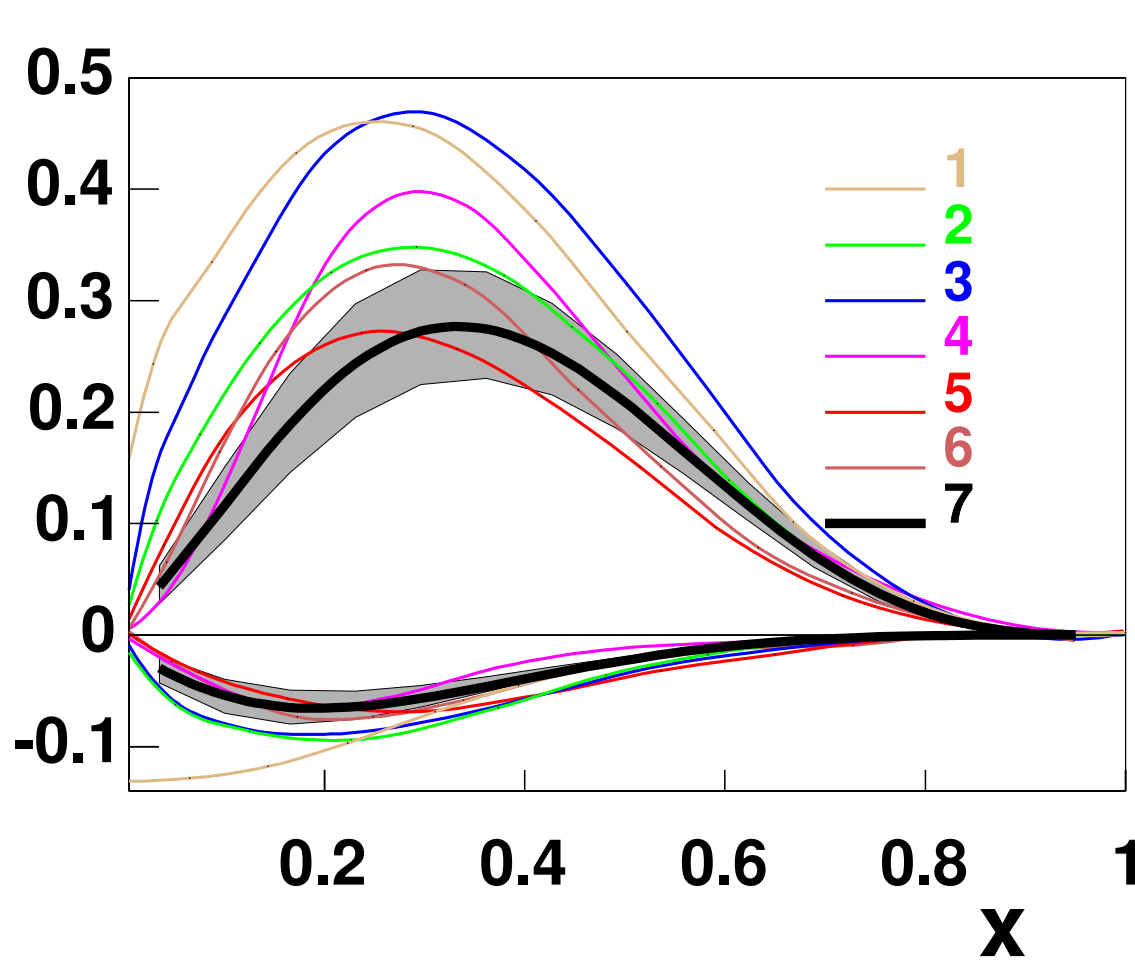
Anselmino et al. 2008



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

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; $L \neq 0$
- 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

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- Sivers effect: in a transversely polarized nucleon quarks are left-right asymmetric around the spin direction; $L \neq 0$
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Open issues:

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

Trieste, 12-16 May, 2008

THE TRANSVERSE SPIN ERA HAS JUST STARTED

Let's enjoy it

THANK YOU