Transverse Spin Effects in Drell–Yan Processes

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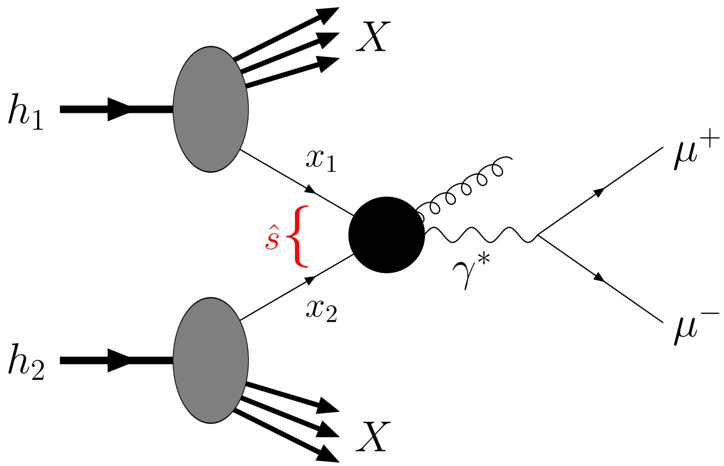
Drell-Yan dilepton production

$$h_1 + h_2 \to \mu^+ + \mu^- + X$$



$\tau \equiv M^2/s\,, \quad z \equiv M^2/\hat{s}$

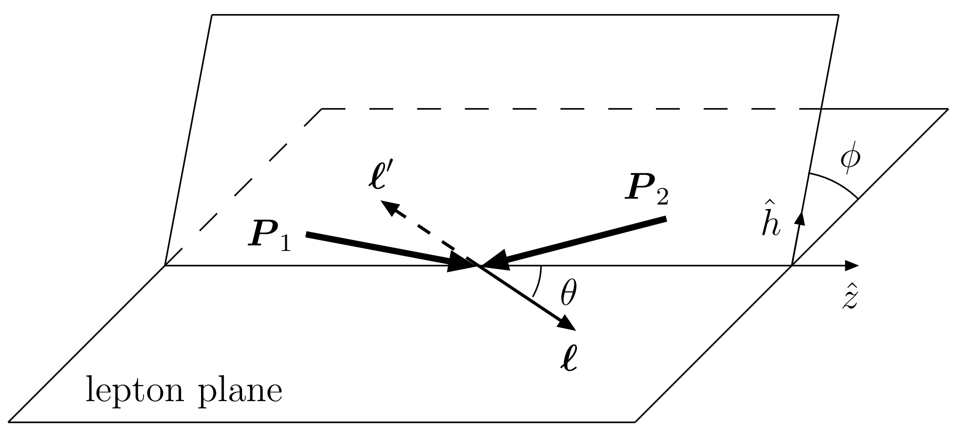
$\hat{s} = x_1 x_2 s\,, \quad x_1 x_2 = \tau/z$

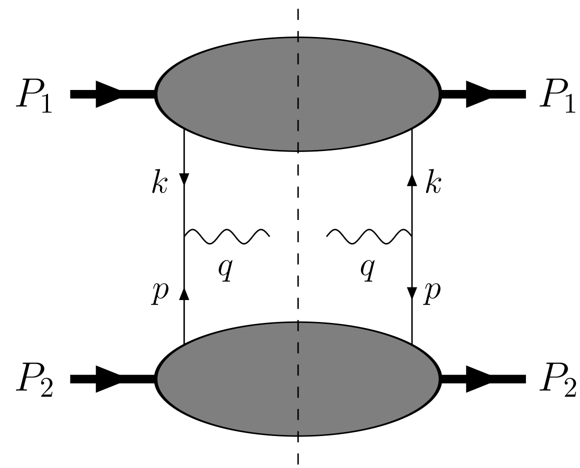
M^2 invariant mass of $\mu^+\mu^-$

At leading order: $q\bar{q}$ annihilation

$$z = 1\,, \quad x_1 x_2 = \frac{M^2}{s}\,, \quad y = \frac{1}{2}\ln\frac{x_1}{x_2} \text{ (rapidity)}$$

Geometry and Kinematics of DY





Collins–Soper frame:

ϕ angle between lepton and hadron plane, $\boldsymbol{q}_T$ transverse momentum of virtual photon

Relation between transverse momenta: $\boldsymbol{p}_T + \boldsymbol{k}_T = \boldsymbol{q}_T$

GSI-HESR ($\bar{p}p$):

Collider: $\bar{p}$ beam 15 Gev, p beam 3.5 GeV, $s = 4E_p E_{\bar{p}} = 200$ GeV^2

Fixed target: $\bar{p}$ beam 15-40 GeV, $s = 2ME_{\bar{p}}$ =30-80 GeV^2

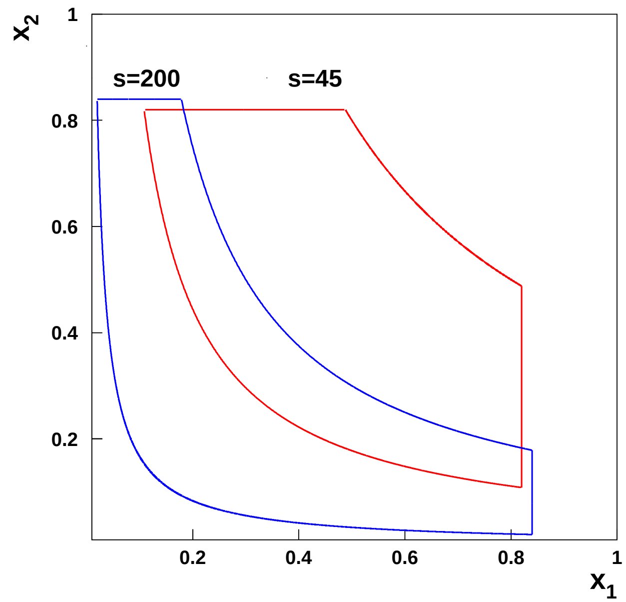
COMPASS (πp): π beam 50-100 GeV, $s = 100$-200 GeV^2

J-PARC (pp): p beam 50 GeV, $s = 100$ GeV^2

Correlations between x_1, x_2, M^2, s

$s = 45$ GeV^2, 2 GeV $\leq M \leq 4$ GeV

$s = 200$ GeV^2, 2 GeV $\leq M \leq 6$ GeV



M must be large enough to apply pQCD

But production rates fall off rapidly with M

Processes and Observables

Double polarization ($\bar{p}^{\uparrow} p^{\uparrow}$, $p^{\uparrow} p^{\uparrow}$)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}\phi} \sim h_1(x_1)\, h_1(x_2)\ \cos 2(\phi - \phi_{S_1} - \phi_{S_2})$$

Single polarization ($\bar{p} p^{\uparrow}$, $p p^{\uparrow}$, $\pi p^{\uparrow}$)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}\phi} \sim f_1(x_1, k_T^2)\, f_{1T}^{\perp}(x_2, k_T^2)\ \sin(\phi{-}\phi_S){+}h_1^{\perp}(x_1, k_T^2)\, h_1(x_2, k_T^2)\ \sin(\phi{+}\phi_S)$$

No polarization ($\bar{p}p$, pp, πp)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}\phi} \sim h_1^{\perp}(x_1, k_T^2)\, h_1^{\perp}(x_2, k_T^2)\ \cos 2\phi$$

Transversity in a nutshell

Transversely polarized quarks (↑↓) in a transversely polarized proton (↑):

$$h_1(x) = q_\uparrow(x) - q_\downarrow(x) \qquad \text{[also called } \Delta_T q(x)\text{]}$$

Field–theoretical definition:

$$h_1(x) = \int \frac{\mathrm{d}\xi^-}{4\pi}\, \mathrm{e}^{\mathrm{i}xP^+\xi^-} \langle P,S|\overline{\psi}(0)\gamma^+\gamma_\perp\gamma_5\psi(\xi)|P,S\rangle\Big|_{\xi^+=\vec{\xi}_\perp=0}$$

Tensor charge: first moment of $h_1 - \overline{h}_1$

$$\langle P,S|\overline{\psi}_q(0)\mathrm{i}\sigma^{\mu\nu}\gamma_5\psi_q(0)|P,S\rangle = 2\,\delta q\, S^{[\mu}P^{\nu]}\,, \qquad \delta q = \int_0^1 \mathrm{d}x\, [h_1^q(x) - \overline{h}_1^q(x)]$$

Leading twist: unsuppressed by powers of $1/Q$

Chirally odd: non diagonal in helicity basis

Non-singlet evolution: no gluonic transversity

Soffer inequality: $|h_1(x)| \leq \frac{1}{2}\,[f_1(x) + g_1(x)]$

The "T-odd" couple: $f_{1T}^{\perp}$ and $h_1^{\perp}$

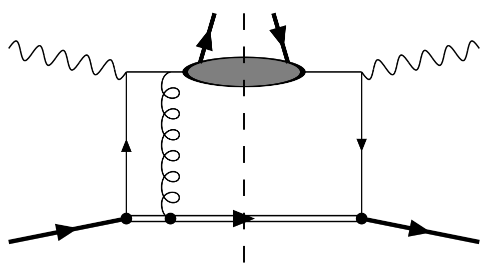
Sivers distribution function: azimuthal asymmetry of unpolarized quarks inside a transversely polarized proton

$$\mathcal{P}_{q/p^\uparrow}(x, \boldsymbol{k}_T) - \mathcal{P}_{q/p^\uparrow}(x, -\boldsymbol{k}_T) = \frac{(\boldsymbol{k}_T \times \hat{\boldsymbol{P}}) \cdot \boldsymbol{S}_T}{M} \, f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)$$

Boer-Mulders distribution function: spin asymmetry of transversely polarized quarks inside an unpolarized proton

$$\mathcal{P}_{q^\uparrow/p}(x, \boldsymbol{k}_T) - \mathcal{P}_{q^\downarrow/p}(x, \boldsymbol{k}_T) = \frac{(\boldsymbol{k}_T \times \hat{\boldsymbol{P}}) \cdot \boldsymbol{S}_{qT}}{M} \, h_1^{\perp}(x, \boldsymbol{k}_T^2)$$

An explicit calculation [Brodsky, Hwang & Schmidt 2002] shows that $f_{1T}^{\perp}$ and $h_1^{\perp}$ are generated by gluon exchange between the struck quark and the spectator:



$\Rightarrow$ $f_{1T}^{\perp}, \; h_1^{\perp}$

Field-theoretical definition of k_T–dependent distributions:

$$\mathcal{P}_{q/p}(x, \boldsymbol{k}_T) = \int \frac{\mathrm{d}\xi^-}{4\pi} \int \frac{\mathrm{d}\boldsymbol{\xi}_T}{(2\pi)^2}\, \mathrm{e}^{\mathrm{i}xP^+\xi^- - \mathrm{i}\mathbf{k}_T\cdot\xi_T} \langle P, S|\overline{\psi}(\xi)\gamma^+ W(0,\xi)\psi(0)|P, S\rangle$$

Time reversal invariance implies [Collins 2002]

$$f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)_{\text{SIDIS}} = -f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)_{\text{DY}}\,, \quad h_1^{\perp}(x, \boldsymbol{k}_T^2)_{\text{SIDIS}} = -h_1^{\perp}(x, \boldsymbol{k}_T^2)_{\text{DY}}\,,$$

What do we know about transversity ?

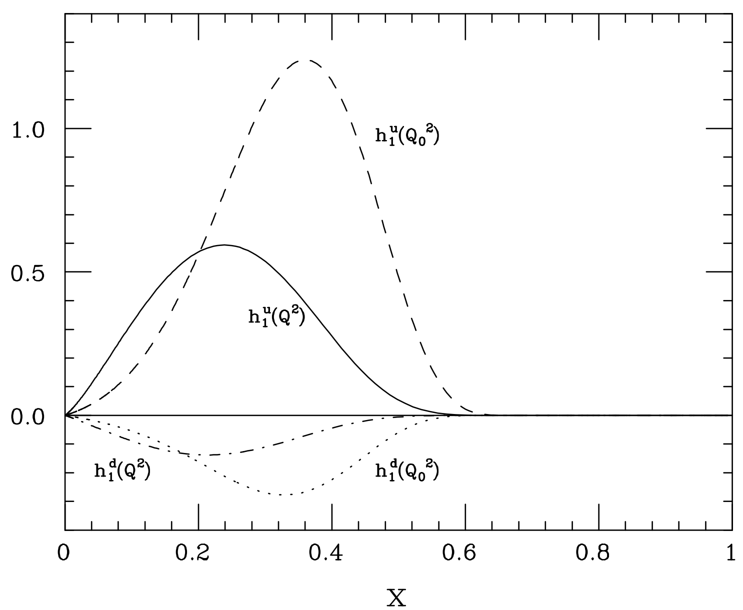
- Models show that $h_1 \simeq g_1$ at a very low scale (< 1 GeV)
  - In NRQM, $h_1 = g_1$ exactly. In relativistic models the difference is due to lower components of wf's: h_1 measures relativistic effects
- Sign and magnitude of antiquark distributions more uncertain

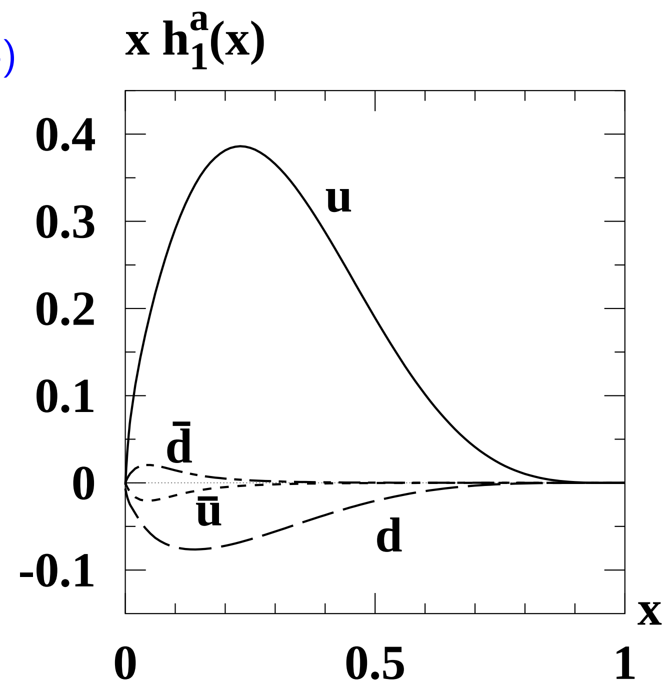
  (But even for helicity densities the situation is unclear)
- QCD evolution of h_1 known up to NLO
  - No mixing with gluons
  - Tensor charges decrease with Q^2
  - Evolution of h_1 different from that of g_1 especially at low x

Model calculations of h_1 (two examples)

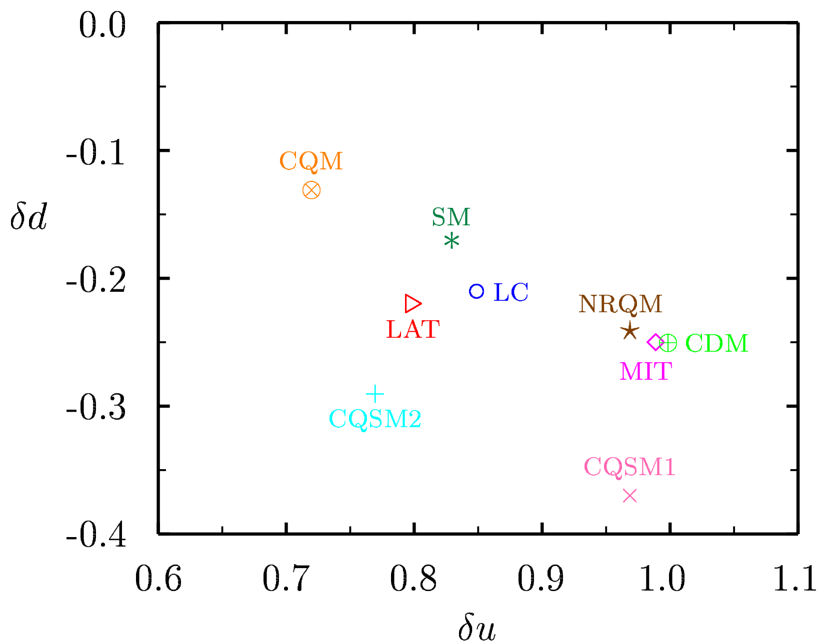
Chiral quark soliton model (Schweitzer et al.)

Chiral chromodielectric model (VB, Calarco & Drago)





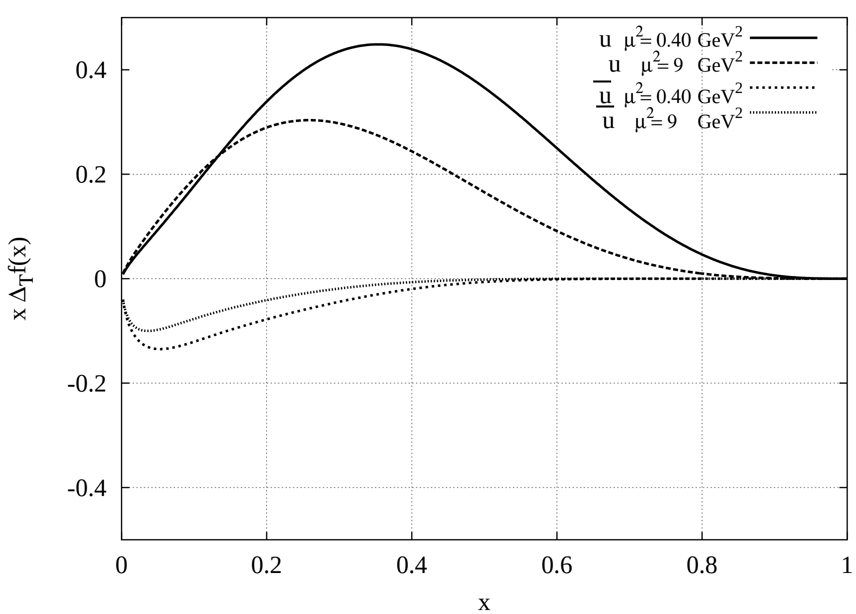
Tensor charges



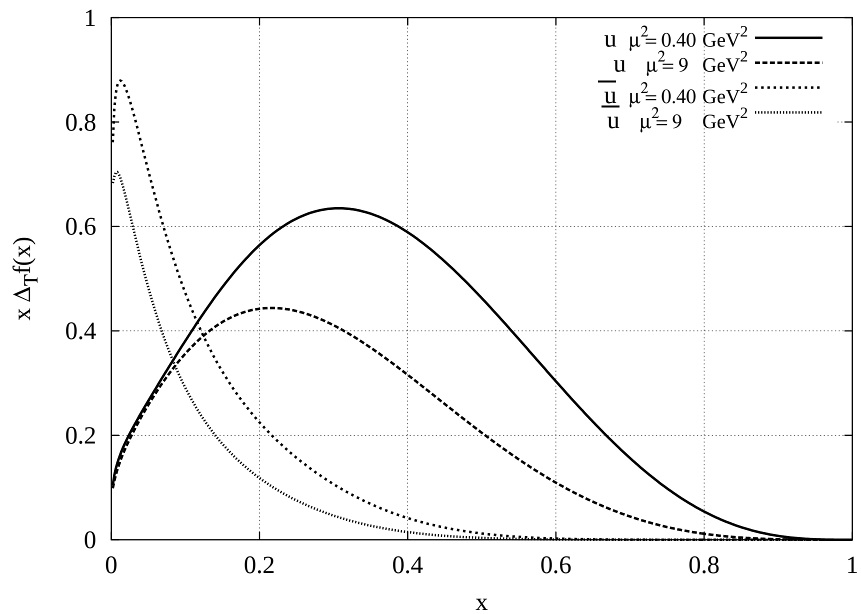
NRQM: Non-Relativistic Quark Model
MIT: MIT Bag Model
CDM: Color Dielectric Model
CQSM1: Chiral Quark Soliton Model 1
CQSM2: Chiral Quark Soliton Model 2
CQM: Chiral Quark Model
LC: Light-Cone Model
SM: Spectator Model
LAT: Lattice QCD

$\delta u \sim 0.7 - 1.0, \quad \delta d \sim -(0.1 - 0.4)$ at $Q^2 = 10$ GeV^2

Using the GRV parametrizations of pdf's to model transversity



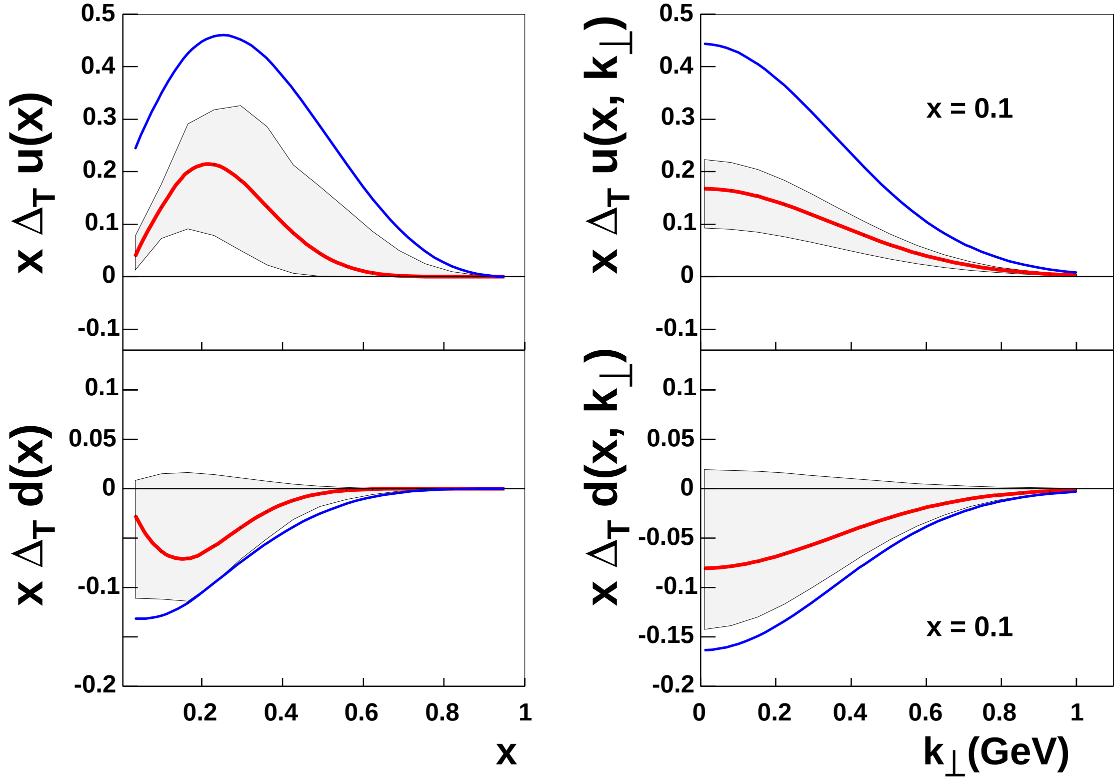
$h_1 = g_1$ at $Q_0^2 = 0.40$ GeV^2



$h_1 = \frac{1}{2}(f_1 + g_1)$ at $Q_0^2 = 0.40$ GeV^2

Transversity from a fit to HERMES, COMPASS and BELLE data

[Anselmino et al. 2007]



What do we know about the Sivers function ?

- Spectator models: simplest way to construct $f_{1T}^{\perp}$, but many free parameters (masses, nucleon-quark-diquark vertices, average transverse momentum)

  Problem: $f_{1T}^{\perp d}$ comes out too small (compared to data)
- Large-N_c prediction: isoscalar $f_{1T}^{\perp}$ suppressed

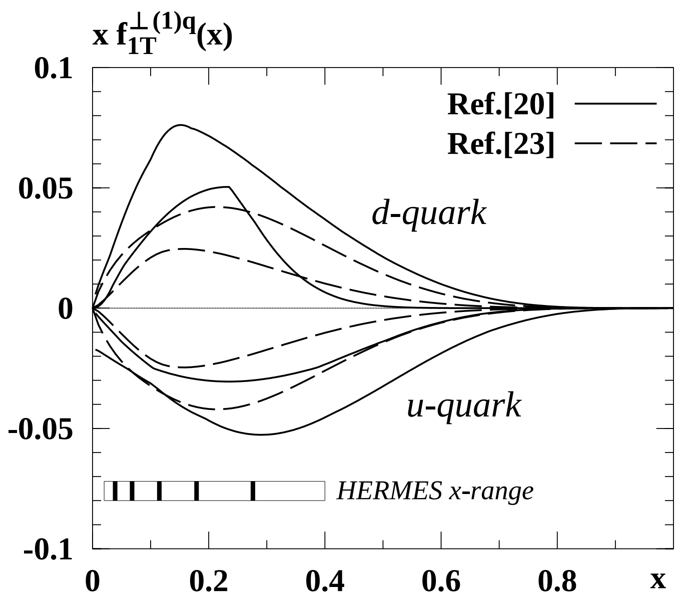
$$f_{1T}^{\perp u} \simeq -f_{1T}^{\perp d}$$

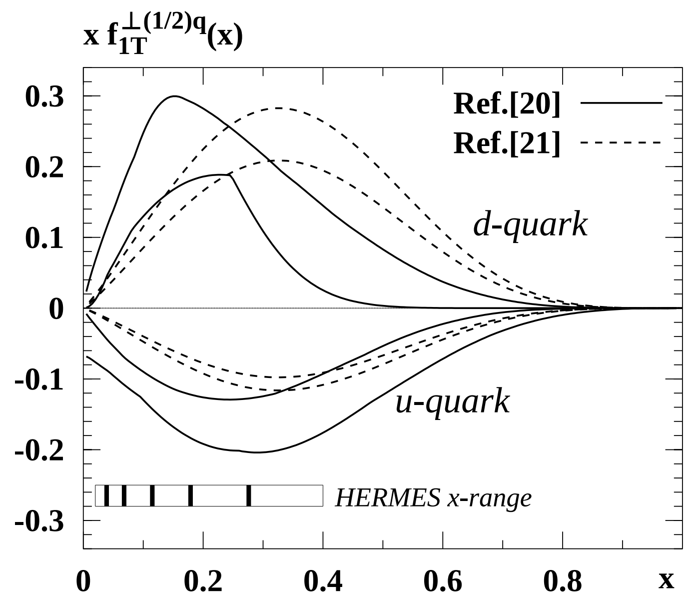
- Transverse distortion of pdf's in impact parameter space [Burkardt]

  Sivers function opposite in sign to the anomalous magnetic moment

  $f_{1T}^{\perp u} < 0$, $f_{1T}^{\perp d} > 0$ (confirmed by data)
- $f_{1T}^{\perp}$ can be extracted from HERMES and COMPASS single-spin asymmetry measurements

Sivers function from fits to HERMES and COMPASS data





[Anselmino et al.] vs. [Collins et al.] [Anselmino et al.] vs. [Vogelsang & Yuan]

What do we know about the Boer–Mulders function ?

- Only one class of data pertinent (perhaps) to $h_1^\perp$: NA10 and E615 measurements of $\cos 2\phi$ asymmetry in $\pi^- N \to \mu^+ \mu^- X$
- Spectator models: $h_1^\perp = f_{1T}^\perp$ if only scalar diquarks are considered.
  k_T-dependence may be adjusted to the Q_T behavior of $\cos 2\phi$ data
- Large-N_c prediction: isovector $h_1^\perp$ suppressed

$$h_1^{\perp u} \simeq h_1^{\perp d}$$

- Burkardt's approach: $h_1^\perp$ related to the first moment of some GPD's
  Lattice results: indication for $h_1^{\perp u} < 0$
- Plausible working hypothesis (?):

$$h_1^{\perp u} = f_{1T}^{\perp u}\,, \quad h_1^{\perp d} = -f_{1T}^{\perp d}$$

Doubly polarized DY production

Double transverse asymmetry : $A_{TT}^{DY} = \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} + \mathrm{d}\sigma^{\uparrow\downarrow}}$

At leading order the hard subprocess is $q\bar{q}$ annihilation:

$$A_{TT}^{DY} \sim \frac{\sum_q e_q^2\, h_{1q}(x_1, M^2)\, \bar{h}_{1q}(x_2, M^2) + [1 \leftrightarrow 2]}{\sum_q e_q^2\, f_{1q}(x_1, M^2)\, \bar{f}_{1q}(x_2, M^2) + [1 \leftrightarrow 2]}$$

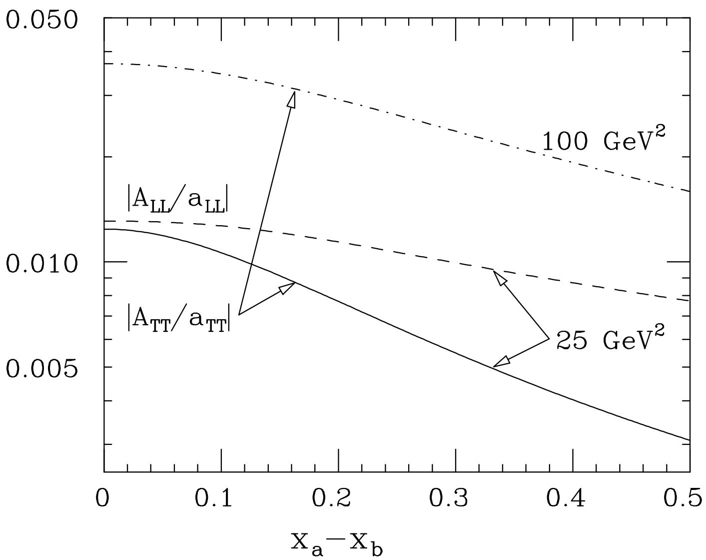
The asymmetry is completely determined by transversity

Predictions for $A_{TT}^{DY}(pp)$ at RHIC

LO at $\sqrt{s} = 100$ GeV

$h_1 = g_1$ at $Q_0^2 = 0.23$ GeV^2

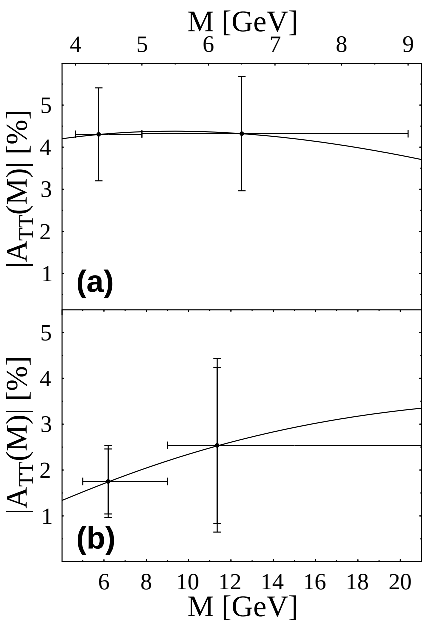
[VB, Calarco & Drago 1997]



NLO at $\sqrt{s} = 200$ GeV

Soffer bound saturated at Q_0

[Martin et al. 1998]



At RHIC energies $A_{TT}^{DY}(pp)$ is expected to be small: $\sim 2 - 3\%$

Why RHIC transverse asymmetries are small:

- $\sqrt{s} = 200$ GeV, $M < 10$ GeV $\Rightarrow$ $x_1 x_2 = M^2/s < 2.5 \times 10^{-3}$: low-$x$ region is probed
- Sea transversity distributions are small. The evolution of transversity is suppressed at low x

Two ways to improve the situation [VB, Calarco & Drago 1997]:

- Moderate energies: with $s \sim 100$ GeV^2 and $M > 4$ GeV, one has $x_1 x_2 > 0.15$ (intermediate-x region)
- Proton–antiproton scattering probes valence $\times$ valence

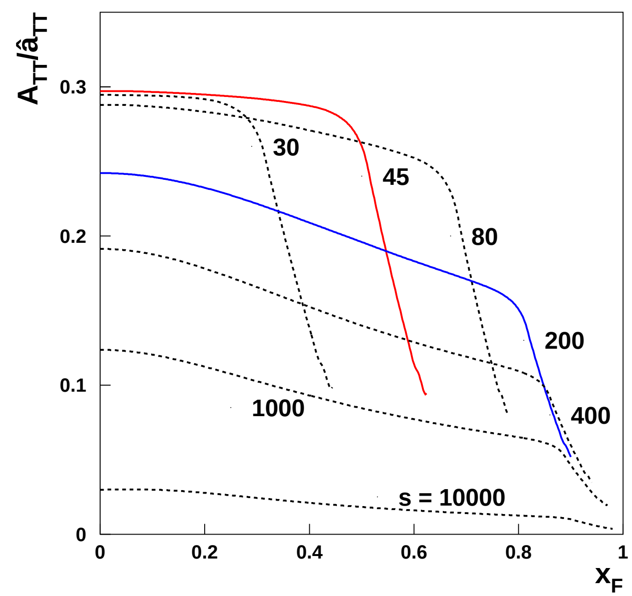
PAX: polarized $\bar{p}$ colliding on polarized p at GSI-HESR [PAX, hep-ex/0505054]

$$s = 45, 200 \text{ GeV}^2\,, \quad M > 2\,\text{GeV}\,, \quad \mathcal{L} > 10^{30}\text{cm}^{-2}\text{s}^{-1}$$

A_{TT} turns out to be large, of order 0.3

LO calculation ($M = 4$ GeV) $\Rightarrow$

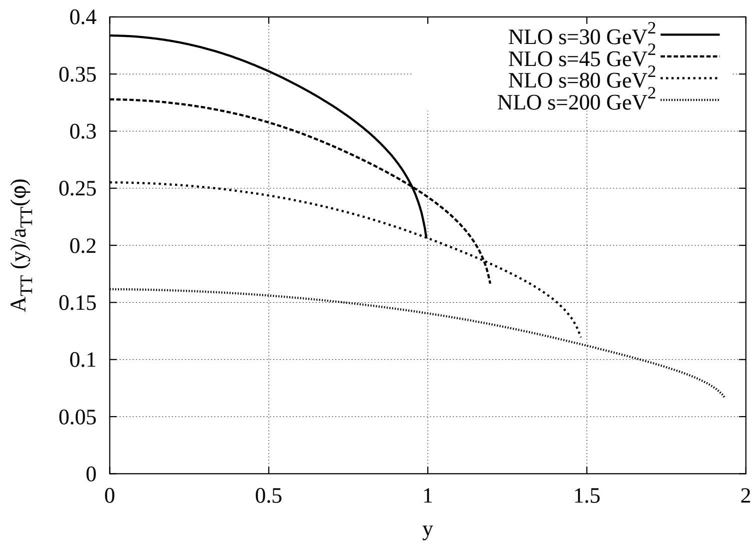
[Anselmino, VB, Drago, Nikolaev 2004]



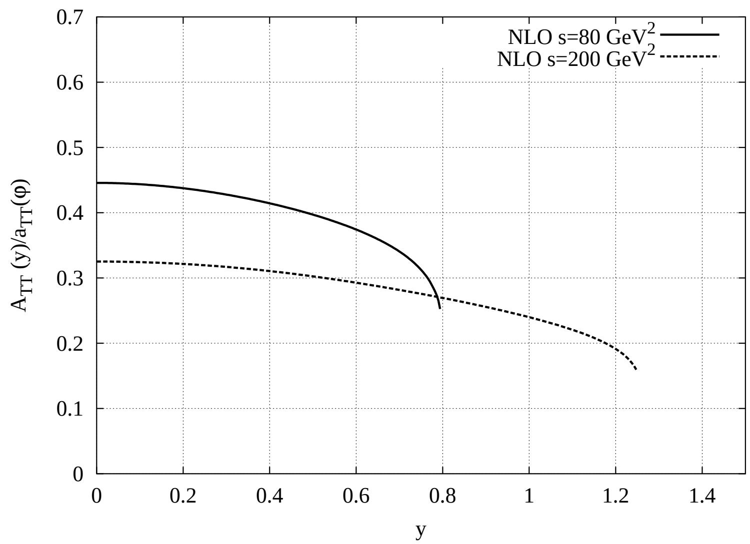
For $p^\uparrow p^\uparrow$ DY at J-PARC asymmetries are expected to be smaller, but still sizable (~ 0.15-0.2). Important information on signs of antiquark distributions

NLO predictions of $A_{TT}^{DY}(\bar{p}p)$ [VB et al. 2005]

Perturbative corrections to the cross sections largely cancel in the ratio. Asymmetries are almost unaffected



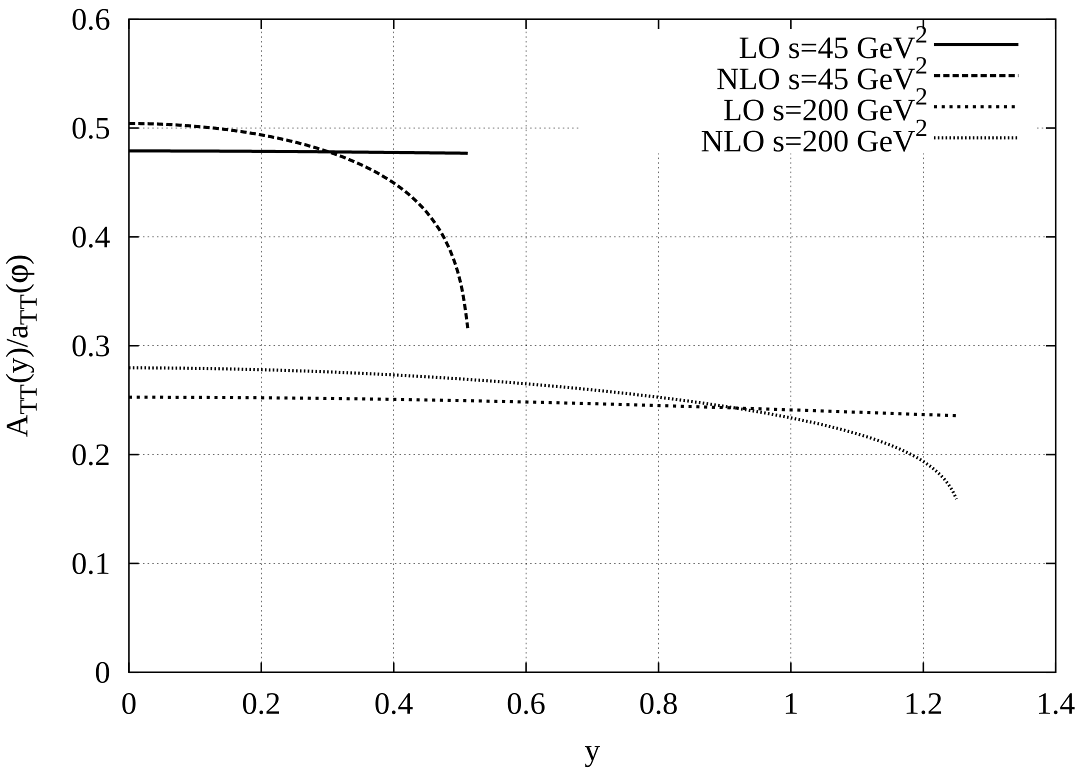
M integrated from 2 to 3 GeV



M integrated from 4 to 7 GeV

Soft-gluon resummation modifies the results by 10 % only [Shimizu, Sterman, Vogelsang, Yokoya 2005]

LO vs. NLO


LO s=45 GeV^2
NLO s=45 GeV^2
LO s=200 GeV^2
NLO s=200 GeV^2
$A_{TT}(y)/a_{TT}(\varphi)$
y
0
0.1
0.2
0.3
0.4
0.5
0.6
0.2
0.4
0.6
0.8
1
1.2
1.4

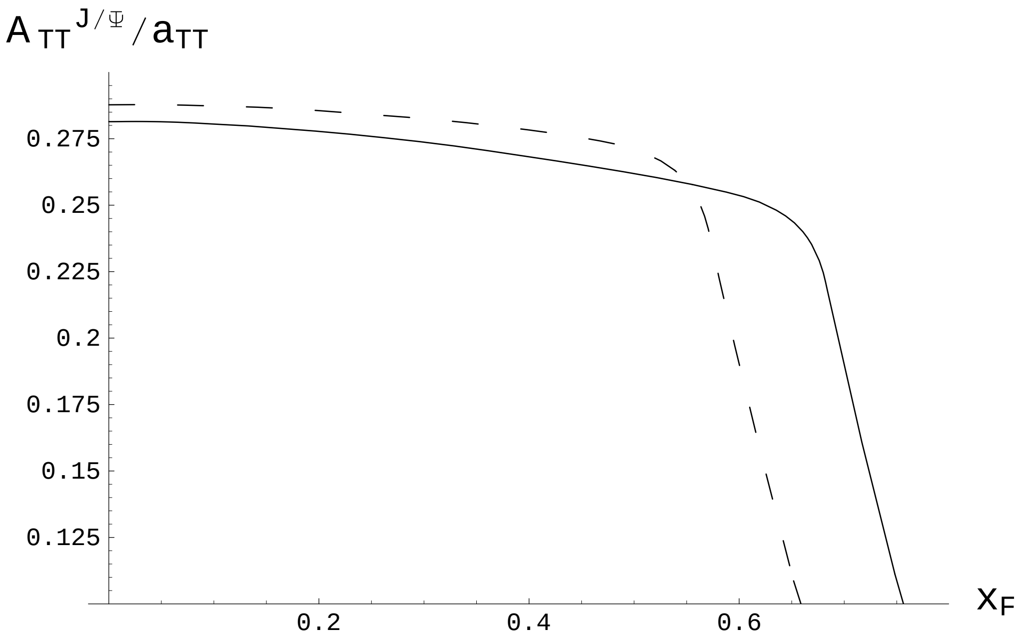
Double transverse DY asymmetry is large, but the production rate falls down rapidly for $M > 3$ GeV

$\Rightarrow$ J/ψ production [Anselmino, VB, Drago, Nikolaev 2004]

- Comparison of J/ψ production in $\bar{p}p$ and pp collisions at $s = 80$ GeV^2 (SPS data) shows dominance of $\bar{q}q$ annihilation: $\sigma(\bar{p}p) \gg \sigma(pp)$
- The helicity structure of $q\bar{q}J/\psi$ is the same as $q\bar{q}\gamma^*$
- Since the u sector dominates, the J/ψ coupling factorizes out

$$A_{TT}^{J/\psi} \sim \frac{h_{1u}(x_1, M_\psi^2)\, h_{1u}(x_2, M_\psi^2)}{f_{1u}(x_1, M_\psi^2)\, f_{1u}(x_2, M_\psi^2)}$$

[Anselmino, VB, Drago, Nikolaev 2004]



$A_{TT}^{J/\psi} \sim 0.3$ (similar results by [Efremov, Goeke & Schweitzer 2004])

Unpolarized DY production

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

NA10 and E615 results for $\pi^- N \to \mu^+ \mu^- X$:

ν increasing with Q_T and large (~ 0.4 at $Q_T = 3$ GeV for $E_\pi = 194$ GeV)

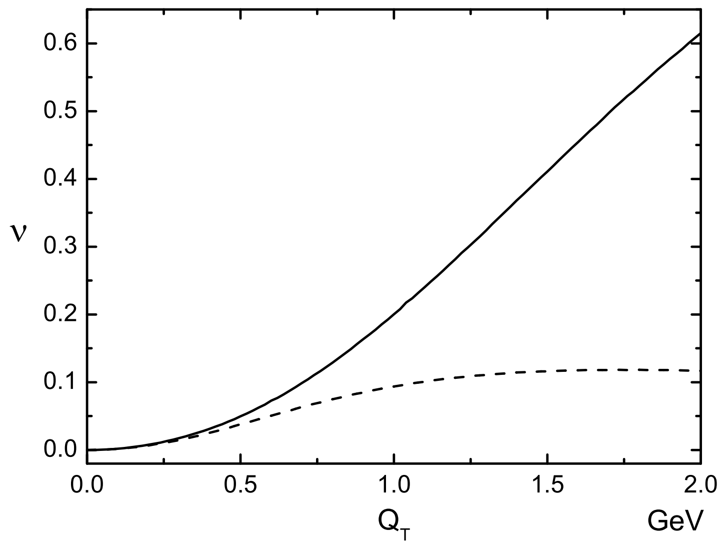
Possible explanations:

- Boer–Mulders mechanism (correlation between transverse spin and transverse momentum of quarks)
- Gluon radiation (but the effect is too small)

Boer-Mulders effect:

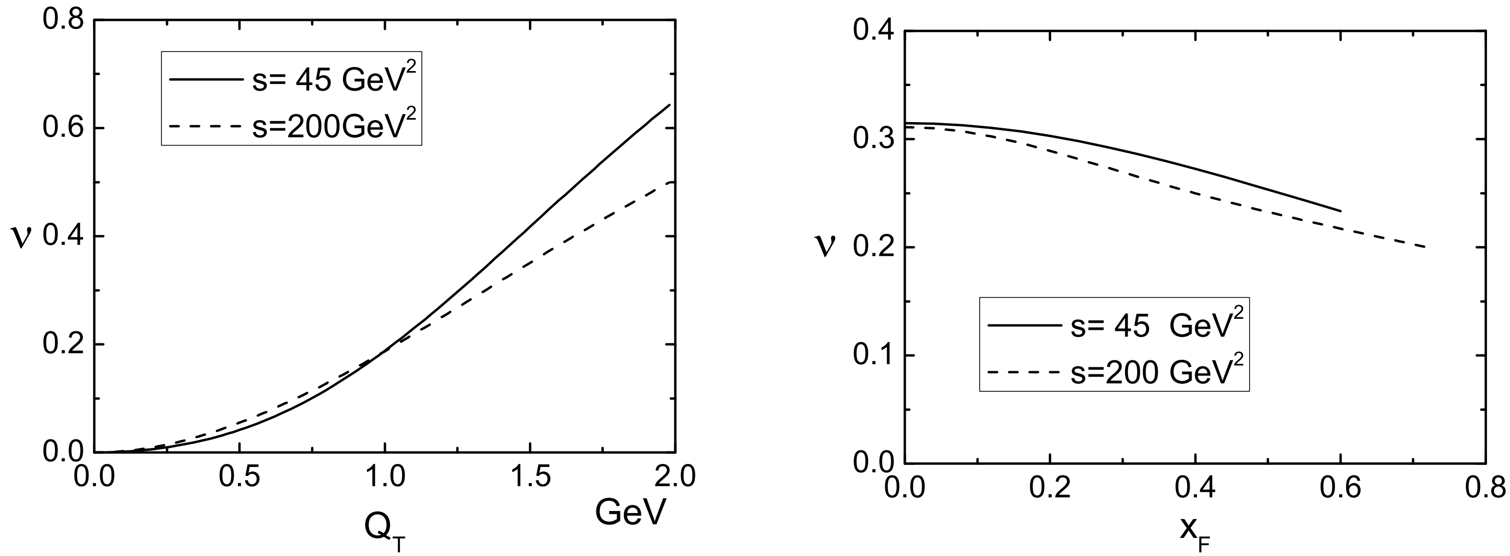
$$\nu \sim \frac{\mathcal{I}\left[(2\,\boldsymbol{k}_T\cdot\hat{\boldsymbol{P}}_{hT}\,\boldsymbol{p}_T\cdot\hat{\boldsymbol{P}}_{hT}-\boldsymbol{k}_T\cdot\boldsymbol{p}_T)\,h_1^\perp\,h_1^\perp\right]}{\mathcal{I}\left[f_1\,f_1\right]}$$

Prediction for ν in $\bar{p}p$ Drell-Yan [VB, Lu and Ma 2007]



$h_1^\perp$ from a spectator model adjusted to NA10 data ($\langle k_T^2\rangle \sim 0.30$ GeV^2)

The ν asymmetry on the J/ψ peak in $\bar{p}p$ DY



Conclusions

- Solid predictions for double–spin DY asymmetry in $\bar{p}p$

  Experimental efforts in this direction worthwhile

- All DY measurements in the $s = 100$-200 GeV^2 region are important:
  - $\bar{p}^{\uparrow}p^{\uparrow} \Rightarrow$ valence h_1, $p^{\uparrow}p^{\uparrow} \Rightarrow$ sea h_1
  - $\bar{p}p, \pi p \Rightarrow h_1^{\perp}$
  - $\bar{p}p^{\uparrow}, pp^{\uparrow}, \pi p^{\uparrow} \Rightarrow f_{1T}^{\perp}$ via $\sin(\phi - \phi_S)$
  - $\bar{p}p^{\uparrow} \Rightarrow h_1^{\perp}, h_1$ via $\sin(\phi + \phi_S)$

- We need a general framework for a global fit of DY, SIDIS and e^+e^- data

  What can we safely learn from models ? What can we reasonably assume ?
  What can we effectively extract ?

- Theoretical duties:

  Better understanding of higher twists (both from a formal and a phenomenological viewpoint)

  Investigate the QCD evolution of k_T-dependent distributions (neglected so far in all analyses)