Transverse Spin Phenomenology

An Overview

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Outline

1. Transverse spin effects: where we stand, where we are going
2. The three main distribution functions:

   Transversity, Sivers, Boer–Mulders
3. The explored territory ...

   Collins and Sivers effects in semiinclusive DIS on $p^{\uparrow}, D^{\uparrow}$
4. ... and its surroundings

   Neutron target, other observables, azimuthal asymmetries and Boer-Mulders effect
5. The unexplored territory: Drell–Yan processes
6. Concluding remarks

Transverse spin effects: generalities

Spin four-vector: $S^\mu = \lambda \frac{P^\mu}{M} + S_\perp^\mu \,, \qquad S^\mu S_\mu = -1$

The spin transverse component of fast particles is suppressed by M/E

Naïve conclusion: transverse spin effects are irrelevant at high energies

In inclusive DIS transverse spin effects are indeed subdominant (twist-3):

Quark-parton model: $g_1(x) + g_2(x) = \frac{1}{2} \sum_a e_a^2 g_T^a(x)$

$$g_T(x) = g_T^{WW}(x)\,[\text{twist 2}] + \tilde{g}_T(x)[\text{twist 3}]$$

Recent data from JLab at $Q^2 \sim 1$ GeV^2 [JLab E97-103] show evidence of higher-twist effects ($g_2 \neq g_2^{WW}$)

There are high-energy hadronic processes where transverse polarization effects are unsuppressed and dominant: e.g., transversely polarized Drell–Yan production [Ralston and Soper 1979; Artru and Mekhfi 1990; Jaffe and Ji 1991; Cortes, Pire and Ralston 1992]

A new leading twist quark distribution function: transversity distribution

Other transverse spin effects arise from various k_T-dependent distributions [Kotzinian; Mulders et al.; ... 1993-98]

SIDIS experiments with transversely polarized targets ($p^{\uparrow}$, $D^{\uparrow}$) [HERMES, COMPASS]

Transverse spin phenomena: where we stand

Transverse single-spin asymmetries well established and sizable

This is a highly non-trivial result:

- Initial-state interactions generate unsuppressed spin asymmetries
- Final-state interactions do not wash out spin effects

First extractions of Sivers function and transversity from data

Transverse spin phenomena: where we are going

For a truly global analysis of transverse spin data we need:

- Many observables (i.e., a large variety of processes and targets) and a limited set of distribution functions to be fitted (h_1, $f_{1T}^{\perp}$, $h_1^{\perp}$, $H_1^{\perp}$)

  $\longrightarrow$ Warning: any experimental preanalysis should be consistent with subsequent fits

- A general theoretical framework, comprising:
  - A choice of functional forms for the x and k_T-dependence: e.g. $x^{\alpha}(1-x)^{\beta}$ and Gaussians in k_T
  - Physical constraints (positivity, Soffer bound, ...)
  - A number of model assumptions (relation between h_1 and g_1, large-N_c expectations, lattice results, ...), to be progressively reduced
  - Q^2 evolution of distributions and full theoretical understanding of processes

$\boxed{\text{The three main distribution functions related to transverse spin}}$

- Transversity distribution $h_1(x)$
- Sivers distribution $f_{1T}^{\perp}(x, k_T^2)$
- Boer–Mulders distribution $h_1^{\perp}(x, k_T^2)$

Related quantity (couples to h_1): Collins fragmentation function $H_1^{\perp}(z, P_T^2)$

Transversity: a summary

Transversely polarized quarks ($\uparrow\downarrow$) in a transversely polarized proton ($\Uparrow$):

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

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

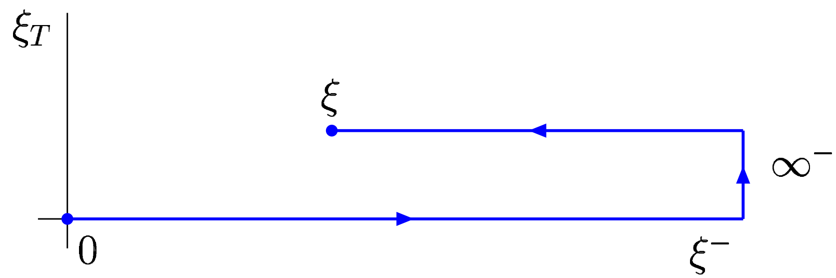
Non-singlet evolution: no gluonic transversity

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

$\boxed{k_T\text{-dependent distributions}}$

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

Wilson line $W_C = \mathrm{P}\ \exp\left[-\mathrm{i}g \int_C A(x)\cdot \mathrm{d}x\right]$: path C depends on the process



SIDIS : $W(0,\xi) = W(0^-, 0_T; \infty^-, 0_T)W(\infty^-, 0_T; \infty^-, \xi_T)W(\infty^-, \xi_T; \xi^-, \xi_T)$

In light-cone gauge the potential at ∞^- does not vanish [Belitsky, Ji & Yuan 2003]

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

Transverse spin naturally couples to transverse momenta. Many possible correlations between $\boldsymbol{k}_T$, $\boldsymbol{S}_T$ and $\boldsymbol{S}_{qT}$ giving rise to single-spin asymmetries.

$f_{1T}^{\perp}$ and $h_1^{\perp}$ measure the correlations: $(\hat{\boldsymbol{P}} \times \boldsymbol{k}_T) \cdot \boldsymbol{S}_T$ and $(\hat{\boldsymbol{P}} \times \boldsymbol{k}_T) \cdot \boldsymbol{S}_{qT}$

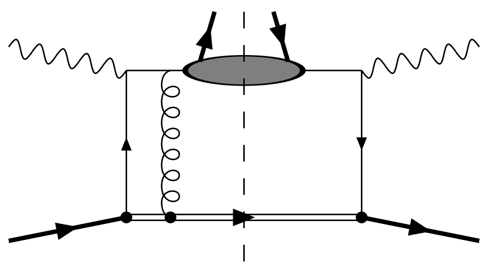
Sivers distribution function: azimuthal asymmetry of unpolarized quarks inside a transversely polarized proton

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

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:



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

Time reversal invariance implies [Collins 2002]

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

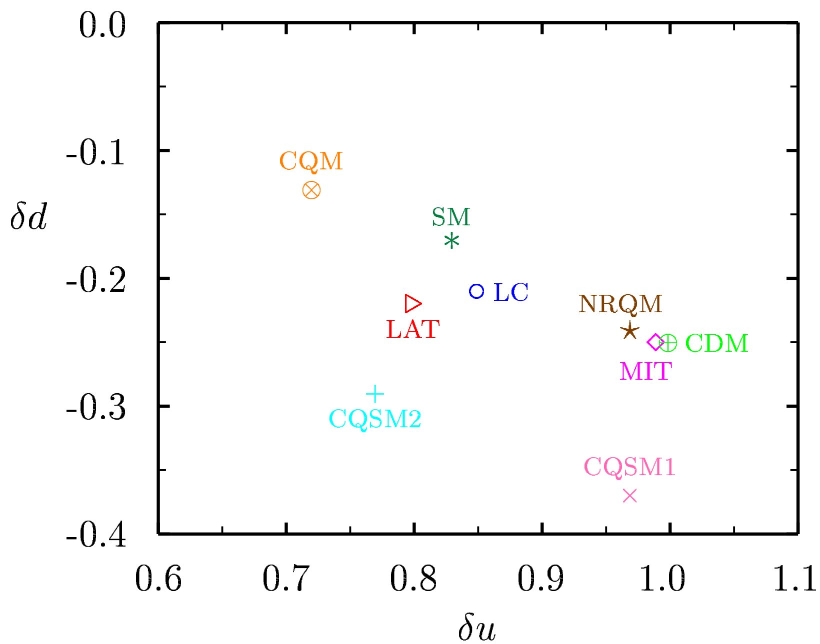
Can be checked by comparing SIDIS to single-polarized DY

What we know about transversity

- Models show that $h_1 \simeq g_1$ at very low scales (< 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 unsettled)
- 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
- First extraction of h_1 (in combination with $H_1^{\perp}$) from a fit to HERMES, COMPASS, BELLE data [Anselmino et al. 2006]

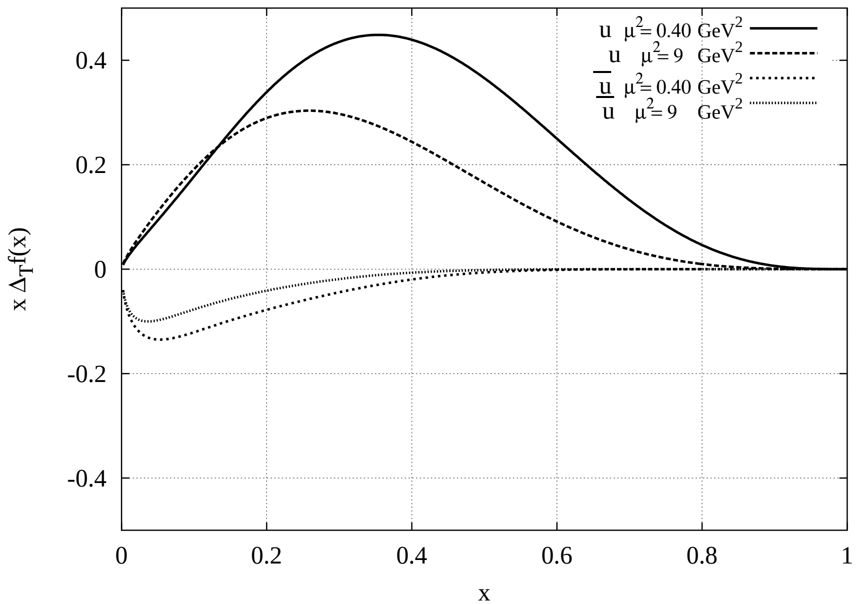
Tensor charges in various models



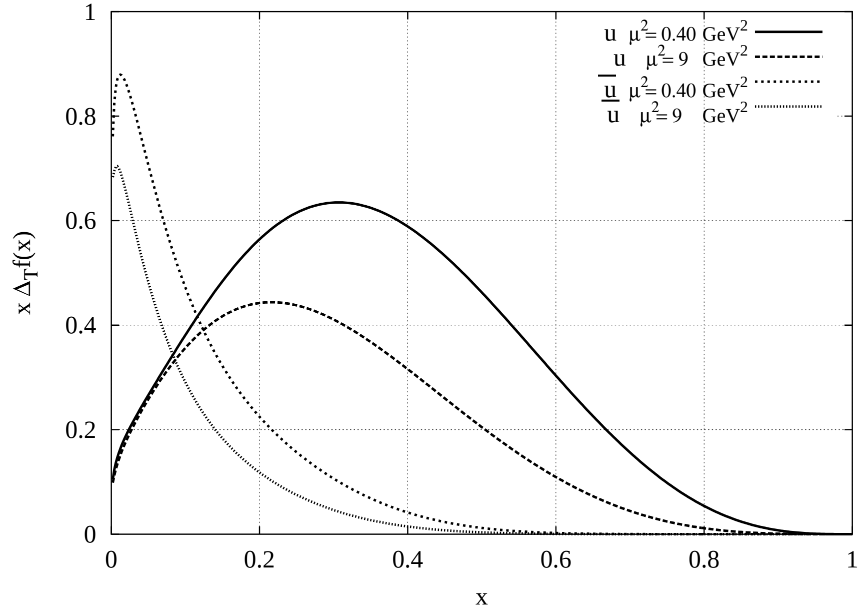
NRQM: Non-Relativistic Quark Model
MIT: MIT Bag Model
CDM: Color Dielectric Model
CQSM1: Chiral Quark Soliton Model 1
CQSM2: Chiral Quark Soliton Model 2
CQM: Chiral Quark Model
LC: Light-Cone Model
SM: Spectator Model
LAT: Lattice QCD

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

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

What 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

What we know about the Boer–Mulders function

- Only one class of data pertinent 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:

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

The explored territory

Pion leptoproduction from a transversely polarized target:

$$e\,p^{\uparrow}\,(D^{\uparrow})\;\rightarrow\;e'\,\pi\,X$$

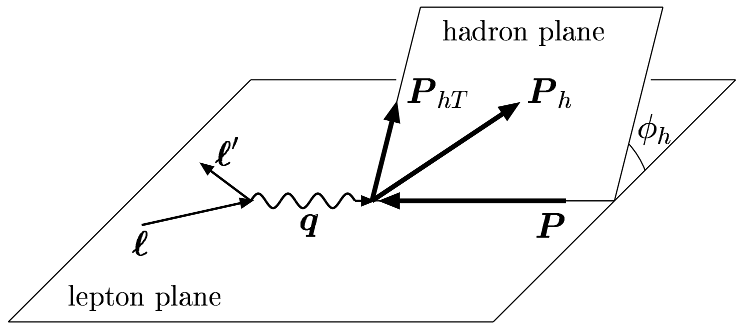
Collins and Sivers effects with different angular distributions

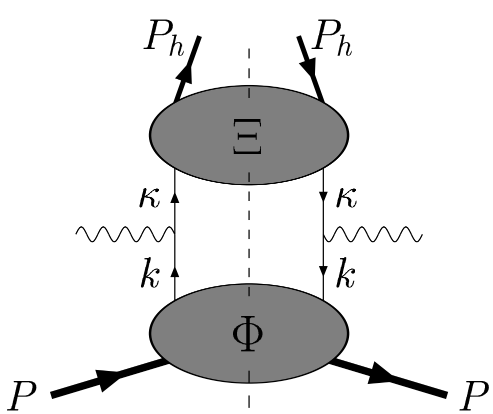
Another explored land: $p\,p^{\uparrow}\;\rightarrow\;h\,X$

Large SSA's, but theoretically complicated and unclear

Semi-inclusive DIS with a transversely polarized target

$e\,p^{\uparrow} \to e'\,h\,X$





$W^{\mu\nu} \sim \mathrm{Tr}\,[\Phi\,\gamma^{\mu}\,\Xi\gamma^{\nu}]$

Ξ fragmentation matrix

Two sources of single-spin transverse asymmetries:

- azimuthal asymmetry of unpolarized quarks inside the transversely polarized proton (Sivers effect) [f_1 couples to $f_{1T}^{\perp}$]
- spin asymmetry of transversely polarized quarks fragmenting into an unpolarized hadron (Collins effect) [h_1 couples to $H_1^{\perp}$]

  Collins fragmentation function:

$$\mathcal{N}_{h/q^\uparrow}(z,\boldsymbol{P}_{hT}) - \mathcal{N}_{h/q^\downarrow}(z,\boldsymbol{P}_{hT}) = \frac{(\hat{\boldsymbol{\kappa}}_T \times \boldsymbol{P}_{hT})\cdot \boldsymbol{S}_{qT}}{zM_h}\, H_1^{\perp}(z,\boldsymbol{P}_{hT}^2)$$

Transversely polarized pion leptoproduction cross section:

$$\begin{aligned} \mathrm{d}\sigma_{UT} \quad \sim \quad & A(y)\,\mathcal{I}\left[\frac{\boldsymbol{\kappa}_T\cdot\hat{\boldsymbol{P}}_{hT}}{M_h}\,h_1^a\,H_1^{\perp a}\right]\sin(\phi_h+\phi_S) \quad \text{Collins} \\ & +B(y)\,\mathcal{I}\left[\frac{\boldsymbol{k}_T\cdot\hat{\boldsymbol{P}}_{hT}}{M_h}\,f_{1T}^{\perp a}\,D_1^a\right]\sin(\phi_h-\phi_S) \quad \text{Sivers} \\ & +\sin(3\phi_h-\phi_S) \quad \text{term} \end{aligned}$$

Convolutions defined as:

$$\mathcal{I}[f\,D] \equiv \int \mathrm{d}^2\boldsymbol{k}_T \int \mathrm{d}^2\boldsymbol{\kappa}_T\,\delta^2(\boldsymbol{k}_T-\boldsymbol{P}_{hT}/z-\boldsymbol{\kappa}_T) f(x,\boldsymbol{k}_T^2)\,D(z,\boldsymbol{\kappa}_T^2)$$

Assuming Gaussian dependence on transverse momenta, $\mathcal{I}\,[f\;D] \propto f\;D$

Angular distributions disentangled by taking azimuthal moments, e.g.:

$$\langle\sin(\phi_h+\phi_S)\rangle \equiv \frac{\int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\;\sin(\phi_h+\phi_S)\,[\mathrm{d}\sigma(\phi_h,\phi_S)-\mathrm{d}\sigma(\phi_h,\phi_S+\pi)]}{\int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\,[\mathrm{d}\sigma(\phi_h,\phi_S)+\mathrm{d}\sigma(\phi_h,\phi_S+\pi)]}$$

Collins asymmetries

Transversity couples to Collins function:

$$A_T^{\pi^+}(p) \sim 4\, h_1^u\, H_1^{\perp\mathsf{fav}} + h_1^d\, H_1^{\perp\mathsf{unf}}$$

$$A_T^{\pi^-}(p) \sim 4\, h_1^u\, H_1^{\perp\mathsf{unf}} + h_1^d\, H_1^{\perp\mathsf{fav}}$$

Indications from data:

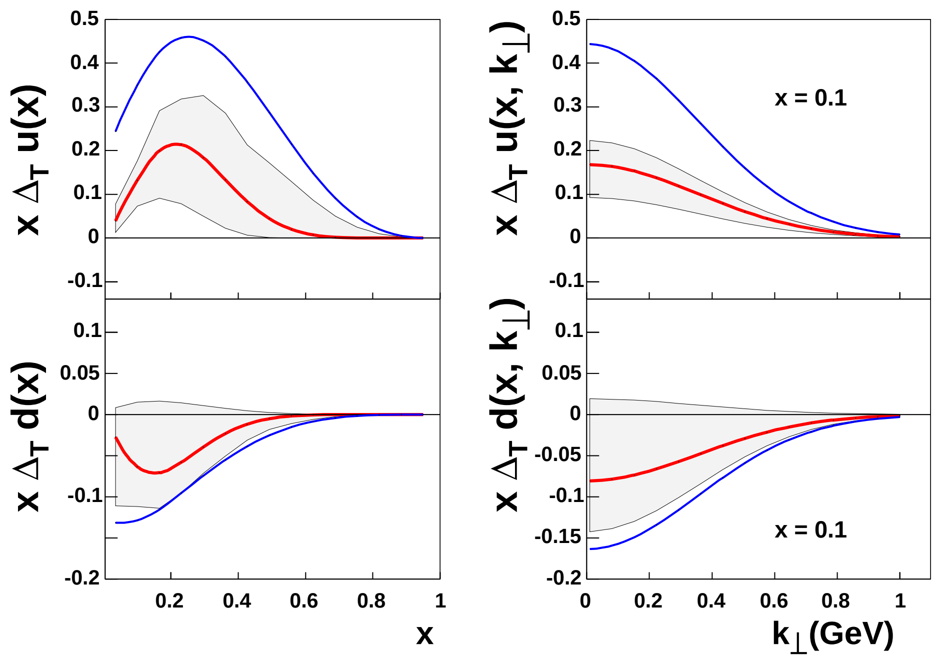
- h_1^u positive, h_1^d negative
- Large unfavored Collins functions (with $H_1^{\perp\mathsf{fav}}$ negative)

Independent information on $H_1^\perp$:

e^+e^- data at b-factories: direct measurement of $H_1^\perp$ [Belle]

Transversity from a fit to HERMES, COMPASS and BELLE data

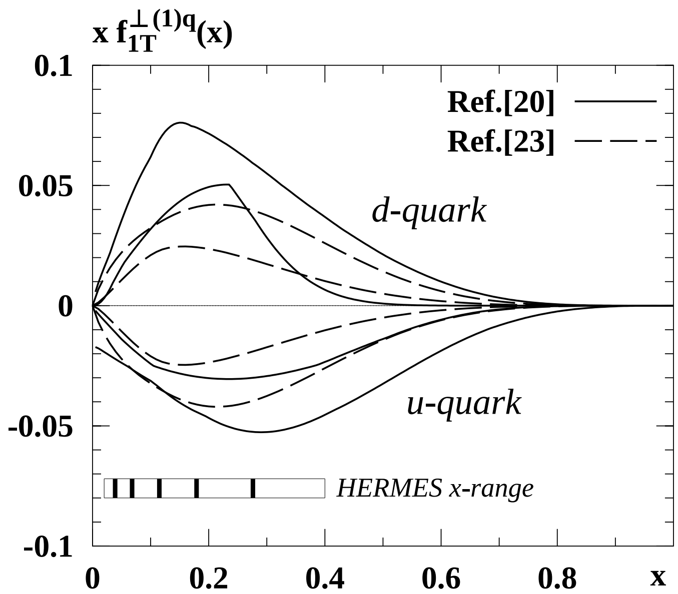
[Anselmino et al. 2007, see Prokudin's talk]

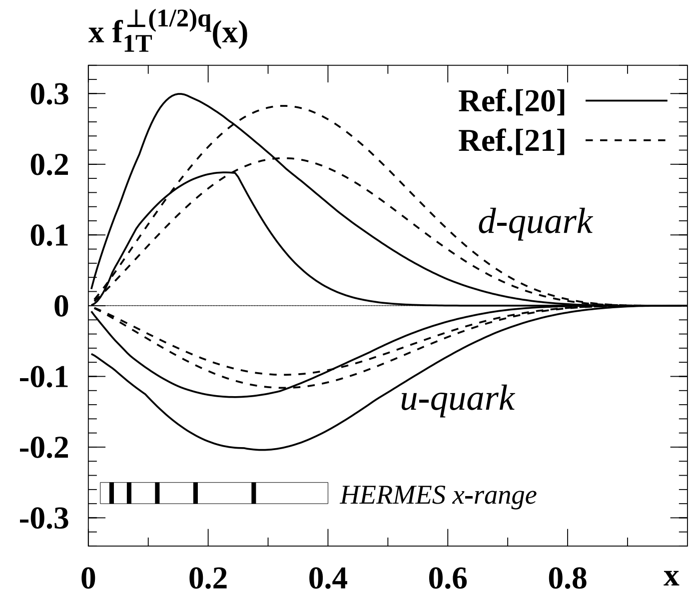


Transversity parametrized as $h_1(x) = \frac{1}{2}\, N\, x^{\alpha}(1-x)^{\beta}\, [f_1(x) + g_1(x)]$

Central values much below the Soffer bound

Sivers function from fits to HERMES and COMPASS data





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

$$f_{1T}^{\perp}(x,k_T^2) = N x^a (1-x)^b \, \frac{M M_0}{k_T^2 + M_0^2} \, f_1(x,k_T^2)$$

Gaussian k_T dependence with $\langle k_T^2 \rangle = 0.25$ GeV^2

$\boxed{\text{On the edge of the explored territory}}$

Neutron target: $e\, n^{\uparrow} \to e'\, \pi\, X$

Other occurrences of transversity in polarized SIDIS

Azimuthal asymmetries in unpolarized SIDIS

Transversely polarized neutron target [JLab exp. E03-004]

Kinematics: $x = 0.19 - 0.34$, $Q^2 = 1.7 - 2.7$ GeV^2

Collins asymmetries:

$$A_T^{\pi^+}(n) \sim 4\, h_1^d\, H_1^{\perp\mathsf{fav}} + h_1^u\, H_1^{\perp\mathsf{unf}}$$

$$A_T^{\pi^-}(n) \sim 4\, h_1^d\, H_1^{\perp\mathsf{unf}} + h_1^u\, H_1^{\perp\mathsf{fav}}$$

Combining p and n, π^+ and π^- one can disentangle h_1^u, h_1^d, $H_1^{\perp\mathsf{fav}}$ and $H_1^{\perp\mathsf{unf}}$

Other transverse spin observables in $e^{(\rightarrow)}p^{\uparrow(\rightarrow)} \rightarrow e'\pi X$

$\boldsymbol{P}_{hT}$ distributions:

- Unpolarized lepton beam: $\mathrm{d}\sigma_{UL} \sim h_{1L}^{\perp} \otimes H_1^{\perp} \, \sin 2\phi_h$

  Collins effect with longitudinally polarized target

- Longitudinally polarized lepton beam: $\mathrm{d}\sigma_{LT} \sim g_{1T} \otimes H_1^{\perp} \, \cos(\phi_h - \phi_S)$

  Longitudinally polarized quarks inside a transversely polarized hadron

Integrated cross-sections (at twist 3):

- Unpolarized lepton beam: $\mathrm{d}\sigma_{UT} \sim h_1(x)\, \widetilde{H}(z) \, \sin \phi_S$

  h_1 couples to the twist-3 fragmentation function $\widetilde{H}$

- Longitudinally polarized lepton beam: $\mathrm{d}\sigma_{LT} \sim h_1(x)\, \widetilde{E}(z) \, \sin \phi_S$

  h_1 couples to the twist-3 fragmentation function $\widetilde{E}$

The distributions g_{1T} and $h_{1L}^{\perp}$ are related to g_1 and h_1, respectively:

$$\frac{g_{1T}^{(1)}(x)}{x} = \int_x^1 \frac{\mathrm{d}y}{y}\, g_1(y) - \frac{m}{M}\int_x^1 \frac{\mathrm{d}y}{y^2}\, h_1(x) - \int_x^1 \frac{\mathrm{d}y}{y}\, \tilde{g}_T(x)$$

$$\frac{h_{1L}^{\perp(1)}(x)}{x^2} = -\int_x^1 \frac{\mathrm{d}y}{y}\, h_1(y) + \frac{m}{M}\int_x^1 \frac{\mathrm{d}y}{y^3}\, g_1(x) + \int_x^1 \frac{\mathrm{d}y}{y^2}\, \tilde{h}_L(x)$$

Neglecting quark mass terms and twist-3 contributions (related to quark-gluon correlators) we get Wandzura-Wilczek-type relations

Azimuthal asymmetries in unpolarized SIDIS

The Boer-Mulders function $h_1^{\perp}$ produces azimuthal asymmetries in unpolarized processes

Observed $\cos 2\phi_h$ asymmetries in πN Drell-Yan (NA10) and in SIDIS (EMC, ZEUS) at large Q^2

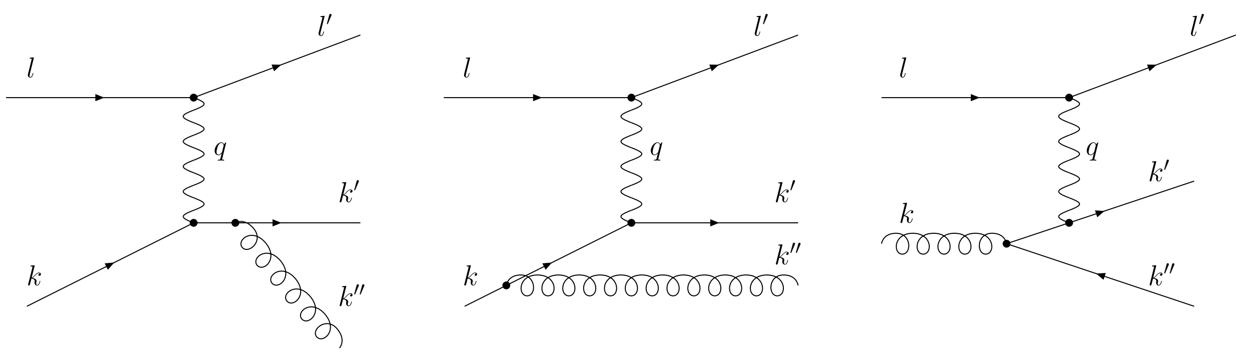
Sources of $\cos 2\phi_h$ asymmetries in SIDIS:

- Non-collinear kinematics (Cahn effect, twist 3)
- Boer-Mulders mechanism (leading twist)
- Perturbative gluon radiation

Cahn + Boer–Mulders effects:

$$\begin{aligned} \mathrm{d}\sigma|_{\cos 2\phi} \quad \sim \quad & \mathcal{I}\left[\frac{2(\boldsymbol{k}_T\cdot\hat{\boldsymbol{P}}_{hT})^2-\boldsymbol{k}_T^2}{Q^2}\,f_1\,D_1\right]\cos 2\phi_h \\ & + \mathcal{I}\left[\frac{2(\boldsymbol{k}_T\cdot\hat{\boldsymbol{P}}_{hT})(\kappa_T\cdot\hat{\boldsymbol{P}}_{hT})-\boldsymbol{k}_T\cdot\boldsymbol{\kappa}_T}{zMM_h}\,h_1^\perp\,H_1^\perp\right]\cos 2\phi_h \end{aligned}$$

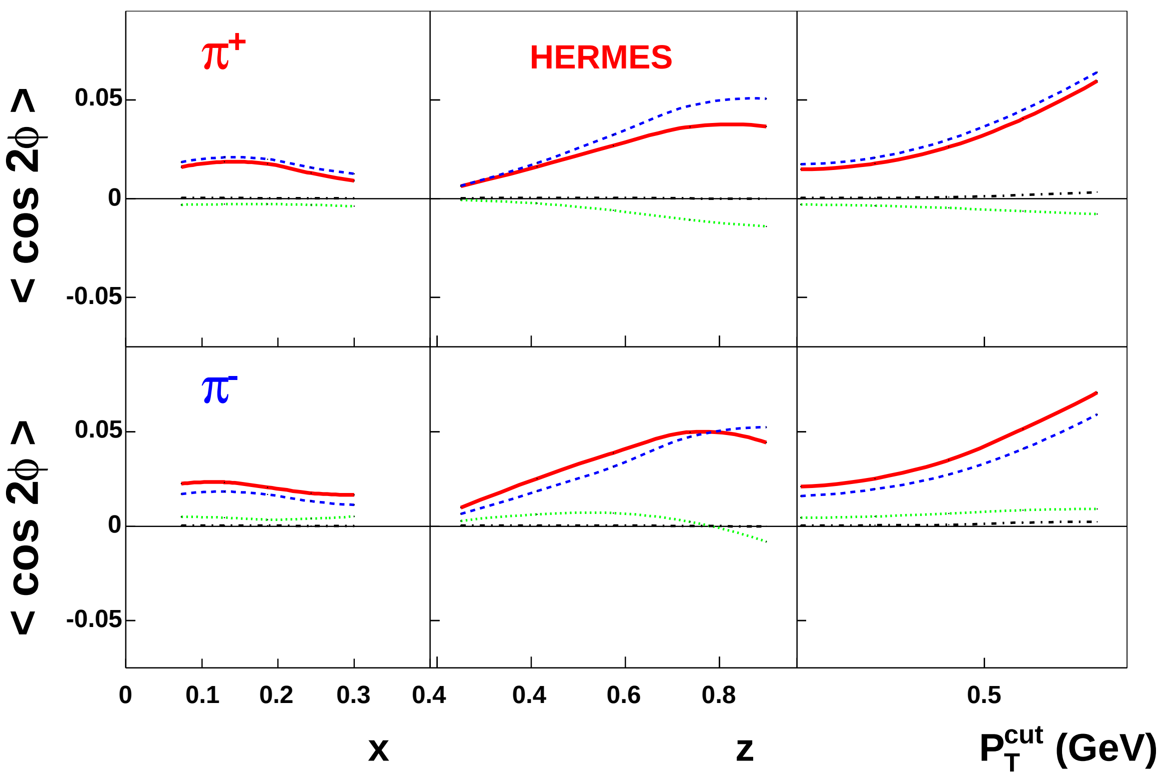
Perturbative contribution:



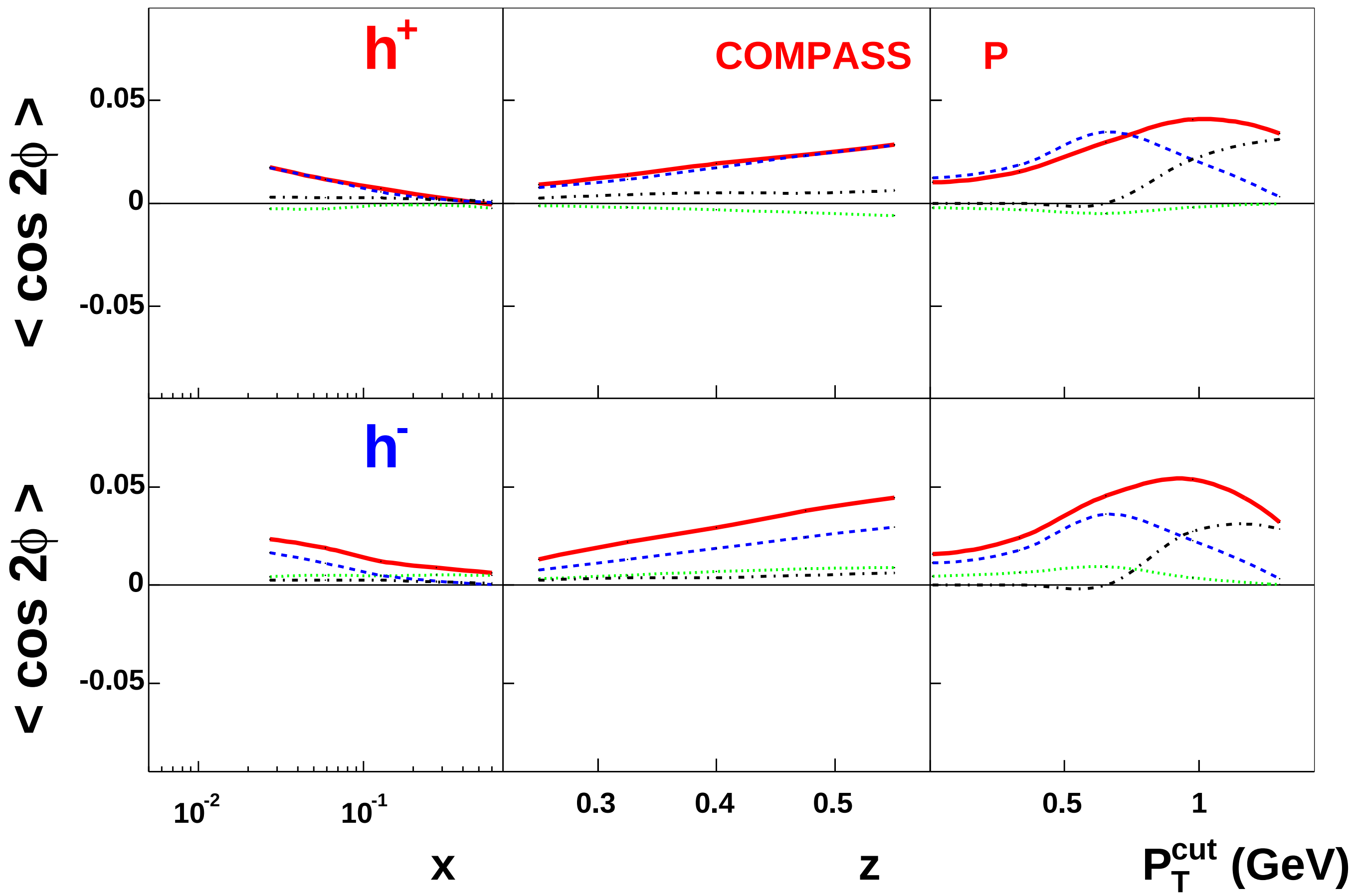
Predictions for $\cos 2\phi$ asymmetry in SIDIS

[VB, Ma, Prokudin 2007]

Assume $h_1^{\perp u} = f_{1T}^{\perp u}$, $h_1^{\perp d} = -f_{1T}^{\perp d}$, with $f_{1T}^{\perp}$ and $H_1^{\perp}$ from fits to data



Full = Cahn (HT) + Boer-Mulders + NLO QCD



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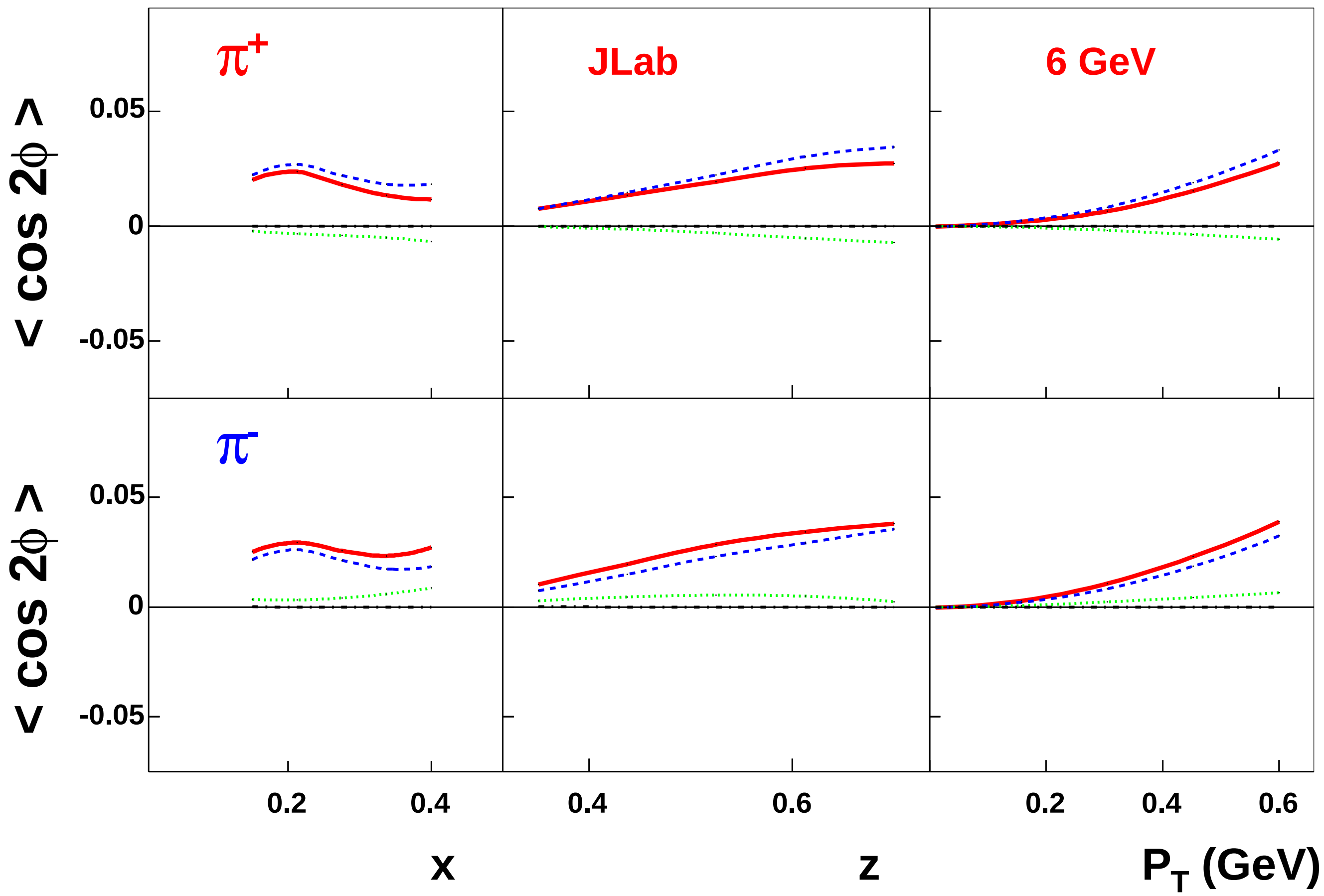
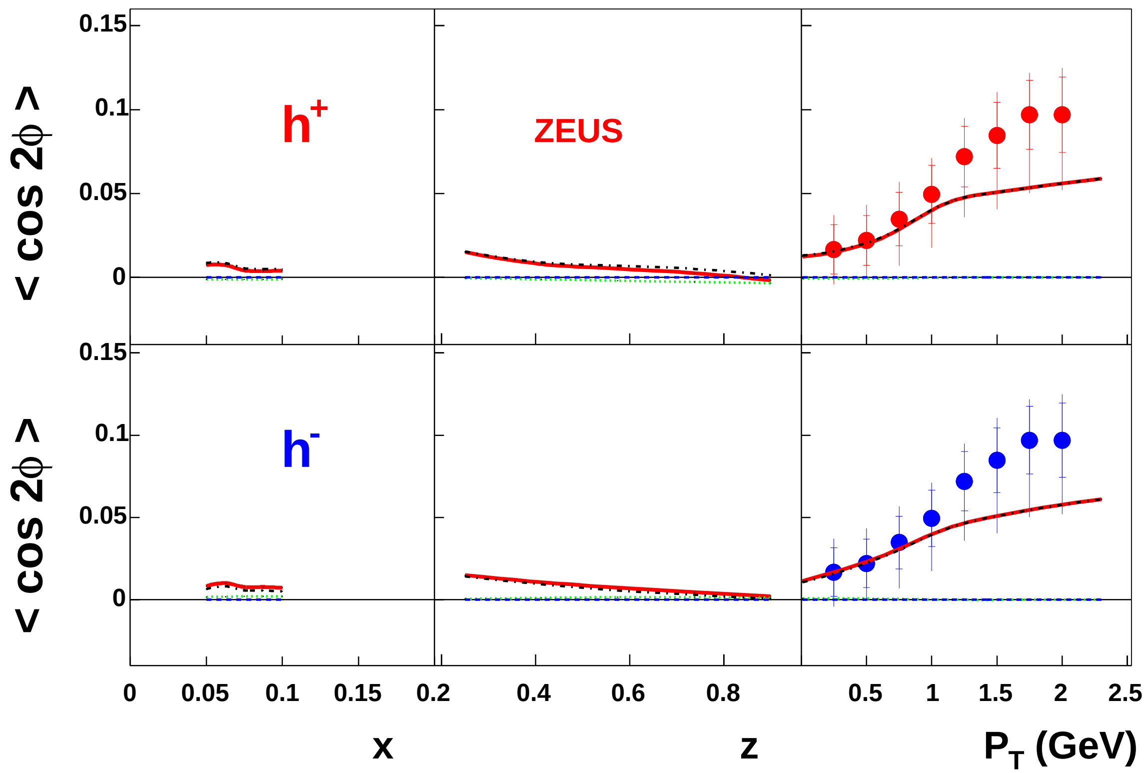


Full = Cahn (HT) + Boer-Mulders + NLO QCD

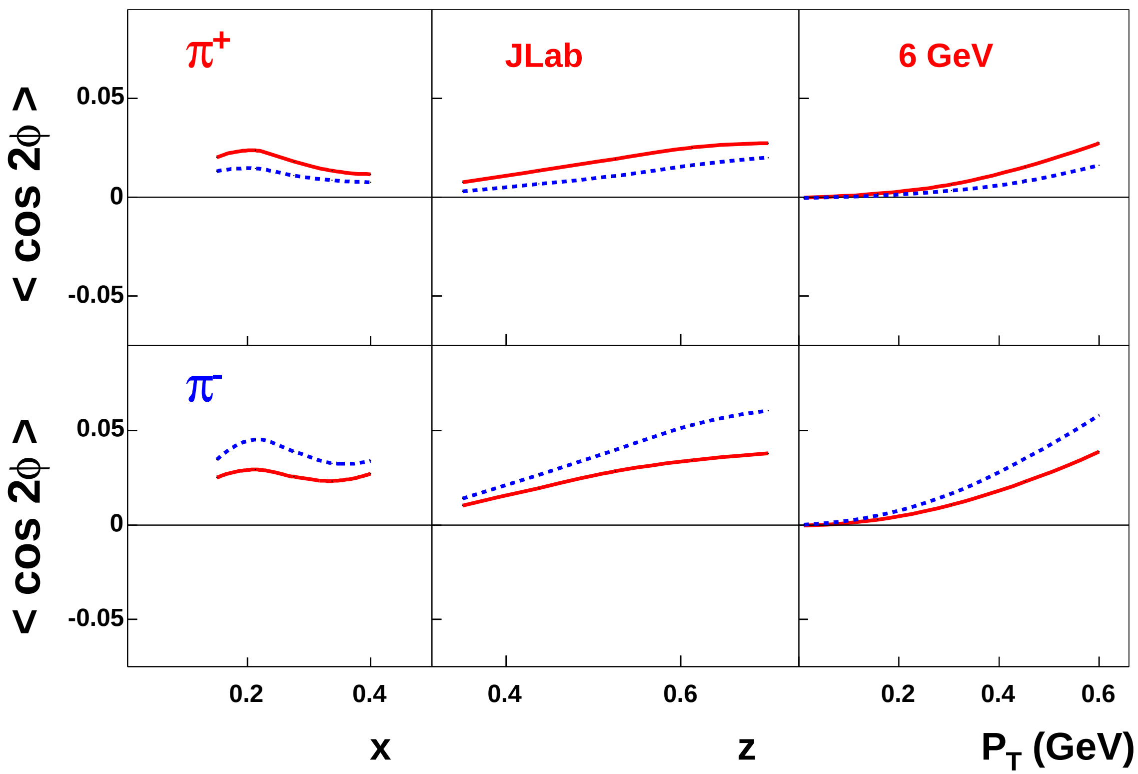
$\cos 2\phi$ asymmetry at large Q^2 (theory vs. ZEUS data)



Fully perturbative effect

Two different assumptions for the sign of $h_1^{\perp d}$:

$h_1^{\perp d} = -f_{1T}^{\perp d} < 0$ vs. $h_1^{\perp d} = f_{1T}^{\perp d} > 0$



Comparison of π^+ and π^- asymmetries can give information on the sign of $h_1^{\perp d}$

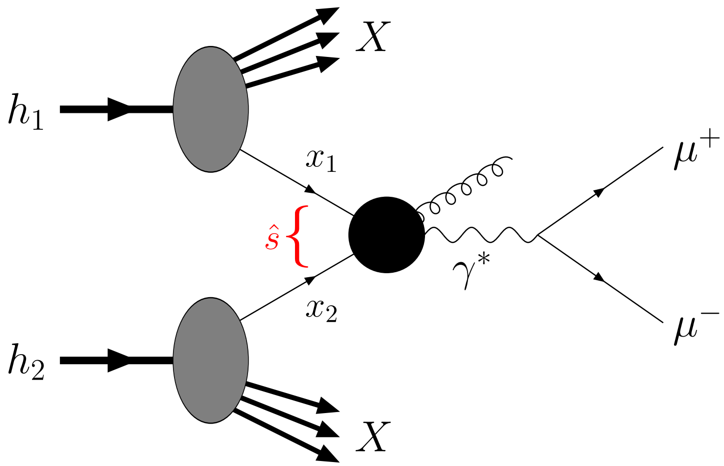
$$\boxed{\text{The unexplored territory}}$$

Transverse spin effects in Drell–Yan processes at moderate energies

$$\bar{p}^{\uparrow}p^{\uparrow}\,,\ p^{\uparrow}p^{\uparrow}\,,\ \bar{p}p^{\uparrow}\,,\ pp^{\uparrow}\,,\ \pi p^{\uparrow}\,,\ \bar{p}p\,,\ pp\,,\ \pi p$$

Drell-Yan dilepton production

$$h_1 \; + h_2 \; \rightarrow \; \mu^+ \; + \mu^- \; + X$$



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

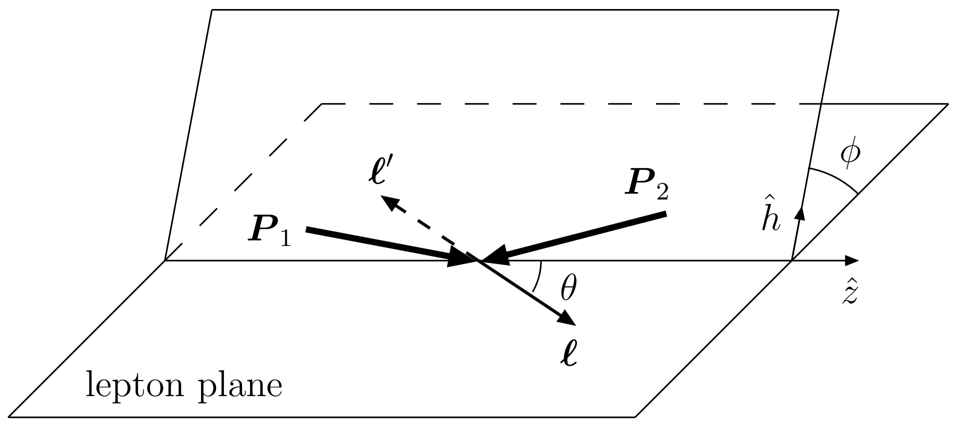
$\hat{s} = x_1 x_2 s \, , \quad x_1 x_2 = \tau/z$

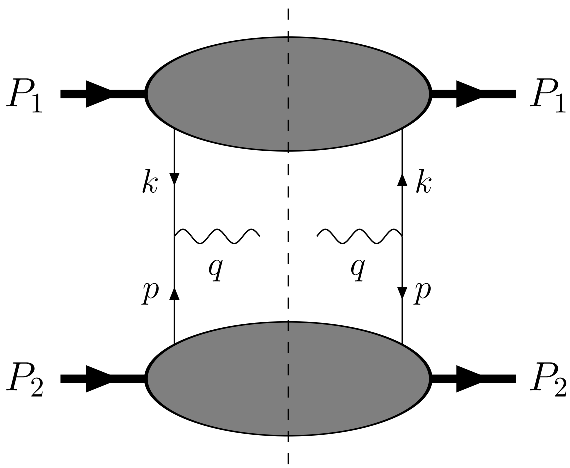
M^2 invariant mass of $\mu^+\mu^-$

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

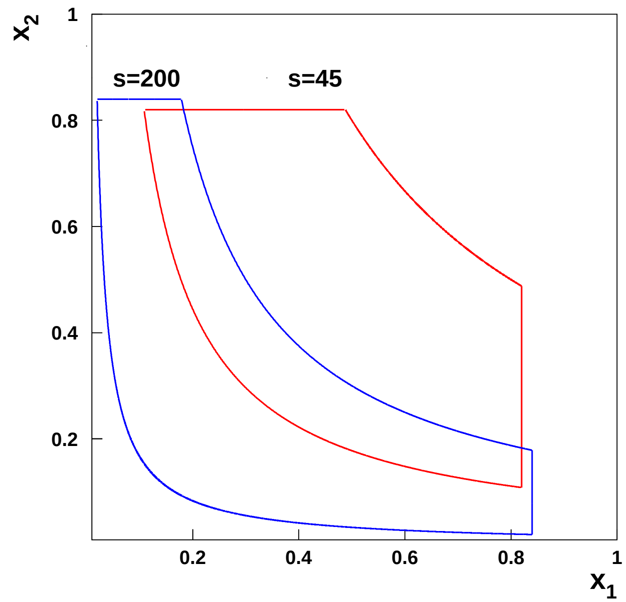
COMPASS (πp): π beam 50-100 GeV, $s = 100$-200 GeV^2

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

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

No polarization ($\bar{p}p$, pp, πp)

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

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

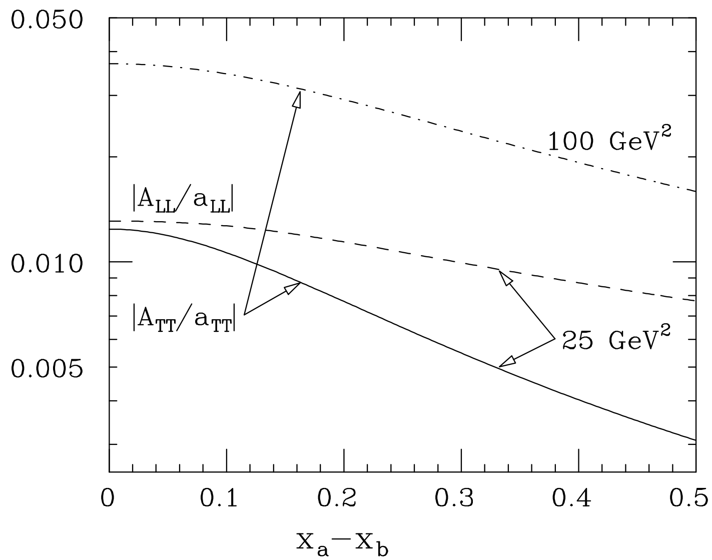
$h_1 = g_1$ at $Q_0^2 = 0.23$ GeV^2

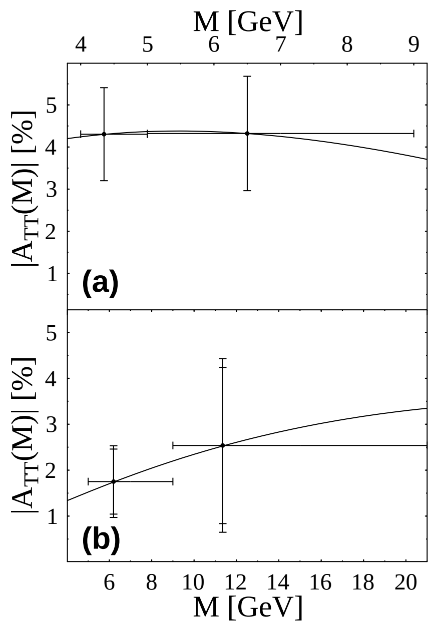
[VB, Calarco & Drago 1997]

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

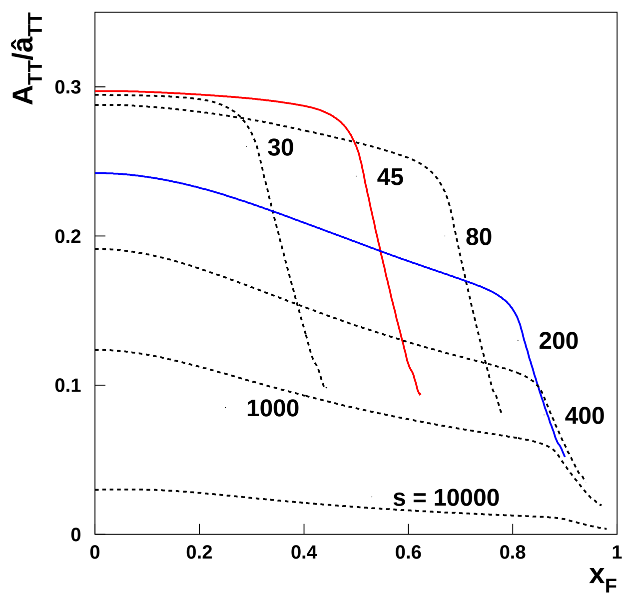
PAX: polarized $\bar{p}$ colliding on polarized p at GSI-HESR [PAX, hep-ex/0505054]

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

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

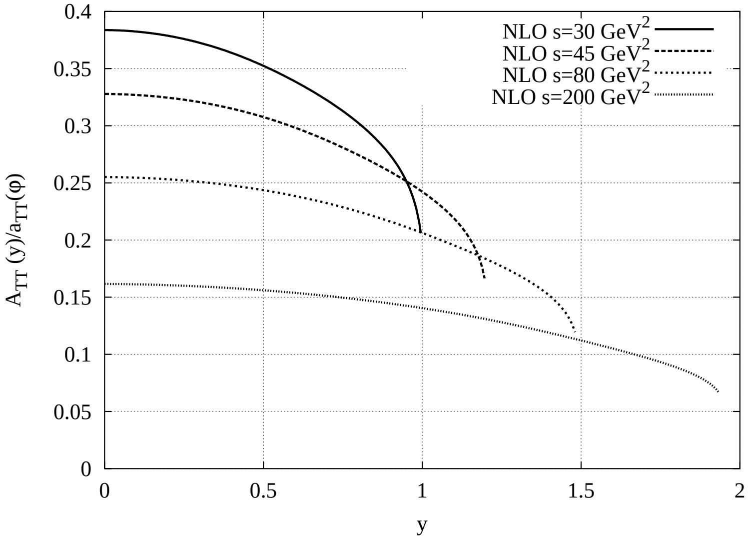
LO calculation ($M = 4$ GeV) $\Rightarrow$

[Anselmino, VB, Drago, Nikolaev 2004]

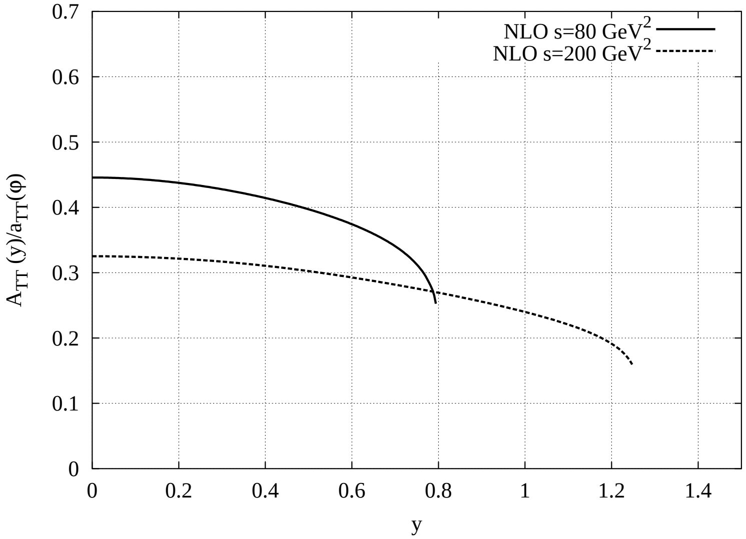


For $p^{\uparrow}p^{\uparrow}$ DY at J-PARC asymmetries are expected to be smaller, but still sizable (~ 0.15-0.2). Important information on signs of antiquark distributions

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



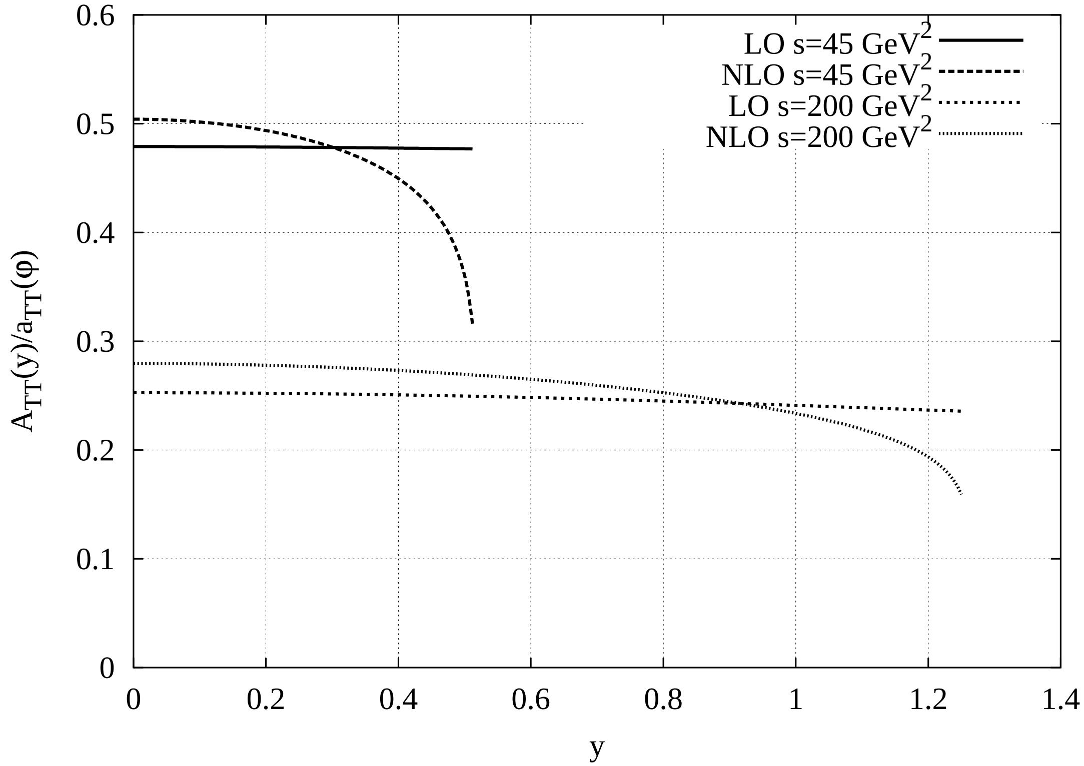
M integrated from 2 to 3 GeV



M integrated from 4 to 7 GeV

Soft-gluon resummation modifies the results by 10 % only [Shimizu et al. 2005]

Leading order vs. Next-to-leading order



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

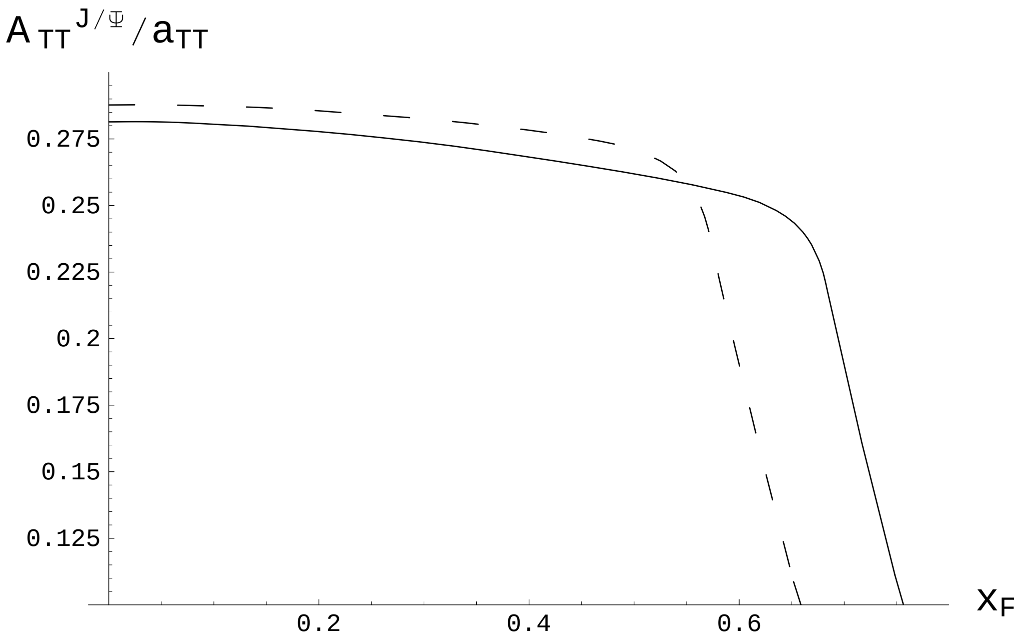
Double transverse DY asymmetries are large, but production rates fall down rapidly for $M > 3$ GeV

$\Rightarrow J/\psi$ 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 (~ 0.2 at $Q_T = 2$ GeV for $E_\pi = 194$ GeV)

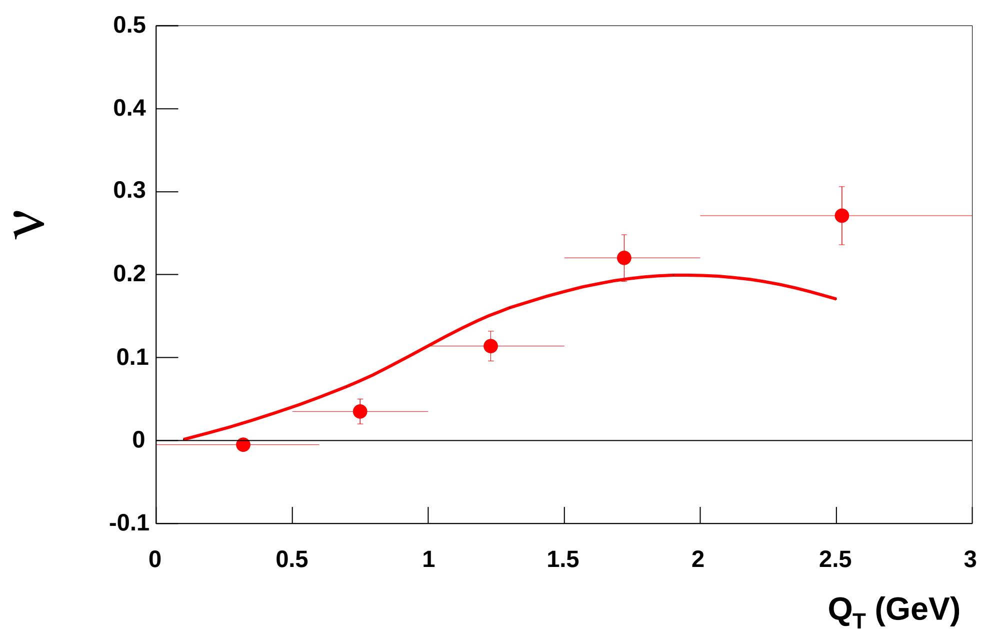
Possible explanations:

- Gluon radiation: partonic asymmetry $\hat{\nu} \sim Q_T^2/(M^2 + 3Q_T^2/2)$
  This contribution turns out to be small when pdf's are inserted
- Boer–Mulders mechanism (correlation between transverse spin and transverse momentum of quarks)

Boer-Mulders effect:

$$\nu \sim \frac{\mathcal{I}\left[\left(2\,\boldsymbol{k}_T\cdot\hat{\boldsymbol{P}}_{hT}\,\boldsymbol{p}_T\cdot\hat{\boldsymbol{P}}_{hT}-\boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)h_1^\perp\,\bar{h}_1^\perp\right]}{\mathcal{I}\left[f_1\,\bar{f}_1\right]}$$

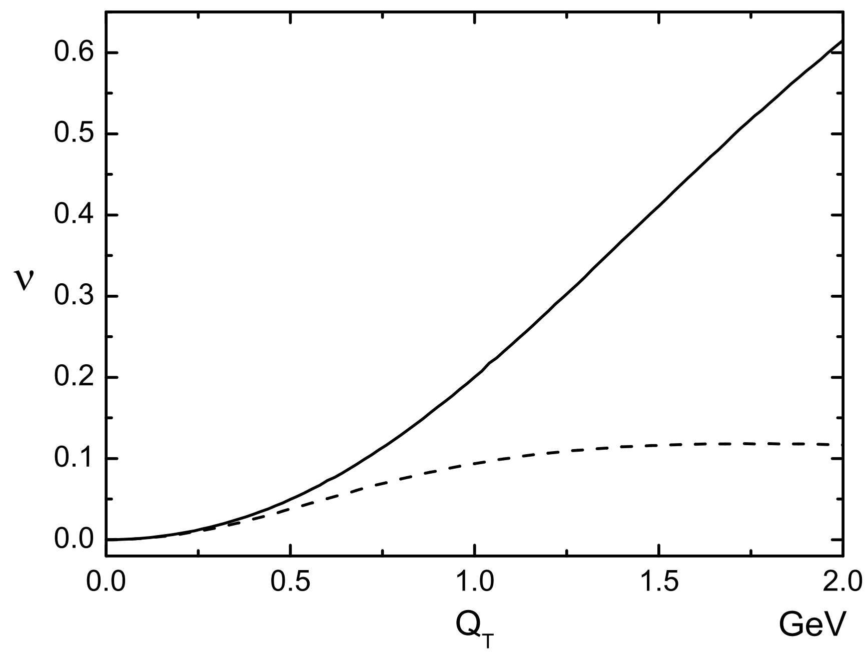
Assume $h_1^{\perp u} = f_{1T}^{\perp u}$, with $f_{1T}^{\perp}$ from fits to Sivers asymmetry data, and
$(\bar{h}_1^\perp/\bar{f}_1)_{\pi^-} = (h_1^\perp/f_1)_p$ for u [VB, Prokudin 2007]



Prediction for ν in $\bar{p}p$ Drell-Yan

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

[VB, Lu and Ma 2007]



Solid curve: expectation for $s = 45$ GeV^2 and $M^2 = 5$ GeV^2

The role of DY processes

- $\bar{p}^\uparrow p^\uparrow \;\Rightarrow$ valence h_1, $\quad p^\uparrow p^\uparrow \;\Rightarrow$ sea h_1
- $\bar{p}p \;\Rightarrow\; h_1^\perp$ (Also $\pi p \Rightarrow\; h_1^\perp$, but involves $h_1^{\perp\pi}$)
- $\bar{p}p^\uparrow, pp^\uparrow, \pi p^\uparrow \;\Rightarrow\; f_{1T}^\perp$ via $\sin(\phi - \phi_S)$
- $\bar{p}p^\uparrow \;\Rightarrow\; h_1^\perp, h_1$ via $\sin(\phi + \phi_S)$

DY processes explore a wider range of Q^2 compared to SIDIS

Missing theoretical ingredients for a global analysis

- Transverse motion of quarks and higher twists
  - Full understanding of their interplay
  - Systematic phenomenological study of higher twist effects at moderate energies
- Q^2 evolution of k_T-dependent distributions
  - Very little known

    QCD equations of motion relate k_T moments to twist-3 distributions, whose evolution is known in the large N_c limit [Henneman, Boer, Mulders 2002]

Conclusions

- Transverse single-spin asymmetries are firmly established
- We learned a lot about initial/final–state effects and correlations between transverse spin and transverse motion of quarks
- From the theoretical point of view, transverse spin phenomena are quite well understood, but some aspects (higher twists, QCD evolution, ...) require further study
- Perspectives and goals:
  - Complete theoretical study of processes (perturbative contributions, transverse spin effects, higher twists, ...)
  - SIDIS: increased statistics, extended kinematic ranges (in x and Q^2), more targets and observables
  - New processes: $p\bar{p}$ DY at GSI, pp DY at J-PARC, πp at COMPASS
  - Ultimately: a global analysis of SIDIS, DY, e^+e^-, ...