T-odd effects in hadronic collisions

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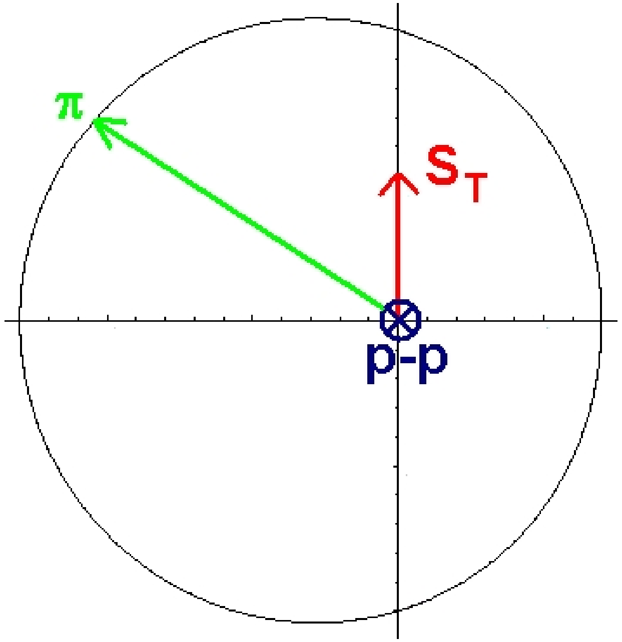
Outline

- Motivation from spin physics
- Sivers effect ($f_{1T}^{\perp}$)
  - Sivers effect asymmetries in hadronic collisions
  - What is (T-)odd about it
- BM effect ($h_1^{\perp}$)
  - Azimuthal asymmetries in unpolarized hadronic collisions
- Relation to GPDs
- Relation to twist-3 effects

Left-right asymmetries

Large single spin asymmetries in $p^\uparrow p \to \pi X$ have been observed at high $\sqrt{s}$

E704 Collab. ('91); STAR ('02); BRAHMS ('05); ...



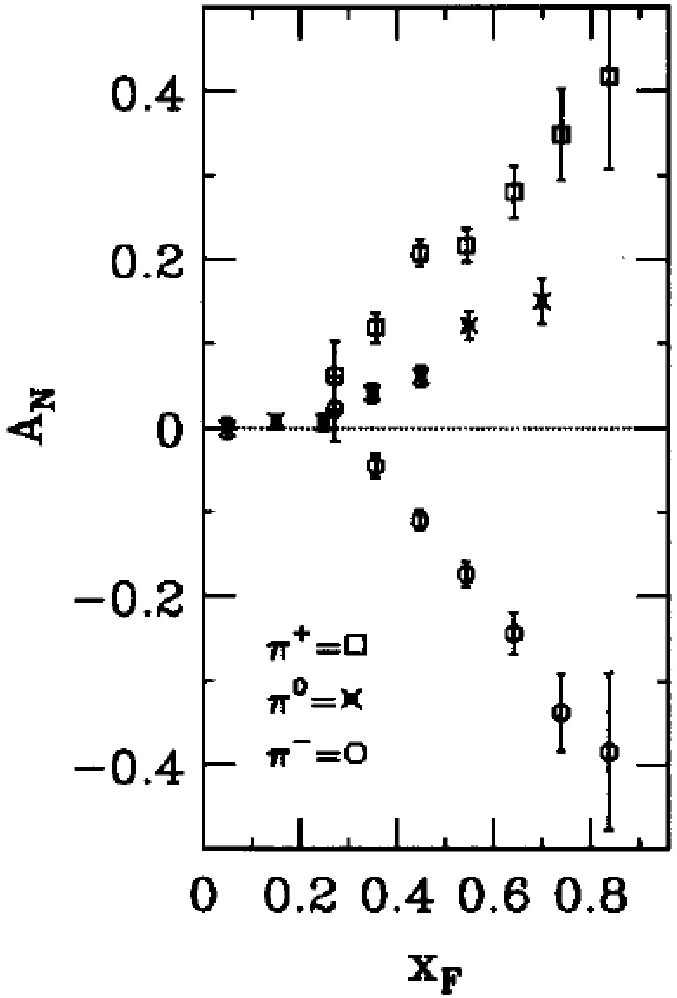
A left-right asymmetry

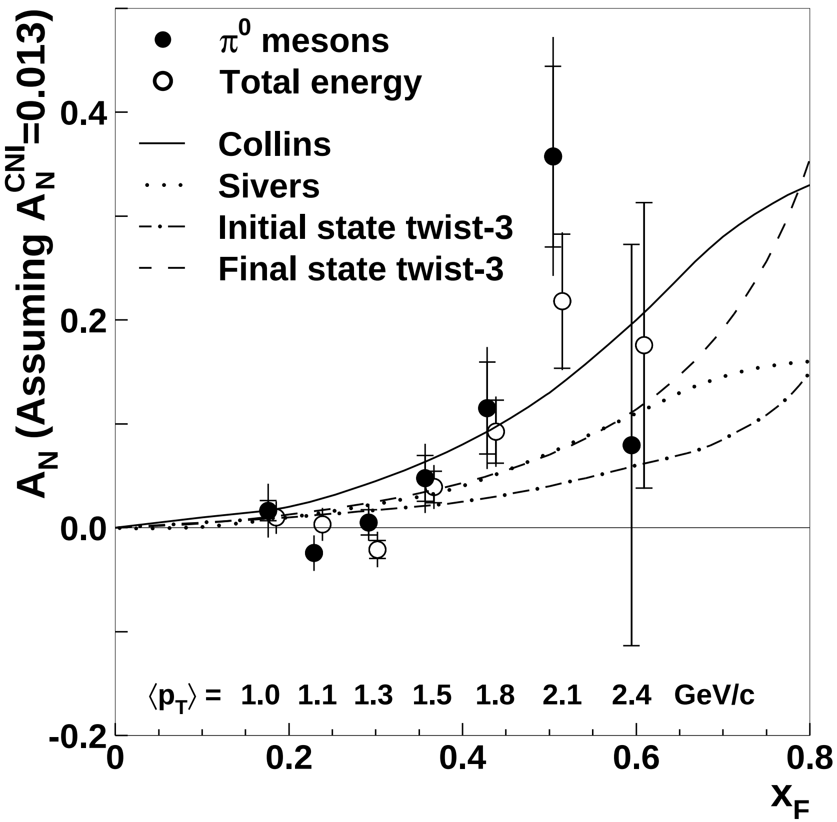
Pion distribution is asymmetric depending on transverse spin direction and on pion charge

The perturbatively generated SSA is very small (involves helicity flip)

Clearly a nonperturbative spin-orbit coupling, but how to describe such effects in a factorized, partonic approach in order to make predictions?

Single spin asymmetries in $p^{\uparrow}p \to \pi X$





E704 data, $\sqrt{s} \approx 20$ GeV

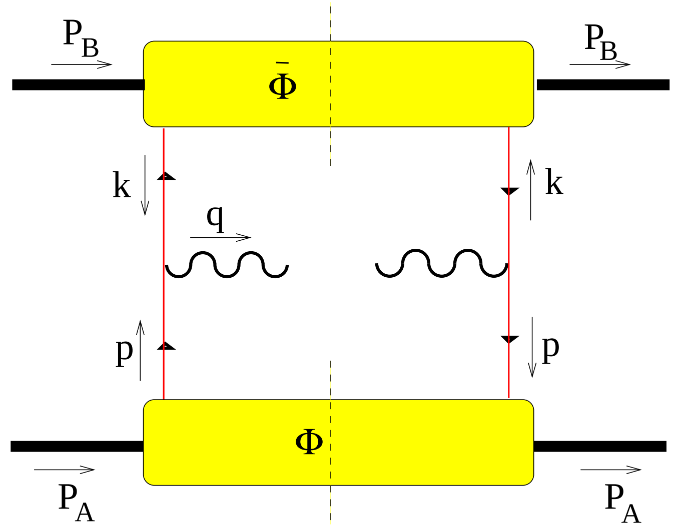
STAR data $\sqrt{s} = 200$ GeV

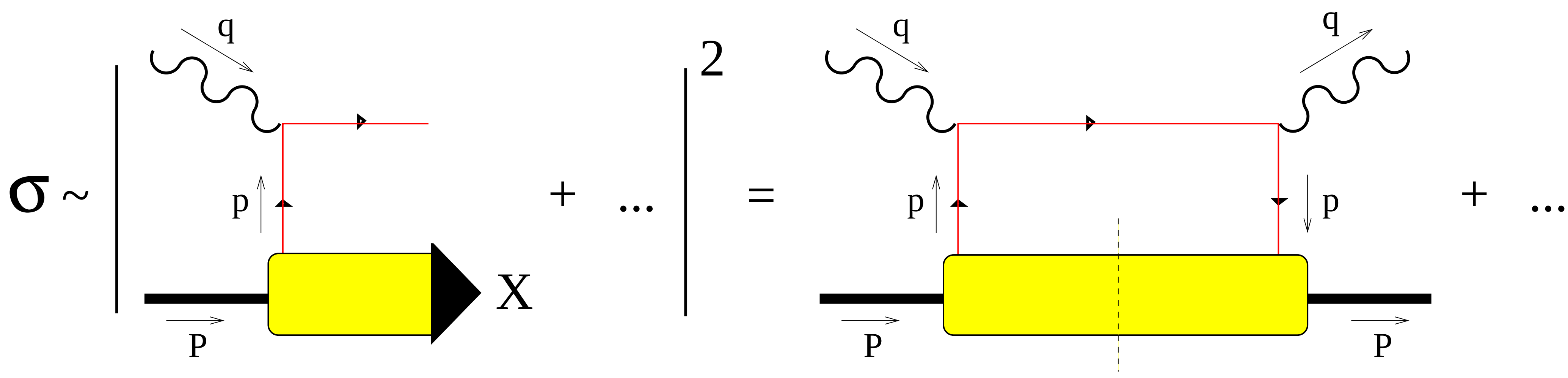
Partonic correlators

Theoretical description of the cross sections is based on factorization:

$$
\begin{aligned}
\sigma_{\rm DIS} &= H_{\rm DIS} \otimes \Phi \\
\sigma_{\rm DY} &= H_{\rm DY} \otimes \Phi \otimes \bar{\Phi} \\
\sigma_{\rm SIDIS} &= H_{\rm SIDIS} \otimes \Phi \otimes \Delta
\end{aligned}
$$

$$
\Phi \propto \langle P|\overline{\psi}(0)\psi(\xi)|P\rangle
$$





Transverse Momentum of Quarks

For spin-orbit couplings it is natural to consider transverse momentum (TM) of the quarks inside a hadron

Natural, but more than just an extension of $f_1^q(x) \to f_1^q(x, \boldsymbol{k}_T^2)$

$\boldsymbol{k}_T$-odd functions may arise, that vanish upon integration over all $\boldsymbol{k}_T$

And also new spin-dependent terms may arise

Ralston & Soper '79; Sivers '90; Mulders & Tangerman '95; D.B. & Mulders '98

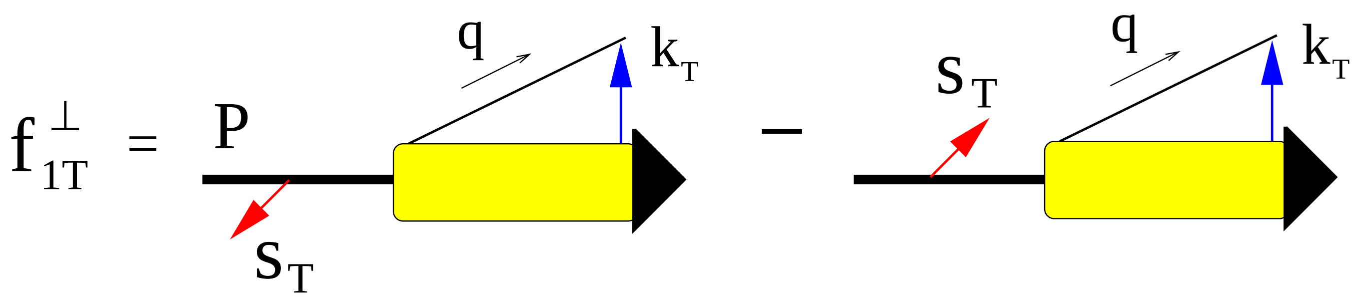
Include partonic transverse momentum $\Phi(x) \to \Phi(x, \boldsymbol{k}_T)$: TMD factorization

TMD = transverse momentum dependent parton distribution function

Can be probed in for instance semi-inclusive DIS or Drell-Yan (DY)

Sivers effect

Proposal of a $\boldsymbol{k}_T$ *and* $\boldsymbol{S}_T$ dependent distribution function by Sivers ('90)



Captures nonperturbative spin-orbit coupling effects inside a polarized proton

$$\Phi(x, \boldsymbol{k}_T) = \frac{1}{2} f_1(x, \boldsymbol{k}_T^2)\, \not{P} + \frac{\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)}{2M} f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)\, \not{P} + \ldots$$

Proposed to explain data on $p^{\uparrow} + p \to \pi^0 + X$ at $\sqrt{s} \approx 7$ GeV (Antille *et al.* '80)

TMD factorization of $p + p \to \pi + X$ not established (power suppressed asymmetry), but it works phenomenologically

Anselmino *et al.*, since '95

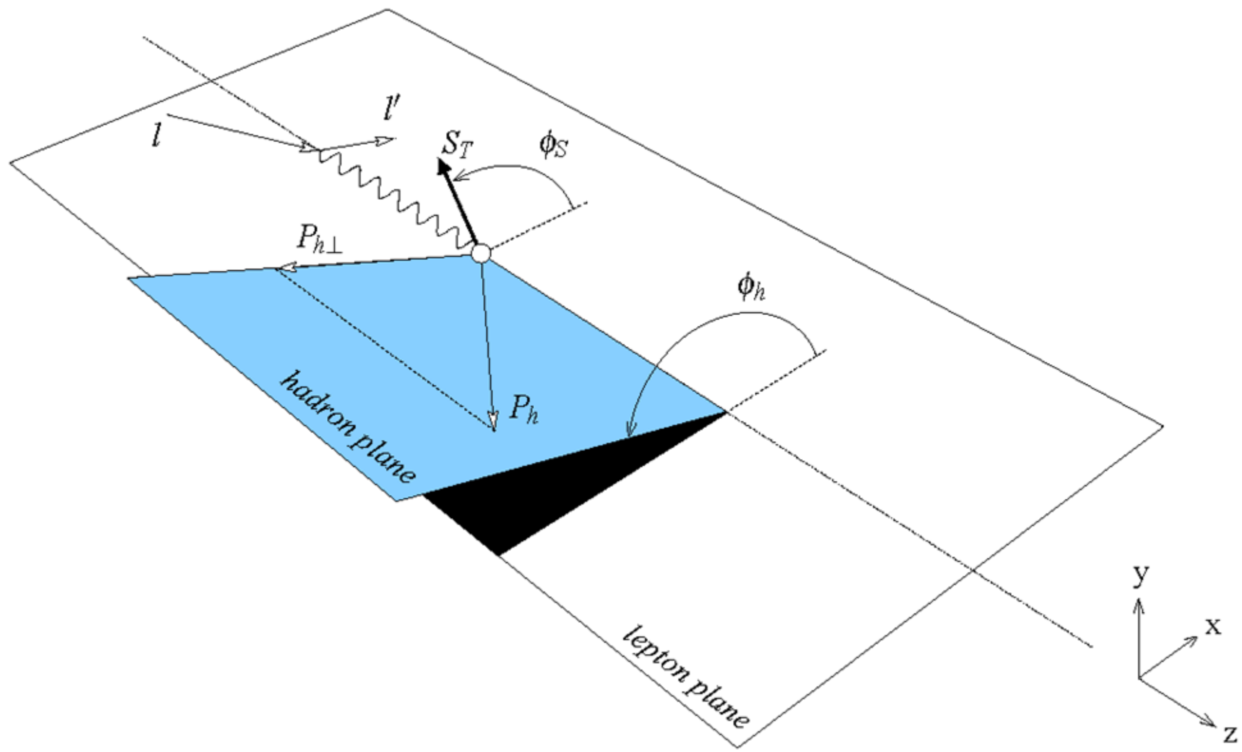
Sivers effect in semi-inclusive DIS

Sivers effect leads to an unsuppressed $\sin(\phi_h - \phi_S)$ asymmetry in $e\,p^\uparrow \to e'\,h\,X \propto f_{1T}^\perp D_1$

D.B. & Mulders '98

SIDIS

$e\,p \to e'\,h\,X$



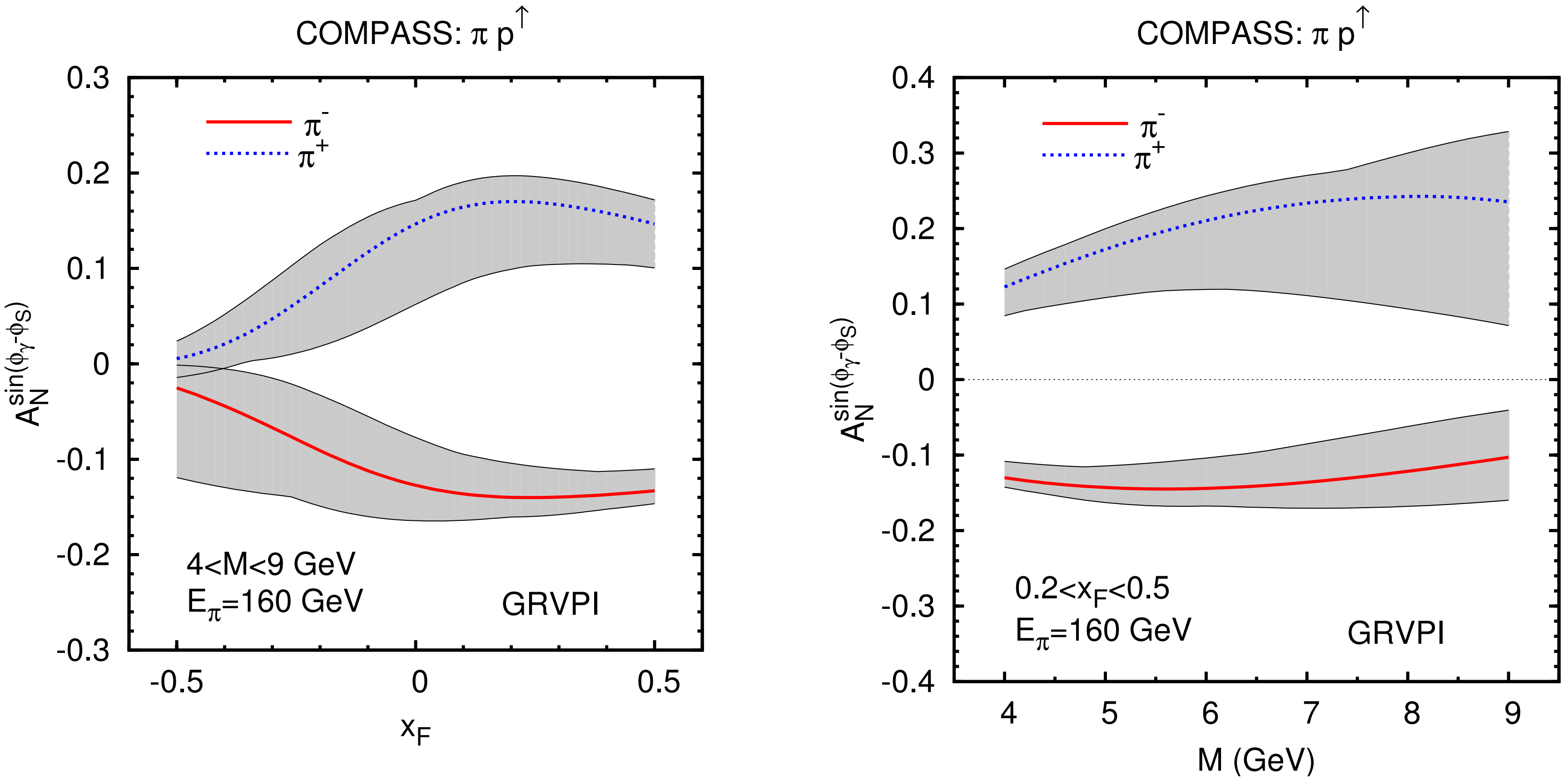
Such an asymmetry has been clearly observed by the HERMES Collaboration

TMD (or Collins-Soper) factorization established [later more]

Sivers effect in Drell-Yan

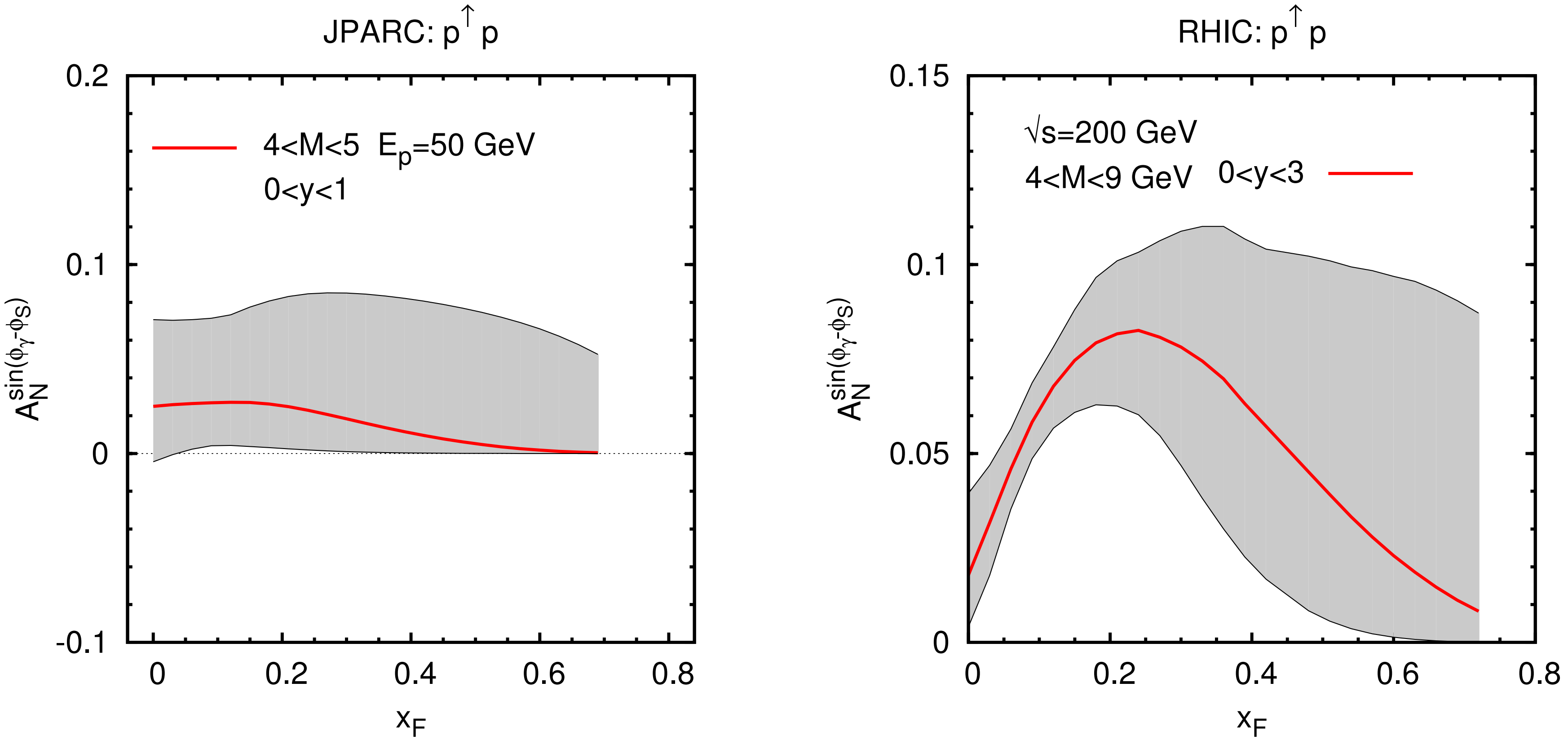
Sivers effect also leads to a $\sin(\phi - \phi_S)$ asymmetry in Drell-Yan $\propto f_{1T}^{\perp} \bar{f}_1$

Some predictions based on fit to SIDIS data:



Anselmino *et al.* '09

Sivers effect in Drell-Yan



Anselmino *et al.* '09

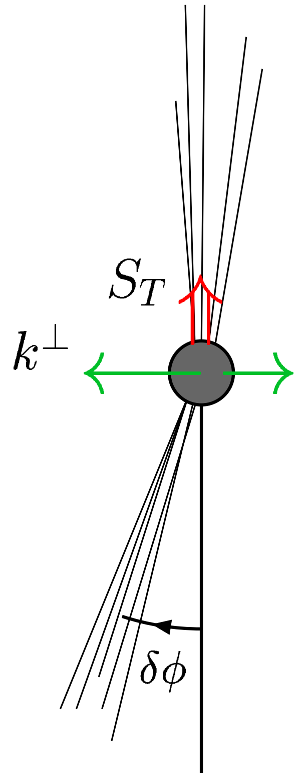
These $p^{\uparrow}p$ DY data are kinematically largely complementary to SIDIS data

Sivers effect in dijet production

Asymmetric jet or hadron correlations in $p^{\uparrow}\, p \to h_1\, h_2\, X$

D.B. & Vogelsang '04

Bacchetta *et al.* '05



Sivers effect $\Rightarrow \sin \delta\phi$ asymmetry

$\delta\phi =$ dijet imbalance angle

RHIC data consistent with zero at the few percent level

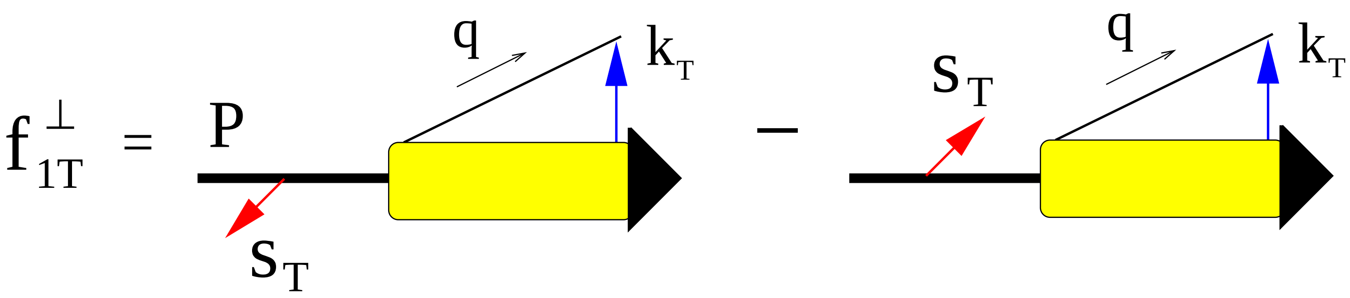
STAR Collaboration, Abelev *et al.* '07

Theoretically this Sivers asymmetry is not as straightforward as in SIDIS or DY

Potential problems with factorization

Collins & Qiu '07, Collins '07

T-odd effects



The Sivers function is a $\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)$ correlation, which is T-odd

since under time reversal transformation: $\boldsymbol{P} \to -\boldsymbol{P}$ and $\boldsymbol{S} \to -\boldsymbol{S}$

Sivers function is often called "naive" T-odd, as time reversal also interchanges $i \leftrightarrow f$

$$e\,p \to e'\,h\,X \quad \stackrel{T}{\leftrightarrow} \quad e'\,h\,X \to e\,p$$

which cannot be compared in practice, but theoretically also difficult because:

multiparticle out-states are nontrivially related to multiparticle in-states

A T-odd correlation as part of a process does not need to imply time reversal violation

De Rújula, Kaplan & De Rafael '71; Hagiwara, Hikasa, Kai '83

T-odd effects and factorization

But factorization allows one to go a step further:

$$T\sigma_{\rm SIDIS} = T(H \otimes \Phi \otimes \Delta) = H \otimes T(\Phi \otimes \Delta)$$

T stands for the actual time reversal operation

One could select the T-invariant part of Δ and conclude $f_{1T}^{\perp}$ *is* time reversal violating
Collins '93

Based on gauge variant operator definition:

$$P\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)\, f_{1T}^{\perp}(x, \boldsymbol{k}_T^2) \propto \text{F.T.}\, \langle P, S_T | \overline{\psi}(0)\, \gamma^+\, \psi(\xi) | P, S_T \rangle \big|_{\xi=(\xi^-, 0^+, \boldsymbol{\xi}_T)}$$

Thanks to a model calculation by Brodsky, Hwang & Schmidt '02 taking into account final state interactions (FSI), Collins realized this conclusion is invalid

One has to consider the proper gauge invariant definition of $\Phi(x, \boldsymbol{k}_T)$

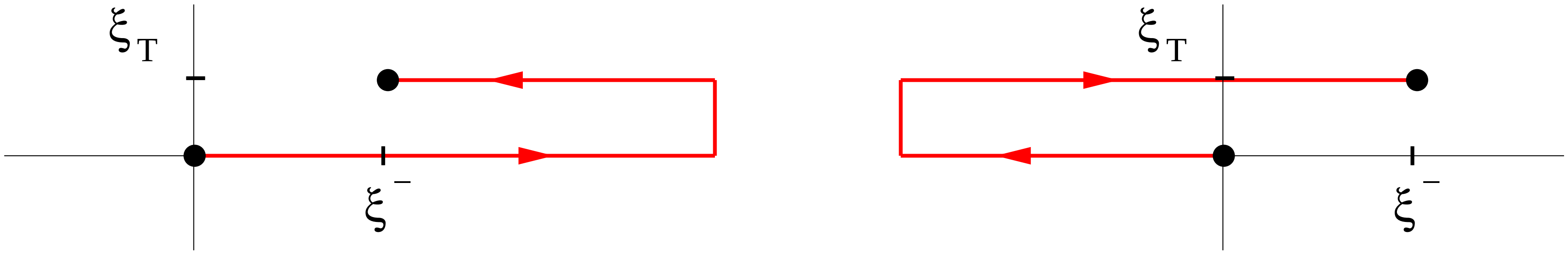
Link structure of TMDs

$\Phi(x, \boldsymbol{k}_T)$ is a matrix element of operators that are nonlocal *off* the lightcone

$$\Phi(x, \boldsymbol{k}_T) = \text{F.T.}\, \langle P|\, \overline{\psi}(0)\, \mathcal{L}[0,\xi]\, \psi(\xi)\ |P\rangle\big|_{\xi=(\xi^-,0^+,\boldsymbol{\xi}_T)}$$

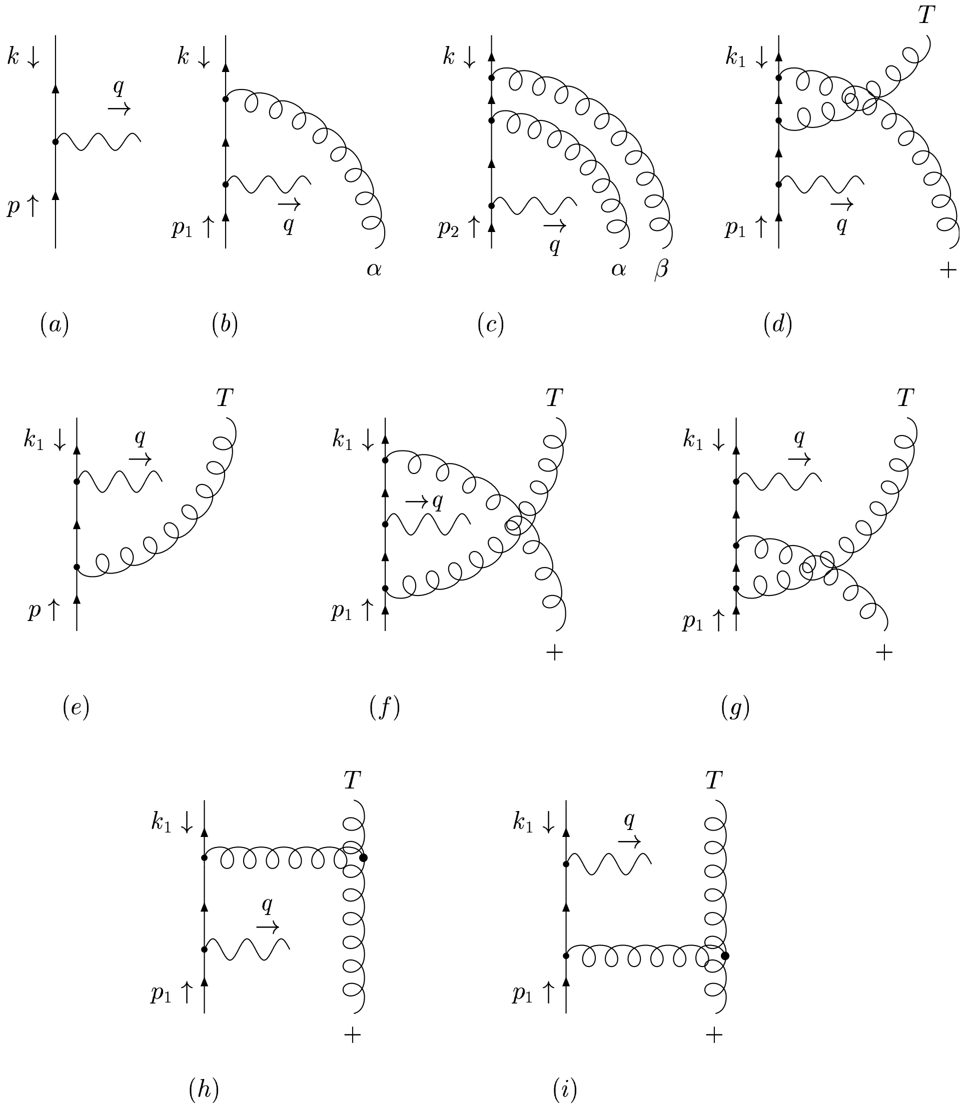
$$\mathcal{L}[0,\xi] = \mathcal{P}\exp\left(-ig\int_{\mathcal{C}[0,\xi]} ds_\mu\, A^\mu(s)\right)$$

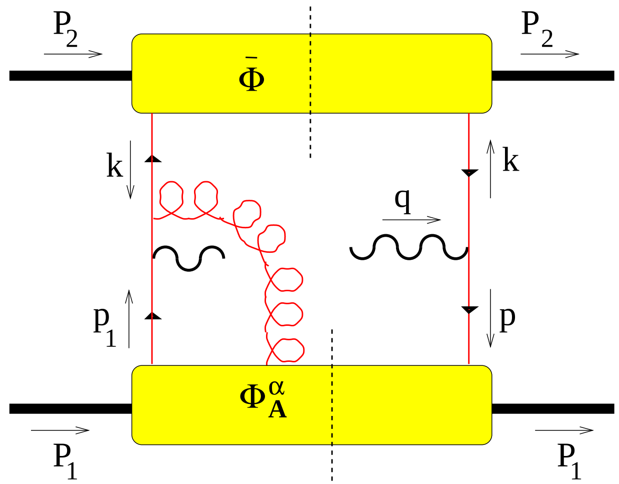
Proper gauge invariant definition of TMDs in SIDIS contains a future pointing Wilson line (FSI), whereas in Drell-Yan (DY) it is past pointing (ISI)



$$P\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)\, f_{1T}^{\perp[\mathcal{C}]}(x, \boldsymbol{k}_T^2) \propto \text{F.T.}\, \langle P, S_T|\overline{\psi}(0)\, \mathcal{L}[0,\xi]\, \gamma^+\, \psi(\xi)|P, S_T\rangle\big|_{\xi=(\xi^-,0^+,\boldsymbol{\xi}_T)}$$

Obtaining the link structure





path-ordered exponentials in off-lightcone non-local operators

D.B. & Mulders '00

Belitsky, Ji & Yuan '03

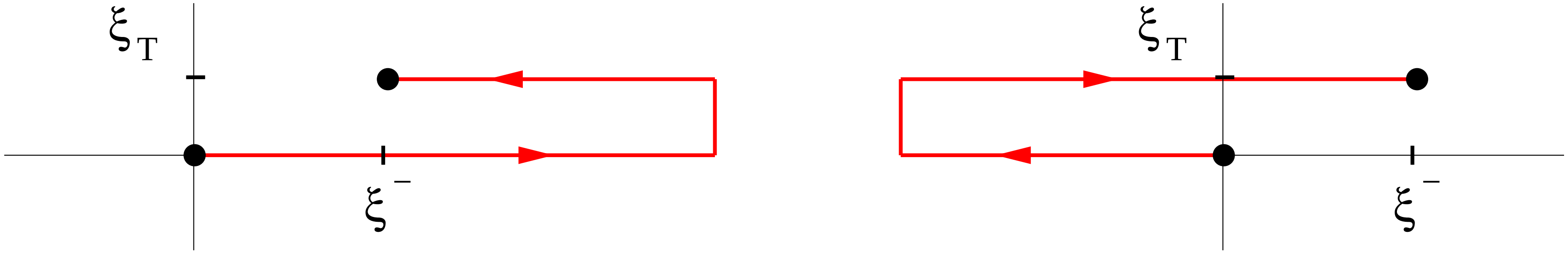
DY: ISI

SIDIS: FSI

Link structure of TMDs

Time reversal invariance relates $\Phi^{[+]}(x, p_T)$ of SIDIS to $\Phi^{[-]}(x, p_T)$ of Drell-Yan

Collins '02



Time reversal invariance does not yield a constraint on $\Phi^{[\pm]}$, but a relation

$$f_{1T}^{\perp[+]} = -f_{1T}^{\perp[-]}$$

Ignoring the link dependence yields $f_{1T}^{\perp} = 0$ because of time reversal invariance

$f_{1T}^{\perp[\pm]}$ could be called naive T-odd (since not exchanging ISI and FSI)

$\Phi(x, \boldsymbol{k}_T)$ contains parts that depend on H, universality is lost for those parts

But predictability is not lost!

Process dependence of TMDs

There is a *calculable* process dependence, which yields the relation (Collins '02):

$$(f_{1T}^{\perp})_{\mathrm{SIDIS}} \quad = \quad -(f_{1T}^{\perp})_{\mathrm{DY}} \qquad \text{to be tested}$$

The color flow of a process is crucial (usually not the case in high energy scattering!)

The more hadrons are observed, the more complicated the end result (ISI *and* FSI)

Bomhof, Mulders & Pijlman '04

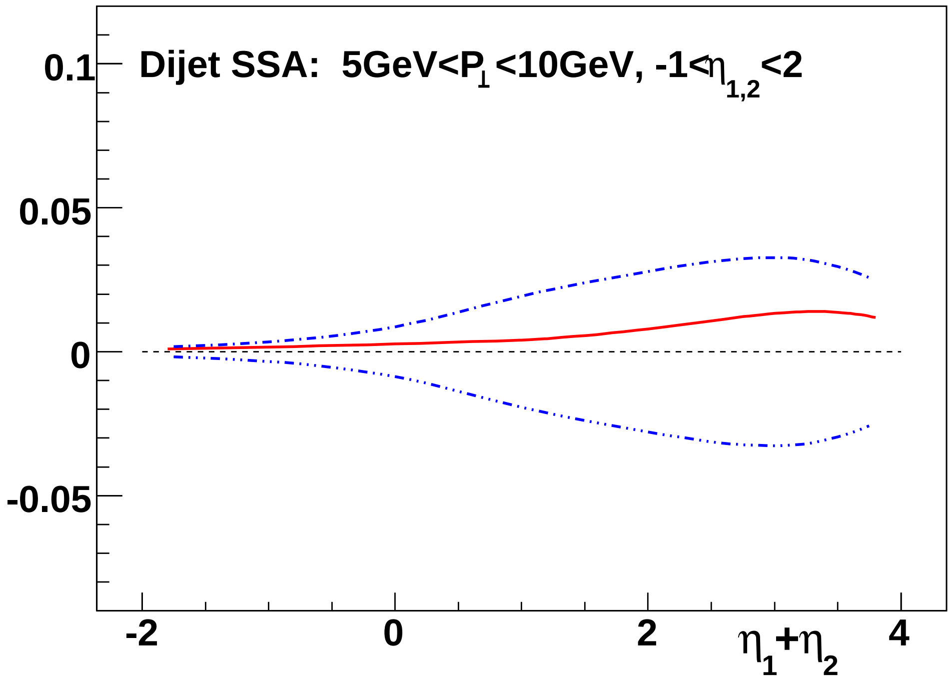
E.g. for asymmetric jet correlations:

$p^{\uparrow}\, p \longrightarrow \text{jet jet}\, X \ (\propto f_{1T}^{\perp})$

Bomhof *et al.* '07

Factorization debated for this process

Not simply $\Phi \otimes \bar{\Phi} \otimes H \otimes \Delta \otimes \Delta$



Collins-Soper factorization

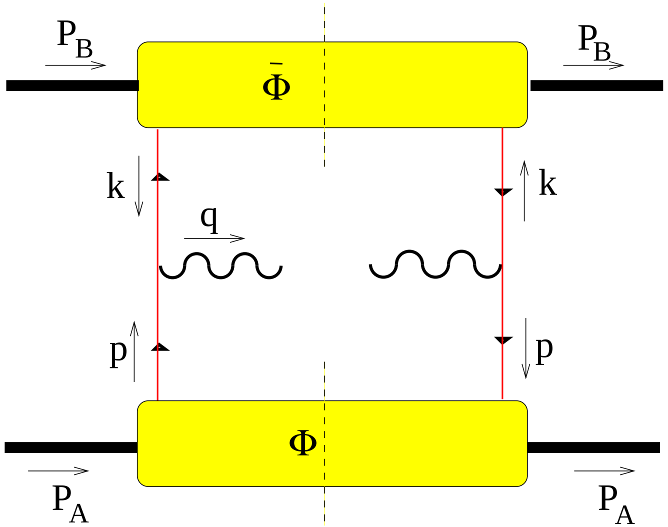
Collins-Soper factorization in DY:

$$\Phi \otimes \bar{\Phi} \otimes H \otimes U$$

U is called the soft factor, a correlator of Wilson lines

Collins & Soper '81; Ji, Ma & Yuan '04 & '05

At tree level ($U(l_T^2) \propto \delta(l_T^2)$) this corresponds to the often used description:

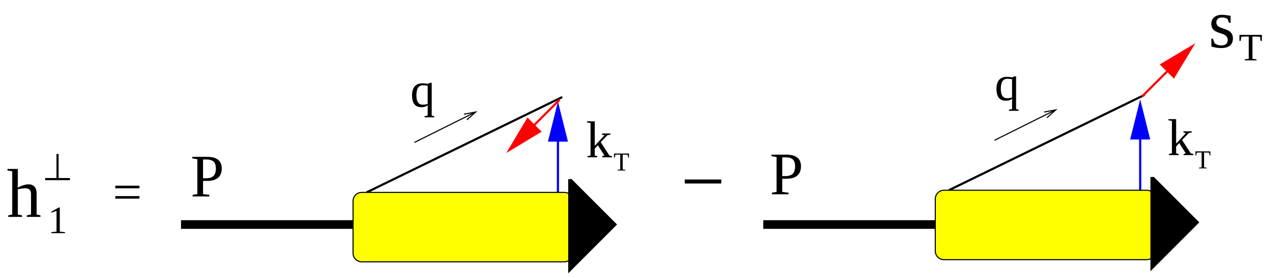


Extension to $p\,p \to h\,h'\,X$ not clear

Transverse quark polarization

Besides $f_{1T}^{\perp}$ there is another (naive) T-odd distribution function:

$$\Phi(x, \boldsymbol{k}_T) = \frac{1}{2} f_1(x, \boldsymbol{k}_T^2)\, \not{P} + \frac{\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)}{2M} f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)\, \not{P} + i h_1^{\perp}(x, \boldsymbol{k}_T^2)\, \frac{\not{P}\, \not{\boldsymbol{k}}_T}{M} + \ldots$$



D.B. & Mulders '98

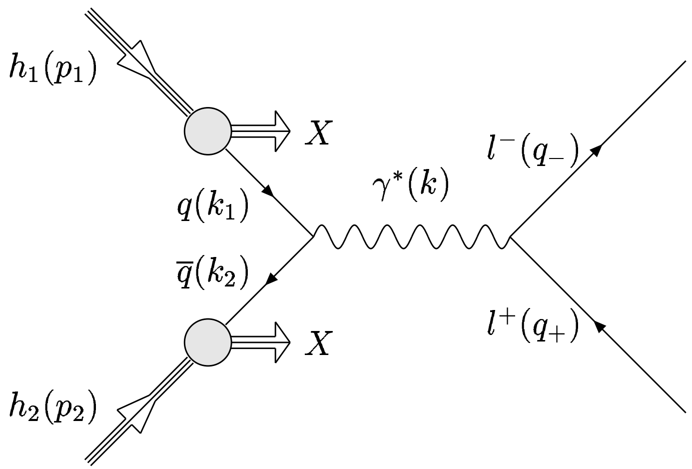
Transversely polarized quarks inside an *unpolarized* hadron

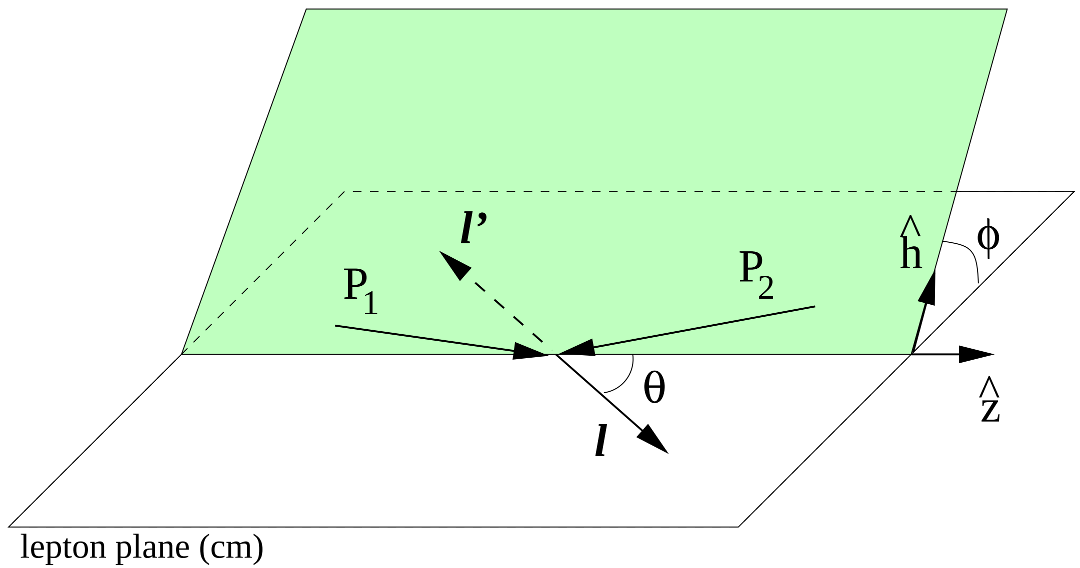
Allowed by the symmetries as long as $\boldsymbol{k}_T \neq 0$

It generates azimuthal asymmetries in unpolarized collisions, e.g. in DY

There is very interesting data from the 1980s on $\pi^- N \to \mu^+ \mu^- X$
It shows an anomalously large $\cos 2\phi$ asymmetry (w.r.t. pQCD predictions)

Azimuthal asymmetries in Drell-Yan in theory



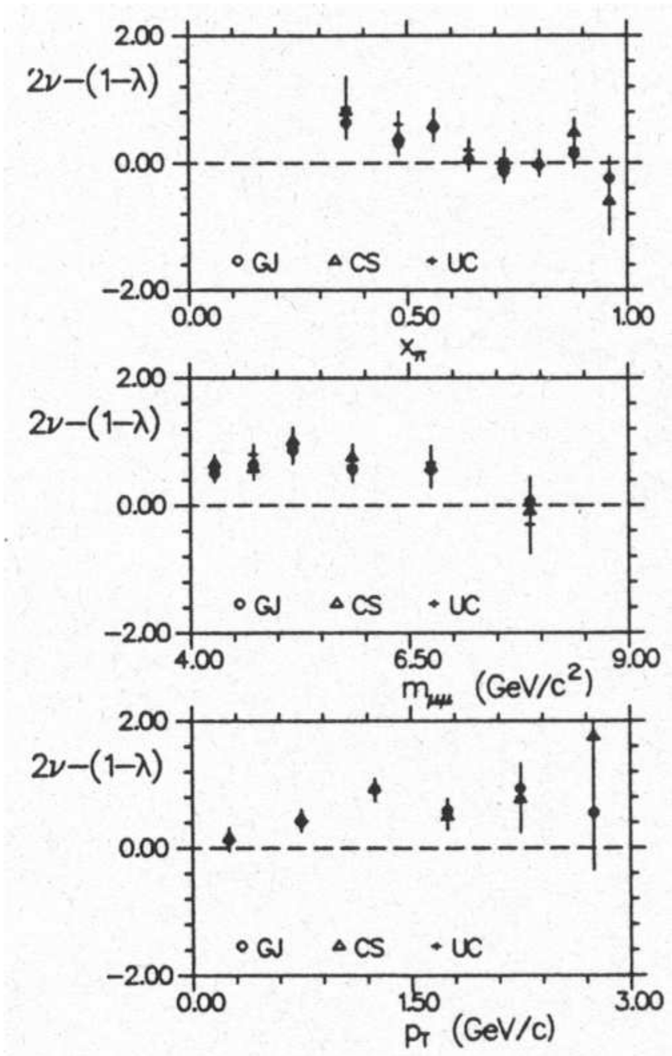


$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

Collinear factorization: Mirkes & Ohnemus '95

Parton Model	$\mathcal{O}(\alpha_s^0)$	$\lambda = 1, \ \mu = \nu = 0$	
LO pQCD	$\mathcal{O}(\alpha_s^1)$	$1 - \lambda - 2\nu = 0$	Lam-Tung relation
NLO	$\mathcal{O}(\alpha_s^2)$	$1 - \lambda - 2\nu \neq 0$	small and positive

Azimuthal asymmetries in Drell-Yan in experiment



Data: $1 - \lambda - 2\nu \neq 0$ large and negative!

NA10 Collab. ('86/'88) & E615 Collab. ('89)

Data for $\pi^- N \to \mu^+ \mu^- X$, with $N = D, W$

$\sqrt{s} \approx 20 \pm 3$ GeV

lepton pair invariant mass $Q \sim 4 - 12$ GeV

Nonzero $h_1^\perp$ offers an explanation of this anomalous Drell-Yan data

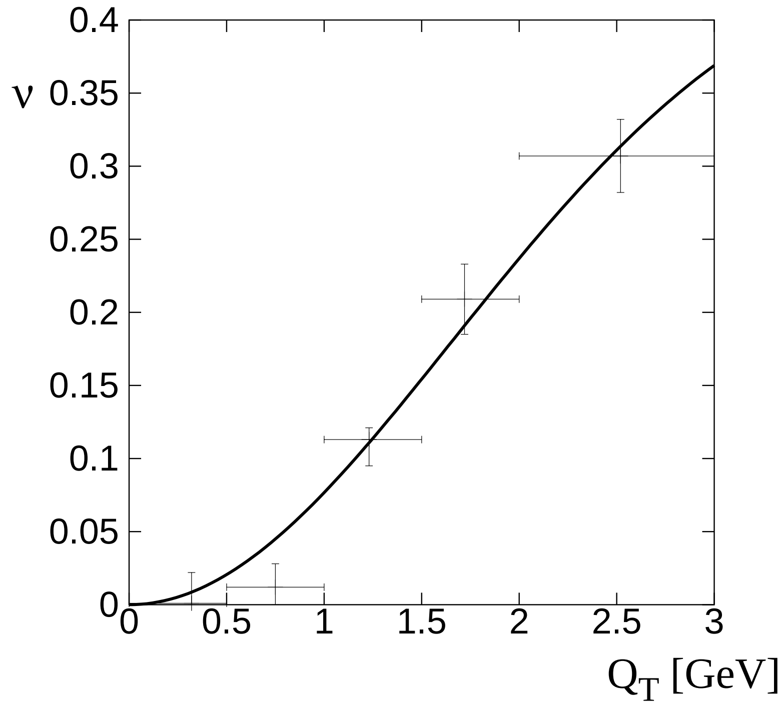
D.B. '99

Explanation in terms of $h_1^\perp$

$$(1 - \lambda - 2\nu) \propto h_1^\perp(\pi)\, h_1^\perp(N)$$

Fit $h_1^\perp$ to data by assuming Gaussian TM dependence

D.B. '99



Many model calculations of $h_1^\perp$ and its asymmetries have been performed

Goldstein & Gamberg '02, '07; D.B., Brodsky & Hwang '03

Lu & Ma '04, '05; Barone, Lu & Ma '07; Zhang, Lu, Ma & Schmidt '08

Courtoy, Scopetta & Vento '09; Lu & Schmidt '09

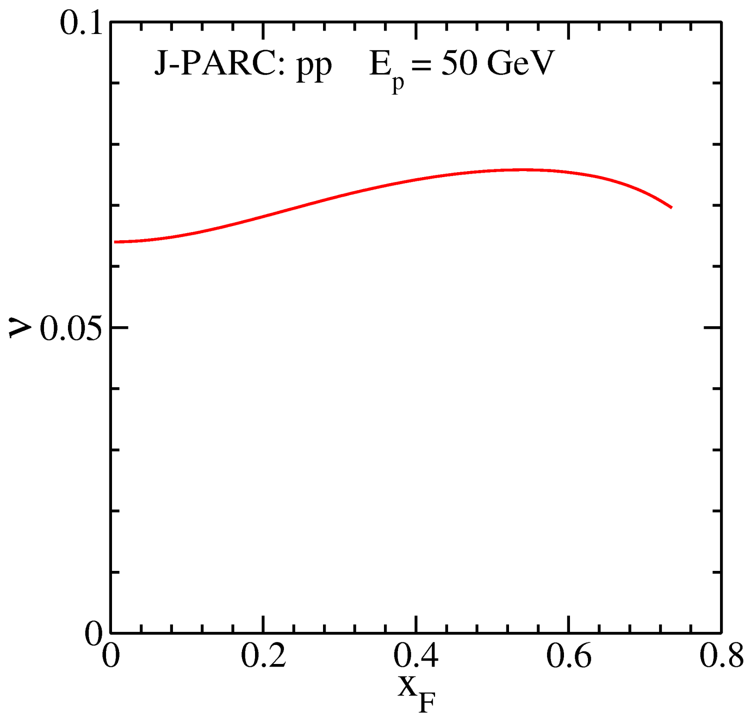
Allows to predict other observables, such as DY for $pp, \bar{p}p$, $p^\uparrow p$, $p^\uparrow \pi$, etc

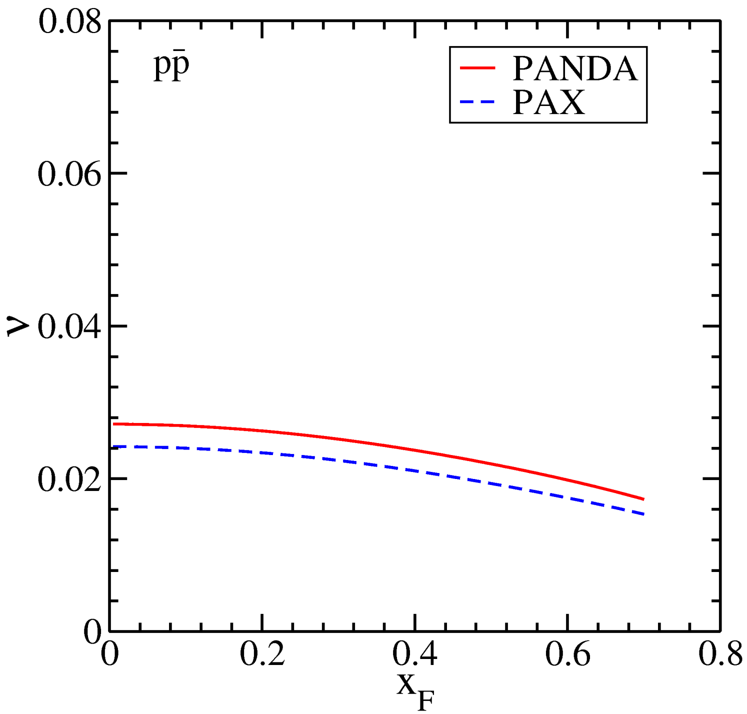
New unpolarized DY data

Asymmetry for $p\,p$ and $p\,d$ expected to be smaller, as confirmed by recent Fermilab data
FNAL-E866/NuSea Collaboration, L.Y. Zhu *et al.* '07 & '09 → [next talk]

Asymmetry for $\bar{p}\,p$ expected to be very similar to $\pi\,p$ (both have valence antiquarks)

Although this depends on the kinematics too of course:





Lu & Schmidt '09

$h_1^\perp$ in dijet production

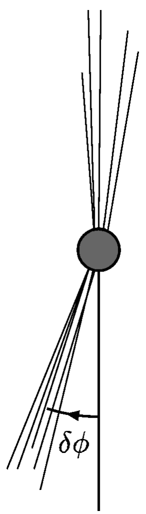
$h_1^\perp$ of quarks *and gluons* contributes to the dijet imbalance $\delta\phi$ distribution
Lu & Schmidt '08; D.B., Mulders & Pisano '09

$h_1^{\perp\, g}$: linearly polarized gluons inside an unpolarized hadron (T-, chiral- & $\boldsymbol{k}_T$-even)

In the plane transverse to the collision axis: $\delta\phi = \phi_{j_1} - \phi_{j_2} - \pi$

In unpolarized scattering its distribution is often used to extract $\langle k_T^2 \rangle$ of partons

Sizeable $h_1^\perp$ contributions can modify the $\delta\phi$ distribution (especially in $p\,\bar{p} \to$ jet jet X)



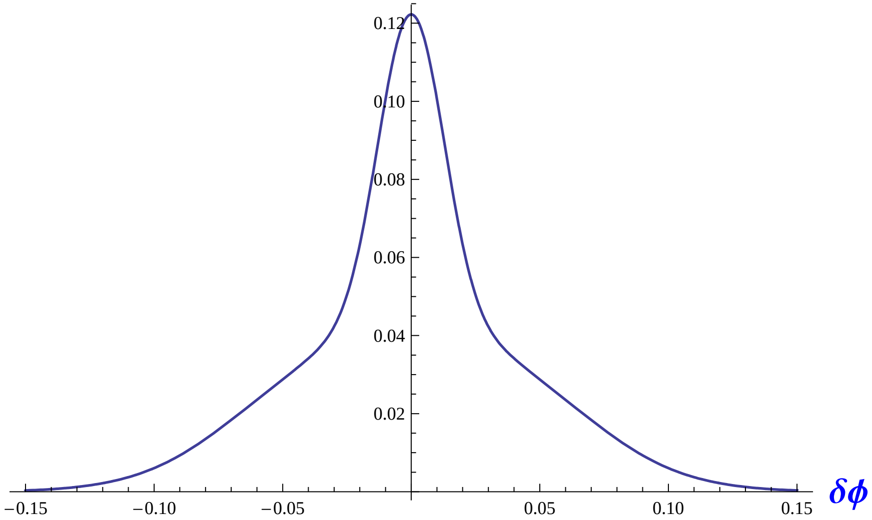


Illustration of a possible modification by $h_1^\perp$

Possible relation between TMDs and GPDs

If the Sivers effect describes spin-orbit coupling, one may expect a relation with OAM and hence with GPDs

A relation between $f_{1T}^{\perp}$ and the GPD E has been put forward

Burkardt '04; Burkardt & Hwang '04

$$f_{1T}^{\perp(1)}(x) \equiv \int d^2\boldsymbol{k}_T \frac{\boldsymbol{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \boldsymbol{k}_T^2) \propto S_T \times b_\perp \int db_\perp^2 \, \boldsymbol{I}(b_\perp^2) \frac{\partial}{\partial b_\perp^2} E(x, b_\perp^2)$$

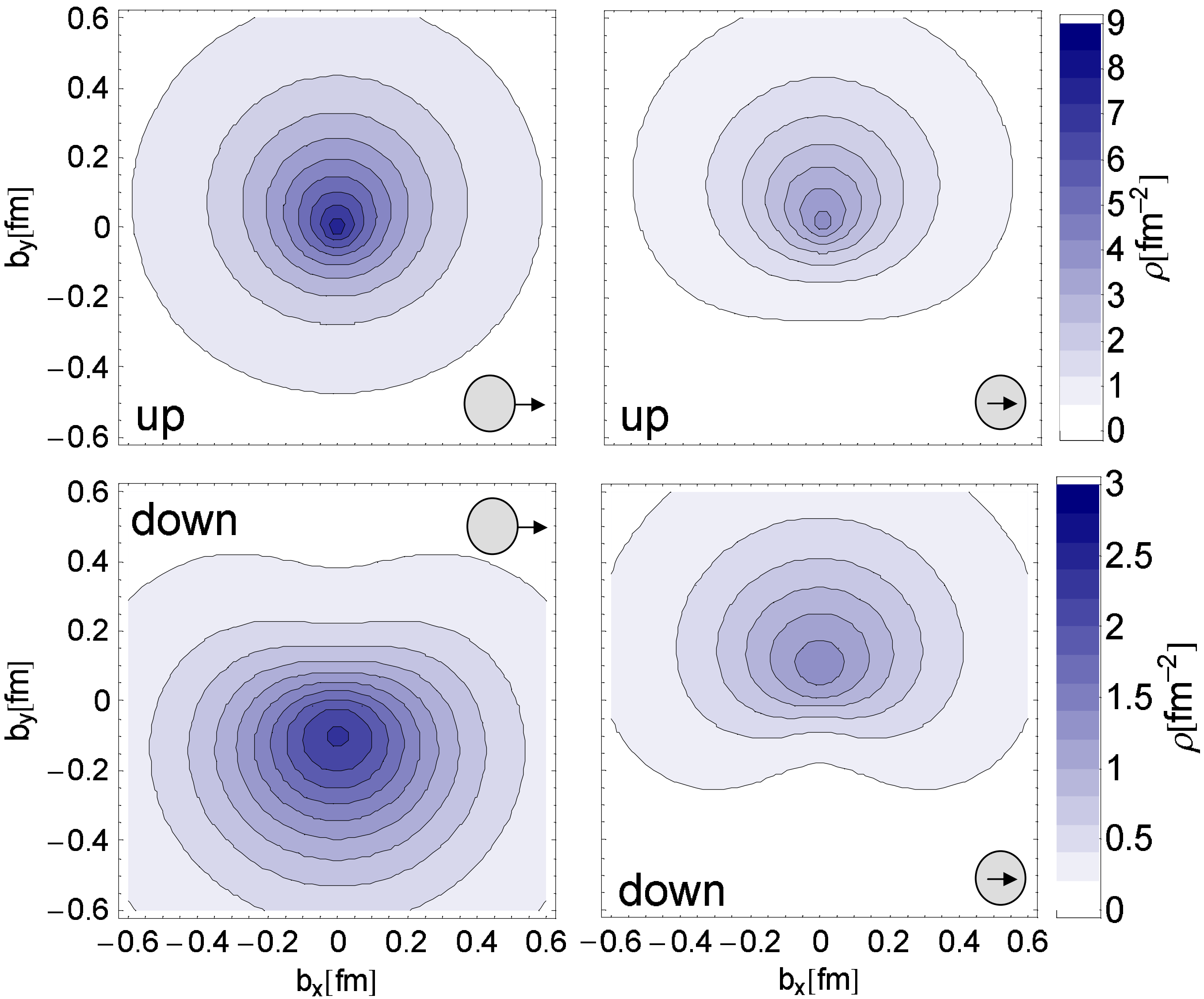
Note: $\boldsymbol{k}_T$ and $\boldsymbol{b}_\perp$ are not each other's Fourier conjugates

The factor $\boldsymbol{I}(b_\perp^2)$ is called the lensing function

Allows to link the Sivers function to the anomalous magnetic moment of u, d

A similar relation between $h_1^{\perp}$ and the chiral-odd GPD combination $\bar{E}_T \equiv E_T + 2\tilde{H}_T$

Lattice results



$S_T \times b_\perp$ correlations exist!

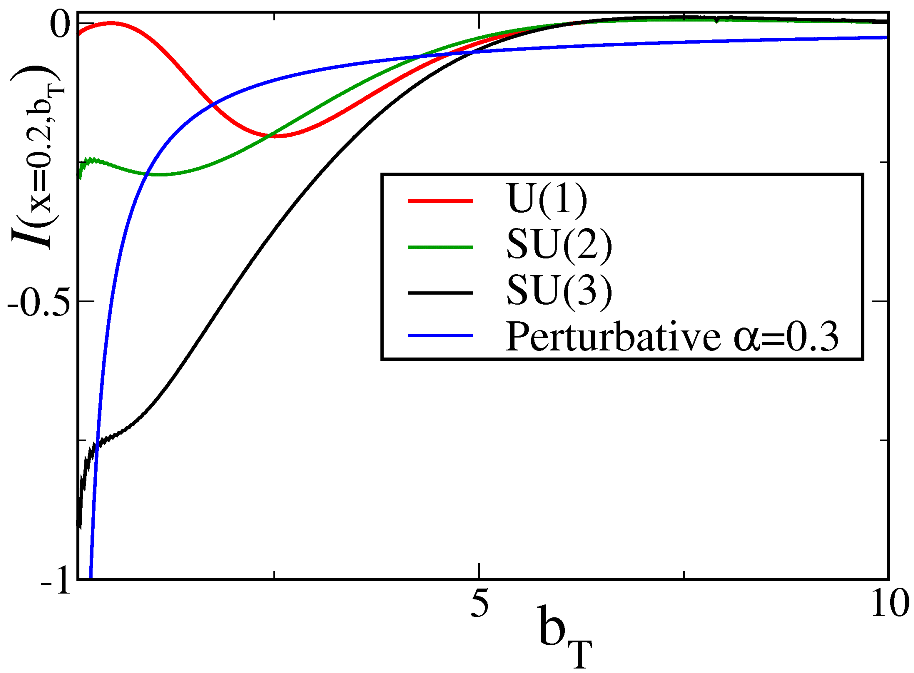
QCDSF & UKQCD Collaboration, Göckeler *et al.* '07

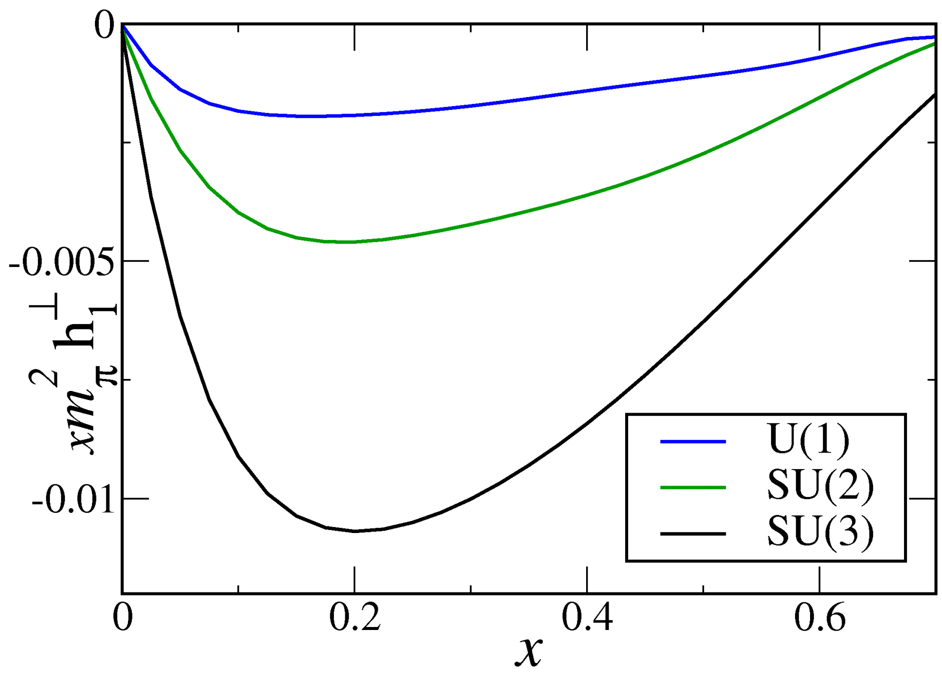
$h_1^{\perp\, u}$ same sign as $h_1^{\perp\, d}$

Burkardt & Hannafious '07

The lensing function

The lensing function has recently been calculated in an eikonal approach





Gamberg & Schlegel '09

Other explanations of the asymmetries

Qiu-Sterman effect proposed as a mechanism for single spin asymmetries in $p^{\uparrow}\, p \to \pi\, X$

Qiu & Sterman '91

It is a collinear twist-3 function relevant for the high-p_T description

$$T(x, S_T) \overset{A^+=0}{\propto} \text{F.T.} \langle P|\, \overline{\psi}(0) \int d\eta^-\, F^{+\alpha}(\eta^-)\, \gamma^+\, \psi(\xi^-)\, |P\rangle$$

Applicable when collinear factorization is justified

The Sivers effect in Drell-Yan deals with a multi-scale process: M, Q_T and Q

TMD or Collins-Soper factorization applies when $Q_T^2 \ll Q^2$

Collins & Soper '81; Ji, Ma & Yuan '04 & '05

Collinear factorization applies when $Q_T^2 \sim Q^2$

These two descriptions can actually be connected!

Ji, Qiu, Vogelsang, Yuan '06

Large transverse momentum tails

Consider the large transverse momentum tails of TMDs:

$$f_1(x, \boldsymbol{p}_T^2) \overset{\boldsymbol{p}_T^2 \gg M^2}{\sim} \alpha_s \frac{1}{\boldsymbol{p}_T^2} \left(K \otimes f_1\right)(x)$$

$$f_{1T}^{\perp}(x, \boldsymbol{p}_T^2) \overset{\boldsymbol{p}_T^2 \gg M^2}{\sim} \alpha_s \frac{M^2}{\boldsymbol{p}_T^4} \left(K' \otimes f_{1T}^{\perp(1)}\right)(x)$$

$$f_{1T}^{\perp(1)}(x) \equiv \int d^2\boldsymbol{k}_T \frac{\boldsymbol{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \boldsymbol{k}_T^2) \propto T(x, S_T)$$

The first transverse moment of the Sivers function is the Qiu-Sterman function

D.B., Mulders & Pijlman '03

The Qiu-Sterman effect determines the large p_T behavior of the Sivers effect

This yields precisely the high Q_T result!

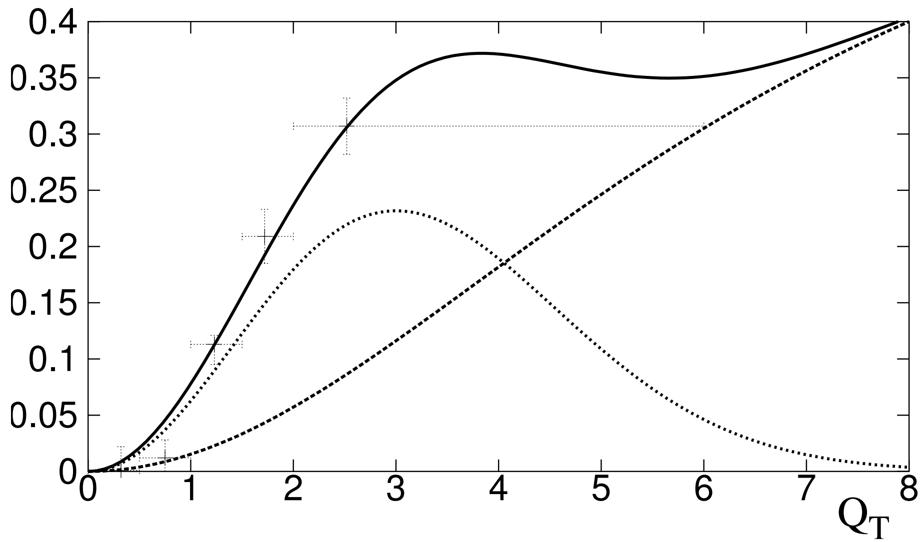
Ji, Qiu, Vogelsang, Yuan '06

Thanks to this one can consider the integral of the Sivers asymmetry over all Q_T

$\cos 2\phi$ asymmetry as function of Q_T

The high-p_T tail of $h_1^\perp$ is related to a chiral-odd QS effect (power suppressed)

But the $\cos(2\phi)$ asymmetry at high Q_T is dominated by the perturbative contribution



$$\nu = \nu_{h_1^\perp} + \nu_{\mathrm{pert}} + \mathcal{O}\left(\frac{Q_T^2}{Q^2}, \frac{M^2}{Q_T^2}\right)$$

Bacchetta, D.B., Diehl, Mulders '08

This time the integral over all Q_T picks up both contributions

The Q_T^2-weighted asymmetry is mostly sensitive to the high Q_T perturbative result

The Q_T^2-weighted asymmetry at tree level and at order α_s are very different expressions

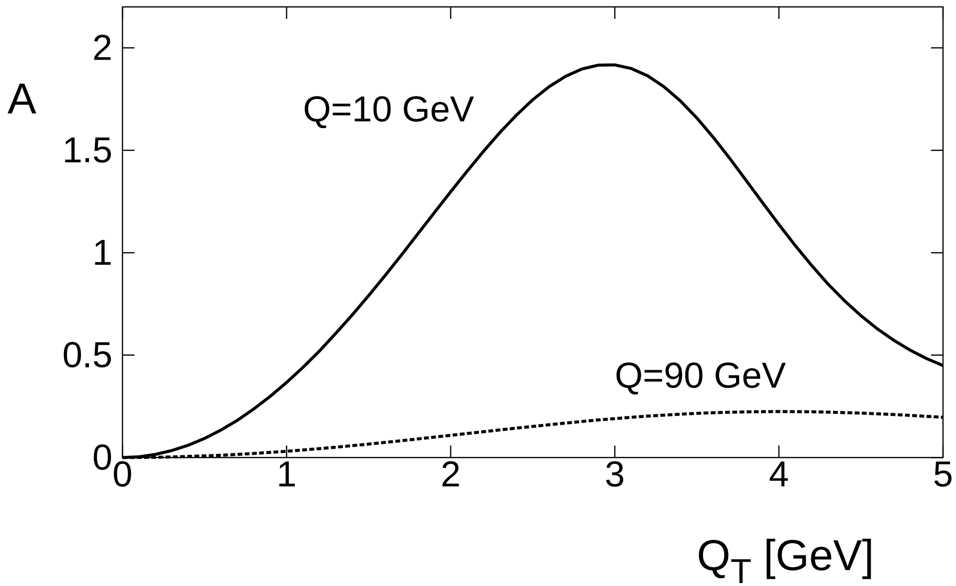
Very different from Sivers effect asymmetries

$\cos 2\phi$ asymmetry from $h_1^\perp$ beyond tree level

Collins-Soper factorization dictates the Q^2 dependence of azimuthal asymmetries

Assuming Gaussian k_T dependence for $h_1^\perp$, its contribution to ν is proportional to

$$\mathcal{A}(Q_T) \equiv M^2 \frac{\int_0^\infty db\, b^3\, J_2(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}{\int_0^\infty db\, b\, J_0(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}$$



D.B. '01

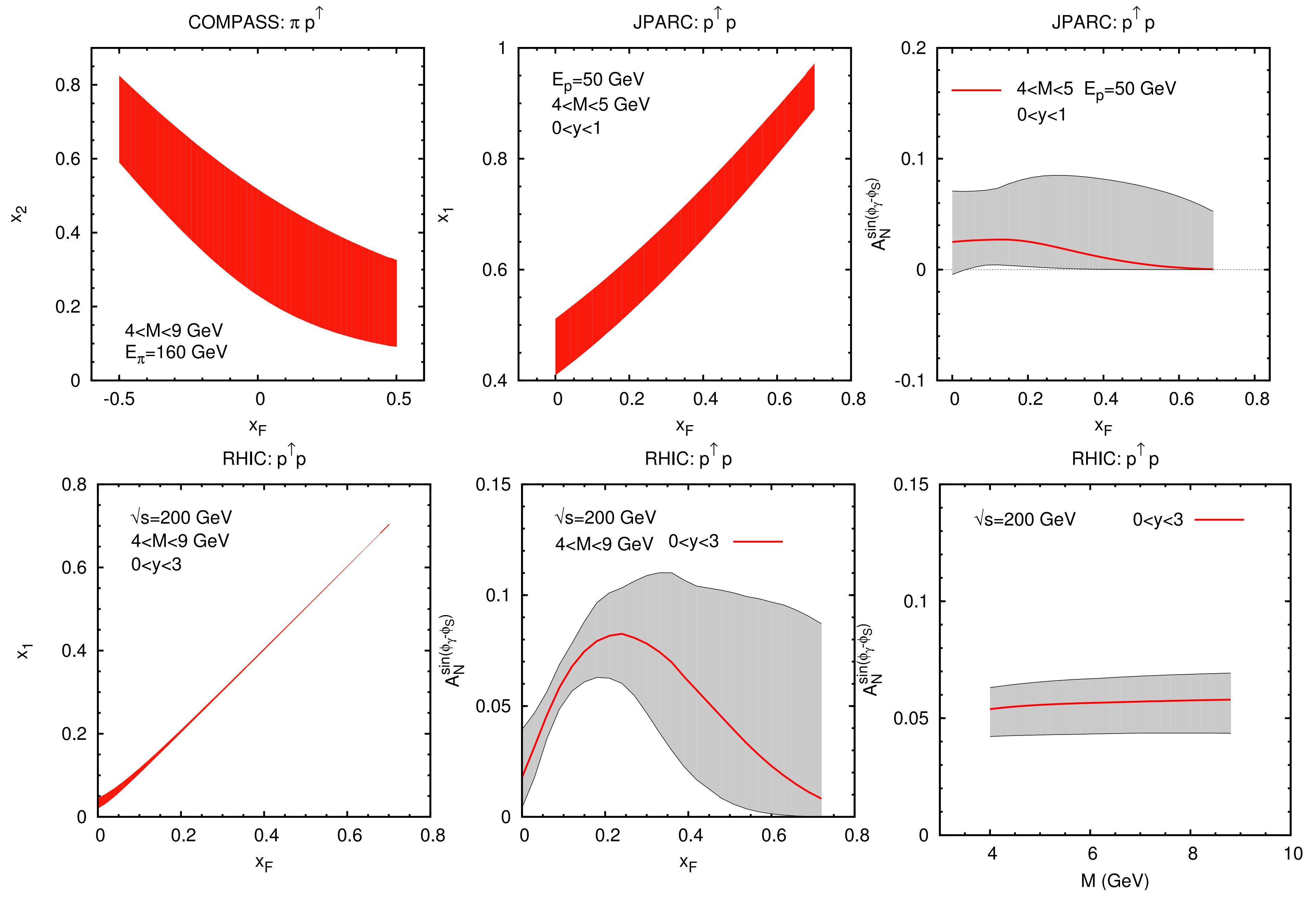
Considerable Sudakov suppression with increasing Q: $\sim 1/Q$ (effectively twist-3)

On the other hand, the perturbative contribution falls off as $1/Q^2$

Conclusions

- Sivers & BM effects are naive T-odd effects:
  their correlations are T-odd, but distributions multiplying them are process dependent
- These naive T-odd effects give rise to many different azimuthal asymmetries
  Several such asymmetries are visible in the available data
- Calculable process dependence, so universality is lost, but predictability is not
  Tests of this are expected soon
- Lattice results on asymmetric GPDs suggest these TMD effects are nonzero
- Q_T and Q dependence of TMD asymmetries dictated by factorization
- Factorization for DY under control, for dijet and dihadron production not (yet?)
- All in all, a lot of theoretical & experimental progress in recent years!

Back-up Slides


COMPASS: π p↑
4<M<9 GeV
E_π=160 GeV
x_2
x_F
JPARC: p↑ p
E_p=50 GeV
4<M<5 GeV
0<y<1
x_1
x_F
JPARC: p↑ p
4<M<5 E_p=50 GeV
0<y<1
$A_N^{\sin(\phi_\gamma-\phi_S)}$
x_F
RHIC: p↑p
√s=200 GeV
4<M<9 GeV
0<y<3
x_1
x_F
RHIC: p↑ p
√s=200 GeV
4<M<9 GeV 0<y<3
$A_N^{\sin(\phi_\gamma-\phi_S)}$
x_F
RHIC: p↑ p
√s=200 GeV
0<y<3
$A_N^{\sin(\phi_\gamma-\phi_S)}$
M (GeV)

T-odd effects and factorization

But factorization allows one to go a step further:

$$T\sigma_{\rm DIS} = T(H \otimes \Phi) = H \otimes T\Phi$$

Here T stands for the actual time reversal operation

Time reversal invariance leads to the constraint

$$(-i\gamma_5 C)\Phi(x, \bar{P}, \bar{S})(-i\gamma_5 C) = \Phi(x, P, S)^*$$

where $\bar{P} = (P^0, -\boldsymbol{P})$, etc

T-odd correlations in the parametrization of $\Phi(x)$ are really time reversal violating

So what about processes involving TMDs?

$$T\sigma_{\rm SIDIS} = T(H \otimes \Phi \otimes \Delta) = H \otimes T(\Phi \otimes \Delta)$$

Here one could select the T-even part of Δ and conclude $f_{1T}^{\perp}$ is time reversal violating
Collins '93

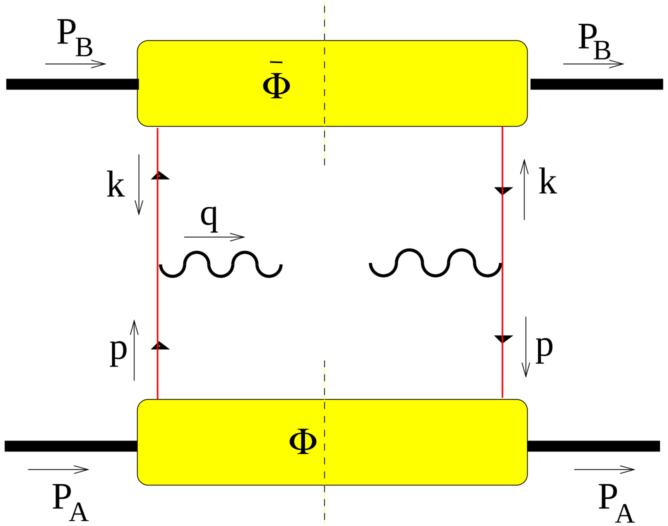
Collins-Soper factorization

$$W^{\mu\nu}_{\rm DY} \quad \propto \quad \left|H\big(x_1, x_2, Q^2\big)\right|^2 \sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, d^2\boldsymbol{l}_T\, \delta^{(2)}(\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{l}_T - \boldsymbol{q}_T)$$

$$\times\, \mathrm{Tr}\left\{\Phi^a(x_1, \boldsymbol{p}_T)\gamma^\mu \bar{\Phi}^a(x_2, \boldsymbol{k}_T)\gamma^\nu\right\} U(l_T^2) \;+\; \mathcal{O}(Q_T^2/Q^2)$$

Collins & Soper '81; Ji, Ma & Yuan '05

At tree level ($U(l_T^2) \propto \delta(l_T^2)$) this corresponds to the often used description:



Extension to $p\,p \to h\,h'\,X$ not clear

$h_1^\perp$ in $p\,\bar{p} \to \gamma$ jet X

$$\frac{d\sigma^{h_1\,h_2\to\gamma\ \text{jet}\ X}}{d\eta_\gamma\, d\eta_j\, d^2\boldsymbol{K}_{\gamma\perp}\, d^2\boldsymbol{q}_\perp} \quad\propto\quad \left(1+\nu_{\mathrm{DY}}\, R \cos 2(\phi_\perp-\phi_\gamma)\right)$$

ν_{DY} probed at the scale $|\boldsymbol{K}_{\gamma\perp}|$ $(\neq Q)$

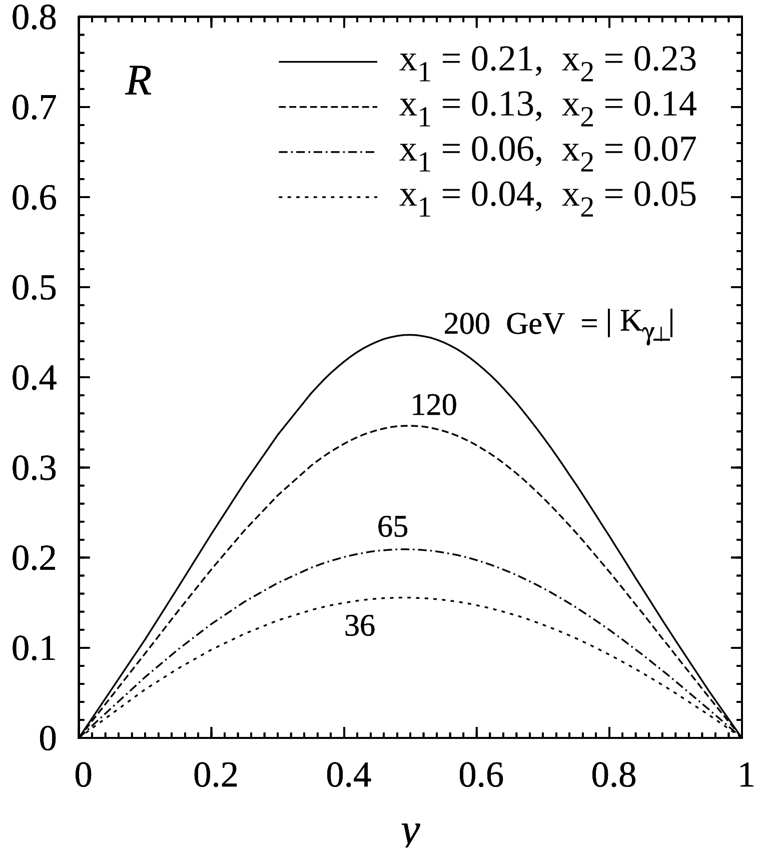
Proportionality factor R only function of f_1

$$y \equiv -\frac{\hat{t}}{\hat{s}} = \frac{1}{e^{\eta_\gamma-\eta_j}+1}$$

For typical Tevatron kinematics in the central region (DØ, arXiv:0804.1107)

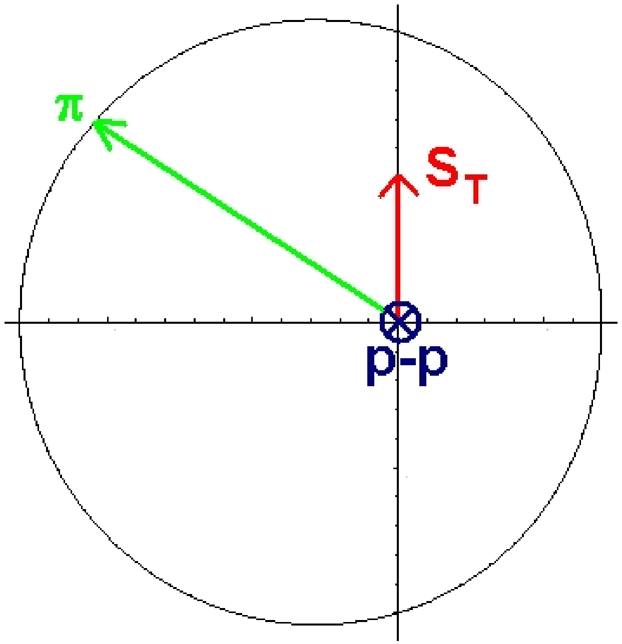
$\nu_{\mathrm{DY}}\, R \sim 5-15\%$ expected

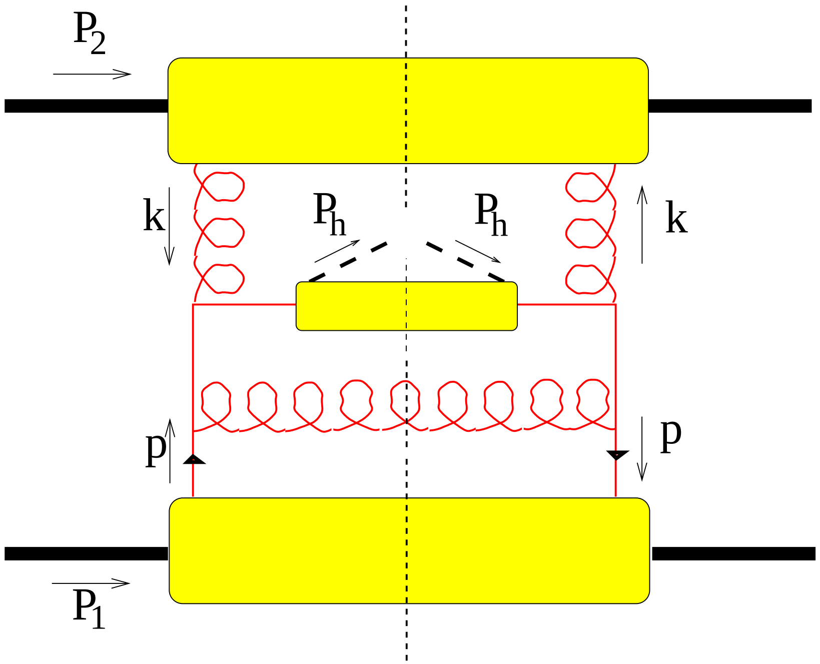
D.B., Mulders & Pisano '08



Single spin asymmetries in $p^{\uparrow}p \to \pi X$

SSA in $p\,p^{\uparrow} \to \pi\,X$ [E704, AGS, STAR, BRAHMS]





Description in terms of Sivers (and Collins) effect studied extensively

Anselmino, Boglione, D'Alesio, Murgia, and collaborators, since 1995

Twist-3 (factorization not proven) remains to be connected to Qiu-Sterman effect

The polarized Drell-Yan process

In the case of one transversely polarized hadron beam:

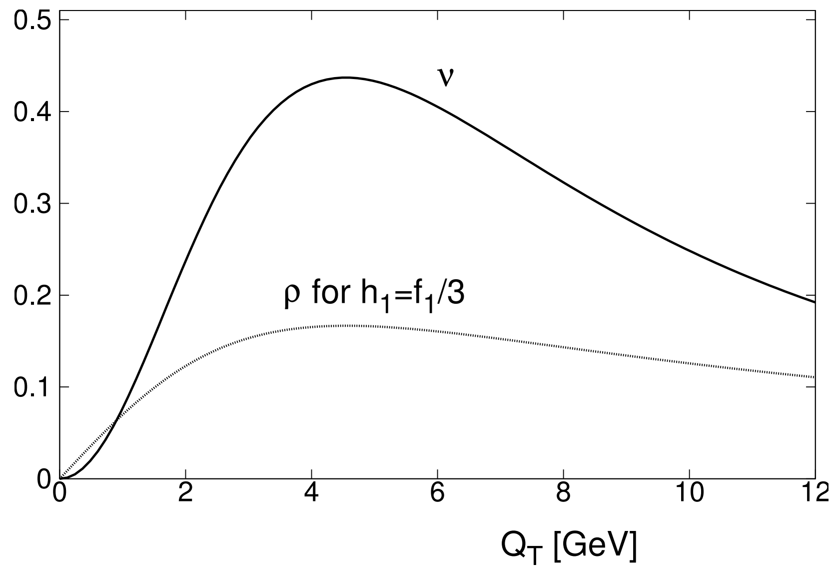
$$\frac{d\sigma}{d\Omega\, d\phi_S} \propto 1 + \cos^2\theta + \sin^2\theta \left[\frac{\nu}{2}\, \cos 2\phi - \rho\, |\boldsymbol{S}_T|\, \sin(\phi+\phi_S)\right] + \ldots$$

Assuming u-quark dominance and Gaussian k_T-dependence for $h_1^\perp$:

$$\nu \quad \propto \quad h_1^\perp\, h_1^\perp$$

$$\rho \quad \propto \quad h_1\, h_1^\perp$$

$$\rho = \frac{1}{2}\sqrt{\frac{\nu}{\nu_{\mathsf{max}}}\,\frac{h_1^u}{f_1^u}}$$



First extraction of h_1 from HERMES, COMPASS, BELLE data indicates $h_1 \approx f_1/3$

Anselmino *et al.* '07

DY at Compass

Measurement of ν and ρ with only one polarized beam offers a probe of *transversity*

The distribution of transversely polarized quarks inside a transversely polarized hadron

The COMPASS experiment plans to extract them using $\pi^{\pm} p^{\uparrow}$ Drell-Yan

Would provide valuable information on the flavor dependence of h_1 and $h_1^{\perp}$

Especially $\pi^{+}p^{\uparrow}$ is of interest, since no data yet and it provides information on the d-quark ratio $h_1^{\perp d/p}/h_1^{d/p}$, without suppression by a charge-squared factor

Using the input on $h_1^{\perp}$ from for example unpolarized $p\,\bar{p}$ Drell-Yan would allow for an extraction of h_1 from $\pi^{\pm}p^{\uparrow}$ Drell-Yan at COMPASS

Future DY data

Usually Drell-Yan data is taken in the safe region, cutting out the resonances (J/ψ and Υ)

They are however also vector particles

Anselmino, Barone, Drago & Nikolaev '04

Note that the NA10 data ('86) on the Υ is very similar to that above/below it