

The role of gauge invariance in single-spin asymmetries

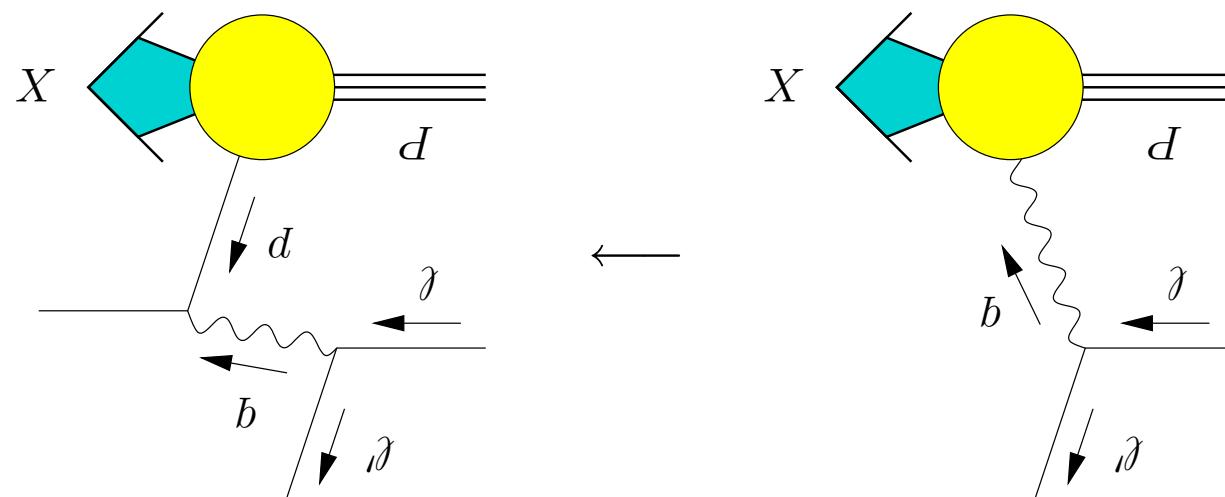
Cedran Bomhof

- $X \downarrow d \leftarrow d \downarrow X$ and $d \downarrow d \leftarrow d \downarrow d$ •
their consequences.
- Introduction to Wilson lines and

Wilson line

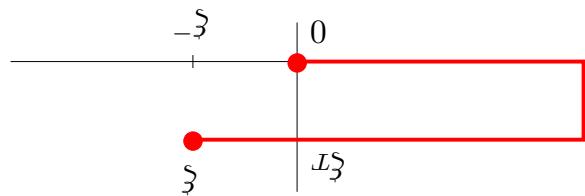
$$\langle D | (\not{z}) b \overbrace{(\not{z}^{'}) n}^{(0)} (0) \not{b} | D \rangle_{\text{LT}} \propto (x) f$$

$$(x)_{\text{parton}} \rho_{\text{parton}} (x) f \exp \int^b \sum \propto \rho_{\text{Hadron}}$$

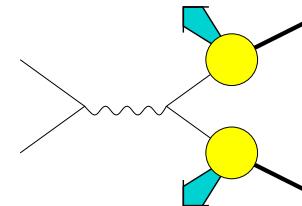


deep inelastic scattering

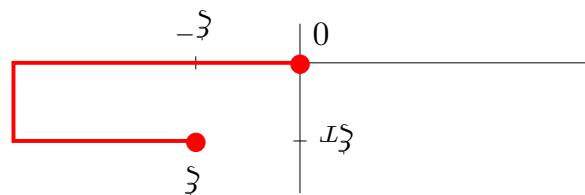
Boer, Mulders, Pijlman; NPB667,201(2003)
 Belitsky, Ji, Yuan; NPB656,165(2003)
 Ji, Yuan; PLB543,66(2002)



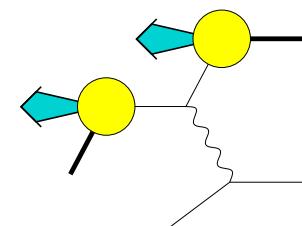
$\vdots [-] \mathcal{H}$



- Drell-Yan ($h_1 + \underline{h}_2 + \gamma \leftarrow X$)



$\vdots [+] \mathcal{H}$



- SIDIS ($X + h_1 + \gamma \leftarrow h_2 + \ell$)

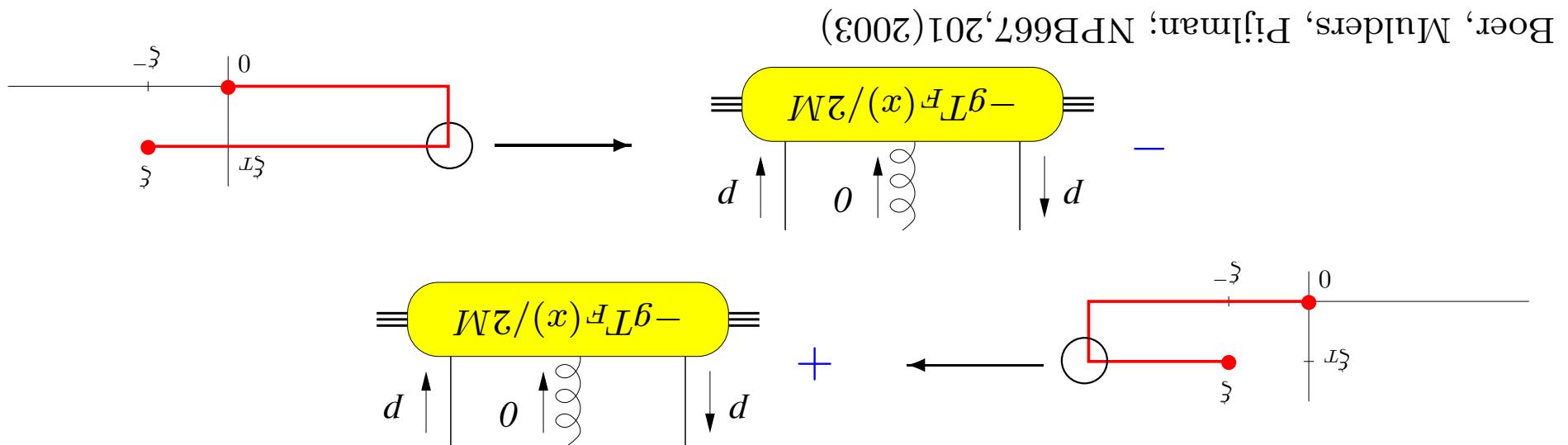
$$(z)A \cdot z p \int^{\mathcal{C}} \exp iy \cdot A(z) = (\xi, 0) \mathcal{H}_{\mathcal{C}}$$

Wilson lines in SIDIS and DY

Brodsky, Hwang, Schmidt; PLB530, 99 (2002) Collins; PLB536, 43 (2002)

$$\frac{dA_N^{\text{DY}}}{d\phi_{q\bar{q}\gamma}^L(x_1)} \propto -f_L(x_2)$$

$$\frac{dA_N^{\text{SIDIS}}}{d\phi_{q\gamma b}(x_1)} \propto +D_L(z_1)$$

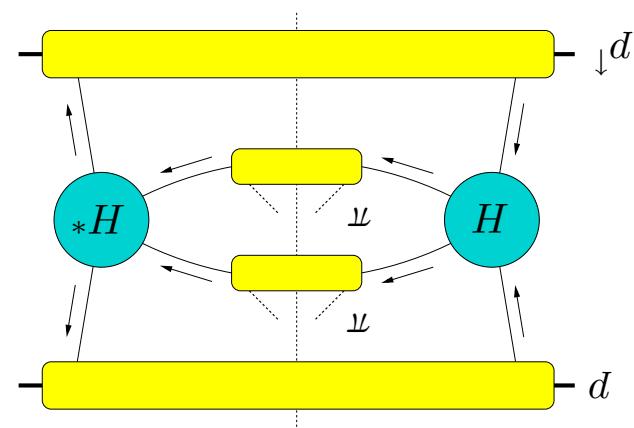
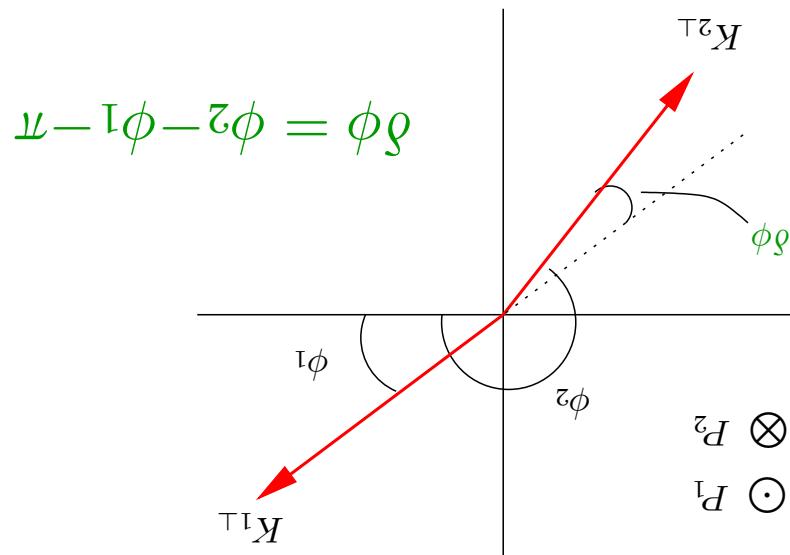


$$(x)_{(\text{I})}^{\text{LT}f} \mp \propto \langle (\zeta)b_+ \wedge (\zeta, 0)_{[\mp]} \mathcal{U}(0) \bar{b} \rangle_{LT} k_T dk_- d^2k_- \int \propto (x)_{[\mp]}^{\text{LT}f}$$

collinear T -odd distribution functions

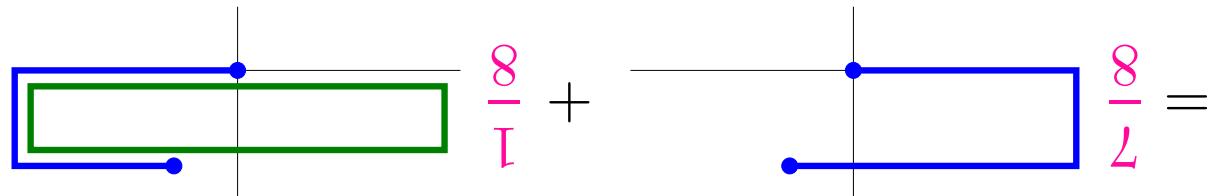
$$\text{Weighted azimuthal asymmetry: } \langle \sin(\phi) \rangle = \int \frac{d\phi}{2\pi} \sin(\phi)$$

Bacchetta et al; PRD72,034030(2005)
Boer, Vogelsang; PRD69,094025(2004)

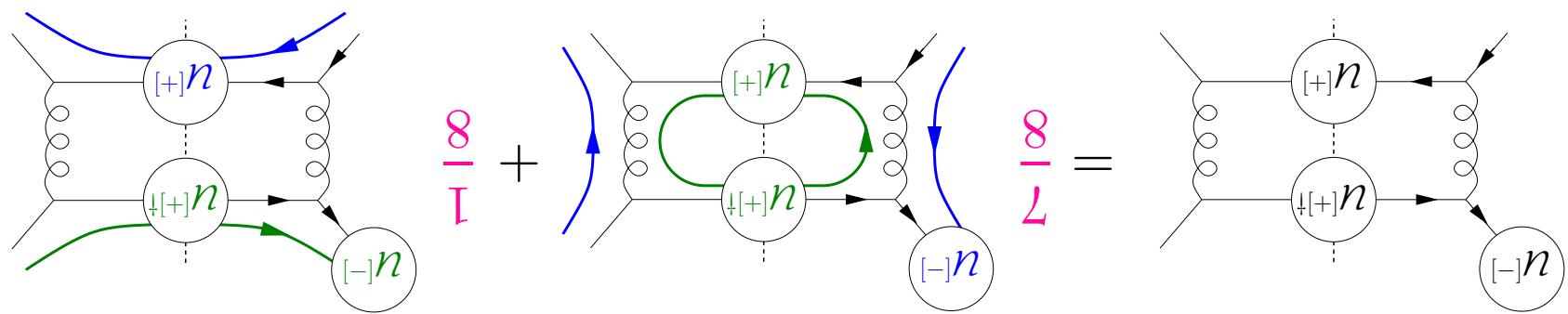


in $d \downarrow d \leftarrow d \downarrow d$ or $X \ell \ell \leftarrow d \downarrow d \cdot X \pi \pi \leftarrow d \downarrow d$
example of azimuthal asymmetry

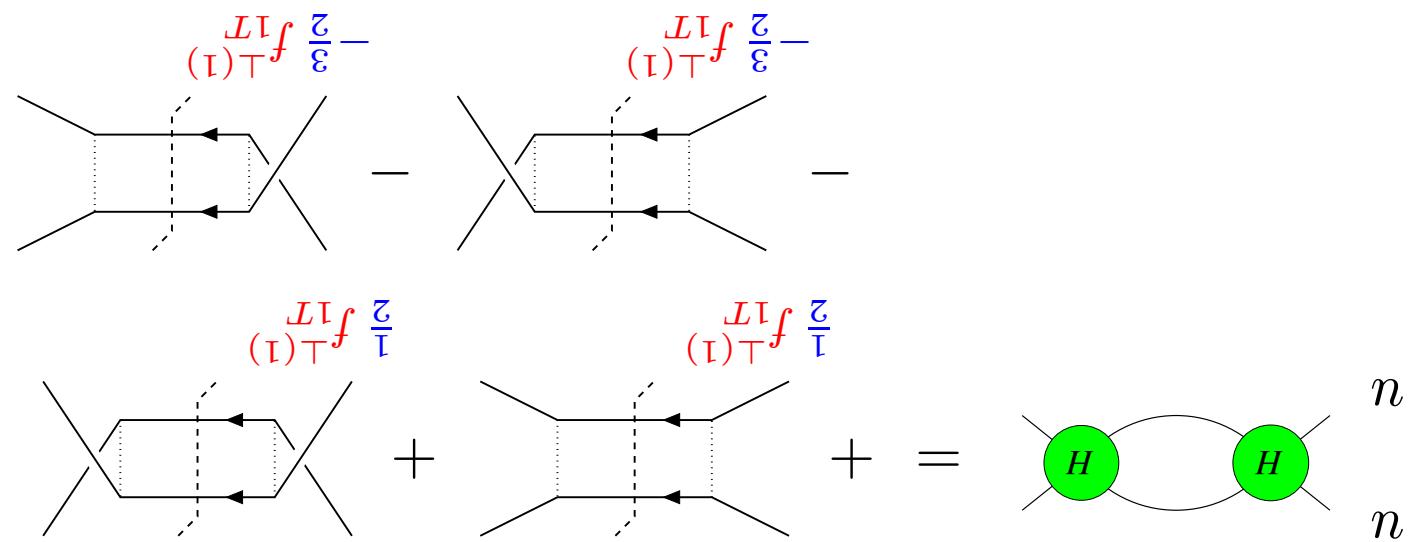
$$(x)_{(I)\top} \overset{L}{f} \frac{\psi}{\zeta} = \{ (x)_{(I)\top} \overset{L}{f} + \} \times \frac{8}{I} + \{ (x)_{(I)\top} \overset{L}{f} - \} \times \frac{8}{L} = \underline{pn} \leftarrow \underline{pn} ((x)_{(I)\top} \overset{L}{f})$$



$$\frac{e}{[+]n_+[-]n_-} [+]n \frac{8}{I} + [-]n \frac{8}{L} = \text{Wilson Line}$$



Wilson line in $ud \rightarrow ud$ scattering



using the ‘universal’ Sivers function $f_{\text{LT}}^{(1)}$

Sivers effect in identical-quark scattering

Bacchetta et al; PRD72,034030(2005) see also: Kouvaris, et al; PRD74,114013(2006)
 Eguchi, Koike, Tanaka; NPB763,198(2007)
 Ratcliffe, Terzyan; hep-ph/0703293
 Qi, Vogelsang, Yuan; arXiv:0704.1153
 CB, Mulders; JHEP02,029(2007)

$$\begin{aligned}
 & (\sin(\phi) d\phi) \neq dS_{uu \leftarrow uu} \\
 & + \frac{3}{2} \quad + \frac{3}{2} \\
 & + \frac{1}{2} \quad = \quad + \frac{1}{2} \\
 & dS_{uu \leftarrow uu}
 \end{aligned}$$

with gluonic pole cross section

$$\langle \sin(\phi) d\phi \rangle \propto f_{T(1)}^{LT}(x_1) f_1(x_2) dS_{uu \leftarrow uu} D_1(z_1) D_1(z_2)$$

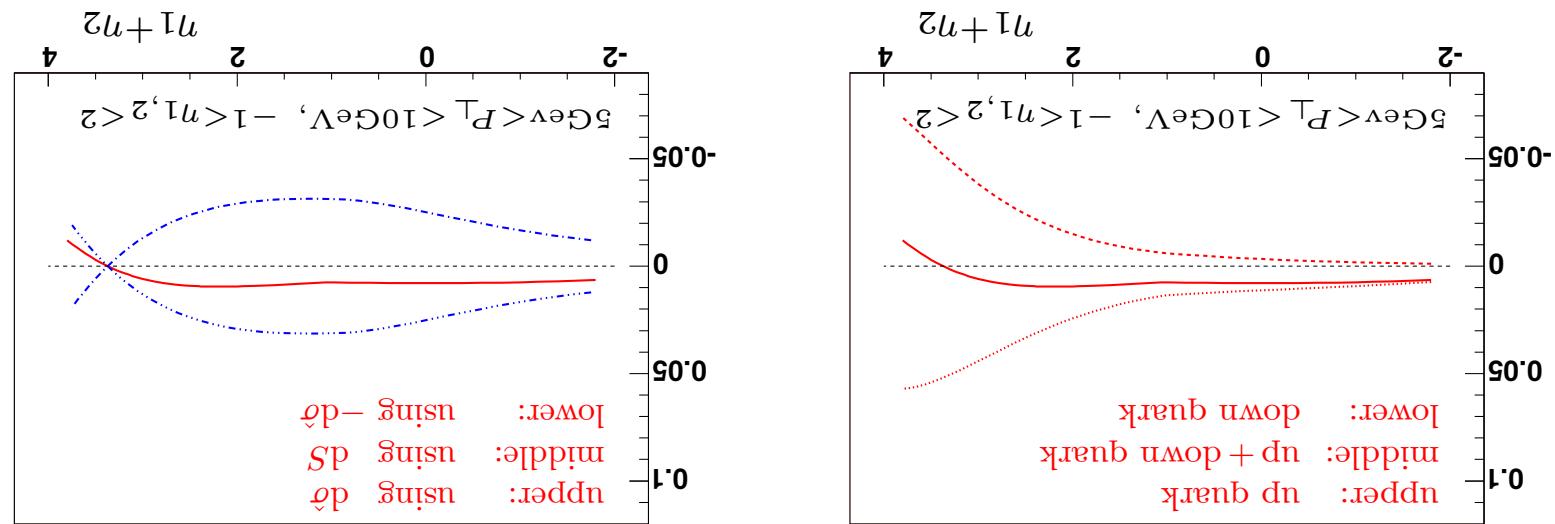
Hadronic scattering cross section

Sivers effect in identical-quark scattering

$$M(x) = -gT^F(x)/2M = (x)_{\perp(1)} \textcolor{violet}{f}_{\perp}^{LT} \textcolor{blue}{p}^L$$

$$M(x) = -gT^F(x)/2M = (x)_{\perp(1)} \textcolor{violet}{f}_{\perp}^{LT} \textcolor{blue}{n}^L$$

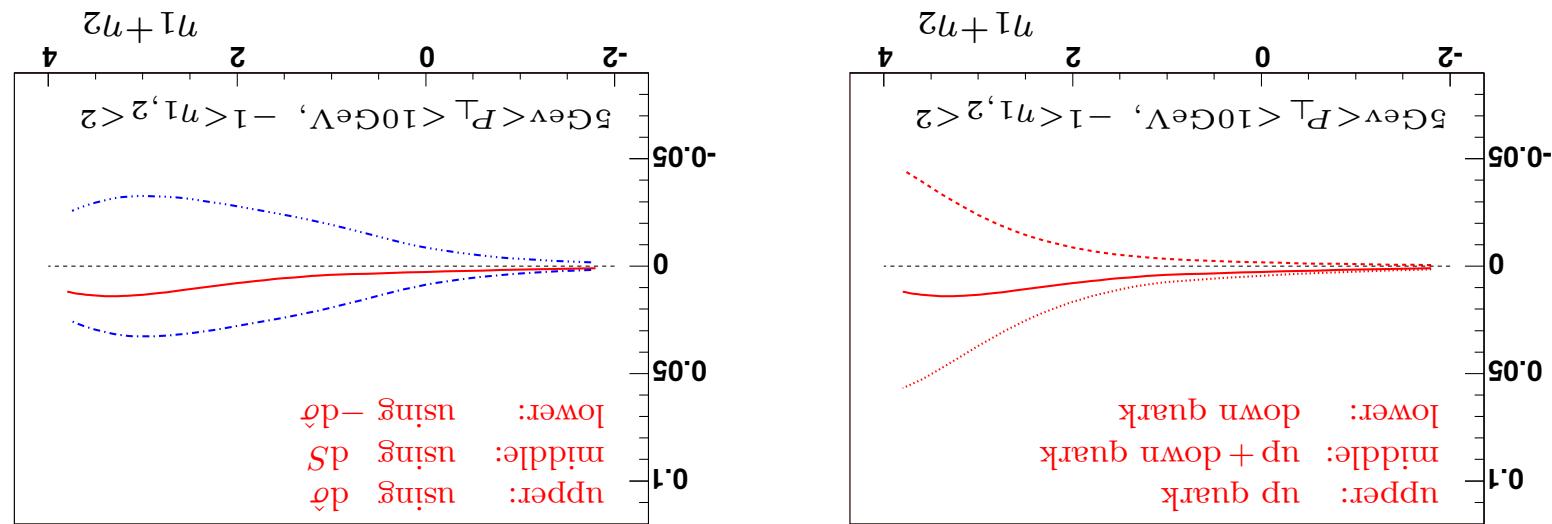
$$\frac{\langle d\phi_{UU} \rangle}{\langle 2P_\perp \sin(\phi) d\phi_{TU}/M \rangle} = -2 \sum_{\substack{cd \\ \text{red}}} x_1 f^a(x_1) x_2 f^b(x_2) \sum_{\substack{cd \\ \text{blue}}} \langle d\phi_{cd} \rangle$$

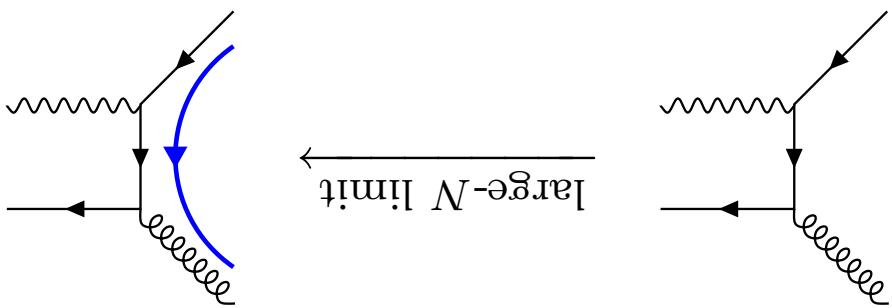


$$\frac{f_{\text{LT}}^{\perp(1/2)} = 2.76 x(1-x) p(x)}{(x) n(x)(1-x)}$$

Yuan; AIP Conf. Proc 842, 383 (2006)

$$\frac{\sum x_1 f_a(x_1) x_2 f_b(x_2) d\phi_{aq \leftrightarrow cd}}{\sum x_1 f_{\text{LT}}^{\perp(1/2)}(x_1) x_2 f_b(x_2)} = \frac{\langle d\phi_{UU} \rangle}{\langle \text{sign}(g\phi) d\phi_{TU} \rangle}$$





Dominant partonic channel:

Anselmino et al.; PRD72,094007(2005)

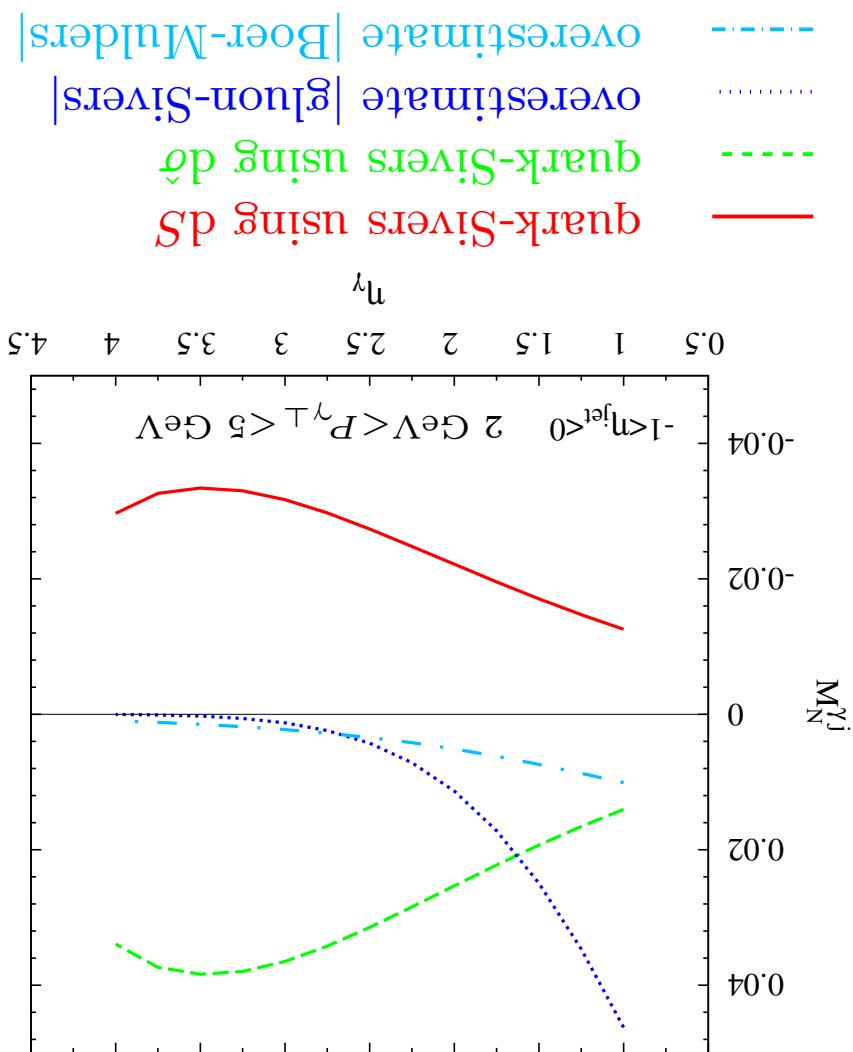
Sivers functions:

$$\frac{\sum_{\substack{aq \leftarrow cd}} x_1 f^a(x_1) x_2 f^b(x_2) d\phi_{aq \leftarrow cd}}{\sum_{\substack{qbSp \\ (I)}} x_1 f^I_T(x_1) x_2 f^b(x_2)} = \langle d\phi \rangle$$

$$M_{\gamma^*}^N = \frac{\langle 2P_{\gamma^*} \cos(\phi_{\gamma}) \sin(\phi_{\gamma}) d\phi / M \rangle}{M_N}$$

Bacchetta et al.; hep-ph/0703153

$d_{\downarrow} \gamma_j X$ asymmetry



asymmetries

- used to test our understanding of the physics underlying single-spin production in proton-proton scattering are processes that can be produced from Drell-Yan scattering, also dijet production or photon-jet interactions can be accounted for by taking gluonic pole cross sections as hard scattering functions
- In other processes, such as $d \downarrow p \rightarrow jjX$ the initial and final state due to the past pointing Wilson line
- In Drell-Yan scattering the Sivers function appears with a minus sign rise to leading order SSAs
- Final and initial state interactions, embodied by the Wilson lines, give

summary