

$X \pi\pi \leftarrow d_\downarrow d$ •

their consequences.

- Introduction to gauge-links and
- Introduction to PDFs.

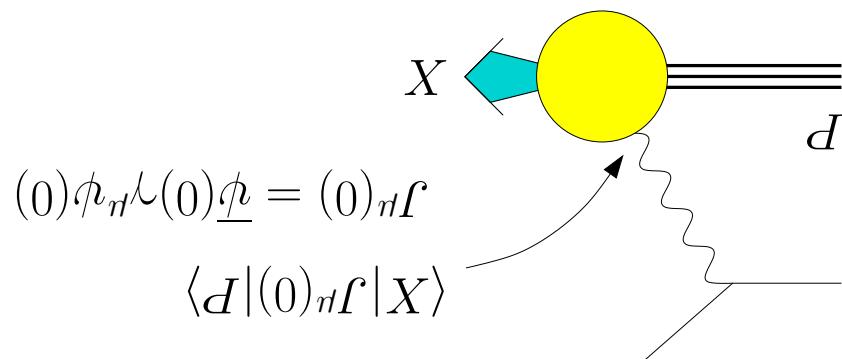
Cedran Bomhof

Sivers Effect Asymmetries in
Hadron-Hadron Collisions

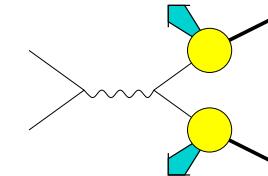
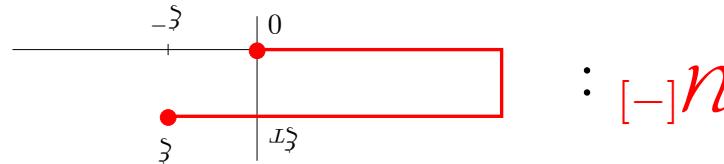
the $f(x)$ are universal

$$\langle D | \underline{\phi}(x) \underline{\phi}(0) \underline{n} | D \rangle \propto f(x)$$

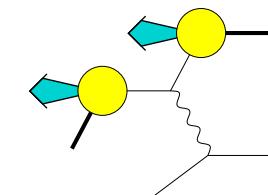
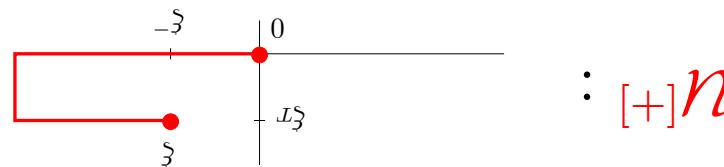
$$(x) d\omega_{\text{parton}}(x) \propto \exp \int \sum^b \propto d\omega_{\text{Hadron}}$$



deep inelastic scattering



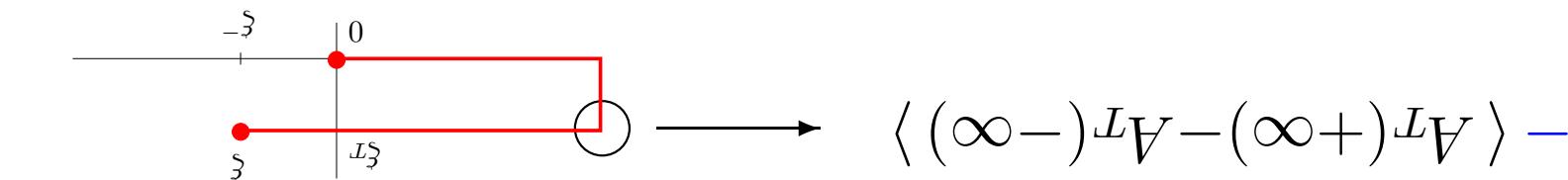
- Drell-Yan ($h_1 + h_2 \rightarrow \ell^+ \ell^-$)



- SIDIS ($\ell + h_1 \rightarrow \ell' + h_2$)

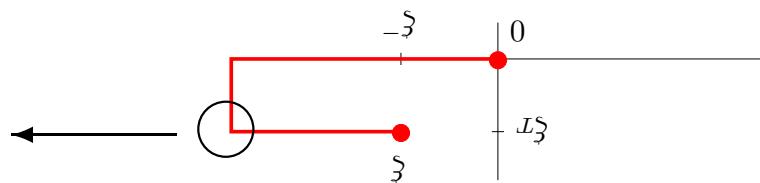
$$(z) A \cdot z p \int_C \exp i y d\theta = (\zeta, 0)_C$$

gauge-link in SIDIS and DY



(in light-cone gauge)

$$\langle (\infty-) A^T - (\infty+) A^T \rangle +$$



$$(x)_{(1)\top}^{L\Gamma f} \mp \infty$$

$$\langle (\xi) \phi_+ \wedge (\xi, 0)_{[\mp]} \mathcal{N}(0) \underline{\phi} \rangle Lf \text{ } \textcolor{brown}{k} \text{ } k_T p_- k_T \int \infty (x)_{[\mp]}^{(1)\top} (x)_{(1)\top}^{L\Gamma f}$$

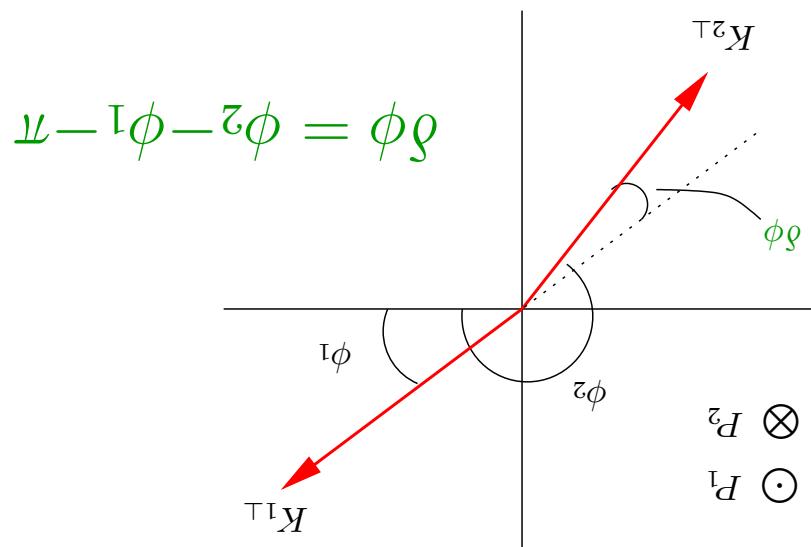
$$:(x)_{(1)\top}^{L\Gamma f}:$$

**T-odd distribution functions
consequences of gauge-links for**

is sensitive to intrinsic transverse momenta.

$$\langle \sin(\phi) \rangle = \int \frac{d\phi}{2\pi} \sin(\phi)$$

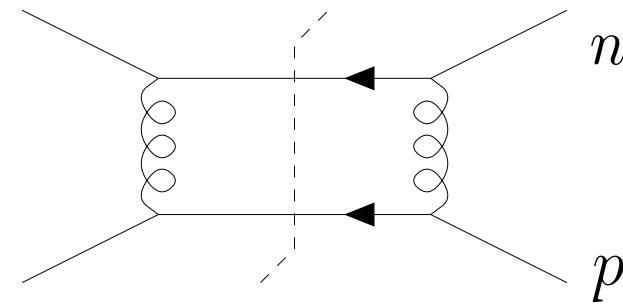
The weighed cross section



example of azimuthal asymmetry in $p \rightarrow \pi \pi X$ Transverse Plane:

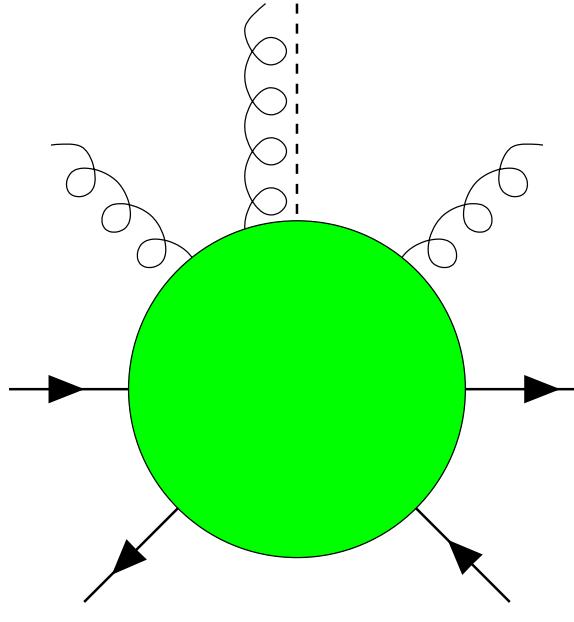
$$[+]n_{[\square]}n \times \frac{4}{1} - \epsilon/[+]n_{[\square]}n_{\text{Tr}} \times \frac{4}{5} =$$

$$\begin{array}{c} \text{Diagram: Two horizontal lines with red dots at ends. The top line is double-lined. A vertical dashed line passes through the middle.} \\ \times \frac{4}{1} - \end{array} \quad \begin{array}{c} \text{Diagram: Similar to the first, but the top line is orange.} \\ \times \frac{4}{5} \end{array}$$



e.g. ud -scattering:

example of gauge-link in $X \leftarrow d \downarrow d$

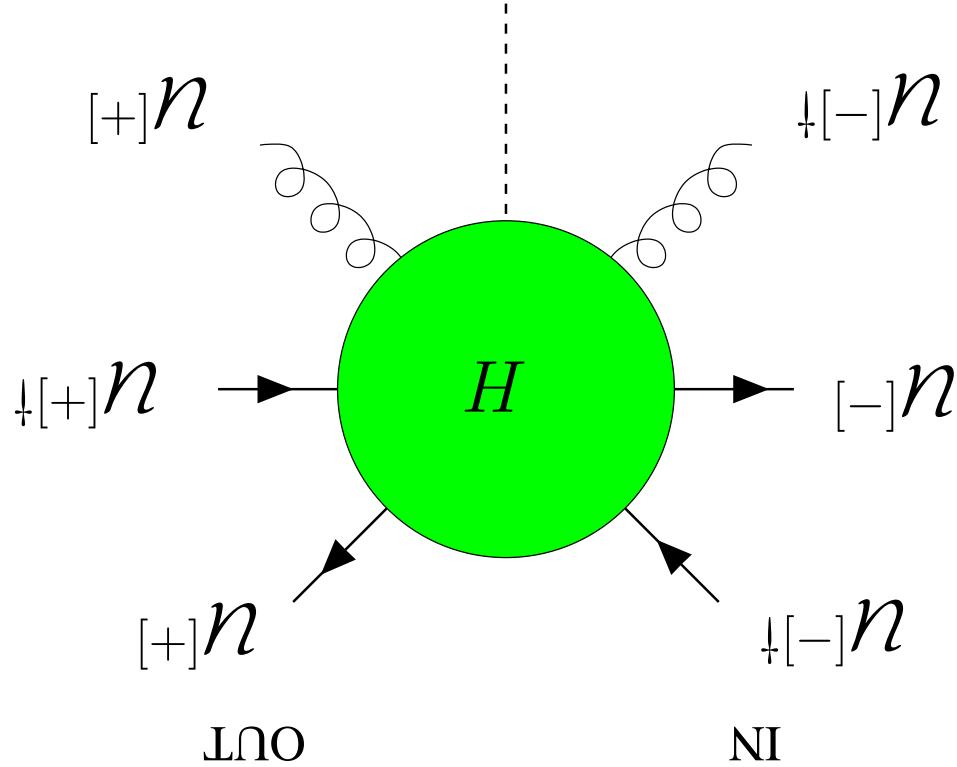


OUT

IN

Take some hard scattering process H .
Resumming all collinear gluon interactions ...

calculating gauge-links

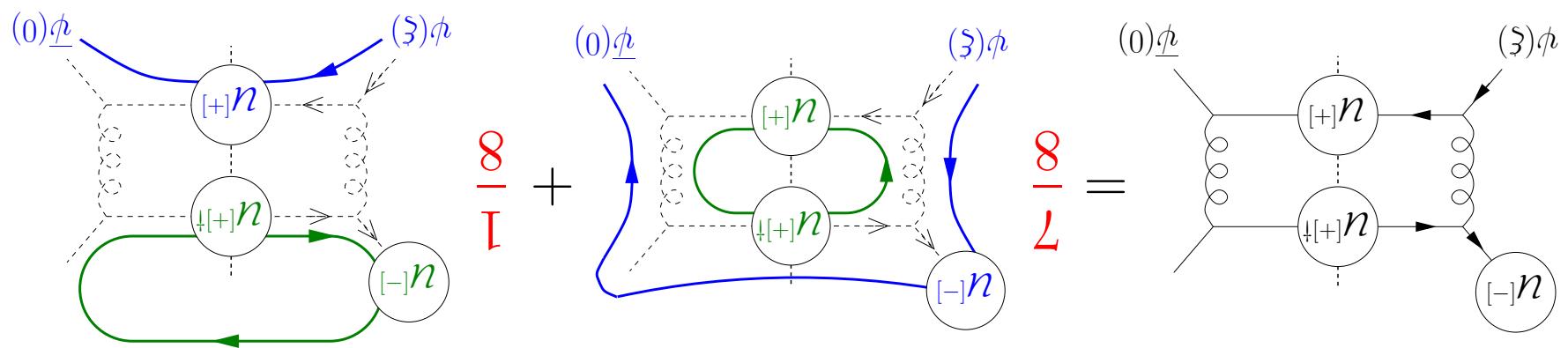


Take some hard scattering process H .
 Resumming all collinear gluon interactions ...
 amounts to attaching Wilson lines on all the external legs.

calculating gauge-links

$$\frac{\epsilon}{\downarrow[\square]n^{x_L}} [+]n \frac{8}{L} + [-]n \frac{8}{L} =$$

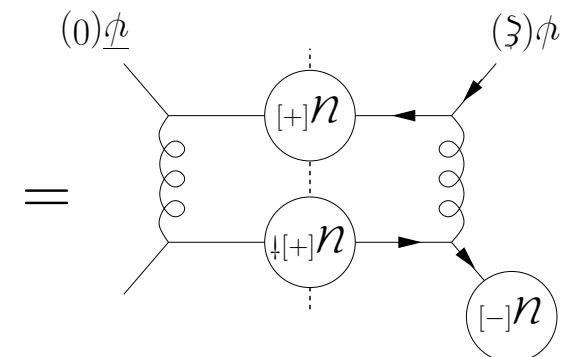
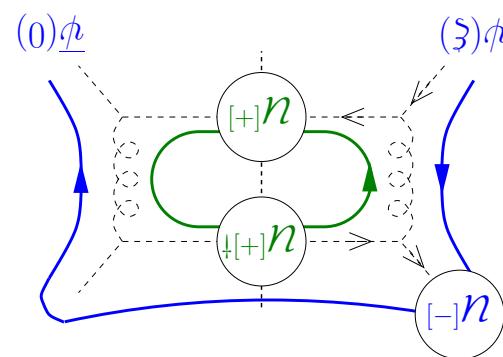
$$\frac{\epsilon}{[(-)n_{\downarrow(+)}n^{x_L}]^{+}} [+]n \frac{8}{L} + \frac{\epsilon}{[(+)n_{\downarrow(+)}n^{x_L}]^{-}} [-]n \frac{8}{L} =$$



calculating gauge-links, example: ud

$$[-]n =$$

$$\frac{N}{[+]n_{\downarrow}[+]n]x_L} [-]n =$$

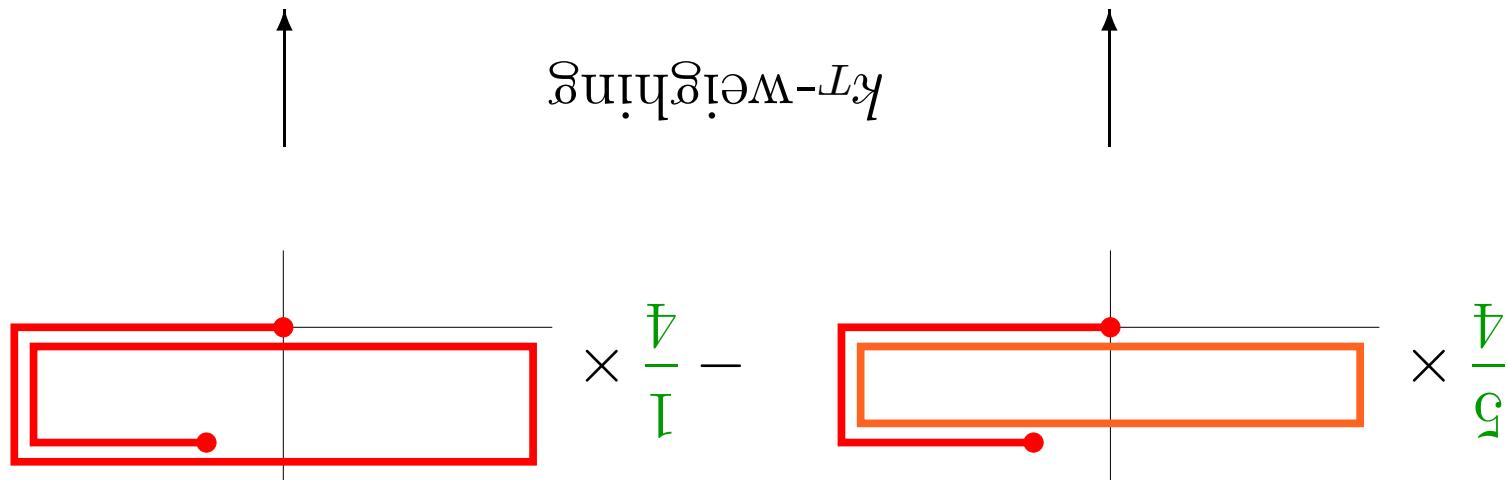


$$\infty \leftarrow N$$

calculating gauge-links, example: $ud \rightarrow ud$

$$\langle (\infty -)A^T(\infty) - A^T(-) \rangle \times \frac{2}{1} =$$

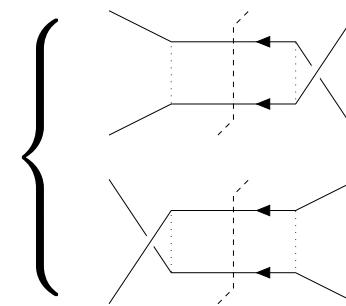
$$\langle (\infty -)A^T(\infty) - A^T(-) \rangle \textcolor{red}{3} \times \frac{4}{1} - \langle (\infty -)A^T(\infty) - A^T(-) \rangle \times \frac{4}{5}$$



consequence for T -odd functions

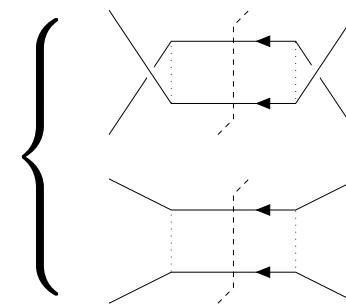
$$[-]n_{[\square]}n^{\frac{4}{5}} - \wp/[+]n(\square)n^{\frac{4}{5}} = n$$

$$\text{Sivers effect} = -\frac{2}{3} f_{T(I)}^{1T}$$



$$[-]n_{[\square]}n^{\frac{4}{5}} - \wp/[+]n(\square)n^{\frac{4}{5}} = n$$

$$\text{Sivers effect} = \frac{1}{2} f_{T(I)}^{1T}$$



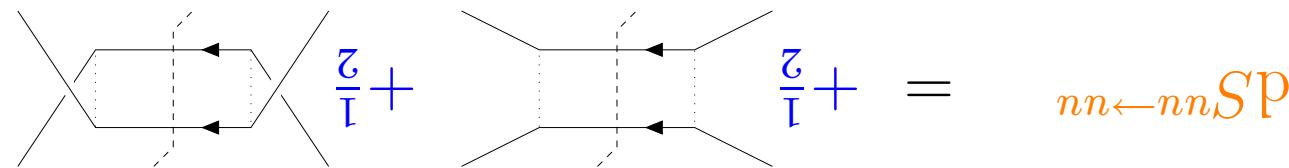
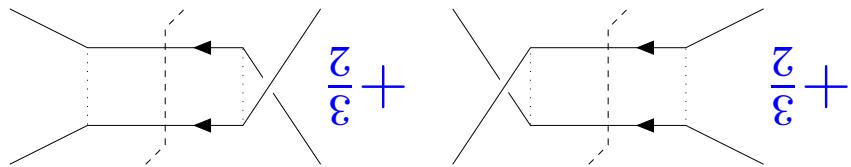
Sivers effects in identical-quark scattering

$$\begin{array}{c}
 -\frac{2}{3} f_{\perp T}^{LT}(1) \\
 \text{---} \\
 \text{---} \\
 -\frac{2}{3} f_{\perp T}^{LT}(1) \\
 + \quad \quad \quad + = \\
 \frac{1}{2} f_{\perp T}^{LT}(1) \quad \quad \quad \frac{1}{2} f_{\perp T}^{LT}(1) \\
 \text{---} \quad \quad \quad \text{---} \\
 \text{---} \quad \quad \quad \text{---} \\
 n \quad \quad \quad n
 \end{array}$$

using the 'universal' Sivers function $f_{\perp T}^{LT}(1)$

Sivers effects in identical-quark scattering

$$\not \rightarrow d\omega(nn \leftarrow nn)$$



with gluonic pole cross section

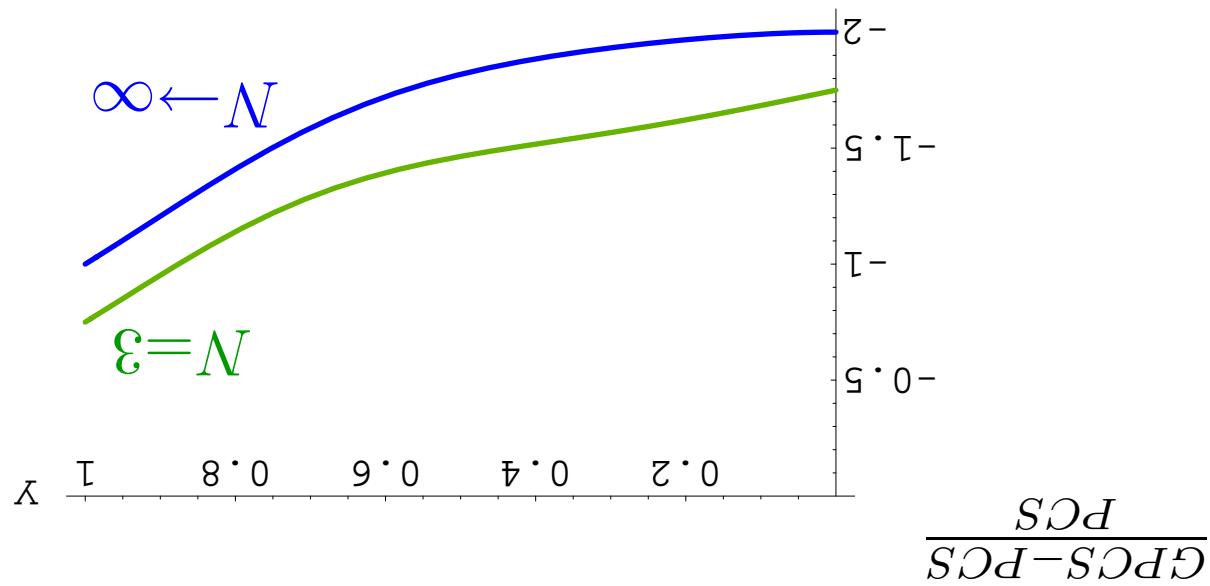
$$d\omega_{\text{HADRON}} \propto f_{\perp(1)}^{\perp L}(x_1) f_1(x_2) dS_{nn \leftarrow nn} D_1(z_1) D_1(z_2)$$

Hadronic scattering cross section

Sivers effects in identical-quark scattering

θ : polar angle of outgoing pion in c.o.m.

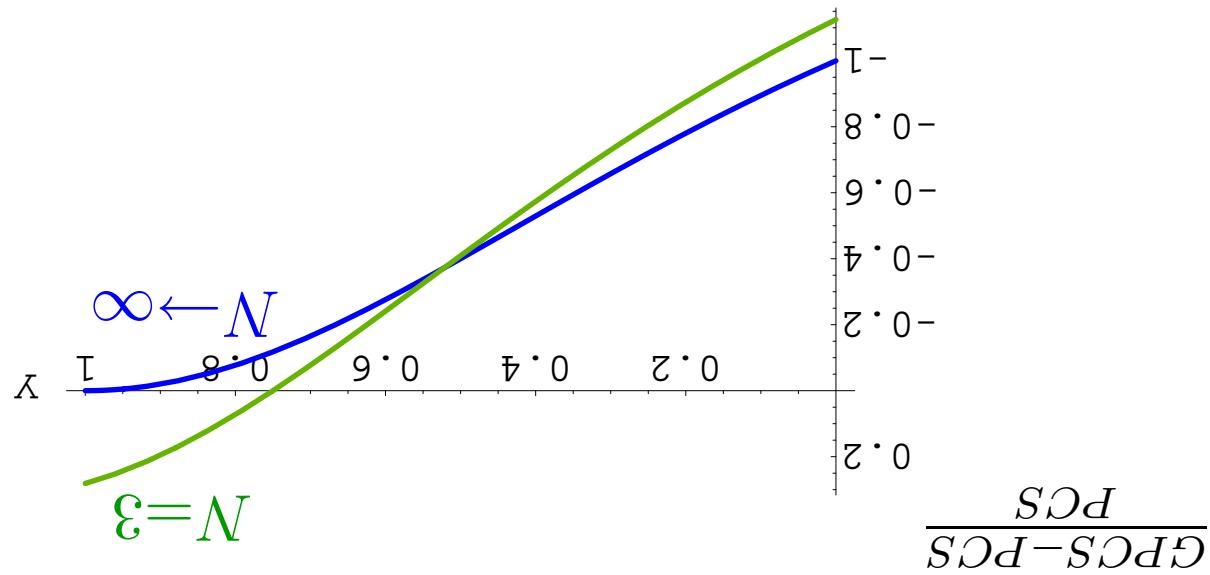
$$y = -t/s = \cos^2(\frac{\theta}{2})$$



comparing GPCS and PCS in $q\bar{q} \rightarrow b\bar{b}$

θ : polar angle of outgoing pion in c.o.m.

$$y = -t/s = \cos^2(\frac{\theta}{2})$$



comparing GPCS and PCS in $gg \rightarrow gg$

+ gluon-Sivers contributions

+ Collins effect contributions

$$\begin{aligned}
 & + M_2 \sum_{i=1}^{b_2} h_1(x_1) h_{1T}(x_2) D_1(z_1) D_1(z_2) \\
 & \frac{dS_{\text{BOER-MULDERS}}}{d\hat{t}} \\
 & \propto M_1 \sum_{i=1}^{b_1} f_1(x_1) f_{1T}(x_2) D_1(z_1) D_1(z_2) \\
 & \frac{dS_{\text{SIVVERS}}}{d\hat{t}}
 \end{aligned}$$

sin(ϕ) d ϕ
()

weighted scattering cross section

- Gauge-links can be calculated by resumming all initial and/or final state interactions of collinear gluons.
- Consequence of the gauge-links is that T -odd functions appear with different calculable strengths in the different scattering channels.
- Azimuthal asymmetries in $d \downarrow d \rightarrow \pi\pi X$ can be written as a convolution of universal PDFs, FFs and process-dependent hard parts, the gluonic pole cross sections are, in general, different from the partonic cross sections.

summary