

Universality of single spin asymmetries in hard processes

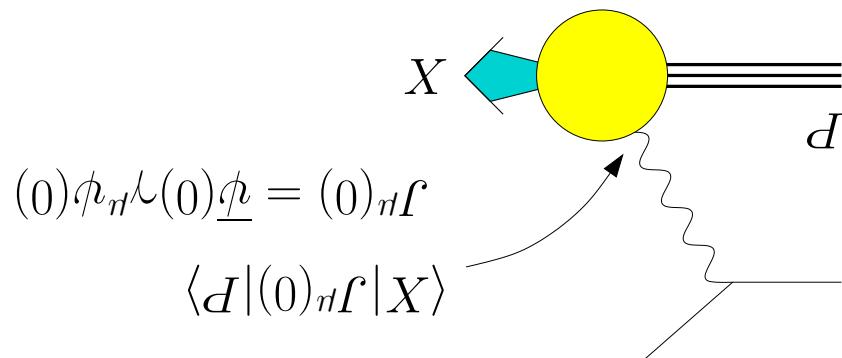
Cedran Bomhof

- $X \pi\pi \leftarrow d_\downarrow d$
- their consequences.
- Introduction to gauge-links and
- Introduction to PDFs.

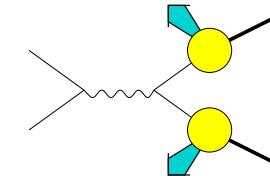
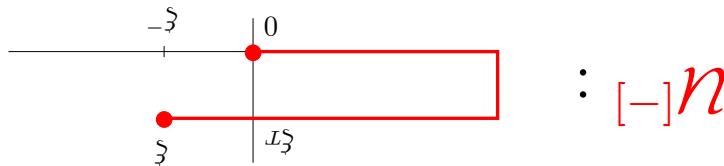
the $f(x)$ are universal

$$\langle D | (\textcolor{blue}{S}) \phi (\textcolor{red}{S}^* 0) \underline{n}(0) \underline{\phi} | D \rangle \propto f(x)$$

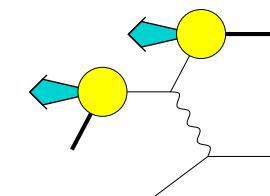
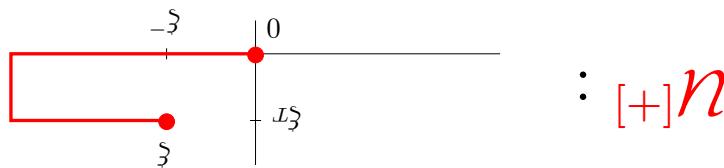
$$(x) d\omega_{\text{parton}}(x) f(x) \propto \int \sum_b d\omega_{\text{Hadron}}$$



deep inelastic scattering



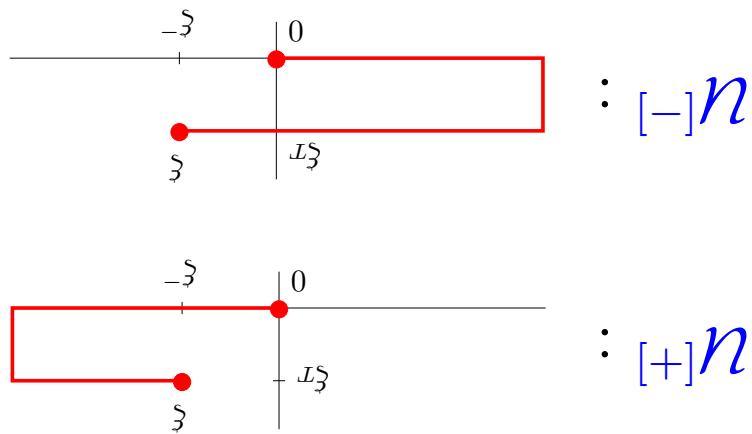
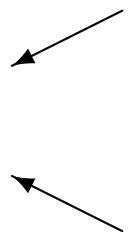
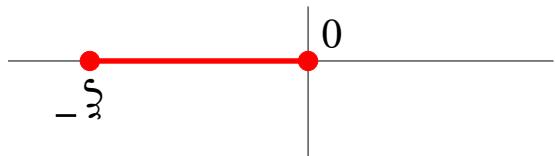
- DRILL-Yan ($h_1 + \underline{h}_2 + \gamma \leftarrow \underline{\gamma} + h_2$)



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

$$(z)A \cdot z p \int_C dy dx \epsilon dy = (\zeta, 0)_\mathcal{O} n$$

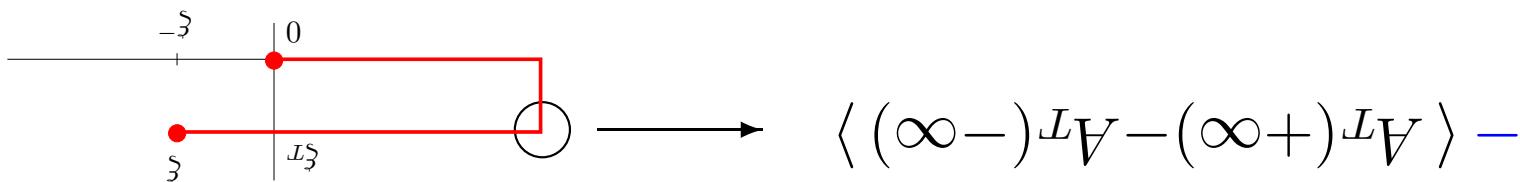
gauge-link



$$(x)^\dagger f \propto \langle (\xi) \phi_+ \nu(\xi, 0)_{[\mp]} n(0) \underline{\phi} \rangle T \int dk_- p_- k_-^2 \int \propto (x)_{[\mp]}^\dagger f$$

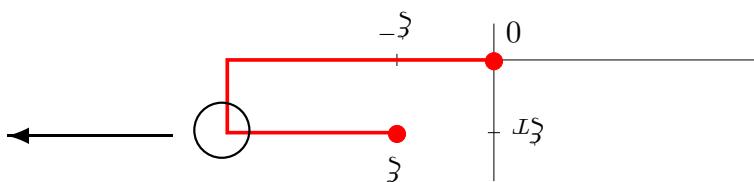
⇒ $f_1(x)$ is T -even functions, e.g.

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



(in light-cone gauge)

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



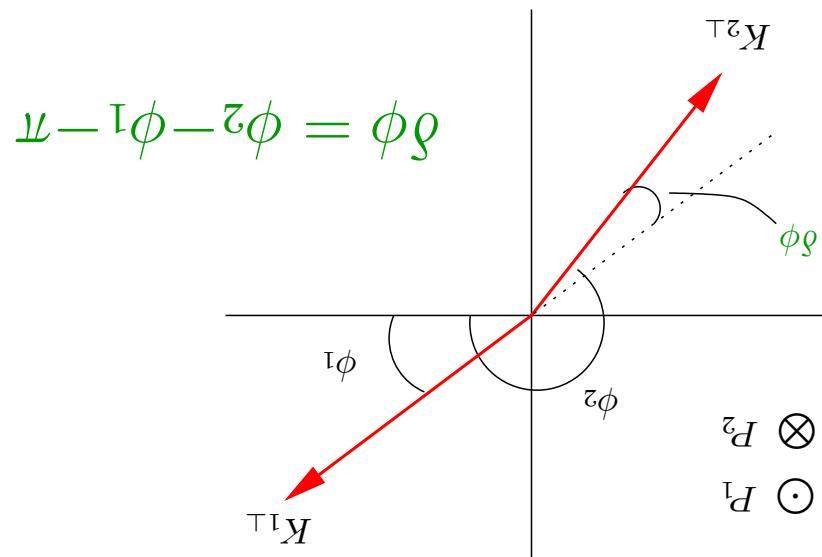
$$(x)_{(1)\top}^{L\Gamma f} \mp \infty$$

$$\langle (\zeta)\phi_+(\zeta,0)_{[\mp]} n(0)\underline{\phi} \rangle Lf \text{ is } k_T p_- k_T \int \infty (x)_{[\mp]}^{(1)\top} (L\Gamma f)$$

: $(x)_{(1)\top}^{L\Gamma f}$ \Leftarrow T -odd functions, e.g. Sivers f_T

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

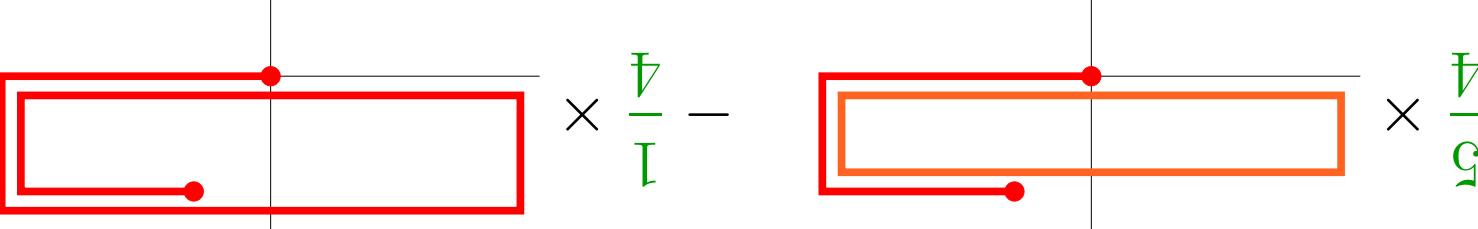
$$\langle \sin(\phi) \rangle = \int \frac{d\phi}{2\pi} \sin(\phi)$$



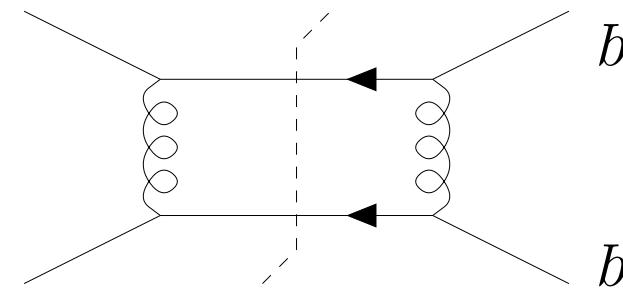
Transverse plane:

azimuthal asymmetry in $X_{\perp\perp} \leftarrow d_\downarrow d_\uparrow$

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



$$\times \frac{4}{1} -$$



e.g. $q\bar{q}$ -scattering:

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

$$\begin{array}{c}
 \text{Diagram 1: } \zeta \text{ on the left, } 0 \text{ on the right} \\
 \hline
 \text{Diagram 2: } \zeta \text{ on the left, } 0 \text{ on the right} \\
 = \\
 \times \frac{4}{1} - \text{Diagram 3: } \zeta \text{ on the left, } 0 \text{ on the right} \times \frac{4}{5} \\
 \uparrow \\
 \text{Diagram 4: } \zeta \text{ on the left, } 0 \text{ on the right} \times \frac{4}{1} - \text{Diagram 5: } \zeta \text{ on the right, } 0 \text{ on the left} \times \frac{4}{5} \\
 \uparrow
 \end{array}$$

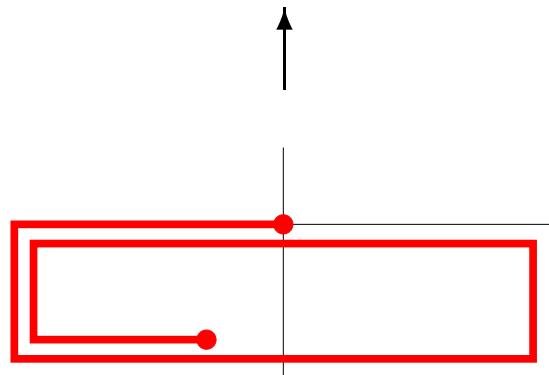
The diagram illustrates a subtraction of two terms. The first term is a horizontal line with a red dot at ζ and a black dot at 0. The second term is $\frac{4}{1}$ times a similar line where the red dot is at 0 and the black dot is at ζ . This is followed by a minus sign. The third term is $\frac{4}{5}$ times a horizontal line with a red dot at ζ and a black dot at 0. Below this, there is another minus sign. The fourth term is $\frac{4}{1}$ times a horizontal line with a red dot at ζ and a black dot at 0. The fifth term is $\frac{4}{5}$ times a horizontal line with a red dot at 0 and a black dot at ζ .

k_T -integration:

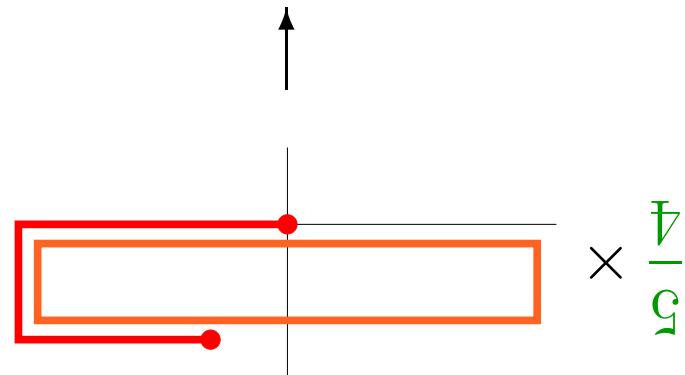
consequence for T -even functions

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

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



$$\times -\frac{4}{1}$$



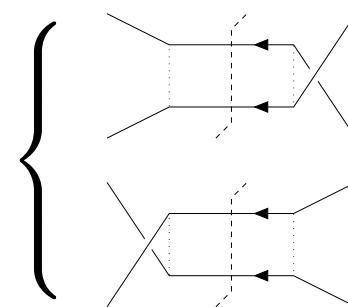
$$\times \frac{4}{5}$$

k_T -weighting:

consequence for T -odd functions

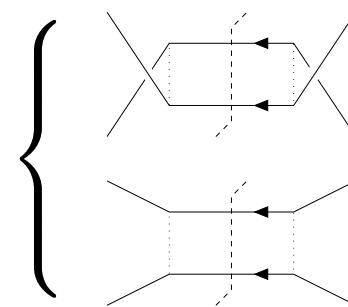
$$\text{Sivers effect} = -\frac{2}{3} f_{T(I)}^{LT}$$

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

 \Leftarrow 

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

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

 \Leftarrow 

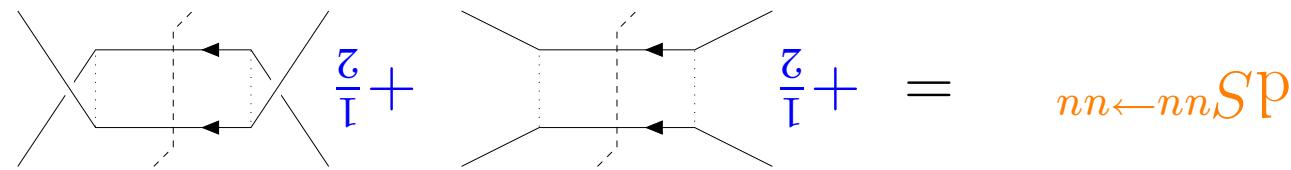
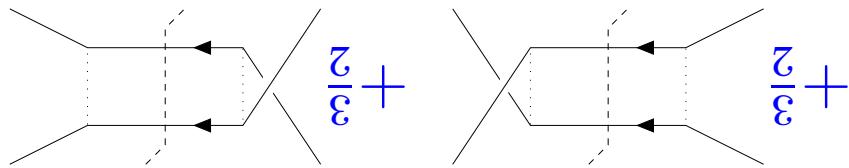
Sivers effects in identical-quark scattering

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

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

identical quark scattering

$\propto d\omega(nn \leftarrow nn)$



with gluonic pole cross section

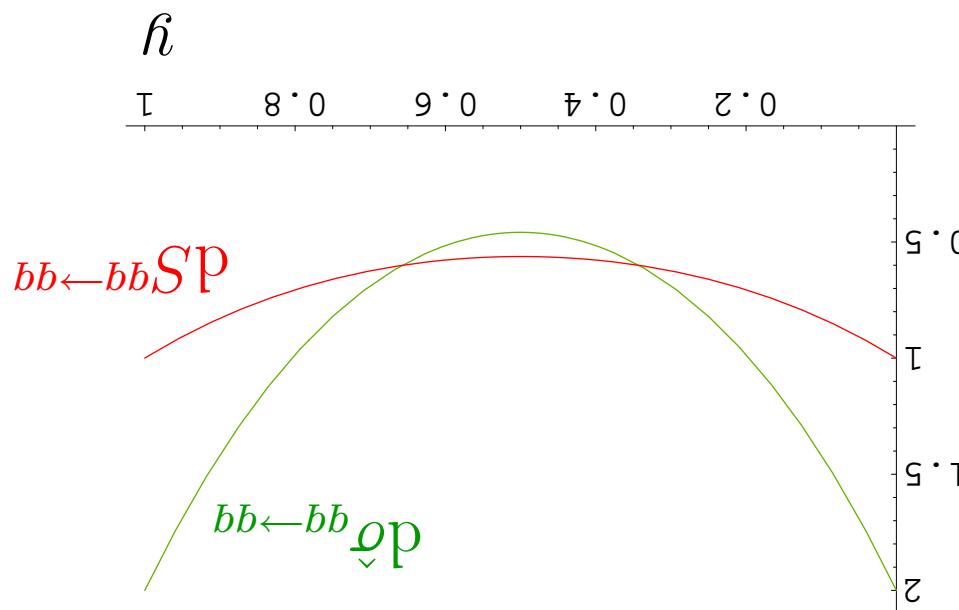
$$d\omega_{\text{HADRON}} \propto f_{\perp(1)}^{\perp}(x_1) f_1(x_2) dS_{nn \leftarrow nn} D_1(z_1) D_1(z_2)$$

Hadronic scattering cross section

identical quark scattering

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

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



comparison of partonic and
gluonic pole cross section

+ Gluon scattering contributions

+ Collins effect contributions

$$\begin{aligned}
 & + M_2 \sum_{i=1}^{b_2} h_1(x_1) h_{1T}(x_2) D_1(z_1) D_1(z_2) \\
 & \frac{d\sigma_{\text{BOER-MULDERS}}}{ds} \\
 & \propto M_1 \sum_{i=1}^{b_1} f_1(x_1) f_{1T}(x_2) D_1(z_1) D_1(z_2) \\
 & \frac{d\sigma_{\text{STIERS}}}{ds} \\
 & \langle \sin(\phi) d\phi \rangle
 \end{aligned}$$

weighted scattering cross section

- Gauge-links can be calculated by resumming all initial and/or final state interactions of collinear gluons.
- Gauge-links can be calculated by that T -odd functions appear with different calculable strengths in the different scattering channels.
- Consequence of the gauge-links is that T -odd 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