Gluon TMDs and Heavy Quark Pair Production in *ep* and *pp* Collisions

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3D Parton Distributions:
Path to the LHC

INFN - Laboratori Nazionali di Frascati
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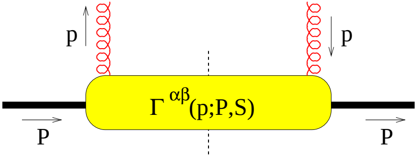
Outline

- Definition of gluon TMDs of the proton
- Azimuthal asymmetries in heavy quark pair and dijet production in DIS
  - Close analogy with study of quark TMDs in SIDIS
  - Maximal allowed asymmetries
- Related observables at LHC/RHIC: study of process dependence of TMDs
- Sign change test of gluon Sivers function and other T-odd TMDs

The gluon correlator describes the hadron → gluon transition



Gluon momentum $p^\alpha = x\,P^\alpha + p_T^\alpha + p^-\,n^\alpha$, with $n^2{=}0$ and $n{\cdot}P \neq 0$

Proton spin vector: $S^\alpha = \frac{S_L}{M_h}\left(P^\alpha - \frac{M_h^2}{P\cdot n}\,n^\alpha\right) + S_T$, with $S_L^2 + \boldsymbol{S}_T^2 = 1$

Definition of $\Gamma^{\alpha\beta}$ for a spin-1/2 hadron

$$\Gamma^{\alpha\beta} = \frac{n_\rho\, n_\sigma}{(P{\cdot}n)^2} \int \frac{\mathrm{d}(\xi{\cdot}P)\,\mathrm{d}^2\xi_T}{(2\pi)^3}\; e^{ip\cdot\xi}\,\langle P,S|\,\mathrm{Tr}\big[\,F^{\alpha\rho}(0)\,U_{[0,\xi]}\,F^{\beta\sigma}(\xi)\,U'_{[\xi,0]}\,\big]\,|P,S\rangle\,\big]_{\xi\cdot n=0}$$

Mulders, Rodrigues, PRD 63 (2001) 094021

U, U': process dependent gauge links

Transverse projectors: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$, $\quad \epsilon_T^{\alpha\beta} \equiv \epsilon^{\alpha\beta\gamma\delta} P_\gamma n_\delta$

Parametrization of $\Gamma^{\alpha\beta}$ (at "Leading Twist" and omitting gauge links)

$$\Gamma_U^{\alpha\beta}(x, \boldsymbol{p}_T) = \frac{x}{2}\left\{- g_T^{\alpha\beta} f_1^g(x, \boldsymbol{p}_T^2) + \left(\frac{p_T^\alpha p_T^\beta}{M_h^2} + g_T^{\alpha\beta}\frac{\boldsymbol{p}_T^2}{2M_h^2}\right) h_1^{\perp\, g}(x, \boldsymbol{p}_T^2)\right\} \quad \text{[unp. hadron]}$$

Mulders, Rodrigues, PRD 63 (2001) 094021
Meissner, Metz, Goeke, PRD 76 (2007) 034002

- f_1^g : unpolarized TMD gluon distribution
- $h_1^{\perp\, g}$: T-even distribution of linearly polarized gluons inside an unp. hadron

Parametrization of $\Gamma^{\alpha\beta}$ (at "Leading Twist" and omitting gauge links)

$$\Gamma_T^{\alpha\beta}(x,\boldsymbol{p}_T) = \frac{x}{2}\Big\{ g_T^{\alpha\beta}\,\frac{\epsilon_T^{\rho\sigma}\,p_{T\rho}\,S_{T\sigma}}{M_h}\,f_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2) + i\epsilon_T^{\alpha\beta}\,\frac{p_T\cdot S_T}{M_h}\,g_{1T}^{g}(x,\boldsymbol{p}_T^2)$$
$$-\frac{p_{T\rho}\epsilon_T^{\rho\{\alpha}S_T^{\beta\}} + S_{T\rho}\epsilon_T^{\rho\{\alpha}p_T^{\beta\}}}{4M_h}\,h_{1T}^{g}(x,\boldsymbol{p}_T^2) + \frac{p_{T\rho}\,\epsilon_T^{\rho\{\alpha}p_T^{\beta\}}}{2M_h^2}\,\frac{p_T\cdot S_T}{M_h}\,h_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2)\Big\}$$

[transv. pol. hadron]

Mulders, Rodrigues, PRD 63 (2001) 094021
Meissner, Metz, Goeke, PRD 76 (2007) 034002

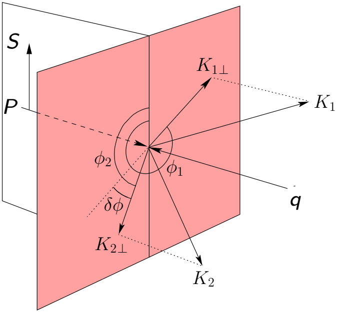
- $f_{1T}^{\perp\,g}$: T-odd distributions of unp. gluons inside a transversely pol. hadron
- h_{1T}^{g}, $h_{1T}^{\perp\,g}$: helicity flip distributions like h_{1T}^{q}, $h_{1T}^{\perp\,q}$, but T-odd, chiral even!

Transversity $h_1^q \equiv h_{1T}^q + \frac{\boldsymbol{p}_T^2}{2M_p^2}\,h_{1T}^{\perp\,q}$ survives under p_T integration, unlike h_1^g

Gluon TMDs probed directly in $e(\ell) + p(P, S) \to e(\ell') + Q(K_1) + \overline{Q}(K_2) + X$

Boer, Mulders, CP, Zhou, JHEP 1608 (2016) 001

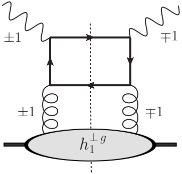
- the $Q\overline{Q}$ pair is almost back to back in the plane $\perp$ to q and P
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$$

$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2$$

$\Longrightarrow$ Correlation limit: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, $\quad |\boldsymbol{K}_\perp| \approx |\boldsymbol{K}_{1\perp}| \approx |\boldsymbol{K}_{2\perp}|$



y_1 (y_2) rapidities of Q ($\bar{Q}$) in the $\gamma^* p$ cms; x_B, y: DIS variables

$$\boldsymbol{q}_T = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T)$$
$$\boldsymbol{K}_\perp = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp)$$
$$\boldsymbol{S}_T = |\boldsymbol{S}_T|(\cos\phi_S, \sin\phi_S)$$ in a frame where $\phi_\ell = \phi_{\ell'} = 0$

At LO in pQCD: only $\gamma^* g \to Q\overline{Q}$ contributes

$$\mathrm{d}\sigma(\phi_S, \phi_T, \phi_\perp) = \mathrm{d}\sigma^U(\phi_T, \phi_\perp) + \mathrm{d}\sigma^T(\phi_S, \phi_T, \phi_\perp)$$

Angular structure of the unpolarized cross section for $ep \to e' Q\overline{Q}X$, $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\frac{\mathrm{d}\sigma^U}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}y\,\mathrm{d}x_B\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0^U + A_1^U\cos\phi_\perp + A_2^U\cos 2\phi_\perp\right\} f_1^g(x, \boldsymbol{q}_T^2) \quad + \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp\, g}(x, \boldsymbol{q}_T^2)$$
$$\times \left\{B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos 2(\phi_T - 2\phi_\perp)\right\}$$

The different contributions can be isolated by defining

$$\langle W(\phi_\perp, \phi_T)\rangle = \frac{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, W(\phi_\perp, \phi_T)\,\mathrm{d}\sigma}{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\,\mathrm{d}\sigma}\,, \qquad W = \cos 2\phi_T,\ \cos 2(\phi_\perp - \phi_T), \ldots$$

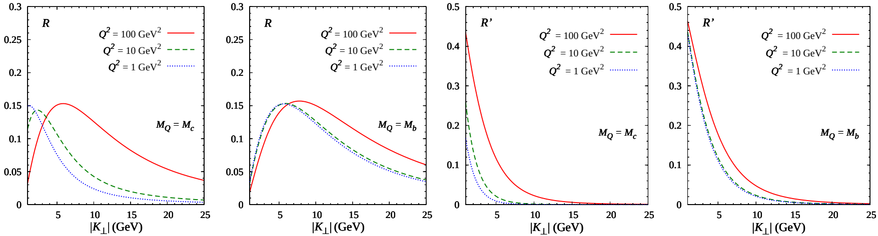
$h_1^{\perp\, g}$ in $ep \to e' Q\overline{Q} X$
Maximal asymmetries

Positivity bound for $h_1^{\perp\, g}$: $\quad |h_1^{\perp\, g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2}\; f_1^g(x, \boldsymbol{p}_T^2)$

It can be used to estimate maximal values of the asymmetries

Asymmetries usually larger when Q and $\overline{Q}$ have same rapidities

Upper bounds on $R \equiv |\langle \cos 2(\phi_T - \phi_\perp)\rangle|$ and $R' \equiv |\langle \cos 2\phi_T \rangle|$ at $y = 0.01$



CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024
Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001

SSAs in $ep^\uparrow \to e' Q\overline{Q} X$

Angular structure of the single polarized cross section for $ep^\uparrow \to e' Q\overline{Q} X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$
\begin{aligned}
\mathrm{d}\sigma^T \propto\ & \sin(\phi_S - \phi_T)\Big[A_0^T + A_1^T \cos\phi_\perp + A_2^T \cos 2\phi_\perp\Big] f_{1T}^{\perp\, g} + \cos(\phi_S - \phi_T)\Big[B_0^T \sin 2\phi_T \\
& + B_1^T \sin(2\phi_T - \phi_\perp) + B_2^T \sin 2(\phi_T - \phi_\perp) + B_3^T \sin(2\phi_T - 3\phi_\perp) + B_4^T \sin(2\phi_T - 4\phi_\perp)\Big] h_{1T}^{\perp\, g} \\
& + \Big[B_0'^{\,T} \sin(\phi_S + \phi_T) + B_1'^{\,T} \sin(\phi_S + \phi_T - \phi_\perp) + B_2'^{\,T} \sin(\phi_S + \phi_T - 2\phi_\perp) \\
& \quad + B_3'^{\,T} \sin(\phi_S + \phi_T - 3\phi_\perp) + B_4'^{\,T} \sin(\phi_S + \phi_T - 4\phi_\perp)\Big] h_{1T}^{g}
\end{aligned}
$$

The ϕ_S dependent terms can be singled out by means of azimuthal moments A_N^W

$$
A_N^{W(\phi_S, \phi_T)} \equiv 2\, \frac{\int \mathrm{d}\phi_T\, \mathrm{d}\phi_\perp\, W(\phi_S, \phi_T)\, \mathrm{d}\sigma_T(\phi_S, \phi_T, \phi_\perp)}{\int \mathrm{d}\phi_T\, \mathrm{d}\phi_\perp\, \mathrm{d}\sigma_U(\phi_T, \phi_\perp)}
$$

$$
A_N^{\sin(\phi_S - \phi_T)} \propto \frac{f_{1T}^{\perp\, g}}{f_1^g} \qquad A_N^{\sin(\phi_S + \phi_T)} \propto \frac{h_1^g}{f_1^g} \qquad A_N^{\sin(\phi_S - 3\phi_T)} \propto \frac{h_{1T}^{\perp\, g}}{f_1^g}
$$

Same modulations as in SIDIS for quark TMDs ($\phi_T \to \phi_h$)

Boer, Mulders, PRD D57 (1998) 5780

Omitted factors in $A_N^{\sin(\phi_S - 3\phi_T)}$, $A_N^{\sin(\phi_S + \phi_T)}$ $\to 0$ if $y \to 1$ ($x \to 0$ if $s/Q^2 \to \infty$)

SSAs in $ep^\uparrow \to e' Q\overline{Q} X$

$$\frac{A_N^{\sin(\phi_S - 3\phi_T)}}{A_N^{\sin(\phi_S + \phi_T)}} = -\frac{\boldsymbol{q}_T^2}{2M_p^2} \frac{h_{1T}^{\perp\, g}}{h_1^g}$$ direct probe of the relative magnitude of the two TMDs

Alternatively, azimuthal angles defined w.r.t. $\phi_\perp$ instead of ϕ_ℓ (integrated over)
$A_N^{W_\perp}$ with $W_\perp = \sin(\phi_S^\perp - \phi_T^\perp)$, $\sin(\phi_S^\perp + \phi_T^\perp)$, $\sin(\phi_S^\perp - 3\phi_T^\perp)$

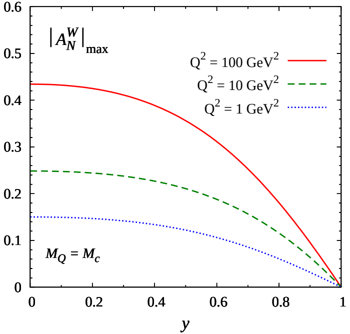
Positivity bounds of T-odd gluon TMDs used to estimate maximal SSAs

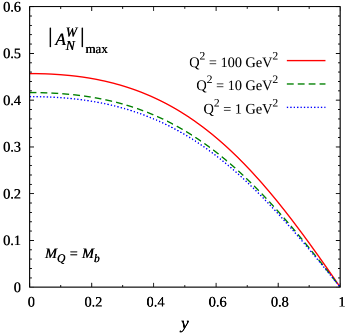
$$\frac{|\boldsymbol{p}_T|}{M_p} |f_{1T}^{\perp\, g}| \leq f_1^g \qquad \frac{|\boldsymbol{p}_T|}{M_p} |h_1^g| \leq f_1^g \qquad \frac{|\boldsymbol{p}_T|^3}{2M_p^3} |h_{1T}^{\perp\, g}| \leq f_1^g$$

Upper bound of the Sivers asymmetries is 1

SSAs A_N^W in $ep^\uparrow \to e' Q\overline{Q} X$
Upper bounds

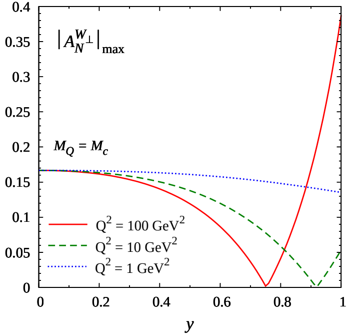
Maximal values for $|A_N^W|$, $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$ $\quad$ ($|\boldsymbol{K}_\perp| = 1$ GeV)

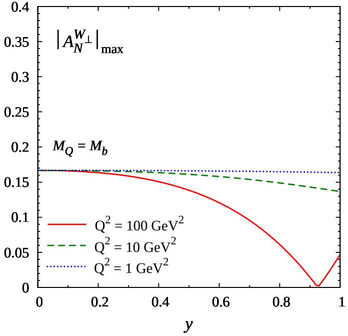




SSAs $A_N^{W_\perp}$ in $ep^\uparrow \to e' Q\overline{Q} X$
Upper bounds

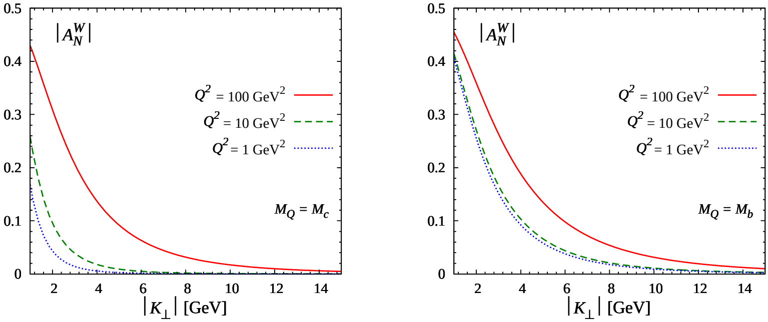
Maximal values for $|A_N^{W_\perp}|$, $W_\perp = \sin(\phi_S^\perp + \phi_T^\perp)$, $\sin(\phi_S^\perp - 3\phi_T^\perp)$ $\quad$ ($|\boldsymbol{K}_\perp| = 1$ GeV)



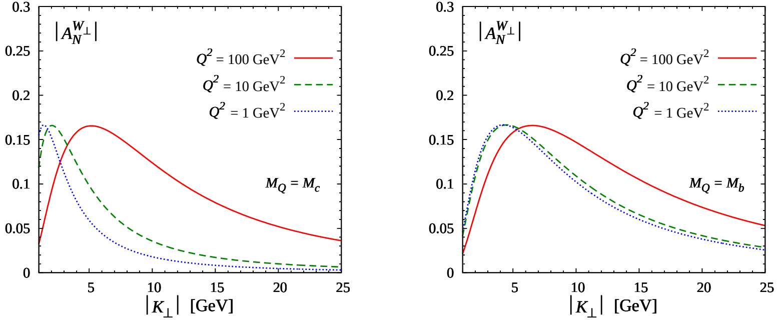


$|A_N^{W_\perp}|$ do not vanish when $y \to 0$, zero crossing

$|A_N^W|$ *vs* $|\boldsymbol{K}_\perp|$ at $y = 0.1$; same upper bounds as $|\langle \cos 2\phi_T \rangle|$



$|A_N^{W_\perp}|$ *vs* $|\boldsymbol{K}_\perp|$ at $y = 0.1$; same upper bounds as $|\langle \cos 2(\phi_T - \phi_\perp)\rangle|$

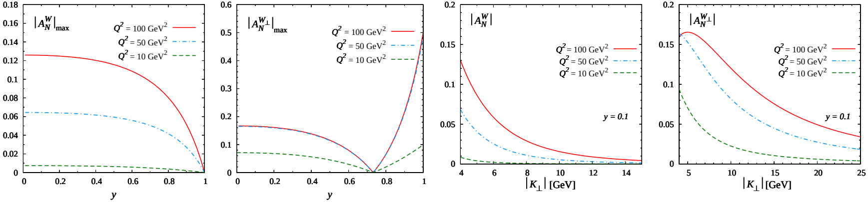


SSAs in $ep^{\uparrow} \to e'\,\mathrm{jet\,jet}\,X$

Results can be obtained by taking $M_Q = 0$ in the expressions for $ep \to e' Q\bar{Q}X$

Contribution to the denominator also from $\gamma^* q \to gq$, negligible at small-x

Upper bounds for A_N^W and $A_N^{W_\perp}$ for $K_\perp \geq 4$ GeV

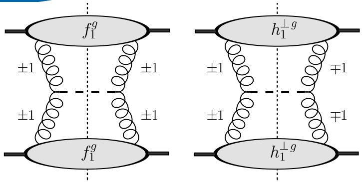


Asymmetries much smaller than in $c\bar{c}$ case for $Q^2 \leq 10$ GeV^2

Gluon polarization and the Higgs boson
$p\,p \to H\,X$ at the LHC

The dominant production channel is $gg \to H$

$h_1^{\perp\,g}$ contributes to the q_T-spectrum at LO

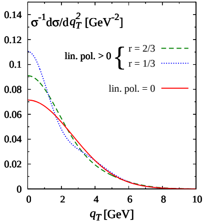


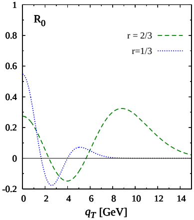
q_T-distribution of the Higgs boson

$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad R = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x,\boldsymbol{p}_T^2)$$

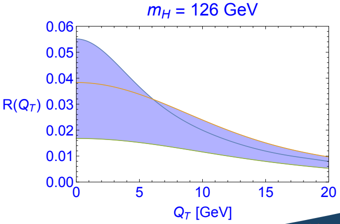
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002
Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Gaussian Model





TMD evolution



Study of $H \to \gamma\gamma$ and interference with $gg \to \gamma\gamma$

3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

$C = +1$ quarkonium production

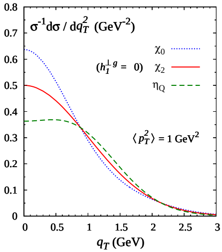
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

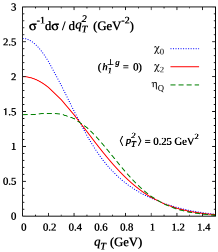
$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \left[1 - R(\boldsymbol{q}_T^2)\right] \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_{Q0})} \frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \left[1 + R(\boldsymbol{q}_T^2)\right] \qquad \text{[scalar]}$$

$$\frac{1}{\sigma(\chi_{Q2})} \frac{d\sigma(\chi_{Q2})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g$$

Boer, CP, PRD 86 (2012) 094007





Proof of factorization at NLO for $p\,p \to \eta_Q\, X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

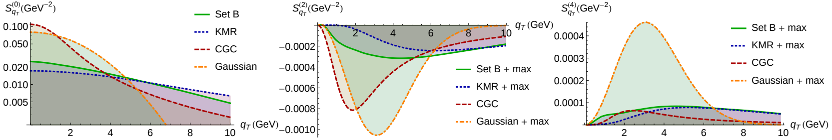
Study of $p\,p \to \eta_c\, X$ at NLO with TMD evolution (LHCb data)

Echevarria, Kasemets, Lansberg, CP, Signori, *in preparation* (2016)

$$p\, p \to J/\psi(\Upsilon) + \gamma\, X$$

First determination of $h_1^{\perp g}$ and f_1^g could be possible now at the LHC

Color Singlet mechanism dominates: TMD factorization might hold



den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

$$\frac{1}{\sigma}\frac{d\sigma}{d^2 q_T} \equiv \mathcal{S}^{(0)}_{q_T} \Longrightarrow f_1^g \otimes f_1^g \quad \left[h_1^{\perp g} \text{ does not contribute} \neq H + \text{jet}\right]$$

$$\mathcal{S}^{(2)}_{q_T} \equiv \langle \cos 2\phi \rangle_{q_T} \Longrightarrow f_1^g \otimes h_1^{\perp g} \qquad \mathcal{S}^{(4)}_{q_T} \equiv \langle \cos 4\phi \rangle_{q_T} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

The gluon Sivers function
$p^{\uparrow} p \to J/\psi + \gamma X$

Transversely polarized proton $\Longrightarrow$ Extraction of $f_{1T}^{\perp\, g}$

Possible at the future AFTER@LHC and, in principle, at RHIC

Angular structure of the cross section for $p^{\uparrow} p \to J/\psi + \gamma X$

$$\frac{\mathrm{d}\sigma_{UT}}{\mathrm{d}y_\psi\, \mathrm{d}y_\gamma\, \mathrm{d}^2\boldsymbol{K}_\perp\, \mathrm{d}^2\boldsymbol{q}_T} \propto \sin\phi_S\, f_1^g \otimes f_{1T}^{\perp\, g} + B \Big\{ \sin(\phi_S - 2\phi)\, f_1^g \otimes h_{1T}^g$$
$$+ \sin\phi_S \cos 2\phi\ [f_1^g \otimes h_{1T}^{\perp\, g} + h_1^{\perp\, g} \otimes f_{1T}^{\perp\, g}]$$
$$+ \sin\phi_S \cos 4\phi\ [h_1^{\perp\, g} \otimes h_{1T}^g + h_1^{\perp\, g} \otimes h_{1T}^{\perp\, g}]$$
$$+ \cos\phi_S \sin 2\phi\ [f_1^g\, \overline{\otimes}\, h_{1T}^{\perp\, g} + h_1^{\perp\, g}\, \overline{\otimes}\, f_{1T}^{\perp\, g}]$$
$$+ \cos\phi_S \sin 4\phi\ [h_1^{\perp\, g}\, \overline{\otimes}\, h_{1T}^g + h_1^{\perp\, g}\, \overline{\otimes}\, h_{1T}^{\perp\, g}] \Big\} \qquad \phi \equiv \phi_T - \phi_\perp$$

Lansberg, CP, Schlegel, in preparation

$pp \to J/\psi\, J/\psi\, X$ under study, in a region where Color Singlet dominates

Complementary Processes

$ep \to e' Q\overline{Q} X$, $ep \to e'\, \mathrm{jet}\, \mathrm{jet}\, X$ probe gluon TMDs with $[++]$ gauge links (WW)

$pp \to \gamma\, \mathrm{jet}\, X$ probes an entirely independent gluon TMD: $[+-]$ links (dipole)

Talk by D. Boer

Related Processes

In $pp \to \gamma\gamma X$ and/or other CS final state: gluon TMDs have $[--]$ gauge links

Qiu, Schlegel, Vogelsang, PRL **107** (2011) 062001

Analogue of the sign change of $f_{1T}^{\perp\, q}$ between SIDIS and DY (true also for h_1^g and $h_{1T}^{\perp\, g}$)

$$f_{1T}^{\perp\, g\, [e\, p^{\uparrow} \to e'\, Q\overline{Q}\, X]} = -f_{1T}^{\perp\, g\, [p^{\uparrow}\, p \to \gamma\, \gamma\, X]}$$

Motivation to study the gluon Sivers effect at RHIC and AFTER@LHC

Brodsky, Fleuret, Hadjidakis, Lansberg, Phys. Rept. 522 (2013) 239

T-even gluon TMDs probed in DIS are the same as in $pp \to H/\eta_{c,b}/\ldots X$

$$h_1^{\perp\, g\, [e\, p \to e'\, Q\overline{Q}\, X]} = h_1^{\perp\, g\, [p\, p \to H\, X]}$$

TMD observables at EIC and LHC can be either related or complementary

Conclusions

- Azimuthal asymmetries in heavy quark pair and dijet production in DIS could probe WW-type gluon TMDs (similar to SIDIS for quark TMDs)
- Asymmetries maximally allowed by positivity bounds of gluon TMDs can be sizeable in specific kinematic region
- Study of TMDs and asymmetries in the small-x region

  Boer, Mulders, CP, Zhou, JHEP 1608 (2016) 001

  Talks by D. Boer and P. Mulders
- Different behaviour of WW and dipole gluon TMDs accessible at RHIC could be tested experimentally
- Such observables could be part of both the *spin* and the *small-x* program at a future EIC