# Momentum imbalance observables as a probe of gluon TMDs

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Opening new horizons

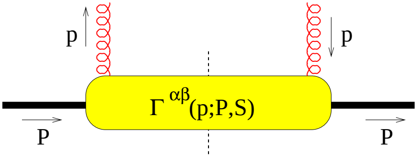
# Outline

- Gluon TMDs for a spin-1/2 hadron
- Observables depending on transverse momentum imbalance in:
  - Electroproduction of heavy quark and jet pairs
  - Hadroproduction of Higgs+jet
  - Hadroproduction of $J/\psi(\Upsilon) + \gamma$
- Conclusions

# Gluon correlator

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 $n{\cdot}P{=}1$
transverse projectors: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$, $\epsilon_T^{\alpha\beta} \equiv \epsilon^{\alpha\beta\gamma\delta} P_\gamma n_\delta$
Spin vector: $S^\alpha = S_L\left(P^\alpha - M_h^2\,n^\alpha\right) + S_T$, with $S_L^2 + \boldsymbol{S}_T^2 = 1$




Definition for a spin-1/2 hadron, in terms of QCD operators on the light front (LF) $\xi \cdot n = 0$ [$U$, $U'$: process dependent gauge links]:

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

Mulders, Rodrigues, PRD 63 (2001) 094021

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

$$\Phi_U^{\alpha\beta}(x, \boldsymbol{p}_T) = \frac{1}{2x}\left\{-\, g_T^{\alpha\beta} f_1^g(x,\, \boldsymbol{p}_T^2) + \left(\frac{p_T^\alpha p_T^\beta}{M_h^2} + g_T^{\alpha\beta}\, \frac{\boldsymbol{p}_T^2}{2M_h^2}\right) h_1^{\perp\, g}(x,\, \boldsymbol{p}_T^2)\right\} \text{[unp. hadron]}$$

$$\Phi_L^{\alpha\beta}(x,\, \boldsymbol{p}_T) = \frac{1}{2x}\, S_L \left\{ i\epsilon_T^{\alpha\beta}\, g_{1L}^g(x, \boldsymbol{p}_T^2) + \frac{p_{T\rho}\, \epsilon_T^{\rho\{\alpha}\, p_T^{\beta\}}}{M_h^2}\, h_{1L}^{\perp\, g}(x, \boldsymbol{p}_T^2)\right\} \text{[long. pol. hadron]}$$

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

[transv. pol. hadron]

- $f_1^g$ : unpolarized TMD gluon distribution
- $h_1^{\perp\, g}$: (helicity-flip, rank-2 in $p_T$) distribution of linearly polarized gluons inside an unpol. hadron. It is $T$-even $\Longrightarrow$ $h_1^{\perp\, g} \neq 0$ in absence of ISI or FSI
  Mulders, Rodrigues, PRD 63 (2001) 094021
- $f_{1T}^{\perp\, g}$: $T$-odd distribution of unp. gluons inside a transversely pol. hadron
  Sivers, PRD 41 (1990) 83

# Phenomenology of gluon TMDs

All TMDs receive contributions from ISI/FSI, which can render them process dependent and even lead to factorization breaking effects

Several processes have been suggested to access $f_{1T}^{\perp g}$

Boer, Lorcé, CP, Zhou, 1504.04332

$h_1^{\perp g}$ is still unknown experimentally. It can be probed by looking at the transverse momentum imbalance of two particles or jets:

- In $p\,p$ collisions, *i.e.* $p\,p \to \gamma\,\gamma\,X$ or $J/\psi\,\gamma\,X$ (RHIC, LHC)
  Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001
  den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001
- In $e\,p$ collisions, *i.e.* simpler measurements of azimuthal asymmetries in heavy quark or jet pair production (EIC, LHeC)

$$\mathcal{A}_{2\phi} \quad \sim \quad \cos 2\phi \; h_1^{\perp g} \qquad \text{[Only one TMD involved]}$$

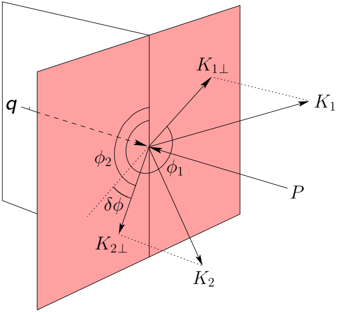
Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001

# Electroproduction of heavy quarks

$$e(\ell) + h(P) \;\rightarrow\; e(\ell') + Q(K_1) + \bar{Q}(K_2) + X$$

the $Q\bar{Q}$ 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 $\gamma^*$

$\phi_\ell = \phi_{\ell'} = 0$




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

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

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

# Calculation of the cross section

## TMD Master Formula

$$d\sigma = \frac{1}{2s}\frac{d^3\ell'}{(2\pi)^3\,2E'_e}\frac{d^3K_1}{(2\pi)^3\,2E_1}\frac{d^3K_2}{(2\pi)^3\,2E_2}\int dx\, d^2\boldsymbol{p}_T\,(2\pi)^4\delta^4(q+p-K_1-K_2)$$

$$\times\sum_{a,b,c}\frac{1}{Q^4}\,L(\ell,q)\otimes\Phi_a(x,\boldsymbol{p}_T)\otimes\left|H_{\gamma^*\,a\to b\,c}(q,p,K_1,K_2)\right|^2$$

Leptonic tensor: $L^{\mu\nu}(\ell,q) = -g^{\mu\nu}\,Q^2 + 2\,(\ell^\mu\ell'^\nu + \ell^\nu\ell'^\mu)$, $\quad Q^2 = -q^2$

At LO in pQCD: $|H_{\gamma^*\,a\to b\,c}|^2 = |H_{\gamma^*\,g\to Q\,\bar{Q}}|^2$ from the diagrams

$\gamma^* g \to Q\bar{Q}$:

# Angular structure of the cross section

In the photon-hadron cms: $y_1$ ($y_2$) rapidity of $Q$ ($\bar{Q}$)

DIS variables: $x_B = \frac{Q^2}{2P\cdot q}\,,\quad y = \frac{P\cdot q}{P\cdot \ell}$

$$\boldsymbol{q}_T = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T) \quad \boldsymbol{K}_\perp = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp)$$

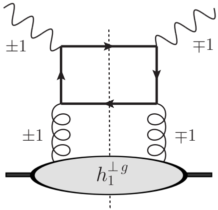
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}y\,\mathrm{d}x_B\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0 + A_1\cos\phi_\perp + A_2\cos 2\phi_\perp\right\} f_1^g + \frac{\boldsymbol{q}_T^2}{M_h^2}\, h_1^{\perp\, g}\Big\{B_0\cos 2(\phi_\perp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

Integrating over $\phi_T$, $\phi_\perp \Longrightarrow A_0\, f_1^g$

# $q_T$-imbalance observables

Example of diagram contributing to $B_i^{(\prime)}$: gluon helicities flip

$A_i$: gluon helicities do not flip



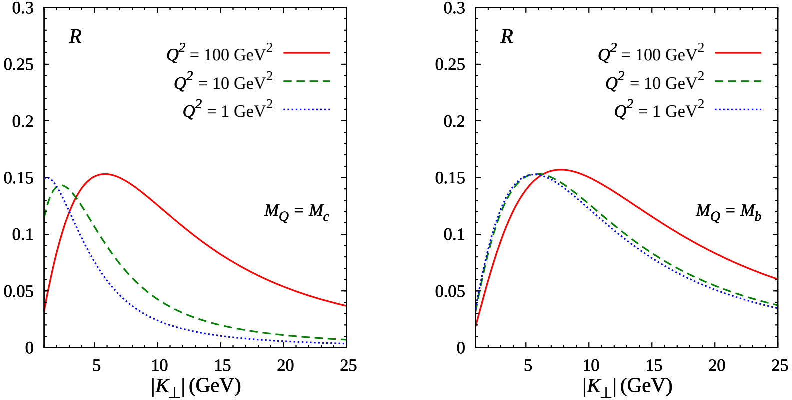

The different contributions can be isolated by defining

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

Positivity bound: $\quad |h_1^{\perp\, g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_h^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2) \qquad \boldsymbol{p}_T^2 = \boldsymbol{q}_T^2$

# Maximum asymmetries in $ep \to e' Q \bar{Q} X$

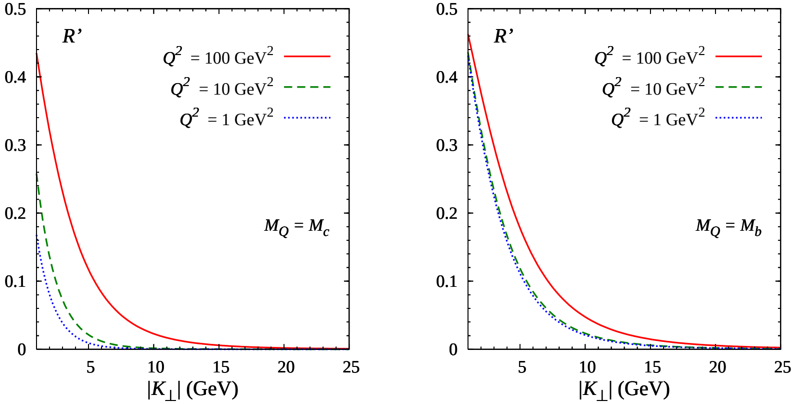
$R$: upper bound on $|\langle \cos 2(\phi_\perp - \phi_T) \rangle|$




CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024

# Maximum asymmetries in $ep \to e' Q \bar{Q} X$

$R$: upper bound on $|\langle \cos 2\phi_T \rangle|$




CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024

# Dijet production in *ep* and *pp* collisions

Results for $eh \to e' \,\mathrm{jet}\,\mathrm{jet}\, X$ can be obtained by taking $M_Q = 0$ in the expressions for the asymmetries in $ep \to e' Q\bar{Q}X$.
The denominator receives a contribution also from $\gamma^* q \to gq$

$h_1^{\perp\, g}$ contributes to the dijet imbalance in hadronic collisions, commonly used to extract the average partonic $p_T$. Complication!

Boer, Mulders, CP, PRD 80 (2009) 094017

Azimuthal asymmetries in $pp \to Q\bar{Q}X$ and $pp \to \mathrm{jet}\,\mathrm{jet}\, X$ suffer from factorization breaking contributions and would allow us to quantify the importance of ISI/FSI

Rogers, Mulders, PRD 81 (2010) 094006

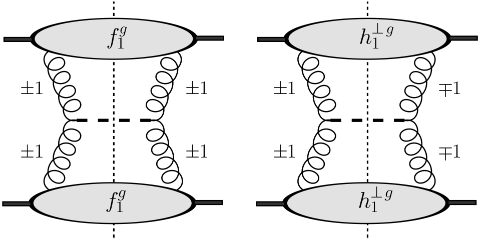
# $h_1^{\perp\, g}$ in $pp \to H\, X$

Talks by D. Boer and M. Echevarria

Higgs boson production happens mainly via $gg \to H$

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011) 297




The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low $q_T$

Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002

Echevarria, Kasemets, Mulders, CP, arXiv:1502.05354

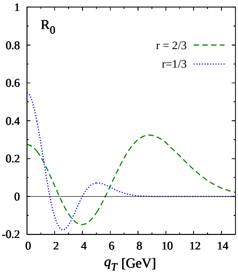
## Transverse spectrum of the Higgs boson

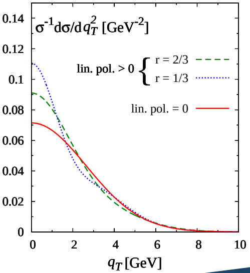
$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad R_0 = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x,\boldsymbol{p}_T^2)$$

Gaussian model for both $f_1^g$ and $h_1^{\perp\,g}$:

$$f_1^g(x,\boldsymbol{p}_T^2) = \frac{f_1^g(x)}{\pi\langle p_T^2\rangle} \exp\left(-\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right)$$

$$h_1^{\perp g}(x,\boldsymbol{p}_T^2) = \frac{M^2 f_1^g(x)}{\pi\langle p_T^2\rangle^2}\,\frac{2(1-r)}{r} \exp\left(1 - \frac{1}{r}\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right) \qquad 0 < r < 1$$




$\langle p_T^2\rangle = 7\ \mathrm{GeV}^2$

# Higgs plus jet production

Motivations: azimuthal asymmetries can be defined [$\neq pp \to HX$]
study of the TMD evolution by tuning the hard scale
Nonuniversality and factorization breaking effects

Boer, CP, PRD 91 (2015) 074024

## TMD Master Formula

$$d\sigma = \frac{1}{2s} \frac{\mathrm{d}^3 \boldsymbol{K}_H}{(2\pi)^3\, 2K_H^0} \frac{\mathrm{d}^3 \boldsymbol{K}_\mathrm{j}}{(2\pi)^3\, 2K_\mathrm{j}^0} \sum_{a,b,c} \int \mathrm{d}x_a\, \mathrm{d}x_b\, \mathrm{d}^2 \boldsymbol{p}_{aT}\, \mathrm{d}^2 \boldsymbol{p}_{bT}\, (2\pi)^4$$
$$\times\, \delta^4(p_a + p_b - q)\, \mathrm{Tr}\left\{ \Phi_a(x_a, \boldsymbol{p}_{aT}) \Phi_b(x_b, \boldsymbol{p}_{bT}) \left| \mathcal{M}^{ab \to Hc} \right|^2 \right\}$$

Higgs and jet almost back to back in the $\perp$ plane: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

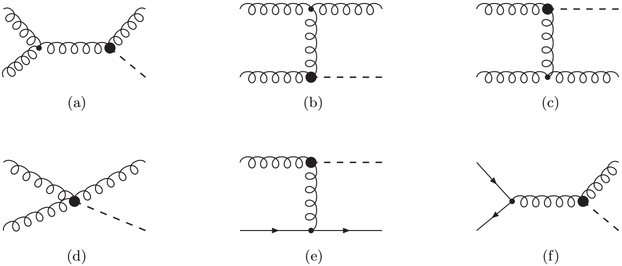
$$\boldsymbol{q}_T = \boldsymbol{K}_{HT} + \boldsymbol{K}_{\mathrm{j}T}, \qquad \boldsymbol{K}_\perp = (\boldsymbol{K}_{HT} - \boldsymbol{K}_{\mathrm{j}T})/2$$

fwo

# Feynman diagrams

At LO in pQCD the partonic subprocesses that contribute are

$$g\,g \to H\,g \qquad g\,q \to H\,q \qquad q\,\bar{q} \to H\,g$$




Quark masses taken to be zero, except for $M_t \to \infty$

Kauffman, Desai, Risal, PRD 55 (1997) 4005

No indications that TMD factorization can be broken due to color entanglement

Rogers, Mulders, PRD 81 (2010) 094006

# Angular structure of the cross section

Focus on $gg \to Hg$ (dominant at the LHC). In the hadronic c.m.s.:

$$\boldsymbol{q}_T = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T) \quad \boldsymbol{K}_\perp = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp) \quad \phi \equiv \phi_T - \phi_\perp$$

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}y_H\,\mathrm{d}y_j\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \qquad \frac{\mathrm{d}\sigma}{\sigma} \equiv \frac{\mathrm{d}\sigma}{\int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2 \int_0^{2\pi} \mathrm{d}\phi\,\mathrm{d}\sigma}$$

## Normalized cross section for $p\,p \to H\,\mathrm{jet}\,X$

$$\frac{\mathrm{d}\sigma}{\sigma} = \frac{1}{2\pi}\,\sigma_0(\boldsymbol{q}_T^2)\left[1 + R_0'(\boldsymbol{q}_T^2) + R_2(\boldsymbol{q}_T^2)\cos 2\phi + R_4(\boldsymbol{q}_T^2)\cos 4\phi\right]$$

$$\sigma_0(\boldsymbol{q}_T^2) \equiv \frac{f_1^g \otimes f_1^g}{\int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2\, f_1^g \otimes f_1^g}$$

# TMD observables

The three contributions can be isolated by defining the observables

$$\langle \cos n\phi \rangle_{q_T} \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi \, \cos n\,\phi \, \mathrm{d}\sigma}{\mathrm{d}\sigma} \qquad (n = 0, 2, 4)$$

such that

$$\langle \cos n\phi \rangle = \int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2 \, \langle \cos n\phi \rangle_{q_T}$$

$$\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \langle 1 \rangle_{q_T} \implies 1 + R_0' \propto f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi \rangle_{q_T} \implies R_2 \propto f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi \rangle_{q_T} \implies R_4 \propto h_1^{\perp g} \otimes h_1^{\perp g}$$

# Models for the TMD gluon distributions

## $f_1^g$: Gaussian + tail

$$f_1^g(x, \boldsymbol{p}_T^2) = f_1^g(x)\, \frac{R^2}{2\pi}\, \frac{1}{1 + \boldsymbol{p}_T^2\, R^2} \qquad R = 2\ \mathrm{GeV}^{-1}$$

## $h_1^{\perp\, g}$: Maximal polarization and Gaussian + tail

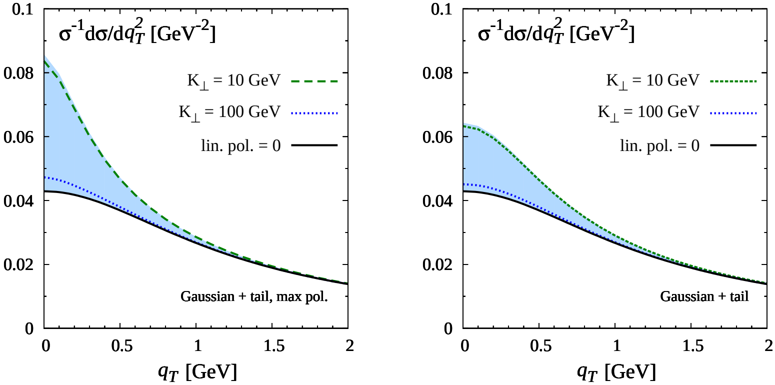
$$h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) = \frac{2 M_p^2}{\boldsymbol{p}_T^2}\, f_1^g(x, \boldsymbol{p}_T^2) \qquad [\textit{max pol.}]$$

$$h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) = 2\, f_1^g(x)\, \frac{M_p^2 R_h^4}{2\pi}\, \frac{1}{(1 + \boldsymbol{p}_T^2 R_h^2)^2} \qquad R_h = \frac{3}{2} R$$

Boer, den Dunnen, NPB 886 (2014) 421

# $q_T$-distribution

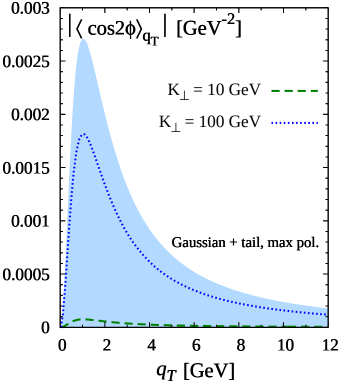
Configuration in which the Higgs and the jet have same rapidities

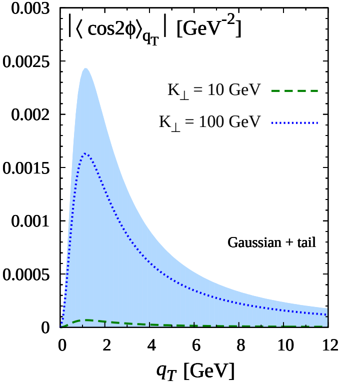



Effects largest at small $q_T$ (hard to measure), but model dependent!

# Azimuthal $\cos 2\phi$ asymmetries

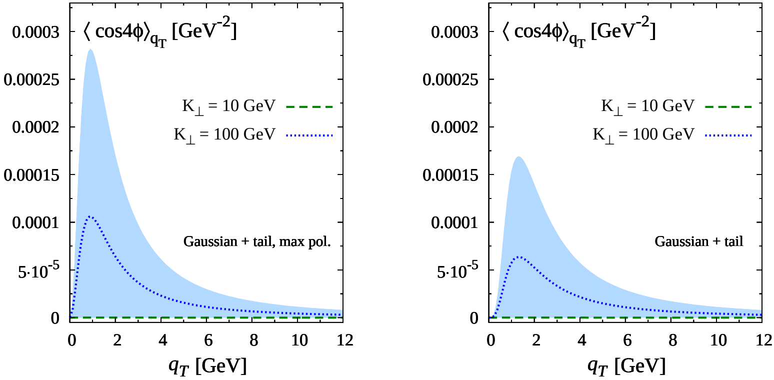
Sensitive to the sign of $h_1^{\perp\, g}$: $\langle \cos 2\phi \rangle_{q_T} < 0 \implies h_1^{\perp\, g} > 0$



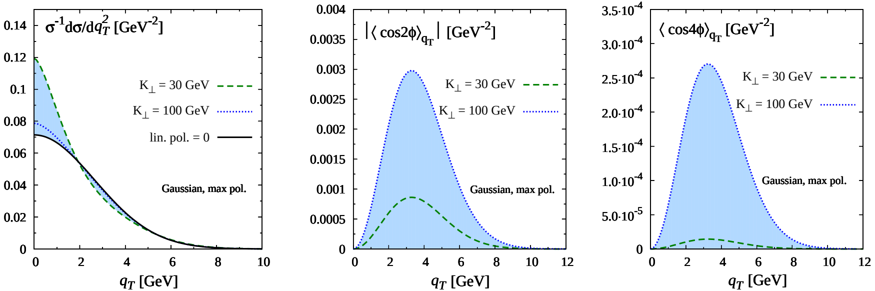

$q_{T\mathrm{max}} = M_H/2$ $\langle \cos 2\phi \rangle \approx 12\%$ at $K_\perp = 100$ GeV

# Azimuthal $\cos 4\phi$ asymmetries




$q_{T\,\mathrm{max}} = M_H/2$ $\quad$ $\langle \cos 4\phi \rangle \approx 0.1 - 0.2\%$ at $K_\perp = 100$ GeV

# Gaussian model for the unpolarized TMDs

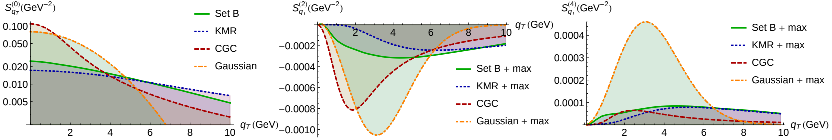



$q_{T\max} = K_\perp/2$ , $\langle \cos 2\phi \rangle \approx 9\%$, $\langle \cos 4\phi \rangle \approx 0.4\%$ at $K_\perp = 100$ GeV

# $J/\psi + \gamma$ production in hadronic collisions

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

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

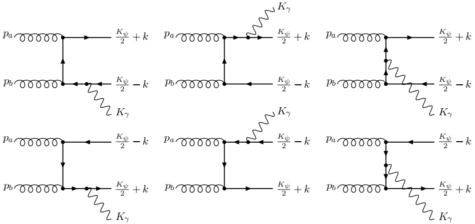
$$\mathcal{S}_{q_T}^{(2)} \equiv \langle \cos 2\phi \rangle_{q_T} \Longrightarrow f_1^g \otimes h_1^{\perp g} \qquad \mathcal{S}_{q_T}^{(4)} \equiv \langle \cos 4\phi \rangle_{q_T} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

Polarized proton with $\boldsymbol{S}_T = |\boldsymbol{S}_T|(\cos\phi_S, \sin\phi_S) \Longrightarrow f_{1T}^{\perp g}$ Possible at the future AFTER@LHC and, in principle, at RHIC

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

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

Lansberg, CP, Schlegel, in preparation

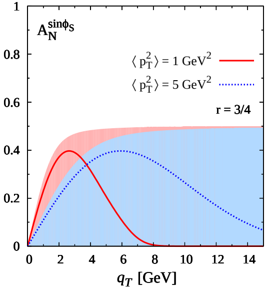



Feynman diagrams at LO pQCD

(Color Singlet Model)

# Upper bounds of the Sivers asymmetry

$$A_N^{\sin\phi_S} \equiv \frac{\int \mathrm{d}\phi_S \, \sin\phi_S \, [\mathrm{d}\sigma(\phi_S) - \mathrm{d}\sigma(\phi_S+\pi)]}{\int \mathrm{d}\phi_S \, [\mathrm{d}\sigma(\phi_S) + \mathrm{d}\sigma(\phi_S+\pi)]} = \frac{\int \mathrm{d}\phi_S \, \sin\phi_S \, \mathrm{d}\sigma_{UT}}{\int \mathrm{d}\phi_S \, \mathrm{d}\sigma_{UU}}$$




$$A_N^{\sin\phi_S} = |\boldsymbol{S}_T| \, \frac{f_1^g \otimes f_{1T}^{\perp g}}{2 \, f_1^g \otimes f_1^g}$$

Positivity bound

$$\frac{|\boldsymbol{p}_T|}{M_h} \, |f_{1T}^{\perp g}(x, \boldsymbol{p}_T^2)| \leq f_1^g(x, \boldsymbol{p}_T^2)$$

## Gaussian model for $f_{1T}^{\perp g}$

$$f_{1T}^{\perp g}(x, \boldsymbol{p}_T^2) = \frac{M \, f_1^g(x)}{\pi \langle p_T^2 \rangle^{3/2}} \sqrt{\frac{2e(1-r)}{r}} \, \exp\left(-\frac{1}{r} \, \frac{\boldsymbol{p}_T^2}{\langle p_T^2 \rangle}\right) \qquad 0 < r < 1$$

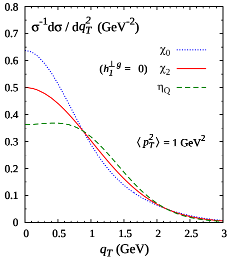
## Transverse spectra of $\eta_Q$ and $\chi_{QJ}$ $(Q = c, b)$

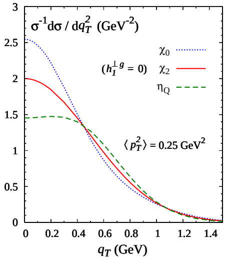
$$\frac{1}{\sigma(\eta_Q)}\frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto 1 - R_0(\boldsymbol{q}_T^2) \quad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_Q)}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \quad \text{[scalar]}$$

Effects of $h_1^{\perp g}$ on higher angular momentum states are suppressed

Boer, CP, PRD 86 (2012) 094007




Proof of TMD factorization at NLO only for $\eta_Q$ production

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

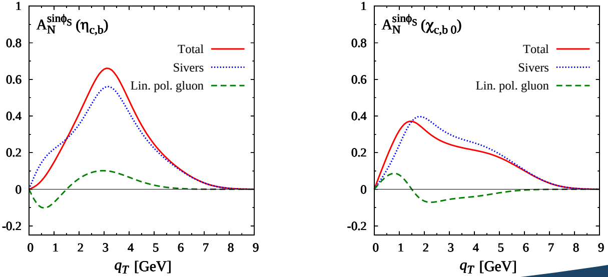
## $A_N^{\sin\phi_S}$ for $p^\uparrow p \to \eta_Q\, X$ and $p^\uparrow p \to \chi_{QJ}\, X$

$$A_N^{\sin\phi_S}(\eta_Q) = \frac{|\boldsymbol{S}_T|}{2(1-R_0)\, f_1^g \otimes f_1^g} \left\{ f_1^g \otimes f_{1T}^{\perp\, g} + h_1^{\perp\, g} \otimes h_{1T}^g + h_1^{\perp\, g} \otimes h_{1T}^{\perp\, g} \right\}$$

$$A_N^{\sin\phi_S}(\chi_{Q0}) = \frac{|\boldsymbol{S}_T|}{2(1+R_0)\, f_1^g \otimes f_1^g} \left\{ f_1^g \otimes f_{1T}^{\perp\, g} - h_1^{\perp\, g} \otimes h_{1T}^g - h_1^{\perp\, g} \otimes h_{1T}^{\perp\, g} \right\}$$

$$A_N^{\sin\phi_S}(\chi_{Q2}) = \frac{|\boldsymbol{S}_T|}{2\, f_1^g \otimes f_1^g}\, f_1^g \otimes f_{1T}^{\perp\, g}$$

Upper bounds (Gaussian models for TMDs)



# Conclusions

- The cleanest way to probe gluon TMDs would be to look at $q_T$-distributions and azimuthal asymmetries in $e\, p^{(\uparrow)} \to e' Q \bar{Q} X$ and/or $e\, p^{(\uparrow)} \to e' \, \mathrm{jet}\, \mathrm{jet}\, X$
- $h_1^{\perp\, g}$ produces a modulation of the transverse spectrum of $H$+jet and leads to azimuthal asymmetries in $p\, p \to H\, \mathrm{jet}\, X$
- First determination of $h_1^{\perp g}$ and $f_1^g$ could come from $J/\psi(\Upsilon)$ $+\,\gamma$ production at the running experiments at the LHC. In experiments with polarized protons, $f_{1T}^{\perp}$ could also be accessed