# Gluon TMDs and Heavy Quark Production at an EIC

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and at a future EIC

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# Quark TMDs

| QUARKS | *unpolarized* | *chiral* | *transverse* |
| --- | --- | --- | --- |
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_{1T}$, $h_{1T}^\perp$ |

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)

- $h_1^{\perp\, q}$: $T$-odd distribution of transversely polarized quarks inside an unp. hadron
- $h_{1T}^q$, $h_{1T}^{\perp\, q}$: helicity flip distributions: $T$-even and chiral odd
- 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

They are known and can all be accessed in semi-inclusive DIS (SIDIS)

# Gluon TMDs

| GLUONS | *unpolarized* | *circular* | *linear* |
|---|---|---|---|
| U | $f_1^g$ | | $h_1^{\perp g}$ |
| L | | $g_{1L}^g$ | $h_{1L}^{\perp g}$ |
| T | $f_{1T}^{\perp g}$ | $g_{1T}^g$ | $h_{1T}^g,\ h_{1T}^{\perp g}$ |

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

- $h_1^{\perp g}$: $T$-even distribution of linearly polarized gluons inside an unp. hadron
- $h_{1T}^g$, $h_{1T}^{\perp g}$: helicity flip distributions like $h_{1T}^q$, $h_{1T}^{\perp q}$, but $T$-odd, chiral even!
- $h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2} h_{1T}^{\perp g}$ does not survive under $p_T$ integration, unlike transversity

In contrast to quark TMDs, gluon TMDs are almost unknown



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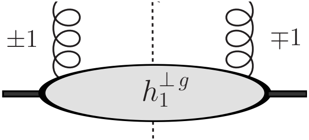
The distribution of linearly polarized gluons inside an unpolarized proton: $h_1^{\perp\, g}$

Gluons inside an unpolarized hadron can be linearly polarized

It requires nonzero transverse momentum



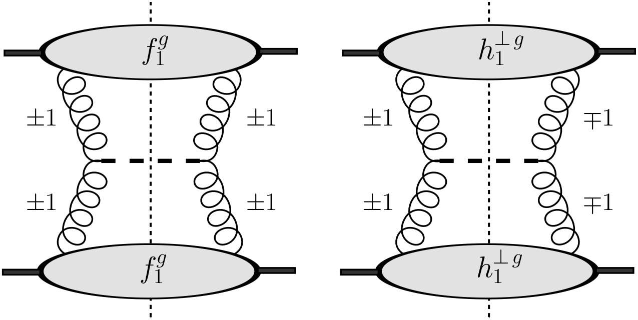

Interference between $\pm 1$ gluon helicity states

It does not need ISI/FSI to be nonzero, unlike the Sivers function. However it is affected by them $\Longrightarrow$ process dependence

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

Pol. gluons affect the Higgs transverse spectrum at NNLO pQCD

Catani, Grazzini, NPB 845 (2011)



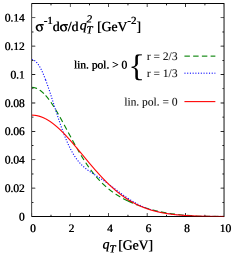

The nonperturbative distribution can be present at tree level and would contribute to Higgs production at low $q_T$

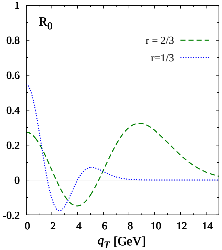
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012)

## $q_T$-distribution of the Higgs boson

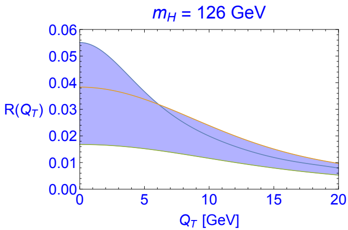
$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad R = \frac{h_1^{\perp\,g} \otimes h_1^{\perp\,g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp\,g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$

Gaussian Model




TMD evolution




Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

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

Boer, den Dunnen, CP, Schlegel, PRL 111 (2013)

# $C = +1$ quarkonium production

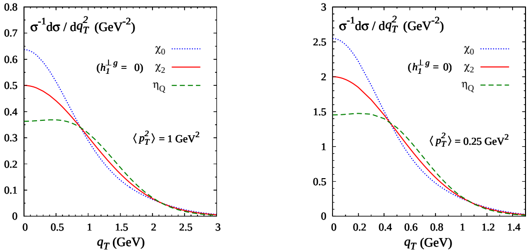
## $q_T$-distribution of $\eta_Q$ and $\chi_{QJ}$ $(Q = c, b)$ in the kinematic region $q_T \ll 2M_Q$

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

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

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

Boer, CP, PRD 86 (2012) 094007




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

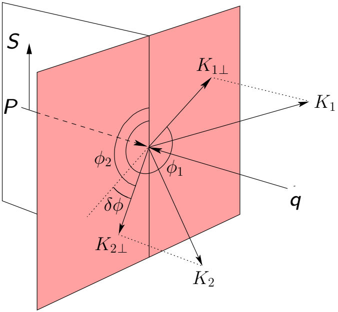
Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

# Heavy quark pair production at an EIC

## 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)

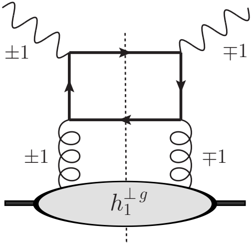
- the $Q\overline{Q}$ pair is almost back to back in the plane $\perp$ to $q$ and $P$
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon $\gamma^*$




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

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

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




$\phi_T, \phi_\perp, \phi_S$ azimuthal angles of $q_T, K_\perp, S_T$

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 $ep \to e' Q\overline{Q}X$, $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$**

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

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 $ep \to e' Q \overline{Q} X$

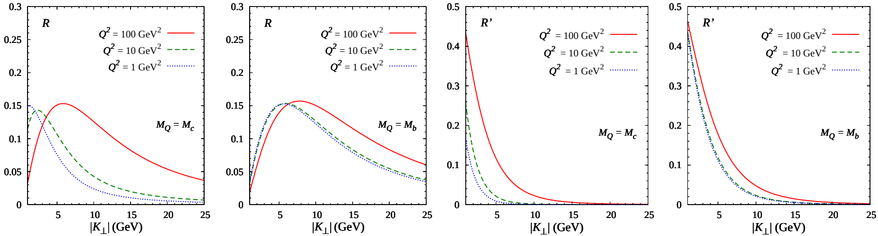
## Maximal asymmetries

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

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

# Spin asymmetries in $ep^\uparrow \to e' Q\overline{Q} X$

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

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

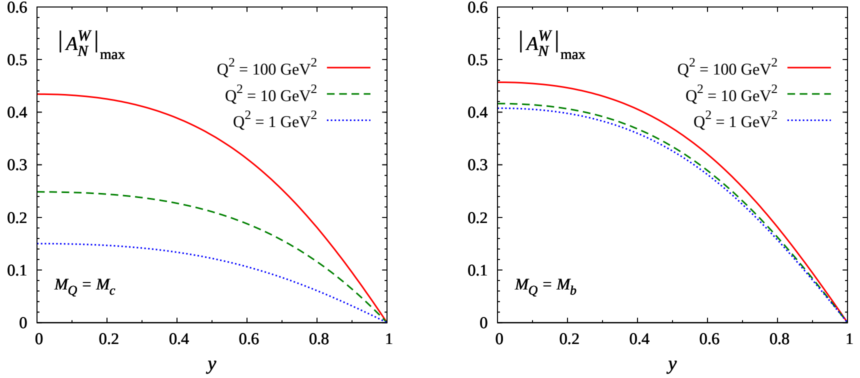
The $\phi_S$ dependent terms can be singled out by means of azimuthal moments $A_N^W$

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

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

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

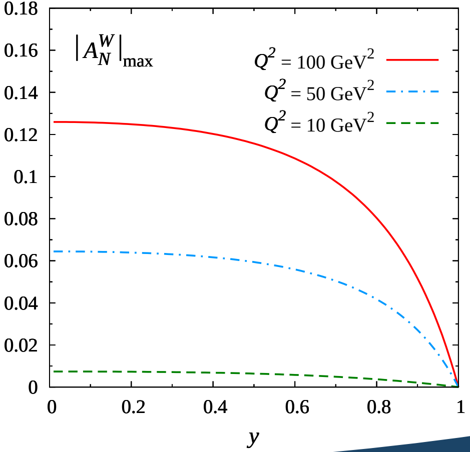
Maximal values for $|A_N^W|$, $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$ $\quad (|\boldsymbol{K}_\perp| = 1$ GeV$)$



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

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

Upper bounds for $A_N^W$ for $K_\perp \geq 4$ GeV



# Process dependence of gluon TMDs

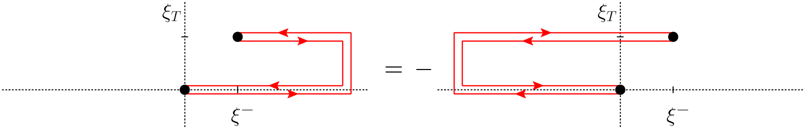
## Related Processes

$ep^{\uparrow} \to e' Q\overline{Q}X$, $ep^{\uparrow} \to e'$ jet jet $X$ probe GSF with $[++]$ gauge links (WW)

$p^{\uparrow}p \to \gamma\gamma X$ (and/or other CS final state) probe GSF with $[--]$ gauge links

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

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




Boer, Mulders, CP, Zhou (2016)

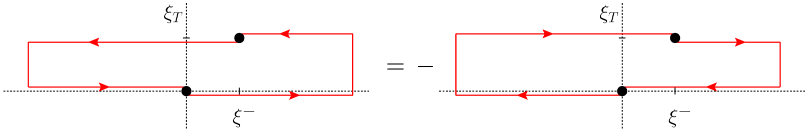
We expect to measure the same $h_1^{\perp\, g}$ and $f_1^g$ in both processes

Motivation to study gluon Sivers effects at both RHIC and the EIC

## Complementary Processes

$ep^{\uparrow} \to e' Q\overline{Q} X$ probes a GSF with $[++]$ gauge links (WW)

$p^{\uparrow} p \to \gamma \, \text{jet} \, X$ $(gq \to \gamma q)$ probes a gluon TMD with : $[+-]$ links (DP)




At small-$x$ the WW Sivers function appears to be suppressed by a factor of $x$ compared to the unpolarized gluon function, unlike the dipole one

The DP gluon Sivers function at small-$x$ is the **spin dependent odderon** (single spin asymmetries from a single Wilson loop matrix element)

Boer, Echevarria, Mulders, Zhou, PRL 116 (2016)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

# $J/\psi$-pair production at the LHC

Lansberg, CP, Scarpa, Schlegel, in progress

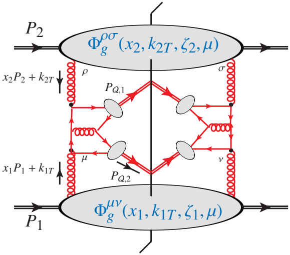
# $J/\psi$-pair production at the LHC

$J/\psi$'s are relatively easy to detect. Accessible at the LHC: already studied by LHCb, CMS & ATLAS

LHCb PLB 707 (2012)
CMS JHEP 1409 (2014)
ATLAS EPJC 77 (2017)

$gg$ fusion dominant, negligible $q\bar{q}$ contributions even at AFTER@LHC energies

Lansberg, Shao, NPB 900 (2015)

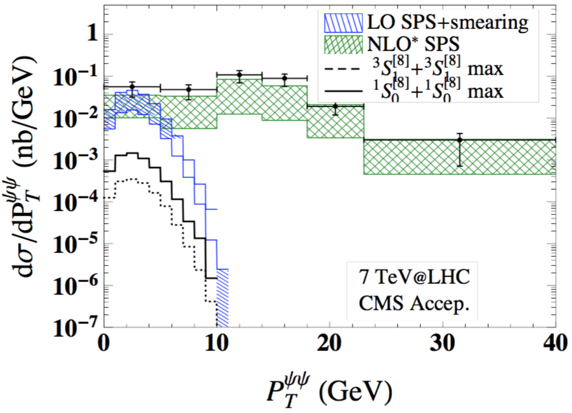



No final state gluon needed for the Born contribution in the Color Singlet Model. Pure colorless final state, hence simple color structure because one has only ISI

Lansberg, Shao, PRL 111 (2013)

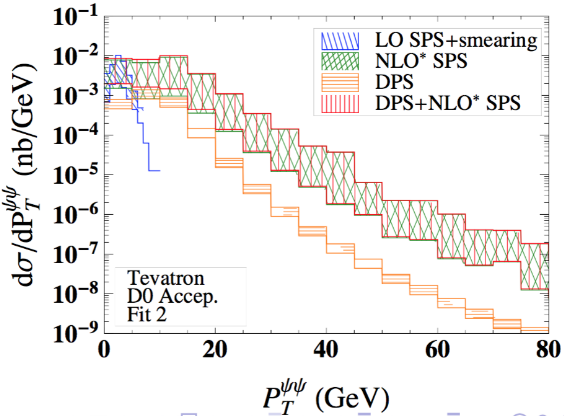
Negligible Color Octet contributions, in particular at low $P_T^{\psi\psi}$
[Black/dashed curves vs blue ones]

Lansberg, Shao PLB 751 (2015)

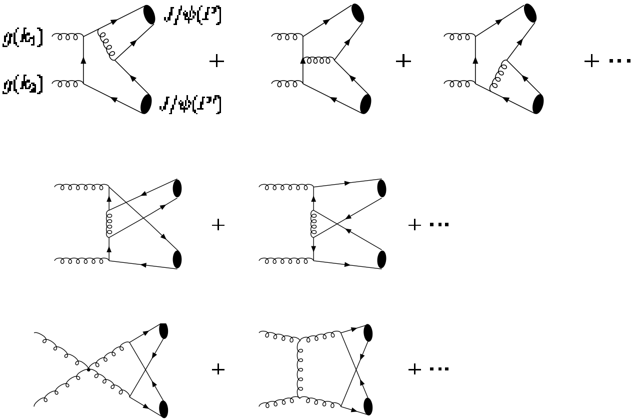


At low $P_T^{\Psi\Psi}$, small double parton scattering (DPS) contributions, otherwise required by the CMS, ATLAS data at large rapidity separations $\Delta y$ of the $J/\psi$'s

Lansberg, Shao, PLB 751 (2015)



At LO pQCD in the Color Singlet Model, one needs to consider 36 diagrams




Qiao, Sun, Sun, JPG 37 (2010)

$$\frac{d\sigma}{dQ\,dY\,d^2q_T\,d\Omega} \approx A\, f_1^g \otimes f_1^g + B\, f_1^g \otimes h_1^{\perp g} \cos(2\phi_{CS}) + C\, h_1^{\perp g} \otimes h_1^{\perp g} \cos(4\phi_{CS})$$

- valid up to corrections $\mathcal{O}\,(q_T/Q)$
- $Y$: rapidity of the $J/\psi$-pair, along the beam in the hadronic c.m. frame
- $d\Omega = d\cos\theta_{CS}\, d\phi_{CS}$: solid angle for $J/\psi$-pair in the Collins-Soper frame

Analysis similar to the one for $pp \to \gamma\gamma X$, $pp \to J\psi\,\gamma^{(*)}\,X$, $pp \to H\,\mathrm{jet}\,X$

Qiu, Schlegel, Vogelsang, PRL 107 (2011)
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014)
Lansberg, CP, Schlegel, NPB 920 (2017)
Boer, CP, PRD 91 (2015)

The three contributions can be disentangled by defining the transverse moments

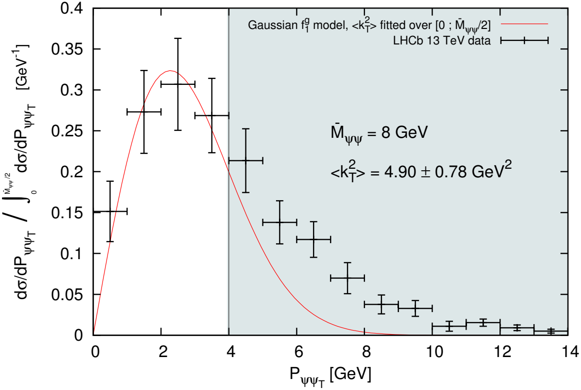
$$\langle \cos n\phi_{CS} \rangle \equiv \frac{\int_0^{2\pi} d\phi_{CS}\, \cos(n\,\phi_{CS})\, \frac{d\sigma}{dQ\,dY\,d^2q_T\,d\Omega}}{\int_0^{2\pi} d\phi_{CS}\, \frac{d\sigma}{dQ\,dY\,d^2q_T\,d\Omega}} \qquad (n = 2, 4)$$

$$\int d\phi_{CS}\, d\sigma \implies f_1^g \otimes f_1^g$$

$$\langle \cos 2\phi_{CS} \rangle \implies f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi_{CS} \rangle \implies h_1^{\perp g} \otimes h_1^{\perp g}$$

We consider $q_T = P_T^{\Psi\Psi} \leq M_{\Psi\Psi}/2$ in order to have two different scales




LHCb Coll., JHEP 06 (2017)

Gaussian model:
$$f_1^g(x, \boldsymbol{k}_T^2) = \frac{f_1^g(x)}{\pi\langle k_T^2\rangle} \exp\left(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2\rangle}\right)$$

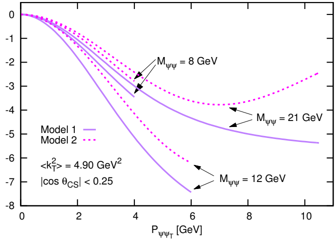
# $J/\psi$-pair production
## $\langle \cos n\phi_{CS} \rangle$ at $\sqrt{s} = 13$ TeV

At $\Delta y \approx 0$ the modulation $C$ of $cos4\phi$ saturates its upper bound $|C| = A$

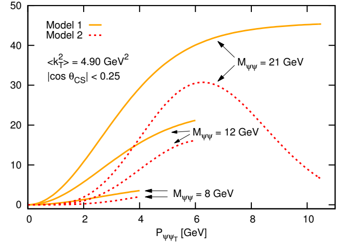
The $\cos 2\phi$ modulation can fix the sign of $h_1^{\perp\, g}$

$M_{\Psi\Psi} = 8,\ 12,\ 21$ GeV relevant for LHCb, CMS, ATLAS

$\langle \cos 2\phi_{CS} \rangle$ (%)




$\langle \cos 4\phi_{CS} \rangle$ (%)




### Models for $h_1^{\perp\, g}$

$$(1)\quad h_1^{\perp g}(x, \boldsymbol{k}_T^2) = \frac{2M^2}{\boldsymbol{k}_T^2}\, f_1^g(x, k_T^2)\,; \qquad (2)\quad h_1^{\perp g}(x, \boldsymbol{k}_T^2) = \frac{M\, f_1^g(x)}{\pi \langle k_T^2 \rangle^{3/2}} \sqrt{\frac{2e(1-r)}{r}}\ \exp\left(-\frac{1}{r}\,\frac{\boldsymbol{k}_T^2}{\langle k_T^2 \rangle}\right)\ r = 2/3$$

## 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
- Different behavior of WW and dipole gluon TMDs accessible at RHIC, AFTER@LHC and at EIC, overlap of both *spin* and *small-x* programs
- First extraction of unpolarized gluon TMD from LHC data on di-$J/\Psi$