Spin studies in unpolarized pp and ep collisions

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Workshop "Physics at A Fixed-Target ExpeRiment (AFTER) using the LHC beams"

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- The distribution of linearly polarized gluons in an unpolarized hadron $h_1^{\perp\, g}$
- Azimuthal asymmetries in $e\, p \to e'\, Q\, \bar{Q}\, X$, $e\, p \to e'\, \mathrm{jet}\, \mathrm{jet}\, X$
- Comparison with $p\, p \to Q\, \bar{Q}\, X$ and $p\, p \to \mathrm{jet}\, \mathrm{jet}\, X$
- Modulation of the cross section for Higgs and (pseudo)scalar quarkonia production

Gluon distributions

- Experimental and theoretical investigations of gluons inside hadrons focussed so far on their momentum and helicity distributions:
  - $g(x)$: *unpolarized* gluons with collinear momentum fraction x in *unp.* hadrons
  - $\Delta g(x)$: *circularly polarized* gluons with mom. fraction x in *polarized* hadrons

- Taking into account the transverse momentum $\boldsymbol{p}_T$ of the gluon:

$$(\Delta)g(x) \longrightarrow (\Delta)g(x, \boldsymbol{p}_T^2)$$

  and other transverse momentum dependent gluon pdfs (TMDs) can be nonzero

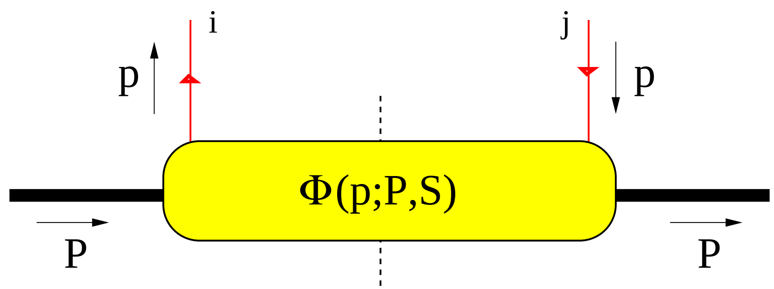
- In this framework, gluons do not have to be unpolarized, even if the parent hadron itself is unpolarized (different polarization mode compared to Δg)!

- Nontrivial property that has received much more attention in the quark sector. Models suggest that $h_1^{\perp\, g}$ may reach its maximally allowed size at small x

Meissner, Metz, Goeke, PRD 76 (2007) 034002
Metz, Zhou, PRD 84 (2011) 051503
Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003

Quark and antiquark correlators

- Parton correlators describe the hadron $\to$ parton transitions and can be parameterized in terms of TMDs. Parton momentum $p \approx xP + p_T$



- For an unp. hadron with momentum P, at leading twist (LT), omitting gauge links

$$\Phi_q(x,p_T;P) = \frac{1}{2}\left\{ f_1^q(x,\boldsymbol{p}_T^2)\, \not{P} + i h_1^{\perp\, q}(x,\boldsymbol{p}_T^2)\, \frac{[\not{p}_T, \not{P}]}{2M} \right\}$$

  - $f_1^q(x,\boldsymbol{p}_T^2) \equiv q(x,\boldsymbol{p}_T^2)$ is the unpolarized quark distribution; $M^2 = P^2$
  - $h_1^{\perp q}(x,\boldsymbol{p}_T^2)$ is the T-odd, quark transverse spin distribution in an unp. hadron

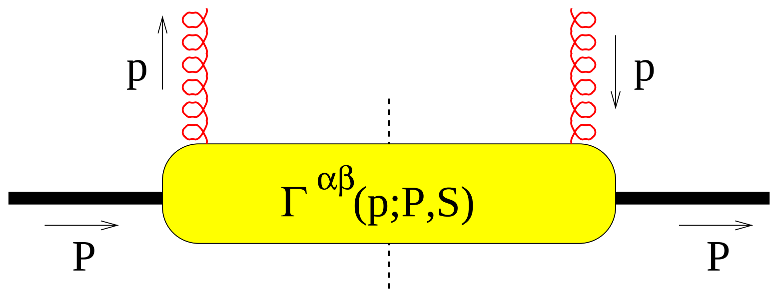
Boer, Mulders, PRD 57 (1998) 5780

- $h_1^{\perp q}(x,\boldsymbol{p}_T^2) = 0$ in the absence of initial or final state interactions (ISI/FSI)

- The antiquark corr. $\bar{\Phi}_q$ is obtained from Φ_q by replacing $f_1^q \to f_1^{\bar{q}}$ and $h_1^{\perp\, q} \to h_1^{\perp\, \bar{q}}$

Gluon correlator

- We introduce the light-like vector n conjugate to P satisfying $n^2{=}0$ and $n{\cdot}P{>}0$, and define the transverse projector $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta / P{\cdot}n - n^\alpha P^\beta / P{\cdot}n$



- For a gluon momentum $p = x\,P + p_T + p^- n$, at LT and omitting gauge links

$$\Phi_g^{\alpha\beta}(x,p_T;P) \equiv \Gamma^{\alpha\beta} = \frac{-1}{2x}\left\{ g_T^{\alpha\beta}\, f_1^g(x,\boldsymbol{p}_T^2) - \left(\frac{p_T^\alpha p_T^\beta}{M^2} + g_T^{\alpha\beta}\,\frac{\boldsymbol{p}_T^2}{2M^2}\right) h_1^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\}$$

  - $f_1^g(x,\boldsymbol{p}_T^2) \equiv g(x,\boldsymbol{p}_T^2)$ is the usual unpolarized gluon distribution; $p_T^2 = -\boldsymbol{p}_T^2$
  - $h_1^{\perp\, g}(x,\boldsymbol{p}_T^2)$ is the T-even distribution of linearly pol. gluons in an unp. hadron

Mulders, Rodrigues, PRD 63 (2001) 094021

- $h_1^{\perp\, g}$ is a helicity-flip distribution, and a second rank tensor in p_T (p_T-even)
- $h_1^{\perp g}(x,\boldsymbol{p}_T^2) \neq 0$ in the absence of ISI or FSI, but, as any TMD, it will receive contributions from ISI/FSI $\longrightarrow$ it can be nonuniversal!

The function $h_1^{\perp\,g}$: phenomenology

- So far no experimental studies of the function $h_1^{\perp\,g}$ have been performed

- $h_1^{\perp\,g}$ contributes to the so-called dijet imbalance in hadronic collisions, commonly used to extract the average partonic intrinsic transverse momentum. Complication!

  It is likely too hard to measure the azimuthal asymmetry for $p\,p \to \mathrm{jet\,jet}\,X$,

$$\mathcal{A} \quad \sim \quad \cos 4\phi \; h_1^{\perp\,g} \otimes h_1^{\perp\,g}$$

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

- Similar to azimuthal asymmetry appearing in the Drell-Yan process:

$$\nu_{\mathrm{DY}} \quad \sim \quad \cos 2\phi \; h_1^{\perp\,q} \otimes h_1^{\perp\,\bar{q}}$$

Boer, PRD 60 (1999) 014012

- In $h\,h$ collisions: problems because of factorization breaking effects

Rogers, Mulders, PRD 81 (2010) 094006

- Unlike $h_1^{\perp\,q}$, $h_1^{\perp\,g}$ does not need to appear in pairs, hence a safe extraction of $h_1^{\perp\,g}$ in a simpler manner could be possibile, for example from $\quad \mathcal{A} \quad \sim \quad \cos 2\phi \; h_1^{\perp\,g}$

Electroproduction of heavy quark and jet pairs

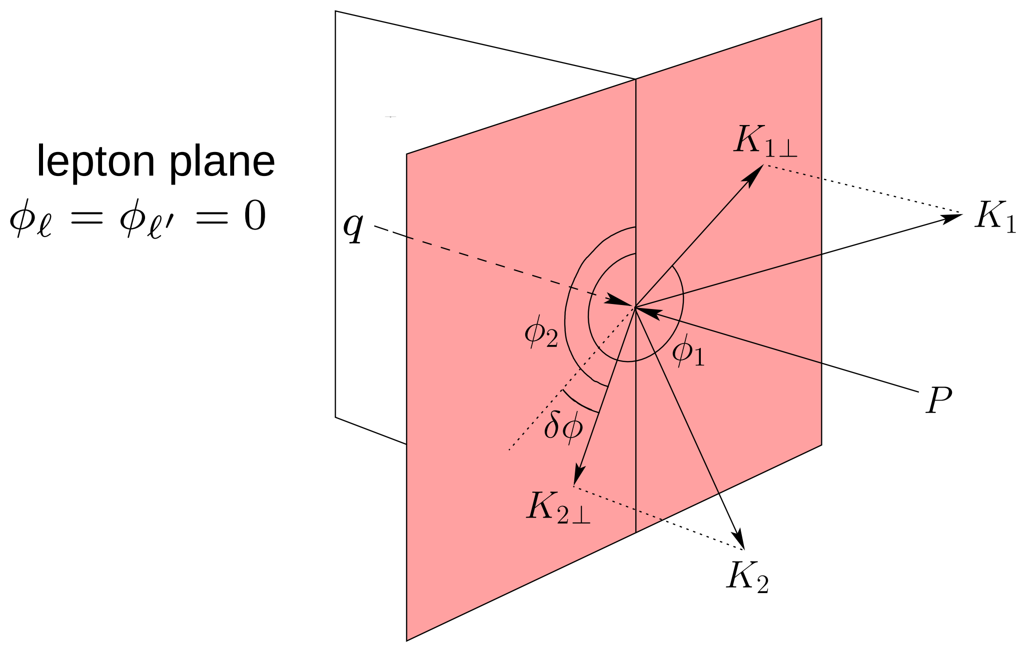
- In $e\,p$ instead of $p\,p$ collisions: only one TMD is involved; TMD factorization holds for the processes:

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

$$e(\ell) + h(P) \;\to\; e(\ell') + \mathrm{jet}(K_1) + \mathrm{jet}(K_2) + X$$

the $Q\bar{Q}$ or jet pairs are almost back-to-back in the plane perpendicular to q and P, $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^* with $Q^2 = -q^2$

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



Best measured at an Electron-Ion Collider (USA) or at the LHeC (CERN)

- At high energies the cross sections factorize in a leptonic tensor L, a soft parton correlator Φ for the incoming hadron and a hard part H (LO pQCD)

TMD master formula:

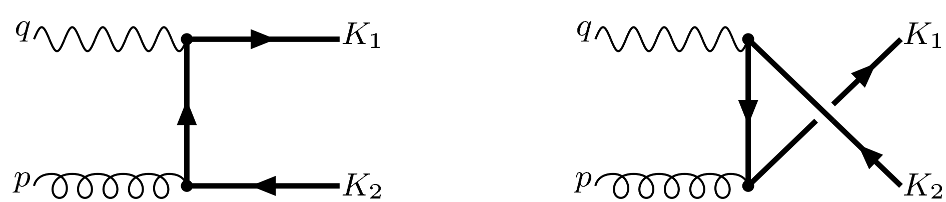
$$d\sigma = \frac{1}{2s}\frac{d^3\ell'}{(2\pi)^3\,2E'_e}\frac{d^3K_1}{(2\pi)^3\,2E_1}\frac{d^3K_2}{(2\pi)^3\,2E_2}\int dx\,d^2\boldsymbol{p}_T\,(2\pi)^4\delta^4(q+p-K_1-K_2)$$
$$\times\sum_{a,b,c}\frac{1}{Q^4}L(\ell,q)\otimes\Phi_a(x,\boldsymbol{p}_T)\otimes|H_{\gamma^*\,a\to b\,c}(q,p,K_1,K_2)|^2$$

- Leptonic tensor:

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

- In $Q\,\bar{Q}$ production:

$$\gamma^*(q) + g(p) \to Q(K_1) + \bar{Q}(K_2):$$



Electroproduction of heavy quarks

- Approximation: $|q_T| \ll |K_\perp|$; with $K_\perp \equiv (K_{1\perp} - K_{2\perp})/2$, $q_T \equiv K_{1\perp} + K_{2\perp}$

$$\frac{d\sigma}{d^2\boldsymbol{K}_\perp d^2\boldsymbol{q}_T} \propto A_0 + A_1 \cos\phi_\perp + A_2 \cos 2\phi_\perp + \boldsymbol{q}_T^2 \Big[B_0 \cos 2(\phi_\perp - \phi_T) + B_1 \cos(\phi_\perp - 2\phi_T) + B_1' \cos(3\phi_\perp - 2\phi_T) + B_2 \cos 2\phi_T + B_2' \cos 2(2\phi_\perp - \phi_T) \Big]$$

Boer, Brodsky, Buffing, Mulders, CP, in preparation

  - $\phi_\perp$ (ϕ_T): azimuthal angle of $\boldsymbol{K}_\perp$ ($\boldsymbol{q}_T$)
  - The terms A_i, with $i = 0, 1, 2$, depend only on f_1^g
  - $B_i^{(\prime)}$ contain the information on linearly polarized gluons, $B_i^{(\prime)} \propto h_1^{\perp\, g}$

- Average values of the functions $W(\phi_\perp, \phi_T) = \cos 2(\phi_\perp - \phi_T)$, $\cos(\phi_\perp - 2\phi_T)$, ...

$$\langle\, W(\phi_\perp, \phi_T)\,\rangle = \frac{\int d\phi_\perp \mathrm{d}\phi_T\, W(\phi_\perp, \phi_T)\, d\sigma(\phi_\perp, \phi_T)}{\int d\phi_\perp d\phi_T\, d\sigma(\phi_\perp, \phi_T)}$$

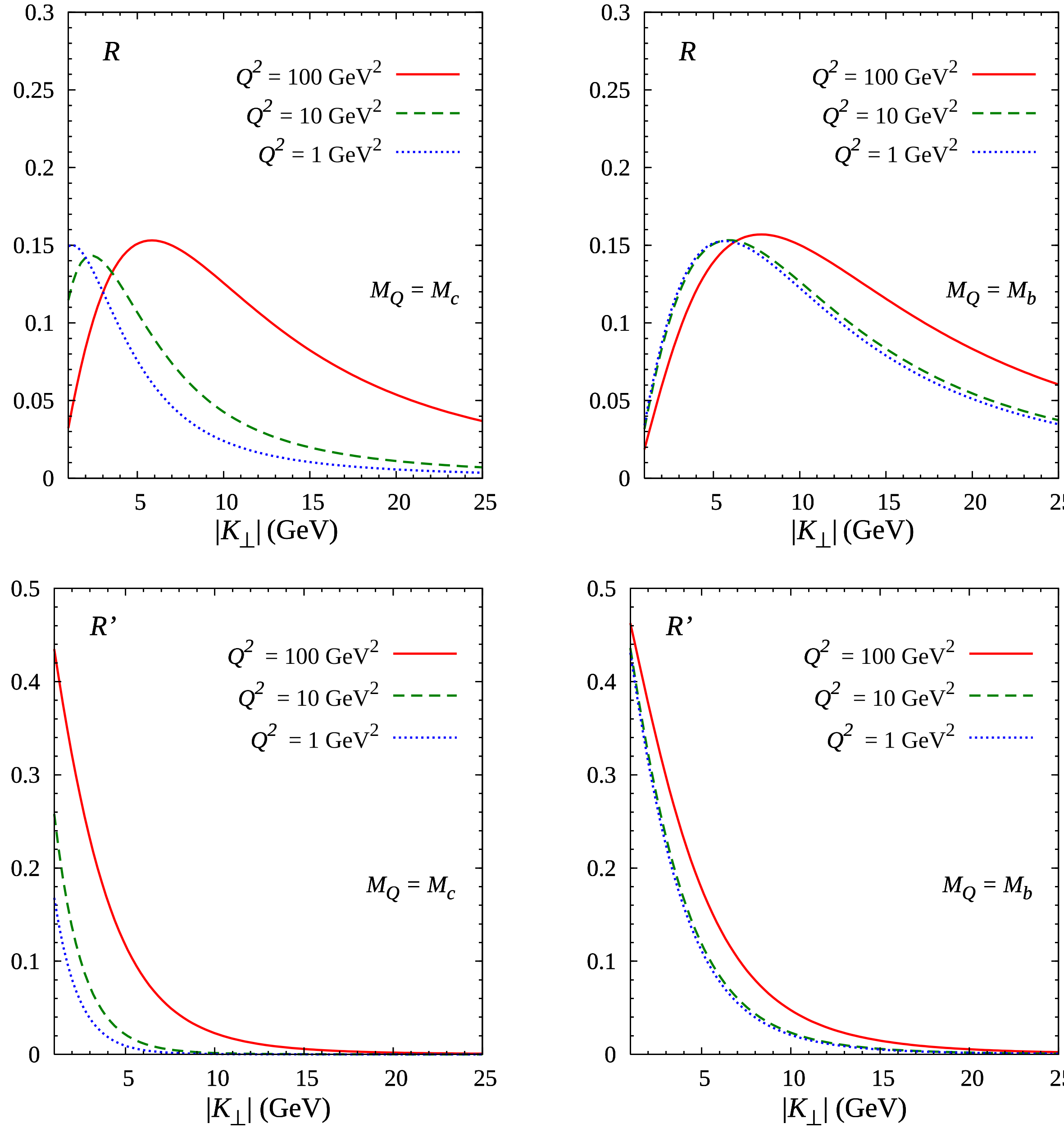
will single out B_0, B_1, ...

Maximum values of the asymmetries

$$\frac{\boldsymbol{p}_T^2}{2M^2}\,|h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)| \le f_1^g(x,\boldsymbol{p}_T^2)$$

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

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



Electroproduction of two jets

- The cross section for the process

$$e(\ell) + h(P) \;\to\; e(\ell') + \mathrm{jet}(K_1) + \mathrm{jet}(K_2) + X$$

with the two jets back-to-back has the same angular structure as $e\,h \to e\,Q\,\bar{Q}\,X$

  - The terms $B_i^{(\prime)}$ obtained from the ones for $e\,h \to e\,Q\,\bar{Q}\,X$ by taking $M_Q = 0$
  - smaller asymmetries: also $\gamma^* q \to q\bar{q}$ and not just $\gamma^* g \to gq$ contributes to A_0
  - Reconstruction of the transverse momenta $K_{i\perp}$ of the jets or heavy quarks is essential, accuracy $\delta K_\perp$ has to satisfy $\delta K_\perp \ll |q_T| \ll |K_\perp|$

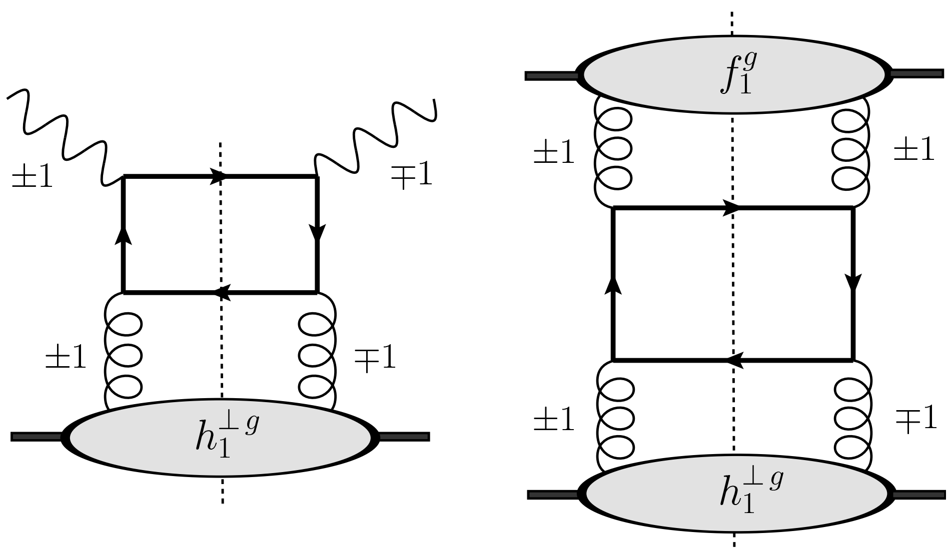
Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001

- Assuming TMD factorization, $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, at LO pQCD, for the process

$$h_1(P_1)+h_2(P_2) \to Q(K_1)+\bar{Q}(K_2)+X:$$

$$\frac{d\sigma}{d^2\boldsymbol{K}_\perp d^2\boldsymbol{q}_\perp} \propto A + B\,\boldsymbol{q}_T^2 \cos 2(\phi_T - \phi_\perp) + C\,\boldsymbol{q}_T^4 \cos 4(\phi_T - \phi_\perp)$$

$$A:\ f_1^q \otimes f_1^{\bar{q}},\quad f_1^g \otimes f_1^g \qquad B:\ h_1^{\perp\,q} \otimes h_1^{\perp\,\bar{q}},\quad \frac{M_Q^2}{M_\perp^2} f_1^g \otimes h_1^{\perp\,g} \qquad C:\ h_1^{\perp\,g} \otimes h_1^{\perp\,g}$$



$e\,h \to e'\,Q\,\bar{Q}\,X$ $\qquad$ $h_1\,h_2 \to Q\,\bar{Q}\,X$

in $h\,h$ collisions helicity flip is required in quark propagators $\Longrightarrow M_Q^2/M_\perp^2$ factor

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

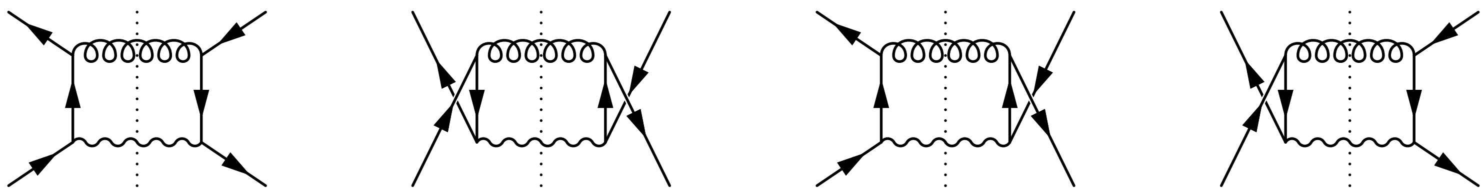
- Importance of the contribution from $h_1^{\perp\, q}$ can be assessed by a comparison to

$$h_1(P_1)+h_2(P_2)\to\gamma(K_\gamma)+\text{jet}(K_j)+X$$

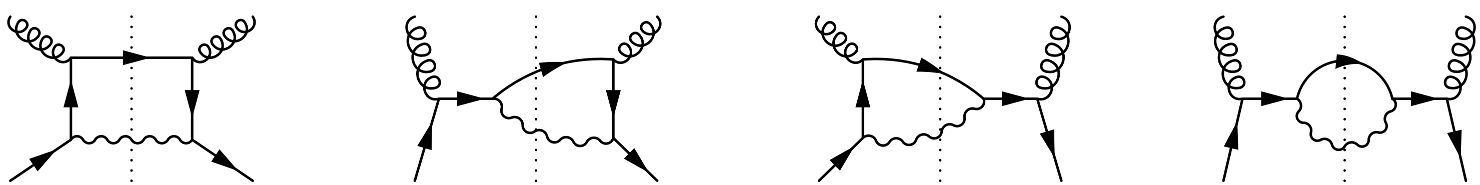
D. Boer, P. Mulders, CP, PLB 660 (2008) 360

- To LO in pQCD the reaction is mediated by the $2\to 2$ partonic subprocesses

$q\bar{q}\to\gamma g$:



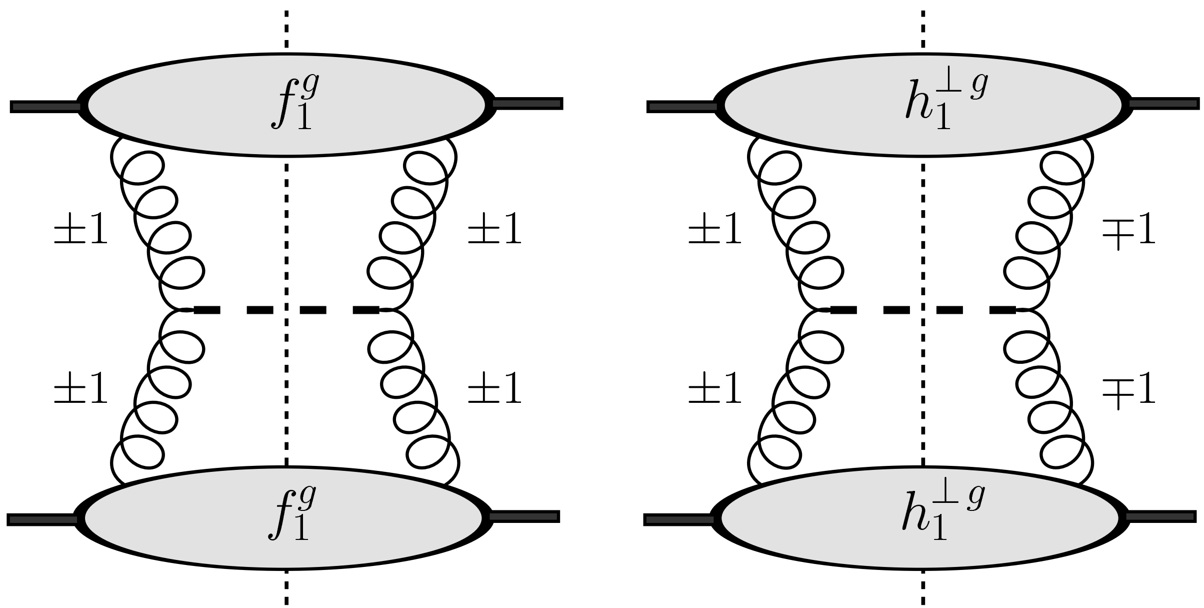
$qg\to\gamma q$:



- $h_1^{\perp\, g}$: power-suppressed contribution; only $\cos 2\phi$ asymm. $\sim\ h_1^{\perp\, q}\otimes h_1^{\perp\, \bar{q}}$ as in DY

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

- Higgs boson production happens mainly via $gg \to H$
- Pol. gluons affect the Higgs transverse momentum distribution 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



The LHC can be viewed also as a *polarized* gluon collider!

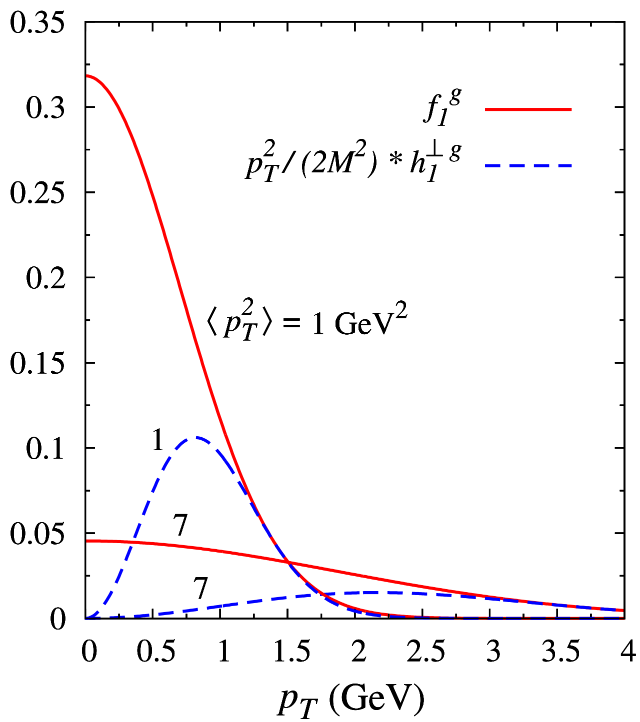
- The angular independent cross section has the form:

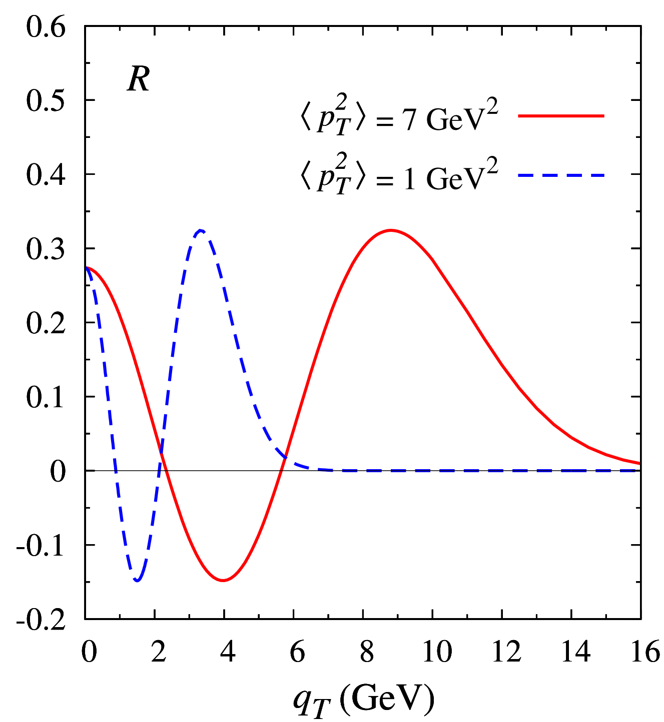
$$\frac{1}{\sigma}\frac{d\sigma}{dq_T^2} \propto 1 \pm R(q_T) \qquad R(q_T) = \frac{\mathcal{C}[w_H\, h_1^{\perp\, g}\, h_1^{\perp\, g}]}{\mathcal{C}[f_1^g\, f_1^g]} \qquad (+\text{ for } H^0;\ -\text{ for } A^0)$$

$R = 0$ for a spin 2 particle with the same couplings of a Kaluza-Klein graviton

Ellis, Hwang, JHEP 09 (2012) 071

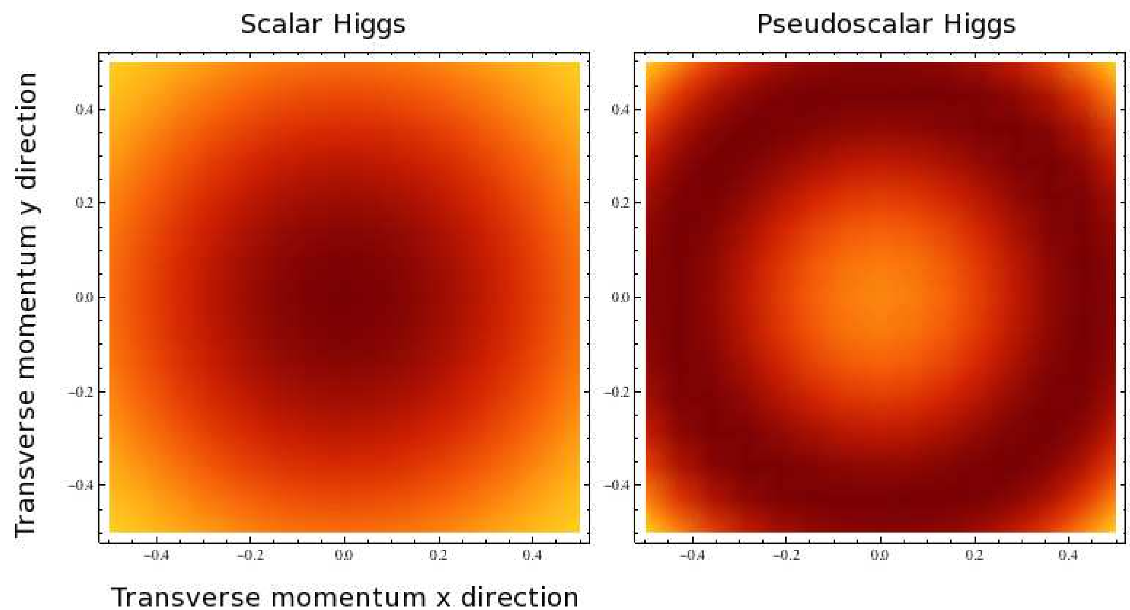
- Gaussian model for f_1^g and $h_1^{\perp\, g}$; $h_1^{\perp\, g}$ is close to its bound for large p_T:





On-shell Higgs boson

Characteristic modulation; overall sign determined by the parity of the Higgs



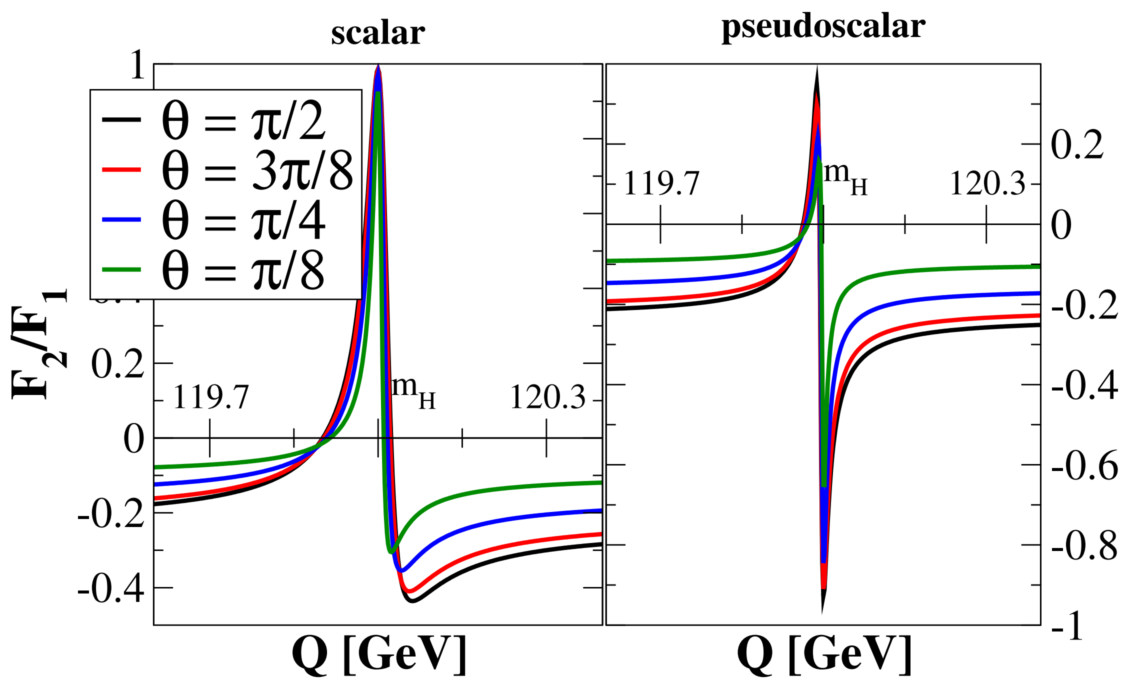
- In reality the Higgs will decay. Background processes may dilute the modulation
- $H \to \gamma\gamma$ has been studied so far
  Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
- Linearly polarized gluons contribute also to $gg \to \gamma\gamma$ without Higgs
  Nadolsky, Balazs, Berger, Yuan, PRD 76 (2007) 013008
  Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

$gg \to \gamma\gamma$

$$\int d\phi \, \frac{d\sigma}{d^4q \, d\Omega} \propto 1 + \frac{F_2}{F_1}(Q,\theta) \, R(q_T)$$

$d\Omega = d\cos\theta d\phi$ solid angle element for each photon in the Collins-Soper frame

q: momentum of the photon pair; $Q = \sqrt{q^2}$



- Discernable only in a narrow region around the Higgs mass (here $M_H = 120$ GeV)
- Other decay channels are under investigation

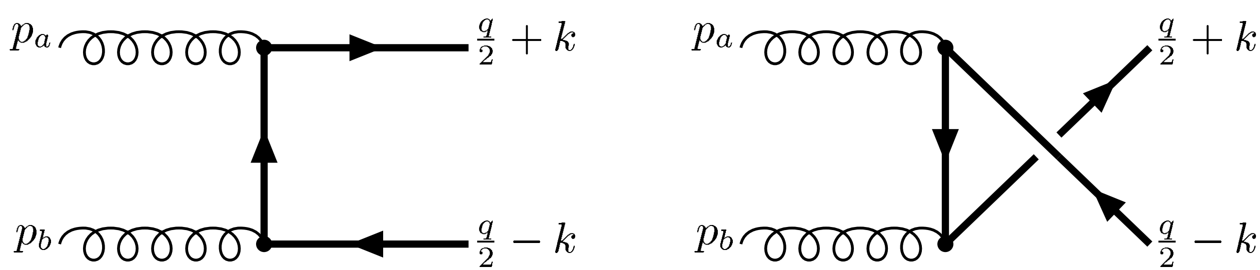
Boer, den Dunnen, CP, Schlegel, Vogelsang, in preparation

- $C = +$ quarkonia ($\eta_{c,b}$, $\chi_{c,b}$) produced in pp collisions: reliable gluon probes
  Brodsky, Fleuret, Hadjidakis, Lansberg, Phys.Rept. 522 (2013) 239

- The process

$$h(P_A)+h(P_B) \to Q\bar{Q}[^{2S+1}L_J](q)+X$$

is studied in the TMD factorization approach, in combination with NRQCD based color-singlet model, for $q_T^2 \ll 4M_Q^2$. At LO pQCD described by



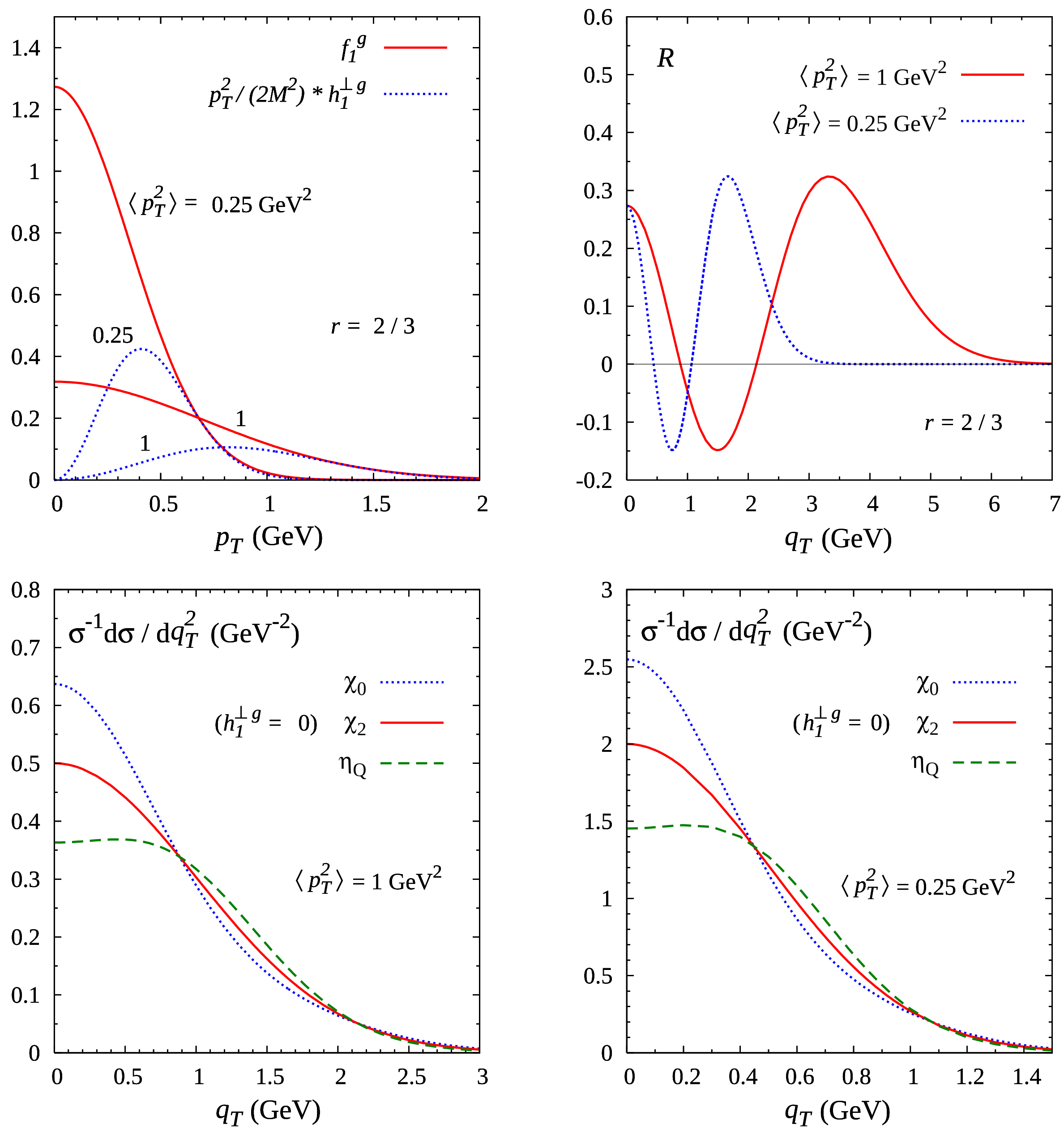
- Similarly to the Higgs case:

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

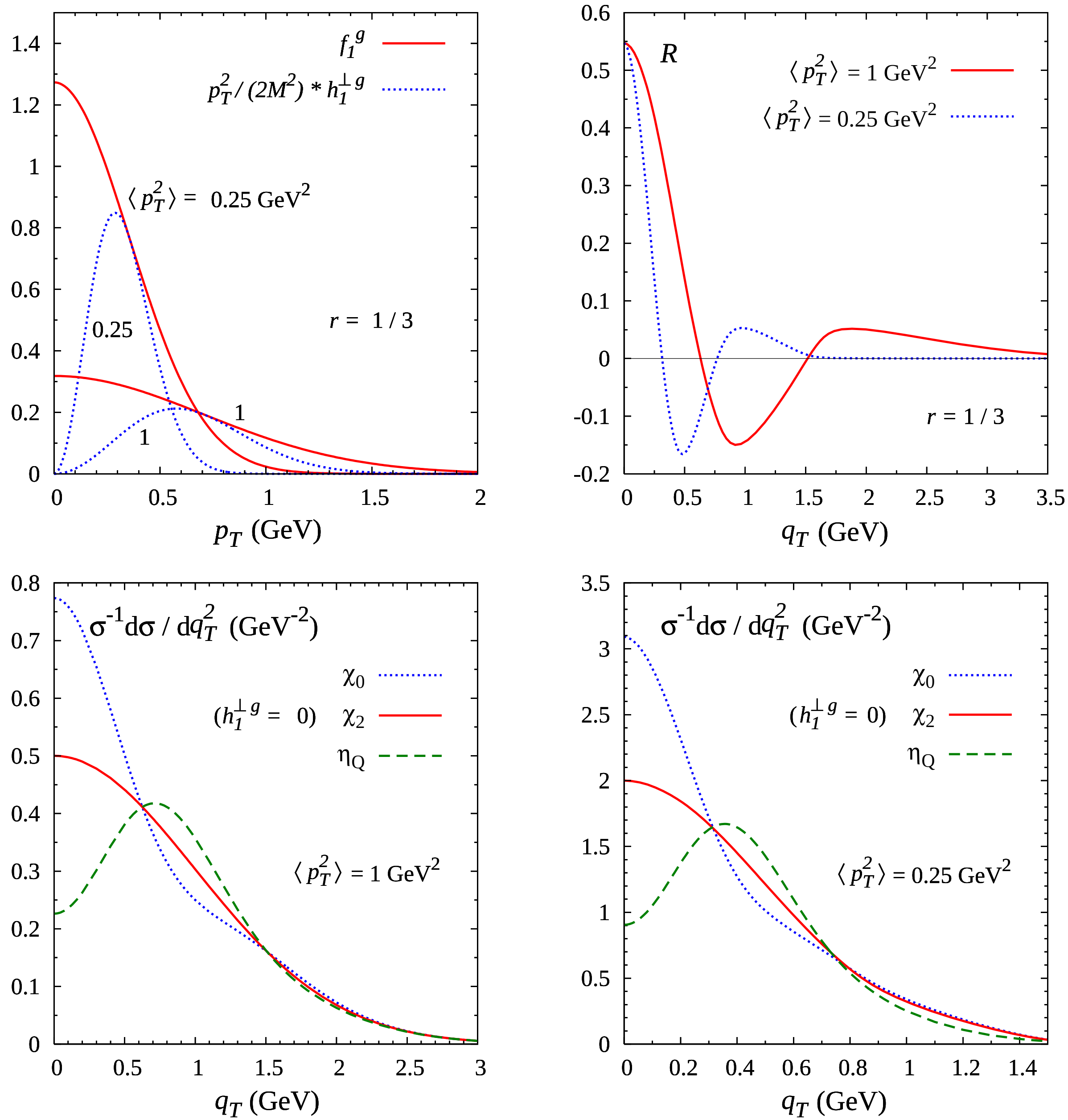
$$\frac{1}{\sigma(\chi_Q)}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad \text{[scalar]}$$

The effects of $h_1^{\perp\, g}$ on higher angular momentum bound states are suppressed
Boer, Pisano, PRD 86 (2012) 094007

Transverse momentum distributions



Different Gaussian input for $h_1^{\perp g}$



- $h_1^{\perp\, g}$ receives contributions from ISI/FSI (gauge links) which make it process dependent and can even break factorization

- It is possibile to define five independent $h_1^{\perp\, g}$ functions with specific color structures. Depending on the process, one extracts different combinations of them

  Buffing, Mukherjee, Mulders, in preparation

- In $ep \to e' Q\bar{Q}X$ and in all the processes with a colorless final state, $pp \to \gamma\gamma X$, $pp \to H/\eta_c/\chi_{c0}/...X$, only two $h_1^{\perp\, g}$functions appear (in the same combination)

- In $pp \to Q\bar{Q}X$ and $pp \to \mathrm{jet}\,\mathrm{jet}\,X$ problems with factorization breaking terms.

  Even if we assume TMD factorization, more functions appear due to the more complicated structure in color space of the diagram(s) involved

  Boer, Brodsky, Buffing, Mulders, CP, in preparation

Summary and conclusions

- Measurements of the $\cos 2\phi$ azimuthal asymmetries of heavy quark and jet pair production in $e\,p$ (EIC, LHeC) and in $p\,p$ collisions (RHIC, LHC) can probe the distribution of linearly polarized gluons inside unpolarized hadrons $h_1^{\perp\,g}$

- $h_1^{\perp\,g}$ contributes also to diphoton, quarkonia and even Higgs production in $p\,p$ collisions. It leads to a modulation of the angular independent transverse momentum distribution of (pseudo)scalar particles

- Relative simple measurements, polarized beams are not required

- Promising prospect for the extraction of $h_1^{\perp\,g}$ in the future and for the study of its process dependence and evolution with energy scale

Once $h_1^{\perp\,g}$ is known, polarized processes without polarized beams at our disposal