Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER*

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Workshop on Charmonium production and decays: new results and perspectives

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- The distribution of linearly polarized gluons in an unpolarized hadron $h_1^{\perp\, g}$
- Azimuthal asymmetries for $Q\,\bar{Q}$, dijet production in ep collisions; $\gamma\gamma$ in pp collisions
- Modulation of the cross section for hadroproduction of Higgs and scalar quarkonia

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* PRD 86 (2012) 094007; in collaboration with Daniel Boer (KVI, U. Groningen)

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:

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

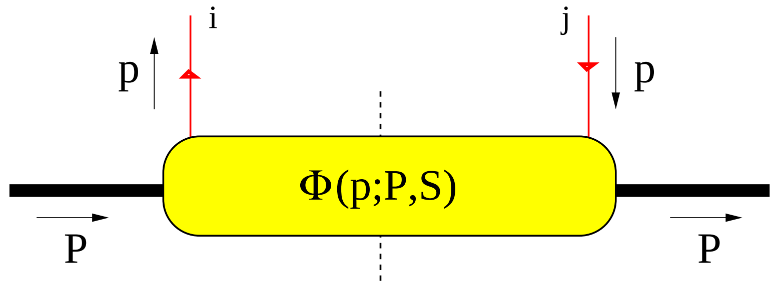
  and other transverse momentum dependent gluon pdfs (TMDs) can be nonzero

- 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

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

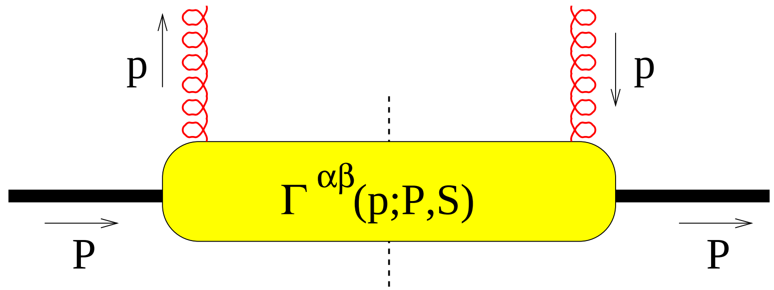
Boer, Mulders, PRD 57 (1998) 5780

- $h_1^{\perp q}(x,\boldsymbol{p}_T^2) = 0$ 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

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

$$\mathcal{A}_{2\phi} \quad \sim \quad \cos 2\phi\, h_1^{\perp\,g}$$

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

- Azimuthal asymmetries in $p\,p \to \gamma\,\gamma\,X$ (RHIC, LHC)

$$\mathcal{A}_{2\phi} \quad \sim \quad \cos 2\phi\, f_1^g \otimes h_1^{\perp\,g}$$

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

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

- Models suggest that $h_1^{\perp\,g}$ may reach its maximally allowed size at small x

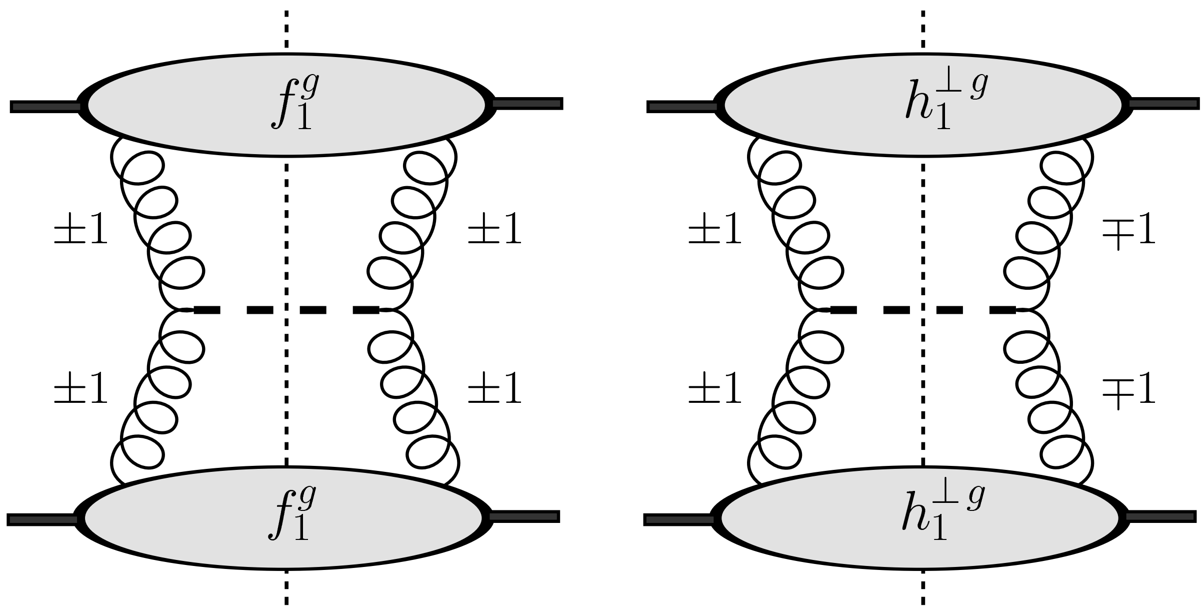
Meissner, Metz, Goeke, PRD 76 (2007) 034002
Metz, Zhou, PRD 84 (2011) 051503
Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003

$h_1^{\perp\,g}$ 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!

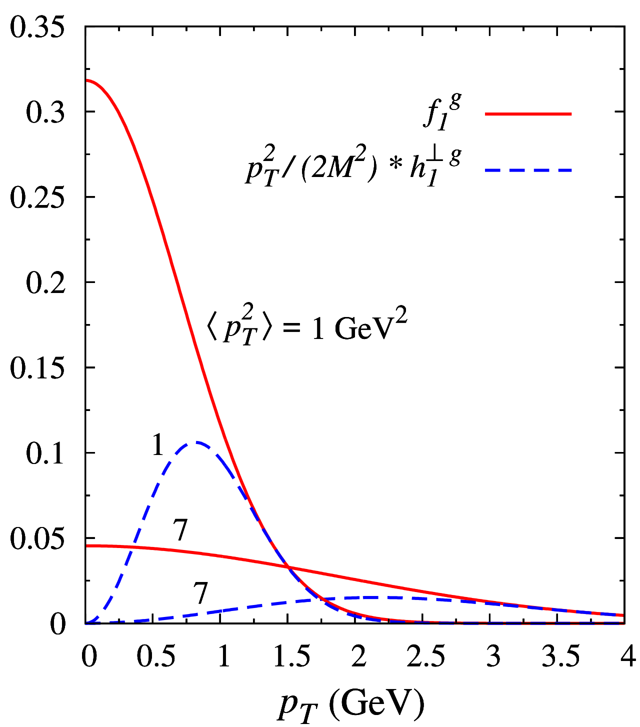
- The angular independent cross section has the form:

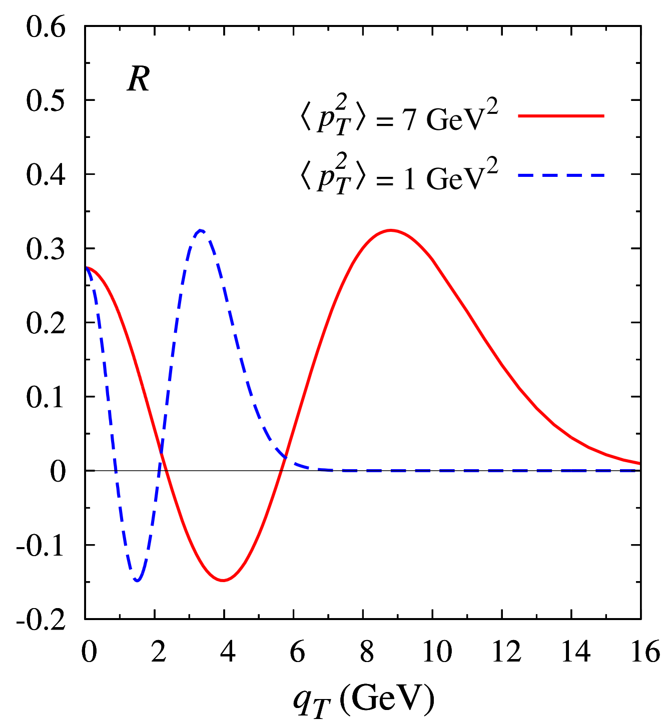
$$\frac{1}{\sigma}\frac{d\sigma}{dq_T^2} \propto 1 \pm R(q_T) \qquad R(q_T) = \frac{\mathcal{C}[w_H\, h_1^{\perp\, g}\, h_1^{\perp\, g}]}{\mathcal{C}[f_1^g\, f_1^g]} \qquad (+\text{ for } H^0;\, -\text{ for } A^0)$$

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

Ellis, Hwang, JHEP 09 (2012) 071

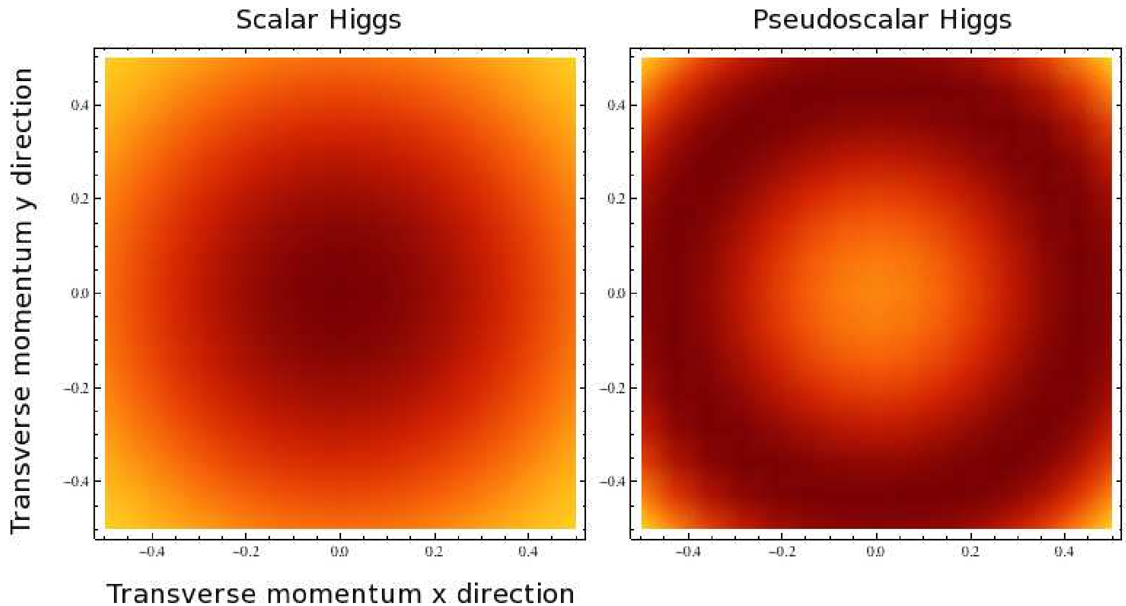
- Gaussian model for f_1^g and $h_1^{\perp\, g}$; $h_1^{\perp\, g}$ is close to its bound for large p_T:





On-shell Higgs boson

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



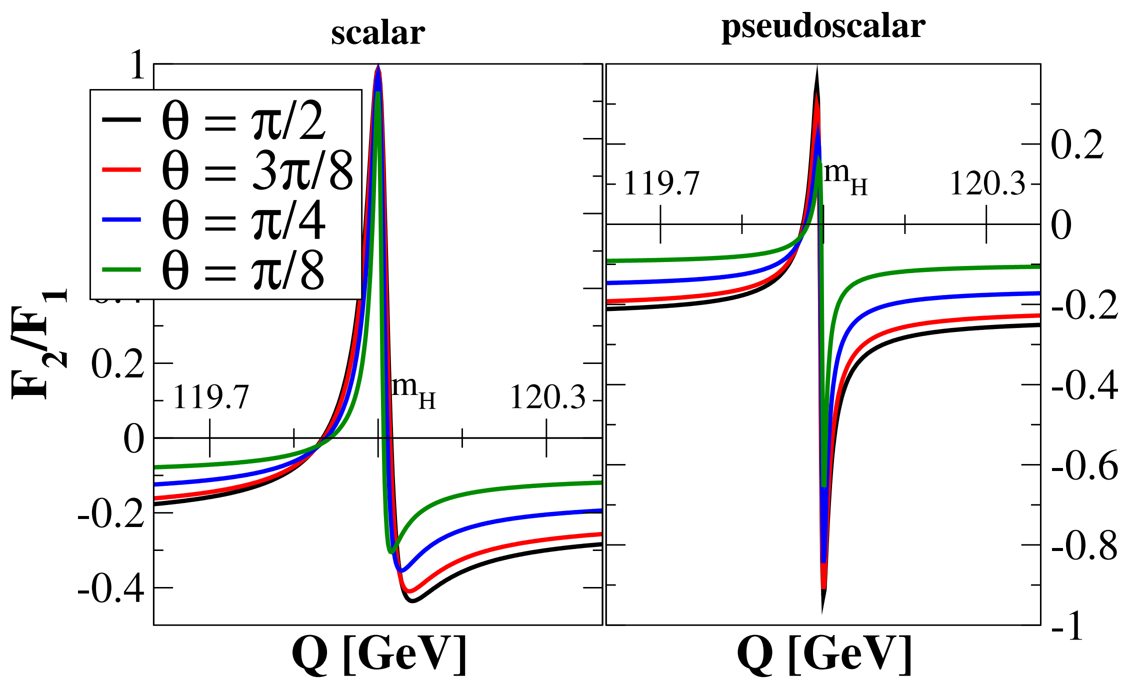
- In reality the Higgs will decay. Background processes may dilute the modulation
- $H \to \gamma\gamma$ has been studied so far
  Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
- Linearly polarized gluons contribute also to $gg \to \gamma\gamma$ without Higgs
  Nadolsky, Balazs, Berger, 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; $\quad Q = \sqrt{q^2}$



- 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

Quarkonium production

- $C=+$ quarkonia ($\eta_{c,b}$, $\chi_{c,b}$) produced in pp collisions: reliable gluon probes

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

- $h(P_A)+h(P_B) \to Q\bar{Q}[^{2S+1}L_J](q)+X$ is dominated by the partonic reaction

  $$g(p_a) + g(p_b) \to Q\bar{Q}[^{2S+1}L_J](q)$$

  with the $Q\bar{Q}$ pair in a bound state described by a nonrelativistic wave function

- Hadrons produced in $2 \to 1$ processes have small transverse momentum $q_T = p_{aT} + p_{bT}$ are mostly lost down the beam pipe at colliders like the LHC

- They could be detected by forward detectors at LHCb

  Barsuk, He, Kou, Viaud, PRD 86 (2012) 034011

  or in fixed target experiments, like the proposed AFTER@LHC

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

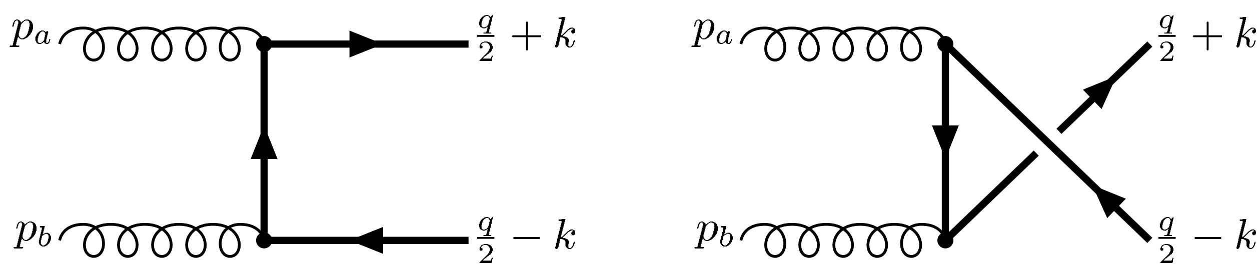
Calculation of the cross section

- The process is studied in the TMD factorization approach, in combination with NRQCD based color-singlet model, for $q_T^2 \ll 4M_Q^2$

TMD master formula:

$$d\sigma = \frac{1}{2s}\,\frac{d^3\boldsymbol{q}}{(2\pi)^3\,2q^0}\int dx_a\,dx_b\,d^2\boldsymbol{p}_{aT}\,d^2\boldsymbol{p}_{bT}\,(2\pi)^4\delta^4(p_a+p_b-q)$$
$$\times \mathrm{Tr}\left\{\Phi_g(x_a,\boldsymbol{p}_{aT})\Phi_g(x_b,\boldsymbol{p}_{bT})\overline{\sum_{\text{colors}}}\left|\mathcal{A}\left(g\,g\to Q\bar{Q}[^{2S+1}L_J]\right)\right|^2\right\}$$

- At LO pQCD described by



- At low q_T, color-octet contributions are suppressed

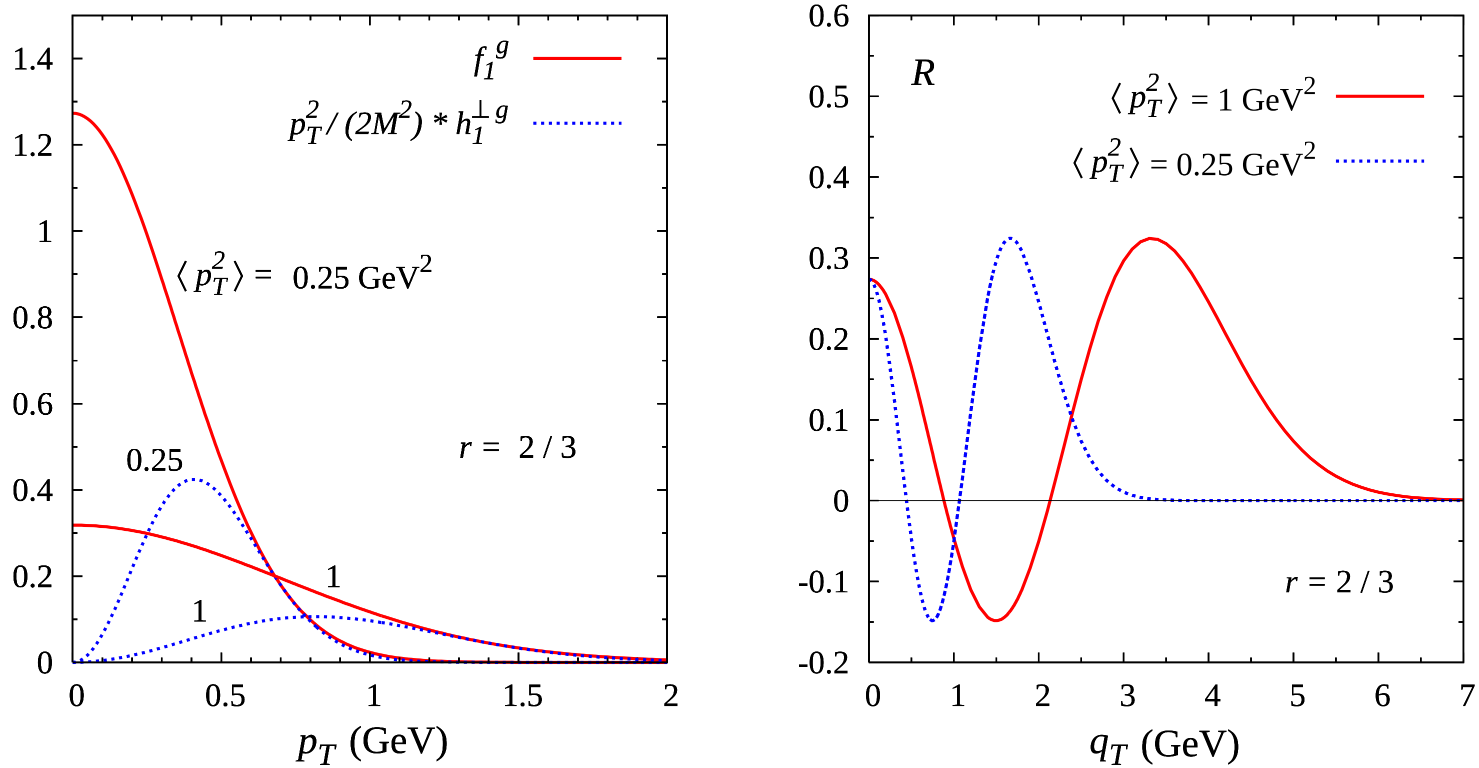
Bodwin, Braaten, Lee, PRD 72 (2005) 014004
Bodwin, Braaten, Lepage, PRD 51 (1995) 1125

Gaussian model for the TMDs

$h_1^{\perp g}$ is constrained by a model-independent positivity bound

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

Standard approach: TMDs have a Gaussian dependence on transverse momentum



The width $\langle p_T^2 \rangle$ will depend on the energy scale, set by the quarkonium mass M

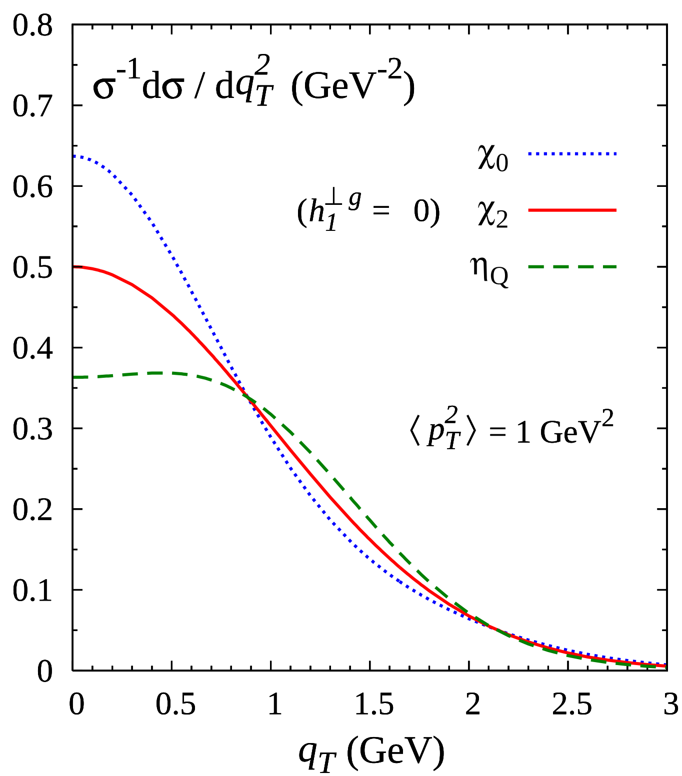
Aybat, Rogers, PRD 83 (2011) 114042

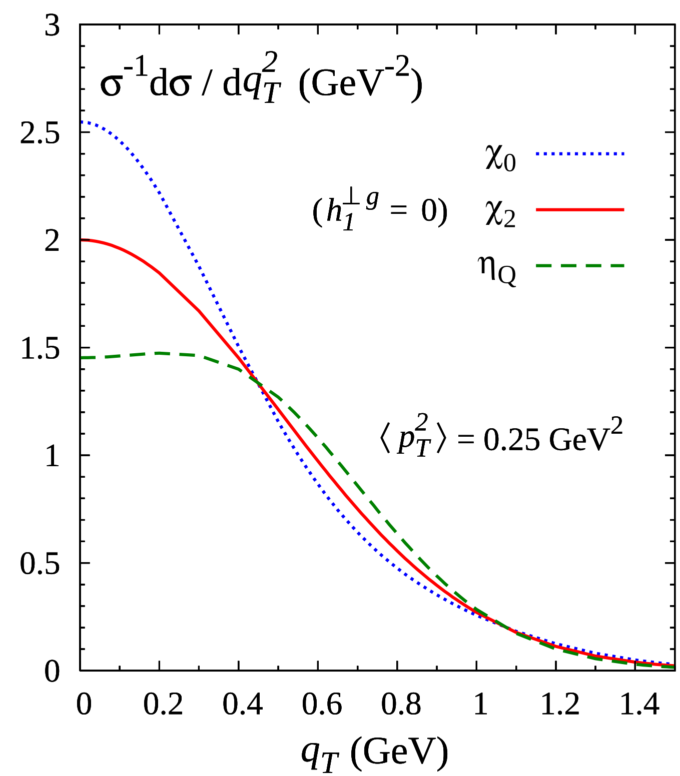
- Similarly to the Higgs case:

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

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

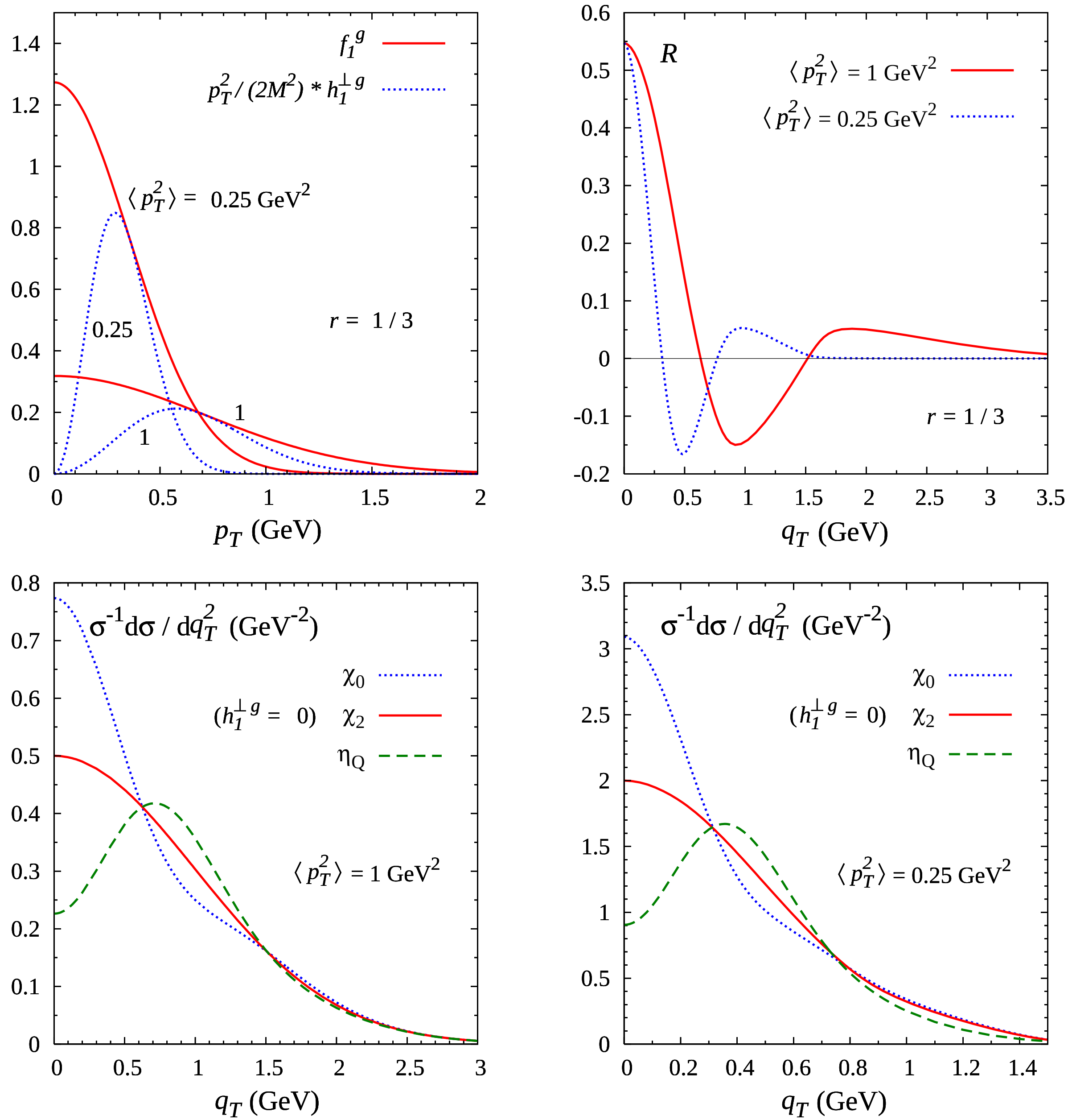
The effects of $h_1^{\perp\, g}$ on higher angular momentum bound states are suppressed





Boer, CP, PRD 86 (2012) 094007

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



Summary and conclusions

- $C = +$ quarkonium production in pp collisions studied within the framework of TMD factorization in combination with NRQCD based color-singlet model

- $h_1^{\perp\, g}$ leads to a modulation of the angular independent transverse momentum distribution of scalar (χ_{c0}, χ_{b0}) and pseudoscalar (η_c, η_b) quarkonia: double node structure, sign depends on the parity of the particle

- Polarized beams are not required, no angular analysis needs to be performed; experimental opportunities offered by LHCb and the proposed AFTER@LHC

- Together with a similar study in the Higgs sector, quarkonium production can be used to extract $h_1^{\perp\, g}$ and to study its scale dependence over a large energy range

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