TMD gluon distributions and quarkonium production in unpolarized pp collisions

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- $h_1^{\perp\,g}$: distribution of linearly polarized gluons inside an unpolarized hadron
- 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
- New: f_1^g (unpolarized gluon TMD) and $h_1^{\perp g}$ can be probed via $J/\psi(\Upsilon)+\gamma$ at LHC

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

  M. Schlegel's talk

- 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

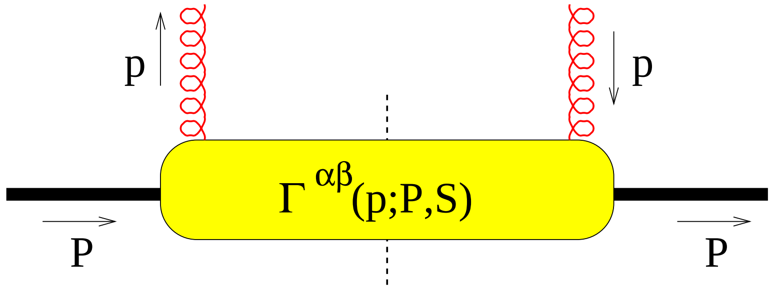
- Once $h_1^{\perp\, g}$ is known, polarized processes without polarized beams at our disposal

Gluon correlator

- The gluon correlator describes the hadron $\to$ gluon transition

  Gluon momentum $\quad p = x\,P + p_T + p^- n,$ with $n^2{=}0$ and $n{\cdot}P{=}1$

  transverse projector: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$



- It is parametrized in terms of TMDs. At "Leading Twist" and omitting gauge links:

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

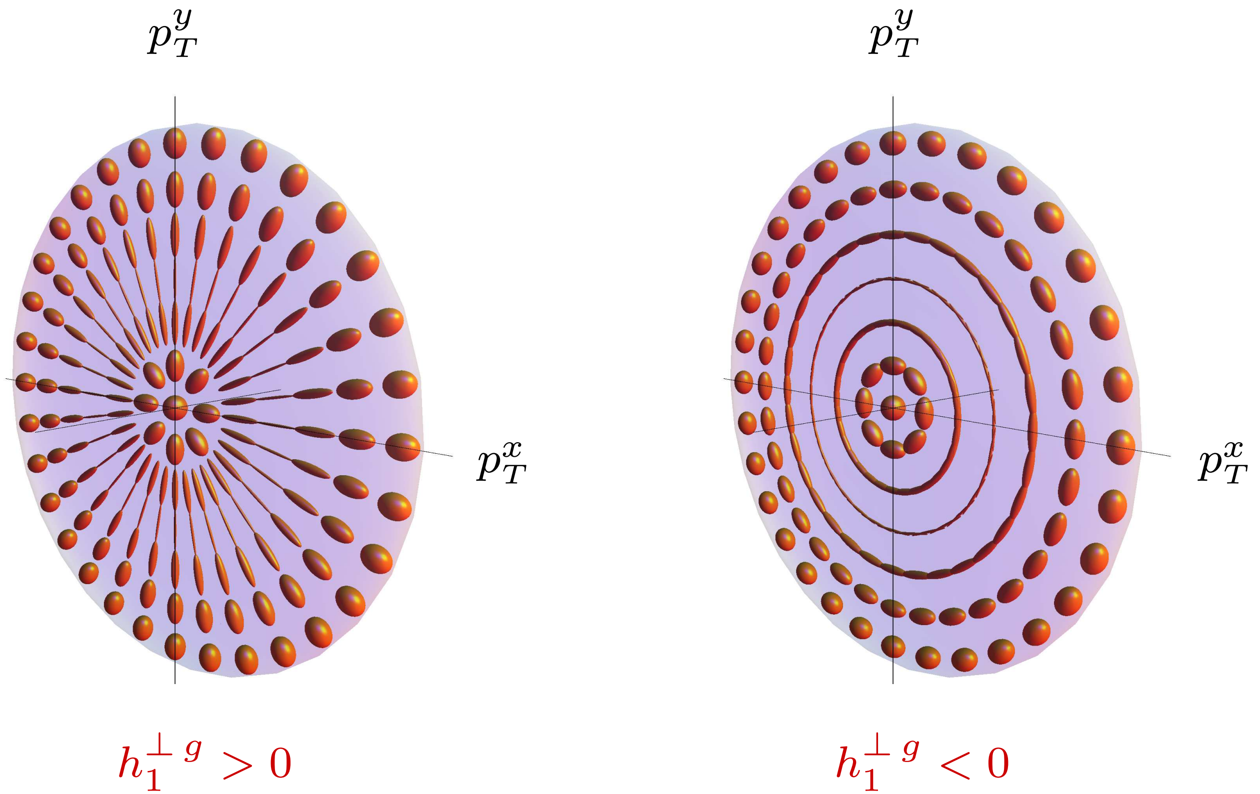
  - $f_1^g(x,\boldsymbol{p}_T^2) \equiv g(x,\boldsymbol{p}_T^2)$ is the usual unpolarized gluon distribution; $p_T^2 = -\boldsymbol{p}_T^2$
  - $h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)$ is the T-even distribution of linearly pol. gluons in an unp. hadron

  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!

- Transverse momentum plane. $h_1^{\perp\, g}$ is taken to be a Gaussian



- The ellipsoid axis lengths are proportional to the probability of finding a gluon with a linear polarization in that direction

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

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

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

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

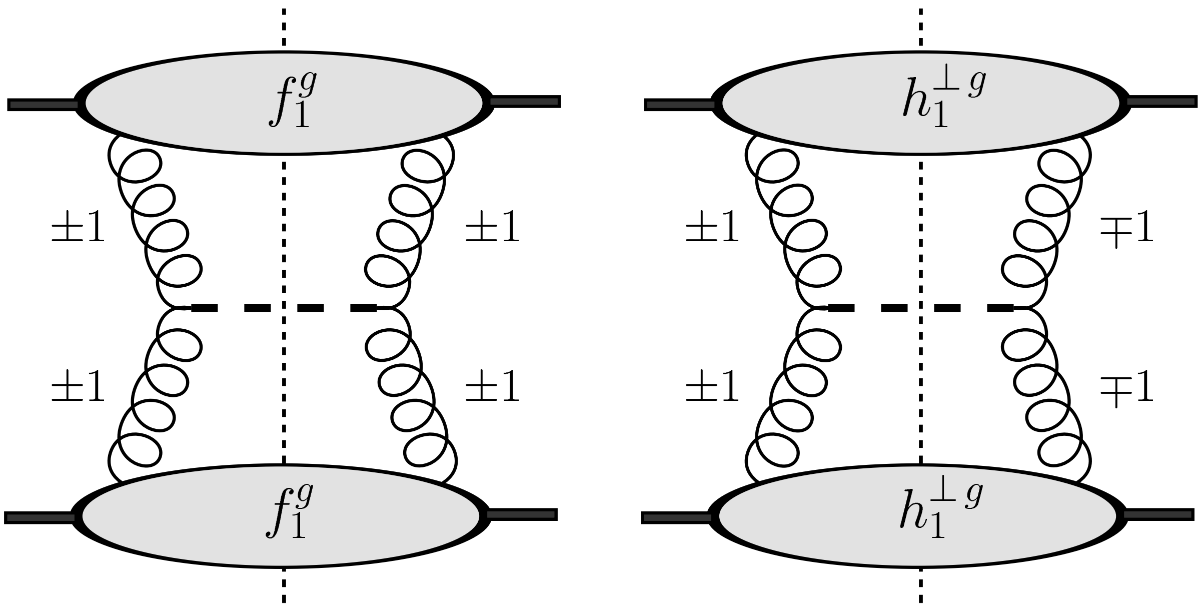
Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

- 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!

On-shell Higgs boson

- The angular independent cross section has the form:

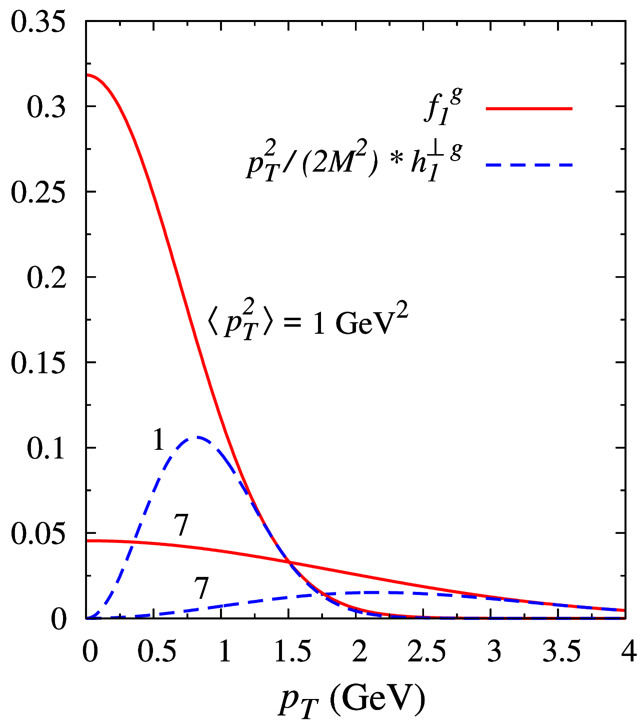
$$\frac{1}{\sigma}\frac{d\sigma}{dq_T^2} \propto 1 \pm R(q_T) \qquad R(q_T) = \frac{\mathcal{C}[w_H\, h_1^{\perp\, g}\, h_1^{\perp\, g}]}{\mathcal{C}[f_1^g\, f_1^g]} \qquad (+\ \text{for}\ H^0;\ -\ \text{for}\ A^0)$$

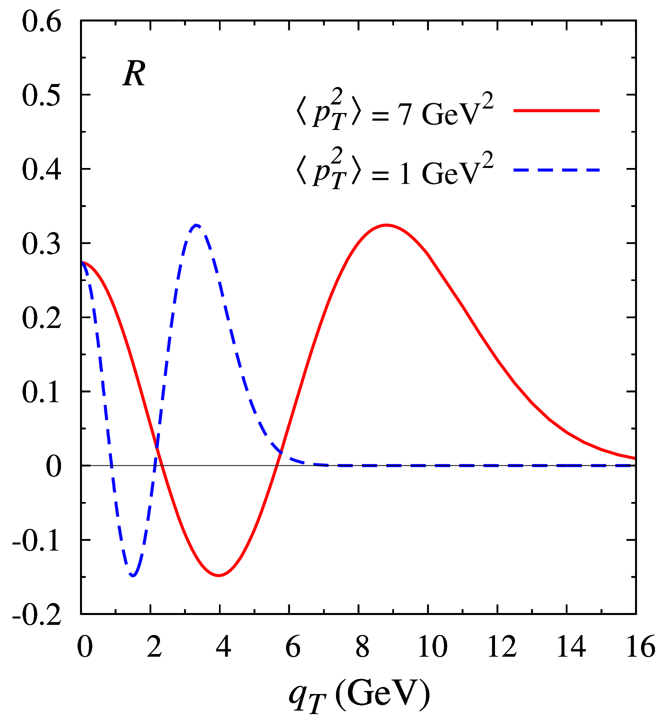
$R = 0$ for a spin 2 particle with the same couplings of a Kaluza-Klein graviton

Ellis, Hwang, JHEP 09 (2012) 071

Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002

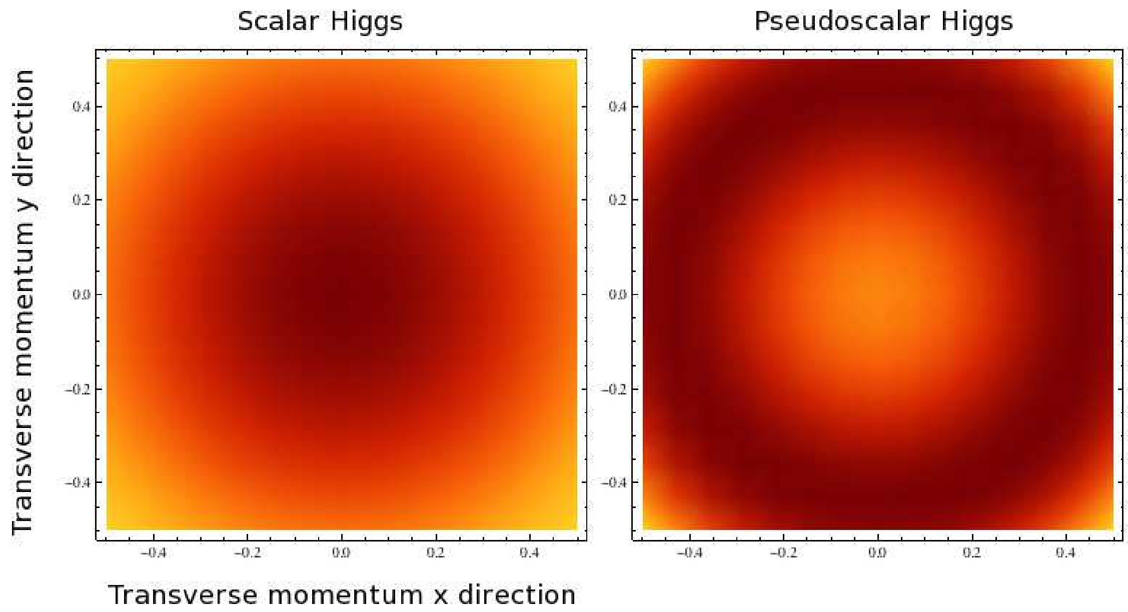
- Gaussian model for f_1^g and $h_1^{\perp\, g}$; $h_1^{\perp\, g}$ is close to its bound for large p_T:





On-shell Higgs boson

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



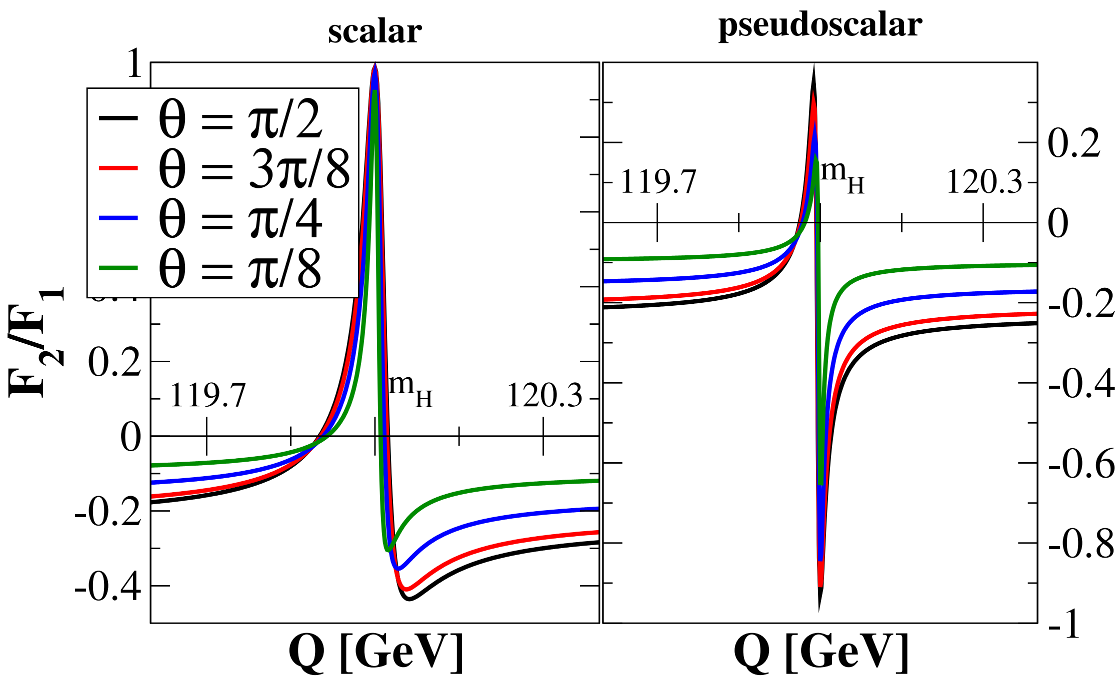
- In reality the Higgs will decay. Background processes may dilute the modulation
- $H \to \gamma\gamma$ has been studied so far
  Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
- Linearly polarized gluons contribute also to $gg \to \gamma\gamma$ without Higgs
  Nadolsky, Balazs, Berger,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

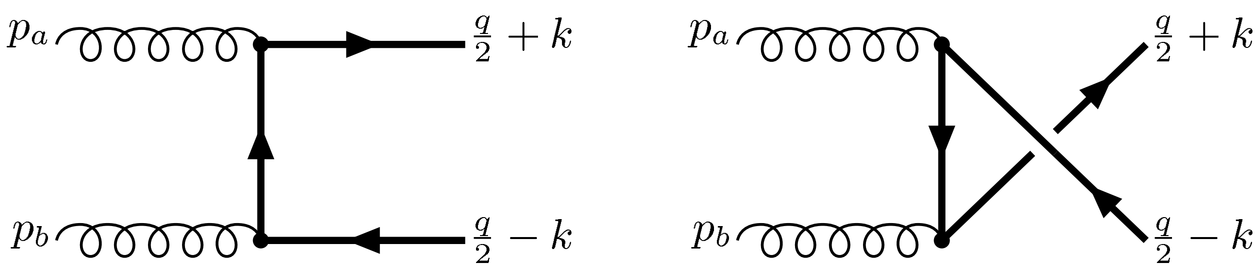
Calculation of the cross section

- 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:

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

- At LO pQCD described by



- At low q_T, color-octet contributions are suppressed

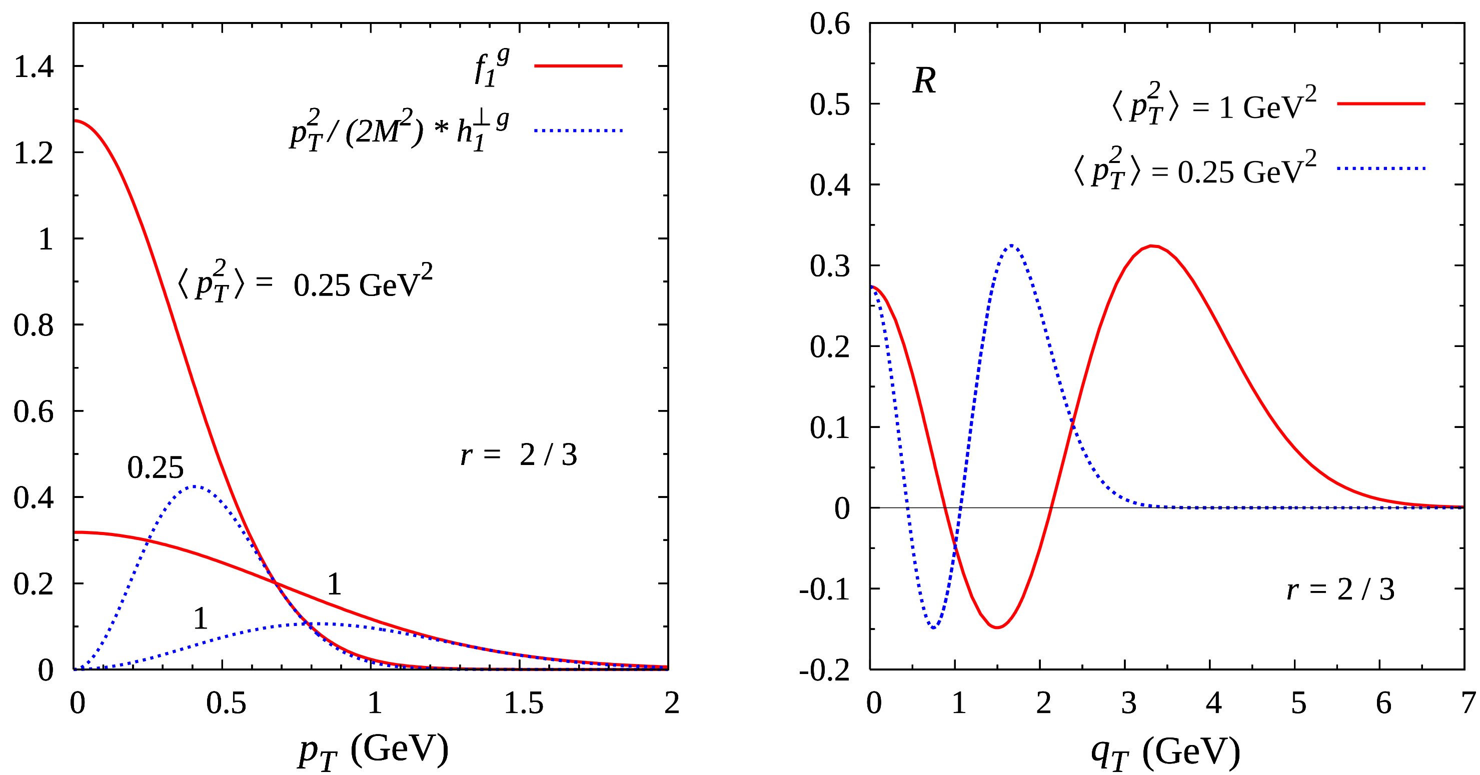
Bodwin, Braaten, Lee, PRD 72 (2005) 014004
Bodwin, Braaten, Lepage, PRD 51 (1995) 1125

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

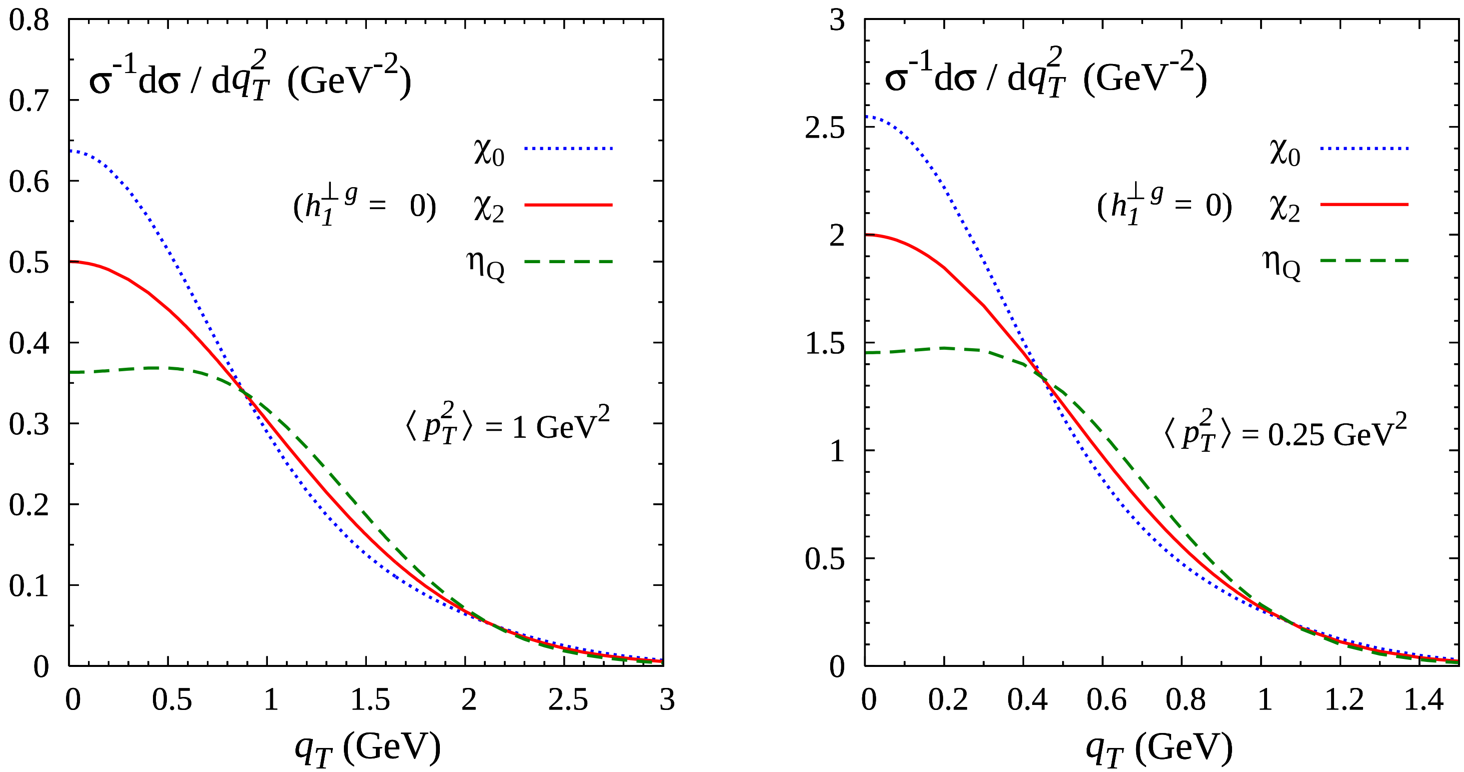
Transverse momentum distributions

- Similarly to the Higgs case:

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

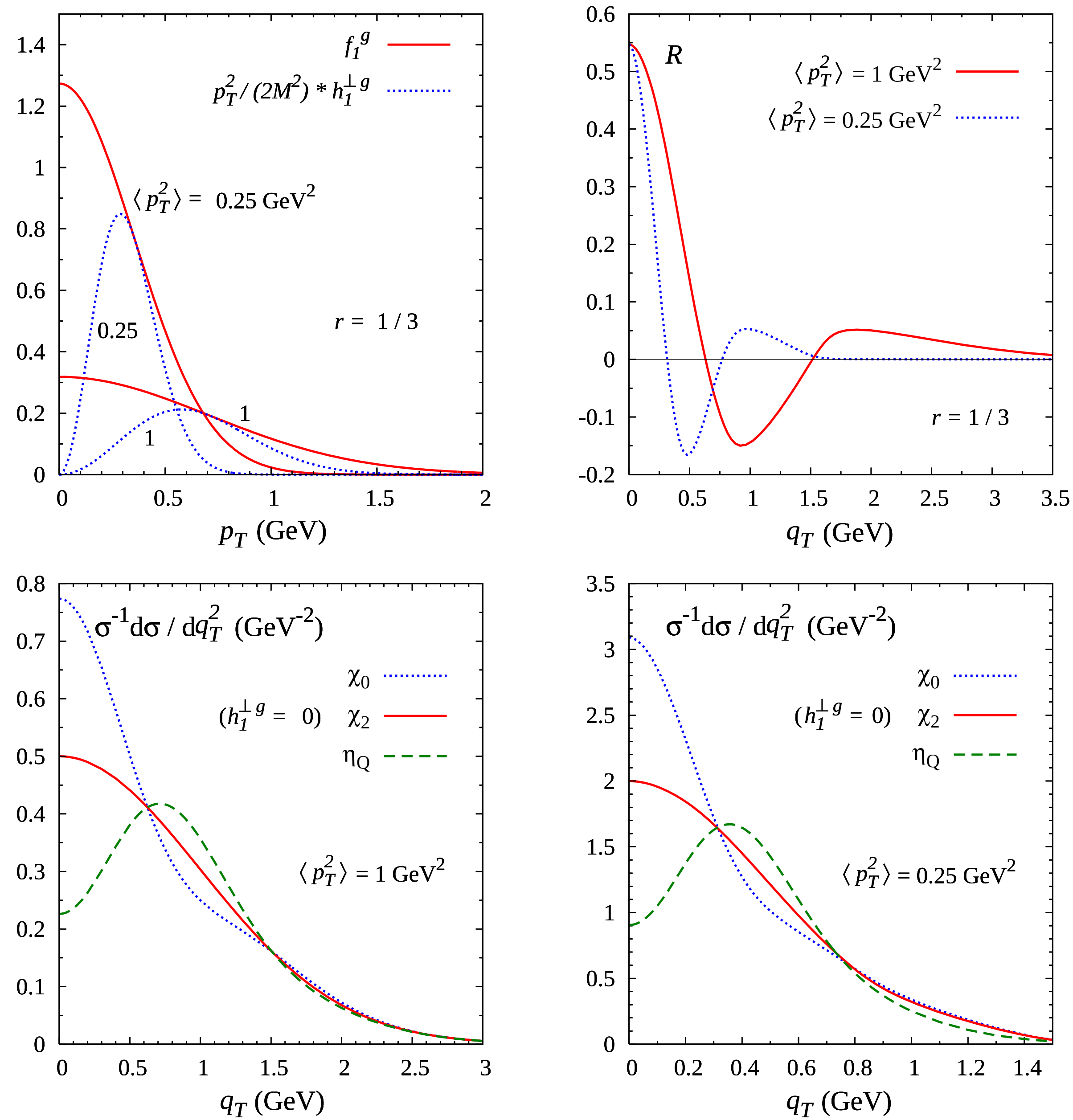
$$\frac{1}{\sigma(\chi_Q)}\frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto 1 + R(\boldsymbol{q}_T^2) \qquad \text{[scalar]}$$

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



Boer, CP, PRD 86 (2012) 094007

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



Gauge links and factorization breaking

- $h_1^{\perp\, g}$ 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, PRD 88 (2013) 054027

- 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 $pp \to \mathrm{jet\,jet}\, X$ 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

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

$pp \to \mathcal{Q} + \gamma + X$

- Quarkonium $\mathcal{Q} \equiv Q\bar{Q}[^3S_1]$ and isolated γ produced almost back-to-back

  den Dunnen, Lansberg, CP, Schlegel, in preparation

- Accessible at the LHC : only the transverse momentum of the $\mathcal{Q} + \gamma$ pair needs to be small, not the individual ones

- Study of TMD evolution by tuning the invariant mass of $\mathcal{Q} + \gamma$ (evolution scale)

- Color octet (CO) contributions to $\mathcal{Q} + \gamma$ likely smaller than for inclusive $\mathcal{Q}$

  Kim, Lee, Song, PRD 55 (1997) 5429
  Li, Wang, PLB 672 (2009) 51
  Lansberg, PLB 679 (2009) 340

- CO further suppressed w.r.t. CS contributions when $\mathcal{Q}$ and γ are back-to-back

  Mathews, Sridhar, Basu, PRD 60 (1999) 014009

Calculation of the cross section

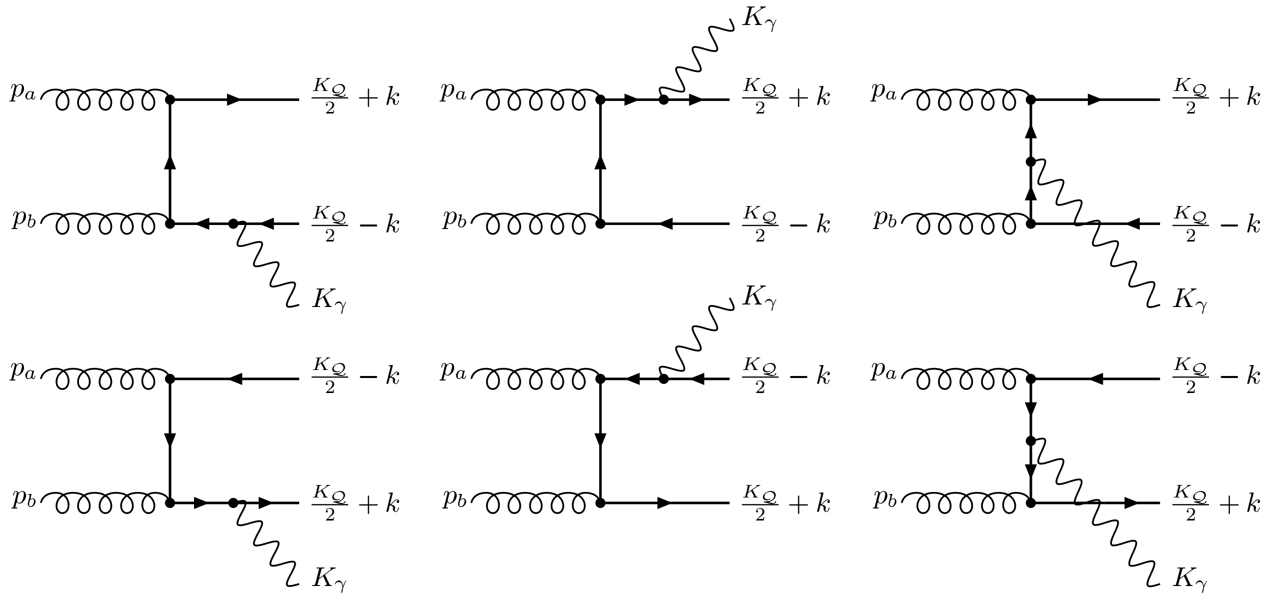
- TMD factorization approach, in combination with the color-singlet model, for $q_T^2 \ll Q^2$, with $q_T = K_{\mathcal{Q}T} + K_{\gamma T}$, $Q^2 \equiv q^2 = (K_{\mathcal{Q}T} + K_{\gamma T})^2$

TMD master formula:

$$d\sigma = \frac{1}{2s} \frac{d^3\boldsymbol{K}_{\mathcal{Q}}}{(2\pi)^3\, 2K^0_{\mathcal{Q}}} \frac{d^3\boldsymbol{K}_{\gamma}}{(2\pi)^3\, 2K^0_{\gamma}} \int dx_a\, dx_b\, d^2\boldsymbol{p}_{aT}\, d^2\boldsymbol{p}_{bT}\, (2\pi)^4 \delta^4(p_a + p_b - q)$$

$$\times \mathrm{Tr}\left\{ \Phi_g(x_a, \boldsymbol{p}_{aT}) \Phi_g(x_b, \boldsymbol{p}_{bT}) \overline{\sum_{\text{colors}}} \left| \mathcal{A}\left(g\, g \to Q\bar{Q}[^3S_1]\right)\right|^2 \right\}$$

Feynman diagrams at LO pQCD:



Structure of the cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q\mathrm{d}Y\mathrm{d}^2 q_T \mathrm{d}\Omega} \propto A\, f_1^g \otimes f_1^g + B\, f_1^g \otimes h_1^{\perp g} \cos(2\phi_{CS}) + C\, h_1^{\perp g} \otimes h_1^{\perp g} \cos(4\phi_{CS})$$

- valid up to corrections $\mathcal{O}\left(q_T^2/Q^2\right)$
- Y: rapidity of the $\mathcal{Q}+\gamma$ pair, along the beams in the hadronic c.m. frame
- $\mathrm{d}\Omega = \mathrm{d}\cos\theta_{CS}\, \mathrm{d}\phi_{CS}$: solid angle element for $\mathcal{Q}$ and γ in the Collins-Soper frame

The three contributions can be disentangled by defining the transverse moments

$$\mathcal{S}_{q_T}^{(n)} = \pi \left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q\,\mathrm{d}Y\,\mathrm{d}\cos\theta_{CS}}\right)^{-1} \int \mathrm{d}\phi_{CS}\ \cos(n\phi_{CS})\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\,\mathrm{d}Y\,\mathrm{d}^2\boldsymbol{q}_T \mathrm{d}\Omega} \qquad (n = 0, 2, 4)$$

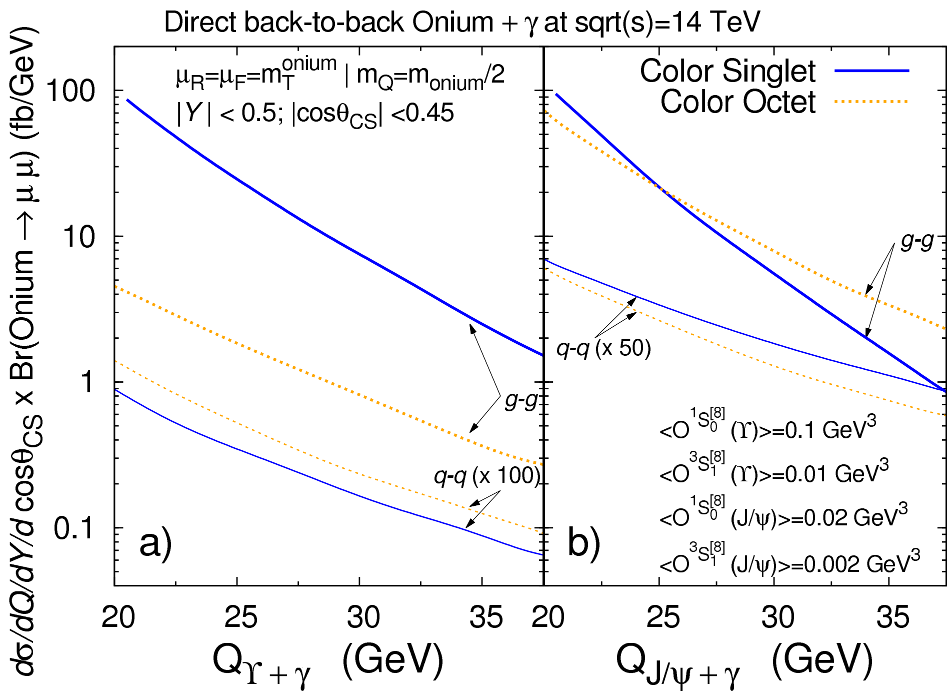
$$\mathcal{S}_{q_T}^{(0)} \Longrightarrow f_1^g \otimes f_1^g$$

$$\mathcal{S}_{q_T}^{(2)} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\mathcal{S}_{q_T}^{(4)} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

Color Singlet vs Color Octet contributions

- Process dominated by gg fusion

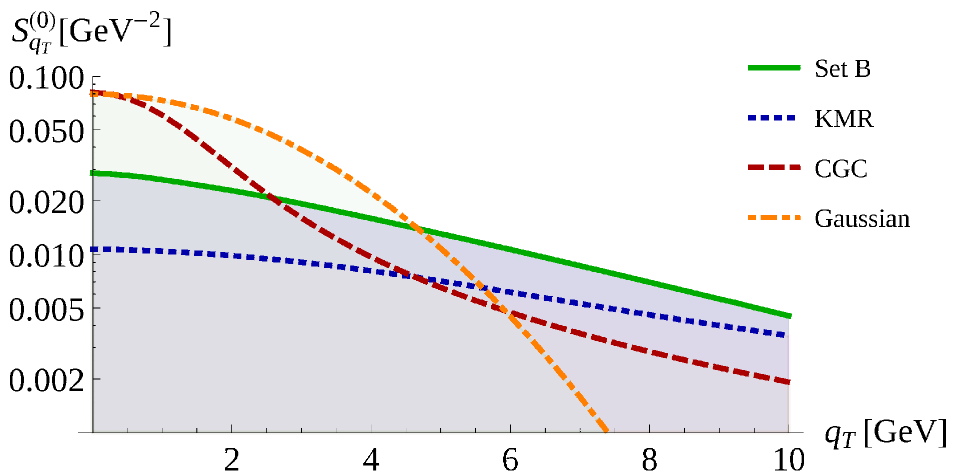


- CS yield is clearly dominant for the Υ, above the CO one for J/ψ at low Q
- Further suppression of CO contributions by isolating $\mathcal{Q}$ (not needed for Υ)

Kraan, AIP Conf. Proc. 1038 (2008) 45
Kikola, NP Proc. Suppl. 214 (2011) 177

$\mathcal{S}_{q_T}^{(0)}$: *Model predictions for $\Upsilon + \gamma$ production at $\sqrt{s} = 8$ TeV*

Q = 20 GeV, $\quad Y = 0, \quad \theta_{CS} = \pi/2$

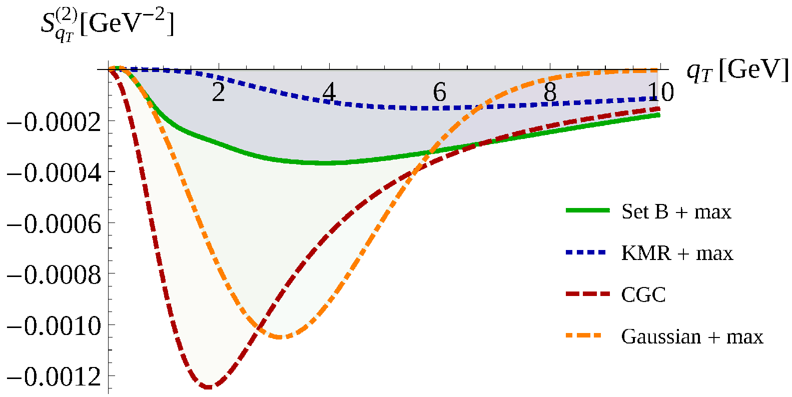


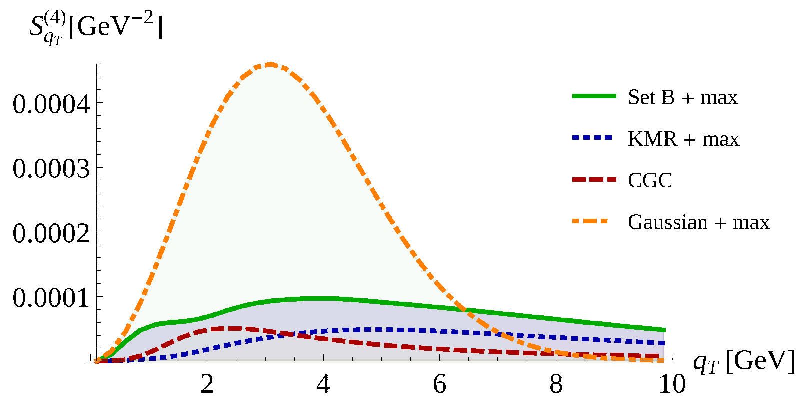
Models for f_1^g: assumed to be the same as for Unintegrated Gluon Distributions

- Set B: B0 solution to CCFM equation with input based on HERA data
  Jung et *al.*, EPJC 70 (2010) 1237
- KMR: Formalism embodies both DGLAP and BFKL evolution equations
  Kimber, Martin, Ryskin, PRD 63 (2010) 114027
- CGC: Color Glass Condensate Model
  Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003
  Metz, Zhou, PRD 84 (2011) 051503

$\mathcal{S}_{q_T}^{(2,4)}$: Model predictions for $\Upsilon + \gamma$ production at $\sqrt{s} = 8$ TeV

Q = 20 GeV, $Y = 0$, $\theta_{CS} = \pi/2$





$h_1^{\perp g}$: predictions only in the CGM: in the other models saturated to its upper bound

$\mathcal{S}_{q_T}^{(2,4)}$ smaller than $\mathcal{S}_{q_T}^{(0)}$: can be integrated up to $q_T = 10$ GeV

$$1.2\% \text{ (KMR)} < \quad \left| \int \mathrm{d}q_T^2 \mathcal{S}_{q_T}^{(2)} \right| \quad < 2.9\% \text{ (Gauss)}$$

$$0.2\% \text{ (CGC)} < \quad \int \mathrm{d}q_T^2 \; \mathcal{S}_{q_T}^{(4)} \quad 0.2\% \text{ (Gauss)}$$

Possible determination of the shape of f_1^g and verification of a non-zero $h_1^{\perp g}$

Conclusions

- $h_1^{\perp\, g}$ leads to a modulation of the angular independent transverse momentum distribution of scalar (χ_{c0}, χ_{b0}) and pseudoscalar (η_c, η_b) quarkonia: the sign will depend 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

- 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. Similar results for $J/\psi(\Upsilon) + Z$, but higher luminosity is required

  den Dunnen, Lansberg, CP, Schlegel, in preparation

- Together with a similar study in the Higgs sector, quarkonium production can be used to extract gluon TMDs and to study their process and scale dependences