Impact of gluon polarization on Higgs production at the LHC

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REF 2014: Resummation, Evolution, Factorization

Antwerp, Belgium
8-11 December 2014

- $h_1^{\perp\, g}$: 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
- Both effects are present in Higgs + jet production in pp collisions

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 ($h_1^{\perp\, g}$: different polarization mode compared to Δg)!

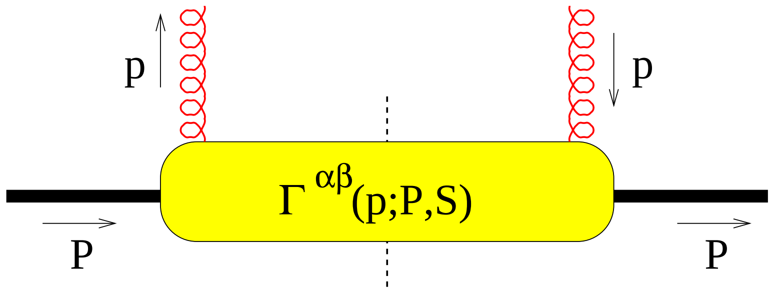
- Nontrivial property that has received much more attention in the quark sector

- 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 $p = x\,P + p_T + p^- n$, 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:

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

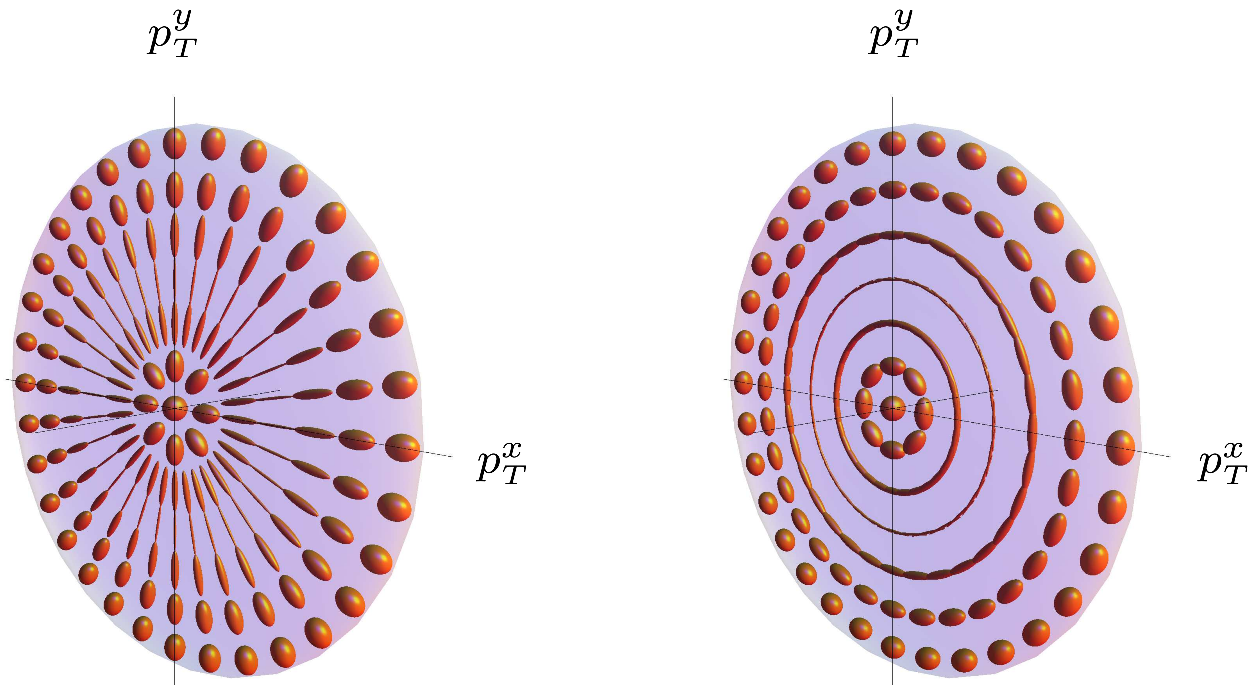
  - $f_1^g(x,\boldsymbol{p}_T^2) \equiv g(x,\boldsymbol{p}_T^2)$ is the usual unpolarized gluon distribution; $p_T^2 = -\boldsymbol{p}_T^2$
  - $h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)$ is the T-even distribution of linearly pol. gluons in an unp. hadron

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)

Visualization of the gluon polarization

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



$h_1^{\perp\, g} > 0$ $\qquad$ $h_1^{\perp\, g} < 0$

- 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)

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

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

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

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

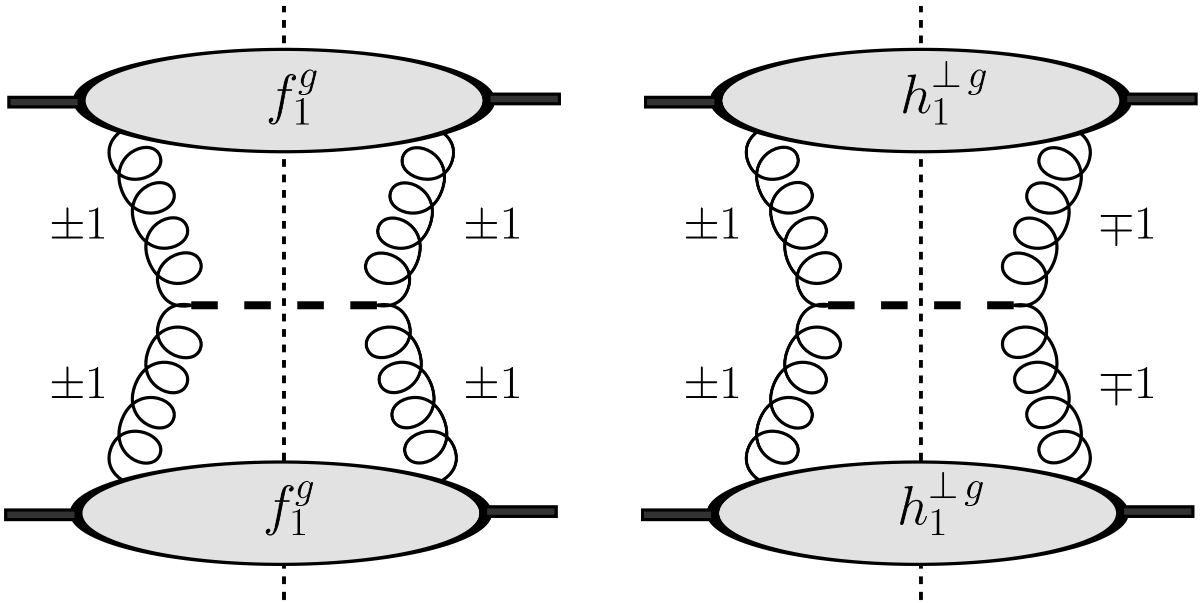
Meissner, Metz, Goeke, PRD 76 (2007) 034002
Metz, Zhou, PRD 84 (2011) 051503
Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003

Inclusive Higgs boson production

- 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!

Inclusive Higgs boson boson

- $h(P_A)+h(P_B) \to H(q)+X$ is dominated by the gluon fusion process
$$g(p_a) + g(p_b) \to H(q)$$

TMD master formula:

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

- When $q_T \ll M_H$, the angular independent cross section has the form:

$$\frac{1}{\sigma}\frac{d\sigma}{dq_T^2} \propto 1 + R(q_T) \qquad R(q_T) = \frac{\mathcal{C}[w_0\,h_1^{\perp\,g}\,h_1^{\perp\,g}]}{\mathcal{C}[f_1^g\,f_1^g]}$$

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

$$\mathcal{C}[w\,f\,g] \equiv \int d^2\boldsymbol{p}_{aT}\int d^2\boldsymbol{p}_{bT}\,\delta^2(\boldsymbol{p}_{aT}+\boldsymbol{p}_{bT}-\boldsymbol{q}_T)\,w(\boldsymbol{p}_{aT},\boldsymbol{p}_{bT})\,f(x_a,\boldsymbol{p}_{aT}^2)\,g(x_b,\boldsymbol{p}_{bT}^2)$$

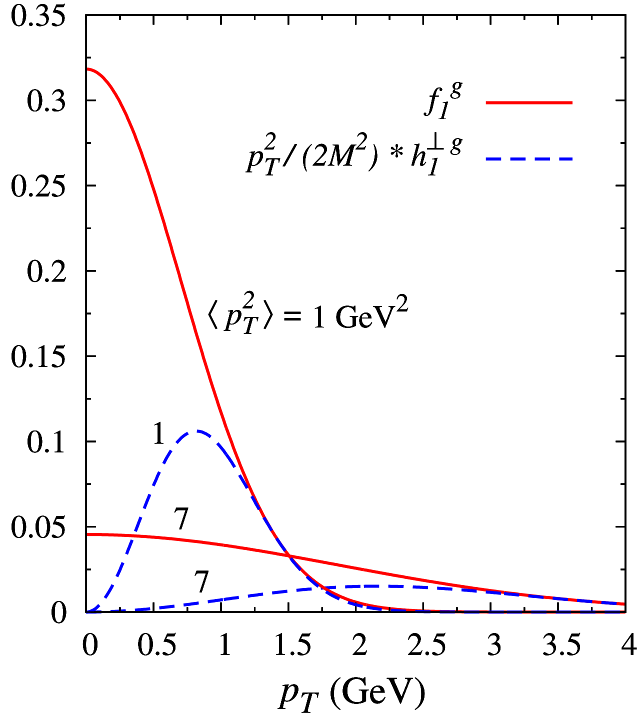
$$w_0 = \frac{1}{2M_p^4}\left[(\boldsymbol{p}_{aT}\cdot\boldsymbol{p}_{bT})^2 - \frac{1}{2}\,\boldsymbol{p}_{aT}^2\boldsymbol{p}_{bT}^2\right]$$

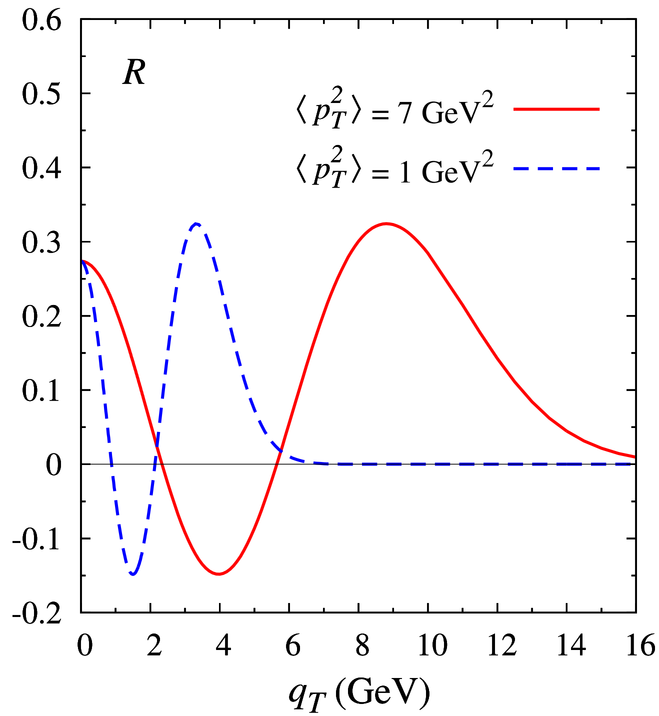
Input distributions

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

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

- Model for f_1^g and $h_1^{\perp\, g}$Gaussian dependence on transverse momentum; $h_1^{\perp\, g}$ is close to its bound for large p_T:

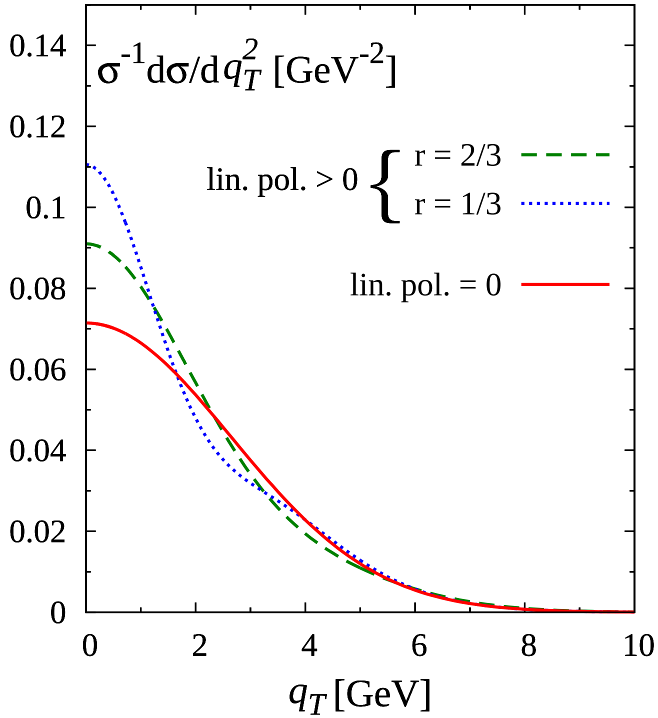




- The width $\langle p_T^2 \rangle$ will depend on the energy scale, set by the Higgs mass M_H

Aybat, Rogers, PRD 83 (2011) 114042

Transverse momentum distribution for $pp \to H\,X$



- 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 111 (2013) 032002
- Linearly polarized gluons contribute also to $gg \to \gamma\gamma$ without Higgs

  Nadolsky, Balazs, Berger, Yuan, PRD 76 (2007) 013008

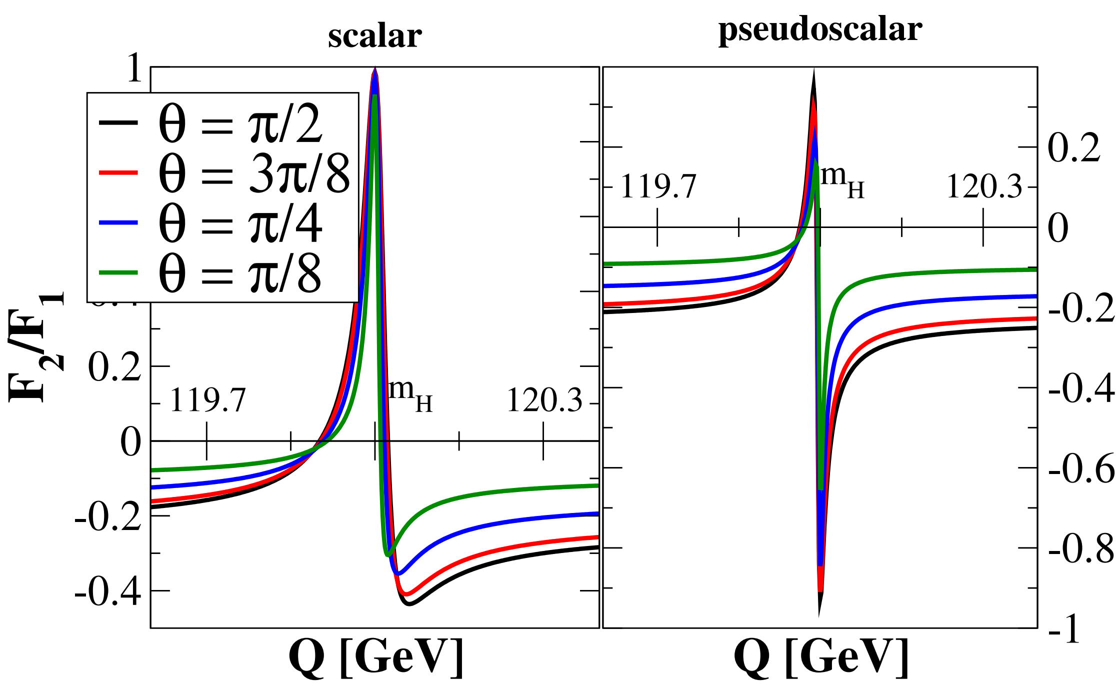
  Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

$gg \to \gamma\gamma$

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

$d\Omega = d\cos\theta d\phi$ 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

Transverse spectra of C-even quarkonia

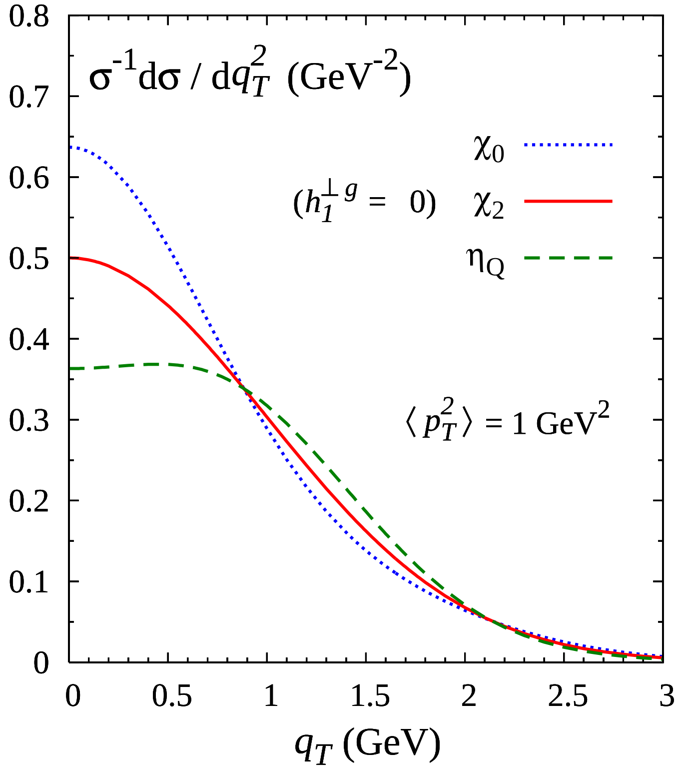
J. Lansberg's talk

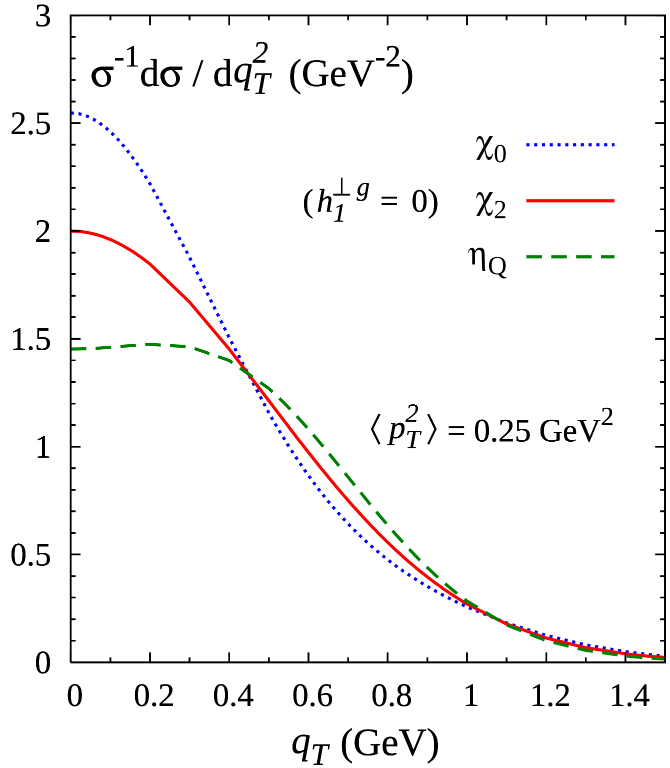
- Similarly to the Higgs case:

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

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

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





Boer, CP, PRD 86 (2012) 094007

Higgs plus jet production

- Advantage: only the transverse momentum of the H + jet pair q_T needs to be small, not the individual ones, K_{HT} and $K_{\mathrm{j}T}$
- Study of TMD evolution by tuning the invariant mass of H +jet (evolution scale)
- TMD factorization approach: correlation limit $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$,

$$\boldsymbol{q}_T = \boldsymbol{K}_{HT} + \boldsymbol{K}_{\mathrm{j}T}, \quad \boldsymbol{K}_\perp = (\boldsymbol{K}_{HT} - \boldsymbol{K}_{\mathrm{j}T})/2, \quad M_\perp = \sqrt{M_H^2 + K_{H\perp}^2}$$

TMD master formula:

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

Partonic subprocesses contributing at LO pQCD: $gg \to Hg, \quad qg \to Hq, \quad q\bar{q} \to Hg$

Boer, CP, NIKHEF-2014-049

Angular structure of the cross section

In the hadronic center of mass frame, focus on $gg \to Hg$:

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

$$\frac{\mathrm{d}\sigma}{\sigma} = \frac{\mathrm{d}\sigma}{\int_0^{q_{T\max}^2} \mathrm{d}\boldsymbol{q}_T^2 \int_0^{2\pi} \mathrm{d}\phi\,\mathrm{d}\sigma} = \frac{1}{2\pi}\,\sigma_0(\boldsymbol{q}_T^2)\,\left[1 + R_0(\boldsymbol{q}_T^2) + R_2(\boldsymbol{q}_T^2)\cos 2\phi + R_4(\boldsymbol{q}_T^2)\cos 4\phi\right]$$

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}y_H\,\mathrm{d}y_\mathrm{j}\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \qquad \sigma_0(\boldsymbol{q}_T^2) \equiv \frac{\mathcal{C}[f_1^g\, f_1^g]}{\int_0^{q_{T\max}^2} \mathrm{d}\boldsymbol{q}_T^2\,\mathcal{C}[f_1^g\, f_1^g]}$$

The three contributions can be disentangled by defining the TMD observables

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

$$\frac{1}{\sigma}\,\frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \langle 1\rangle_{q_T} \quad \Longrightarrow \quad f_1^g \otimes f_1^g, \quad h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi\rangle_{q_T} \quad \Longrightarrow \quad f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi\rangle_{q_T} \quad \Longrightarrow \quad h_1^{\perp g} \otimes h_1^{\perp g}$$

q_T-distribution

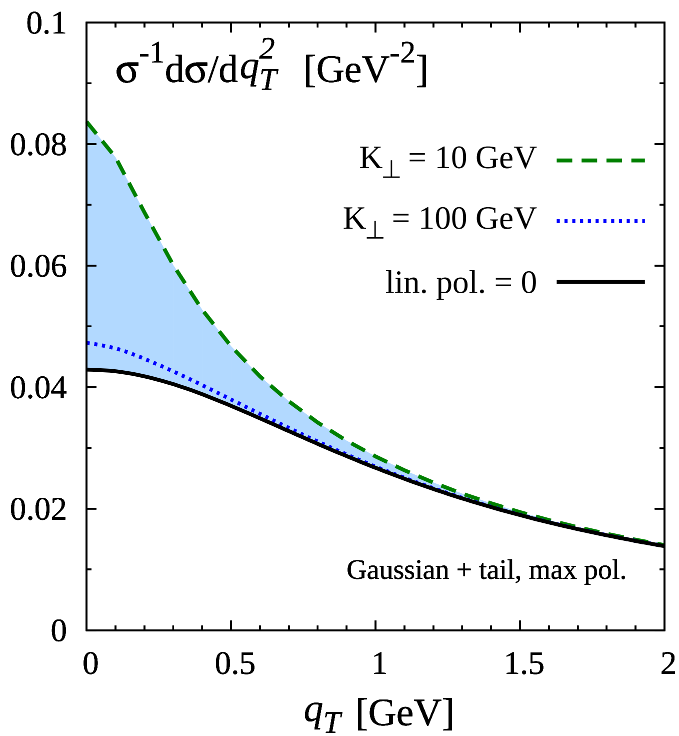
Models for the TMD gluon distribution:

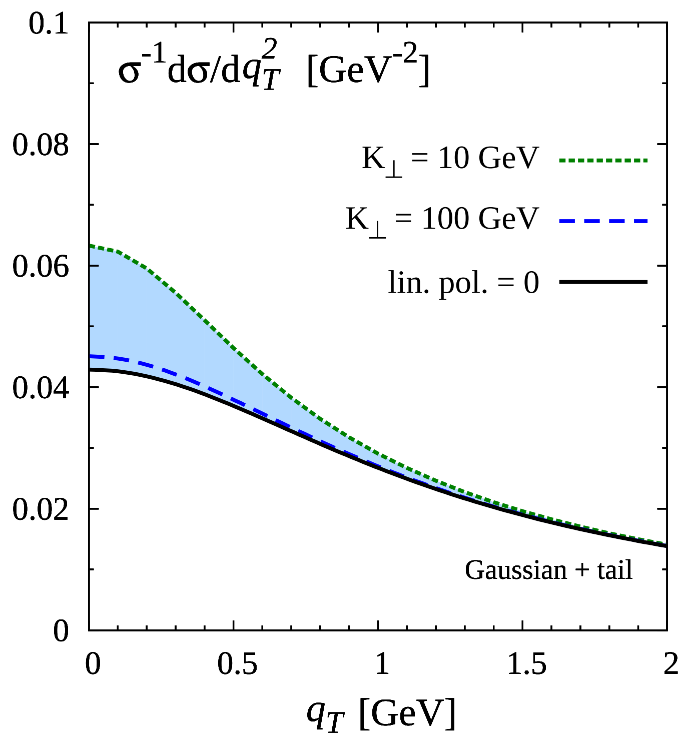
$$\text{Gaussian + tail} \quad f_1^g(x, \boldsymbol{p}_T^2) = f_1^g(x) \frac{R^2}{2\pi} \frac{1}{1 + \boldsymbol{p}_T^2 R^2} \qquad R = 2 \text{ GeV}^{-1}$$

$$\text{Maximal polarization} \quad h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) = \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$

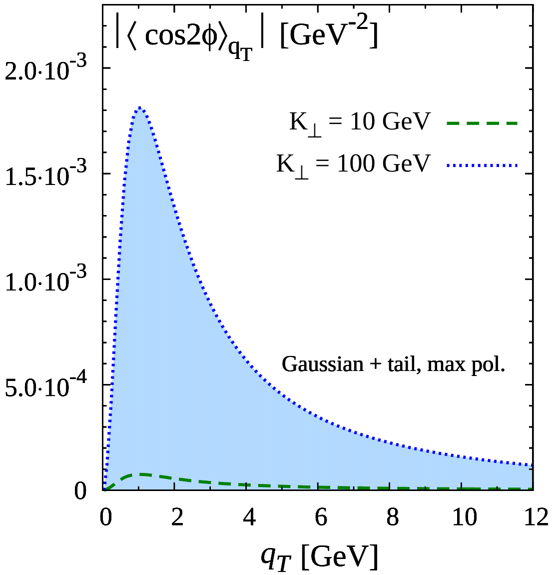
$$\text{Gaussian + tail} \quad h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) = 2\, f_1^g(x) \frac{M_p^2 R_h^4}{2\pi} \frac{1}{(1 + \boldsymbol{p}_T^2 R_h^2)^2}, \qquad R_h = 3/2\, R$$

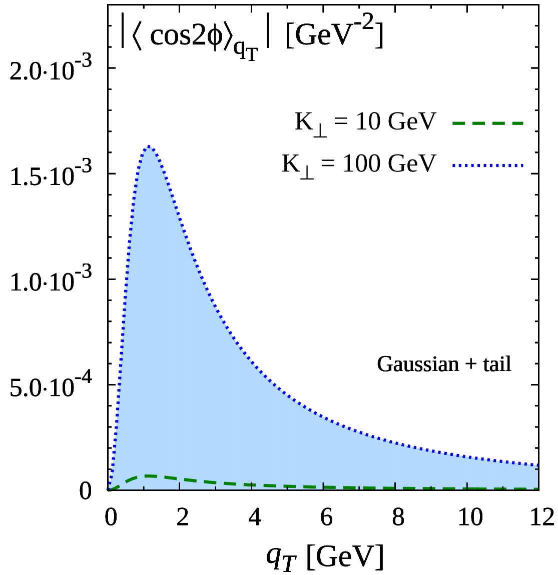
Boer, den Dunnen, NPB 886 (2014) 421





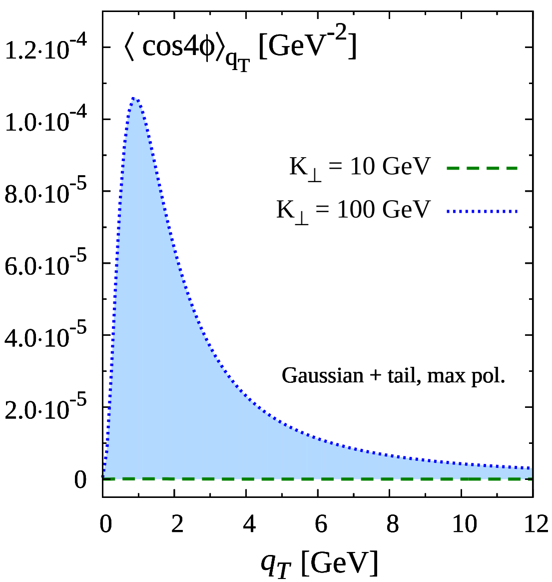
Azimuthal asymmetries

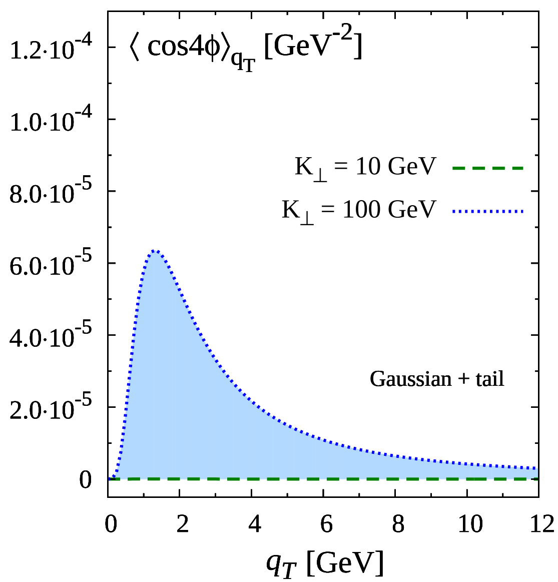




$q_{T\max} = M_H/2$

$\langle \cos 2\phi \rangle \approx 12\%$
at $K_\perp = 100$ GeV





$\langle \cos 4\phi \rangle \approx 0.1 - 0.2\%$
at $K_\perp = 100$ GeV

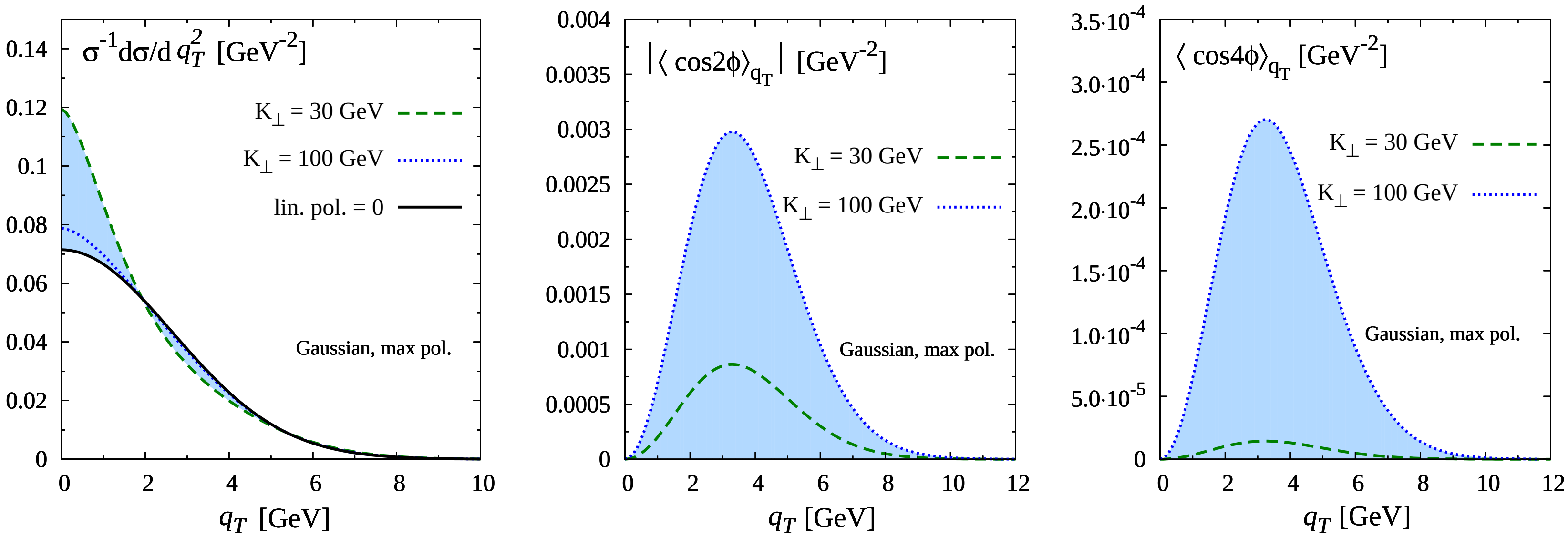
Alternative model for the TMDs

Gaussian model for the unpolarized gluon distribution

$$f_1^g(x, \boldsymbol{p}_T^2) = \frac{f_1^g(x)}{\pi \langle p_T^2 \rangle} \exp\left[-\frac{\boldsymbol{p}_T^2}{\langle p_T^2 \rangle}\right], \qquad \langle p_T^2 \rangle = 7\ \mathrm{GeV}^2$$

Maximal polarization for the distribution of linearly polarized gluons

$$h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) \quad = \quad \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$



$q_{T\max} = K_\perp/2$

$\langle \cos 2\phi \rangle \approx 9\%$ at $K_\perp = 100$ GeV

$\langle \cos 4\phi \rangle \approx 0.4\%$ at $K_\perp = 100$ GeV

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 $pp \to H\,\mathrm{jet} X$: color entanglement, but TMD factorization could hold (maybe)

- 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

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

Conclusions

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

- Polarized beams are not required, no angular analysis needs to be performed; such effects could be measured at the LHC

- $h_1^{\perp\, g}$ leads to a modulation of the transverse spectrum of the $H - \gamma$ pair and to azimuthal asymmetries in $pp \to H\,\mathrm{jet}\,X$

- 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.

  J. Lansberg's talk

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