Linear polarization of gluons and Higgs+jet production at the LHC

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Vlaanderen
Opening new horizons

Gluon distributions

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:

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

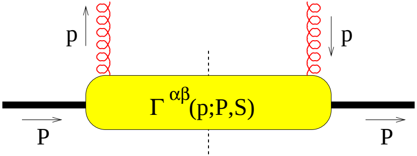
and other transverse momentum dependent gluon pdfs (TMDs) $\neq 0$

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

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



Definition for an unpolarized hadron, in terms of QCD operators on the light front (LF) $\xi \cdot n = 0$ [U, U': process dependent gauge links]:

$$\Phi_g^{\mu\nu}(x, \boldsymbol{p}_T) \equiv \Gamma^{\mu\nu} = \frac{n_\rho\, n_\sigma}{(p{\cdot}n)^2} \int \frac{\mathrm{d}(\xi{\cdot}P)\, \mathrm{d}^2\xi_T}{(2\pi)^3}\; e^{ip\cdot\xi}\, \langle P|\, \mathrm{Tr}\big[\, F^{\mu\rho}(0)\, U_{[0,\xi]}\, F^{\nu\sigma}(\xi)\, U'_{[\xi,0]}\,\big]\, |P\rangle\, \big|_{\mathrm{LF}}$$

Mulders, Rodrigues, PRD 63 (2001) 094021

Gluon correlator

At "Leading Twist" and omitting gauge links:

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

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

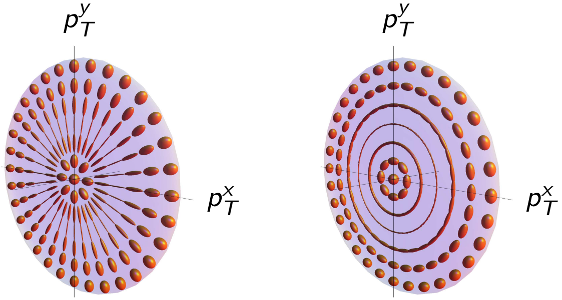
Mulders, Rodrigues, PRD 63 (2001) 094021

$h_1^{\perp\, g}$ is a T-even, helicity-flip distribution, and a rank-2 tensor in p_T

$h_1^{\perp g}(x,\boldsymbol{p}_T^2) \neq 0$ in the absence of ISI or FSI, but, as any TMD, it will receive contributions from ISI/FSI $\longrightarrow$ it can be nonuniversal

Visualization of the gluon polarization

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



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

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

No experimental studies of the function $h_1^{\perp\,g}$ have been performed

- Measurements of the $\cos 2\phi$ azimuthal asymmetries in heavy quark and jet pair production in $e\,p$ collisions (EIC, LHeC)

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

Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001
CP, Boer, Brodsky, Mulders, Buffing, JHEP 1310 (2013) 024

- Asymmetries in $p\,p \to \gamma\,\gamma\,X$ or $p\,p \to J/\psi\,\gamma\,X$ (RHIC, LHC)

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

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

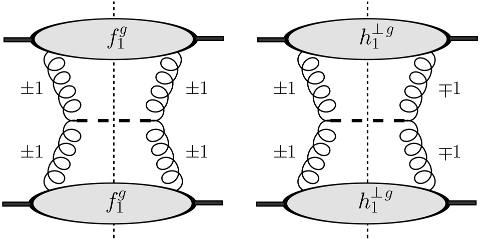
Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

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

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

Pol. gluons affect the Higgs transverse spectrum 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

Echevarria, Kasemets, Mulders, CP, arXiv:1502.05354

Talk by T. Kasemets

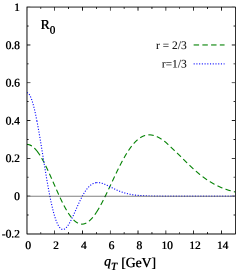
Transverse spectrum of the Higgs boson

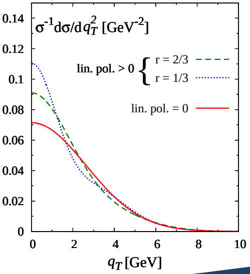
$$\frac{1}{\sigma}\frac{d\sigma}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad R_0 = \frac{h_1^{\perp g} \otimes h_1^{\perp g}}{f_1^g \otimes f_1^g} \qquad |h_1^{\perp g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$$

Gaussian model for both f_1^g and $h_1^{\perp g}$:

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

$$h_1^{\perp g}(x, \boldsymbol{p}_T^2) = \frac{M^2 f_1^g(x)}{\pi\langle p_T^2\rangle^2} \frac{2(1-r)}{r} \exp\left(1 - \frac{1}{r}\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right) \qquad 0 < r < 1$$





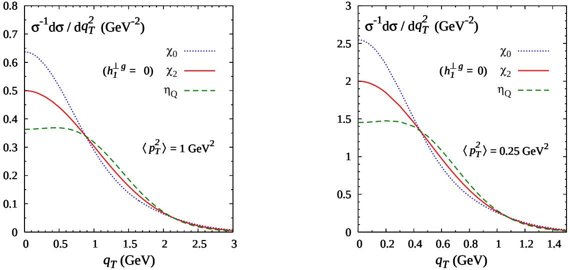
$$\langle p_T^2\rangle = 7\ \mathrm{GeV}^2$$

Transverse spectra of C-even quarkonia η_Q and χ_Q $(Q = c, b)$

$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto 1 - R_0(\boldsymbol{q}_T^2) \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_Q)} \frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto 1 + R_0(\boldsymbol{q}_T^2) \qquad \text{[scalar]}$$

Boer, CP, PRD 86 (2012) 094007



Effects of $h_1^{\perp g}$ on higher angular momentum states are suppressed

Higgs plus jet production

Advantage: study of the TMD evolution by tuning the hard scale

Boer, CP, PRD 91 (2015) 074024

TMD Master Formula

$$d\sigma = \frac{1}{2s}\frac{\mathrm{d}^3\boldsymbol{K}_H}{(2\pi)^3\,2K_H^0}\frac{\mathrm{d}^3\boldsymbol{K}_\mathrm{j}}{(2\pi)^3\,2K_\mathrm{j}^0}\sum_{a,b,c}\int \mathrm{d}x_a\,\mathrm{d}x_b\,\mathrm{d}^2\boldsymbol{p}_{aT}\,\mathrm{d}^2\boldsymbol{p}_{bT}\,(2\pi)^4$$
$$\times\,\delta^4(p_a+p_b-q)\mathrm{Tr}\left\{\Phi_g(x_a,\boldsymbol{p}_{aT})\Phi_g(x_b,\boldsymbol{p}_{bT})\left|\mathcal{M}^{ab\to Hc}\right|^2\right\}$$

Higgs and jet almost back to back in the $\perp$ plane: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

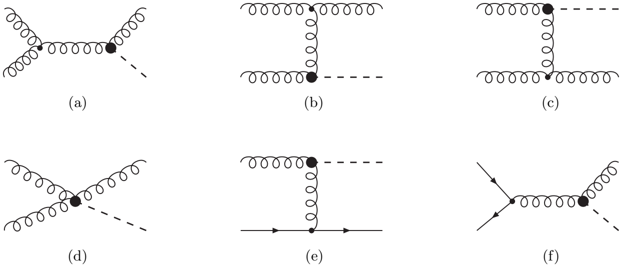
$$\boldsymbol{q}_T = \boldsymbol{K}_{HT} + \boldsymbol{K}_{\mathrm{j}T}, \qquad \boldsymbol{K}_\perp = (\boldsymbol{K}_{HT} - \boldsymbol{K}_{\mathrm{j}T})/2$$

$|\boldsymbol{K}_\perp|$: evolution scale, only $|\boldsymbol{q}_T|$ of the pair needs to be small

Feynman diagrams

At LO in pQCD the partonic subprocesses that contribute are

$g\,g \to H\,g \qquad g\,q \to H\,q \qquad q\,\bar{q} \to H\,g$



Quark masses taken to be zero, except for $M_t \to \infty$
Kauffman, Desai, Risal, PRD 55 (1997) 4005

No indications that TMD factorization can be broken due to color entanglement
Rogers, Mulders, PRD 81 (2010) 094006

Angular structure of the cross section

Focus on $gg \to Hg$ (dominant at the LHC). In the hadronic c.m.s.:

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

$$\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}y_H\,\mathrm{d}y_\mathrm{j}\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \qquad \frac{\mathrm{d}\sigma}{\sigma} \equiv \frac{\mathrm{d}\sigma}{\int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2 \int_0^{2\pi} \mathrm{d}\phi\,\mathrm{d}\sigma}$$

Normalized cross section for $p\,p \to H\,\mathrm{jet}\,X$

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

$$\sigma_0(\boldsymbol{q}_T^2) \equiv \frac{f_1^g \otimes f_1^g}{\int_0^{q^2_{T\max}} \mathrm{d}\boldsymbol{q}_T^2\, f_1^g \otimes f_1^g}$$

TMD observables

The three contributions can be isolated by defining the observables

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

such that

$$\langle \cos n\phi \rangle = \int_0^{q^2_{T\mathrm{max}}} \mathrm{d}\boldsymbol{q}_T^2 \, \langle \cos n\phi \rangle_{q_T}$$

$$\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}^2 q_T} \equiv \langle 1 \rangle_{q_T} \implies 1 + R_0 \propto f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\langle \cos 2\phi \rangle_{q_T} \implies R_2 \propto f_1^g \otimes h_1^{\perp g}$$

$$\langle \cos 4\phi \rangle_{q_T} \implies R_4 \propto h_1^{\perp g} \otimes h_1^{\perp g}$$

Models for the TMD gluon distributions

f_1^g: Gaussian + tail

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

$h_1^{\perp\,g}$: Maximal polarization and Gaussian + tail

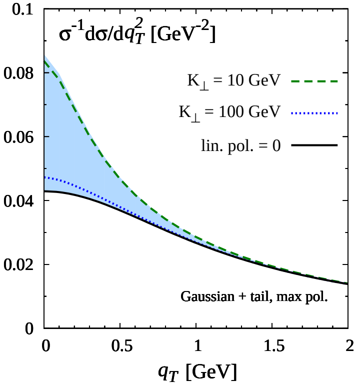
$$h_1^{\perp\,g}(x,\boldsymbol{p}_T^2) = \frac{2M_p^2}{\boldsymbol{p}_T^2}\,f_1^g(x,\boldsymbol{p}_T^2) \qquad [\mathit{max\ pol.}]$$

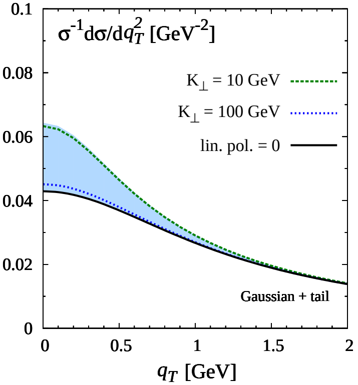
$$h_1^{\perp\,g}(x,\boldsymbol{p}_T^2) = 2\,f_1^g(x)\,\frac{M_p^2 R_h^4}{2\,\pi}\,\frac{1}{(1+\boldsymbol{p}_T^2 R_h^2)^2} \qquad R_h = \frac{3}{2}\,R$$

Boer, den Dunnen, NPB 886 (2014) 421

q_T-distribution

Configuration in which the Higgs and the jet have same rapidities

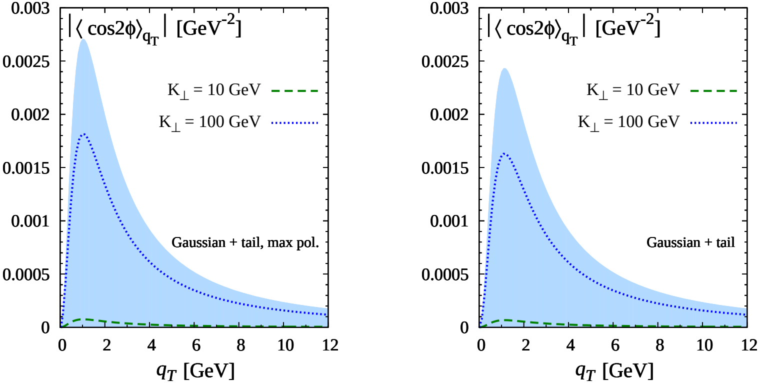




Effects largest at small q_T (hard to measure), but model dependent!

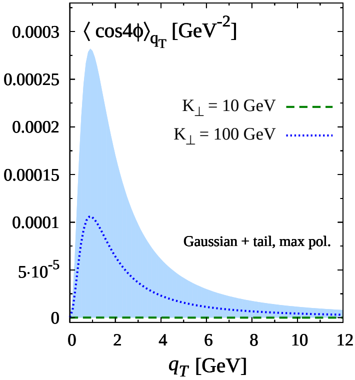
Azimuthal $\cos 2\phi$ asymmetries

Sensitive to the sign of $h_1^{\perp\, g}$: $\langle \cos 2\phi \rangle_{q_T} < 0 \implies h_1^{\perp\, g} > 0$



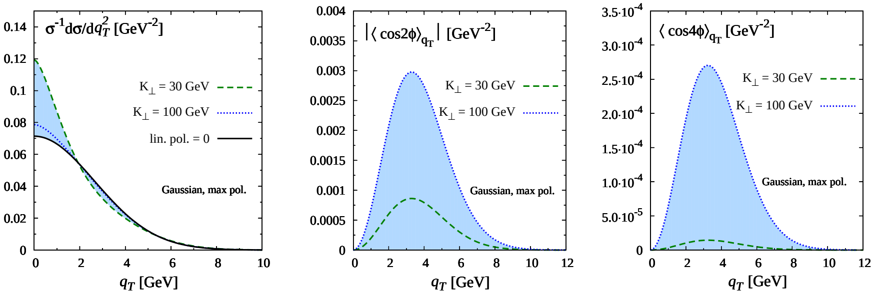
$q_{T\,\mathrm{max}} = M_H/2$ $\quad\quad$ $\langle \cos 2\phi \rangle \approx 12\%$ at $K_\perp = 100$ GeV

Azimuthal $\cos 4\phi$ asymmetries



$q_{T\,\mathrm{max}} = M_H/2$ $\langle \cos 4\phi \rangle \approx 0.1 - 0.2\%$ at $K_\perp = 100$ GeV

Gaussian model for the unpolarized TMDs



$q_{T\max} = K_\perp/2$, $\langle\cos 2\phi\rangle \approx 9\%$, $\langle\cos 4\phi\rangle \approx 0.4\%$ at $K_\perp = 100$ GeV

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

- $h_1^{\perp\, g}$ produces a modulation of the transverse spectrum of the H+jet 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.
  den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

- Higgs and quarkonium production can be used to extract gluon TMDs and to study their process and scale dependences