The Linearly Polarized Gluon:

Spin Physics with Quarkonia without Polarized Nucleons

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3DSPIN MAPPING THE PROTON IN 3D

UNIVERSITÀ DI PAVIA

Studies of gluons inside hadrons have focussed so far on their momentum and helicity distributions

- $g(x)$: *unpolarized* gluons with collinear momentum fraction x inside *unpolarized* 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:

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

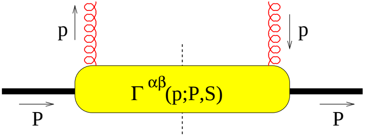
and other transverse momentum dependent gluon pdfs (TMDs) $\neq 0$

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

The gluon correlator describes the hadron $\rightarrow$ gluon transition

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

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



Parametrization in terms of TMDs (omitting gauge links)

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

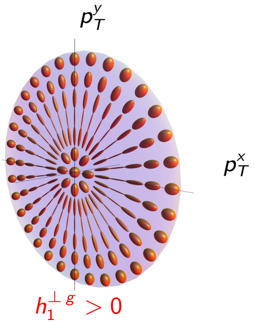
- $f_1^g(x,\boldsymbol{p}_T^2)$ unpolarized TMD gluon distribution; $p_T^2 = -\boldsymbol{p}_T^2$
- $h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)$ distribution of linearly pol. gluons in an unp. hadron

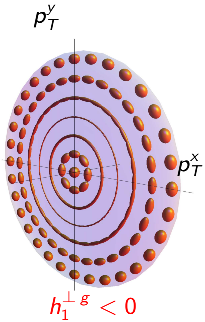
Mulders, Rodrigues, PRD 63 (2001) 094021

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

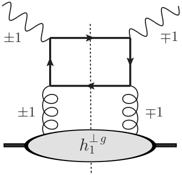
$h_1^{\perp g}(x, \boldsymbol{p}_T^2) \neq 0$ in the absence of ISI or FSI, but, as any TMD, it will receive contributions from ISI/FSI $\longrightarrow$ it can be nonuniversal

In the transverse momentum plane ($h_1^{\perp g}$ 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



Ideal process: $e(\ell) + p(P) \to e(\ell') + Q(K_1) + \bar{Q}(K_2) + X$

y_1 (y_2) rapidities of Q $(\bar{Q})$ in the $\gamma^* p$ cms; x_B, y: DIS variables

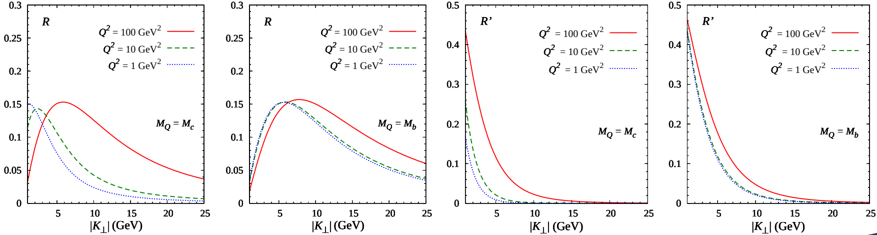
$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp} = |\boldsymbol{q}_T|(\cos\phi_T, \sin\phi_T)$$
$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2 = |\boldsymbol{K}_\perp|(\cos\phi_\perp, \sin\phi_\perp)$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}y\,\mathrm{d}x_B\,\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0 + A_1\cos\phi_\perp + A_2\cos 2\phi_\perp\right\} f_1^g$$

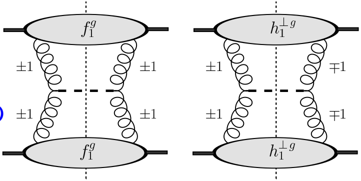
$$+ \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp g} \left\{B_0 \cos 2(\phi_\perp - \phi_T) + B_1\cos(\phi_\perp - 2\phi_T) + B_1'\cos(3\phi_\perp - 2\phi_T) + B_2\cos 2\phi_T + B_2'\cos 2(2\phi_\perp - \phi_T)\right\}$$

$|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

Upper bounds on the asymmetries $R \equiv |\langle\cos 2(\phi_\perp - \phi_T)\rangle|$ **and** $R' \equiv |\langle\cos 2\phi_T\rangle|$



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



At LHC the dominant channel is $gg \to H$

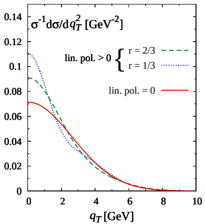
$h_1^{\perp\, g}$ contributes to the Higgs q_T-spectrum at LO

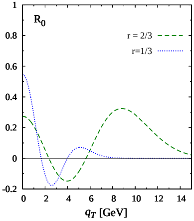
q_T-distribution of the Higgs boson

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

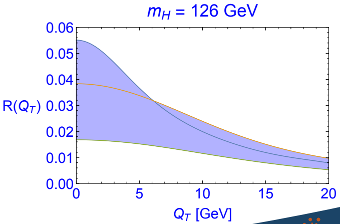
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002
Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Gaussian Model





With TMD evolution



Study of $H \to \gamma\gamma$ and interference with $gg \to \gamma\gamma$

$C = +1$ quarkonia

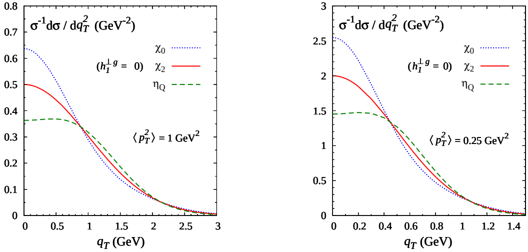
q_T-distribution of η_Q and χ_{QJ} $(Q = c, b)$ at $q_T \ll 2M_Q$

$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 - R_0(\boldsymbol{q}_T^2)] \qquad \text{[pseudoscalar]}$$

$$\frac{1}{\sigma(\chi_{Q0})} \frac{d\sigma(\chi_{Q0})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g \, [1 + R_0(\boldsymbol{q}_T^2)] \qquad \text{[scalar]}$$

$$\frac{1}{\sigma(\chi_{Q2})} \frac{d\sigma(\chi_{Q2})}{d\boldsymbol{q}_T^2} \propto f_1^g \otimes f_1^g$$

Boer, CP, PRD 86 (2012) 094007



Proof of factorization at NLO for $p\,p \to \eta_Q\,X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

Study of $p\,p \to \eta_c\,X$ at NLO with TMD evolution (LHCb data)

Echevarria, Kasemets, Lansberg, Signori

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

den Dunnen,blue Lansberg, CP, Schlegel, PRL 112 (2014) 212001

- 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 $\mathcal{Q} - \gamma$ back-to-back

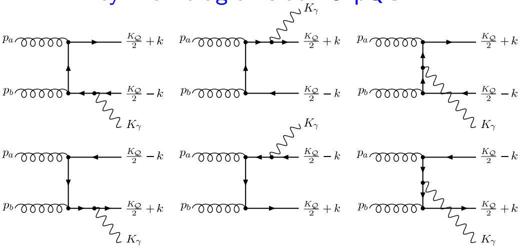
  Mathews, Sridhar, Basu, PRD 60 (1999) 014009

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

TMD Master Formula

$$\mathrm{d}\sigma = \frac{1}{2s} \frac{d^3 \boldsymbol{K}_{\mathcal{Q}}}{(2\pi)^3\, 2K^0_{\mathcal{Q}}} \frac{d^3 \boldsymbol{K}_\gamma}{(2\pi)^3\, 2K^0_\gamma} \int dx_a\, dx_b\, d^2\boldsymbol{p}_{aT}\, d^2\boldsymbol{p}_{bT}\, (2\pi)^4 \delta^4(p_a + p_b - q)$$
$$\times \mathrm{Tr}\left\{ \Gamma_g(x_a, \boldsymbol{p}_{aT}) \Gamma_g(x_b, \boldsymbol{p}_{bT}) \overline{\sum_{\text{colors}}} \left| \mathcal{A}\left(g\, g \to Q\bar{Q}[^3S_1] \right) \right|^2 \right\}$$

Feynman diagrams at LO pQCD:



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

- valid up to corrections $\mathcal{O}(q_T/Q)$
- 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 for $\mathcal{Q}$ - γ in the Collins-Soper frame

Analysis similar to the one for $pp \to \gamma\gamma X$

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

The three contributions can be disentangled by defining the transverse moments

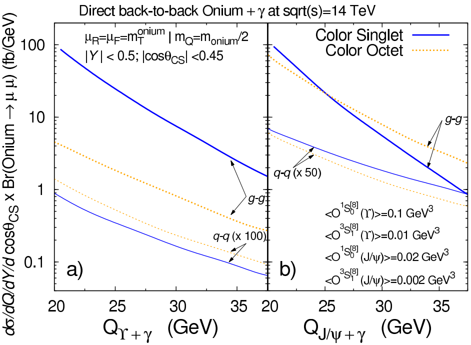
$$\mathcal{S}_{q_T}^{(n)} \equiv \frac{\int_0^{2\pi} \mathrm{d}\phi_{CS}\, \cos(n\,\phi_{CS})\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\,\mathrm{d}Y\,\mathrm{d}^2 q_T\,\mathrm{d}\Omega}}{\int_0^{q_T^{2\,\max}} dq_T^2 \int_0^{2\pi} \mathrm{d}\phi_{CS}\, \frac{\mathrm{d}\sigma}{\mathrm{d}Q\,\mathrm{d}Y\,\mathrm{d}^2 q_T\,\mathrm{d}\Omega}} \qquad (n = 0, 2, 4) \quad q_T^{2\,\max} = \frac{Q^2}{4}$$

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

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

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

Process dominated by gg fusion

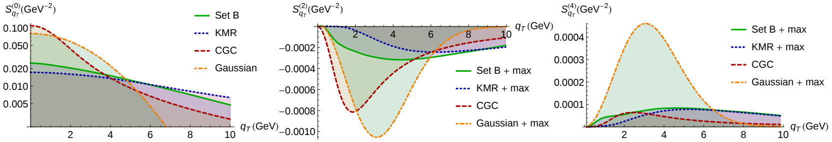


CS yield is clearly dominant for the Υ, above the CO one for J/ψ at low Q

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

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



den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

f_1^g: Models for Unintegrated Gluon Distributions
$h_1^{\perp g}$: predictions only in the CGC: otherwise 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

$$2.0\% \,(\mathrm{KMR}) < \quad \left| \int \mathrm{d}q_T^2 \mathcal{S}_{q_T}^{(2)} \right| \quad < 2.9\% \,(\mathrm{Gauss})$$

$$0.3\% \,(\mathrm{CGC}) < \quad \int \mathrm{d}q_T^2 \, \mathcal{S}_{q_T}^{(4)} \quad < 1.2\% \,(\mathrm{Gauss})$$

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

Wilson lines 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

  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 due to factorization breaking. Same holds for quarkonium production in pp in the CO and CEM models

  CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024
  Mukherjee, Rajesh, arXiv:1511.04319

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

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

Other opportunity offered by analysing $J/\psi + J/\psi$ production at the LHC

F. Scarpa's talk

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