Probing the gluon TMDs with quarkonia

Jean-Philippe Lansberg[*]

IPN Orsay, Paris Sud U., CNRS/IN2P3, Université Paris-Saclay, F-91406 Orsay, France
E-mail: Jean-Philippe.Lansberg@in2p3.fr

Cristian Pisano

Dipartimento di Fisica, Università di Cagliari, and INFN, Sezione di Cagliari Cittadella
Universitaria, I-09042 Monserrato (CA), Italy

Florent Scarpa

IPN Orsay, Paris Sud U., CNRS/IN2P3, Université Paris-Saclay, F-91406 Orsay, France & Van
Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4,
9747 AG Groningen, The Netherlands

Marc Schlegel

Department of Physics, New Mexico State University, Las Cruces, NM 88003, USA

We briefly review how quarkonium hadroproduction can be used to access the polarised and unpolarised gluon TMDs.

XXVI International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2018)
16-20 April 2018
Kobe, Japan

---

[*]Speaker.

1. Introduction

Transverse-Momentum-Dependent (TMD) factorisation [1, 2, 3, 4] allows one to study the impact of the polarisation of partons with nonzero transverse momentum –even inside unpolarised hadrons– via the appearance of azimuthal modulations. At hadron colliders, these modulations mostly come from gluons and these new phenomena are encapsulated in the distribution $h_1^{\perp g}(x, \boldsymbol{k}_T^2)$ of linearly-polarised gluons [5]. In practice, one expects $\cos 2\phi$ ($\cos 4\phi$) modulations in the yield of two-particle final states. These follow from single (double) gluon-helicity flips in gluon-fusion processes. The correlation between the polarisation of these gluons and their transverse momentum can also alter the transverse-momentum spectrum of the produced system. One example is that of the Brout-Englert-Higgs H^0 boson [6, 7] produced after double gluon-helicity flips.

We review here how some processes involving quarkonium production can help experimentally determine these poorly known gluon distributions. First, we start with the production of a pseudoscalar quarkonium which is very similar to the H^0 case. Second, we discuss the production of a J/ψ or Υ in association with a photon or a Z^0 boson. Third, we report on the unique case of di-J/ψ production which is expected to exhibit the largest possible $\cos 4\phi$ modulations and for which data exist allowing for the first extraction of the unpolarised gluon distributon $f_1^g(x, \boldsymbol{k}_T^2)$ using recent LHCb data.

2. TMD factorisation and quarkonium production

As clear from its name, TMD factorisation extends collinear factorisation by accounting for the parton transverse momenta, generally denoted $\boldsymbol{k}_T$. In the case of quarkonium-production processes, it is applicable either when a single quarkonium $\mathcal{Q}$ is produced with a transverse momentum, P_{fT}, typically smaller than half of its mass or when a quarkonium is produced in a set of two particles whose transverse momentum, P_{fT}, is also smaller than half of its invariant mass, M_f. In both cases, the observed final state should be colourless (see *e.g.* [8]). This imposes the quarkonia to be produced by Colour Singlet (CS) transitions (or equally speaking according to the CS Model (CSM)) and excludes the production in association with light hadrons, charm or beauty hadrons.

Under the TMD factorisation, the cross section for any gluon-fusion process can be expressed –up to corrections suppressed by powers of the observed-system transverse momentum– as a contraction and a convolution of a partonic short-distance contribution, $\mathcal{M}_{\mu\rho}$, with two gluon TMD correlators Φ_g evaluated at $(x_1, \boldsymbol{k}_{1T})$ and $(x_2, \boldsymbol{k}_{2T})$. $\mathcal{M}^{\mu\rho}$ is simply calculated in perturbative QCD through a series expansion in α_s [9] using Feynman graphs. Overall, we have

$$d\sigma = \frac{(2\pi)^4}{8s^2} \int d^2\boldsymbol{k}_{1T} d^2\boldsymbol{k}_{2T} \delta^2(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{P_f}_T) \mathcal{M}_{\mu\rho} (\mathcal{M}_{\nu\sigma})^*$$
$$\times \Phi_g^{\mu\nu}(x_1, \boldsymbol{k}_{1T}) \Phi_g^{\rho\sigma}(x_2, \boldsymbol{k}_{2T}) d\mathcal{R}, \quad (2.1)$$

where $s = (P_1 + P_2)^2$ is the hadronic centre-of-mass system (c.m.s.) energy squared, P_f is the momentum of the observed final state, and where the phase-space element of the outgoing particles is denoted by $d\mathcal{R}$. In addition, the gluon four-momenta k_i are decomposed according to $k = xP + k_T + k^- n$ [n refers to a light-like vector ($n^2 = 0$) satisfying $n \cdot P \neq 0$], $k_T^2 = -\boldsymbol{k}_T^2$ and $g_T^{\mu\nu} = g^{\mu\nu} - (P^\mu n^\nu + P^\nu n^\mu)/P \cdot n$.

In the case of unpolarised protons, the correlator can be parametrised [5, 10, 11] in terms of the two aforementionned and independent TMDs, the unpolarised distribution $f_1^g(x, \mathbf{k}_T^2)$ and the distribution of linearly polarised gluons $h_1^{\perp g}(x, \mathbf{k}_T^2)$,[1]

$$\Phi_g^{\mu\nu}(x, \mathbf{k}_T) = -\frac{1}{2x} \left\{ g_T^{\mu\nu} f_1^g - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\mathbf{k}_T^2}{2M_p^2} \right) h_1^{\perp g} \right\}, \tag{2.2}$$

Following [14], the structure of the TMD differential cross section for an observed system of 2 colourless particles reads

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_f \mathrm{d}Y_f \mathrm{d}^2 \mathbf{P}_{fT} \mathrm{d}\Omega} = \mathcal{J} \times \left\{ F_1 \mathcal{C} \left[f_1^g f_1^g \right] + F_2 \mathcal{C} \left[w_2 h_1^{\perp g} h_1^{\perp g} \right] + \right.$$
$$\left. \cos 2\phi_{\mathrm{CS}} \left(F_3 \mathcal{C} \left[w_3 f_1^g h_1^{\perp g} \right] + F_3' \mathcal{C} \left[w_3' h_1^{\perp g} f_1^g \right] \right) + \cos 4\phi_{\mathrm{CS}} F_4 \mathcal{C} \left[w_4 h_1^{\perp g} h_1^{\perp g} \right] \right\}, \tag{2.3}$$

where $\mathrm{d}\Omega = \mathrm{d}\cos\theta_{\mathrm{CS}} \mathrm{d}\phi_{\mathrm{CS}}$, θ_{CS} and ϕ_{CS} are the Collins-Soper (CS) angles [15] and Y_f is the pair rapidity – $\mathbf{P}_{fT}$ and Y_f are defined in the hadron c.m.s. In the CS frame, the $\mathcal{Q}$ direction is along $\vec{e} = (\sin\theta_{\mathrm{CS}}\cos\phi_{\mathrm{CS}}, \sin\theta_{\mathrm{CS}}\sin\phi_{\mathrm{CS}}, \cos\theta_{\mathrm{CS}})$. The overall factor, $\mathcal{J}$, is specific to the mass of the final-state particles and the analysed differential cross sections, and the hard factors F_i do not depend on the rapidity of the pair nor on its transverse momentum.

For a single-particle (here quarkonium) production,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Y \mathrm{d}^2 \mathbf{P}_{fT}} = \mathcal{J}' \times \left\{ F_1 \mathcal{C} \left[f_1^g f_1^g \right] + F_2 \mathcal{C} \left[w_2 h_1^{\perp g} h_1^{\perp g} \right] \right\} \tag{2.4}$$

It is interesting to note that the TMDs appear in both above equations Eq. (2.3) and Eq. (2.4) in a factorised way from the hard-scattering coefficients through universal convolutions which read

$$\mathcal{C}[w f g] \equiv \int \mathrm{d}^2 \mathbf{k}_{1T} \int \mathrm{d}^2 \mathbf{k}_{2T} \, \delta^2(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{P}_{fT}) w(\mathbf{k}_{1T}, \mathbf{k}_{2T}) f(x_1, \mathbf{k}_{1T}^2) g(x_2, \mathbf{k}_{2T}^2), \tag{2.5}$$

where $w(\mathbf{k}_{1T}, \mathbf{k}_{2T})$ are generic transverse weights and $x_{1,2} = \exp[\pm Y_f] M_f / \sqrt{s}$. The $w(\mathbf{k}_{1T}, \mathbf{k}_{2T})$ are identical for all the gluon-induced processes with unpolarised protons and can be found in [14]. For any process, one can show that $F_{2,3,4}^{(')} \leq F_1$.

The azimuthal modulations can be studied by evaluating [for $n = 2, 4$] weighted differential cross sections normalised to the azimuthally independent term like

$$\frac{\int d\phi_{\mathrm{CS}} \cos n\phi_{\mathrm{CS}} \dfrac{d\sigma}{dM_f dY_f d^2 \mathbf{P}_{fT} d\Omega}}{\int d\phi_{\mathrm{CS}} \dfrac{d\sigma}{dM_f dY_f d^2 \mathbf{P}_{fT} d\Omega}}. \tag{2.6}$$

One then gets that, in a single phase-space point, such $\cos 2\phi_{\mathrm{CS}}$ modulations are proportional to $F_3 \mathcal{C} \left[w_3 f_1^g h_1^{\perp g} \right] + F_3' \mathcal{C} \left[w_3' h_1^{\perp g} f_1^g \right]$ and the $\cos 4\phi_{\mathrm{CS}}$ modulations to $F_4 \mathcal{C} \left[w_4 h_1^{\perp g} h_1^{\perp g} \right]$.

---

[1]For gluon TMDs free from rapidity divergences from gauge links with paths (partly) along the light front $\xi \cdot n = 0$, a *soft factor* [1, 12, 13] is required. It does not play a role here and we therefore consider it as implicit.

3. Pseudoscalar-quarkonium production

The case of the pseudoscalar-quarkonium production was first studied under the TMD factorisation by Boer and Pisano in Ref. [16]. It is very similar to that of H^0 boson and is particularly interesting since $F_2 = -F_1$. From this, it follows that the $\boldsymbol{P_{fT}}$ modulations generated by $h_1^{\perp g}(x, \boldsymbol{k}_T^2)$ are maximum. There are however some caveats. First, the domain where the TMD factorisation can be applied for η_c production is admittedly very small since $P_{\eta_c T}$ should remain below $1 \sim 1.5$ GeV. As for now, η_c production was only studied by LHCb [17] for $P_{\eta_c T}$ larger than 6 GeV. Studies at lower $P_{\eta_c T}$ would require a specific effort on the triggers and on the background subtraction with however few hopes to reach $1 \sim 1.5$ GeV. Studies in the fixed-target mode at $\sqrt{s_{NN}} = 115$ GeV [18, 19, 20] with a smaller combinatorial background may be more promising. $\eta_c(2S)$ production may be another option [21]. Slightly higher $P_{\eta_c T}$ may be dealt with by matching the TMD-factorised cross section with the collinearly factorised one with PDFs. However, this may preclude the extraction of experimental constraints on the TMDs [22]. Some of these caveats could be avoided by focusing one's effort on the η_b case. However, it remains experimentally inaccessible at the LHC owing to its very small branchings to usable decay channels.

4. $J/\psi + \gamma$ and $\Upsilon + \gamma$

As we have just seen, the restriction $\boldsymbol{P_{fT}} \lesssim M_f/2$ is extremely detrimental for the $2 \to 1$ case. To bypass this constraint, it is thus expedient to consider 2-particle final states where M_f can be tuned to reach the optimal kinematical range for $\boldsymbol{P_{fT}}$ given the expected yields. Along these lines, we proposed [23] to study the associated production of $J/\psi + \gamma$ and $\Upsilon + \gamma$ at the LHC whose QCD corrections have been studied in the collinear factorisation in [24, 25, 26].

If one is mainly interested in the extraction of f_1^g via the $\boldsymbol{P_{fT}}$ dependence of the cross section, this process is interesting since F_2 vanishes. As such, it is the complete opposite case compared to η_c where the $\boldsymbol{P_{fT}}$ modulation from $h_1^{\perp g}$ are maximum. As what concerns the azimuthal modulations, F_3 is power suppressed in M_f while F_4 scales like F_1 offering interesting opportunities to extract $h_1^{\perp g}(x, \boldsymbol{k}_T^2)$ with existing LHC data by looking at $\cos 4\phi_{\text{CS}}$ modulations. The ratio F_4/F_1 is however significantly smaller than unity and, in practice, the $\cos 2\phi_{\text{CS}}$ modulations are not necessarily much smaller. Studies in the fixed-target mode with a LHCb-like detector are feasible and may bring about constraints at x as high as 0.5 [18, 27].

Similarly, J/ψ and Υ can be gluo-produced in association with an off-shell photon or a Z boson. We studied this case in Ref. [14]. The rates are however probably too small [28], even at the LHC, for azimuthal-modulation studies. In addition, there may be a significant contamination by Double Parton Scatterings (DPSs) [29, 30] in the currently accessible region at the LHC [31].

5. Vector-quarkonium-pair production

The third case we discuss here is that of the production of a pair of J/ψ or Υ. As compared to the former processes, these reactions are extremely appealing for the following reasons:

- the hard-scattering coefficients F_i are extremely favourable to the observation of azimuthal modulations [32];
- significant data sample have already been collected at the LHC and the Tevatron at different invariant masses [33, 34, 35, 36, 37];

- the DPS contamination is probably on the order of 10% [38, 36], where the azimuthal modulations are expected to be the largest;
- the contamination from the non-TMD-factorising colour-octet transitions is also negligible –as expected from its v^8 suppression– in this region [39, 40, 38].

As what concerns the hard-scattering coefficients, it is interesting to look at them both in the large and small $M_f = M_{QQ}$ limits. Indeed, when M_{QQ} becomes much larger than the quarkonium mass, M_Q, one finds [32] that, for $\cos\theta_{CS} \to 0$ (*i.e.* small Δy),

$$F_4 \to F_1, \quad F_2 \to \frac{81 M_Q^4 \cos\theta_{CS}^2}{2 M_{QQ}^4} \times F_1, \quad F_3 \to \frac{-24 M_Q^2 \cos\theta_{CS}^2}{M_{QQ}^2} \times F_1. \tag{5.1}$$

The result $F_4 \to F_1$ in this limit is thus far unique among all the gluon-TMD-sensitive processes, making di-quarkonium production the most sensitive probe of $h_1^{\perp g}$.
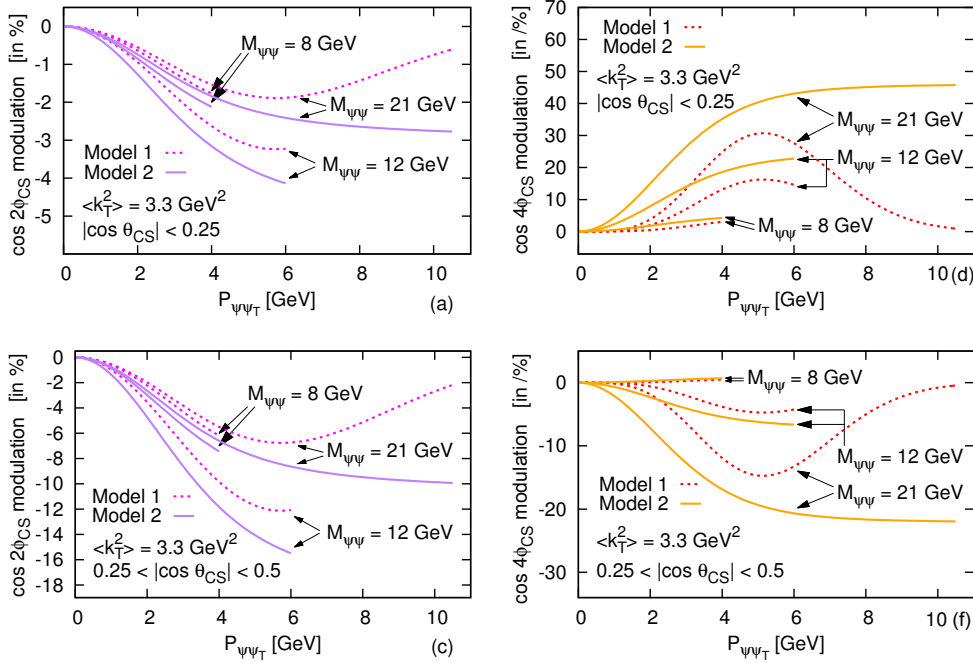

Figure 1: $\cos n\phi_{CS}$ modulations for $n = 2, 4$ computed for $|\cos\theta_{CS}| < 0.25$ and for $0.25 < \cos\theta_{CS} < 0.5$ for both our models of $h_1^{\perp g}$, for 3 values of M_{QQ} (8, 12 and 21 GeV) relevant respectively for the LHCb [37], CMS [35] and ATLAS [36] kinematics. The spectra are plotted up to $M_{QQ}/2$. Our results do not depend on Y_{QQ}.

For M_f close to $2M_Q$ –its minimum value, $F_2 \to 3/787 \times F_1$ and $F_{3,4} \to 0$. Even though F_2 is not strictly zero, like in the $Q + \gamma$ case, it is always very small and generates negligible modulations to the P_{fT}-differential cross section. Based on this, we performed in Ref. [32] the first extraction of f_1^g using the latest LHCb data [37]. Assuming a Gaussian k_T dependence we obtained $\langle k_T^2 \rangle = 3.3 \pm 0.8$ GeV^2 which encapsulates both non-perturbative and perturbative effects since the scale relevant for such data sample is on the order of 8 GeV. Using this $\langle k_T^2 \rangle$ value and modellings of $h_1^{\perp g}$ such as the Gaussian form of Ref. [6] (Model 1) or saturating the positivity bound [5, 41]

(Model 2), we obtained the $\cos n\phi_{\rm CS}$ modulations shown in Fig. 1 where we note that the $\cos 2\phi_{\rm CS}$ modulations are becoming larger for increasing $\cos\theta_{\rm CS}$.

6. Conclusions

Quarkonium hadroproduction offers interesting possibilities to study gluon TMDs which only start to be investigated. We briefly reviewed here the cases of single-pseudoscalar-quarkonium production, vector-quarkonium pair production and associated production of a vector quarkonium with a photon or a Z^0 boson. The most promising case is that of $J/\psi + J/\psi$ which we expect to be studied soon at the LHC along the lines presented here, *i.e.* with a dedicated measurement of the $\cos 2\phi_{\rm CS}$ and $\cos 4\phi_{\rm CS}$ modulations.

These would complement –with a clean access to f_1^g and $h_1^{\perp g}$– future target-spin asymmetry studies (see *e.g.* [42, 18]) to measure the gluon Sivers function $f_{1T}^{\perp g}$ as well as distributions of linearly-polarised gluons in a transversely polarised proton, h_{1T}^g and $h_{1T}^{\perp g}$, allowing for a complete gluon tomography of the proton.

References

[1] J. Collins, *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **32**, 1 (2011).

[2] S. M. Aybat, T. C. Rogers, *Phys. Rev.* **D83**, 114042 (2011).

[3] M. G. Echevarria, A. Idilbi, I. Scimemi, *JHEP* **07**, 002 (2012).

[4] R. Angeles-Martinez, *et al.*, *Acta Phys. Polon.* **B46**, 2501 (2015).

[5] P. J. Mulders, J. Rodrigues, *Phys. Rev.* **D63**, 094021 (2001).

[6] D. Boer, W. J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang, *Phys. Rev. Lett.* **108**, 032002 (2012).

[7] D. Boer, W. J. den Dunnen, C. Pisano, M. Schlegel, *Phys. Rev. Lett.* **111**, 032002 (2013).

[8] D. Boer, *Few Body Syst.* **58**, 32 (2017).

[9] J. P. Ma, J. X. Wang, S. Zhao, *Phys. Rev.* **D88**, 014027 (2013).

[10] S. Meissner, A. Metz, K. Goeke, *Phys. Rev.* **D76**, 034002 (2007).

[11] D. Boer, *et al.*, *JHEP* **10**, 013 (2016).

[12] M. G. Echevarria, A. Idilbi, I. Scimemi, *Phys. Lett.* **B726**, 795 (2013).

[13] M. G. Echevarria, T. Kasemets, P. J. Mulders, C. Pisano, *JHEP* **07**, 158 (2015). [Erratum: JHEP05,073(2017)].

[14] J.-P. Lansberg, C. Pisano, M. Schlegel, *Nucl. Phys.* **B920**, 192 (2017).

[15] J. C. Collins, D. E. Soper, *Phys. Rev.* **D16**, 2219 (1977).

[16] D. Boer, C. Pisano, *Phys. Rev.* **D86**, 094007 (2012).

[17] R. Aaij, *et al.*, *Eur. Phys. J.* **C75**, 311 (2015).

[18] C. Hadjidakis, *et al.*, arXiv:1807.00603 (2018).

[19] S. J. Brodsky, F. Fleuret, C. Hadjidakis, J. P. Lansberg, *Phys. Rept.* **522**, 239 (2013).

[20] J. P. Lansberg, S. J. Brodsky, F. Fleuret, C. Hadjidakis, *Few Body Syst.* **53**, 11 (2012).

[21] J.-P. Lansberg, H.-S. Shao, H.-F. Zhang, arXiv:1711.00265 .

[22] M. G. Echevarria, T. Kasemets, J.-P. Lansberg, C. Pisano, A. Signori, *Phys. Lett.* **B781**, 161 (2018).

[23] W. J. den Dunnen, J. P. Lansberg, C. Pisano, M. Schlegel, *Phys. Rev. Lett.* **112**, 212001 (2014).

[24] R. Li, J.-X. Wang, *Phys. Lett.* **B672**, 51 (2009).

[25] J. P. Lansberg, *Phys. Lett.* **B679**, 340 (2009).

[26] R. Li, J.-X. Wang, *Phys. Rev.* **D89**, 114018 (2014).

[27] J. P. Lansberg, *et al.*, *EPJ Web Conf.* **85**, 02038 (2015).

[28] B. Gong, J.-P. Lansberg, C. Lorce, J. Wang, *JHEP* **03**, 115 (2013).

[29] J.-P. Lansberg, H.-S. Shao, *JHEP* **10**, 153 (2016).

[30] J.-P. Lansberg, H.-S. Shao, N. Yamanaka, *Phys. Lett.* **B781**, 485 (2018).

[31] G. Aad, *et al.*, *Eur. Phys. J.* **C75**, 229 (2015).

[32] J.-P. Lansberg, C. Pisano, F. Scarpa, M. Schlegel, *Phys. Lett.* **B784**, 217 (2018).

[33] R. Aaij, *et al.*, *Phys. Lett.* **B707**, 52 (2012).

[34] V. M. Abazov, *et al.*, *Phys. Rev.* **D90**, 111101 (2014).

[35] V. Khachatryan, *et al.*, *JHEP* **09**, 094 (2014).

[36] M. Aaboud, *et al.*, *Eur. Phys. J.* **C77**, 76 (2017).

[37] R. Aaij, *et al.*, *JHEP* **06**, 047 (2017).

[38] J.-P. Lansberg, H.-S. Shao, *Phys. Lett.* **B751**, 479 (2015).

[39] P. Ko, C. Yu, J. Lee, *JHEP* **01**, 070 (2011).

[40] Y.-J. Li, G.-Z. Xu, K.-Y. Liu, Y.-J. Zhang, *JHEP* **07**, 051 (2013).

[41] S. Cotogno, T. van Daal, P. J. Mulders, *JHEP* **11**, 185 (2017).

[42] D. Kikola, *et al.*, *Few Body Syst.* **58**, 139 (2017).