PROCEEDINGS OF SCIENCE

Associated-quarkonium production

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

We discuss the growing interest to measure associated-quarkonium production in a number of channels at the LHC. Whereas back-to-back production of quarkonium + isolated photon provides a unique way to extract gluon TMDs, observables such as quarkonium + W/Z can be of great help to better understand the quarkonium production mechanism as well as to shed light on double-parton scatterings. Along these lines, we also argue that quarkonium-pair production is a potentially rich source of information which only has started to be harvested. Finally, we discuss the relevance of studying the production of quarkonium + heavy-quark, as *e.g.* J/ψ + charm and Υ + non-prompt J/ψ.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects,
28 April - 2 May 2014
Warsaw, Poland

*Speaker.

PoS(DIS2014)151

1. Introduction

Since the start-up of the LHC, the ATLAS, ALICE, CMS and LHCb detectors have collected data at higher energies, at higher transverse momenta, with better precision and with more exclusivity towards direct production compared to that which was achieved before. Unfortunately, all this seems insufficient to clear up the complexity of the quarkonium-production mechanism. In this context, a growing attention was directed towards the study of Associated-Quarkonium Production (AQP) channels. In a number of cases, they are expected to put specific constraints on certain parameters of the theoretical approaches proposed to describe quarkonium production.

One of the reasons for the complications in describing these elementary reactions is certainly connected to the large expected impact of perturbative corrections in α_s. It is for instance well known that α_s^4 and α_s^5 corrections to the colour-singlet mechanism (CSM) [3] have a significant impact on the P_T dependence of the J/ψ and Υ cross sections observed in high-energy hadron collisions [4, 5, 6, 7] as well as on their polarisation [6, 8, 9, 10]. NLO corrections to the colour-octet mechanism (COM) cannot also be overlooked since they significantly affect polarisation predictions and the extraction [11] of the non-perturbative octet matrix elements (also referred to as LDMEs). All this renders the phenomenological analyses rather complex to interpret owing to the large uncertainties in the current theoretical predictions. On the contrary, when one focuses on the P_T-integrated yields, both for the charmonia and the bottomonia, the CSM contributions agree relatively well with the existing data at colliders energies [12, 13].

The introduction of new observables, such as AQP channels, may thus be of great help. For some, the impact of QCD corrections is expected to be smaller, thus with smaller uncertainties on the renormalisation scale for instance. Others are expected to be specifically discrimant towards the separation of CO and CS contributions, being particularly sensitive to either of these contributions. Finally, some AQP reactions have similar properties as the inclusive-production reactions and simply provide further constraints for the fits of NRQCD LDMEs.

2. Quarkonium plus Quarkonium

We start with the first AQP ever measured, *i.e.* that of a pair of J/ψ's. It has been measured for the first time at large x_F by the CERN-NA3 collaboration [14, 15] in the eighties. The rates were higher than expected and they seemed to be only explainable by the coalescence of a double intrinsic-charm pair in the proton projectile [16]. Recently, LHCb has also studied this process at the LHC [17]. It is important to realise that the cross section measured by LHCb covers a totally different region than NA3, which a priori should be accounted for by the conventional pQCD approaches, *e.g.* by the CSM. As a matter of fact, the P_T-integrated rate seen by LHCb is in very good agreement with the recent theoretical expectations from the CSM at LO [18, 19]. As far as the P_T-integrated yields are concerned, it is reasonable to say that the CSM predictions are as satisfactory for double J/ψ production as for single J/ψ production.

Last year, we evaluated the leading-P_T contribution at NLO, dubbed as NLO*, for J/ψ pair production along with that of $J/\psi + \eta_c$ at LO [20] using the automated matrix element and event generator HELAC-ONIA [21]. Our partial NLO* evaluation has been confirmed by a full NLO evaluation by Sun and Chao [22]. We have found that the NLO* is indeed enhanced w.r.t. LO for increasing P_T. It is already 8 times larger for $P_T \gtrsim 5$ GeV and nearly 400 times larger for

$P_T \gtrsim 30$ GeV. This is compatible with a relative suppression scaling as P_T^{-2} between the LO and NLO topologies, which justifies the use of the NLO* approximation (see [7]). As regards the P_T spectrum for $J/\psi + \eta_c$ at LO, it lies exactly in between these cases.

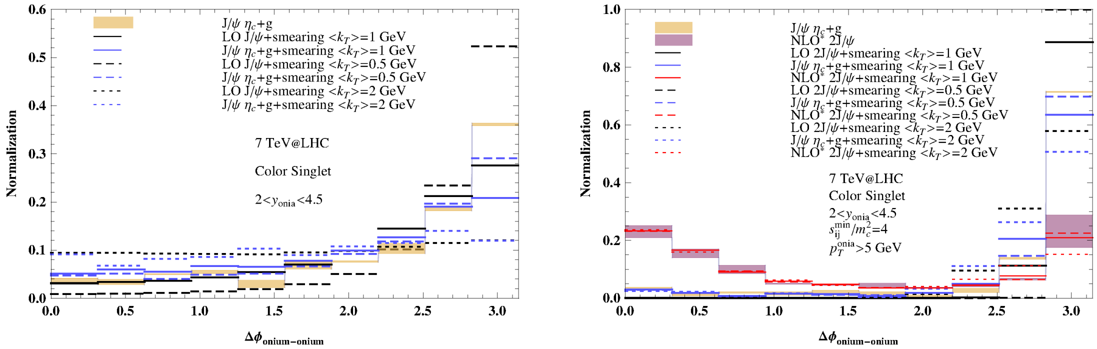


Figure 1: Azimuthal distribution of quarkonium pairs for different initial k_T of the colliding partons with (left) and without (right) a P_T cut on one of the quarkonium.

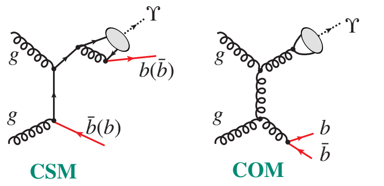
In addition to the yields and their kinematical dependences, we have also looked at the azimuthal correlations between the quarkonia. At NLO$^{(\star)}$, the presence of a gluon in the final state of the leading topologies naturally creates an imbalance between the quarkonia, which are then not necessarily created back to back ($\Delta\phi = \pi$). The presence of initial k_T in the colliding partons is also another source of imbalance. If $\langle k_T \rangle$ is as high as 2 GeV, the azimuthal distribution is completely flattened (see Fig. 1 (left)); in other words, the quarkonia are completely decorrelated in azimuth. If one imposes a P_T cut on one of the quarkonia, they remain produced back to back, except for $J/\psi - J/\psi$ at NLO (see Fig. 1 (right)). Indeed, there is a possibility that the J/ψ pair be produced recoiling on a gluon. In such a case, the quarkonia are "near" to each other ($\Delta\phi \simeq 0$). These results, in any case, show that one has to be careful when trying to separate out the contribution of Single-Parton Scatterings (SPS) –expected to be *anti*-correlated– from that of Double-Parton Scatterings –expected to be uncorrelated– uniquely from the analysis of the azimuthal distributions. Our findings confirm the discussion in [26].

Finally, let us add that double J/ψ production has recently been studied by D0 at Fermilab [23] and by CMS at the LHC [24]. These studies respectively brought in new information about the rapidity and the P_T difference dependence. A possible next step might be to look at the polarisation as we did at NLO$^{(\star)}$ in [20].

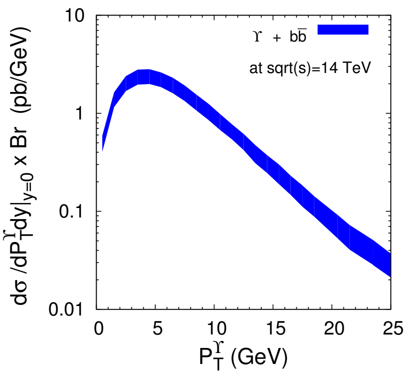
3. Quarkonium plus heavy quarks: $J/\psi + c$ and $\Upsilon +$ non-prompt J/ψ

In addition to quarkonium-pair production, LHCb has recently investigated the production of J/ψ with charm hadrons [25]. Depending on the scheme considered for the number of flavours, this process can come from partonic sub-processes such as $gc \to J/\psi c$ [12] or $gg \to J/\psi c\bar{c}$ [5]. A comparison with the LHCb data [25] is not straighforward since one has to take into account in the kinematics the charm-quark fragmentation. In addition, the LHCb data are only for P_T^C of the charm hadrons above 3 GeV. In $2 \to 2$ processes, this automatically excludes $P_T^{J/\psi} \leq 3$ GeV. QCD corrections may therefore be important for these kinematical configurations. As for now, these reactions have only been evaluated at LO and the current theoretical uncertainties from the scales and from the charm-quark mass are unfortunately large. In spite of this, the theory-data comparison hints at an important DPS contribution. Yet, since the P_T spectra of the J/ψ's produced with a charmed hadron and of those without tend to differ, SPS contributions may be sizeable. Overall, much still has to be learnt from these interesting pieces of data.

Along the same lines, bottomonia can also be produced with a beauty hadron. Since these are usually studied via their weak decay into a J/ψ, final states such as $\Upsilon +$ non-prompt J/ψ are also worth investigating. As for $J/\psi +$charm, one can look at the event topology, in particular, at how "near" (or "far") the heavy-flavoured particle is (w.r.t. the quarkonium). This can indeed be an interesting way to pin down the dominant production (SPS) mechanism[1]. If one assumes that such a reaction is initated by gluon fusion, the leading-P_T processes for, respectively the CSM and COM contributions, are as depicted on Fig. 2 (a). One clearly sees that the COM contributions can only produce two beauty hadrons (*i.e.* J/ψ's) back-to-back to the Υ. At large enough P_T^Υ, one would not expect at all beauty hadrons "near" the Υ. This is precisely the opposite of what one expects from the CSM, where one beauty hadron would be "near" and one "away". The cross section for the LHC kinematics is shown on Fig. 2 (b). Since about 1% of b quarks eventually end up decaying into a J/ψ, one can reasonably expect up to 400 $\Upsilon +$ non-prompt J/ψ events at $P_T^\Upsilon \simeq 10$ GeV with an integrated luminosity of 20 fb^{-1} at the LHC.



(a) Leading-P_T CSM and COM graphs



(b) CSM crosss-section at the LHC

Figure 2: Hadroproduction of $\Upsilon + b\bar{b}$

4. Quarkonium plus a back-to-back isolated photon

The production of a quarkonium associated with an isolated photon has been discussed in the literature at many instances since the early 90's. The yields have been evaluated at NLO in [9] and a partial NNLO (NNLO*) evaluation has been performed [10]. This observable is an interesting complement to inclusive measurements. For instance, it may put stringent constraints on the CO LDMEs[2]. Yet, the expected rates are necessarily lower than for inclusive quarkonium production and the theoretical uncertainties are not necessarily smaller.

In this context, it is worth noting that the requirement for back-to-back quarkonium–photon production selects out an interesting part of the phase space where (i) neither the QCD corrections, (ii) nor the CO contributions, are kinematically enhanced, and where (iii) an extension of collinear factorisation – the TMD factorisation– can fully be applied, providing a rigourous set of tools to study the transverse dynamics of the gluon content of the proton. This is what we discussed in [28].

In particular, we computed the expected rates at the LHC, which are summarised in Table (1). On the one hand, we can see that, at the LHC, this observable is essentially from gluon fusion,

[1] In the case of DPS production, one naturally expects the absence of any kind of correlations.

[2] An updated NLO analysis taking into account CO channels recently showed that some of the NLO fits of CO LDMEs [11] provided unphysical predictions –to be precise, negative yields– for $J/\psi + \gamma$ production [27].

making it an excellent gluon probe. On the other hand, it is most likely a pure CS yield in the Υ case whereas, in the J/ψ case, the predicted CS yield is above the CO ones where the cross section for accessible events ($J/\psi-\gamma$ invariant mass pair between 20 and 25 GeV) is the highest. For the sake of TMD factorisation applicability, it may also be worth isolating the J/ψ in order to prevent any contamination from CO transitions.

$\frac{d\sigma(\Upsilon+\gamma)}{dQdY d\cos\theta}$Br					$\frac{d\sigma(J/\psi+\gamma)}{dQdY d\cos\theta}$Br				
Q (GeV)	gg CS (fb/GeV)	$q\bar{q}$ CS (fb/GeV)	gg CO (fb/GeV)	$q\bar{q}$ CO (fb/GeV)	Q (GeV)	gg CS (fb/GeV)	$q\bar{q}$ CS (fb/GeV)	gg CO (fb/GeV)	$q\bar{q}$ CO (fb/GeV)
20	100	9×10^{-3}	5	1.5×10^{-2}	20	100	1.4×10^{-1}	70	1.2×10^{-1}
25	25	3.5×10^{-3}	2	5×10^{-3}	25	20	7×10^{-2}	20	5×10^{-2}
30	8	1.5×10^{-3}	0.8	2.5×10^{-3}	30	6	4×10^{-2}	8	3×10^{-2}

Table 1: Cross section for back-to-back quarkonium–photon production at $\sqrt{s}$ =7 TeV for gluon fusion and quark-annhilation and for CS and CO transitions for different pair invariant masses, Q, and for $|Y|<0.5$ & $|\cos\theta|<0.45$ (see [28]).

Our conclusion is that such an observable can already be studied at the LHC with data on tapes (about 20 fb^{-1} of pp collisions). In particular, one should be able to extract – for the first time – the transverse momentum dependence of the gluon content in the proton and to tell whether the distribution of linearly polarised gluon in an unpolarised proton is nonzero. It has to be noted that such an observable is also sensitive to gluons at lower energies, such as at the proposed fixed-target experiment using the LHC beams [29] (AFTER@LHC). With 20 fb^{-1} of pp data at $\sqrt{s}=115$ GeV, it should be possible to probe the gluon TMDs up to $x\simeq0.5$ [30] with this process at $Q\simeq10$ GeV.

5. Quarkonium plus W/Z bosons

The production of a quarkonium associated with a vector boson has also been the object of a number of studies. Previous theoretical analyses of $J/\psi+W$ production at hadron colliders [31, 32, 33] focused on the leading contributions in α or α_s, only arising from COM. For a long time, it was believed that *"$\psi+W$ offers a clean test of the colour-octet contributions"* [31] and that *"If the $J/\psi+W$ production is really detected, it would be a solid basis for testing the color-octet mechanism of the NRQCD"* [33], the latter statement being made following a NLO study in α_s.

In [34], we have shown that the CSM contributions to direct $J/\psi+W^\pm$ are not small at all as compared to that from CO transitions. These CSM contributions are due to two sub-processes: a) the fusion of a gluon and a strange quark which turns into a charm quark by the emission of the W, followed by the fragmentation of the charm quark into a $J/\psi+c$ pair; b) the quark q and antiquark $\bar{q}'$ annihilation into an off-shell photon, $\gamma^\star$, and a W, followed by the fluctuation of the $\gamma^\star$ into a J/ψ. The former process appears at $\alpha_s^3\alpha$ and the latter at α^3 compared to $\alpha_s^2\alpha$ for the COM process. The CSM contributions were earlier disregarded since formally appearing at higher orders in α or α_s despite the suppression of the CO in the v expansion of NRQCD.

At the Tevatron, we found that the COM contribution was significantly larger than that of the CSM via sg fusion, but of similar size as the CSM contribution via $\gamma^\star$. At LHC energies, our results was that the three contributions were of the same order. As a result, the total CSM cross section is about twice as large as the COM one at 7 TeV, probably a little more at 14 TeV and at large P_T –because of the most favourable running of α w.r.t α_s for increasing scales. Yet, at LHC energies, based on the ATLAS results [35], it seems that there is a significant DPS contribution.

We have also studied the hadroproduction of $J/\psi+Z$ and $\Upsilon+Z$ at NLO in [36]. We found out that the quarkonium polarisation is not affected by the QCD corrections, whereas these significantly affect the yield for increasing P_T.

6. Conclusion

A number of associated-quarkonium-production channels have been theoretically studied since the early nineties. Thanks to the large luminosities recently collected at both Fermilab and the LHC, a number of experimental studies have been –and are being– carried out. There is no doubt that the confrontation between these theory predictions and these measurements will bring in very soon new information which will be very useful in order to solve the quarkonium-production puzzles. They may also play a key role in the understanding of DPS physics.

References

[1] J. P. Lansberg, Int. J. Mod. Phys. A **21**, 3857 (2006).
[2] N. Brambilla *et al.* Eur. Phys. J. C **71**, 1534 (2011).
[3] C-H. Chang, Nucl. Phys. B **172**, 425 (1980); R. Baier and R. Rückl, Phys. Lett. B **102**, 364 (1981); R. Baier and R. Rückl, Z. Phys. C **19**, 251 (1983).
[4] J. Campbell, F. Maltoni and F. Tramontano, Phys. Rev. Lett. **98**, 252002 (2007).
[5] P. Artoisenet, J. P. Lansberg and F. Maltoni, Phys. Lett. B **653**, 60 (2007).
[6] B. Gong and J. X. Wang, Phys. Rev. Lett. **100**, 232001 (2008); Phys. Rev. D **78**, 074011 (2008).
[7] P. Artoisenet, J. Campbell, J.P. Lansberg, F. Maltoni, F. Tramontano, Phys. Rev. Lett. **101**, 152001 (2008). J. P. Lansberg, Eur. Phys. J. C **61**, 693 (2009).
[8] J. P. Lansberg, Phys. Lett. B **695**, 149 (2011).
[9] R. Li and J. X. Wang, Phys. Lett. B **672**, 51 (2009).
[10] J. P. Lansberg, Phys. Lett. B **679**, 340 (2009).
[11] M. Butenschoen and B. A. Kniehl, Phys. Rev. Lett. **108** (2012) 172002 K.-T. Chao, Y.-Q. Ma, H.-S. Shao, K. Wang, Y.-J. Zhang, Phys. Rev. Lett. **108** (2012) 242004; B. Gong, L.-P. Wan, J.-X. Wang, H.-F. Zhang, Phys. Rev. Lett. **110** (2013) 042002; Phys. Rev. Lett. **112** (2014) 032001; H. -S. Shao, Y. -Q. Ma, K. Wang, K. -T. Chao, Phys. Rev. Lett. **112** (2014) 182003.
[12] S. J. Brodsky and J. P. Lansberg, Phys. Rev. D **81**, 051502 (2010).
[13] J. P. Lansberg, PoS ICHEP **2010**, 206 (2010).
[14] J. Badier *et al.* [NA3 Collaboration], Phys. Lett. B **114** (1982) 457.
[15] J. Badier *et al.* [NA3 Collaboration], Phys. Lett. B **158**, 85 (1985).
[16] R. Vogt and S. J. Brodsky, Phys. Lett. B **349** (1995) 569
[17] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **707** (2012) 52
[18] C. -F. Qiao, L. -P. Sun and P. Sun, J. Phys. G **37** (2010) 075019
[19] A. V. Berezhnoy, A. K. Likhoded, A. V. Luchinsky, A. A. Novoselov, Phys. Rev. D **84** (2011) 094023
[20] J. -P. Lansberg and H. -S. Shao, Phys. Rev. Lett. **111** (2013) 12, 122001
[21] H. -S. Shao, Comput. Phys. Commun. **184** (2013) 2562
[22] L. -P. Sun, H. Han and K. -T. Chao, arXiv:1404.4042 [hep-ph].
[23] V. M. Abazov *et al.* [D0 Collaboration], arXiv:1406.2380 [hep-ex].
[24] V. Khachatryan *et al.* [CMS Collaboration], arXiv:1406.0484 [hep-ex].
[25] R. Aaij *et al.* [LHCb Collaboration], JHEP **1206** (2012) 141
[26] C. H. Kom, A. Kulesza and W. J. Stirling, Phys. Rev. Lett. **107** (2011) 082002
[27] R. Li and J. -X. Wang, Phys. Rev. D **89** (2014) 114018
[28] W. J. den Dunnen, J. -P. Lansberg, C. Pisano and M. Schlegel, Phys. Rev. Lett. **112** (2014) 212001
[29] S. J. Brodsky, F. Fleuret, C. Hadjidakis and J. P. Lansberg, Phys. Rept. **522** (2013) 239
[30] J.P. Lansberg, talk at "Transversity 2014", 9-13 June 2014, Chia, Italy.
[31] V. D. Barger, S. Fleming and R. J. N. Phillips, Phys. Lett. B **371**, 111 (1996).
[32] B. A. Kniehl, C. P. Palisoc and L. Zwirner, Phys. Rev. D **66**, 114002 (2002).
[33] G. Li, M. Song, R. -Y. Zhang and W. -G. Ma, Phys. Rev. D **83**, 014001 (2011).
[34] J. P. Lansberg and C. Lorce, Phys. Lett. B **726** (2013) 218
[35] G. Aad *et al.* [ATLAS Collaboration], JHEP **1404** (2014) 172
[36] B. Gong, J. -P. Lansberg, C. Lorce and J. Wang, JHEP **1303** (2013) 115