\( J/\psi + Z \) production at the LHC

Jean-Philippe Lansberg\(^1\),\(^a\) and Hua-Sheng Shao\(^2\)

\(^1\)IPNO, Université Paris-Saclay, Univ. Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France
\(^2\)Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Abstract. We briefly review recent results which we have obtained in the study of \( J/\psi + Z \) production at the LHC. Considering our NLO computation in the Colour Evaporation Model (CEM) as an upper theory limit for the single-parton-scattering contributions, we claim that the existing data set from ATLAS points at a dominant double-parton-scattering contribution with an effective cross section smaller than that for jet-related observables. As a side product of our analysis, we have computed, for the first time, the one-loop QCD corrections to the \( J/\psi P_T \)-differential cross section in the CEM.

1 Introduction

Thanks to the high luminosities collected at the LHC and the Tevatron, observing associated production of a quarkonium with a vector boson or a heavy quark is not any more uncommon. The same applies to quarkonium-pair production. Indeed, nearly a dozen of experimental analyses \([1–11]\) are now available along with many relevant theoretical works. Some gave predictions before these analyses \([12–25]\); some helped at the interpretation of these results \([26–34]\). Let us emphasise that many of these theoretical works relied on automated tools adapted to quarkonium production. Let us cite Madonia \([35]\), Helac-Onia \([36, 37]\) and FDC \([38]\). We focus here on the associated production of a \( Z \) boson with a prompt\(^1\) \( J/\psi \) at the LHC.

2 Colour Evaporation Model up to one loop in \( \alpha_s \)

As announced, CEM predictions can be considered as a realistic upper theory value for a class of associated-production observables where the gluon fragmentation is expected to be dominant. This is the case of \( J/\psi + Z \), but obviously also of single-\( J/\psi \) production at large \( P_T \). In order to consistently fix the required parameter for such an upper theory value for our \( J/\psi + Z \) NLO analysis, we have performed in \([32]\) the first one-loop analysis of the differential cross section of single-\( J/\psi \) hadroproduction.

Let us first recall that the CEM can be seen as the application to quarkonium production \([39, 40]\) of the principle of quark-hadron duality. Quarkonium-production cross sections are obtained by integrating the cross section for \( Q\bar{Q} \) pair production in an invariant-mass region where its hadronisation into a quarkonium is likely. This means that, in practice, one considers the range between \( 2m_Q \) and the

---

\(^a\)e-mail: Jean-Philippe.Lansberg@in2p3.fr

\(^1\)We just performed a similar analysis \([34]\) of the non-prompt sample of ATLAS.
threshold to produce open-heavy-flavour hadrons, referred to as $2m_H$. One then multiplies this partial heavy-quark cross section by a phenomenological factor which accounts for the probability, $P_Q$, that the pair eventually hadronises into a given quarkonium state. Our computation then reduces to that of

$$\sigma_{Q}^{(N)LO, \text{ direct/prompt}} = P_{Q} \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q}^{(N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}. \quad (1)$$

Owing to the simplicity of the model, the direct or prompt yields are obtained from the same computation but with a different overall factor. Different attempts to "improve" the model focusing on specific mechanisms [41–44] have been made (see [45] for a brief overview of some of them) but they do not seem to be the object of a consensus as far as their relevance is concerned.

![Figure 1](image-url)

**Figure 1.** The ATLAS data [46] compared to the CEM results for $d\sigma/dy/dp_T$ of $J/\psi$ + a recoiling parton at (a) LO and (b) NLO at $\sqrt{s} = 8$ TeV. [The theoretical uncertainty band is from the scale variation (see the text)]. [Plots from [32].]

A NLO comparison with $p_T$-integrated data from fixed-target experiments as well as from colliders was performed in [47]. The agreement was found to be satisfactory. An interesting study of the relation between heavy-flavour and quarkonium production in the CEM can also be found in [48]. Along the lines of this analysis, we have decided to stick to $m_c = 1.27$ GeV. In any case, there is a significant correlation between the fit value of the phenomenological parameter $P_Q$ and $m_Q$; as such,
the choice of the quark mass is probably less critical than for other processes like open heavy-flavour production or quarkonium production in the colour-singlet model\footnote{See \cite{49,50} for some examples.} for instance.

As what regards the $P_T$ spectrum of single $J/\psi$’s, the CEM is known to provide too hard a $P_T$ spectrum. However, before our study, such a statement was relying on studies using hard-scattering matrix elements at $\alpha_s^2$. These are indeed NLO (one loop) for the $P_T$-integrated yield but not for the $P_T$-differential cross section whose Born-order contribution is at $\alpha_s^3$. It was therefore legitimate to wonder whether the $P_T$ spectrum computed up to $\alpha_s^3$ would be different.

Given the direct connection between the CEM and heavy-quark production, such a computation is in fact possible with modern tools of automated NLO frameworks, with some slight tunings. We have thus used MadGraph5\_aMC@NLO \cite{51} to perform our (N)LO CEM calculations for $J/\psi + a$ recoiling parton with a finite $P_T$. Since the heavy-quark mass dependence is de facto absorbed in the CEM parameter, the main theoretical uncertainties are coming from the renormalisation $\mu_R$ and factorisation $\mu_F$ scale variations which account for the unknown higher-order corrections. In practice, we have varied them independently within $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$ where the central scale $\mu_0$ is the transverse mass of the $J/\psi$ in $J/\psi +$ parton. We note the reduced theoretical uncertainties at NLO. We have used the NLO NNPDF 2.3 PDF set \cite{52} with $\alpha_s(M_Z)=0.118$ provided by LHAPDF \cite{53}.

Fitting recent 8 TeV ATLAS data \cite{46} with $m_c=1.27$ GeV, we have obtained $\sigma_{J/\psi}^{NLO,\text{prompt}}=0.014\pm0.001$ and $\sigma_{J/\psi}^{NLO,\text{prompt}}=0.009\pm0.0004$. The $K$ factor affecting the $P_T$ slope is close to 1.6. As announced, the CEM yields start to depart from the data when $P_T$ increases (see Fig. 1), both at LO and NLO. This confirms that the CEM can indeed be seen as an upper theory limit for $J/\psi$ production processes dominated by gluon-fragmentation channels.

### 3 $J/\psi + Z$ production at the LHC

Cross section predictions for the associated production of a $J/\psi$ and a $Z$ boson at the LHC were provided up to NLO accuracy in \cite{15,19}. However, ATLAS found out \cite{3} larger SPS yields than expected if the DPS rates were assumed to be compatible with jet-related observables, \textit{i.e.} with $\sigma_{\text{eff}}$ on the order of 15 mb.

![Figure 2](https://example.com/figure2.png)

\textbf{Figure 2.} (a) Comparison between the ATLAS $P_T^{J/\psi}$-differential cross section and our theoretical results for $J/\psi + Z$ at NLO CEM SPS + DPS. (b) Idem for the CMS acceptance (see \cite{32} for details). [Plots from \cite{32}].
In [32], we have shown that it would very unlikely that the SPS contributions from any sensible approach would be compatible with the DPS-subtracted data using DPS contributions assuming $\sigma_{\text{eff}} = 15 \text{ mb}$. Indeed, the CEM yield (computed up to NLO), which we consider to be an upper limit of the SPS contributions, does not agree with such an assumption on the DPS yield. We further showed that the data could accommodate a $\sigma_{\text{eff}}$ as low as 5 mb, which in turn gives a smaller DPS-subtracted yield closer to the SPS theoretical expectations. Yet, additional data are welcome to draw firmer conclusions. Comparisons with the ATLAS data are shown on Fig. 2 for the $P_{T}^{J/\psi}$-differential cross section (along with predictions for the CMS acceptance) and for the (uncorrected) azimuthal distribution on Fig. 3a.

### Figures

**Figure 3.** (a) Comparison between the (uncorrected) ATLAS azimuthal event distribution and our theoretical results for $J/\psi + Z$ at NLO CEM SPS + DPS effectively folded with an assumed ATLAS efficiency (see [32] for details). (b) Our ranges for $\sigma_{\text{eff}}$ extracted from the $J/\psi + Z$ data (4.7$^{+2.7}_{-1.9}$ mb) [32] and from di-$J/\psi$ data [27] (8.2$^{+2.0}_{-2.9}$ mb) compared with other extractions [5, 10, 54–60]. [Plots from [32].]

### 4 Conclusion

In the recent semesters, a significant number of experimental studies of associated-production of quarkonia have been lately carried out. We have reviewed one of them: the production of a $Z$ boson along with a prompt $J/\psi$. We have found that the DPS contributions are indispensable to describe the data, pointing at a somewhat small $\sigma_{\text{eff}}$ (see Fig. 3b) as do most of the other quarkonium-associated-production observables.

### Acknowledgements

The work of J.P.L. is supported in part by the French CNRS via the LIA FCPPL (Quarkonium4AFTER) and the Défi Inphyniti-Théorie LHC France. H.S.S. is supported by the ERC grant 291377 LHCtheory: Theoretical predictions and analyses of LHC physics: advancing the precision frontier.
References

[1] R. Aaij et al. (LHCb), Phys. Lett. B707, 52 (2012), 1109.0963
[2] R. Aaij et al. (LHCb), JHEP 06, 141 (2012), [Addendum: JHEP03,108(2014)], 1205.0975
[3] G. Aad et al. (ATLAS), Eur. Phys. J. C75, 229 (2015), 1412.6428
[4] V. Khachatryan et al. (CMS), JHEP 09, 094 (2014), 1406.0484
[5] V.M. Abazov et al. (D0), Phys. Rev. D90, 111101 (2014), 1406.2380
[6] G. Aad et al. (ATLAS), JHEP 04, 172 (2014), 1401.2831
[7] G. Aad et al. (ATLAS), Phys. Rev. Lett. 114, 121801 (2015), 1501.03276
[8] R. Aaij et al. (LHCb), JHEP 07, 052 (2016), 1510.05949
[9] V.M. Abazov et al. (D0), Phys. Rev. Lett. 116, 082002 (2016), 1511.02428
[10] ATLAS (ATLAS) (2016), ATLAS-CONF-2016-047
[11] V. Khachatryan et al. (CMS) (2016), 1610.07095
[12] P. Artoisenet, J.P. Lansberg, F. Maltoni, Phys. Lett. B653, 60 (2007), hep-ph/0703129
[13] R. Li, J.X. Wang, Phys. Lett. B672, 51 (2009), 0811.0963
[14] J.P. Lansberg, Phys. Lett. B679, 340 (2009), 0901.4777
[15] S. Mao, M. Wen-Gan, L. Gang, Z. Ren-You, G. Lei, JHEP 02, 071 (2011), [Erratum: JHEP12,010(2012)], 1102.0398
[16] C.H. Kom, A. Kulesza, W.J. Stirling, Phys. Rev. Lett. 107, 082002 (2011), 1105.4186
[17] L. Gang, M. Wen-Gan, S. Mao, Z. Ren-You, G. Jian-You, JHEP 01, 034 (2013), 1212.2417
[18] L. Gang, W. ShuangTe, S. Mao, L. JiPing, Phys. Rev. D85, 074026 (2012), 1203.0799
[19] B. Gong, J.P. Lansberg, C. Lorce, J. Wang, JHEP 03, 115 (2013), 1210.2430
[20] J.P. Lansberg, H.S. Shao, Phys. Rev. Lett. 111, 122001 (2013), 1308.0474
[21] J.P. Lansberg, C. Lorce, Phys. Lett. B726, 218 (2013), [Erratum: Phys. Lett.B738,529(2014)], 1303.5327
[22] W.J. den Dunnen, J.P. Lansberg, C. Pisano, M. Schlegel, Phys. Rev. Lett. 112, 212001 (2014), 1401.7611
[23] J.P. Lansberg, H.S. Shao, Nucl. Phys. B900, 273 (2015), 1504.06531
[24] A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky, Phys. Rev. D94, 054017 (2016), 1606.06767
[25] S. Koshkarev, S. Groote (2016), 1607.00619
[26] L.P. Sun, H. Han, K.T. Chao, Phys. Rev. D94, 074033 (2016), 1404.4042
[27] J.P. Lansberg, H.S. Shao, Phys. Lett. B751, 479 (2015), 1410.8822
[28] Z.G. He, B.A. Kniehl, Phys. Rev. Lett. 115, 022002 (2015), 1509.02786
[29] S.P. Baranov, A.H. Rezaeian, Phys. Rev. D93, 114011 (2016), 1511.04089
[30] C. Borschensky, A. Kulesza, A. Kulesza (2016), 1610.00666
[31] H.S. Shao, Y.J. Zhang, Phys. Rev. Lett. 117, 062001 (2016), 1605.03061
[32] J.P. Lansberg, H.S. Shao, JHEP 10, 153 (2016), 1608.03198
[33] J.P. Lansberg, H.S. Shao, PoS DIS2016, 165 (2016), 1611.02192
[34] J.P. Lansberg, H.S. Shao (2016), 1611.09303
[35] P. Artoisenet, F. Maltoni, T. Stelzer, JHEP 02, 102 (2008), 0712.2770
[36] H.S. Shao, Comput. Phys. Commun. 184, 2562 (2013), 1212.5293
[37] H.S. Shao, Comput. Phys. Commun. 198, 238 (2016), 1507.03435
[38] J.X. Wang, Nucl. Instrum. Meth. A534, 241 (2004), hep-ph/0407058
[39] H. Fritzsch, Phys. Lett. B67, 217 (1977)
[40] F. Halzen, Phys. Lett. B69, 105 (1977)
[41] A. Edin, G. Ingelman, J. Rathsman, Phys. Rev. D56, 7317 (1997), hep-ph/9705311
[42] J. Damet, G. Ingelman, C. Brenner Mariotto, JHEP 09, 014 (2002), hep-ph/0111463
[43] C. Brenner Mariotto, M.B. Gay Ducati, G. Ingelman, Eur. Phys. J. C23, 527 (2002), hep-ph/0111379
[44] Y.Q. Ma, R. Vogt (2016), 1609.06042
[45] J.P. Lansberg, Int. J. Mod. Phys. A21, 3857 (2006), hep-ph/0602091
[46] G. Aad et al. (ATLAS), Eur. Phys. J. C76, 283 (2016), 1512.03657
[47] Y. Feng, J.P. Lansberg, J.X. Wang, Eur. Phys. J. C75, 313 (2015), 1504.00317
[48] R.E. Nelson, R. Vogt, A.D. Frawley, Phys. Rev. C87, 014908 (2013), 1210.4610
[49] S.J. Brodsky, J.P. Lansberg, Phys. Rev. D81, 051502 (2010), 0908.0754
[50] J.P. Lansberg, Phys. Lett. B695, 149 (2011), 1003.4319
[51] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, JHEP 07, 079 (2014), 1405.0301
[52] R.D. Ball et al., Nucl. Phys. B867, 244 (2013), 1207.1303
[53] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, G. Watt, Eur. Phys. J. C75, 132 (2015), 1412.7420
[54] T. Akesson et al. (Axial Field Spectrometer), Z. Phys. C34, 163 (1987)
[55] J. Alitti et al. (UA2), Phys. Lett. B268, 145 (1991)
[56] F. Abe et al. (CDF), Phys. Rev. D47, 4857 (1993)
[57] F. Abe et al. (CDF), Phys. Rev. D56, 3811 (1997)
[58] V.M. Abazov et al. (D0), Phys. Rev. D81, 052012 (2010), 0912.5104
[59] G. Aad et al. (ATLAS), New J. Phys. 15, 033038 (2013), 1301.6872
[60] S. Chatrchyan et al. (CMS), JHEP 03, 032 (2014), 1312.5729