

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

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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/ψ 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 analysis [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 prompt¹ J/ψ at the LHC.

2 Colour Evaporation Model up to one loop in α_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/ψ 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/ψ 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

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¹We 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, \mathcal{P}_Q , that the pair eventually hadronises into a given quarkonium state. Our computation then reduces to that of

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

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.

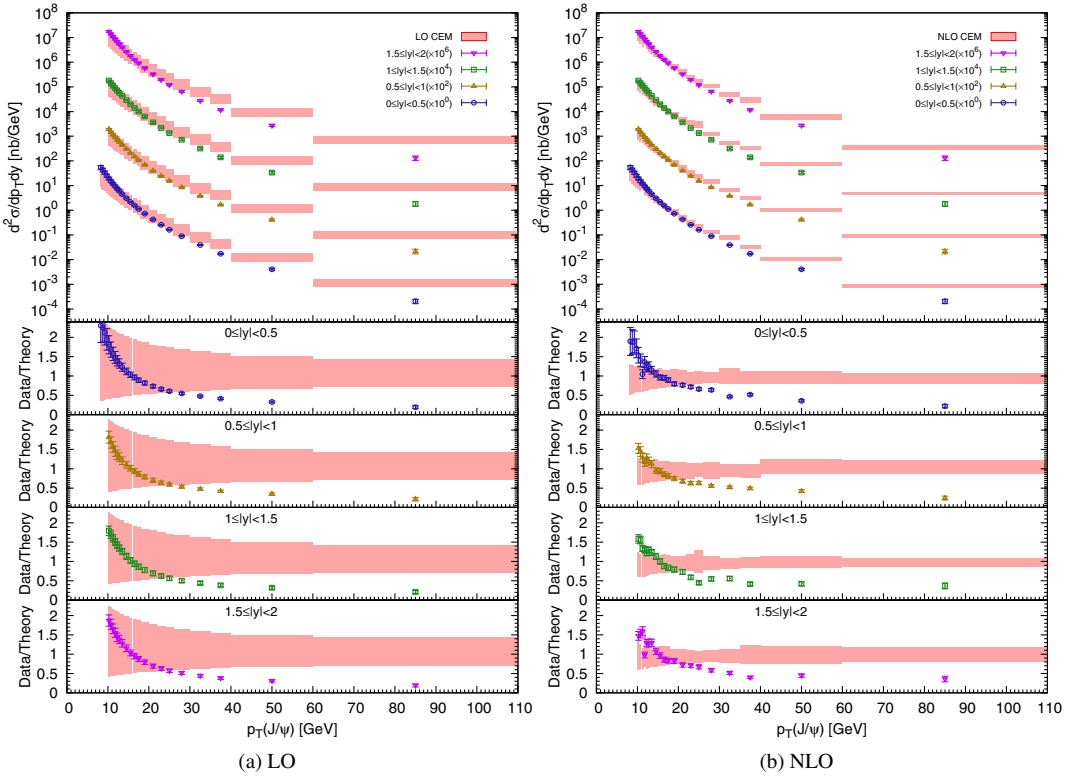


Figure 1. The ATLAS data [46] compared to the CEM results for $d\sigma/dy/dP_T$ of J/ψ + a recoiling parton at (a) LO and (b) NLO at $\sqrt{s} = 8$ TeV. [The theoretical uncertainty band is from the scale variation (see the text)]. [Plots from [32].]

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 \mathcal{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 model² for instance.

As what regards the P_T spectrum of single J/ψ '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 α_s^3 . 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 α_s^3 . It was therefore legitimate to wonder whether the P_T spectrum computed up to α_s^4 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 [51] to perform our (N)LO CEM calculations for J/ψ + 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 μ_R and factorisation μ_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 μ_0 is the transverse mass of the J/ψ in J/ψ + parton. We note the reduced theoretical uncertainties at NLO. We have used the NLO NNPDF 2.3 PDF set [52] with $\alpha_s(M_Z) = 0.118$ provided by LHAPDF [53].

Fitting recent 8 TeV ATLAS data [46] with $m_c = 1.27$ GeV, we have obtained $\mathcal{P}_{J/\psi}^{\text{LO,prompt}} = 0.014 \pm 0.001$ and $\mathcal{P}_{J/\psi}^{\text{NLO,prompt}} = 0.009 \pm 0.0004$. 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/ψ production processes dominated by gluon-fragmentation channels.

3 J/ψ + Z production at the LHC

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

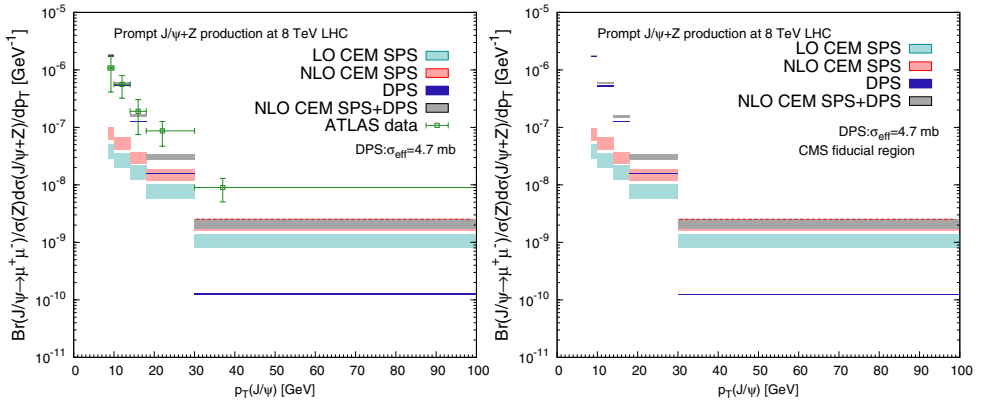


Figure 2. (a) Comparison between the ATLAS $P_T^{J/\psi}$ -differential cross section and our theoretical results for J/ψ + Z at NLO CEM SPS + DPS. (b) Idem for the CMS acceptance (see [32] for details). [Plots from [32]].

²See [49, 50] for some examples.

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 $\sigma_{\text{eff}} = 15$ 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 σ_{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.

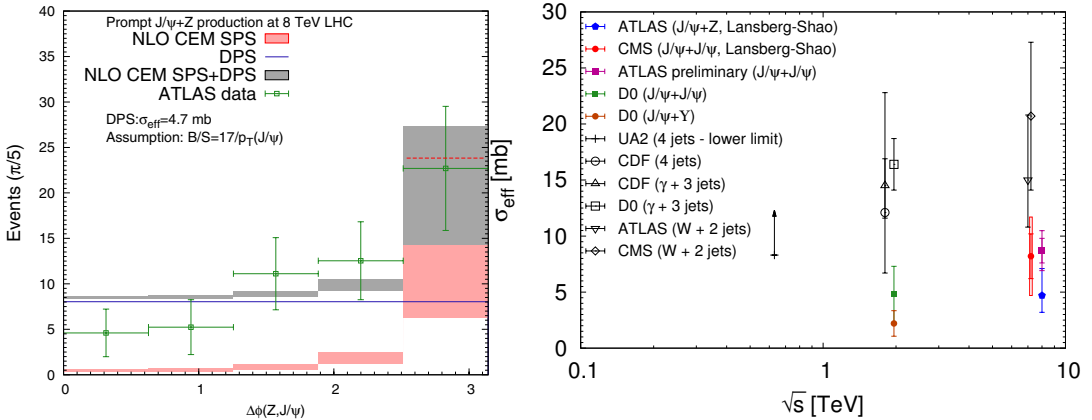


Figure 3. (a) Comparison between the (uncorrected) ATLAS azimuthal event distribution and our theoretical results for $J/\psi + Z$ at NLO CEM SPS + DPS effectively folded with an assumed ATLAS efficiency (see [32] for details). (b) Our ranges for σ_{eff} extracted from the $J/\psi + Z$ data ($4.7^{+2.4}_{-1.5}$ mb) [32] and from di- J/ψ data [27] ($8.2 \pm 2.0 \pm 2.9$ 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/ψ . We have found that the DPS contributions are indispensable to describe the data, pointing at a somewhat small σ_{eff} (see Fig. 3b) as do most of the other quarkonium-associated-production observables.

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