Phenomenological analysis of associated production of $Z^0 + b$ in the $b \to J/\psi X$ decay channel at the LHC

Jean-Philippe Lansberg [a], Hua-Sheng Shao [b,*]

[a] *IPNO, Université Paris-Saclay, Univ. Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France*
[b] *Theoretical Physics Department, CERN, CH-1211, Geneva 23, Switzerland*

Abstract

The ATLAS collaboration recently reported on the first observation of associated-production of a Z^0 boson with a J/ψ. We recently claimed that the corresponding yield of the *prompt J/ψ* was dominated by double parton scatterings in the ATLAS acceptance with a somewhat small value of σ_{eff}. We also found out that single parton scatterings were only dominant at large transverse momenta. We present here the first phenomenological analysis of another part of the ATLAS data sample, namely of a Z^0 boson plus a *non-prompt J/ψ*. Our study is performed at next-to-leading order in α_s and includes parton-shower effects via the MADGRAPH5_AMC@NLO framework. We find out that the data, unlike the case of prompt $J/\psi + Z^0$, do not hint at significant DPS contributions. Owing to the current experimental and theoretical uncertainties, there is still a room for these but with a lower limit of σ_{eff} close to 5 mb. We stress the importance of QCD corrections to account for the ATLAS data.

1. Introduction

Thanks to the large luminosities of the LHC, the study of differential distributions of associated production of vector bosons with open- and hidden-heavy flavour became accessible. These are particularly interesting because they can give access to information on double parton

---

* Corresponding author.
  E-mail address: huasheng.shao@cern.ch (H.-S. Shao).

scatterings (DPS). These, as opposed to the conventional single parton scatterings (SPS), consist in two simultaneous partonic scatterings during a single proton–proton collision.

The relevance of DPS is known to increase for increasing energies at hadron–hadron colliders which explains why they have only started to be systematically studied with the advent of the Tevatron and the LHC. This is also why they remain poorly understood. Yet, the measurement of fundamental SM parameters like the bottom-quark Yukawa coupling via H^0 and vector-boson associated production requires the reanalysis of these processes by taking into account DPS. New physics searches via same-sign W boson-pair production also requires a good control on the DPS.

Recent DPS studies based on quarkonium-pair production [1–5] indicate a smaller σ_{eff} – a parameter characterising the importance of the DPS ($\sigma^{\mathrm{DPS}} \propto 1/\sigma_{\mathrm{eff}}$) – than the jet-related final states. We should however note that all these extractions were carried out under a simplified – but commonly used – assumption whereby both scatterings occur independently without affecting each others' kinematics. As such, their individual cross sections appear in a factorised way, in what we call the "pocket formula". As of today, there do not exist proofs of such a factorised formula. Recent and less recent theoretical DPS studies have identified factorisation-breaking effects (see *e.g.* [6–29]) and have thus shown that such a factorised "pocket formula" can only be an approximation and we stress that it should only be considered as such. That being said, given the other theoretical and experimental uncertainties involved in such extractions, such a simplification is perfectly sound.

Quarkonia being produced via the gluon–gluon initial states, their pair production could help us probe the transverse correlations of the gluon–gluon in a proton (see *e.g.* [20]). In fact, many quarkonium associated production processes have been recently measured. Let us cite J/ψ pair production by LHCb [30], D0 [1], CMS [31] and ATLAS [32], $J/\psi + \Upsilon$ production by D0 [3], $\Upsilon(1S)$ pair production by CMS [33], $J/\psi + Z^0/W^{\pm}$ production by ATLAS [34,35], $J/\psi/\Upsilon +$ *charm* by LHCb [36,37], with their theory counterparts for $J/\psi + J/\psi$ [38–40,2,41–45], $J/\psi + \Upsilon$ [41,4], $\Upsilon + \Upsilon$ [41] and $Z^0 +$ prompt J/ψ [46].

The observed different trend between the extracted values of σ_{eff} for jets and quarkonia may be the first hint of a nontrivial flavour dependence of these correlations. Along these lines, the associated production of a vector boson with heavy flavours, which we treat here, could be an unique playground to probe corresponding quark–gluon correlations.

In this paper, we are in particular interested in the associated production of a Z^0 boson with a b quark, via the observation of a non-prompt J/ψ, as measured by the ATLAS collaboration [34]. This production channel is thus supposed to probe the underlying process $pp \to Z^0 + b\bar{b} + X$.[1] At the LHC, such partonic reactions are usually proposed to be studied via Z^0 plus b-jet. We however stress that both final states are complementary since looking at the b via non-prompt J/ψ allows one to access lower P_T than with b-jets. For this process, we will show that going to lower P_T gives the best prospects to dig out the DPS contributions, since they happen not to be large in general.

In addition, $Z^0 + b\bar{b}$ production is an important observable as it can be an irreducible background to $Z^0 + H^0$ production followed by $H \to b\bar{b}$, $Z^0 + H^0$ being one of the four main H^0 production processes at the LHC. It could also be one of the crucial processes to directly probe the bottom-Higgs Yukawa coupling. The next-to-leading order (NLO) QCD corrections

---

[1] For the SPS, it proceeds via $gg \to Z^0 + b\bar{b} + X$ in the 4 flavour scheme and $gb \to Z^0 + b$ in the 5 flavour scheme.

Table 1

Phase–space definition for the fiducial/inclusive production cross section for $J/\psi + Z$ as measured in the ATLAS detector and foreseen for the CMS detector.

Z boson selection		
P_T (trigger lepton) > 25 GeV, P_T (sub-leading lepton) > 15 GeV, $|\eta(\text{lepton from } Z)| < 2.5$		
J/ψ selection		
ATLAS fiducial [34]	ATLAS inclusive [34]	CMS fiducial [61]
$8.5 < P_T^{J/\psi} < 100$ GeV	$8.5 < P_T^{J/\psi} < 100$ GeV	$8.5 < P_T^{J/\psi} < 100$ GeV
$|y_{J/\psi}| < 2.1$	$|y_{J/\psi}| < 2.1$	$|y_{J/\psi}| < 2.1$
P_T (leading muon) > 4.0 GeV		$|\eta(\text{muon})| < 2.5$
$|\eta(\text{leading muon})| < 2.5$		
either $\begin{pmatrix} P_T \text{ (sub-leading muon)} > 2.5 \text{ GeV} \\ 1.3 \leq |\eta(\text{sub-leading muon})| < 2.5 \end{pmatrix}$		
or $\begin{pmatrix} P_T \text{ (sub-leading muon)} > 3.5 \text{ GeV} \\ |\eta(\text{sub-leading muon})| < 1.3 \end{pmatrix}$		

to $pp \to Z^0 + b\bar{b} + X$ have extensively been studied in the literature [47–50].[2] Yet, all the existing phenomenological studies focused on b-jets, hence the absence of data-theory comparisons in [34]. The present study, relying on existing and validated automated tools, like MADGRAPH5_AMC@NLO [52] and PYTHIA 8.1 [53], therefore fills a gap in the literature with the first phenomenological analysis of $Z + b$ in the $b \to J/\psi X$ decay channel.

The structure of the article is as follows. Next section contains a short description of the computation set-up including the definition of the fiducial cuts as well as our results. We will compare our theoretical results with the ATLAS data and extract the information of σ_{eff}. Besides, a theoretical prediction will be given for the ongoing CMS measurement. Finally, we draw our conclusions in section 3.

2. Framework and results

2.1. Framework

Let us now describe how we have computed the (differential) yields to be compared to the measurement of the ATLAS collaboration recently reported in [34]. In order to generate the (N)LO event sample for $pp \to Z^0 + b\bar{b} + X$ in the 3-initial-quark-flavour scheme, we have used MADGRAPH5_AMC@NLO [52]. For the record, this single framework includes MADLOOP [54] and MADFKS [55] to handle the virtual and real pieces respectively; the former module uses the OPP method [56,57] whereas the latter uses the FKS subtraction method [58]. It also automatically uses the MC@NLO approach [59] to match NLO matrix elements to parton showers. The spin-entangled $Z^0 \to e^+e^-$ decays were then performed by the MADSPIN module [60] and we have used PYTHIA 8.1 [53] to account for the parton showers, the hadronisation and the other decays. All this allowed us to compute the yield in the ATLAS and CMS fiducial regions (see Table 1).

As what regards the choice of the renormalisation scale μ_R and factorisation scale μ_F, we have chosen as a central value $\mu_0 = \frac{H_T}{2}$, where H_T is the transverse mass sum of the final states. For the PDFs, we have used CTEQ6L1 (CTEQ6M) [62] for the LO (NLO) computation. The

---

[2] The NLO electroweak corrections to the similar process $pp \to Z^0 + t\bar{t} + X$ were also recently made available [51].

Table 2
Values of the Standard-Model parameters with the dimension-full quantity in units of GeV.

Parameter	Value	Parameter	Value
m_Z	91.188	n_{lf}	3
m_c	1.5	G_μ	$1.1987498350461625 \ 10^{-5}$
m_b	4.75	α_{em}^{-1}	137
m_t	173.0	CKM V_{ij}	δ_{ij}

integrated fragmentation fraction of b-hadrons to J/ψ was taken to be 1.15% from Ref. [63], which is also close to other estimations in the literature (see e.g. Refs. [64,65]). The other relevant Standard Model parameters are reported in Table 2.

2.2. Our results for the SPS contributions

In the ATLAS fiducial and inclusive regions (defined in Table 1), we have obtained the following (N)LO SPS cross sections for *non-prompt $J/\psi + Z$ production* at the LHC for $\sqrt{s} = 8$ TeV:

$$\sigma^{\text{LO SPS, ATLAS fidu.}}(^{\text{np}}J/\psi + Z) = 1215^{+383.5}_{-272.4} \text{ fb};$$

$$\sigma^{\text{NLO SPS, ATLAS fidu.}}(^{\text{np}}J/\psi + Z) = 1760^{+240.9}_{-220.8} \text{ fb},$$

$$\sigma^{\text{LO SPS, ATLAS incl.}}(^{\text{np}}J/\psi + Z) = 1999^{+619.7}_{-442.5} \text{ fb};$$

$$\sigma^{\text{NLO SPS, ATLAS incl.}}(^{\text{np}}J/\psi + Z) = 2922^{+392.9}_{-361.1} \text{ fb}, \tag{1}$$

where the theoretical uncertainty includes the renormalisation scale μ_R and factorisation scale μ_F uncertainty $\frac{\mu_0}{2} \leq \mu_R, \mu_F \leq 2\mu_0$, varied independently.

In absence of such predictions in the literature, no comparison was made by ATLAS in Ref. [34]. We proceed now to the comparison to their results presented in the form of yield ratio in order to reduce some systematical uncertainties attached to the detection of the Z boson, namely:

$$^{\text{np}}R(J/\psi + Z) = \text{Br}(J/\psi \to \mu^+\mu^-) \times \frac{\sigma(J/\psi + Z)}{\sigma(Z)} \tag{2}$$

We therefore also need to use the Z production cross section with the ATLAS cuts and have decided to simply take $\sigma^{\text{ATLAS}}(Z) \times \text{Br}(Z \to e^+e^-) = 533.4$ fb used by ATLAS for the comparison with the *prompt $J/\psi + Z$* theory predictions. The latter was estimated at the next-to-next-to leading order by FEWZ [66]. We have also checked this estimation with MADGRAPH5_AMC@NLO by including the parton shower effects via the MC@NLO [59] approach and have obtained a similar value within the theory uncertainty.

Our results and those of ATLAS are shown in Fig. 1 and in Table 3. The NLO corrections in α_s increase the $Z+$ non-prompt J/ψ SPS yield by a factor of 1.46. Overall the SPS yield ends up to be close to the ATLAS measurement and hence leaves a small room for the DPS yield. We also note that the relative scale uncertainty is also reduced from 30% at LO to 13% at NLO.
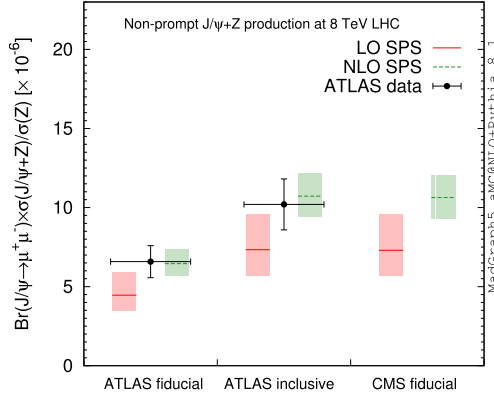
Fig. 1. Total cross section ratio $^{np}R(J/\psi + Z)$ for the non-prompt $J/\psi + Z$ production at 8 TeV LHC.

Table 3
Comparison of the cross section ratio $^{np}R(J/\psi + Z)$ between the theoretical calculations and the experimental data [34] at 8 TeV LHC.

	Experiment $[10^{-7}]$	LO SPS $[10^{-7}]$	NLO SPS $[10^{-7}]$	DPS ($\sigma_{\text{eff}} = 5 \div 15$ mb) $[10^{-7}]$
ATLAS fiducial	$65.8 \pm 9.2 \pm 4.2$	$44.6^{+14.1}_{-10.0}$	$64.6^{+8.8}_{-8.1}$	–
ATLAS inclusive	$102 \pm 15 \pm 5 \pm 3$	$73.3^{+22.7}_{-16.2}$	$107^{+14.4}_{-13.2}$	$8.25 \div 24.75$
CMS fiducial	–	$73.0^{+22.7}_{-16.2}$	$106^{+15.3}_{-12.4}$	–

2.3. Discussion about the DPS contributions

Let us now turn to the discussion of the DPS contributions. ATLAS [34] has made an estimation of the DPS yield using the data for single Z and non-prompt J/ψ production and using the simple "pocket formula".[3]

$$\sigma^{\text{DPS}}(J/\psi + Z) = \frac{\sigma(J/\psi)\sigma(Z)}{\sigma_{\text{eff}}}. \tag{3}$$

By assuming $\sigma_{\text{eff}} = 15$ mb, they quoted $^{np}R(J/\psi + Z) = 8.25 \times 10^{-7}$ from DPS. If one uses a value of 5 mb, more in line with the conclusions of our study of *prompt* $J/\psi + Z$ [46], $^{np}R(J/\psi + Z)$ is thus naturally three times as large. As evident from Table 3, such a value is only marginally compatible with the ATLAS measurements owing to the experimental and (SPS) theoretical uncertainties.

In fact, this also means that we can extract a lower limit on σ_{eff}, corresponding to a maximum allowed DPS yields, now that we have at disposal a SPS computation. Contrary to other cases which we previously analysed [2,46], we cannot extract an upper limit since the SPS yield alone is compatible with the data. We evaluate the {68%; 95%} confidence level upper limit on the SPS yield simply as follows:

$$\sigma^{\text{DPS,max}} = (\sigma^{\text{ATLAS data}} + \{1; 2\} \times \delta\sigma^{\text{ATLAS data}}) - (\sigma^{\text{SPS}} - \{1; 2\} \times \delta\sigma^{\text{SPS}}), \tag{4}$$

---

[3] Let us recall at this stage our caveat mentioned in the introduction that there do not exist proofs of such a formula and that factorisation-breaking effects have been discussed in a number of recent studies (see *e.g.* [6–29]).
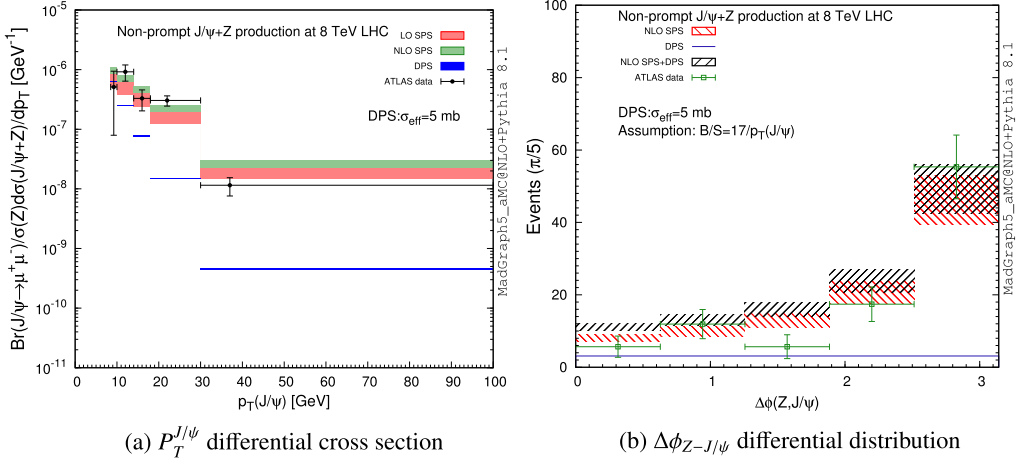
Fig. 2. Differential cross section/distributions for non-prompt $J/\psi + Z$ production: p_T distribution of J/ψ (a) and azimuthal angle distribution (b). (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

where σ generically denotes the central value of the $J/\psi + Z$ cross section and $\delta\sigma$ is the standard deviation of this cross section. The lower value of σ_{eff} at 68% (95%) confidence level is then 5.0 mb (2.3 mb), which is compatible with the σ_{eff} extraction from the other quarkonium-related measurements [1,31,2–4,46] and it is close to the range $\sigma_{\text{eff}} = 4.7^{+2.4}_{-1.5}$ mb we obtained for prompt $J/\psi + Z$ production [46].

2.4. Comparison with differential distributions

Let us now turn to the comparison of the differential distributions between the theoretical results and the ATLAS data, which in fact allows us to draw similar conclusions. Still by lack of SPS predictions, ATLAS could only compare its measurement of the transverse-momentum P_T spectrum of non-prompt J/ψ to their estimation of the DPS yield. As expected from the near dominance of SPS for this process (see above), they found out a very large discrepancy (gap between the data and the blue histogram).

Adding the SPS contribution which we have computed largely fills the gap between theory and experiment as can be noted in Fig. 2a. Only remains a small discrepancy in the last $P_T^{J/\psi}$ bin which should however be confirmed by forthcoming measurements as well as more accurate theoretical calculations, with *e.g.* an improved description of the b quark fragmentation, an account of even higher order QCD corrections, and a matching between different initial-quark flavour number schemes. Similar to the prompt $J/\psi + Z$ production, the DPS contributions exhibit a softer $P_T^{J/\psi}$ spectrum than the SPS ones.

Unlike the $P_T^{J/\psi}$ spectrum, ATLAS did not provide the efficiency-corrected azimuthal angle correlation between J/ψ and Z, $\Delta\phi_{Z-J/\psi}$. Although such a distribution may significantly be smeared by non-perturbative intrinsic initial parton k_T [2,38] in the low P_T region, we do not think that such a smearing effect will be large here because of the ATLAS $P_T^{J/\psi}$ cut which is as large as 8 GeV. Therefore, the investigation of this correlation may indeed reveal the importance of DPS directly. However, in order to make a fair comparison, one has to unfold the efficiency

Table 4

The estimation of the number of the signal events S (before the efficiency corrections) for non-prompt $J/\psi + Z$ in each $P_T^{J/\psi}$ bin with the assumption $B/S = 17/P_T^{J/\psi}$.

$P_T^{J/\psi}$ [GeV]	S
(8.5, 10)	4.2
(10, 14)	32.7
(14, 18)	15.6
(18, 30)	47.1
(30, 100)	12.7
(8.5, 100)	112.3

since it is largely dependent on $P_T^{J/\psi}$ and hence impacts the collected number of events reported in this distribution. Along the same lines as Ref. [46] and thus by assuming the background events, B, and the signal events, S, to scale like $B/S = 17/P_T^{J/\psi}$, we can evaluate the number of non-prompt $J/\psi + Z$ events in each $P_T^{J/\psi}$, see Table 4. Overall, we evaluate the total number of non-prompt signal events to be 112 vs the ATLAS found $95 \pm 12 \pm 8$, which are roughly consistent. Of course, a more precise comparison will be possible if ATLAS releases a cross section differential in $\Delta\phi_{Z-J/\psi}$. Once the number of signal events is known in each bin, one can fill the $\Delta\phi_{Z-J/\psi}$ distribution according to these numbers using the ratio DPS/SPS in each bin as well as the expected azimuthal DPS and SPS distributions. The former is assumed to be flat (uncorrelated production) see the blue line of Fig. 2b. The latter is obtained from our NLO computation just as the SPS $P_T^{J/\psi}$ spectrum was, see the red histogram of Fig. 2b. The resulting comparison ends up to be satisfactory and confirms that the *non-prompt $J/\psi + Z$* yield in the ATLAS acceptance is dominated by SPS contributions contrary to the *prompt $J/\psi + Z$* yield [46].

As aforementioned, the ratio DPS/SPS increases in the ATLAS acceptance for decreasing $P_T^{J/\psi}$. For the lowest $P_T^{J/\psi}$ bin, it even reaches 20% with $\sigma_{\text{eff}} = 15$ mb (thus 3 times larger for 5 mb). With higher statistics, it will be possible to measure the yield differential in the rapidity difference, Δy, between the Z and the J/ψ. For increasing, Δy, the DPS yield, *i.e.* from two independent scatterings, is favoured with respect to the SPS yield and could eventually be dominant like for quarkonium-pair production [38,2].

3. Conclusions

By providing the first phenomenological analysis of (SPS contributions to) $Z + b$ production in the $b \to J/\psi X$ decay channel, we have filled a gap in the literature and could make the first comparison between theory and the corresponding measurement by the ATLAS collaboration [34]. Unlike the case of *prompt $J/\psi + Z$* production [46], we have found out that the SPS contributions to *non-prompt $J/\psi + Z$* production happen to be dominant and very close to experimental data. This therefore sets up an upper (lower) limit of the DPS yield (σ_{eff}).

Our conclusion is based on a computation including NLO QCD corrections and parton-shower effects using MADGRAPH5_AMC@NLO and PYTHIA 8.1. Our comparison between the theory and the experiment also shows the importance of the QCD corrections, which not only results in a
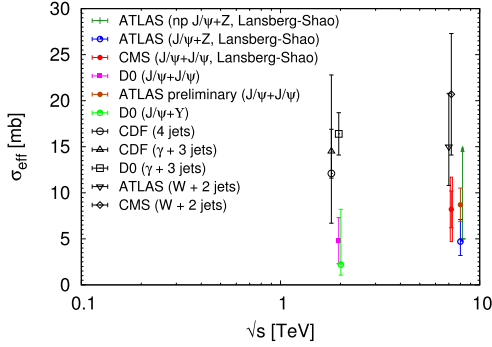
Fig. 3. Extractions of σ_{eff} from quarkonium associated production [46,2,1,32,3] and jet production [67–71] processes at the Tevatron and the LHC. The symbol "np" in the legend refers to non-prompt J/ψ, otherwise it refers to prompt J/ψ. The lower limit (green arrow) $\sigma_{\mathrm{eff}} \geq 5.0$ mb is determined from the present analysis of the ATLAS non-prompt $J/\psi + Z$ sample [34]. The upper limit of $\sigma_{\mathrm{eff}} \leq 8.2$ mb in D0 $J/\psi + \Upsilon$ [3] is refined in Ref. [4]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

smaller scale uncertainty but also improves the agreement with data. An improved determination of σ_{eff} requires a better control on both the theoretical and the experimental uncertainties. This of course holds only if one sticks to the simple "pocket formula" where factorisation between both parton scatterings is implied as done for all the existing σ_{eff} experimental extractions.

Based on the ATLAS measurement [34] at $\sqrt{s} = 8$ TeV, we thus set the lower limit of σ_{eff} to be 5.0 mb at 68% confidence level and 2.3 mb at 95% confidence level. A comparison with other extractions from both quarkonium associated production [46,2,1,32,3] and jet production [67–71] is displayed in Fig. 3. The values of σ_{eff} from quarkonium production are in general lower than those from jet production, although no strong conclusion can be drawn at the moment due to the remaining large uncertainties, some of them inherent to our incomplete knowledge of the quarkonium-production mechanisms [72–74]. If such an observation is confirmed in the future, it may reveal a nontrivial transverse correlations between sets of two partons from a proton or a violation of DPS factorisation, even at high energies. In general, processes as the one discussed here are very important because both scatterings probe different initial states – despite the expected small impact of DPS on the current data set. We emphasise that such a test is very important and, as illustrated here, is feasible at the LHC with higher statistics which would allow one to reach parts of the phase space where DPS contributions are expected to be larger.

Acknowledgements

References

[1] D0 Collaboration, V.M. Abazov, et al., Observation and studies of double J/ψ production at the Tevatron, Phys. Rev. D 90 (11) (2014) 111101, arXiv:1406.2380 [hep-ex].

[2] J.-P. Lansberg, H.-S. Shao, J/ψ-pair production at large momenta: indications for double parton scatterings and large α_s^5 contributions, Phys. Lett. B 751 (2015) 479–486, arXiv:1410.8822 [hep-ph].

[3] D0 Collaboration, V.M. Abazov, et al., Evidence for simultaneous production of J/ψ and Υ mesons, Phys. Rev. Lett. 116 (8) (2016) 082002, arXiv:1511.02428 [hep-ex].

[4] H.-S. Shao, Y.-J. Zhang, Complete study of hadroproduction of a Υ meson associated with a prompt J/ψ, Phys. Rev. Lett. 117 (6) (2016) 062001, arXiv:1605.03061 [hep-ph].

[5] ATLAS Collaboration, M. Aaboud, et al., Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, arXiv:1612.02950 [hep-ex].

[6] V.P. Shelest, A.M. Snigirev, G.M. Zinovev, The multiparton distribution equations in QCD, Phys. Lett. B 113 (1982) 325.

[7] M. Mekhfi, Correlations in color and spin in multiparton processes, Phys. Rev. D 32 (1985) 2380.

[8] A.M. Snigirev, Double parton distributions in the leading logarithm approximation of perturbative QCD, Phys. Rev. D 68 (2003) 114012, arXiv:hep-ph/0304172.

[9] J.R. Gaunt, W.J. Stirling, Double parton distributions incorporating perturbative QCD evolution and momentum and quark number sum rules, J. High Energy Phys. 03 (2010) 005, arXiv:0910.4347 [hep-ph].

[10] B. Blok, Yu. Dokshitzer, L. Frankfurt, M. Strikman, The four jet production at LHC and Tevatron in QCD, Phys. Rev. D 83 (2011) 071501, arXiv:1009.2714 [hep-ph].

[11] F.A. Ceccopieri, An update on the evolution of double parton distributions, Phys. Lett. B 697 (2011) 482–487, arXiv:1011.6586 [hep-ph].

[12] B. Blok, Yu. Dokshitser, L. Frankfurt, M. Strikman, pQCD physics of multiparton interactions, Eur. Phys. J. C 72 (2012) 1963, arXiv:1106.5533 [hep-ph].

[13] A.V. Manohar, W.J. Waalewijn, A QCD analysis of double parton scattering: color correlations, interference effects and evolution, Phys. Rev. D 85 (2012) 114009, arXiv:1202.3794 [hep-ph].

[14] A.V. Manohar, W.J. Waalewijn, What is double parton scattering?, Phys. Lett. B 713 (2012) 196–201, arXiv:1202.5034 [hep-ph].

[15] J.R. Gaunt, Single perturbative splitting diagrams in double parton scattering, J. High Energy Phys. 01 (2013) 042, arXiv:1207.0480 [hep-ph].

[16] T. Kasemets, M. Diehl, Angular correlations in the double Drell–Yan process, J. High Energy Phys. 01 (2013) 121, arXiv:1210.5434 [hep-ph].

[17] H.-M. Chang, A.V. Manohar, W.J. Waalewijn, Double parton correlations in the bag model, Phys. Rev. D 87 (3) (2013) 034009, arXiv:1211.3132 [hep-ph].

[18] M. Rinaldi, S. Scopetta, V. Vento, Double parton correlations in constituent quark models, Phys. Rev. D 87 (2013) 114021, arXiv:1302.6462 [hep-ph].

[19] M. Diehl, T. Kasemets, Positivity bounds on double parton distributions, J. High Energy Phys. 05 (2013) 150, arXiv:1303.0842 [hep-ph].

[20] B. Blok, Yu. Dokshitzer, L. Frankfurt, M. Strikman, Perturbative QCD correlations in multi-parton collisions, Eur. Phys. J. C 74 (2014) 2926, arXiv:1306.3763 [hep-ph].

[21] M. Diehl, T. Kasemets, S. Keane, Correlations in double parton distributions: effects of evolution, J. High Energy Phys. 05 (2014) 118, arXiv:1401.1233 [hep-ph].

[22] K. Golec-Biernat, E. Lewandowska, How to impose initial conditions for QCD evolution of double parton distributions?, Phys. Rev. D 90 (1) (2014) 014032, arXiv:1402.4079 [hep-ph].

[23] F.A. Ceccopieri, A second update on double parton distributions, Phys. Lett. B 734 (2014) 79–85, arXiv:1403.2167 [hep-ph].

[24] J.R. Gaunt, R. Maciula, A. Szczurek, Conventional versus single-ladder-splitting contributions to double parton scattering production of two quarkonia, two Higgs bosons and $c\bar{c}c\bar{c}$, Phys. Rev. D 90 (5) (2014) 054017, arXiv:1407.5821 [hep-ph].

[25] M. Rinaldi, S. Scopetta, M. Traini, V. Vento, Double parton correlations and constituent quark models: a light front approach to the valence sector, J. High Energy Phys. 12 (2014) 028, arXiv:1409.1500 [hep-ph].

[26] T. Kasemets, P.J. Mulders, Constraining double parton correlations and interferences, Phys. Rev. D 91 (2015) 014015, arXiv:1411.0726 [hep-ph].

[27] M.G. Echevarria, T. Kasemets, P.J. Mulders, C. Pisano, Polarization effects in double open-charm production at LHCb, J. High Energy Phys. 04 (2015) 034, arXiv:1501.07291 [hep-ph].

[28] K. Golec-Biernat, E. Lewandowska, M. Serino, Z. Snyder, A.M. Stasto, Constraining the double gluon distribution by the single gluon distribution, Phys. Lett. B 750 (2015) 559–564, arXiv:1507.08583 [hep-ph].

[29] M. Diehl, J.R. Gaunt, D. Ostermeier, P. Plößl, A. Schäfer, Cancellation of Glauber gluon exchange in the double Drell–Yan process, J. High Energy Phys. 01 (2016) 076, arXiv:1510.08696 [hep-ph].

[30] LHCb Collaboration, R. Aaij, et al., Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 707 (2012) 52–59, arXiv:1109.0963 [hep-ex].

[31] CMS Collaboration, V. Khachatryan, et al., Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ Tev, J. High Energy Phys. 09 (2014) 094, arXiv:1406.0484 [hep-ex].

[32] ATLAS Collaboration, T.A. collaboration, Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector.

[33] CMS Collaboration, V. Khachatryan, et al., Observation of $\Upsilon(1S)$ pair production in proton–proton collisions at $\sqrt{s} = 8$ TeV, arXiv:1610.07095 [hep-ex].

[34] ATLAS Collaboration, G. Aad, et al., Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Eur. Phys. J. C 75 (5) (2015) 229, arXiv:1412.6428 [hep-ex].

[35] ATLAS Collaboration, G. Aad, et al., Measurement of the production cross section of prompt J/ψ mesons in association with a $W^\pm$ boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 04 (2014) 172, arXiv:1401.2831 [hep-ex].

[36] LHCb Collaboration, R. Aaij, et al., Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 06 (2012) 141, arXiv:1205.0975 [hep-ex], Addendum: J. High Energy Phys. 03 (2014) 108.

[37] LHCb Collaboration, R. Aaij, et al., Production of associated Y and open charm hadrons in pp collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering, J. High Energy Phys. 07 (2016) 052, arXiv:1510.05949 [hep-ex].

[38] C.H. Kom, A. Kulesza, W.J. Stirling, Pair production of J/ψ as a probe of double parton scattering at LHCb, Phys. Rev. Lett. 107 (2011) 082002, arXiv:1105.4186 [hep-ph].

[39] J.-P. Lansberg, H.-S. Shao, Production of $J/\psi + \eta_c$ versus $J/\psi + J/\psi$ at the LHC: importance of real α_s^5 corrections, Phys. Rev. Lett. 111 (2013) 122001, arXiv:1308.0474 [hep-ph].

[40] L.-P. Sun, H. Han, K.-T. Chao, Impact of J/ψ pair production at the LHC and predictions in nonrelativistic QCD, Phys. Rev. D 94 (7) (2016) 074033, arXiv:1404.4042 [hep-ph].

[41] J.-P. Lansberg, H.-S. Shao, Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC), Nucl. Phys. B 900 (2015) 273–294, arXiv:1504.06531 [hep-ph].

[42] S.P. Baranov, A.H. Rezaeian, Prompt double J/ψ production in proton–proton collisions at the LHC, Phys. Rev. D 93 (11) (2016) 114011, arXiv:1511.04089 [hep-ph].

[43] Z.-G. He, B.A. Kniehl, Complete nonrelativistic-QCD prediction for prompt double J/? hadroproduction, Phys. Rev. Lett. 115 (2) (2015) 022002, arXiv:1609.02786 [hep-ph].

[44] A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky, Production of $J/\psi + \chi_c$ and $J/\psi + J/\psi$ with real gluon emission at LHC, Phys. Rev. D 94 (5) (2016) 054017, arXiv:1606.06767 [hep-ph].

[45] C. Borschensky, A. Kulesza, Double parton scattering in pair-production of J/ψ mesons at the LHC revisited, arXiv:1610.00666 [hep-ph].

[46] J.-P. Lansberg, H.-S. Shao, Associated production of a quarkonium and a Z boson at one loop in a quark-hadron-duality approach, J. High Energy Phys. 10 (2016) 153, arXiv:1608.03198 [hep-ph].

[47] J.M. Campbell, R.K. Ellis, Radiative corrections to Z b anti-b production, Phys. Rev. D 62 (2000) 114012, arXiv:hep-ph/0006304.

[48] F. Febres Cordero, L. Reina, D. Wackeroth, NLO QCD corrections to $Zb\bar{b}$ production with massive bottom quarks at the Fermilab Tevatron, Phys. Rev. D 78 (2008) 074014, arXiv:0806.0808 [hep-ph].

[49] F. Febres Cordero, L. Reina, D. Wackeroth, W- and Z-boson production with a massive bottom-quark pair at the large hadron collider, Phys. Rev. D 80 (2009) 034015, arXiv:0906.1923 [hep-ph].

[50] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau, P. Torrielli, W and $Z/\gamma*$ boson production in association with a bottom–antibottom pair, J. High Energy Phys. 09 (2011) 061, arXiv:1106.6019 [hep-ph].

[51] S. Frixione, V. Hirschi, D. Pagani, H.S. Shao, M. Zaro, Electroweak and QCD corrections to top-pair hadroproduction in association with heavy bosons, J. High Energy Phys. 06 (2015) 184, arXiv:1504.03446 [hep-ph].

[52] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].

[53] T. Sjostrand, S. Mrenna, P.Z. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852–867, arXiv:0710.3820 [hep-ph].

[54] V. Hirschi, R. Frederix, S. Frixione, M.V. Garzelli, F. Maltoni, R. Pittau, Automation of one-loop QCD corrections, J. High Energy Phys. 05 (2011) 044, arXiv:1103.0621 [hep-ph].

[55] R. Frederix, S. Frixione, F. Maltoni, T. Stelzer, Automation of next-to-leading order computations in QCD: the FKS subtraction, J. High Energy Phys. 10 (2009) 003, arXiv:0908.4272 [hep-ph].

[56] G. Ossola, C.G. Papadopoulos, R. Pittau, CutTools: a program implementing the OPP reduction method to compute one-loop amplitudes, J. High Energy Phys. 03 (2008) 042, arXiv:0711.3596 [hep-ph].

[57] G. Ossola, C.G. Papadopoulos, R. Pittau, Reducing full one-loop amplitudes to scalar integrals at the integrand level, Nucl. Phys. B 763 (2007) 147–169, arXiv:hep-ph/0609007.

[58] S. Frixione, Z. Kunszt, A. Signer, Three jet cross-sections to next-to-leading order, Nucl. Phys. B 467 (1996) 399–442, arXiv:hep-ph/9512328.

[59] S. Frixione, B.R. Webber, Matching NLO QCD computations and parton shower simulations, J. High Energy Phys. 06 (2002) 029, arXiv:hep-ph/0204244.

[60] P. Artoisenet, R. Frederix, O. Mattelaer, R. Rietkerk, Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations, J. High Energy Phys. 03 (2013) 015, arXiv:1212.3460 [hep-ph].

[61] Y. Kubota, private communication.

[62] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky, W.K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, J. High Energy Phys. 07 (2002) 012, arXiv:hep-ph/0201195.

[63] M. Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, QCD analysis of first b cross-section data at 1.96-TeV, J. High Energy Phys. 07 (2004) 033, arXiv:hep-ph/0312132.

[64] B.A. Kniehl, G. Kramer, Inclusive J/ψ and ψ_{2S} production from B decay in $p\bar{p}$ collisions, Phys. Rev. D 60 (1999) 014006, arXiv:hep-ph/9901348.

[65] P. Bolzoni, B.A. Kniehl, G. Kramer, Inclusive J/ψ and $\psi(2S)$ production from b-hadron decay in p anti-p and pp collisions, Phys. Rev. D 88 (7) (2013) 074035, arXiv:1309.3389 [hep-ph].

[66] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, FEWZ 2.0: a code for hadronic Z production at next-to-next-to-leading order, Comput. Phys. Commun. 182 (2011) 2388–2403, arXiv:1011.3540 [hep-ph].

[67] ATLAS Collaboration, G. Aad, et al., Measurement of hard double-parton interactions in $W(\to l\nu) + 2$ jet events at $\sqrt{s} = 7$ TeV with the ATLAS detector, New J. Phys. 15 (2013) 033038, arXiv:1301.6872 [hep-ex].

[68] CDF Collaboration, F. Abe, et al., Study of four jet events and evidence for double parton interactions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. D 47 (1993) 4857–4871.

[69] CDF Collaboration, F. Abe, et al., Double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. D 56 (1997) 3811–3832.

[70] D0 Collaboration, V.M. Abazov, et al., Double parton interactions in $\gamma + 3$ jet events in pp^- bar collisions $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 81 (2010) 052012, arXiv:0912.5104 [hep-ex].

[71] CMS Collaboration, S. Chatrchyan, et al., Study of double parton scattering using $W + 2$-jet events in proton–proton collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 03 (2014) 032, arXiv:1312.5729 [hep-ex].

[72] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions, Eur. Phys. J. C 76 (3) (2016) 107, arXiv:1506.03981 [nucl-ex].

[73] N. Brambilla, et al., Heavy quarkonium: progress, puzzles, and opportunities, Eur. Phys. J. C 71 (2011) 1534, arXiv:1010.5827 [hep-ph].

[74] J.P. Lansberg, J/ψ, ψ' and Υ production at hadron colliders: a review, Int. J. Mod. Phys. A 21 (2006) 3857–3916, arXiv:hep-ph/0602091.