Perspectives for inclusive quarkonium production in photon-photon collisions at the LHC

M. Klasen\textsuperscript{a}\textsuperscript{*}, J.P. Lansberg\textsuperscript{b}\textsuperscript{†}

\textsuperscript{a}Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier / CNRS-IN2P3 / INPG, 53 Avenue des Martyrs, F-38026 Grenoble, France

\textsuperscript{b}Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 19, D-69120 Heidelberg, Germany

We report on the current status of knowledge on inclusive quarkonium production in high-energy photon-photon collisions. As a perspective for the LHC, we compute various production cross sections via direct photon-photon fusion in ultra-peripheral pp, pA and AA collisions at the LHC using the tree-level quarkonium amplitude generator \textit{MadOnia}.

1. Introduction

In a few months the LHC will start operating and provide physicists with a tremendous amount of new experimental information on the fundamental particles and their interactions. In this context, much is expected from the LHC to elucidate the still ill-understood quarkonium production mechanism (see \cite{1,2,3} for recent reviews). This is of particular importance in view of the possible suppression of quarkonium production after quark-gluon plasma formation in heavy-ion collisions. One of the questions which remains to be answered is in particular the relevance of color-octet transitions in different production regimes or equivalently of the $O(\nu)$ corrections in Non-Relativistic Quantum Chromodynamics (NRQCD) \cite{15}.

The large amount of quarkonia that will be produced in the pp, pA and AA modes at the LHC will allow for even more precise analyses than those performed recently at Run II of the Tevatron \cite{17}. We expect cross section and polarization measurements of inclusive, prompt and (hopefully) direct yields of the $J/\psi$, $\psi'$, $\Upsilon$, $\Upsilon'$ and $\Upsilon''$ mesons. In addition, analyses of their associated production with a heavy-quark pair \cite{8,9} or of other channels would certainly be as interesting and in some cases better suited to disentangle the color-singlet and color-octet transitions and to assess the importance of $s$-channel cuts \cite{10,11} and of the rescattering with comovers \cite{12,13}. Recently, several quarkonium production cross sections have been evaluated at next-to-leading order (NLO) of perturbative QCD \cite{14,15,16}, complementing the pioneering work for color-singlet production in direct $\gamma p$ collisions \cite{17}. The common feature of these calculations is the significant size of the NLO corrections, in particular for large transverse momenta of the quarkonia. The color-singlet prediction can thus be brought considerably closer to the data. As of today, only the color-octet contributions to direct $\gamma\gamma$ collisions have been evaluated at NLO \cite{14,15,16}.

Very little is known yet about NLO effects on the polarization of the produced quarkonia. However, the leading order (LO) NRQCD prediction including sizable color-octet contributions is known to be in conflict with the measurements e.g. in hadroproduction \cite{19,20}. A recent NLO evaluation for $J/\psi$ mesons produced directly as color-singlet states in gluon-gluon fusion changes the LO prediction from almost purely transverse

\textsuperscript{*}Research supported by the French Ministry for Higher Education and Research, CNRS-IN2P3 and ANR.

\textsuperscript{†}Talk given by J.P. Lansberg at the Workshop on “High-energy photon collisions at the LHC”, April 22-25, 2008, CERN, Switzerland.

\textsuperscript{1}Note, however, the recent preprint \cite{18}.
to rather longitudinal polarization at NLO [21]. However, the corresponding unpolarized differential cross section still falls short of the data, preventing any conclusive interpretation of this result [16]. A forthcoming study of both the differential cross section and the polarization at NLO complemented by dominant NNLO corrections might help to elucidate the situation further, at least for hadroproduction [22].

In the absence of an International Linear Collider (ILC), the LHC will, at least in the short term, present an almost unique environment for high-energy photon-photon collisions [23]. These tend to produce much cleaner events than those produced in inelastic hadron collisions. They may also help to validate the only experimental analysis of quarkonium production in photon-photon collisions to date [24], which clearly required important color-octet contributions [25]. We therefore focus here on quarkonium production in photon-photon collisions at the LHC. First, we recall the theoretical status along with more specific results related to the LEP II analysis. We present original results for ultra-peripheral pp, pA and AA collisions obtained with the tree-level quarkonium amplitude generator MadOnia [27], before we present our conclusions and an outlook.

2. Inclusive quarkonium production in photon-photon collisions

Photons can interact either directly with the quarks participating in the hard-scattering process (direct photoproduction) or via their quark and gluon content (resolved photoproduction). Thus, inclusive quarkonium production in photon-photon collisions receives contributions from the direct, single-resolved, and double-resolved channels. All three contributions are formally of the same order in the perturbative expansion and must be included. The $J/\psi$ mesons can be produced directly, or via radiative or hadronic decays of heavier charmonia, such as $\chi_{cJ}$ and $\psi'$ mesons, or via weak decays of $B$ hadrons, where the latter can often be safely neglected. The cross sections of the four residual indirect production channels may be approximated by multiplying the direct-production cross sections of the respective intermediate charmonia with their decay branching fractions to $J/\psi$ mesons.

Invoking the Equivalent Photon Approximation and the factorization theorems of the QCD parton model and NRQCD, the differential cross section can be written as

$$d\sigma(AB \rightarrow AB + H + X) = \int dx_A f_{g/A}(x_A) \times \int dx_B f_{g/B}(x_B) \sum_{a,b,d} \int dx_a f_{a/\gamma}(x_a, M) \times \int dx_b f_{b/\gamma}(x_b, M) \sum_n \langle O^H [n] \rangle \times d\sigma(ab \rightarrow c\bar{c}[n] + d), \quad (1)$$

where $f_{g/A,B}(x_A,B)$ is the equivalent number of transverse photons radiated by the initial-state particles $A$ and $B$, $f_{a,b/\gamma}(x_a,b, M)$ are the parton densities of the photon, $\langle O^H [n] \rangle$ are the operator matrix elements of the $H$ meson, $d\sigma(ab \rightarrow c\bar{c}[n] + d)$ are the differential partonic cross sections, the integrals are over the longitudinal-momentum fractions of the emitted particles w.r.t. the emitting ones, and it is summed over $a,b = \gamma, g, q, \bar{q}$ and $d = g, q, \bar{q}$, with $q = u, d, s$. To leading order in $\alpha_s$, we need to include the $c\bar{c}$ Fock states $n = 3S_1^{(1)}, 3S_0^{(8)}, 3S_1^{(8)}, 3P_1^{(8)}$ if $H = J/\psi, \psi'$ and $n = 3P_1^{(1)}, 3S_1^{(8)}$ if $H = \chi_{cJ}$, where $J = 0, 1, 2$. With the definition $f_{g/\gamma}(x_g, M) = \delta(1-x_g)$, Eq. (1) accommodates the direct, single-resolved, and double-resolved channels. The presence of parton $d$ is to ensure that $P_T$ can take finite values.

In Fig. 1 the $P_T^2$ distribution of $e^+e^- \rightarrow e^+e^- + J/\psi + X$ measured by DELPHI [24] is compared with LO NRQCD and color-singlet predictions [25]. The solid lines and shaded bands represent the central results with MRST98LO parton densities and their uncertainties, respectively, while the dashed lines represent the results obtained with CTEQ5L parton densities. It is clear that at LO the DELPHI data favor the NRQCD prediction, while they significantly overshoot the CSM one. Note, however, that the associated production of $J/\psi$ mesons with additional $c\bar{c}$ pairs can be numerically important [26].
Perspectives for inclusive quarkonium production in photon-photon collisions at the LHC

$e^+ e^- \rightarrow e^+ e^- J/\psi X$ at LEP2

$\sqrt{s} = 197$ GeV

$-2 < y_{J/\psi} < 2$

3. Inclusive quarkonium production in ultra-peripheral collisions at the LHC

We now turn to the calculation of quarkonium production through photon-photon collisions in ultra-peripheral collisions of protons and heavy ions at the LHC. We focus on the production of quarkonia with direct photons, as only these processes have so far been implemented in the tree-level quarkonium amplitude generator MadOnia [27]. This Monte Carlo generator uses a simple method to automatically evaluate arbitrary tree-level amplitudes involving the production or decay of a heavy quark pair $Q\bar{Q}$ in a generic and collinear singularities from the hard regions, where the phase-space integrations can be carried out numerically. One must, of course, verify that the combined result is, to very good approximation, independent of the choices of the cut-off parameters over an extended range of values. One usually works in dimensional regularization in connection with the $\overline{MS}$ renormalization and factorization schemes, so that the NLO result depends on the QCD and NRQCD renormalization scales $\mu$ and $\lambda$, respectively, and on the factorization scale $M$ connected with the collinear splitting of the incoming photons into massless $q\bar{q}$ pairs. While the $\mu$ and $\lambda$ dependences are formally canceled up to terms beyond NLO within direct photoproduction, the $M$ dependence is only compensated by the LO cross section of single-resolved photoproduction. By the same token, the strong $M$ dependence of the latter is considerably reduced. This is of crucial phenomenological importance, as may be appreciated by observing that, at LO, the overwhelming bulk of the cross section of prompt $J/\psi$ production in two-photon collisions is due to single-resolved photoproduction. The naive $K$ factor of direct photoproduction, defined as the NLO to LO ratio, turns out to be very substantial at large values of $P_T$ because fragmentation-prone channels start to open up at NLO. In fact, at $P_T \gg 2m$, the $P_T$ distribution of direct photoproduction at NLO is rather similar to the LO result of single-resolved photoproduction both in shape and normalization.

At NLO, the inclusive production of $J/\psi$ mesons with finite values of $P_T$ has so far only been studied in the color-singlet channel in direct photon-proton [17] and proton-proton [8,16] collisions and in the color-octet channel only in direct photon-photon collisions [14,15]. The technical difficulties that need to be tackled in these calculations include the treatment of UV, collinear, soft, and Coulomb singularities, the NRQCD operator renormalization, the mass factorization, and the analytic evaluation of five-point one-loop integrals with UV, soft, and Coulomb singularities. As for the real corrections, the phase-space slicing method can be employed to demarcate the regions of phase space containing soft

Figure 1. The cross section $d\sigma/dP^2_T$ of $e^+e^- \rightarrow e^+e^- J/\psi + X$ measured by DELPHI [24] as a function of $P^2_T$ is compared with the theoretical predictions of NRQCD and the CSM. The solid and dashed lines represent the central predictions obtained with the ME sets referring to the MRST98LO (default) and CTEQ5L PDFs, respectively, while the shaded bands indicate the theoretical uncertainties on the default predictions.
$2S^1 L_j^{[1,8]}$ state, i.e. the short distance coefficients appearing in the NRQCD factorization formalism. The approach is based on extracting the relevant contributions from the open heavy quark-antiquark amplitudes through an expansion with respect to the quark-antiquark relative momentum and the application of suitable color and spin projectors. Several checks are performed to validate the calculation, including those of gauge invariance and numerical cancellation of contributions bound to vanish due to symmetry conditions. As a typical set for our numerical input, we use a $J/\psi$-meson mass of $m_{J/\psi} = 2m_e = 3$ GeV, electromagnetic and strong coupling constants of $\alpha = 1/137$ and $\alpha_s(\mu_r)$ with $\mu_r = \sqrt{m^2 + P_T^2}$, and color-singlet and color-octet operator expectation values of $\langle O(3^{s1}) \rangle = 1.16$ GeV$^3$ and $\langle O(3^{s8}) \rangle = 1.06 \cdot 10^{-2}$ GeV$^3$.

### 3.1. Photon flux

A reasonable analytic approximation for the photon flux in ultra-peripheral collisions of protons and/or heavy ions $A$ and $B$ is obtained by integrating the differential flux in impact parameter space over radii larger than $R_A + R_B$, where the proton radius is $R_p = 0.6$ fm and the radii of heavier nuclei are $R_{A,B} = R_0 (A,B)^{1/3}$ with $R_0 = 1.2$ fm and $A, B$ the nucleon numbers. The integrated flux is then given by

$$f_{\gamma/A}(x) = \frac{2Z^2\alpha}{\pi \epsilon x} \left[ \omega K_0(\omega) K_1(\omega) - \frac{\omega^2}{2} \left( K_1^2(\omega) - K_0^2(\omega) \right) \right].$$

Here $Z$ is the proton or nuclear charge, $x = k/E$ is the fraction of the beam energy $E$ of the protons or heavy ions with mass $m$ carried by the almost real photon with energy $k$ and virtuality $-q^2 < 1/R_{A,B}^2$, $K_{0,1}$ are the 0th- and 1st-order modified Bessel functions of the third kind, and $\omega = x m (R_A + R_B)$. The beam energies and corresponding expected luminosities for the LHC can be found in Tab. 1 of [23]. Note, however, that for protons we do not use the spectrum above but rather the one in Eq. (D.7) of [28], both for pp and pPb collisions. In the latter case, this gives us a first reasonable approximation of the photon flux, but the difference in the minimum value of the impact parameter $(2R_p$ vs. $R_p + R_{Pb})$ should be taken into account in the future.

### 3.2. Numerical results

We present here our numerical results for $J/\psi$-production in direct photon-photon collisions for three different hadron-beam combinations: proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 14$ TeV, proton-lead (pPb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s} = 8.8$ TeV, and lead-lead (PbPb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s} = 5.5$ TeV. The expected luminosities listed in Tab. 1 of [23] are $10^7$ mb$^{-1}$ s$^{-1}$, $420$ mb$^{-1}$ s$^{-1}$ and $0.42$ mb$^{-1}$ s$^{-1}$.

In order for the transverse momentum of the produced $J/\psi$ mesons to be balanced, it must be produced in association with at least one other particle. The direct production of a color-singlet with one or two gluons is forbidden by color conservation and charge conjugation. The same holds for light $q\bar{q}$ pairs, which originate from gluon splitting. The dominant channels are thus the associated production of a color singlet with a photon or an additional $c\bar{c}$ pair or the associated production of a color octet with a gluon. Note that in principle these final states are experimentally distinguishable.

The transverse-momentum spectra for $J/\psi$ mesons produced in pp, pPb, and PbPb collisions are shown in Fig. 2 (top, center, and bottom) for central rapidity $y = 0$. All cross sections have been multiplied by the branching ratio of 5.88 % for $J/\psi \rightarrow \mu^+\mu^-$. As one can see, the cross sections for PbPb collisions are more than three orders of magnitude larger than the ones for pPb, and six orders of magnitude larger than those for pp. Indeed, the two-photon spectra for heavy ions are enhanced by factors of $Z^2$ for pPb and $Z^4$ for PbPb up to corrections due to different minimum impact parameters for an ultra-peripheral collisions. Note also that for instance the cross section for $J/\psi c\bar{c}$ decreases faster as a function of $P_T$ for PbPb than for pp. This can be traced back to the harder spectrum of $\gamma$ from p than for Pb.

As we have seen above, the expected luminosi-
Perspectives for inclusive quarkonium production in photon-photon collisions at the LHC

Figure 2. Transverse-momentum spectra of \( J/\psi \)-mesons produced in association with photons (dotted), \( \bar{c}c \) pairs (full) and gluons (dashed) in pp (top), pPb (center) and PbPb (bottom) collisions. While the first two processes produce directly a color-singlet, the latter produces necessarily an intermediate color-octet state due to color conservation.

ties for heavy-ion runs are also much smaller and scale, in fact, like \( Z^2 \). Taking into account the run duration (10⁷ sec for pp and 10⁶ sec for pPb and PbPb), the number of events will be comparable to, if not a bit larger than in the pp runs. Note that ultraperipheral collisions of lead ions can be triggered on by requiring the detection of a forward neutron emitted by a lead ion, that was excited during the collision [23].

In each plot, we show three curves corresponding to the associated production of \( J/\psi \) mesons with photons (dotted) and \( \bar{c}c \) pairs (full) directly through an \( S \)-wave color-singlet state and with gluons (dashed) through an intermediate color-octet \( S \)-wave state. The associated production with photons and gluons receives contributions from exactly the same Feynman diagrams, so that the two curves show nearly the same shape. They differ only in normalization due to different couplings (electromagnetic vs. strong) and operator matrix elements (singlet vs. octet), the former difference being slightly \( P_T \)-dependent due to the running of \( \alpha_s \) that we took into account. The associated production of \( J/\psi \) mesons with an additional \( \bar{c}c \) pair allows, however, for different recombinations of the intermediate charm quarks, leading to a very different and visibly much flatter \( P_T \)-distribution than in the other two cases. In particular, this channel becomes dominant already for \( P_T > 2 \) GeV.

4. Conclusion

As we have seen, the mechanism of inclusive production of heavy quark-antiquark bound states (quarkonia) is still far from being understood. Leading-order calculations seem to indicate a large contribution from intermediate color-octet states in agreement with the effective field theory of NRQCD, but this leads to contradictions with the observed quarkonium polarization. Next-to-leading order corrections are known to be very important, but are so far only available for a restricted number of partonic processes.

Proton-proton and heavy-ion collisions at the LHC will soon allow for studies of very high-energy photon collisions. We have demonstrated that the production of quarkonia in these colli-
sions will have observable rates at least in pp, but possibly also in pPb and PbPb scattering. The associated production of $J/\psi$ mesons with photons, gluons and $c\bar{c}$ pairs will lead to experimentally distinguishable final states, which are sensitive to different intermediate color states. Together with their discriminating transverse-momentum spectra, this will hopefully provide crucial new experimental information on this longstanding issue.

Acknowledgments

We thank P. Artoisenet and F. Maltoni for sharing their results for pp-collisions at 14 TeV with us and D. d’Enterria and T. Pierzchala for useful discussions.

REFERENCES

1. J. P. Lansberg, Int. J. Mod. Phys. A 21 (2006) 3857.
2. N. Brambilla et al. [Quarkonium Working Group], CERN Report No. 2005-005, arXiv:hep-ph/0412158.
3. M. Krämer, Prog. Part. Nucl. Phys. 47 (2001) 141.
4. G. T. Bodwin, E. Braaten and G. P. Lepage, Phys. Rev. D 51 (1995) 1125 [Erratum-ibid. D 55 (1997) 5853].
5. G. C. Nayak, J. W. Qiu and G. Sterman, Phys. Rev. D 74 (2006) 074007; ibid. 72 (2005) 114012; Phys. Lett. B 613 (2005) 45.
6. D. E. Acosta et al. [CDF Collaboration], Phys. Rev. D 71 (2005) 032001.
7. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 94 (2005) 232001.
8. P. Artoisenet, J. P. Lansberg and F. Maltoni, Phys. Lett. B 653 (2007) 60.
9. P. Artoisenet, arXiv:0804.2975 [hep-ph].
10. H. Haberzettl and J. P. Lansberg, Phys. Rev. Lett. 100 (2008) 032006.
11. J. P. Lansberg, J. R. Cudell and Yu. L. Kalinovsk, Phys. Lett. B 633 (2006) 301.
12. P. Hoyer and S. Peigne, Phys. Rev. D 59 (1999) 034011.
13. N. Marchal, S. Peigne and P. Hoyer, Phys. Rev. D 62 (2000) 114001.
14. M. Klasen, B. A. Kniehl, L. N. Mihaila and M. Steinhauser, Phys. Rev. D 71 (2005) 014016.
15. M. Klasen, B. A. Kniehl, L. N. Mihaila and M. Steinhauser, Nucl. Phys. B 713 (2005) 487.
16. J. Campbell, F. Maltoni and F. Tramontano, Phys. Rev. Lett. 98 (2007) 252002.
17. M. Krämer, Nucl. Phys. B 459 (1996) 3.
18. B. Gong, X. Q. Li and J. X. Wang, arXiv:0805.4751 [hep-ph].
19. A. Abulencia et al. [CDF Collaboration], Phys. Rev. Lett. 99 (2007) 132001.
20. D. E. Acosta et al. [CDF Collaboration], Phys. Rev. Lett. 88 (2002) 161802.
21. B. Gong and J. X. Wang, arXiv:0802.3727 [hep-ph].
22. P. Artoisenet, J. Campbell, J. P. Lansberg, F. Maltoni and F. Tramontano, arXiv:0806.3282 [hep-ph].
23. K. Hencken et al., Phys. Rept. 458 (2008) 1.
24. J. Abdallah et al. [DELPHI Collaboration], Phys. Lett. B 565 (2003) 76.
25. M. Klasen, B. A. Kniehl, L. N. Mihaila and M. Steinhauser, Phys. Rev. Lett. 89 (2002) 032001.
26. C. F. Qiao and J. X. Wang, Phys. Rev. D 69 (2004) 014015.
27. P. Artoisenet, F. Maltoni and T. Stelzer, JHEP 0802 (2008) 102 arXiv:0712.2770 [hep-ph].
28. V. M. Budnev, I. F. Ginzburg, G. V. Meledin and V. G. Serbo, Phys. Rept. 15 (1974) 181.