Evidence for Colour-Octet Mechanism from CERN LEP2 $\gamma\gamma \rightarrow J/\psi + X$ Data

M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser
II. Institut für Theoretische Physik, Universität Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany

Abstract

We present theoretical predictions for the transverse-momentum distribution of $J/\psi$ mesons promptly produced in $\gamma\gamma$ collisions within the factorization formalism of nonrelativistic quantum chromodynamics, including the contributions from both direct and resolved photons, and we perform a conservative error analysis. The fraction of $J/\psi$ mesons from decays of bottom-flavoured hadrons is estimated to be negligibly small. New data taken by the DELPHI Collaboration at LEP2 nicely confirm these predictions, while they disfavour those obtained within the traditional colour-singlet model.

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Since its discovery in 1974, the $J/\psi$ meson has provided a useful laboratory for quantitative tests of quantum chromodynamics (QCD) and, in particular, of the interplay of perturbative and nonperturbative phenomena. The factorization formalism of nonrelativistic QCD (NRQCD) [1] provides a rigorous theoretical framework for the description of heavy-quarkonium production and decay. This formalism implies a separation of short-distance coefficients, which can be calculated perturbatively as expansions in the strong-coupling constant $\alpha_s$, from long-distance matrix elements (MEs), which must be extracted from experiment. The relative importance of the latter can be estimated by means of velocity scaling rules, i.e., the MEs are predicted to scale with a definite power of the heavy-quark $(Q)$ velocity $v$ in the limit $v \ll 1$. In this way, the theoretical predictions are organized as double expansions in $\alpha_s$ and $v$. A crucial feature of this formalism is that it takes into account the complete structure of the $Q\overline{Q}$ Fock space, which is spanned by the states $n = 2S+1L^{(c)}_f$ with definite spin $S$, orbital angular momentum $L$, total angular momentum $J$, and color multiplicity $c = 1, 8$. In particular, this formalism predicts the existence of color-octet (CO) processes in nature. This means that $Q\overline{Q}$ pairs are produced at short distances in CO states and subsequently evolve into physical, color-singlet (CS) quarkonia by the nonperturbative emission of soft gluons. In the limit $v \to 0$, the traditional CS model (CSM) [2,3,4] is recovered. The greatest triumph of this formalism was that it was able to correctly describe [5,6] the cross section of inclusive charmonium hadroproduction measured in $p\bar{p}$ collisions at the Fermilab Tevatron [7], which had turned out to be more than one order of magnitude in excess of the theoretical prediction based on the CSM.

In order to convincingly establish the phenomenological significance of the CO processes, it is indispensable to identify them in other kinds of high-energy experiments as well. Studies of charmonium production in $ep$ photoproduction, $ep$ and $\nu N$ deep-inelastic scattering, $e^+e^-$ annihilation, $\gamma\gamma$ collisions, and $b$-hadron decays may be found in the literature; see Ref. [8] and references cited therein. Furthermore, the polarization of charmonium, which also provides a sensitive probe of CO processes, was carefully investigated [9,10,11]. None of these studies was able to prove or disprove the NRQCD factorization hypothesis.

Very recently, the DELPHI Collaboration has presented preliminary data on the inclusive cross section of $J/\psi$ photoproduction in $\gamma\gamma$ collisions ($e^+e^- \to e^+e^- J/\psi + X$) at CERN LEP2, taken as a function of the $J/\psi$ transverse momentum ($p_T$) [12]. The $J/\psi$ mesons were identified through their decays to $\mu^+\mu^-$ pairs, and events where the system $X$ contains a prompt photon were suppressed by requiring that at least four charged tracks were reconstructed. The luminosity-weighted average $e^+e^-$ center-of-mass (c.m.) energy was $\sqrt{s} = 197$ GeV, the scattered positrons and electrons were antitagged, with maximum angle $\theta_{\text{max}} = 32$ mrad, and the $\gamma\gamma$ c.m. energy was constrained to be $W \leq 35$ GeV in order to reject the major part of the non-two-photon events. The total cross section was found to be $\sigma(e^+e^- \to e^+e^- J/\psi + X) = (45.3 \pm 18.8)$ pb.

In this Letter, we seize the opportunity to confront this data with up-to-date theoretical predictions based on NRQCD and the CSM, in order to find out if it is able to discriminate between the two. In want of the full next-to-leading-order (NLO) corrections, it is indispensable to perform a comprehensive and conservative analysis of the theor-
ical uncertainties. Doing this, we shall find that this data clearly favors the NRQCD prediction, while the CSM one significantly falls short of it.

The 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, the process $e^+e^- \rightarrow e^+e^- J/\psi + X$ 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. This may be understood by observing that the parton density functions (PDFs) of the photon have a leading behavior proportional to $\alpha \ln(M^2/\Lambda^2_{QCD}) \propto \alpha/\alpha_s$, where $\alpha$ is the QED fine-structure constant, $M$ is the factorization scale, and $\Lambda_{QCD}$ is the asymptotic scale parameter of QCD.

In $\gamma\gamma$ collisions, $J/\psi$ 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. The respective decay branching fractions are $B(\chi_{c0} \rightarrow J/\psi + \gamma) = (0.66\pm0.18)\%$, $B(\chi_{c1} \rightarrow J/\psi + \gamma) = (27.3\pm1.6)\%$, $B(\chi_{c2} \rightarrow J/\psi + \gamma) = (13.5\pm1.1)\%$, $B(\psi' \rightarrow J/\psi + X) = (55\pm5)\%$, and $B(B \rightarrow J/\psi + X) = (1.16\pm0.10)\%$ [13]. The OPAL Collaboration has recently measured the total cross section of open-bottom production in $\gamma\gamma$ collisions at LEP2, under similar kinematic conditions as DELPHI [12] ($\sqrt{s} = 194$ GeV, $\theta_{\text{max}} = 33$ mrad, and $10 \leq W \leq 60$ GeV), to be $\sigma(e^+e^- \rightarrow e^+e^- b\bar{b} + X) = (14.2\pm5.9)$ pb [12]. The cross section for $J/\psi$ mesons from $b$-hadron decays may thus be estimated to be $(0.33\pm0.14)$ pb, which is less than 1% of the total $J/\psi$ cross section measured by DELPHI and can 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 Weizs"acker-Williams approximation [15] and the factorization theorems of the QCD parton model [16] and NRQCD [1], the differential cross section of $e^+e^- \rightarrow e^+e^- H + X$, where $H$ denotes a generic charmonium state, can be written as

$$d\sigma(e^+e^- \rightarrow e^+e^- H + X) = \int dx_+ f_{\gamma/e}(x_+) \int dx_-$$

$$\times f_{\gamma/e}(x_-) \sum_{a,b,d} \int dx_+ f_{a/\gamma}(x_a, M) \int dx_+ f_{b/\gamma}(x_b, M)$$

$$\times \sum_n \langle O^H[n] \rangle d\sigma(ab \rightarrow c\bar{c}[n] + d),$$

where $f_{\gamma/e}(x_\pm)$ is the equivalent number of transverse photons radiated by the initial-state positrons and electrons [17], $f_{a/\gamma}(x_a, M)$ are the PDFs of the photon, $\langle O^H[n] \rangle$ are the MEs 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 $a, b = \gamma, g, q, \overline{q}$ and $d = g, q, \overline{q}$, with $q = u, d, s$. To leading order in $v$, we need to include the $c\bar{c}$ Fock states $n = ^3S_1^{(1)}, ^1S_0^{(8)}, ^3S_1^{(8)}, ^3P_J^{(8)}$ if $H = J/\psi, \psi'$ and $n = ^3P_J^{(1)}, ^3S_1^{(8)}$ if $H = \chi_{cJ}$, where $J = 0, 1, 2$. With the definition $f_{\gamma/\gamma}(x_\gamma, M) = \delta(1 - x_\gamma)$, 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;
if it were absent, then $p_T$ would essentially be zero, so that only the lowest bin of the DELPHI data could be described.

We analytically calculated the cross sections of all contributing partonic subprocesses and compared our results with the literature. Specifically, these include $\gamma\gamma \rightarrow c\bar{c}[3S_1^{(8)}]g$ \cite{18,19,20}; $\gamma g \rightarrow c\bar{c}[3S_1^{(1)}]g$ \cite{3}, $c\bar{c}[8]g$ \cite{10,21,22}; $\gamma q \rightarrow c\bar{c}[8]q$ \cite{10,21,22}; $gg \rightarrow c\bar{c}[3S_1^{(1)}]g$ \cite{3}, $c\bar{c}[3P_J^{(1)}]g$ \cite{3}, $c\bar{c}[8]g$ \cite{3}; $gg \rightarrow c\bar{c}[3P_J^{(1)}]q$ \cite{4}, $c\bar{c}[8]q$ \cite{3,11}; and $q\bar{q} \rightarrow [3P_J^{(1)}]g$ $\gamma \bar{c}$, $c\bar{c}[8]g$ \cite{3}, where $n = 8$ collectively denotes $n = 1S_0^{(8)}, 3S_1^{(8)}, 3P_0^{(8)}$. In the limit $p_T \rightarrow 0$, some of these cross sections are plagued by collinear and infrared singularities. This happens whenever the respective 2 → 1 partonic subprocess, $ab \rightarrow c\bar{c}[n]$, exists, namely, for $\gamma\gamma \rightarrow c\bar{c}[3P_{0,2}^{(1)}]$, $\gamma g \rightarrow c\bar{c}[8] [21,22,23]$, $gg \rightarrow c\bar{c}[8] [24]$, and $q\bar{q} \rightarrow c\bar{c}[3S_1^{(8)}] [24]$, where $n = 8'$ stands for $n = 1S_0^{(8)}, 3P_0^{(8)}$. In a full NLO analysis, these singularities would be factorized at scale $M$ and absorbed into the bare PDFs and MEs so as to renormalize the latter. In our LO analysis, we refrain from presenting predictions for the $p_T$ distribution in the lowest $p_T$ bin. Instead, we consider the cross section arising from the 2 → 1 partonic subprocesses.

In our numerical analysis, we use $m_c = (1.5 \pm 0.1)$ GeV, $\alpha = 1/137.036$, and the lowest-order (LO) formula for $\alpha_s^{(n_f)}(\mu)$ with $n_f = 3$ active quark flavors. As for the photon PDFs, we use the LO set from Glück, Reya, and Schienbein (GRS) \cite{25}, which is the only available one that is implemented in the fixed-flavor-number scheme, with $n_f = 3$. We choose the renormalization and factorization scales to be $\mu = \xi_M m_T$ and $M = \xi_M m_T$, respectively, where $m_T = \sqrt{2m_c^2 + p_T^2}$ is the transverse mass of the $H$ meson, and independently vary the scale parameters $\xi_M$ and $\xi_M$ between 1/2 and 2 about the default value 1. As for the $J/\psi$, $\chi_c J$, and $\psi'$ ME’s, we adopt the set determined in Ref. \cite{11} by fitting the Tevatron data \cite{7} using the LO proton PDFs from Martin, Roberts, Stirling, and Thorne (MRST98LO) \cite{26} as our default and the one referring to the LO proton PDFs from the CTEQ Collaboration (CTEQ5L) \cite{27} for comparison (see Table I in Ref. \cite{11}). In the first (second) case, we employ $\Lambda_{QCD}^{(3)} = 204$ MeV (224 MeV), which corresponds to $\Lambda_{QCD}^{(4)} = 174$ MeV \cite{24} (192 MeV \cite{27}), so as to conform with the fit \cite{11}. Incidentally, the GRS photon PDFs are also implemented with $\Lambda_{QCD}^{(3)} = 204$ MeV \cite{25}. In the cases $\psi = J/\psi, \psi'$, the fit results for $\langle O_3^{[1S_0^{(8)}]} \rangle$ and $\langle O_3^{[3P_0^{(8)}]} \rangle$ are strongly correlated, and one is only sensitive to the linear combination

$$M_\psi^r = \langle O_3^{[1S_0^{(8)}]} \rangle + \frac{r}{m_c^2} \langle O_3^{[3P_0^{(8)}]} \rangle,$$  \hspace{1cm} (2)

with an appropriate value of $r$ \cite{3,11}. Since Eq. (1) is sensitive to a different linear combination of $\langle O_3^{[1S_0^{(8)}]} \rangle$ and $\langle O_3^{[3P_0^{(8)}]} \rangle$ than appears in Eq. (2), we write $\langle O_3^{[1S_0^{(8)}]} \rangle = \kappa M_\psi^r$ and $\langle O_3^{[3P_0^{(8)}]} \rangle = (1 - \kappa)(m_c^2/r) M_\psi^r$ and vary $\kappa$ between 0 and 1 about the default value 1/2. The $J$-dependent MEs $\langle O_3^{[3P_J^{(1)}]} \rangle$, $\langle O_{\chi J}^{[3P_J^{(1)}]} \rangle$, and $\langle O_{\chi J}^{[3S_1^{(8)}]} \rangle$ satisfy the multiplicity relations collected in Eq. (4) of Ref. \cite{28}, which follow to leading order in $v$

\footnote{Leaving aside obvious typographical errors, we disagree with Eq. (7) and the subsequent equation in Ref. \cite{13} and with Eq. (4) in Ref. [21].}
from heavy-quark spin symmetry. In order to estimate the theoretical uncertainties in our predictions, we vary the unphysical parameters $\xi_\mu$, $\xi_M$, and $\kappa$ as indicated above, take into account the experimental errors on $m_c$, the decay branching fractions, and the default MEs, and switch from our default ME set to the CTEQ5L one, properly adjusting $\Lambda_{QCD}^{(3)}$. We then combine the individual shifts in quadrature, allowing for the upper and lower half-errors to be different.

In Fig. 1, we confront the $p_T^2$ distribution of $e^+e^- \to e^+e^-J/\psi + X$ measured by DELPHI [12] with our NRQCD and CSM predictions. The solid lines and shaded bands represent the central results, evaluated with our default settings, and their uncertainties, respectively. We observe that the DELPHI data clearly favors the NRQCD prediction, while it significantly overshoots the CSM one. This is even more apparent from the data-over-theory representations shown in Fig. 2. This qualitative observation can be substantiated by considering the $\chi^2$ values for the $N = 9$ data points with $p_T^2 \geq 0.25 \text{GeV}^2$. In fact, the NRQCD central prediction yields $\chi^2/N = 0.49$, which is to be compared with 1.79 for the CSM one. The situation is very similar for the MEs pertinent to the CTEQ5L PDFs (dashed lines), the corresponding results being 0.62 and 1.76, respectively. As for the integral over the range $1 \leq p_T^2 \leq 10 \text{GeV}^2$, the DELPHI, NRQCD, and CSM results read $(6.4 \pm 2.0) \text{ pb}$, $4.7^{+1.9}_{-1.2} \text{ pb}$, and $0.39^{+0.16}_{-0.09} \text{ pb}$, respectively, i.e., the DELPHI measurement and the NRQCD prediction mutually agree within errors, while the CSM prediction significantly falls short of the DELPHI result, by a factor of 16 as far as the central values are concerned. In Fig. 3 we study the normalized cross section $(1/\sigma)d\sigma/dp_T^2$, which is particularly sensitive to the shape of the $p_T^2$ distribution and offers the advantage that the theoretical uncertainty is greatly reduced. We observe that both NRQCD and the CSM describe the shape of the measured $p_T^2$ distribution well within its errors, the respective $\chi^2/N$ values being 0.35 and 0.68, respectively.

Taking as the reference quantity the $p_T^2$ distribution integrated from 0.25 to 10 GeV$^2$, the direct, single-resolved, and double-resolved channels account for 1%, 98%, and 1% of the NRQCD prediction, respectively. The situation is very similar for the CSM, except that direct photoproduction is forbidden at LO. In NRQCD, 91% of the $J/\psi$ mesons are directly produced, while 9% stem from the decays of $\chi_{cJ}$ and $\psi'$ mesons. In the CSM, direct production happens less frequently, in 77% of the cases. As explained above, the contribution from $b$-hadron decays is negligible. Consequently, the ratio of the direct and indirect yields lends itself as a useful discriminator between NRQCD and the CSM, and it would be desirable to measure it in $\gamma\gamma$ collisions. In NRQCD, the most important error sources include the variations of $\xi_\mu$, $m_c$, and $\kappa$, which, in average, make up 55%, 24%, and 11% of the total error square $(\delta_1 \sigma)^2 + (\delta_2 \sigma)^2$, respectively. In the CSM, the largest errors are related to $\xi_\mu$ (59%), $m_c$ (30%), and $\xi_M$ (7%). It is generally believed that the magnitude of unknown higher-order corrections may be estimated by scale variations of the known results. For the single-resolved channel, which greatly dominates our results, the NLO corrections in the CSM are known to be moderate at small values of $p_T$ [29]. A similar observation was made in Ref. [20] for the direct channel, by studying the real radiative corrections in full NRQCD. This indicates that the $\xi_\mu$ and $\xi_M$ variations of the LO result may indeed provide a realistic estimate of the size of unknown higher-order
corrections.

Recent analyses [30] indicate that the overall description of the Tevatron [4] and HERA data on inclusive charmonium production can be improved by adopting the $k_T$ factorization approach. It would be interesting to find out if this is also true for the DELPHI data [12].

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Figure 1: The cross section \( \frac{d\sigma}{dp_T^2} \) of \( e^+e^- \rightarrow e^+e^-J/\psi + X \) measured by DELPHI [12] as a function of \( p_T^2 \) 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 [26] (default) and CTEQ5L [27] PDFs, respectively, while the shaded bands indicate the theoretical uncertainties on the default predictions. The arrows indicate the NRQCD prediction for \( p_T = 0 \) and its \( 3P_J^{(1)}, 1S_0^{(8)}, 3S_1^{(8)}, \) and \( 3P_J^{(8)} \) components.
Figure 2: Data-over-theory representation of Fig. [1]
Figure 3: The normalized cross section $(1/\sigma)d\sigma/dp_T^2$ of $e^+e^-\rightarrow e^+e^-J/\psi + X$ measured by DELPHI [12] as a function of $p_T^2$ is compared with the default theoretical predictions of NRQCD and the CSM. The shaded bands indicate the theoretical uncertainties.