PHYSICAL REVIEW D VOLUME 55, NUMBER 11 1 JUNE 1997

Associated $J/\psi+\gamma$ photoproduction as a probe of the color-octet mechanism

Matteo Cacciari*
Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

Mario Greco†
INFN, Laboratori Nazionali di Frascati and Dipartimento di Fisica, Università di Roma III, Italy

Michael Krämer‡
Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, England

(Received 15 November 1996)

The associated production of a J/ψ and a photon in photon-hadron collisions is considered and shown to be a good probe of the presence of color-octet-mediated channels in quarkonia production, as predicted by the factorization approach within NRQCD. Total and differential cross sections for photoproduction at fixed target experiments and at DESY HERA are presented. Associated $J/\psi+\gamma$ production at hadron colliders is briefly discussed. [S0556-2821(97)02111-5]

PACS number(s): 13.60.Le, 12.38.Bx, 13.85.Qk

I. INTRODUCTION

The study of heavy quarkonia production is a good testing ground for our understanding of the transition region between the realms of perturbative and nonperturbative quantum chromodynamics (QCD). While the creation of heavy quarks in a hard-scattering process can be calculated in perturbative QCD [1], the subsequent transition from the heavy-quark pair to a physical bound state introduces nonperturbative aspects. Different production models have been devised, and all of them have to deal with the problem of properly describing and matching these two phases of QCD.

The color evaporation model (CEM) [2] rests on duality arguments [3] in assuming that $c\bar{c}$ pairs produced with an invariant mass below that of a $D\bar{D}$ meson threshold (taking charm as an example of heavy quark) will eventually hadronize into a charmonium state. Since this assumption is only qualitative, this model of course is unable to predict the production rate of a particular quarkonium state. It is therefore not very suitable for the study of exclusive final states.

The color singlet model (CSM) [4] tries to overcome this difficulty of the CEM by making a very precise request: the $Q\bar{Q}$ pair must be produced in the short-distance interaction with the same spin, angular momentum, and colour quantum numbers of the quarkonium state. The hadronization into the observable particle is described by a single nonperturbative parameter that can be measured, for instance, in electromagnetic decays and used to make absolute predictions for production rates. Despite its physical transparency and predictive power, the CSM is clearly not a complete theory: There are no theorems that guarantee that the simple factorization of the quarkonium production cross section into a short-distance part and a single nonperturbative parameter is valid in higher orders of perturbation theory. In fact, in the case of hadronic production or decay of P-wave quarkonia, the radiative corrections to the short-distance cross section contain infrared divergences that cannot be factored into a single nonperturbative quantity. This failure is to be attributed to an incomplete description of the quarkonium wave function, in that the color singlet model ignores the contributions from higher Fock state components.

A rigorous framework for treating quarkonium production and decays which resolves these problems has recently been developed by Bodwin, Braaten, and Lepage (BBL) [5]. The so-called nonrelativistic QCD (NRQCD) factorization approach (FA) uses an effective-field-theory framework in NRQCD to separate the short-distance scale of annihilation and production of heavy quarkonium from the long-distance scales associated to the quarkonium structure. It extends the CSM by allowing $Q\bar{Q}$ pairs with spin, angular momentum, and color quantum numbers different from those of the observed quarkonium to hadronize into the latter. In this respect, the factorization formalism recovers some of the qualitative features of the CEM. The general expression for the production cross section within the NRQCD factorization approach reads

$$d\sigma(H+X)=\sum_n d\hat{\sigma}(Q\bar{Q}[n]+X)\langle\mathcal{O}^H[n]\rangle. \qquad (1)$$

Here $d\hat{\sigma}(Q\bar{Q}[n]+X)$ describes the short-distance production of a $Q\bar{Q}$ pair in the color-spin-angular-momentum state n, and $\langle\mathcal{O}^H[n]\rangle$, formally a vacuum expectation value of a NRQCD operator (see [5] for details), describes the hadronization of the $Q\bar{Q}$ pair into the observable quarkonium state H. One must note that the cross section is no longer given by a single product of a short-distance and a long-distance term as in the CSM, but rather by a sum of such terms. Infrared singularities which eventually show up in some of the short-distance coefficients would be absorbed into the long-distance part of other terms, thereby ensuring a well-defined

*Electronic address: cacciari@desy.de
†Electronic address: greco@lnf.infn.it
‡Electronic address: Michael.Kraemer@rl.ac.uk

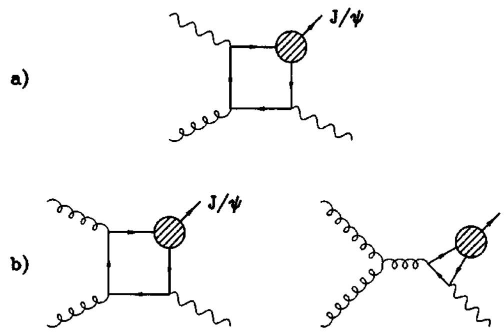

FIG. 1. Diagrams contributing within the factorization approach to $J/\psi+$photon associated production in direct (a) and resolved (b) photon collisions.

overall result. The relative importance of the various contributions in Eq. (1) can be estimated by using NRQCD velocity scaling rules [6].

In particular the BBL approach (also referred to as FA) has been applied to describe quarkonia production at the Tevatron [7] providing a successful picture [8] of the production rates of J/ψ and ψ'—much larger than earlier predictions—which is related to the relevance of color-octet contributions in the production mechanism (see also [9,10] and references therein). It is to be noted that this successful description relies on a certain number of nonperturbative parameters having to be fitted to the data. Therefore additional and more extensive comparisons with experimental data coming also from other kinds of reactions are necessary to finally assess the validity of this approach. To this aim, calculations of inclusive quarkonia production in e^+e^- annihi-

TABLE I. Values of the NRQCD matrix elements used in the numerical analysis, with the velocity and mass scaling. v is the velocity of the heavy quark in the quarkonium rest frame. For charmonium it holds $v^2 \simeq 0.23$. It also holds $\langle \mathcal{O}^{J/\psi}[^3P_J,\underline{8}]\rangle \simeq (2J+1)\langle \mathcal{O}^{J/\psi}[^3P_0,\underline{8}]\rangle$.

$\langle \mathcal{O}^{J/\psi}[^3S_1,\underline{1}]\rangle$	1.16 GeV^3	$m_c^3 v^3$
$\langle \mathcal{O}^{J/\psi}[^1S_0,\underline{8}]\rangle$	10^{-2} GeV^3	$m_c^3 v^7$
$\langle \mathcal{O}^{J/\psi}[^3S_1,\underline{8}]\rangle$	10^{-2} GeV^3	$m_c^3 v^7$
$\langle \mathcal{O}^{J/\psi}[^3P_0,\underline{8}]\rangle/m_c^2$	10^{-2} GeV^3	$m_c^3 v^7$

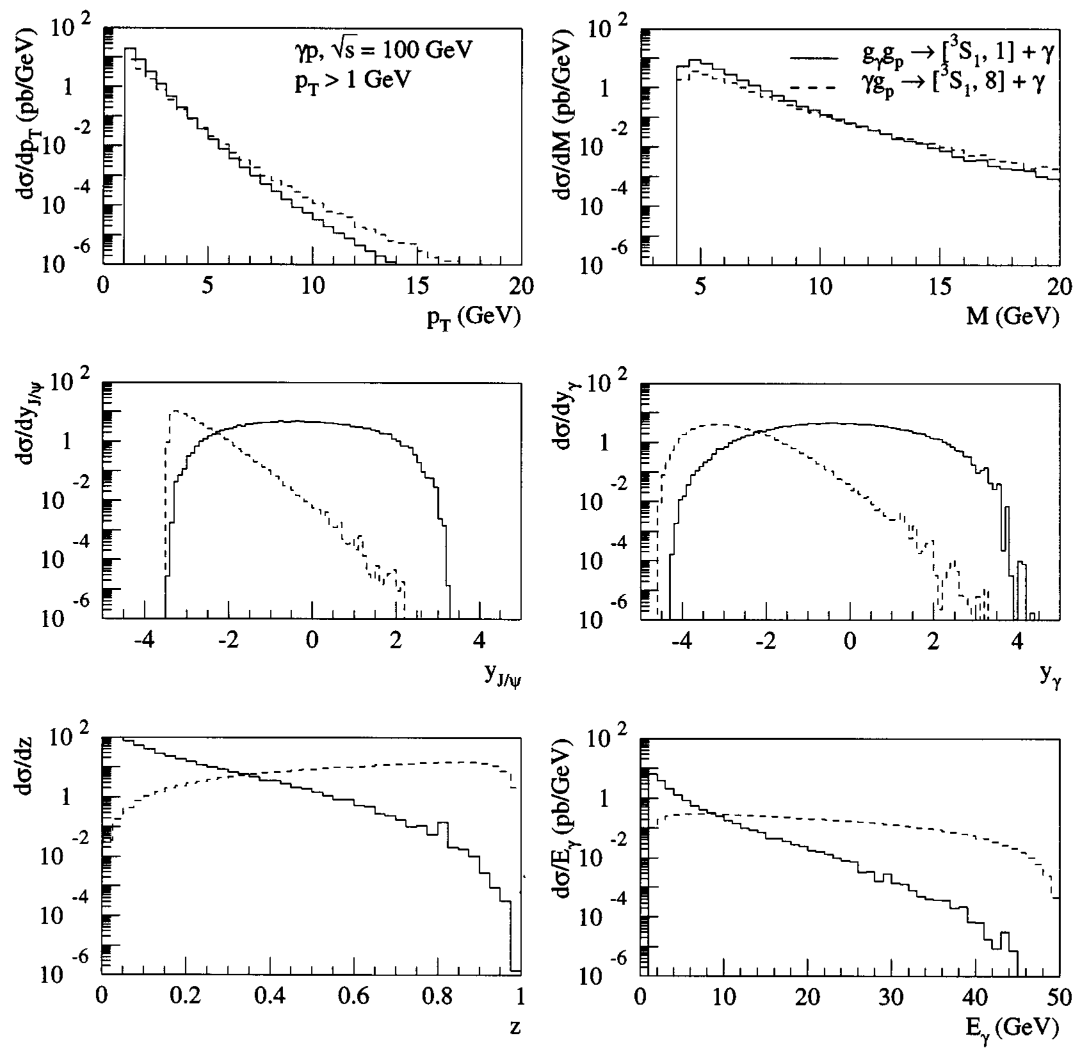

FIG. 2. Differential distributions in γp collision at $\sqrt{s}=100$ GeV. A minimum-p_T cut of 1 GeV is applied.

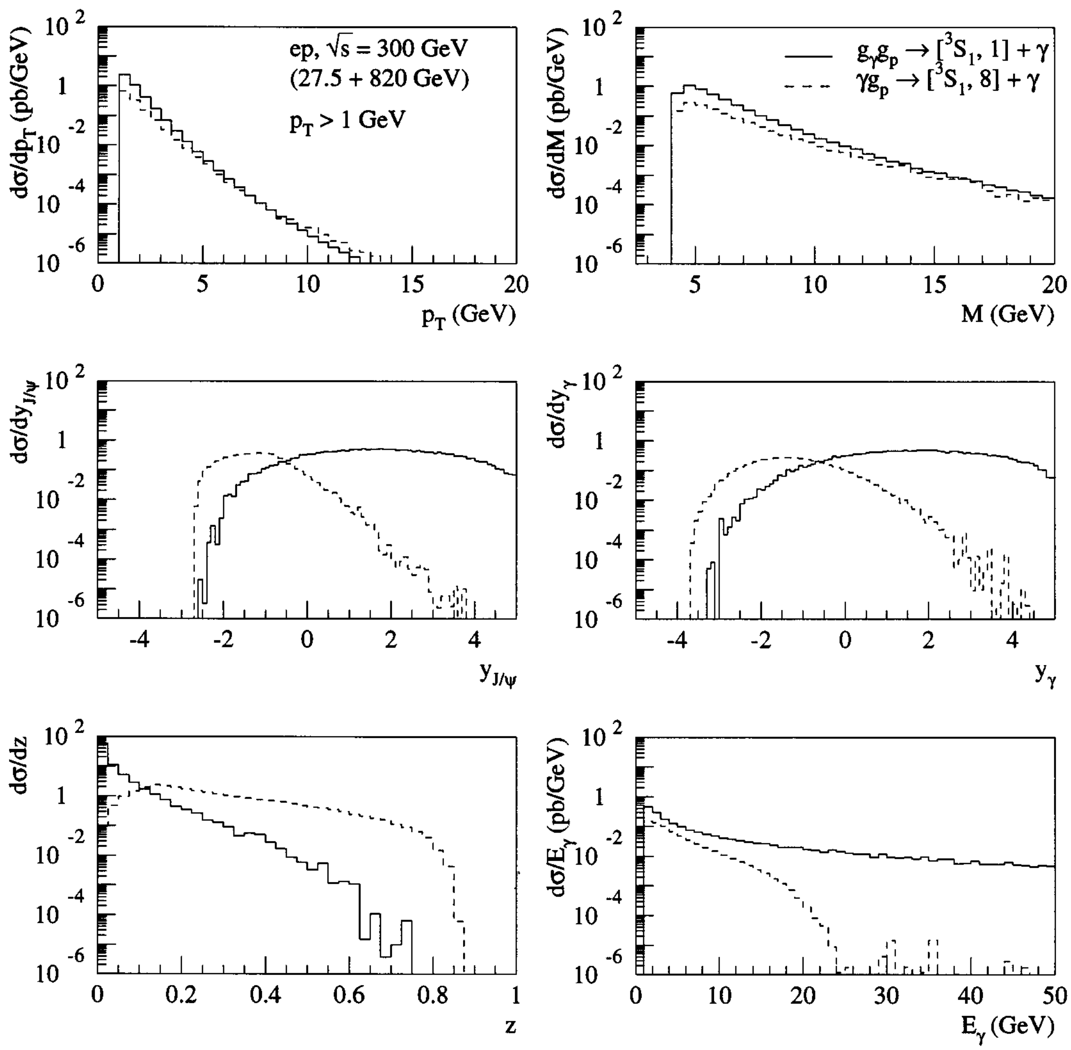

FIG. 3. Differential distributions in ep collision at $\sqrt{s}=300$ GeV. A minimum-p_T cut of 1 GeV is applied.

lation [11], Z decays [12], hadronic collisions at fixed-target experiments [13], B decays [14], and γp collisions (both for S-wave [15–18] and P-wave [19,20] states) have recently been performed within its frame. From [15,17], in particular, the predictions based on the leading color-octet contribution appear not to agree with recent experimental data obtained at the DESY ep collider HERA by the H1 Collaboration [21], indicating either a reduced phenomenological importance of the color-octet terms than suggested by the Tevatron data analysis [8] or the possible relevance of higher-order corrections.

In this paper we will consider the associated production of a J/ψ and a photon, where the photon has to be directly produced in the short-distance interaction, i.e., it should not come, for instance, from the radiative decay of a P-wave quarkonium into a J/ψ. This process must therefore have a very distinctive experimental signature, namely a J/ψ balanced in p_T by the hard photon. We will argue that the study of this reaction in γp collisions provides a powerful tool for assessing the importance of color-octet terms in quarkonia production. This process will moreover be seen to be a particularly sensitive probe of the NRQCD matrix element $\langle \mathcal{O}^{J/\psi}[^3S_1,8]\rangle$, and can therefore provide an important consistency check of the color-octet explanation of the large-p_T data at the Tevatron. First results of our analysis have already been presented in [20].

The paper is organized as follows. In Sec. II we will introduce the basic diagrams which contribute to $J/\psi+\gamma$ photoproduction and discuss why this process provides a clear signature of color-octet terms. Numerical results and Conclusions will follow in Secs. III–V, respectively.

II. $J/\psi+\gamma$ PRODUCTION

Associated $J/\psi+\gamma$ production has been studied in hadronic collisions by various authors over the recent years [22]. Kim and Reya [23] pointed out that $J/\psi+\gamma$ photo- and electroproduction represents a powerful tool for discriminating between the color-evaporation model and the color-singlet model. The reason for this will be discussed below. Since all previous calculations were based on the color-singlet or color-evaporation model it is worth reconsidering $J/\psi+\gamma$ production within the context of the new factorization approach. We will in fact demonstrate that this reaction is a particularly sensitive probe of the presence of color-octet mediated channels in J/ψ production.

TABLE II. Results for the total cross sections (in pb). Notice that while in the first data column E_γ refers to the incoming photon beam energy in the last one it refers instead to the produced outgoing photon.

Channel		γp $E_\gamma=100$ GeV $p_T>1$ GeV	γp $\sqrt{s}=100$ GeV $p_T>1$ GeV	ep $\sqrt{s}=300$ GeV $p_T>1$ GeV	ep $\sqrt{s}=300$ GeV $p_T>1$ GeV $-3<\eta<3$ $E_\gamma>2$ GeV
	${}^1S_0,\underline{8}$	-	-	-	-
Direct	${}^3S_1,\underline{8}$	0.48	7.67	0.63	0.44
	${}^3P_J,\underline{8}$	-	-	-	-
	${}^1S_0,\underline{8}$	0.0013	0.35	0.044	0.020
	${}^3S_1,\underline{1}$	0.072	16.70	2.05	0.75
	${}^3S_1,\underline{8}$	0.0012	0.27	0.033	0.012
Resolved	${}^3P_0,\underline{8}$	0.0046	1.03	0.13	0.048
	${}^3P_1,\underline{8}$	0.0005	0.14	0.018	0.007
	${}^3P_2,\underline{8}$	0.0045	0.97	0.12	0.043

Before presenting our results within the BBL formalism, let us briefly review the reason why associated $J/\psi+\gamma$ production provides a good discrimination between the CEM and the CSM in photoproduction. Because of the color constraint of the CSM, the leading-order contribution, Fig. 1(a),

$$\gamma p\to\gamma+g_p\to c\bar{c}[{}^3S_1,\underline{1}]+\gamma\to J/\psi+\gamma, \qquad (2)$$

obviously vanishes in the color-singlet model, since only one gluon is attached to the $c\bar{c}$ line. In order to allow for a second gluon one must either go to higher order in α_s for the direct photon process given above or consider a *resolved photon process*:

$$\gamma p\to g_\gamma+g_p\to c\bar{c}[{}^3S_1,\underline{1}]+\gamma\to J/\psi+\gamma. \qquad (3)$$

In both cases, we can expect a suppression of $J/\psi+\gamma$ photoproduction within the CSM. This is not the case in the CEM. Since the color constraint is absent, the process can proceed via the direct production channel giving a $c\bar{c}$ pair of invariant mass smaller than that of a $D\bar{D}$ pair threshold:

$$\gamma p\to\gamma+g_p\to c\bar{c}[M_{c\bar{c}}<M_{D\bar{D}}]+\gamma\to J/\psi+\gamma. \qquad (4)$$

Kim and Reya have indeed argued that at HERA within the CEM one should expect about a factor of 5 more $J/\psi+\gamma$ events than predicted by the CSM.

As stated before, the factorization approach shares some features of the CEM by allowing color-octet intermediate states. For this case, in particular, it allows the $J/\psi+\gamma$ production to proceed also via direct photon interactions through a color-octet $c\bar{c}$ pair. To be more specific, the following short-distance process can contribute.

Direct photon [Fig. 1(a)]:

$$\gamma+g_p\to c\bar{c}[{}^1S_0,\underline{8}]+\gamma,$$

$$\gamma+g_p\to c\bar{c}[{}^3S_1,\underline{8}]+\gamma,$$

$$\gamma+g_p\to c\bar{c}[{}^3P_J,\underline{8}]+\gamma.$$

Resolved photon [Fig. 1(b)]:

$$g_\gamma+g_p\to c\bar{c}[{}^1S_0,\underline{8}]+\gamma,$$

$$g_\gamma+g_p\to c\bar{c}[{}^3S_1,\underline{1}]+\gamma \quad \text{(standard CSM process)},$$

$$g_\gamma+g_p\to c\bar{c}[{}^3S_1,\underline{8}]+\gamma,$$

$$g_\gamma+g_p\to c\bar{c}[{}^3P_J,\underline{8}]+\gamma.$$

Light-quark initiated processes are strongly suppressed and can safely be neglected. Resolved production of a color-singlet χ_J state and a hard photon, with the χ_J radiatively decaying into J/ψ plus an unobserved soft photon, could constitute a background to our signal, but turns out to be zero.

According to the NRQCD velocity scaling rules [6] and fits to the Tevatron data [8], the color-octet nonperturbative matrix elements that enter associated $J/\psi+\gamma$ production should be suppressed by about 2 orders of magnitude compared to the color-singlet matrix element. Still, however, the two following features can be qualitatively expected.

(i) The production of color-octet states via a direct process—rather than a resolved one—will at least partially compensate for the smaller matrix elements. We should therefore expect a sizable increase in the overall cross section due to color-octet channels.

(ii) The distribution in the inelasticity of the J/ψ, namely the ratio of its energy over the initial photon energy in the proton rest frame, usually indicated with z (in a generic frame $z=p_{J/\psi}\cdot p_p/p_\gamma\cdot p_p$), will be more peaked towards one for the color-octet induced processes. This is again due to the presence of a direct photon coupling as opposed to the resolved one, where the g_γ only carries part of the photon energy into the reaction.

These qualitative features are in fact born out by our numerical analysis to be presented and discussed in the next section. The parton cross sections (5) have been evaluated using the algebraic computer program FORM [24]. We note here that the direct photon diagram in Fig. 1(a) happens to

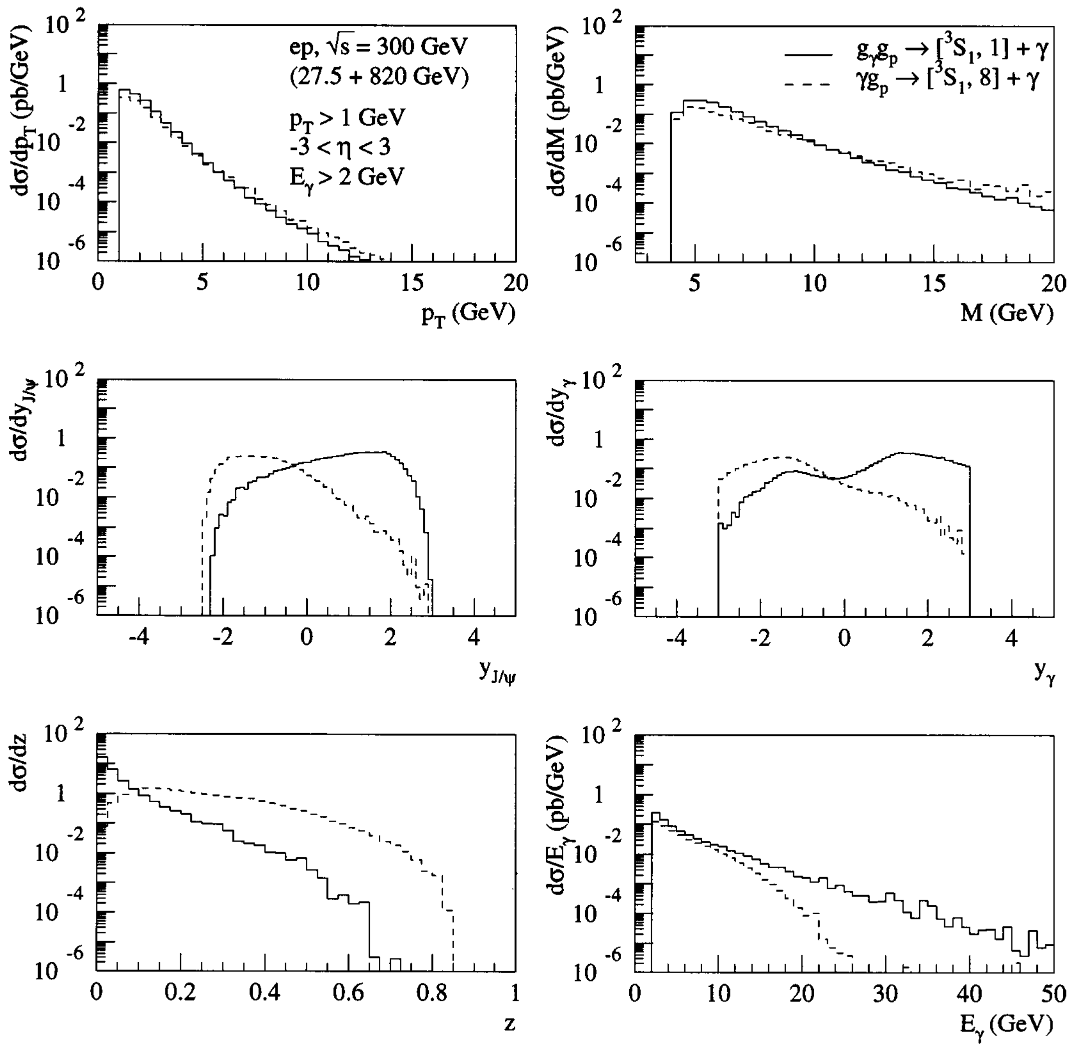

FIG. 4. Differential distributions in ep collision at $\sqrt{s}=300$ GeV. A minimum-p_T cut of 1 GeV, a minimum outgoing photon energy cut of 2 GeV, and a pseudorapidity cut $|\eta_{J/\psi,\gamma}|<3$ are applied.

contribute to $[{}^3S_1,\underline{8}]$ production only. Moreover, due to the triple-gluon vertex in the second diagram of Fig. 1(b), the cross sections for the resolved photon contribution to ${}^1S_0$ and ${}^3P_{0,2}$ octet states display a collinear and infrared singularity in the $p_T=0$ and $z=1$ end point. Rather than properly subtracting it we will avoid this phase-space region by applying a minimum-p_T cut.

III. NUMERICAL RESULTS

The numerical results have been obtained by adopting the following set of parameters. As for the strong coupling, we employ the leading-order (LO) formula

$$\alpha_s(\mu)=\frac{12\pi}{(33-2n_f)\ln(\mu^2/\Lambda^2)} \qquad (5)$$

with $n_f=4$ and $\Lambda^{(4)}_{\mathrm{LO}}=120$ MeV. The scale μ has been taken equal to the transverse J/ψ mass, namely $\mu=M_T=\sqrt{4m_c^2+p_T^2}$, and the charm mass m_c has been taken equal to 1.5 GeV. For both the proton and the resolved photon structure functions the GRV92 leading-order parton densities [25] have been employed, evaluated at the factorization scale $\mu_F=M_T$.

Finally, the nonperturbative matrix elements have been fixed to values compatible with both the NRQCD scaling rules and with the Tevatron fits, as in [15]. Their values are summarized in Table I.

We first compare the total cross sections given by the various production channels, with a fixed $p_T>1$ GeV cut applied to avoid the infrared-collinear singularities in some of the cross sections. Table II shows the results for (a) γp collisions in a fixed target setup, with an incoming photon energy of 100 GeV, (b) γp collisions at a center-of-mass energy of 100 GeV and (c) HERA kinematics, i.e., 27.5 GeV electron and 820 GeV proton collisions. For case (c) the electroproduction cross sections have been evaluated by averaging the photoproduction ones weighted by the usual Weizsäcker-Williams flux factor:

$$\sigma_{ep}(s)=\int_{y_{\min}}^{y_{\max}}dy\,f_{\gamma/e}(y)\,\sigma_{\gamma p}(ys). \qquad (6)$$

TABLE III. Results for the total cross sections in hadron collisions (in pb).

Channel	$\sigma_{p\bar{p}}(J/\psi+\gamma)$ (pb) $\sqrt{s}=1800$ GeV $p_T>4$ GeV $\lvert\eta_{J/\psi,\gamma}\rvert<0.6$ $E_\gamma>2$ GeV
$^3S_1,\underline{1}$	93.2
$^1S_0,\underline{8}$	12.3
$^3S_1,\underline{8}$	1.5
$^3P_0,\underline{8}$	10.0
$^3P_1,\underline{8}$	13.8
$^3P_2,\underline{8}$	7.7

with

$$f_{\gamma/e}(y)=\frac{\alpha}{2\pi}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + 2m_e^2 y\left(\frac{1}{Q^2_{\max}}-\frac{1}{Q^2_{\min}}\right)\right], \quad (7)$$

where $y=E_\gamma/E_e$, $Q^2_{\min}=m_e^2y/(1-y)$, and m_e is the electron mass. We adopt $Q^2_{\max}=4\ \text{GeV}^2$ and $y_{\min}=0.15$, $y_{\max}=0.86$ according to [26].

The results presented in Table II clearly show that in a typical fixed target setup, with a photon beam energy of 100 GeV, the cross section is dominated by the direct photon production of a color-octet $^3S_1$ state. Although the cross section is small, the observation of this process at fixed-target experiments would therefore already provide good evidence for the importance of color-octet contributions.

At a higher center-of-mass energy, on the other hand, the production of a J/ψ via a color-singlet $^3S_1$ state in resolved photon collisions and via a color-octet $^3S_1$ state in direct photon collisions represents the major part of the cross section. The numbers presented in Table II indicate that at HERA energies color-octet channels could amount to about 40% of the overall production rate. The presence of color-octet contributions can however not be assessed from total cross sections alone, given the large normalization uncertainties present in the calculation from higher-order corrections, parton distribution functions, and charm quark mass values, as well as unknown higher-twist contributions.

Therefore, we propose to study differential distributions to disentangle the color-octet contributions from the standard color-singlet one.

In Fig. 2 we show the differential distributions related to the total γp cross sections at $\sqrt{s}=100$ GeV with a minimum-p_T cut of 1 GeV, presented in Table II. The distributions due to color-singlet $[^3S_1,\underline{1}]$ production in resolved photon collisions (continuous line) and to color-octet $[^3S_1,\underline{8}]$ production in direct photon collisions (dashed line) only are shown. The distributions due to the other color-octet processes do indeed present the same features as the ones of $[^3S_1,\underline{1}]$, also being produced in resolved photon interactions, but are suppressed in magnitude, as can be seen from Table II. Their inclusion would therefore not change the picture we are going to discuss.

As expected, the effect of the color-octet $[^3S_1,\underline{8}]$ contribution produced in direct photon processes can easily be seen in at least some of the plots. While the p_T of the J/ψ and the invariant mass distribution M of the $J/\psi-\gamma$ pair are pretty similar for the color-singlet and color-octet-induced channels, the z, rapidity, and photon energy distributions do indeed show a strikingly different behavior.

Recalling that we put ourselves in the so-called ''HERA frame,'' with the photon (or the electron) traveling in the direction of negative rapidities, we notice how the direct photon coupling favors the production of the quarkonium and of the photon in the negative rapidities region. This contrasts the case of resolved photon production of color-singlet $^3S_1$ states, which are uniformly produced around the central rapidity region.

As for the z distribution, the resolved photon process predicts a decrease of the cross section going towards the high-z region. The direct photon process does, on the other hand, predict the opposite behavior: the cross section now increases going towards $z=1$. The small dip in the last few bins is due to the minimum-p_T cut.

The photon energy distribution behaves similarly to the z distribution, and is predicted to be much harder in direct photon processes.

The above distributions (the shapes of which have been checked to be robust with respect to a higher p_T cut, to be sure of the absence of $p_T^{\min}$ effects) provide a clear experimental signature; in particular the observation of a substantial fraction of $J/\psi+\gamma$ events in the high-z region would already be good evidence for the presence of color-octet contributions to the J/ψ production cross section.

However, since actually HERA provides electron-proton interactions, we are going to investigate how the distributions look like in this frame. For consistency, we will first consider, in Fig. 3, the differential cross section corresponding to the total ep cross section shown in Table II. Successively, the effect of some experimental-like cuts will be taken into account.

Comparing Fig. 3 with Fig. 2 we notice that, due to the system now being boosted in the proton direction (i.e., positive rapidities), the non-Lorentz-invariant observables are affected. More precisely, the rapidity distributions of both the J/ψ and of the photon are slightly smeared and shifted towards positive rapidities. The largest difference can however be observed in the photon energy distributions: the one due to the resolved photon process is hardened with respect to γp interactions, while the one due to direct photon interaction is greatly softened. This can be understood assuming that most of the very energetic photons in direct photon collisions are produced in the incoming photon direction (see the rapidity distribution). The effect of a boost of the event in the opposite direction will then soften this distribution. In resolved photon interactions, on the other hand, events of this kind are produced more uniformly around the central rapidity region, and the boost will then also harden at least part of them.

The effect of applying some realistic experimental cuts can be appreciated in Fig. 4. Since the produced photon must be clearly visible in the event, it is now required to lie (together with the J/ψ) within the pseudorapidity region $|\eta|<3$ and to have an energy, in the lab frame, greater than 2

GeV. This last requirement also ensures that it will not be mistaken with a photon coming from the radiative decay of a P-wave state to a J/ψ, having energies of a few hundreds MeV. A further experimental selection criterion to exclude radiative decays photons could consist in asking the photon p_T to be roughly opposite to that of the J/ψ. The distributions of Fig. 4 are qualitatively similar to the ones, without cuts, of Fig. 3, showing that color-octet contributions in associated $J/\psi+\gamma$ electroproduction should be visible in the photon fragmentation region (negative rapidities in the HERA frame) or, more clearly, in the large-z region.

IV. $J/\psi+\gamma$ IN HADRON COLLISIONS

Before closing, it is worth noticing that the resolved processes of Fig. 1(b) also contribute to the associated $J/\psi+\gamma$ production in hadron collisions. To check whether a signature for color-octet-mediated processes can be seen at a hadron collider we have evaluated the total $J/\psi+\gamma$ cross section in $p\bar{p}$ collisions at $\sqrt{s}=1800$ GeV. Light-quark initiated processes are suppressed and have been neglected. The following cuts have been imposed:

$$p_T>4 \text{ GeV}, \quad |\eta_{J/\psi,\gamma}|<0.6, \quad E_\gamma>2 \text{ GeV}. \tag{8}$$

The results are displayed in Table III. The color-octet terms can be seen to enhance the cross section by about 50%. However, given the large normalization uncertainties involved and the fact that the differential distributions in this case do not differ substantially from the color-singlet process' ones, we conclude that there is little hope to shed light on the color-octet mechanism via $J/\psi+\gamma$ production in hadron collisions.

V. CONCLUSIONS

The associated $J/\psi+\gamma$ production in ep and γp collisions has been proposed as a powerful tool for establishing the presence of quarkonia production processes mediated by color-octet $Q\bar{Q}$ states, as suggested by the factorization approach of Bodwin, Braaten, and Lepage.

The very fact that color-octet contributions to $J/\psi+\gamma$ photoproduction can proceed also via a direct photon coupling rather than via a resolved one only—as for the color-singlet channel—leads to clean experimental signatures. We have shown that at HERA energies the color-octet terms can increase the cross section by about 50% and, most importantly, produce a J/ψ energy distribution $d\sigma/dz$ strikingly different from the one predicted by the color-singlet channel alone.

The hadroproduction case, taking the Tevatron as an example, has also been investigated. This cross section is also increased by about 50% by octet terms, but no significant signatures in differential distributions can be found.

Note added. After completion of our work analyses of color-octet contributions to associated $J/\psi+\gamma$ production in hadron-hadron [27] and photon-hadron [28] collisions appeared. Their results are consistent with ours, where they do overlap.

[1] J. C. Collins, D. E. Soper, and G. Sterman, Nucl. Phys. **B263**, 37 (1986).

[2] H. Fritzsch, Phys. Lett. **67B**, 217 (1977); F. Halzen, *ibid.* **69B**, 105 (1977); F. Halzen and S. Matsuda, Phys. Rev. D **17**, 1344 (1978); M. Glück, J. Owens, and E. Reya, *ibid.* **17**, 2324 (1978).

[3] A. Bramon, E. Etim, and M. Greco, Phys. Lett. **41B**, 609 (1972).

[4] E. L. Berger and D. Jones, Phys. Rev. D **23**, 1521 (1981); R. Baier and R. Rückl, Phys. Lett. **102B**, 364 (1981); for a recent review see also G. A. Schuler, CERN Report No. CERN-TH.7170/94, hep-ph/9403387 (unpublished).

[5] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995).

[6] G. P. Lepage, L. Magnea, C. Nakhleh, U. Magnea, and K. Hornbostel, Phys. Rev. D **46**, 4052 (1992).

[7] CDF Collaboration, F. Abe *et al.* Phys. Rev. Lett. **69**, 3704 (1992); **71**, 2537 (1993); Fermilab Report No. FERMILAB-CONF-96/156-E (unpublished).

[8] E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995); M. Cacciari, M. Greco, M. L. Mangano, and A. Petrelli, Phys. Lett. B **356**, 560 (1995); P. Cho and A. K. Leibovich, Phys. Rev. D **53**, 150 (1996); **53**, 6203 (1996); M. Cacciari and M. Greco, Phys. Rev. Lett. **73**, 1586 (1994); E. Braaten, M. A. Doncheski, S. Fleming, and M. L. Mangano, Phys. Lett. B **333**, 548 (1994); D. P. Roy and K. Sridhar, *ibid.* **339**, 141 (1994).

[9] M. L. Mangano, in *Tenth Topical Workshop on Proton-Antiproton Collider Physics*, edited by R. Raja and J. Yo (American Institute for Physics, New York, 1995); CERN Report No. CERN-TH-95-190, hep-ph/9507353 (unpublished).

[10] E. Braaten, S. Fleming, and T. C. Yuan, Ohio State University Report No. OHSTPY-HEP-T-96-001, hep-ph/9602374 (unpublished).

[11] E. Braaten and Y.-Q. Chen, Phys. Rev. Lett. **76**, 730 (1996).

[12] K. Cheung, W.-Y. Keung, and T. C. Yuan, Phys. Rev. Lett. **76**, 877 (1996); P. Cho, Phys. Lett. B **368**, 171 (1996).

[13] W.-K. Tang and M. Vänttinen, Phys. Rev. D **53**, 4851 (1996); **54**, 4349 (1996); S. Fleming and I. Maksymyk, *ibid.* **54**, 3608 (1996); S. Gupta and K. Sridhar, *ibid.* **54**, 5545 (1996); M. Beneke and I. Z. Rothstein, *ibid.* **54**, 2005 (1996).

[14] P. Ko, J. Lee, and H. S. Song, Phys. Rev. D **53**, 1409 (1996); S. Fleming, O. F. Hernández, I. Maksymyk, and H. Nadeau, *ibid.* **55**, 4098 (1997).

[15] M. Cacciari and M. Krämer, Phys. Rev. Lett. **76**, 4128 (1996).

[16] J. Amundson, S. Fleming, and I. Maksymyk, University of Texas Report No. UTTG-10-95, hep-ph/9601298 (unpublished).

[17] P. Ko, J. Lee, and H. S. Song, Phys. Rev. D **54**, 4312 (1996).

[18] R. Godbole, D. P. Roy, and K. Sridhar, Phys. Lett. B **373**, 328 (1996).

[19] J. P. Ma, Nucl. Phys. **B460**, 109 (1996).

[20] M. Cacciari and M. Krämer, in *Proceedings of the Workshop Future Physics at HERA*, edited by G. Ingelman, A. De Roeck,

and R. Klanner (DESY, Hamburg, 1996), Vol. 1, p. 416.

[21] H1 Collaboration, S. Aid *et al.*, Nucl. Phys. **B472**, 3 (1996); see also ZEUS Collaboration, M. Derrick *et al.*, Contributed paper No. pa02-047 to the 28th International Conference on High Energy Physics, Warsaw, Poland, 1996 (unpublished).

[22] M. Drees and C. S. Kim, Z. Phys. C **53**, 673 (1992); K. Sridhar, Phys. Lett. B **289**, 435 (1992); R. V. Gavai, R. M. Godbole, and K. Sridhar, *ibid.* **299**, 157 (1993); K. Sridhar, Phys. Rev. Lett. **70**, 1747 (1993); E. L. Berger and K. Sridhar, Phys. Lett. B **317**, 443 (1993); M. A. Doncheski and C. S. Kim, Phys. Rev. D **49**, 4463 (1994); C. S. Kim and E. Mirkes, Phys. Lett. B **346**, 124 (1994); Phys. Rev. D **51**, 3340 (1995); D. P. Roy and K. Sridhar, Phys. Lett. B **341**, 413 (1995); H. A. Peng, Z. M. He, and C. S. Ju, *ibid.* **351**, 349 (1995).

[23] C. S. Kim and E. Reya, Phys. Lett. B **300**, 298 (1993).

[24] J. A. M. Vermaseren, FORM 2.0, CAN, Amsterdam, 1991.

[25] M. Glück, E. Reya, and A. Vogt, Phys. Rev. D **46**, 1973 (1992); Z. Phys. C **53**, 127 (1992); **67**, 433 (1995).

[26] ZEUS Collaboration, M. Derrick *et al.*, Phys. Lett. B **349**, 225 (1995).

[27] C. S. Kim, J. Lee, and H. S. Song, Phys. Rev. D **55,** 5429 (1997).

[28] T. Mehen, Phys. Rev. D **55,** 4338 (1997).