DESY 96-005

DESY 96-005
January 1996

Color-Octet Contributions to J/ψ Photoproduction

Matteo Cacciari[1] and Michael Krämer[2]

Deutsches Elektronen-Synchrotron DESY
D-22603 Hamburg, Germany

Abstract

We have calculated the leading color-octet contributions to the production of J/ψ particles in photon-proton collisions. Using the values for the color-octet matrix elements extracted from fits to prompt J/ψ data at the Tevatron, we demonstrate that distinctive color-octet signatures should be visible in J/ψ photoproduction. However, these predictions appear at variance with recent experimental data obtained at HERA, indicating that the phenomenological importance of the color-octet contributions is smaller than expected from theoretical considerations and suggested by the Tevatron fits.

PACS numbers: 12.38.Bx,13.60.Le,14.40.Gx

[1]e-mail: cacciari@desy.de
[2]e-mail: mkraemer@desy.de

The production of heavy quarkonium states in high energy collisions provides an important tool to study the interplay between perturbative and non-perturbative QCD dynamics. A rigorous framework for treating quarkonium production and decays has recently been developed in Ref.[1]. The factorization approach is based on the use of non-relativistic QCD (NRQCD) to separate the short-distance parts from the long-distance matrix elements and explicitly takes into account the complete structure of the quarkonium Fock space. This formalism implies that so-called color-octet processes, in which the heavy-quark antiquark pair is produced at short distances in a color-octet state and subsequently evolves non-perturbatively into a physical quarkonium, should contribute to the cross section. It has recently been argued in Refs.[2, 3] that quarkonium production in hadronic collisions at the Tevatron can be accounted for by including color-octet processes and by adjusting the unknown long-distance color-octet matrix elements to fit the data.

In order to establish the phenomenological significance of the color-octet mechanism it is necessary to identify color-octet contributions in different production processes. Color-octet production of J/ψ particles in e^+e^- annihilation and Z decays has been studied in Refs.[4]. In this note, we examine the color-octet contributions to J/ψ photoproduction, $\gamma + P \to J/\psi + X$, which proceeds predominantly through photon-gluon fusion. Elastic/diffractive mechanisms [5] and reducible background processes can be eliminated by applying suitable cuts [6]. According to the formalism developed in Ref.[1], the inclusive production cross section can be expressed as a sum of terms, each of which factors into a short-distance coefficient and a long-distance matrix element:

$$\mathrm{d}\sigma(\gamma + g \to J/\psi + X) = \sum_n \mathrm{d}\hat{\sigma}(\gamma + g \to c\bar{c}\,[n] + X)\,\langle 0|\mathcal{O}^{J/\psi}\,[n]|0\rangle\,. \tag{1}$$

Here, $\mathrm{d}\hat{\sigma}$ denotes the short-distance cross section for producing an on-shell $c\bar{c}$-pair in a color, spin and angular-momentum state labelled by n. The NRQCD matrix elements $\langle 0|\mathcal{O}^{J/\psi}\,[n]|0\rangle$ give the probability for a $c\bar{c}$-pair in the state n to form the J/ψ particle. The relative importance of the various terms in (1) can be estimated by using NRQCD velocity scaling rules [7]. For $v \to 0$ (v being the average velocity of the charm quark in the J/ψ rest frame) each of the NRQCD matrix elements scales with a definite power of v and the general expression (1) can be organized into an expansion in powers of v^2.

At leading order in v^2, eq.(1) reduces to the standard factorization formula of the color-singlet model [8]. The short-distance cross section is given by the subprocess

$$\gamma + g \to c\bar{c}\,[\underline{1}, {}^3S_1] + g \tag{2}$$

shown in Fig.1a, with $c\bar{c}$ in a color-singlet state (denoted by $\underline{1}$), zero relative velocity, and spin/angular-momentum quantum numbers ${}^{2S+1}L_J = {}^3S_1$. Higher-order QCD corrections to the short-distance process (2) were found to increase the color-singlet cross section by more than 50%, depending in detail on the choice of parameters [9, 10].

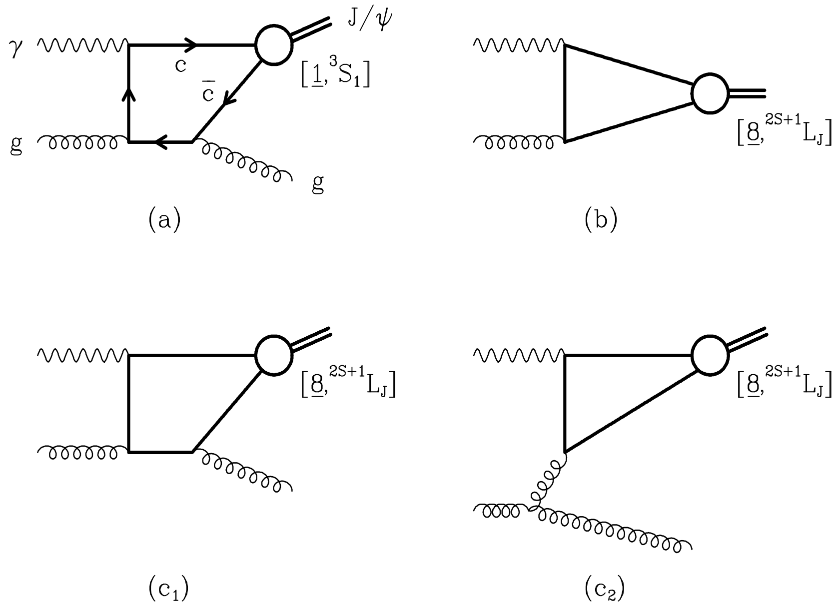

Figure 1: Generic diagrams for J/ψ photoproduction: (a) leading color-singlet contribution; (b) leading color-octet contributions; (c) color-octet contributions to inelastic J/ψ production.

Color-octet configurations are produced at leading order in α_s through the $2 \to 1$ parton processes

$$\begin{aligned} \gamma + g &\to c\bar{c}\,[\underline{8}, {}^1S_0] \\ \gamma + g &\to c\bar{c}\,[\underline{8}, {}^3P_{0,2}] \end{aligned} \tag{3}$$

shown in Fig.1b. The transition of the color-octet $c\bar{c}\,[\underline{8}, {}^{2S+1}L_J]$ pair into a physical J/ψ state through the emission of non-perturbative gluons is described by the long-distance matrix elements $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^{2S+1}L_J]|0\rangle$. They have to be obtained from lattice simulations or measured directly in some production process. According to the velocity scaling rules of NRQCD, the color-octet matrix elements should be suppressed by a factor of v^4 compared to the leading color-singlet matrix element [11]. Color-octet contributions to J/ψ photoproduction can thus become important only if the corresponding short-distance cross sections are enhanced as compared to the color-singlet process. For the partonic cross section of the leading color-octet contributions we find

$$\hat{\sigma}(\gamma + g \to c\bar{c}\,[n] \to J/\psi) = \frac{\pi\,\delta(\hat{s} - 4m_c^2)}{4m_c^2}\,\overline{\sum}|\mathcal{M}(\gamma + g \to c\bar{c}\,[n])|^2\,\langle 0|\mathcal{O}^{J/\psi}\,[n]|0\rangle \qquad (4)$$

with

$$\begin{aligned}
\overline{\sum}|\mathcal{M}(\gamma + g \to c\bar{c}\,[\underline{8}, {}^1S_0])|^2 &= \frac{(4\pi)^2 e_c^2 \alpha\alpha_s}{4m_c} \\
\overline{\sum}|\mathcal{M}(\gamma + g \to c\bar{c}\,[\underline{8}, {}^3P_0])|^2 &= \frac{3(4\pi)^2 e_c^2 \alpha\alpha_s}{4m_c^3} \\
\overline{\sum}|\mathcal{M}(\gamma + g \to c\bar{c}\,[\underline{8}, {}^3P_2])|^2 &= \frac{(4\pi)^2 e_c^2 \alpha\alpha_s}{5m_c^3}\,.
\end{aligned} \qquad (5)$$

The partonic energy squared is denoted by $\hat{s}$, and e_c is the magnitude of the charm quark charge in units of $e = \sqrt{4\pi\alpha}$. We have checked that our results are consistent with those presented in Refs.[3, 12].

In the analyses Refs.[2, 3], color-octet matrix elements have been fitted to prompt J/ψ data from CDF [13] and found to be consistent with the NRQCD velocity scaling rules. The fit-values have, however, large theoretical errors due to the uncertainty in the heavy quark mass and the QCD coupling, unknown higher-order corrections, and higher twist effects [14], and should therefore mainly be regarded as order-of-magnitude estimates. For our numerical analysis we choose the color-octet matrix elements as listed in Table 1, consistent with the velocity scaling rules and the results obtained in Refs.[2, 3]. The color-singlet matrix element has been calculated from the J/ψ wave function at the origin as obtained in the QCD-motivated potential model of Ref.[15] and tabulated in Ref.[16]. At leading order in v^2, the P-wave matrix elements are related by heavy-quark spin symmetry, $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^3P_J]|0\rangle \approx (2J+1)\,\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^3P_0]|0\rangle$.

$\langle 0\|\mathcal{O}^{J/\psi}\,[n]\|0\rangle$	numerical value	scaling
$\langle 0\|\mathcal{O}^{J/\psi}\,[\underline{1}, {}^3S_1]\|0\rangle$	1.16 GeV^3	$m_c^3 v^3$
$\langle 0\|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^1S_0]\|0\rangle$	10^{-2} GeV^3	$m_c^3 v^7$
$\langle 0\|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^3P_0]\|0\rangle / m_c^2$	10^{-2} GeV^3	$m_c^3 v^7$

Table 1: Values of the NRQCD matrix elements used in the numerical analysis, with the velocity and mass scaling.

Due to kinematical constraints, the leading color-octet terms will only contribute to the upper endpoint of the J/ψ energy spectrum, $z \approx 1$ and $p_\perp \approx 0$. The J/ψ energy variable is defined by $z = p \cdot k_\psi \,/\, p \cdot k_\gamma$, with $p, k_{\psi,\gamma}$ being the momenta of the proton and J/ψ, γ particles, respectively, and $p_\perp$ is the J/ψ transverse momentum. The leading color-octet

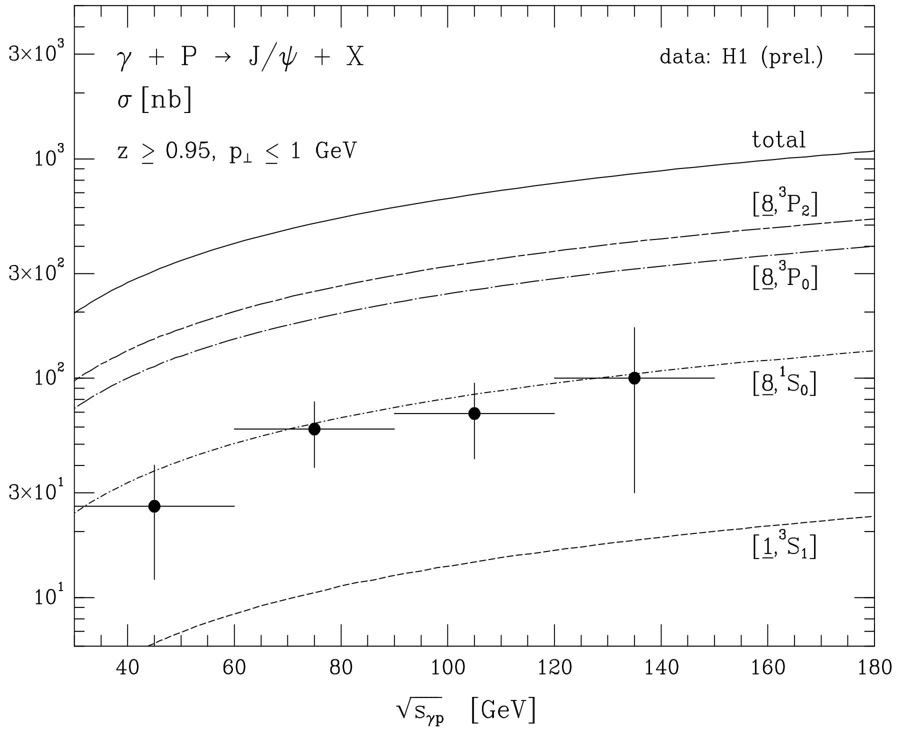

Figure 2: Total cross section for J/ψ photoproduction in the region $z \geq 0.95$ and $p_\perp \leq 1$ GeV as a function of the photon-proton energy. Experimental data from [17].

and color-singlet contributions to the J/ψ photoproduction cross section in the region $z \geq 0.95$ and $p_\perp \leq 1$ GeV are shown in Fig.2. The predictions are compared to experimental data obtained at HERA by the H1 collaboration [17]. We have used $m_c = 1.48$ [15], $\alpha_s(2m_c) = 0.3$, and the values for the NRQCD matrix elements listed in Table 1. The parton cross section has been convoluted with the leading-order GRV parametrization of the gluon density in the proton [18], evaluated at a scale $Q = 2m_c$. Relativistic corrections to the color-singlet channel [19] enhance the large z region, but cannot change the order-of-magnitude suppression of the color-singlet process significantly. The large cross section predicted by the color-octet mechanism appears to be in conflict with the experimental data. This indicates that the value of the color-octet matrix elements $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8},{}^1S_0]|0\rangle$ and $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8},{}^3P_J]|0\rangle$ is more than one order of magnitude smaller than expected from the velocity scaling rules and suggested by the Tevatron fits. It is, however, difficult to put strong upper limits for the octet terms from a measurement of the total cross section since the overall normalization of the theoretical prediction depends strongly on the choice for the charm quark mass and the QCD coupling. Moreover, diffractive production mechanisms which cannot be calculated within perturbative QCD might contaminate the region $z \approx 1$ and make it difficult to extract precise information on the color-octet contributions.

Diffractive processes can be eliminated by restricting the analysis to the inelastic domain $z \leq 0.9$ and $p_\perp \geq 1$ GeV. Color-octet configurations which contribute to inelastic J/ψ photoproduction are produced through the subprocesses

$$\begin{aligned} \gamma + g &\rightarrow c\bar{c}\,[\underline{8}, {}^1S_0] + g \\ \gamma + g &\rightarrow c\bar{c}\,[\underline{8}, {}^3S_1] + g \\ \gamma + g &\rightarrow c\bar{c}\,[\underline{8}, {}^3P_{0,1,2}] + g \end{aligned} \tag{6}$$

as shown in Fig.1c. Light-quark initiated processes are strongly suppressed at HERA energies and can safely be neglected in a first step. The parton cross sections (6) have been evaluated using the algebraic computer program FORM [20]. Details of the calculation and analytic results will be presented in a forthcoming publication [21]. Here we merely note that the cross sections $\gamma + g \rightarrow c\bar{c}\,[\underline{8}, {}^1S_0], [\underline{8}, {}^3P_{0,2}] + g$ are divergent for $z \rightarrow 1$ and $p_\perp \rightarrow 0$, due to the $g \rightarrow gg$ collinear splitting, Fig.1c$_2$. This singularity can be absorbed into the renormalization of the parton densities via mass factorization [21]. In the inelastic region $z \leq 0.9$ and $p_\perp \geq 1$ GeV the cross sections are well-behaved however.

In Fig.3 we show the color-octet and (leading-order) color-singlet contributions to inelastic J/ψ photoproduction compared to experimental data from H1 [17] obtained in the kinematical region $z \leq 0.8$ and $p_\perp \geq 1$ GeV. For the central predictions we have used $m_c = 1.48$ GeV and $\alpha_\mathrm{s} = 0.3$, while the hatched error band indicates how much the color-singlet cross section is altered if m_c and α_s vary in the range 1.4 GeV $\leq m_c \leq$ 1.55 GeV and $0.25 \leq \alpha_\mathrm{s} \leq 0.35$. Adopting the NRQCD matrix elements listed in Table 1 and $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^3S_1]|0\rangle = 10^{-2}$ GeV^3 [2, 3] we find that color-octet and color-singlet contributions to the inelastic cross section are predicted to be of comparable size. The short-distance factors of the $[\underline{8}, {}^1S_0]$ and $[\underline{8}, {}^3P_{0,2}]$ channels are strongly enhanced as compared to the color-singlet term and partly compensate the $\mathcal{O}(10^{-2})$ suppression of the corresponding non-perturbative matrix elements. In contrast, the contributions from the $[\underline{8}, {}^3S_1]$ and $[\underline{8}, {}^3P_1]$ states are suppressed by more than one order of magnitude. Since color-octet and color-singlet processes contribute at the same order in α_s, the large size of the $[\underline{8}, {}^1S_0]$ and $[\underline{8}, {}^3P_{0,2}]$ cross sections could not have been anticipated from naive power counting and demonstrates the crucial dynamical role played by the bound state quantum numbers [22]. Inclusion of the color-octet processes increases the inelastic cross section by about a factor of two, consistent with experimental data. This does, however, not proof the significance of the color-octet terms: as can be seen from Fig.3, the experimental data can be accounted for by the color-singlet process alone, once the theoretical uncertainties due to variation of the charm quark mass and the strong coupling are properly taken into account. This has also been demonstrated in the next-to-leading order analysis of

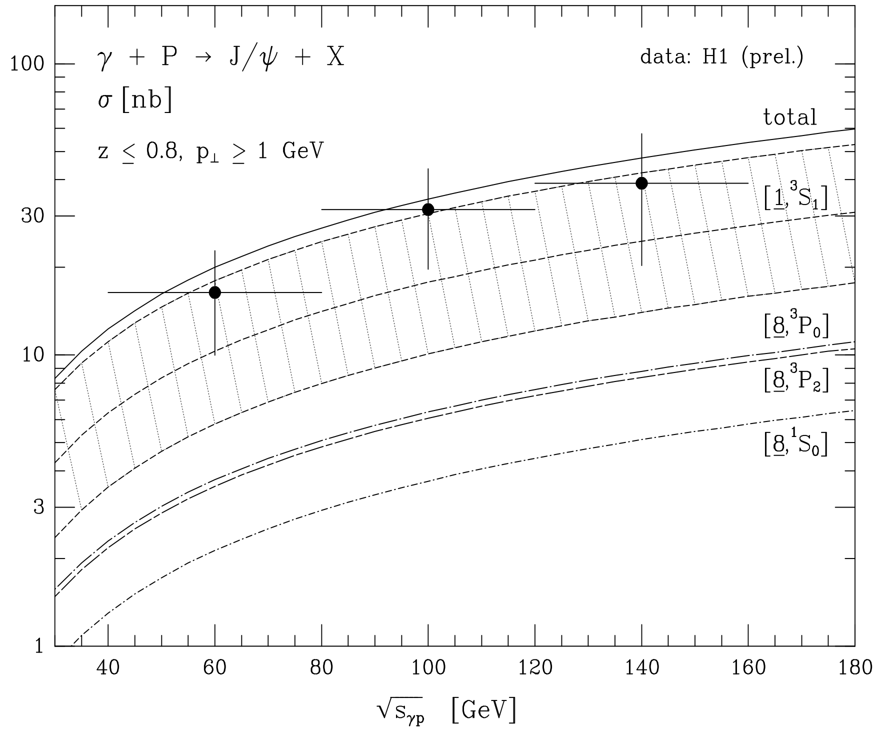

Figure 3: Total cross section for J/ψ photoproduction in the region $z \leq 0.8$ and $p_\perp \geq$ 1 GeV as a function of the photon-proton energy. Experimental data from [17].

Ref.[10]. No strong conclusions on the size of the color-octet terms can thus be deduced from the study of the total inelastic cross section. The same statement holds true for the transverse momentum spectrum, since, at small and moderate $p_\perp$, both color-singlet and color-octet contributions are almost identical in shape. At large transverse momenta, $p_\perp \gtrsim 10$ GeV, charm quark fragmentation dominates over the photon-gluon fusion process [23, 24]. In contrast to what was found at the Tevatron [25], gluon fragmentation into color-octet states is suppressed over the whole range of $p_\perp$ [24].

A distinctive signal for color-octet processes should, however, be visible in the J/ψ energy distribution $\mathrm{d}\sigma/\mathrm{d}z$ shown in Fig.4. We have plotted color-singlet and color-octet contributions at a typical HERA energy of $\sqrt{s_{\gamma p}} = 100$ GeV in the restricted range $p_\perp \geq 1$ GeV, compared to recent experimental data from H1 [26]. Since the shape of the distribution is insensitive to higher-order QCD corrections or to the uncertainty induced by the choice for m_c and α_s, the analysis of the J/ψ energy spectrum $\mathrm{d}\sigma/\mathrm{d}z$ provides a clean test for the underlying production mechanism. The comparison with the experimental data, Fig.4, shows that the J/ψ energy spectrum is adequately accounted for by the color-singlet contribution. The shape predicted by the color-octet contributions is instead in

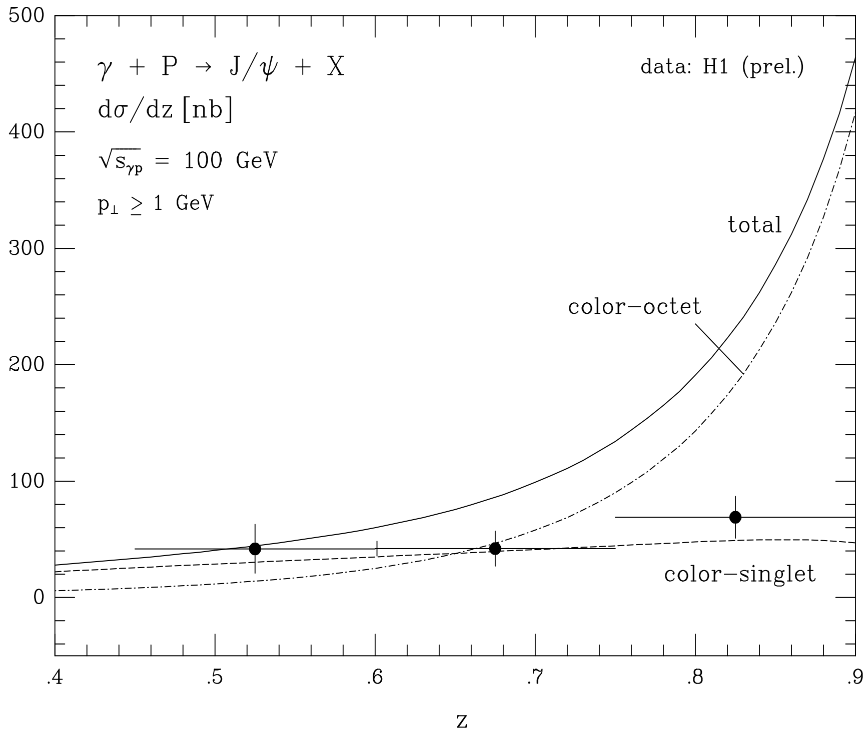

Figure 4: The J/ψ energy distribution $\mathrm{d}\sigma/\mathrm{d}z$ at the photon-proton centre of mass energy $\sqrt{s_{\gamma p}} = 100$ GeV integrated in the range $p_\perp \geq 1$ GeV. Experimental data from [26].

conflict with the experimental data.

In conclusion, we have investigated color-octet contributions to the production of J/ψ particles in photon-proton collisions. Color-octet processes would strongly affect the upper endpoint region of the J/ψ energy spectrum and the shape of the J/ψ energy distribution. However, these predictions appear at variance with recent experimental data obtained at HERA. We conclude that the values of the color-octet matrix elements $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^1S_0]|0\rangle$ and $\langle 0|\mathcal{O}^{J/\psi}\,[\underline{8}, {}^3P_J]|0\rangle$ seem to be more than one order of magnitude smaller than expected from the velocity scaling rules and suggested by the Tevatron fits. With higher statistics data it will be possible to extract more detailed information on the color-octet matrix elements, in particular from the analysis of the J/ψ energy distribution in the inelastic region.

Acknowledgements

It is a pleasure to thank Mario Greco and Peter M. Zerwas for suggestions and comments. Special thanks go to the H1 collaboration, in particular to Beate Naroska, Stephan Schiek and Guido Schmidt, for providing experimental data prior to publication. We have benefitted from conversations with Riccardo Brugnera, Peppe Iacobucci, Wolfgang Kilian, Luca Stanco, Mikko Vänttinen and Paolo Vitulo.

References

[1] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. **D51** (1995) 1125.

[2] E. Braaten and S. Fleming, Phys. Rev. Lett. **74** (1995) 3327; M. Cacciari, M. Greco, M.L. Mangano, and A. Petrelli, Phys. Lett. **B356** (1995) 560.

[3] P. Cho and A.K. Leibovich, CALT-68-1988 and CALT-68-2026.

[4] E. Braaten and Y.-Q. Chen, NUHEP-TH-95-9; K. Cheung, W.-Y. Keung, and T.C. Yuan, FERMILAB-PUB-95/300-T; P. Cho, CALT-68-2020.

[5] A. Donnachie and P.V. Landshoff, Phys. Lett. **B348** (1995) 213; M.G. Ryskin, R.G. Roberts, A.D. Martin, and E.M. Levin, DTP-95-96; T. Ahmed et al. [H1 Collab.], Phys. Lett. **B338** (1994) 507; M. Derrick et al. [ZEUS Collab.], Phys. Lett. **B350** (1995) 120.

[6] H. Jung, G.A. Schuler, and J. Terrón, Int. J. Mod. Phys. **A7** (1992) 7955.

[7] G.P. Lepage, L. Magnea, C. Nakhleh, U. Magnea, and K. Hornbostel, Phys. Rev. **D46** (1992) 4052.

[8] E.L. Berger and D. Jones, Phys. Rev. **D23** (1981) 1521; R. Baier and R. Rückl, Phys. Lett. **102B** (1981) 364.

[9] M. Krämer, J. Zunft, J. Steegborn, and P.M. Zerwas, Phys. Lett. **B348** (1995) 657.

[10] M. Krämer, DESY-95-155, Nucl. Phys. B. in press.

[11] In the case of P-wave quarkonia, color-singlet and color-octet matrix elements contribute at the same order in v, see: G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. **D46** (1992) R1914. Photoproduction of P-wave states has been studied in: J.P. Ma, UM-P-95-96.

[12] S. Fleming and I. Maksymyk, MADPH-95-922.

[13] F. Abe et al. [CDF Collab.], Phys. Rev. Lett. **69** (1992) 3704; A. Sansoni, [CDF Collab.], FERMILAB-CONF-95/263-E.

[14] M. Vänttinen, P. Hoyer, S.J. Brodsky, and W.K. Tang, Phys. Rev. **D51** (1995) 3332; M. Vänttinen and W.K. Tang, SLAC-PUB-95-6931.

[15] W. Buchmüller and S.-H.H. Tye, Phys. Rev. **D24** (1981) 132.

[16] E.J. Eichten and C. Quigg, Phys. Rev. **D52** (1995) 1726.

[17] S. Aid et al. [H1 Collab.], contribution to the Int. Europhysics Conf. on High Energy Physics, Brussels, 1995, and publication in preparation.

[18] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C67** (1995) 433.

[19] W.Y. Keung and I.J. Muzinich, Phys. Rev. **D27** (1983) 1518; H. Jung, D. Krücker, C. Greub, and D. Wyler, Z. Phys. **C60** (1993) 721, H. Khan and P. Hoodbhoy, hep-ph 9511360.

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

[21] M. Cacciari and M. Krämer, in preparation.

[22] R. Baier and R. Rückl, Z. Phys. **C19** (1983) 251.

[23] V.A. Saleev, Mod. Phys. Lett. **A9** (1994) 1083.

[24] R. Godbole, D.P. Roy, and K. Sridhar, TIFR/TH/95-57.

[25] M. Cacciari and M. Greco, Phys. Rev. Lett. **73** (1994) 1586; E. Braaten, M.A. Doncheski, S. Fleming, and M.L. Mangano, Phys. Lett. **B333** (1994) 548; D.P. Roy and K. Sridhar, Phys. Lett. **B339** (1994) 141.

[26] H1 Collaboration, private communication (data analysis as described in Ref.[17]).