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Color-Octet Contributions to J/ψ Photoproduction via Fragmentation at HERA

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Abstract

We study J/ψ photoproduction via fragmentation at next-to-leading order in the QCD-improved parton model, using the nonrelativistic factorization formalism proposed by Bodwin, Braaten, and Lepage. We consider direct and resolved photoproduction of prompt J/ψ mesons and χ_{cJ} mesons radiatively decaying to $J/\psi+\gamma$, taking into account the formation of both color-singlet and color-octet $c\bar{c}$ states. Adopting the values of the long-distance color-octet matrix elements extracted from fits to prompt-J/ψ data recently taken at the Fermilab Tevatron, we predict that measurements of J/ψ photoproduction at DESY HERA should show a distinctive excess over the expectation based on the color-singlet model at small values of the inelasticity variable z. This is complementary to the expected enhancement at $z\lesssim 1$ due to the color-octet contribution to photon-gluon fusion.

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Some time ago, experiments [1] at the Fermilab $p\bar{p}$ collider Tevatron have revealed that the production rate of prompt charmonium at large transverse momentum (p_T) exceeds the most accurate theoretical predictions within the so-called color-singlet model (CSM) [2] by more than one order of magnitude. This surprising observation may be interpreted by taking into account two recent developments that have revolutionized the theoretical description of heavy-quarkonium production in high-energy collisions. Firstly, it has been realized [3] that fragmentation production must dominate at large p_T, which implies that most charmonium in this kinematic domain is produced by the hadronization of individual high-p_T partons. Secondly, a rigorous factorization formalism for quarkonium production based on nonrelativistic quantum chromodynamics (QCD) has been developed [4], which allows for a systematical treatment of the formation of charmonium from color-singlet and color-octet $c\bar{c}$ pairs. This formalism comprises a separation of short-distance parts, which are amenable to perturbative QCD, from long-distance matrix elements, which must be computed through lattice simulations or extracted from experiment, and it takes into account the complete structure of the charmonium Fock space. An important new feature of this approach is the appearance of the so-called color-octet processes, in which a $c\bar{c}$ pair is produced at short distances in a color-octet state and subsequently evolves into physical (color-singlet) charmonium by the nonperturbative emission of soft gluons. In fact, the Tevatron data [1] on prompt charmonium production at large p_T can be successfully interpreted by including the appropriate color-octet processes and adjusting their long-distance matrix elements to fit these data [5].

In order to convincingly establish the phenomenological significance of the color-octet mechanism, it is indispensable to identify the color-octet contributions in other kinds of high-energy experiments as well. On the theoretical side, a first step in this direction has recently been taken in Ref. [6] by investigating the signature of color-octet charmonium production in e^+e^- annihilation on the Z-boson resonance. Although the experimental data from CERN LEP [7] are in agreement with the predicted signature, they do not exclude the hypothesis that the observed prompt-charmonium signal is produced by color-singlet processes alone. The analysis of low-energy e^+e^- data might be more instructive [8].

In this somewhat unsatisfactory situation, it would be very desirable if the experiments at the DESY ep collider HERA could probe the color-octet mechanism of charmonium production and independently measure the magnitude of the color-octet matrix elements. HERA is presently operated in such a way that $E_e = 27.5$ GeV positrons collide head-on with $E_p = 820$ GeV protons in the laboratory frame, so that approximately 300 GeV are available in the center-of-mass (CM) system. Charmonium production at HERA dominantly proceeds via photoproduction, where the incident positrons (or electrons) are scattered by small angles and effectively act as a source of quasi-real photons, which interact with the constituents of the incoming protons via hard scattering. The scattering can either be elastic, diffractive, or inelastic. In elastic scattering the protons stay intact, while in diffractive proton dissociation they are destroyed by a small momentum transfer from the photons. Both mechanisms may be interpreted by assuming that the protons interact with their environs by the exchange of so-called pomerons, so that an adequate theoretical treatment lies beyond the scope of the ordinary QCD-improved parton model. For a dedicated study of the color-octet processes, it is thus necessary to focus attention on inelastic scattering. In terms of the inelasticity variable $z = p_p \cdot p_{J/\psi}/p_p \cdot p_\gamma$, where p_p, p_γ, and $p_{J/\psi}$ are the proton, photon, and J/ψ four-momenta, respectively, this may be achieved by discarding events with z values close to unity. As may be inferred from the relation $z = 2E_p m_T \exp(-y_{\rm lab})/W^2$, where $y_{\rm lab}$ is the J/ψ rapidity in the laboratory frame (with $y_{\rm lab} > 0$ in the proton flight direction), $m_T = (M_{J/\psi}^2 + p_T^2)^{1/2}$ is its transverse mass, and W is the γp CM energy, inelastic events tend to have large $y_{\rm lab}$ and large W.

Recently, the H1 [9] and ZEUS [10] collaborations presented their 1994 data on the inelastic photoproduction of J/ψ mesons, collected in the kinematical ranges $0.45 < z < 0.9$, 30 GeV$< W <$ 150 GeV and $0.3 < z < 0.8$, 60 GeV$< W <$ 130 GeV, respectively. After dividing out the respective integrated photon flux factors, these data were compared [9, 10] with a next-to-leading-order (NLO) calculation [11] of $\gamma + p \to J/\psi + X$ via γg fusion [12] within the CSM, where W was fixed at the representative value W = 100 GeV. Although reasonable agreement was found [9, 10], one should bear in mind that the theoretical prediction strongly depends on the chosen input values for the charm-quark mass m_c, the asymptotic scale parameter Λ, the renormalization scale μ, and the factorization scale M_f, with the normalization uncertainty being as large as a factor of three [11]. One might hence conclude that there is still some room left for alternative J/ψ production mechanisms.

Very recently, the analysis of Ref. [11] was complemented [13] at leading order (LO) by including the $2 \to 2$ color-octet processes $\gamma + g \to c\bar{c}[\underline{8}, n] + g$ and $\gamma + q \to c\bar{c}[\underline{8}, n] + q$, where $n = {}^1S_0, {}^3S_1, {}^3P_J$ with $J = 0, 1, 2$. Adopting the color-octet matrix elements determined from fits [5] to the Tevatron data [1] on prompt J/ψ production, the authors of Ref. [13] found that the channels $\gamma + g \to c\bar{c}[\underline{8}, n] + g$ with $n = {}^1S_0, {}^3P_0, {}^3P_2$, the cross sections of which are divergent in the limit $z \to 1$, due to $g \to gg$ collinear splitting, dramatically increase the cross section of inelastic J/ψ photoproduction at HERA in the upper z range, at $z \gtrsim 0.8$. On the other hand, the color-octet contribution rapidly falls off for z decreasing, and is negligibly small already for $z \lesssim 0.6$ [13].

Being higher twist, γg fusion is only relevant if the produced J/ψ mesons have transverse momentum $p_T \lesssim M_{J/\psi} \approx 3$ GeV. In analogy to the situation at the Tevatron [3], at $p_T \gg M_{J/\psi}$, one expects fragmentation to be the dominant mechanism of inelastic J/ψ photoproduction at HERA, *i.e.*, single partons (mostly c, $\bar{c}$ quarks and gluons) that are produced with high p_T by the hard γp scattering fragment into J/ψ mesons. The purpose of this Letter is to present a NLO analysis of this mechanism in the framework of the QCD-improved parton model, and to assess the potential of HERA to probe the color-octet processes in the range of low to intermediate z values, thus providing an independent check of the Tevatron measurements.

A first study [14] of inelastic J/ψ photoproduction via fragmentation at HERA only included the Bethe-Heitler process $\gamma + g \to c + \bar{c}$ and the Compton process $\gamma + q \to g + q$ followed by $c \to J/\psi$ and $g \to J/\psi$ fragmentation at LO. These processes contribute to direct photoproduction, where the quasi-real photons couple directly to the quarks involved in the hard scattering. In a fraction of time, the quasi-real photons fluctuate into bunches of quarks and gluons, which in turn interact with the proton constituents via hard scattering, while the photon remnants give rise to hadronic activity in the backward direction (resolved photoproduction). The longitudinal-momentum distributions of the partons inside the resolved photons are described by parton density functions (PDF's). At NLO, the direct- and resolved-photon contributions both strongly depend on the factorization scheme and scale, and must be combined in order to give a well-defined physical observable. From previous experience in connection with inclusive pion, kaon [15], and $D^{*\pm}$ [16, 17] photoproduction at HERA, one may infer that, in the case of J/ψ photoproduction via fragmentation, the resolved-photon contribution, which was disregarded in Ref. [14], is likely to be much more important than the direct one. Furthermore, one expects a substantial enhancement due to the NLO corrections, which were neglected in Ref. [14].

The factorization formalism developed in Ref. [4] implies that the charmonium fragmentation functions have the general form

$$D_{i\to H}(x,\mu)=\sum_n d_{i\to n}(x,\mu)\langle 0|\mathcal{O}^H[n]|0\rangle, \tag{1}$$

where $d_{i\to n}(x,\mu)$ gives the probability for the parton i to form a jet that includes a $c\bar{c}$ pair in the state labelled by n carrying the longitudinal-momentum fraction x, and $\langle 0|\mathcal{O}^H[n]|0\rangle$ measures the probability for a pointlike $c\bar{c}$ pair in the state n to bind to form a physical charmonium state H. The coefficient $d_{i\to n}(x,\mu_0)$ at the initial scale $\mu_0=2m_c\approx M_{J/\psi}$ involves only momenta of order m_c, and can thus be calculated in nonrelativistic QCD as a perturbation expansion in the running coupling constant $\alpha_s(\mu_0)$ [3]. The evolution of $D_{i\to H}(x,\mu_0)$ up to higher fragmentation scales μ is ruled by the timelike Altarelli-Parisi equations, which may be conveniently solved at NLO in x space [17].

We take into account prompt J/ψ mesons as well as χ_{cJ} mesons ($J=0,1,2$) that radiatively decay to $J/\psi+\gamma$ with well-known branching fractions [18] (non-prompt J/ψ mesons). The dominant J/ψ (χ_{cJ}) Fock states are $[\underline{1},{}^3S_1]$ and $[\underline{8},{}^3S_1]$ ($[\underline{1},{}^3P_J]$ and $[\underline{8},{}^3S_1]$), respectively. The scaling of the respective matrix elements with the mass m_c and the relative velocity v of the bound c and $\bar{c}$ quarks is indicated in Table 1. In the case of J/ψ (χ_{cJ}), the color-singlet matrix element is related to the (derivative of the) nonrelativisitic radial wave at the origin and may thus be extracted from the measured leptonic (light hadronic) annihilation rate [19]. The color-octet matrix elements have been determined from fits [5] to Tevatron data [1]. The input values [19] adopted in our numerical analysis are also listed in Table 1. In the case of $D_{g\to J/\psi}$, the v^4 suppression of $\langle 0|\mathcal{O}^{J/\psi}[\underline{8},{}^3S_1]|0\rangle$ relative to $\langle 0|\mathcal{O}^{J/\psi}[\underline{1},{}^3S_1]|0\rangle$ is numerically compensated by the fact that $d_{g\to[\underline{8},{}^3S_1]}$ has two powers of α_s less than $d_{g\to[\underline{1},{}^3S_1]}$. Such a compensation does not occur for $D_{c\to J/\psi}$ and $D_{c\to\chi_{cJ}}$, so that color-octet fragmentation is negligible in these cases. The color-singlet and color-octet contributions to $D_{g\to\chi_{cJ}}$ are theoretically intertwined, since $d_{g\to[\underline{1},{}^3P_J]}$ has a logarithmic infrared singularity, which is absorbed into $\langle 0|\mathcal{O}^{\chi_{cJ}}[\underline{8},{}^3S_1]|0\rangle$.

We work at NLO in the $\overline{\mathrm{MS}}$ scheme with $n_f=4$ massless quark flavors, $\Lambda^{(4)}_{\overline{\mathrm{MS}}}=296$ MeV [20], and $\mu=M_f=m_T$. We take c and $\bar{c}$ to be active partons inside the proton and resolved photon, for which we adopt the CTEQ4M [20] and GRV [21] PDF's, respectively. As described in Ref. [16], we adjust the factorization of the final-state collinear singularities associated with c and $\bar{c}$ in such a way that it matches the massive calculation. We treat the quasi-real photon spectrum in the Weizsäcker-Williams approximation with a maximum virtuality of $Q^2_{\max} = 4$ GeV^2 as described in Ref. [16]. We compare our fragmentation results with the LO prediction for direct J/ψ photoproduction via γg fusion within the CSM [12], which we evaluate with the QCD-corrected value of $\langle 0|\mathcal{O}^{J/\psi}[\underline{1}, {}^3S_1]|0\rangle$ specified in Table 1. In this way, we include the bulk of the NLO enhancement, the residual dynamical QCD correction being of order 20% [11]. Direct χ_{cJ} photoproduction via γg fusion is forbidden at LO in the CMS, and it is marginal in the color-octet channel [22]. Resolved J/ψ photoproduction mediated by gg fusion, which receives both color-singlet and color-octet contributions, visibly contributes only at very low z and does not change the qualitative picture of γg fusion [22].

From Fig. 1, we observe that the fragmentation mechanism vastly dominates inelastic J/ψ photoproduction in the lower z range. For a minimum-p_T cut of 4 GeV (8 GeV), its contribution exceeds the one due to γg fusion for $z < 0.4$ (0.75), by factors of about 4 and 200 (20 and 700) at $z = 0.25$ and 0.05, respectively. The bulk of the fragmentation contribution is induced by resolved photons, except for z close to unity, where fragmentation is anyway insignificant. Since we wish to elaborate color-octet signatures at low and intermediate z, we regard γg fusion, which for $z \lesssim 0.6$ is well described by the CSM [13], as a background. As is evident from Fig. 2, we may efficiently suppress this background by introducing a stringent maximum-z cut, of 0.4 say. In fact, if the maximum-z cut is lowered from 0.8 to 0.4, the cross section of γg fusion at $p_T = 2$ GeV (10 GeV) is reduced by a factor of 4.2 (2.8), while that of fragmentation is only insignificantly decreased, by 11% (15%). At $p_T = 2$ GeV (10 GeV), 2% and 30% (4% and 24%) of the fragmentation cross section integrated over $0.05 < z < 0.4$ are due to the prompt color-singlet and non-prompt channels, respectively. Thus, this regime offers a unique laboratory to probe the prompt color-octet channel and thus to measure $\langle 0|\mathcal{O}^{J/\psi}[\underline{8}, {}^3S_1]|0\rangle$, so as to check the Tevatron result. Even for $0.05 < z < 0.8$, the fragmentation cross section in Fig. 2 is in excess of the one due to γg fusion. As may be inferred from Fig. 1, this is subject to change if the minimum-z cut is increased. This is illustrated in Fig. 3, where the ZEUS $J/\psi \to \mu^+\mu^-$ data [10] collected in the interval $0.3 < z < 0.8$ are compared with the respective fragmentation and γg-fusion predictions. We have divided the experimental data points by the estimated extrapolation factor 1.07 which was included in Ref. [10] to account for the unmeasured contribution from $0 < z < 0.3$. In fact, our combined analysis of fragmentation and γg fusion suggests that, at $p_T = 2$ GeV (5 GeV), this factor should be as large as 5.2 (3.4). The corresponding value for $0.05 < z < 0.3$ is 2.6 (2.6). The gap between the combined result for $0.3 < z < 0.8$ and the ZEUS data is partly filled by the dynamical NLO corrections [11] and the color-octet contributions [13] to γg-fusion, which are not included in Fig. 3.

In conclusion, the cross section of inelastic J/ψ photoproduction in ep collisions at low z and large p_T is very sensitive to the color-octet matrix element $\langle 0|\mathcal{O}^{J/\psi}[\underline{8}, {}^3S_1]|0\rangle$. We propose to accordingly extend previous measurements of this cross section at HERA, in order to obtain an independent, nontrivial check of the Tevatron color-octet charmonium puzzle.

Table 1: Values [19] of the matrix elements used in the numerical analysis and their mass and velocity scaling. The relations between the J-dependent matrix elements follow from heavy-quark spin symmetry.

$\langle 0 \vert \mathcal{O}^{J/\psi}[\underline{1}, {}^3S_1] \vert 0 \rangle$	1.13 GeV^3	$[m_c^3 v^3]$
$\langle 0 \vert \mathcal{O}^{J/\psi}[\underline{8}, {}^3S_1] \vert 0 \rangle$	0.014 GeV^3	$[m_c^3 v^7]$
$\langle 0 \vert \mathcal{O}^{\chi_{cJ}}[\underline{1}, {}^3P_J] \vert 0 \rangle / (2J+1)$	0.0880 GeV^5	$[m_c^5 v^5]$
$\langle 0 \vert \mathcal{O}^{\chi_{cJ}}[\underline{8}, {}^3S_1] \vert 0 \rangle / (2J+1)$	0.0076 GeV^3	$[m_c^3 v^5]$

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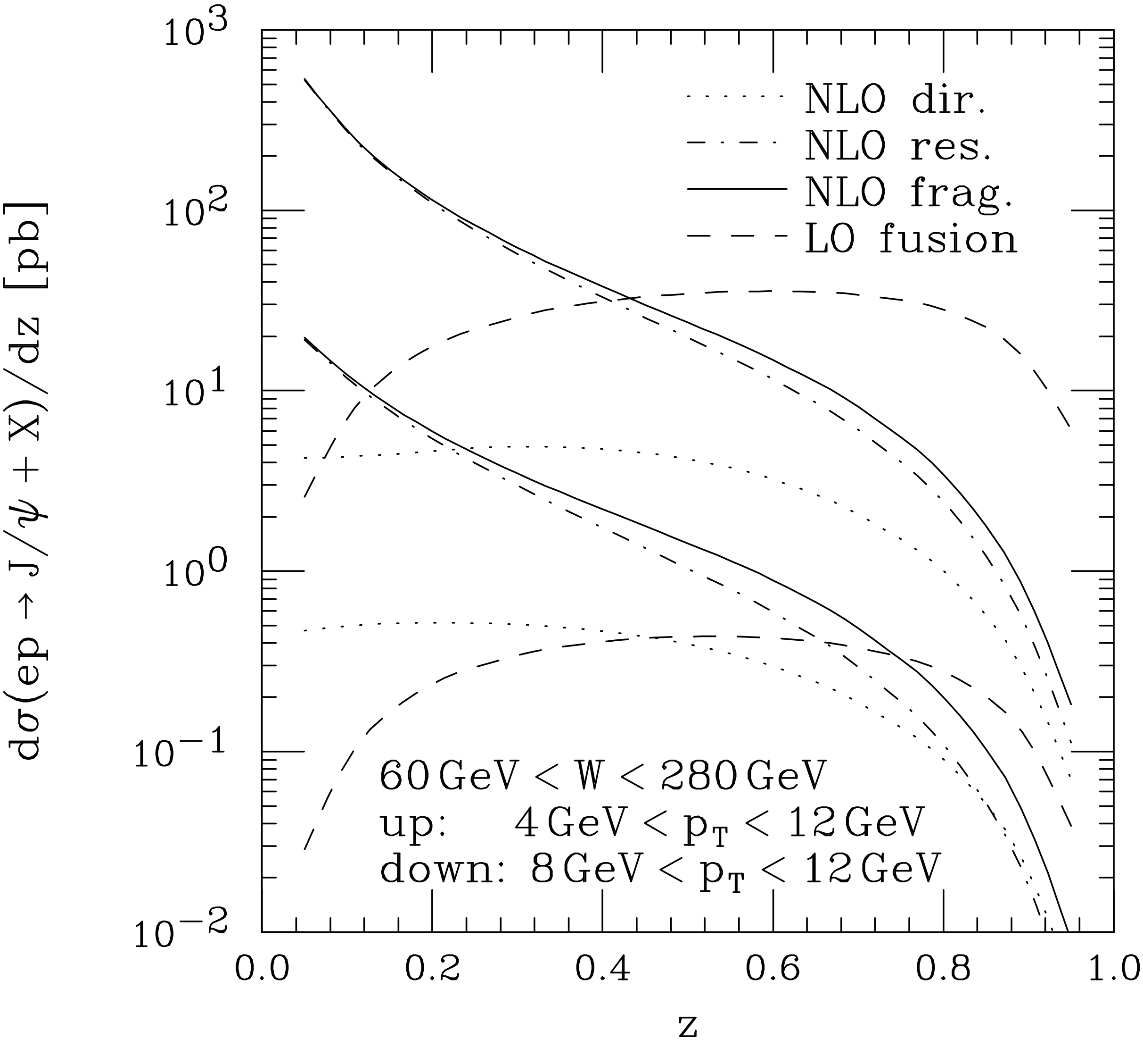

Figure 1: Cross section $d\sigma/dz$ of inelastic J/ψ photoproduction at HERA, integrated over 60 GeV $< W <$ 280 GeV and 4 GeV $< p_T <$ 12 GeV (upper curves) or 8 GeV $< p_T <$ 12 GeV (lower curves). The NLO fragmentation contributions due to direct photons (dotted lines), resolved photons (dot-dashed lines), and their sum (solid lines) are compared with the LO γg-fusion contribution (dashed lines).

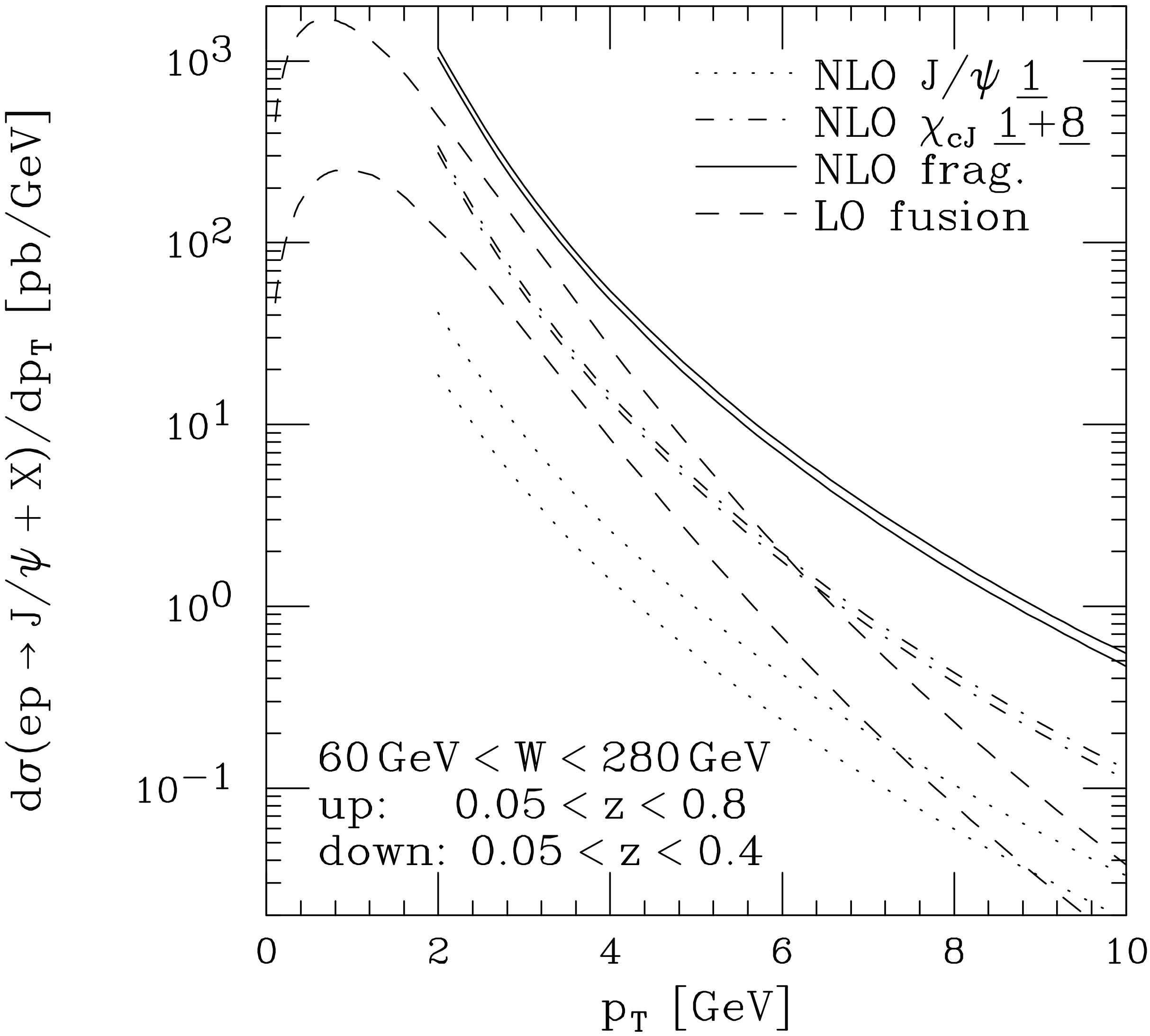

Figure 2: Cross section $d\sigma/dp_T$ of inelastic J/ψ photoproduction at HERA, integrated over 60 GeV $< W <$ 280 GeV and $0.05 < z < 0.8$ (upper curves) or $0.05 < z < 0.4$ (lower curves). The total NLO fragmentation contribution (solid lines) is compared with the LO γg-fusion contribution (dashed lines). For comparison, also the prompt color-singlet (dotted lines) and the non-prompt (dot-dashed lines) fragmentation contributions are shown.

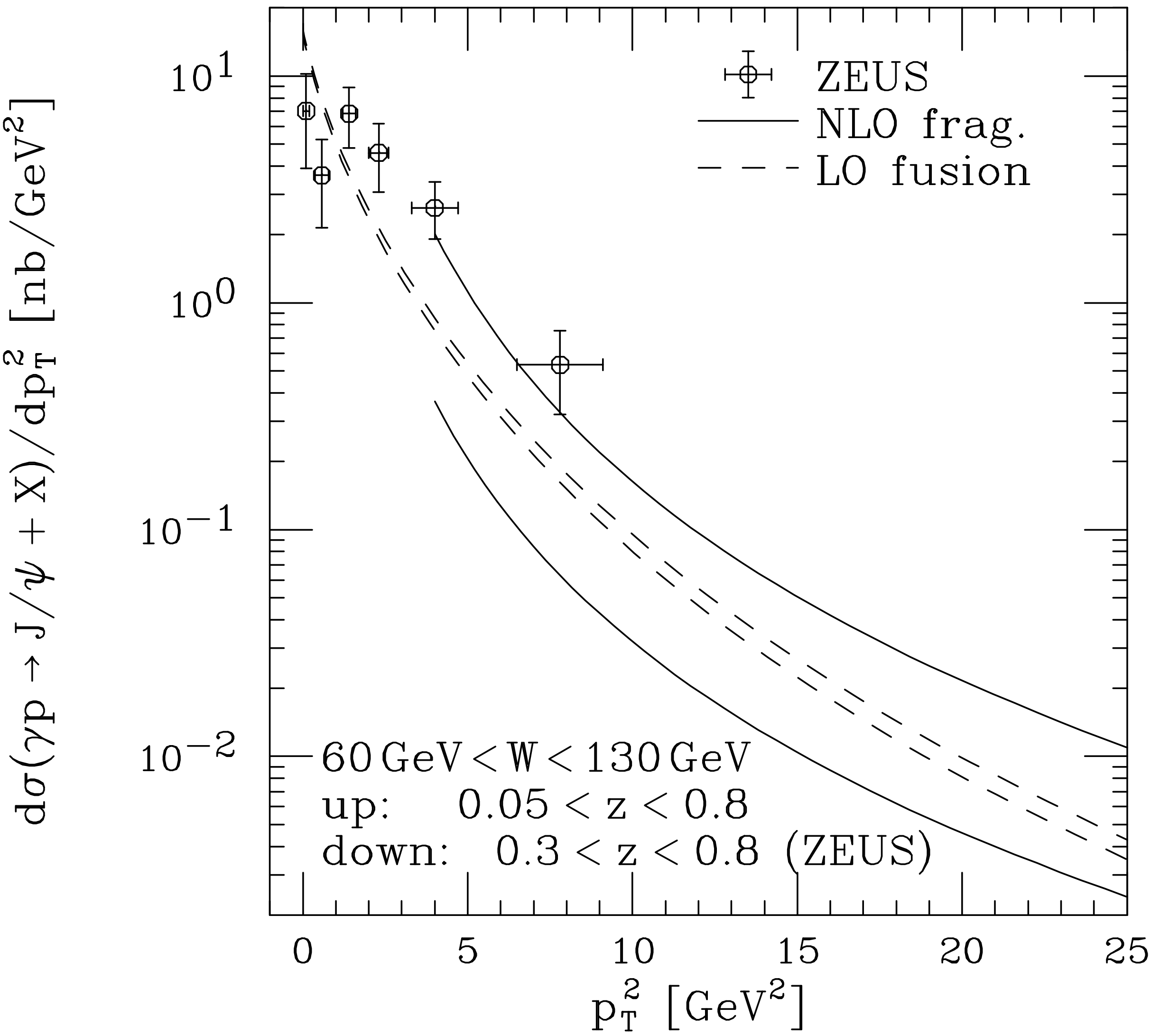

Figure 3: Cross section $d\sigma/dp_T^2$ of inelastic J/ψ photoproduction at HERA, integrated over 60 GeV $< W <$ 130 GeV and $0.3 < z < 0.8$ (lower curves) and divided by the corresponding photon flux factor, 6.66×10^{-2}. The total NLO fragmentation (solid lines) and LO γg-fusion (dashed lines) contributions are compared with the ZEUS data [10]. For comparison, the theoretical results are also shown for $0.05 < z < 0.8$ (upper curves).