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J/ψ production via fragmentation at HERA

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ABSTRACT

We compute the contributions to large-p_T J/ψ production at HERA coming from fragmentation of gluons and charm quarks. We find that the charm quark fragmentation contribution dominates over the direct production of J/ψ via photon-gluon fusion at large-p_T, while the gluon fragmentation is negligibly small over the whole range of p_T. An experimental study of p_T distributions of J/ψ at HERA will provide a direct probe of the charm quark fragmentation functions.

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The anomalously large cross-section for J/ψ production at large transverse momentum, p_T, measured [1] recently in the CDF experiment at the Tevatron has led to a revision of earlier ideas based on the lowest order QCD process of parton fusion. In this approach [2, 3], the dominant contribution to quarkonium production was expected to come from quark-antiquark or gluon-gluon fusion, leading to the formation of a heavy-quark pair in a colour-singlet state with the correct spin, parity and charge-conjugation assignments projected out. Several recent works [4, 5, 6, 7] have drawn attention to additional contributions to quarkonium production coming from the fragmentation of gluons and heavy quark jets. Even though the fragmentation contributions are of higher order in α_s compared to fusion, they are enhanced by powers of p_T^2/m^2, where m is the heavy quark mass. Consequently, they can overtake the fusion contribution at $p_T \gg m$. Indeed, the CDF J/ψ production data [1] has been successfully explained by several authors [8] by taking into account both the fusion and fragmentation contributions. The gluon fragmentation contribution is found to dominate over fusion at large p_T ($p_T > 5$ GeV), while the charm quark fragmentation contribution is much too small. As we shall see in this letter, the photoproduction of J/ψ at HERA presents a complementary process – i.e. the charm quark fragmentation is expected to overtake fusion at large-p_T, while the gluon fragmentation remains small. Thus a measurement of the large-p_T J/ψ production cross-section at HERA will provide a valuable probe for the charm quark fragmentation contribution.

A brief discussion of the colour-singlet model, used in the computation of both fusion and fragmentation contributions, is in order. Strictly speaking, the colour-singlet model is a non-relativistic model where the relative velocity between the heavy quarks in the bound state is ignored. However, in general, the relative velocity, v, in quarkonium systems is not negligible and O(v) corrections need to be taken into account. Starting from a non-relativistic QCD Lagrangian, a systematic analysis using the factorisation method has been recently carried out by Bodwin, Braaten and Lepage [9]. In this formulation, the quarkonium wave-function admits of a systematic expansion in powers of v in terms of Fock-space components : for example, the wave-functions for the P-state charmonia have the conventional colour-singlet P-state component at leading order, but there exist additional contributions at non-leading order in v, which involve octet S-state components; i.e.

$$|\chi_J\rangle = O(1)|Q\bar{Q}[^3P_J^{(1)}]\rangle + O(v)|Q\bar{Q}[^3S_1^{(8)}]g\rangle + \dots \quad (1)$$

In spite of the fact that the octet component in the wave-function is suppressed by a factor of v, it is important for the decays of P-states [10] for the following reasons : 1) The P-state wave-function is already suppressed by a factor of v owing to the angular-momentum barrier; but the corresponding colour-octet component is an S-state which is unhindered by this barrier. The colour-octet component can, therefore, easily compete with the colour-singlet. 2) The second reason is even more compelling : the perturbative analyses of P-wave decays of quarkonia [11] reveal a logarithmic infrared singularity. But the octet component allows the infrared singularity to be absorbed via a wave-function renormalisation, without having to introduce an arbitrary infrared cut-off. So a consistent perturbative treatment of P-state decays necessarily involves the octet component. The price to pay for this is that two independent matrix-elements, viz., the singlet and the octet matrix elements are needed, unlike the case of the colour-singlet model where the entire long-distance information could be factorised into a *single* non-perturbative matrix-element. As in the case of the P-state decay widths, the P-state fragmentation functions also involve the octet component [5]. The octet component appears in the computation of the fusion contribution as well, but is negligible in the large-p_T region of our interest.

For S-state resonances like the J/ψ and the ψ', the octet contribution is suppressed by powers of v. Further, the S-wave amplitude is not infrared divergent and can, therefore, be described in terms of a single colour-singlet matrix-element. But recently, the CDF collaboration has measured [12] the ratio of J/ψ's coming from χ decays to those produced directly and it turns out that the direct S-state production is much larger than the theoretical estimate. It has been suggested [13] that a colour octet component in the S-wave production coming from gluon fragmentation as originally proposed in Ref. [14], can explain this J/ψ anomaly. This corresponds to a virtual gluon fragmenting into an octet $^3S_1$ state which then makes a double E1 transition into a singlet $^3S_1$ state. While this process is suppressed by a factor of v^4 as compared to the colour-singlet process, it is enhanced by a factor of α_s^2. One can fix the value of the colour-octet matrix-element by normalising to the data on direct J/ψ production cross-section from the CDF experiment. The colour-octet contribution to S-state production has also been invoked [14] to explain the large ψ' cross-section measured by CDF [1], but there can be a large contribution to this cross-section coming from the decays of radially excited P-states [15]. Independent tests of the S-state colour octet enhancement are important and there have been recent suggestions [16] as to how one can use e^+e^- collisions to probe the octet contribution. Thus, the possibility of a large colour-octet contribution to the S-state fragmentation function remains open, though theoretically less compelling than for the P-state. We shall see below that the inclusive photoproduction of J/ψ is insensitive to the former, but it is sensitive to the latter.

In this letter, we study inclusive J/ψ production in ep collisions at HERA. The fusion contribution to the photoproduction of J/ψ in the colour-singlet model [2] comes from photon-gluon fusion. Recently, the next-to-leading order corrections to this process have been computed within the colour-singlet model [17] and compared [18] with the results on integrated cross-sections from HERA; and it has been found that the integrated cross-sections at next-to-leading order are in reasonable agreement with the data. The integrated cross-sections are, however, insensitive to the fragmentation contributions, because the latter dominate only at large p_T. To get a handle on the fragmentation contributions to J/ψ production at HERA it is important to study the p_T distributions, rather than integrated cross-sections.

The fusion contribution to the photoproduction of J/ψ in the colour-singlet model takes place through the following subprocess:

$$\gamma + g \rightarrow c\bar{c}[{}^3S_1^{(1)}] + g, \tag{2}$$

where the J/ψ is taken to be the colour-singlet ${}^3S_1$ $c\bar{c}$ state. The p_T differential cross-section for the photoproduction of J/ψ in the colour-singlet model is given as

$$\frac{d\sigma}{dp_T} = \int dz \frac{128\pi^2\alpha_s^2\alpha p_T x G(x) z(1-z) M e_c^2 R_0^2}{27[M^2(1-z)+p_T^2]^2} \cdot f(z, p_T^2), \tag{3}$$

where

$$\begin{aligned} f(z, p_T^2) \quad = \quad & \frac{1}{(M^2+p_T^2)^2} + \frac{(1-z)^4}{[p_T^2 + M^2(1-z)^2]^2} \\ & + \frac{z^4 p_T^4}{(M^2+P_T^2)^2[p_T^2+M^2(1-z)^2]^2}. \end{aligned} \tag{4}$$

In the above equation, the variable z is the inelasticity variable, defined as

$$z = \frac{p_\psi \cdot p_p}{p_\gamma \cdot p_p}, \tag{5}$$

and x is related to p_T and z ,

$$x = \frac{1}{s}\Big[\frac{M^2}{z} + \frac{p_T^2}{z(1-z)}\Big], \tag{6}$$

where $s = 4E_p\nu$ is the photon-proton c.m. energy. As usual, M and R_0 denote the J/ψ mass and wave function at the origin.

The fragmentation contribution is computed by factorising the cross-section for the process $\gamma p \rightarrow (J/\psi, \chi_i)X$ into a part containing the hard-scattering cross-section for producing a gluon or a charm quark and a part which specifies the fragmentation of the gluon or the charm quark into the required charmonium state, i.e.

$$d\sigma(\gamma p \rightarrow (J/\psi, \chi_i)X) = \sum_c \int_0^1 d\omega \; d\sigma(\gamma p \rightarrow cX) D_{c \rightarrow (J/\psi, \chi_i)}(\omega, \mu), \tag{7}$$

where c is the fragmenting parton (either a gluon or a charm quark). $D(\omega, \mu)$ is the fragmentation function and ω is the fraction of the momentum of the parent parton carried by the charmonium state[1]. The fragmentation function is computed perturbatively at an initial scale μ_0 which is of the order of m_c. If the scale μ is chosen to be of the order of p_T, then large logarithms in μ/m_c appear which have then to be resummed using the usual Altarelli-Parisi equation:

$$\mu\frac{\partial}{\partial\mu}D_{i\to(J/\psi,\chi_i)}(\omega) = \sum_j \int_\omega^1 \frac{dy}{y} P_{ij}(\frac{\omega}{y},\mu) D_{j\to(J/\psi,\chi_i)}(y), \tag{8}$$

where the P_{ij} are the splitting functions of a parton j into a parton i. We consider the fragmentation of gluons and charm quarks alone since the light quark contributions are expected to be very small. The gluons are produced via the Compton process:

$$\gamma + q \to q + g, \tag{9}$$

whereas the charm quarks are produced via the Bethe-Heitler process:

$$\gamma + g \to c + \bar{c}. \tag{10}$$

Using these cross-sections, we compute the fragmentation contribution to $d\sigma/dp_T$ which is given by a formula similar to Eq. 3, but with an extra integration over ω, or equivalently over x, because of the relation

$$\omega = \frac{M^2 + p_T^2}{xsz} + z. \tag{11}$$

For the fragmentation functions at the initial scale $\mu = \mu_0$, we use the results of Refs. [4] and [5] for the gluon fragmentation functions into J/ψ or χ states, and Refs. [6] and [7] for the corresponding fragmentation functions of the charm quark. These fragmentation functions include the colour-octet component in the P-state, but do not include any colour-octet contribution in the S-state. For the case of gluon fragmentation, we have separately studied the effect of the S-state colour-octet component by modifying the fragmentation functions as in Ref. [14]. For the charm fragmentation, the S-state colour-octet contributions are sub-dominant and we have neglected these contributions. In principle, at HERA energies we can also expect contributions from B-decays but these turn out to be dominant at values of $z \leq 0.1$ [19], and can, therefore, be safely neglected in our analysis.

We have computed the cross-sections for two representative values of the photon energy, ν, using the MRSD-$'$ structure functions [20] and we have used $Q = p_T/2$ as the choice of scale. In principle, one can integrate over the photon energy spectrum; but for the purposes of studying the relative magnitudes of the fusion and fragmentation contributions to the cross-sections, it is enough and indeed more transparent to

[1] We use the notation ω instead of the more usual z to avoid confusion with the inelasticity parameter, defined in Eq. 5.

present the results for fixed values of ν. In Fig. 1, we present the results for $d\sigma/dp_T$ as a function of p_T, for $\nu = 40$ and 100 GeV. For the inelasticity parameter, we use the cuts $0.1 \leq z \leq 0.9$, as used in the ZEUS experiment at HERA [21]. We find that the fusion contribution, shown by the solid line in Fig. 1, is dominant at low p_T, but the charm quark fragmentation contribution (shown by the dashed-dotted line) becomes important for values of p_T greater than about 10 GeV. The gluon fragmentation contribution (shown by the dashed line in the figure) is smaller by over an order of magnitude throughout the range of p_T considered. Also shown as the dotted line in the figure is the gluon fragmentation contribution including the octet contribution for the S-state, where the numerical value of the octet S-wave matrix element has been determined [13, 14] from the CDF data [12] as mentioned above. The major uncertainty in the prediction is due to the limited information we have on the colour-octet matrix elements; the normalisation of the fragmentation contribution can change by a factor of 2-3, due to this uncertainty [8]. Moreover, next-to-leading order corrections will also change the absolute normalisation of our predictions – for the fusion prediction this is expected to give an enhancement (K-factor) upto a factor of 2 [18] and similar K-factors are also expected in the case of fragmentation contributions. However, our choice of $p_T/2$ as the scale (instead of p_T) is expected to account for the K-factor enhancement, at least in part.

The charm fragmentation subprocess (Eq. 10) is gluon-initiated while the gluon fragmentation subprocess (Eq. 9) is quark-initiated. This explains why the charm fragmentation process dominates. It is important to note that gluon fragmentation turns out to be the most important source of J/ψ production at the Tevatron, while the complementary information on the fragmentation of charm quarks can be studied at HERA. An experimental study of p_T distributions at HERA will provide us with the first direct measurement of the charm quark fragmentation functions.

Since the J/ψ's produced in the fragmentation process are softer in energy than those produced *via* fusion, it turns out that the average value of z for the former are smaller than the latter. To enhance the fragmentation contribution, it is efficient to use a stronger upper cut on z. In Fig. 2, we have shown the cross-sections for J/ψ's produced via fusion and from charm quark fragmentation with $z < 0.5$. We find that this cut helps to cut down the fusion contribution to J/ψ without significantly affecting the charm fragmentation contribution, thereby providing a better signal for the fragmentation process.

To summarise, we have studied the p_T distribution of J/ψ cross-sections at HERA coming from the fusion and fragmentation processes. We find that the large-p_T end is dominated by contributions from charm quark fragmentation. The information that can be obtained from HERA is thus complementary to that obtained from the large-p_T J/ψ production at the Tevatron, which is dominated by the gluon fragmentation contribution. By applying judicious cuts on the inelasticity parameter z it is possible to enhance the charm fragmentation contribution relative to the fusion contribution.

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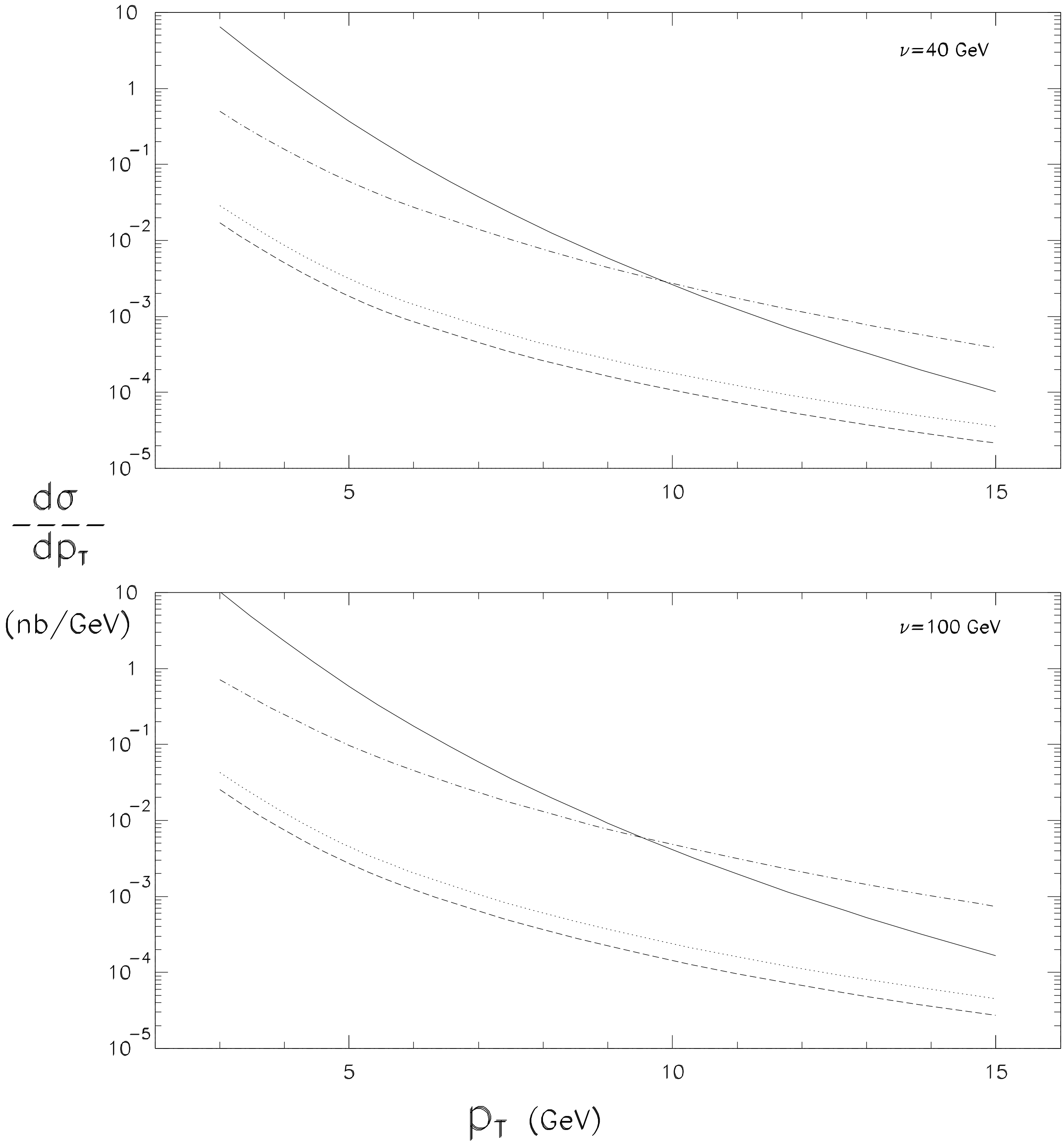

Figure 1: $d\sigma/dp_T$ (in nb/GeV) for inclusive J/ψ production at HERA for photon energy $\nu = 40$ GeV (upper figure) and $\nu = 100$ GeV (lower figure). The solid line represents the fusion contribution and the dashed-dotted line the charm quark fragmentation contribution. The dotted and dashed lines represent the gluon fragmentation contributions with and without a colour-octet component for the S-state. The cut on the inelasticity parameter, z, is $0.1 < z < 0.9$.

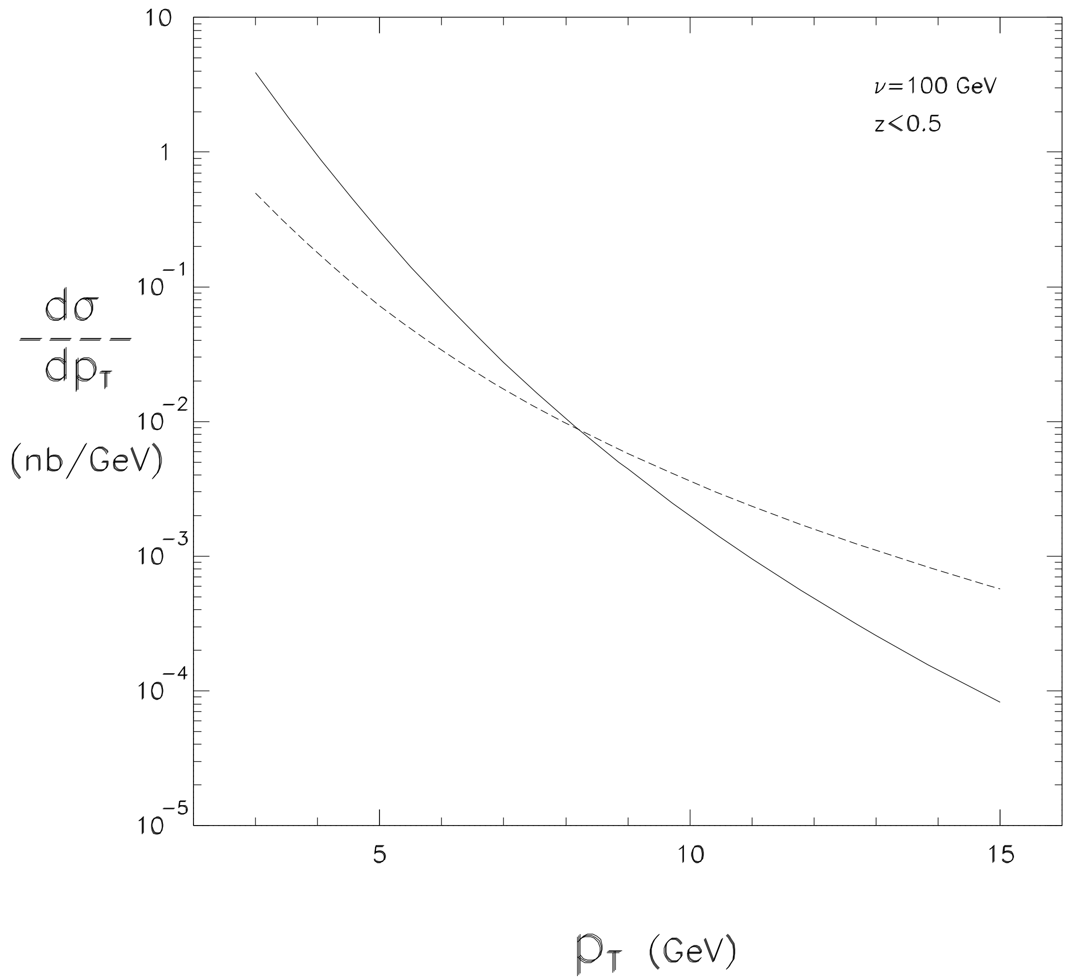

Figure 2: $d\sigma/dp_T$ (in nb/GeV) for photon energy $\nu = 100$ GeV. The solid line represents the fusion contribution, and the dashed line the charm quark fragmentation contribution, using a cut $z < 0.5$.