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 $J/\psi$ production at large transverse momentum, $p_T$, measured \cite{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 \cite{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 \cite{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 $\alpha_s$ 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 $J/\psi$ production data \cite{1} has been successfully explained by several authors \cite{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 $J/\psi$ 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-$p_T$ $J/\psi$ 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 \cite{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.

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

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 \cite{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 \cite{1} 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 \cite{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 $J/\psi$ and the $\psi'$, 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 \cite{12} the ratio of $J/\psi$'s coming from $\chi$ 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 \cite{13} that a colour octet component in the $S$-wave production coming from gluon fragmentation as originally proposed in Ref. \cite{14}, can explain this $J/\psi$ 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 $\alpha_s^2$. One can fix the value of the colour-octet matrix-element by normalising to the data on direct $J/\psi$ production cross-section from the CDF experiment. The colour-octet contribution to $S$-state production has also been invoked \cite{14} to explain the large $\psi'$ cross-section measured by CDF \cite{1}, but there can be a large contribution to this cross-section coming from the decays of radially excited $P$-states \cite{13}. Independent tests of the $S$-state colour octet enhancement are important and there have been recent suggestions \cite{11} 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 $J/\psi$ is insensitive to the former, but it is sensitive to the latter.

In this letter, we study inclusive $J/\psi$ production in $ep$ collisions at HERA. The fusion contribution to the photoproduction of $J/\psi$ in the colour-singlet model \cite{2} comes from photon-gluon fusion. Recently, the next-to-leading order corrections to this process have been computed within the colour-singlet model \cite{17} and compared \cite{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 $J/\psi$ production at HERA it is important to study the $p_T$ distributions, rather than integrated cross-sections.

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

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

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

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

where

$$f(z, p_T^2) = \frac{1}{(M^2 + p_T^2)^2} + \frac{(1-z)^4}{[p_T^2 + M^2(1-z)^2]^2} + \frac{z^4p_T^4}{(M^2 + p_T^2)^2[p_T^2 + M^2(1-z)^2]^2}.$$ 

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

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

and $x$ is related to $p_T$ and $z$,

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

where $s = 4E_p\nu$ is the photon-proton c.m. energy. As usual, $M$ and $R_0$ denote the $J/\psi$ 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.

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

where $c$ is the fragmenting parton (either a gluon or a charm quark). $D(\omega, \mu)$ is the fragmentation function and $\omega$ is the fraction of the momentum of the parent parton.
carried by the charmonium state\textsuperscript{1}. The fragmentation function is computed perturbatively at an initial scale $\mu_0$ which is of the order of $m_c$. If the scale $\mu$ is chosen to be of the order of $p_T$, then large logarithms in $\mu/m_c$ appear which have then to be resummed using the usual Altarelli-Parisi equation:

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

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:

$$
\gamma + q \rightarrow q + g,
$$

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

$$
\gamma + g \rightarrow c + \bar{c}.
$$

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 $\omega$, or equivalently over $x$, because of the relation

$$
\omega = \frac{M^2 + p_T^2}{xs} + z.
$$

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 $J/\psi$ or $\chi$ states, and Refs. \[4\] 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, $\nu$, using the MRSD-\textsuperscript{′} 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 $\omega$ instead of the more usual $z$ to avoid confusion with the inelasticity parameter, defined in Eq. 3.
present the results for fixed values of $\nu$. 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) up to 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 $J/\psi$ 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 $J/\psi$'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 $J/\psi$'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 $J/\psi$ 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 $J/\psi$ 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-$p_T$ $J/\psi$ 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.
References


Figure 1: \( \frac{d\sigma}{dp_T} \) (in nb/GeV) for inclusive J/\( \psi \) 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 $z < 0.5$. 