Charmonium production at the LHC

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ABSTRACT

The analyses of large transverse momentum charmonium production at the Tevatron have shown that fragmentation of gluons is an important production mechanism. We study large-$p_T$ charmonium production in $pp$ collisions at the LHC, and find that due to the copious gluon production at this energy, the gluon fragmentation contribution completely overwhelms the fusion contribution and the charm quark fragmentation contribution. Our analysis shows that for $J/\psi$ production at the LHC, there is a significant event rate even for $p_T \sim 100$ GeV. The measurement of the cross-section at such large values of $p_T$ will provide a very important test of the fragmentation mechanism.

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The production of quarkonia has conventionally been described in terms of the colour-singlet model \[1, 2\]. In this model, a non-relativistic approximation is used to describe the binding of the heavy-quark pair produced via parton-fusion processes, into a quarkonium state. The heavy-quark pair is projected onto a physical quarkonium state using a colour-singlet projection and an appropriate spin-projection. It is also necessary to account for $J/\psi$'s produced via electromagnetic decays of the $P$-states, viz., the $\chi$'s, since inclusive $J/\psi$ production is measured in experiments. In the model, both the direct $S$-state production and the indirect production via $P$-state decays are accounted for. This model has been successfully applied \[2\] to describe large-$p_T J/\psi$ production at the relatively low energies in the ISR experiment. In going from the ISR energy ($\sqrt{s} = 63$ GeV) to the UA1 energy ($\sqrt{s} = 630$ GeV), it was found \[3\] that the production of $b$-quarks and their subsequent decay becomes an important source of $J/\psi$ production. While at the UA1 experiment it was not possible to separate the $b$-quark contribution, the use of the silicon-vertex detector at the CDF experiment in studying $J/\psi$ production in $\bar{p}p$ collisions at the Tevatron ($\sqrt{s} = 1.8$ TeV) allows the subtraction of the $b$-quark contribution from the total yield, thereby providing a measurement of direct inclusive $J/\psi$ production at large-$p_T$. The inclusive $J/\psi$ production cross-section measured by the CDF experiment \[4\] turned out to be an order of magnitude larger than the prediction of the colour-singlet model.

In fact, even before the experimental results from the CDF collaboration were available, it was shown by Braaten and Yuan \[5\] that in addition to the parton fusion contributions taken into account in the colour-singlet model, fragmentation of gluons and charm quarks could be an important source of large-$p_T J/\psi$ production. In the fragmentation process, one considers the production of charmonia from final-state gluons or charm quarks which have large $p_T$, but almost zero virtuality. The fragmentation contribution is computed by factorising the cross-section for the process $AB \rightarrow (J/\psi, \chi_i)X$ (where $A, B$ denote hadrons) 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.

$$ d\sigma(AB \rightarrow (J/\psi, \chi_i)X) = \sum_c \int_0^1 dz \, d\sigma(AB \rightarrow cX)D_{c \rightarrow (J/\psi, \chi_i)}(z, \mu), \quad (1) $$

where $c$ is the fragmenting parton (either a gluon or a charm quark). $D(z, \mu)$ is the fragmentation function and $z$ is the fraction of the momentum of the parent parton carried by the charmonium state. Because the gluon or the $c$-quark fragments into a heavy quarkonium state, the fragmentation function can be computed perturbatively, in the same spirit as in the colour-singlet model. This yields the fragmentation function 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 to be resummed using
the usual Altarelli-Parisi equation:
\[
\mu \frac{\partial}{\partial \mu} D_{i \rightarrow (J/\psi, \chi)}(z) = \sum_j \int_z^1 \frac{dy}{y} P_{ij}(\frac{z}{y}, \mu) D_{j \rightarrow (J/\psi, \chi)}(y),
\]
(2)

where the \( P_{ij} \) are the splitting functions of a parton \( j \) into a parton \( i \). Only the fragmentation of gluons and charm quarks need be considered since the light quark contributions are expected to be very small. The fragmentation functions for the fragmentation of gluons and charm quarks at the initial scale \( \mu_0 \) have been calculated \([5, 6, 7, 8, 9]\) and using these as inputs several authors \([10]\) have computed the contributions coming from fragmentation to the total \( J/\psi \) yield and have found that the gluon fragmentation contribution significantly increases the cross-section, and the order-of-magnitude discrepancy between the theory and the data from the CDF experiment can be resolved. The analyses of the CDF data, thus, demonstrates the importance of the fragmentation mechanism as an important source of \( J/\psi \) production at large \( p_T \).

It is important to study this mechanism in other processes. Some studies have already been made and fragmentation is predicted to have significant effects in \( J/\psi \) photoproduction at large-\( p_T \) at HERA \([11]\), and in \( J/\psi \) pair production at the Tevatron \([12]\). A preliminary study \([13]\) of higher-order corrections to the fragmentation contribution in the case of \( 1S_0 \) production has been made, and shows the possible importance of the higher-order corrections to fragmentation.

Another important aspect of the physics of quarkonia revealed by the analyses of the CDF data is the importance of colour-octet contributions, which are ignored in the colour-singlet model because in this model the relative velocity, \( v \), between the heavy quarks in the bound state is ignored. However \( v \) is, in general, not negligible and \( O(v) \) corrections need to be taken into account. A systematic formulation based on non-relativistic QCD, using the factorisation method has been recently carried out \([14]\), and 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 \( \chi \) states have the 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.

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

The importance of the colour-octet components has already been seen in the analysis of the decays of the \( \chi \) states \([15]\) where the colour-singlet analysis \([16]\) reveals 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. Thus, a consistent perturbation theory of \( \chi \) decays necessiates the inclusion of the octet component of the wave-function. As in the case of decays, the \( P \)-state fragmentation functions are also infra-red divergent \([6]\) and, hence, they include the octet component.
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 [17] 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 [18] that a colour octet component in the $S$-wave production coming from gluon fragmentation as originally proposed in Ref. [19], 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 [19] to explain the large $\psi'$ cross-section measured by CDF [4], but there can be a large contribution to this cross-section coming from the decays of radially excited $P$-states [20]. Independent tests of the $S$-state colour octet enhancement are important and recent work shows that a different linear combination of the same colour octet-matrix elements that appear in the Tevatron analysis also appears in the analyses of photoproduction [21] and hadroproduction experiments [22]. These analyses provide an important cross-check on the colour-octet picture and are very important in constraining the magnitude of the octet contributions.

In this letter, we examine the implications of these two new physics aspects of quarkonium production viz., fragmentation and the colour-octet contributions, for $J/\psi$ and $\psi'$ production at the LHC. At the LHC energy, we expect gluon fragmentation to be the most important source of charmonium production at large $p_T$, and the knowledge of the fragmentation mechanism and the octet wave-functions gleaned from the study of charmonium resonances at the Tevatron can be tested at the LHC. The large-$p_T$ production cross-section for the fusion process is given as

$$\frac{d\sigma}{dp_T}(AB \rightarrow (J/\psi, \chi_i)X) =$$

$$\sum \int dy \int dx_1 x_1 G_{a/A}(x_1)x_2 G_{b/B}(x_2) \frac{4p_T}{2x_1 - \bar{x_T}e^y} \frac{d\hat{\sigma}}{dt}(ab \rightarrow (J/\psi, \chi_i)c). \quad (4)$$

In the above expression, the sum runs over all the partons contributing to the subprocesses $ab \rightarrow (J/\psi, \chi_i)c$; $G_{a/A}$ and $G_{b/B}$ are the distributions of the partons $a$ and $b$ in the hadrons $A$ and $B$ with momentum fractions $x_1$ and $x_2$, respectively. Energy-momentum conservation determines $x_2$ to be

$$x_2 = \frac{x_1 \bar{x_T}e^{-y} - 2\tau}{2x_1 - \bar{x_T}e^y}, \quad (5)$$

3
where \( \tau = M^2/s \), with \( M \) the mass of the resonance, \( s \) the centre-of-mass energy and \( y \) the rapidity at which the resonance is produced.

\[
\bar{x}_T = \sqrt{x_T^2 + 4\tau} \equiv \frac{2M_T}{\sqrt{s}}, \quad x_T = \frac{2p_T}{\sqrt{s}}
\]

(6)

The expressions for the subprocess cross-sections, \( d\hat{\sigma}/d\hat{t} \), are given in Refs. [2] and [23].

For the fragmentation process, the cross-section is given by a formula similar to Eq. (4) but with an extra integration over \( z \), or equivalently over \( x_2 \). We have

\[
\frac{d\sigma}{dp_T}(AB \rightarrow (J/\psi, \chi_i)X) = \sum \int dydx_1dx_2 G_{a/A}(x_1)G_{b/B}(x_2)D_{c \rightarrow (J/\psi, \chi_i)}(z) \frac{2p_T}{z} \frac{d\hat{\sigma}}{d\hat{t}}(ab \rightarrow cd),
\]

(7)

with \( z \) given by

\[
z = \frac{\bar{x}_T}{2} \left( e^{-y} + e^{y} \right).
\]

(8)

For \( d\hat{\sigma}/d\hat{t}(ab \rightarrow cd) \), we have used the lowest-order expressions. For the fragmentation functions at the initial scale \( \mu = \mu_0 \), we use the results of Refs. [5] and [6] for the gluon fragmentation functions into \( J/\psi \) or \( \chi \) states, and Refs. [7], [8] and [9] 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 included the effect of the \( S \)-state colour-octet component by modifying the fragmentation functions as in Ref. [19]. For the charm fragmentation, the \( S \)-state colour-octet contributions are sub-dominant and we have neglected these contributions.

We have computed the cross-sections for the planned LHC energy \( \sqrt{s} = 14 \) TeV using the MRSD-' parton densities [24]. In Fig. 1, we present the \( J/\psi \) production cross-section \( Bd\sigma/dp_T \) as a function of \( p_T \), where \( B \) is the branching ratio of the \( J/\psi \) into leptons. We have assumed a rapidity coverage \(-2.5 \leq y \leq 2.5\) and integrated over the full rapidity interval. The parton densities are evolved to a scale \( Q = \mu/2 \), where \( \mu \) is chosen to be \( M_T \) for the fusion case and equal to \( p_T^c = p_T/z \) for the fragmentation case. The fragmentation functions are evolved to the scale \( p_T/z \). We find that the cross-section for \( J/\psi \) production is completely dominated by the gluon fragmentation contribution (shown by the dotted line in Fig. 1) and is larger than the fusion contribution and the charm-quark fragmentation contribution (shown by the solid and the dashed lines respectively) by about two orders of magnitude. The cross-section for \( J/\psi \) production is large and even at \( p_T = 100 \) GeV, the cross-section is as large as 0.1pb. Assuming a value of luminosity \( \sim 10^4 \) pb\(^{-1}\), typical of that expected at the LHC, we would expect of the order of \( 10^3 \) events even for a \( p_T \) of 100 GeV. For values of \( p_T \) so much larger than the charm quark mass, the fragmentation picture becomes
exact and the prediction of the cross-section using the fragmentation picture should be equal to the experimentally measured cross-section. The experimental measurement of the $J/\psi$ cross-section will, therefore, be a crucial test of the fragmentation picture. Further, for these predictions we have used precisely the same values of the non-perturbative inputs i.e. the colour-octet matrix elements that were determined from the analysis of the CDF data. Therefore, the LHC measurement will also be a test of the magnitude of the colour-octet contributions.

In Fig. 2, we have shown the cross-section for $\psi'$ production at LHC energies. Again, the cross-section is dominated by the octet-enhanced gluon fragmentation contribution. The overall magnitude of the cross-section is smaller than in the case of $J/\psi$ production, but one still expects a comfortably large event rate for $\psi'$ production for $p_T \sim 100$ GeV.

In conclusion, we have studied the contribution to large-$p_T$ $J/\psi$ and $\psi'$ production at the LHC energy, coming from fragmentation of gluons and charm quarks. We find that the cross-section is overwhelmingly dominated by the gluon fragmentation contribution. The full cross-section is large and suggests a significant event rate even for values of $p_T$ much larger than 100 GeV. The measurement of the charmonium cross-sections at LHC will provide a crucial test of the fragmentation picture and provide a check on the magnitude of the colour-octet matrix elements.
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Figure 1: $Bd\sigma/dp_T$ (in nb/GeV) for $J/\psi$ production at 14 TeV c.m. energy with $-2.5 \leq y \leq 2.5$. The solid, dashed and dotted lines represent the fusion, charm quark fragmentation and gluon fragmentation contributions.
Figure 2: $B d\sigma/dp_T$ (in nb/GeV) for $\psi'$ production at 14 TeV c.m. energy with $-2.5 \leq y \leq 2.5$. The solid, dashed and dotted lines represent the fusion, charm quark fragmentation and gluon fragmentation contributions.