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Hadroproduction of J/ψ and Υ in association with a heavy-quark pair

P. Artoisenet [a], J.P. Lansberg [b], F. Maltoni [a,*]

[a] *Center for Particle Physics and Phenomenology (CP3), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[b] *CPHT, Ecole Polytechnique, CNRS, 91128 Palaiseau Cedex, France*

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Abstract

We calculate the cross sections for the direct hadroproduction of J/ψ and Υ associated with a heavy-quark pair of the same flavour at leading order in α_S and v in NRQCD. These processes provide an interesting signature that could be studied at the Tevatron and the LHC and also constitute a gauge-invariant subset of the NLO corrections to the inclusive hadroproduction of J/ψ and Υ. We find that the fragmentation approximation commonly used to evaluate the contribution of these processes to the inclusive quarkonium production sizeably underestimates the exact calculation in the kinematical region accessible at the Tevatron. Both J/ψ and Υ are predicted to be unpolarised, independently of their transverse momentum.

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1. Introduction

Since its introduction in 1995 [1,2], NRQCD has become the standard framework to study heavy-quarkonium physics. NRQCD is a non-relativistic effective theory equivalent to QCD, where inclusive cross sections and decay rates can be factorised as the product of short-distance and long-distance parts. The short-distance coefficients are process-dependent but can be computed in perturbative QCD, the strong coupling constant α_S being the parameter of the expansion. The long-distance matrix elements are process-independent, i.e., universal, but non-perturbative. They can be classified in terms of their scaling in v, the relative velocity of the heavy quarks in the bound state, and as a result, physical quantities can be expressed as a double series in α_S and v.

An innovation of this formalism is the color-octet mechanism: the heavy-quark pair is allowed to be created in a color-octet state over short distances, the color being neutralised over long distances. It is thanks to this very mechanism that it is possible to account for the CDF data [3,4] on the inclusive J/ψ and ψ' cross sections at the Tevatron [5–7]. In this case the color-octet matrix elements fitted from the data roughly scale as the power counting rules of NRQCD predict. On the other hand, the recent data collected at $\sqrt{s} = 1.96$ TeV by the CDF Collaboration [8] have revealed that the J/ψ is unpolarised, in flagrant disagreement with the expectations of NRQCD. It is fair to say that the mechanisms responsible for the quarkonium production at the Tevatron are not completely understood yet (for a recent review see [9]).

Another challenge to theorists has been provided by the recent measurements at B factories, where rates for inclusive and exclusive J/ψ production in association with a $c\bar{c}$ quark pair [10] are far larger than the leading order NRQCD theoretical expectations [11]. In this case, keeping only the leading term in α_S and v in the NRQCD expansion results in a very rough approximation. In addition, as opposed to the production of the J/ψ in hadron collisions, color-octet channels cannot be invoked to bring theoret-

* Corresponding author.
E-mail address: maltoni@fyma.ucl.ac.be (F. Maltoni).

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ical predictions in agreement with the experimental measurement [12]. Inclusion of the α_S^3 (NLO) corrections to this process has been recently found to reduce the discrepancy between theory and measurements [13].

In view of the unexpectedly large measurements for the production of J/ψ associated with a $c\bar{c}$ quark pair in e^+e^- annihilation, it is natural to wonder whether the corresponding production pattern could be large in hadroproduction as well. Besides offering a new interesting signature, such as $\ell^-\ell^+$ in association with one or two heavy quark tags, this process contributes to the α_S^4 (NLO) corrections to the inclusive color-singlet hadroproduction of J/ψ and Υ. Historically, these higher-order contributions to the cross section at the Tevatron were considered in the fragmentation approximation as a first attempt to solve the so-called ψ' anomaly [14,15].

The purpose of this work is to present and discuss the complete tree-level calculation for the associated production of J/ψ and Υ (commonly noted $\mathcal{Q}$) with a heavy-quark pair of the same flavour. Such associated production has been recently discussed in the k_T factorisation formalism [16,17]. Here we consider the leading order term in the NRQCD expansion in the usual collinear factorisation scheme.

This Letter is organised as follows. In Section 2, we briefly describe the method used to compute the associated hadroproduction of a quarkonium with a heavy-quark pair together with the results for the Tevatron and the LHC. In Section 3, we discuss the validity of the fragmentation approximation $Q \to \mathcal{Q}Q$ at the Tevatron. In Section 4 we discuss the polarisation of the quarkonium produced by color-singlet transitions. Finally, Section 5 is devoted to the discussion of our results.

2. The calculation of $p\bar{p} \to \mathcal{Q} + Q\bar{Q}$

2.1. The method

In this section, we present the numerical method used to compute quarkonium production amplitudes. At leading order in v, the invariant amplitude to create a ${}^3S_1$ quarkonium $\mathcal{Q}$ of momentum P and polarisation λ can be expressed as the product of the amplitude to create the corresponding heavy-quark pair, a spin projector $N(\lambda|s_1,s_2)$, and $R(0)$, the radial wave function at the origin in the configuration space,[1] namely, [18,19]

$$\mathcal{M}\big(gg \to \mathcal{Q}^\lambda(P) + X\big) = \sum_{s_1,s_2,i,j} \frac{N(\lambda|s_1,s_2)}{\sqrt{m_Q}} \frac{\delta^{ij}}{\sqrt{N_c}} \frac{R(0)}{\sqrt{4\pi}} \mathcal{M}\big(gg \to Q_i\bar{Q}_j(\mathbf{p}=\mathbf{0}; s_1,s_2) + X\big), \tag{1}$$

where $P = p_Q + p_{\bar{Q}}$, $p = \frac{p_Q - p_{\bar{Q}}}{2}$, s_1 is the quark spin, s_2 the antiquark one and $\frac{\delta^{ij}}{\sqrt{N_c}}$ is the projector onto a color-singlet state. In the non-relativistic limit, the spin projector factor can be written as

$$N(\lambda|s_1,s_2) = \frac{\varepsilon_\mu^\lambda}{2\sqrt{2}m_Q} \bar{v}\left(\frac{\mathbf{P}}{2}, s_2\right)\gamma^\mu u\left(\frac{\mathbf{P}}{2}, s_1\right), \tag{2}$$

where ε_μ^λ is the polarisation vector of the quarkonium.

The amplitude for $gg \to \mathcal{Q}^\lambda(P) + Q\bar{Q}$ involves 42 Feynman diagrams and an analytical computation is not practical (see Fig. 1). We have therefore opted for using a custom version of MadGraph [20], to generate the amplitudes and perform the spin projection numerically. The expression in Eq. (2) can be evaluated with the help of the HELAS subroutines [21], as done in Ref. [11]. We validated our algorithm to generate the amplitudes for quarkonium production and decays by comparing with several known analytical results point-by-point in phase space. Finally, we use the techniques introduced in Ref. [22] to perform the phase-space integration. As an exercise, we have reproduced the cross section and the P_T distribution for B_c^* production at the Tevatron and found agreement with the results of Ref. [23].

At hadron colliders a ${}^3S_1$ quarkonium state is observed through its decay into leptons. In order to keep the spin correlations between the vector-like bound state and the leptons, we can replace ε_μ^λ in Eq. (2) by the leptonic current

$$\frac{\sqrt{3}}{8m_Q\sqrt{\pi}} \bar{u}_{\ell^-}(k_1,\lambda_1)\gamma_\mu v_{\ell^+}(k_2,\lambda_2). \tag{3}$$

The polarisation of the quarkonium can therefore be determined by analysing the angular distribution of the leptons. Defining θ as the angle between the ℓ^+ direction in the quarkonium rest frame and the quarkonium direction in the laboratory frame, the normalised angular distribution $I(\cos(\theta))$ is

$$I(\cos\theta) = \frac{3}{2(\alpha+3)}\big(1 + \alpha\cos^2\theta\big), \tag{4}$$

[1] Up to v^4 corrections, the relation to the NRQCD production matrix element is given by $\langle \mathcal{O}_1\rangle_{J/\psi} = \frac{3N_c}{2\pi}|R(0)|^2$, where the normalisation of Ref. [1] is assumed.

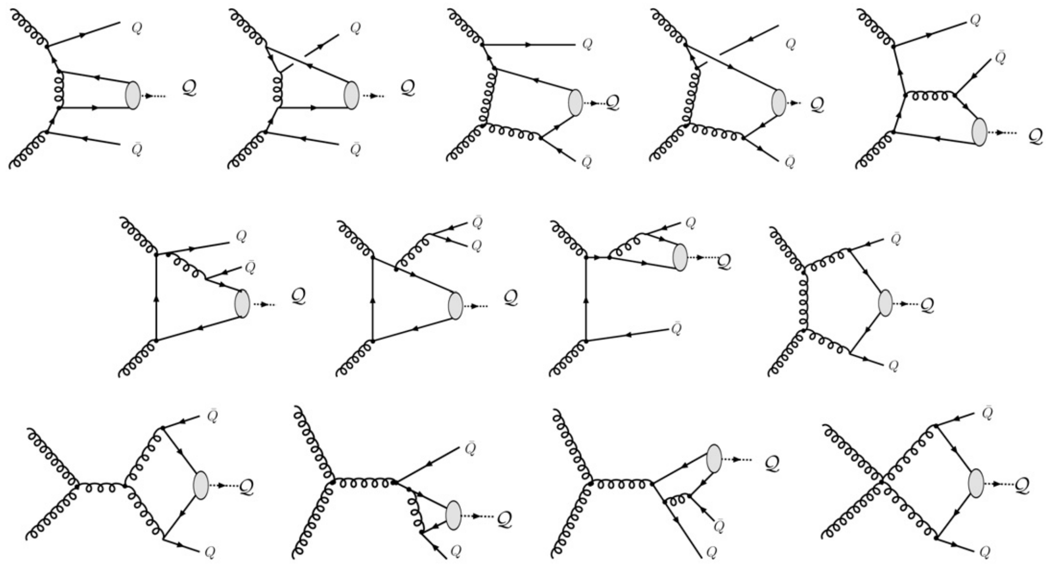


Fig. 1. Representative diagrams contributing at LO in α_S to $gg \to \mathcal{Q} + Q\bar{Q}$ via a ${}^3S_1^{[1]}$ state.

where the relation between α and the polarisation state of the quarkonium is

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}. \tag{5}$$

2.2. Cross sections and results

As for the case of open charm and bottom cross sections, heavy-quarkonium hadroproduction is dominated by gluon fusion. We have checked that the light-quark initiated process for $\mathcal{Q} + Q\bar{Q}$ production is suppressed by three orders of magnitude, and thus this contribution is neglected in the following.

In our numerical studies we have used:

- $|R_{J/\psi}(0)|^2 = 0.81\ \text{GeV}^3$ and $|R_{\Upsilon(1S)}(0)|^2 = 6.48\ \text{GeV}^3$;
- $\mu_0 = \sqrt{(4m_Q)^2 + P_T^2}$;
- $\text{Br}(J/\psi \to \mu^+\mu^-) = 0.0588$ and $\text{Br}(\Upsilon(1S) \to \mu^+\mu^-) = 0.0248$;
- $m_c = 1.5$ GeV and $m_b = 4.75$ GeV;
- pdf set: CTEQ6M [24].

In Fig. 2 we show the P_T distributions of J/ψ and Υ at the Tevatron and the LHC, for both $\mathcal{Q} + g$ and $\mathcal{Q} + Q\bar{Q}$ production. The theoretical error bands in the $\mathcal{Q} + Q\bar{Q}$ curves correspond to the uncertainties from the renormalisation and factorisation scale ($\frac{\mu_0}{2} \leqslant \mu_{f,r} \leqslant 2\mu_0$) and the heavy-quark masses ($m_c = 1.5 \pm 0.1$ GeV or $m_b = 4.75 \pm 0.05$ GeV), combined in quadrature.

We start by considering J/ψ and Υ production at the Tevatron, where a rapidity cut $|y| < 0.6$ is applied. For the charmonium case, we note that the P_T distribution peaks at $P_T \simeq m_Q$ and then it starts a quick decrease, dropping by four orders of magnitude at $P_T \simeq 20$ GeV. In fact, at moderate transverse momentum, $P_T \gtrsim m_Q$, $\mathcal{Q} + Q\bar{Q}$ production has much milder slope compared to that of $\mathcal{Q} + g$. Even though suppressed by α_S, $\mathcal{Q} + Q\bar{Q}$ production starts to be comparable to $\mathcal{Q} + g$ already for $P_T \simeq 4m_Q$. We verified that the topologies where the $\mathcal{Q}$ is produced by two different quark lines always dominate. This feature is to be related with the J/ψ production at e^+e^- colliders, where the presence of two extra charmed mesons seems to indicate that the J/ψ is mostly often created from two different quark lines as well. For the Υ, the curve is less steep in the same P_T range due to the larger value of the b-quark mass.

We have compared our results for the P_T distributions with the corresponding ones of Ref. [16], and found very good agreement. This provides a confirmation that the contributions where the quarkonium is produced from a single quark line are negligible, as the corresponding diagrams are not included in the calculation of Ref. [16]. We find that the total cross sections are also consistent, even though the comparison is less accurate (at the level of 20–30%) since some of the relevant parameters, such as $\alpha(M_Z)$ and the non-perturbative matrix elements are not explicitly quoted in Ref. [16].

The results for the LHC are displayed in Fig. 2(c) and (d). A cut $|y| < 0.5$ has been applied. Since the rapidity distribution is flat in this range, this is equivalent to consider the quarkonium production at zero rapidity. The P_T behaviours for both J/ψ and Υ are very similar to those at the Tevatron while the normalisation is increased by one order of magnitude.

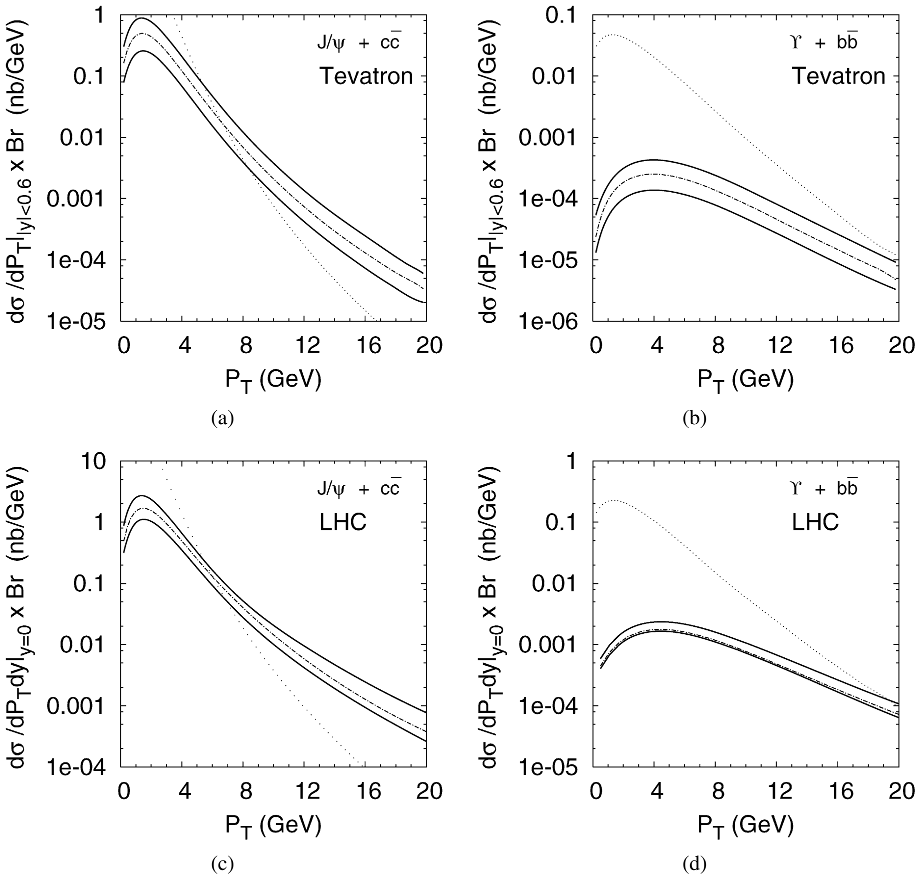


Fig. 2. (a) Differential cross section for the process $p\bar{p} \to J/\psi + c\bar{c}$ at the Tevatron, $\sqrt{s} = 1.96$ TeV. For comparison, the P_T shape associated to the process $p\bar{p} \to J/\psi + g$ is also displayed (dotted line). (b) Same plot for $\Upsilon + b\bar{b}$ production. (c), (d) Same plot as (a), (b) at the LHC, $\sqrt{s} = 14$ TeV.

3. Testing the fragmentation approximation

In this section we discuss the range of applicability of the fragmentation approximation for the process where a $Q\bar{Q}$ pair is produced at high P_T and one of the heavy quarks fragments into a quarkonium state, $Q \to \mathcal{Q}Q$. At sufficiently large P_T, it is expected that the quark-fragmentation contributions would dominate the $\mathcal{Q}Q\bar{Q}$ cross section.

3.1. Heavy-quark fragmentation

In the fragmentation approximation, the cross section for the production of a quarkonium $\mathcal{Q}$ by gluon fusion via a heavy quark Q_i fragmentation is given, at all orders in α_S, by

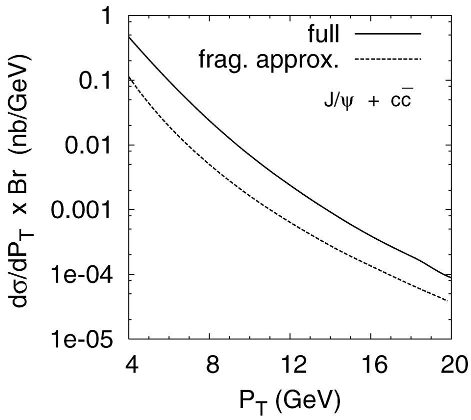
$$d\sigma_{\mathcal{Q}}(P) = \sum_i \int_0^1 dz\, d\sigma_{Q_i}\left(\frac{P}{z}, \mu_{\text{frag}}\right) D_{Q_i \to \mathcal{Q}}(z, \mu_{\text{frag}}), \tag{6}$$

where $d\sigma_{Q_i}(\frac{P}{z}, \mu_{\text{frag}})$ is the differential cross section to produce an *on-shell* heavy quark Q_i with momentum $\frac{P}{z}$ and $D_{Q_i \to \mathcal{Q}}(z, \mu_{\text{frag}})$ is the fragmentation function of Q_i into a quarkonium $\mathcal{Q}$.

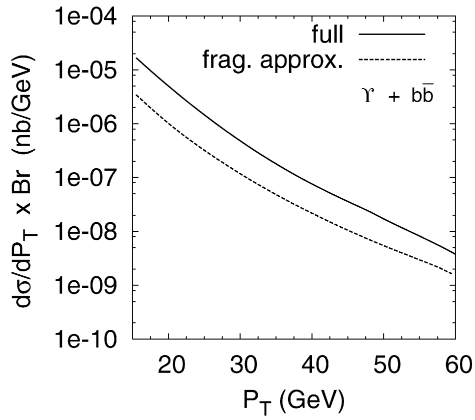
The fragmentation scale, μ_{frag}, is usually chosen to avoid large logarithms of P_T/μ_{frag} in $\sigma_{Q_i}(\frac{P}{z}, \mu_{\text{frag}})$, that is $\mu_{\text{frag}} \simeq P_T$. The summation of the corresponding large logarithms of μ_{frag}/m_Q appearing in the fragmentation function can be obtained via an evolution equation [25–27].

The perturbative quark fragmentation function into quarkonium $\mathcal{Q}$ via a ${}^3S_1^{[1]}$ state at the scale $3m_Q$ is [28]

$$D_{Q \to \mathcal{Q}}(z, 3m_Q) = \frac{8\alpha_S^2(2m_Q)}{27\pi} \frac{|R(0)|^2}{m_Q^3} \frac{z(1-z)^2(16 - 32z + 72z^2 - 32z^3 + 5z^4)}{(2-z)^6}. \tag{7}$$



(a)



(b)

Fig. 3. (a) Comparison between the *full* LO cross section for $p\bar{p} \to J/\psi + c\bar{c}$ and the fragmentation approximation at $\sqrt{s} = 1.96$ TeV. No cut on rapidity is applied. (b) Idem for $p\bar{p} \to \Upsilon + b\bar{b}$.

3.2. Comparison

We now compare the results of the full LO cross sections for $p\bar{p} \to \mathcal{Q} + Q\bar{Q}$ with those calculated in the fragmentation approximation. The same set of parameters of Section 2.2 is employed.[2] The comparison is shown in Fig. 3. The approximation is lower than the full computation in the P_T range accessible at the Tevatron. We have verified that for J/ψ production, the two curves still differ by a little bit less than 10% at $P_T = 80$ GeV. For the Υ, much larger values of P_T are required (Fig. 3(b)).

Therefore, contrary to the common wisdom, in the kinematical region accessible at the Tevatron, $p\bar{p} \to J/\psi + c\bar{c}$, which is an NLO subset of $p\bar{p} \to J/\psi + X$, is not dominated by the fragmentation contributions.

4. Polarisation: $gg \to \mathcal{Q} + Q\bar{Q}$ vs. $gg \to \mathcal{Q} + g$

Let us first review the analytical result for $gg \to \mathcal{Q} + g$, which we used as a check of our numerical procedure. To compute the polarisation parameter α discussed in Section 2.1, it is sufficient to consider the unpolarised (or total) cross section and the longitudinal one in the laboratory frame. The parameter α introduced in Section 2.1 can then be written as

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} = \frac{\sigma_{\text{tot}} - 3\sigma_L}{\sigma_{\text{tot}} + \sigma_L}. \tag{8}$$

The total cross section is calculated from the squared amplitude summed over the quarkonium polarisation which reads [18,29]

$$|\mathcal{M}|^2 = \frac{320 g_S^6 |R(0)|^2 \hat{s}^2 M_{\mathcal{Q}}}{9\pi} \left(\frac{(\hat{t}+\hat{u})^2 + (\hat{s}+\hat{u})^2 + (\hat{s}+\hat{t})^2}{(\hat{s}+\hat{t})^2(\hat{s}+\hat{u})^2(\hat{t}+\hat{u})^2} \right), \tag{9}$$

where $M_{\mathcal{Q}} = 2m_Q$ and $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the usual Mandelstam variables for parton quantities. To compute the squared amplitude for longitudinally polarised quarkonia, we need to define the longitudinal polarisation vector in the laboratory frame:

$$\varepsilon_3^L(P) = a_L k_1 + b_L k_2 + c_L k_4, \tag{10}$$

with

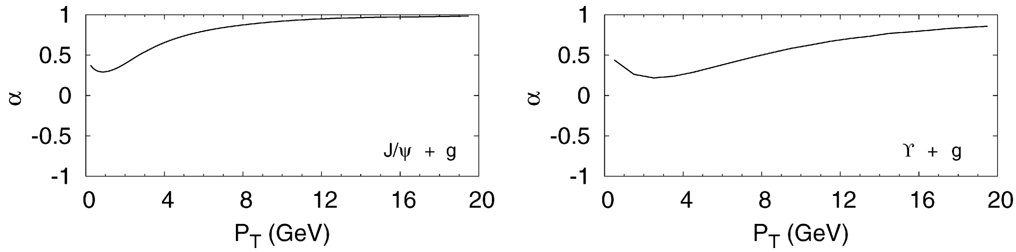
$$a_L = \frac{M_{\mathcal{Q}}^2(x_1 - x_2) - (\hat{t}x_2 + \hat{u}x_1)}{M_{\mathcal{Q}} N},$$

$$b_L = \frac{M_{\mathcal{Q}}^2(x_2 - x_1) - (\hat{t}x_2 + \hat{u}x_1)}{M_{\mathcal{Q}} N},$$

$$c_L = \frac{-M_{\mathcal{Q}}^2(x_1 + x_2) + (\hat{t}x_2 + \hat{u}x_1)}{M_{\mathcal{Q}} N},$$

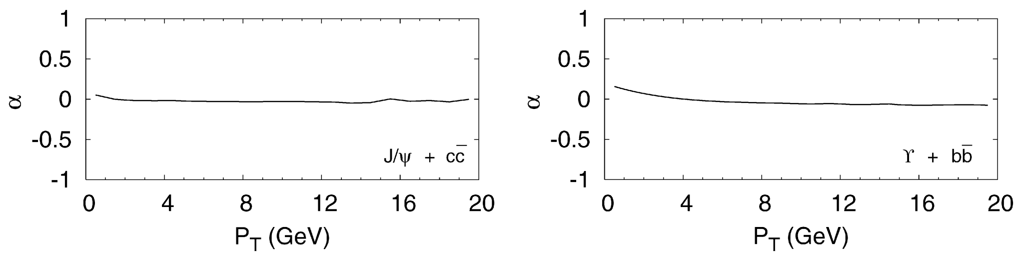
$$N = \sqrt{\left((x_1 - x_2)^2 M_{\mathcal{Q}}^4 - 2(\hat{u}x_1 - \hat{t}x_2)(x_1 - x_2) M_{\mathcal{Q}}^2 + (\hat{t}x_2 + \hat{u}x_1)^2\right)}, \tag{11}$$

[2] For consistency, the coupling constant in the fragmentation function is evaluated at the scale $\sqrt{(4m_Q)^2 + P_T^2}$. Note that this choice, as well as the use of CTEQ6M, leads to smaller cross sections compared those of Ref. [28].



(a) (b)

Fig. 4. Polarisation parameter for $p\bar{p} \to \mathcal{Q} + g$ for J/ψ (a) and Υ (b) at the Tevatron, $\sqrt{s} = 1.96$ TeV.



(a) (b)

Fig. 5. Polarisation parameter for $p\bar{p} \to \mathcal{Q} + Q\bar{Q}$ for J/ψ (a) and Υ (b) at the Tevatron, $\sqrt{s} = 1.96$ TeV.

where x_1 and x_2 are the usual momentum fractions of the incoming gluons. From that definition and Eqs. (10.505) of Ref. [30], we can then easily compute

$$|\mathcal{M}_L|^2 = \frac{640 g_S^6 |R(0)|^2 M_{\mathcal{Q}}^3 \hat{s}\hat{t}\hat{u}}{9\pi(\hat{t}+\hat{u})^2(\hat{s}+\hat{u})^2(\hat{s}+\hat{t})^2} \frac{(\hat{t}^2 x_1^2 + \hat{s}^2(x_1 - x_2)^2 + \hat{u}^2 x_2^2)}{N^2}. \tag{12}$$

If x_1 and x_2 are approximately equal and the masses can be neglected, it is possible to see from Eqs. (9) and (12) that the quarkonia will be transversally polarised. Using the same parameters as for the previous plots, we find that α gets rapidly close to one for $P_T > m_{\mathcal{Q}}$, see Fig. 4. Our results agree with those of Ref. [31].

Note that this behaviour of α is not expected to be seen in the data, since the yield from $p\bar{p} \to \mathcal{Q} + g$ is not dominant, even when only color-singlet channels are considered. For the process $gg \to \mathcal{Q} + Q\bar{Q}$, α remains close to zero in the whole P_T range. Since the latter is the one which dominates over the other color-singlet contributions, we conclude that the quarkonia not produced by a color-octet mechanism will be unpolarised at high P_T. See Fig. 5.

5. Conclusion

In this Letter, we have presented the tree-level calculation for the associated production of J/ψ and Υ with a heavy-quark pair. The motivation was twofold. First, these processes offer a new interesting signature, that could be tested experimentally by measuring the fraction of quarkonium produced with at least one heavy-light quark meson. Second, they contribute to the α_S^4 (NLO) corrections to the inclusive color-singlet hadroproduction of J/ψ and Υ.

We have found that the quark-fragmentation approximation employed to describe quarkonium production should not be applied in the range of transverse momenta reached at the Tevatron and analysed by the CDF Collaboration. The fragmentation approximation actually underestimates the full contribution of $p\bar{p} \to J/\psi + c\bar{c}$ by more than a factor four in the region $P_T \simeq 10$ GeV. This approximation starts to be justified (within 10% of error) only for $P_T \geqslant 80$ GeV. The same conclusion applies for the ψ'. For $p\bar{p} \to \Upsilon + b\bar{b}$ the fragmentation approximation is relevant at even higher P_T, as expected. It is interesting to note that for J/ψ production from e^+e^- annihilation, the fragmentation approximation is only 6% away from the full contribution at $\sqrt{s} = 50$ GeV [11]. One may try to gather an intuitive explanation for such glaring difference by considering the Feynman diagrams contributing to the two processes. In e^+e^- annihilation, there are only four diagrams at leading order, two of which contribute to the fragmentation topologies. On the other hand, the dynamics underlying the $^3S_1$-quarkonia production at the Tevatron is much more involved. The number of Feynman diagrams is significantly larger (42 vs. 4) and only a few of them give rise to fragmentation topologies. As a result, the fragmentation approximation starts to be relevant at a much higher regime in P_T. A similar situation holds for the process $\gamma\gamma \to J/\psi c\bar{c}$ [32] and also for the B_c^* hadroproduction, where the fragmentation approximation is not accurate in the P_T range explored at the Tevatron [23,33]. We have also shown that the J/ψ or Υ produced in association with a heavy-quark pair of the same flavour are *unpolarised*. Further analysis, including combination with the results of Ref. [34] for $pp \to \mathcal{Q} + X$ at NLO and Ref. [35], to compare with the available data from the Tevatron, is ongoing.

In conclusion, we look forward to the measurement of the fraction of events in the J/ψ sample at the Tevatron, with at least one charmed meson in the final state. Such a measurement could also provide further insight to the mechanism responsible for inclusive heavy-quarkonium production at hadron colliders.

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