J/ψ Production via Fragmentation at the Fermilab Tevatron

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The production of J/ψ at large transverse momenta ($p_T > M_{J/\psi}$) in $p\bar{p}$ collisions is considered, including the mechanism of fragmentation. Contributions of fragmentation both to production of J/ψ and to production of χ states followed by radiative decay to J/ψ are taken into account. The latter is found to be dominant and larger than direct production. The overall theoretical estimate is shown to be nearly consistent with the experimental observation.

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The study of the properties of the bound states of heavy quarks plays a central role in the understanding of quantum chromodynamics in that it stands on the very border between perturbative and nonperturbative domains. In particular it is of key importance to have accurate estimates of the production cross sections at large tranverse momenta for precision tests of the theory and possible evidence of new phenomena.

So far there has been an intensive experimental study of the $c\bar{c}$ $1S$ vector bound state, namely J/ψ, in hadron collisions at both UA1 [1] and CDF [2]. The results have been compared with theoretical calculations [3] which take into account two different mechanisms for J/ψ production: direct charmonium production, including the contribution from the χ states, i.e.,

$$gg \to J/\psi g, \qquad gg, q\bar{q} \to \chi g \qquad qg \to \chi q$$
$$\hookrightarrow J/\psi\gamma, \qquad \hookrightarrow J/\psi\gamma, \qquad (1)$$

and the production resulting from B meson decay

$$p\bar{p} \to bX$$
$$\hookrightarrow B \to J/\psi X\,. \qquad (2)$$

A more recent calculation, which makes use of the next-to-leading order (NLO) prediction [4] for b production, is presented in Ref. [5]. These calculations are in disagreement with the results from CDF, the J/ψ rate observed being actually higher, by a factor of 2 or more, than the predicted one [2,5,6].

It has, however, recently been pointed out by Braaten and Yuan [7] that at large p_T an additional production mechanism comes into play, namely the fragmentation of a gluon or a charm quark into a charmonium state. While being of higher order with respect to direct production by a power of the running coupling constant α_s, this mechanism becomes dominant at large p_T because of a factor $O(p_T^2/m_c^2)$ which overcomes the extra power of α_s. The fragmentation functions describing these processes can be calculated perturbatively. Indeed it has been argued in [7] and subsequently shown at leading order (LO) in [8] that J/ψ production via fragmentation will overcome the direct one (i.e., $gg \longrightarrow J/\psi g$) at $p_T \sim 6$–8 GeV. A similar exercise for the χ production, when the total fragmentation probability $\int D_g^\chi$ (see below) times the $gg \longrightarrow gg$ cross sections is compared with the direct production $gg \longrightarrow \chi g$, reveals that fragmentation should dominate for p_T already at ~ 2 GeV. Since this result is at the limit of validity of the fragmentation function approach, we can, however, still expect that the fragmentation mechanism will dominate over the direct one at p_T values as low as 5–6 GeV.

In this Letter we apply these ideas to a quantitative determination of the J/ψ production rate in hadron collisions, also taking into account the production via fragmentation processes of the χ states and subsequent radiative decays to J/ψ.

To this aim the following fragmentation functions play a major role: the gluon fragmentation to J/ψ [7], $D_g^{J/\psi}$ (see Fig. 1); the charm (or anticharm) fragmentation to J/ψ [9], $D_c^{J/\psi}$ (see Fig. 2); the charm fragmentation to χ states [10], D_c^χ; and finally the gluon fragmentation to χ states [11], D_g^χ (see Fig. 3). They have been all calculated by perturbative techniques at an initial scale of the order of the mass of the J/ψ. Of course in the evaluation of the actual cross sections they must be evolved to the appropriate scale [12], and one gets to the

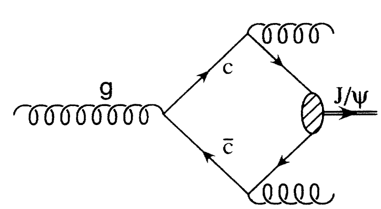

FIG. 1. One of the diagrams for the gluon fragmentation function to the χ states, at the scale $\mu = 2m_c$.

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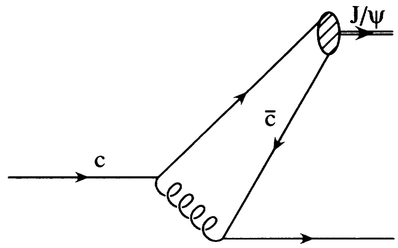

FIG. 2. One of the diagrams for the charm fragmentation function, at the scale $\mu = 3m_c$.

usual expression

$$d\sigma(p\bar{p} \rightarrow J/\psi(p_T) + X) = \sum_i \int_{z_{\min}}^{1} dz\, d\sigma(p\bar{p} \rightarrow i(p_T/z) + X, \mu) D_i^{J/\psi}(z,\mu) \quad (3)$$

for J/ψ production, the sum running over g, c, and $\bar{c}$. A similar formula does hold for χ production [13]. The cross section on the right hand side corresponds to the inclusive production of the parton i, convoluted with the appropriate structure functions [throughout this work we use the (Martin-Roberts-Stirling) MRS-D0 set], and summed over all relevant parton-parton scattering processes. μ is the factorization scale, which we will take to be of order $\mu_0 = \sqrt{p_T^2 + M_{J/\psi}^2}$.

The evolution of the fragmentation functions given above obeys the usual Altarelli-Parisi (AP) equations

$$\mu \frac{\partial}{\partial \mu} D_i^{J/\psi}(z,\mu) = \sum_j \int_z^1 \frac{dy}{y} P_{i\rightarrow j}(z/y,\mu) D_j^{J/\psi}(y,\mu). \quad (4)$$

Furthermore it has been pointed out in Ref. [14] that when one considers the whole set of the AP equations, with the appropriate mixings taken into account, the evolution of the $D_c^{J/\psi}$ will induce a gluon fragmentation function through the splitting $g \longrightarrow c\bar{c}$ and subsequent fragmentation of one of the quarks into a J/ψ (see Fig. 4). This process is of order α_s^3 but, being enhanced by a factor $\log(\mu/M_{J/\psi})$, will dominate over the contribution from $D_g^{J/\psi}$ at large p_T.

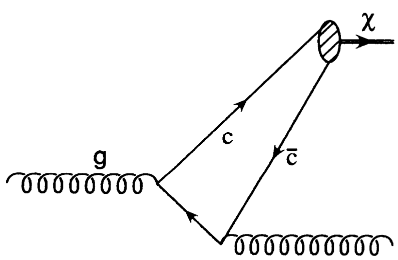

FIG. 3. One of the diagrams for the gluon fragmentation function to the χ states, at the scale $\mu = 2m_c$.

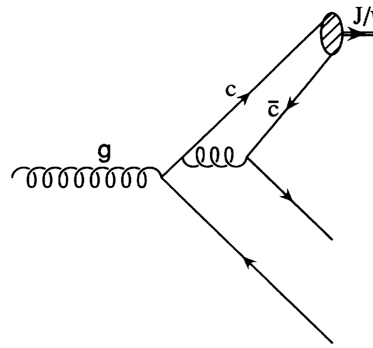

FIG. 4. One of the "perturbative" contributions to the induced gluon fragmentation function, at the scale $\mu = 4m_c$.

We present our results first using the leading order expressions for the partonic cross sections and then, to reduce the theoretical uncertainty, by taking into account the full NLO [15] information on the partonic scattering processes.

We plot in Fig. 5 the LO cross sections, differential in p_T, and integrated over the $\eta < |0.5|$ range, for producing a J/ψ via fragmentation, either directly or after radiative decay of a χ state. We have used for the fragmentation functions the same parameters of Refs. [7,11] [$\alpha_s = 0.26$, $m_c = 1.5$ GeV, $|R_0(0)|^2 = (0.8\text{ GeV})^3$, $H_1 = 15$ MeV, $H_8'(m_c) = 3$ MeV], and the branching ratios given in Ref. [16] [$B(\chi_0 \rightarrow J/\psi) = 0.007$, $B(\chi_1 \rightarrow J/\psi) = 0.27$, $B(\chi_2 \rightarrow J/\psi) = 0.14$, $B(J/\psi \rightarrow \mu^+\mu^-) = 0.0597$]. The initial scales for the evolution of the charm, gluon, and

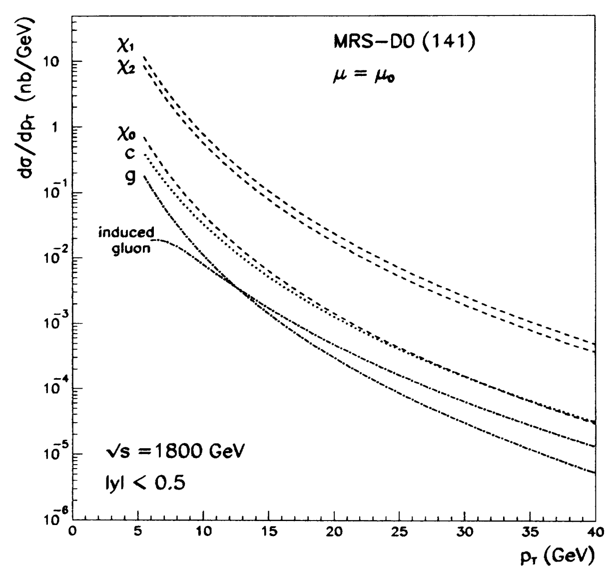

FIG. 5. Leading order differential cross sections due to various fragmentation processes: c, g, induced gluon fragmentation to J/ψ and gluon fragmentation to χ followed by radiative decay to J/ψ are shown.

induced gluon fragmentation functions are, respectively, $\mu_{\rm ini}^c = 3m_c$ (Ref. [9]), $\mu_{\rm ini}^g = 2m_c$ (Ref. [7]), $\mu_{\rm ini}^{\rm ind} = 4m_c$ (Ref. [17]). Finally, we are using $\mu = \mu_0$ for the factorization/renormalization (f/r) scales. The curves labeled by χ are due to gluon fragmentation only. We have not included $c \longrightarrow \chi$ fragmentation contributions since, from the total fragmentation probabilities listed in [10], they can be predicted to lie 2 orders of magnitude below the $c \rightarrow J/\psi$ curve and be therefore surely negligible. From inspection of Fig. 5 the contributions from the χ_1 and χ_2 states can be clearly seen to dominate all over the p_T range considered.

Next we compare, in Fig. 6, the results obtained for the dominant $\chi_1 + \chi_2$ contribution in the LO approach with those obtained by inserting also the next-to-leading partonic cross sections, to order α_s^3, with α_s evaluated to two loop accuracy. We remark that the latter does not result in a full NLO calculation as the initial state evaluation and the evolution kernels of the fragmentation functions are still at leading order. We have explicitly checked that the inclusion of NLO evolution kernels does not change appreciably our results. Figure 6 clearly shows that the higher order terms enhance the cross section by a factor of about 1.5. This is consistent with previous studies of higher order corrections in heavy quark [4,18] and inclusive jets [15,19] production in hadron collisions. The effect of variations of the f/r scales μ between $0.6\mu_0$ and $2\mu_0$ is also shown. As expected, the inclusion of the NLO terms reduces the sensitivity to scale variations.

One more theoretical uncertainty has to be considered, namely the freedom to choose the initial scale for the fragmentation functions evolution around $M_{J/\psi}$. Figure 7 shows the effect of varying $\mu_{\rm ini}^g$ in the range 2–4 GeV.

Finally we show, in Fig. 8 and in Table I, our final prediction for J/ψ production by adding the mechanism of fragmentation to the direct one [20] and to the production from B decays, as taken from Ref. [5], together with the reported theoretical uncertainty. The bands are made by choosing the highest and lowest curve which could be obtained by varying some of the parameters: the factorization/renormalization scale and the value of Λ in the work of Refs. [5,20], again the same scale and the initial scale $\mu_{\rm ini}^g$ in our result. The values of the parameters used for each curve are given in the caption. The total result is obtained by adding together the two highest and the two lowest curves, respectively. The size of the fragmentation contribution is seen to be comparable with the previous estimate for the sum of the two mechanisms considered up to now, leading therefore to a sizable enhancement of the predicted overall production rate, which we also show in the figure.

When we finally compare with CDF data points [2] we see that they are now more compatible with the theoretical band. This improves sensibly the previous situation, where only by making very extreme choices of the parameters one could get close to the experimental findings.

To conclude, we have considered the inclusive production of J/ψ in hadron collisions in the framework of fragmentation functions. We have shown explicitly that the production and successive radiative decays of the χ states plays a dominant role. The overall theoretical estimate,

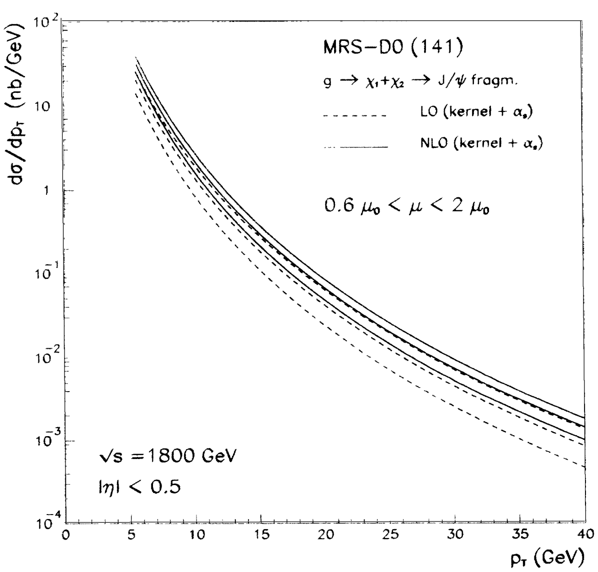

FIG. 6. Leading vs next-to-leading cross section for producing a J/ψ via fragmentation. Only the dominant χ_1 and χ_2 contributions are included.

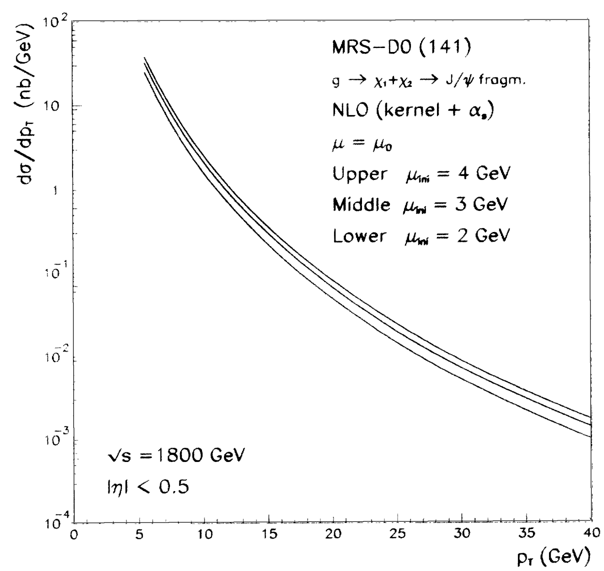

FIG. 7. Theoretical uncertainty due to changes in the initial scale $\mu_{\rm ini}^g$ for the fragmentation functions evolution.

TABLE I. Numerical values of the cross sections (nb/GeV) plotted in Fig. 8 [$B(J/\psi \to \mu^+\mu^-)$ included].

	Direct 20 + B decays 5		Fragmentation		Total	
p_T	Lower	Upper	Lower	Upper	Lower	Upper
5.5	0.52×10^{0}	0.10×10^{1}	0.12×10^{1}	0.28×10^{1}	0.17×10^{1}	0.39×10^{1}
7.5	0.17×10^{0}	0.36×10^{0}	0.30×10^{0}	0.75×10^{0}	0.46×10^{0}	0.11×10^{1}
9.5	0.68×10^{-1}	0.14×10^{0}	0.98×10^{-1}	0.25×10^{0}	0.17×10^{0}	0.39×10^{0}
11.5	0.29×10^{-1}	0.67×10^{-1}	0.39×10^{-1}	0.10×10^{0}	0.67×10^{-1}	0.17×10^{0}
13.5	0.14×10^{-1}	0.31×10^{-1}	0.17×10^{-1}	0.47×10^{-1}	0.32×10^{-1}	0.79×10^{-1}
15.5	0.77×10^{-2}	0.18×10^{-1}	0.86×10^{-2}	0.24×10^{-1}	0.16×10^{-1}	0.41×10^{-1}
17.5	0.43×10^{-2}	0.99×10^{-2}	0.46×10^{-2}	0.13×10^{-1}	0.89×10^{-2}	0.23×10^{-1}
19.5	0.25×10^{-2}	0.62×10^{-2}	0.26×10^{-2}	0.73×10^{-2}	0.52×10^{-2}	0.13×10^{-1}

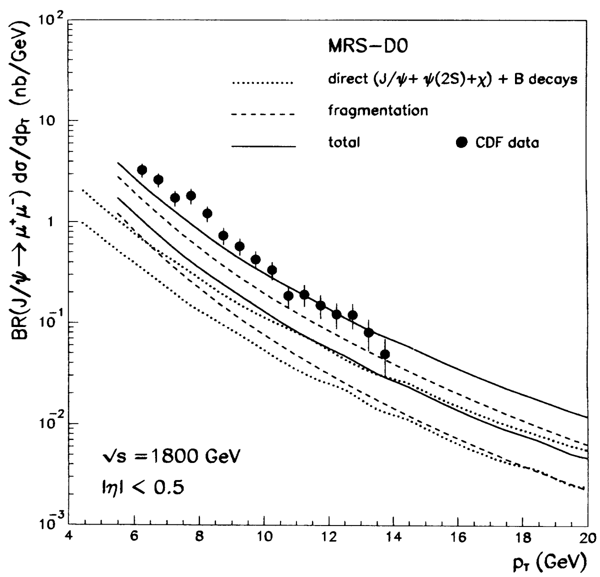

FIG. 8. Theoretical prediction for J/ψ production at Fermilab Tevatron, compared with experimental data from CDF 2. Both the old result (dotted line) from Refs. [5,20] (upper curve: $\mu = m_T/4, \Lambda = 275$ MeV; lower curve $\mu = m_T, \Lambda = 215$ MeV) and the new fragmentation (dashed line) contribution (upper curve: $\mu = 0.6\mu_0$, $\mu_{\rm ini}^{g} = 4$ GeV; lower curve: $\mu = 2\mu_0$, $\mu_{\rm ini}^{g} = 2$ GeV) are included.

including the contribution from B decays, is nearly consistent with the experimental observations.

A more detailed analysis, and a comparison with the most recent Tevatron data, will be presented elsewhere [21].

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Note added.—After this paper was submitted a similar work by Braaten, Doncheski, Fleming, and Mangano on J/ψ and ψ' production has appeared [22].

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