J/ψ pair production at the Fermilab Tevatron

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The double J/ψ production in $p\bar{p}$ collisions is reexamined. It is found that the J/ψ pair production rate obtained in the color-singlet model, at leading order in α_s and with transverse momentum $p_T>4$ GeV, is similar in magnitude to what is derived from the color-octet mechanism. Although the double J/ψ production process was proven to be observable with data yet collected at the Fermilab Tevatron detectors, our findings show that the analysis on this process using the accumulated data would be no help in the aim of clarifying the quarkonium production mechanisms, but can give information on the nature of the color-singlet prescription for charmonium production. Nevertheless, with more data to be collected in the future, the evidently different features of J/ψ pair production in p_T distribution in two different schemes enable experimental study to give a decisive conclusion on them.

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Quarkonium production and decays have long been taken as an ideal means to investigate the nature of QCD and other new phenomena. Hence, to establish a proper theory which can precisely describe heavy quarkonium production and decays is very necessary. A novel effective theory, nonrelativistic QCD (NRQCD) [1], is possibly one theory to this aim which is formulated from the first principles. However, to make a precise prediction for quarkonium production with only the NRQCD is not enough at least for now, since the magnitude of the nonperturbative parameters in the theory are still unknown. The theory itself can at most give out the relative weights of these parameters in orders of v^2 from its ''velocity scaling rules.'' Up to now, on one hand the color-octet [2] mechanism still stands as the most plausible proposal in explaining the large transverse momentum $\psi(\psi')$ production ''anomaly'' discovered at the Fermilab Tevatron [3]; on the other hand, it encounters some difficulties in confronting other phenomena [4]. Especially, a recent study [5] shows that previous calculations about the color-octet contributions to high-p_T $J/\psi(\psi')$ production were overestimated, although not by much. Therefore, to what degree the color-octet mechanism plays a role in quarkonium production is still not clear and an interesting question.

During the past decade, with the advent of NRQCD lots of work has been done to investigate feasible approaches for finding distinct color-octet signals. Unfortunately, the nature appears to be more elusive than expected, and experimental efforts have given no single conclusive answer yet. One interesting point is that once there was a proposal for a ψ production process, which claimed to be favorable for the color-octet production channel, however, people soon found a competitive channel in the color singlet for the same process. For instance, in electron-position scattering Ref. [6] pairs with Ref. [7], and Ref. [8] with Ref. [9] in direct photon-photon collision. This reality indicates as well that more effort is still necesssary before fully understanding the quarkonium production mechanism.

In explaining the high-p_T ψ surplus production discovered by the Collider Detector at Fermilab (CDF) group [3] at the Fermilab Tevatron, the color-octet scenario tells us that the dominant source of charmonium production at large transverse momentum comes from the produced hard gluon followed by its fragmentation into an intermediate color-octet $c\bar{c}$ state, which eventually evolves into quarkonium nonperturbatively. Applying this idea to the double-quarkonium production, Barger *et al.* [10] studied the J/ψ pair production via the double-gluon fragmentation mechanism and found it gives a result which is detectable in previously accumulated data at the Fermilab Tevatron detectors. Hence, they claimed that the measurement of this process in experiment would offer a clean test for the color-octet quarkonium production scheme. In this work we show that at high transverse momentum this scenario really works, however, making a conclusion by using integrated cross section with relatively low p_T cut, e.g., 4 GeV as discussed in their paper, is impossible to this aim.

Within color-singlet model, the partonic processes start at order of α_s^4 for the J/ψ pair production, which include $g+g\to J/\psi+J/\psi$ and $q+\bar{q}\to J/\psi+J/\psi$. Since the latter, the quark annihilation process, gives less contribution at the Tevatron energy, in this Brief Report, we restrict our calculation to the gluon-gluon fusion one, as shown in Fig. 1. The J/ψ pair production via gluon-gluon fusion is similar to the case in photon-photon scattering discussed in Ref. [8], but the extension from there to the present discussion is not trivial. The QCD non-Abelian nature involves more possible sub channels, i.e., the third topological group as shown in the figure.

The differential cross section for quarkonium pair hadroproducion is given by

$$\frac{d\sigma}{dp_T}(p\bar{p}\to 2J/\psi+X)=\sum_{a,b}\int dx_a dy_1 f_{a/p}(x_a) f_{b/\bar{p}}(x_b)$$

$$\times\frac{4p_T x_a x_b}{2x_a-\bar{x}_T e^{y_1}}\frac{d\hat{\sigma}}{dt}(a+b\to 2J/\psi+X), \qquad (1)$$

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where $f_{a/p}$ and $f_{b/\bar{p}}$ denote the parton densities; t, as well as s and u appearing later, is the parton level Mandelstam variable; $y_1(y_2)$ is of the rapidity of produced J/ψ; $\overline{x_T} \equiv 2m_T/\sqrt{\mathbf{S}}$ with $m_T = \sqrt{m^2+p_T^2}$. Here, $\mathbf{S}$ denotes the incident beams total energy square and is taken to be $(1.8\ \mathrm{TeV})^2$ of the Tevatron energy in our subsequent numerical calculations.

The hard scattering differential cross section $d\hat{\sigma}/dp_T$ of gluon-gluon to J/ψ pair can be calculated by the standard way straightforwardly. It is

$$
\begin{aligned}
\frac{d\hat{\sigma}}{dt} = {} & \frac{16\alpha_s^4\pi|R(0)|^4}{81m^2s^8(m^2-t)^4(m^2-u)^4}(2680m^{24}-14984m^{22}t+31406m^{20}t^2-31824m^{18}t^3+17668m^{16}t^4-7172m^{14}t^5 \\
& +2956m^{12}t^6-794m^{10}t^7+47m^8t^8+20m^6t^9+m^4t^{10}-14984m^{22}u+89948m^{20}tu-202576m^{18}t^2u+228560m^{16}t^3u \\
& -153360m^{14}t^4u+76406m^{12}t^5u-30782m^{10}t^6u+7642m^8t^7u-822m^6t^8u-66m^4t^9u+31406m^{20}u^2-202576m^{18}tu^2 \\
& +470856m^{16}t^2u^2-536476m^{14}t^3u^2+361624m^{12}t^4u^2-182454m^{10}t^5u^2+73146m^8t^6u^2-17902m^6t^7u^2+2469m^4t^8u^2 \\
& +36m^2t^9u^2-31824m^{18}u^3+228560m^{16}tu^3-536476m^{14}t^2u^3+571900m^{12}t^3u^3-335186m^{10}t^4u^3+150334m^8t^5u^3 \\
& -58126m^6t^6u^3+12874m^4t^7u^3-2344m^2t^8u^3+17668m^{16}u^4-153360m^{14}tu^4+361624m^{12}t^2u^4-335186m^{10}t^3u^4 \\
& +132502m^8t^4u^4-35306m^6t^5u^4+11928m^4t^6u^4-148m^2t^7u^4+698t^8u^4-7172m^{14}u^5+76406m^{12}tu^5 \\
& -182454m^{10}t^2u^5+150334m^8t^3u^5-35306m^6t^4u^5+1164m^4t^5u^5-1576m^2t^6u^5-1816t^7u^5+2956m^{12}u^6 \\
& -30782m^{10}tu^6+73146m^8t^2u^6-58126m^6t^3u^6+11928m^4t^4u^6-1576m^2t^5u^6+2748t^6u^6-794m^{10}u^7+7642m^8tu^7 \\
& -17902m^6t^2u^7+12874m^4t^3u^7-148m^2t^4u^7-1816t^5u^7+47m^8u^8-822m^6tu^8+2469m^4t^2u^8-2344m^2t^3u^8 \\
& +698t^4u^8+20m^6u^9-66m^4tu^9+36m^2t^2u^9+m^4u^{10}),
\end{aligned}
\tag{2}
$$

where m is the mass of charmonium, the J/ψ; $|R(0)|$ is the magnitude of its radial wave function at origin. In obtaining the above analytical expression, we start from general Feynman rules and project the charm-quark–charm-antiquark pair into the S-wave vector charmonium state in the color singlet.

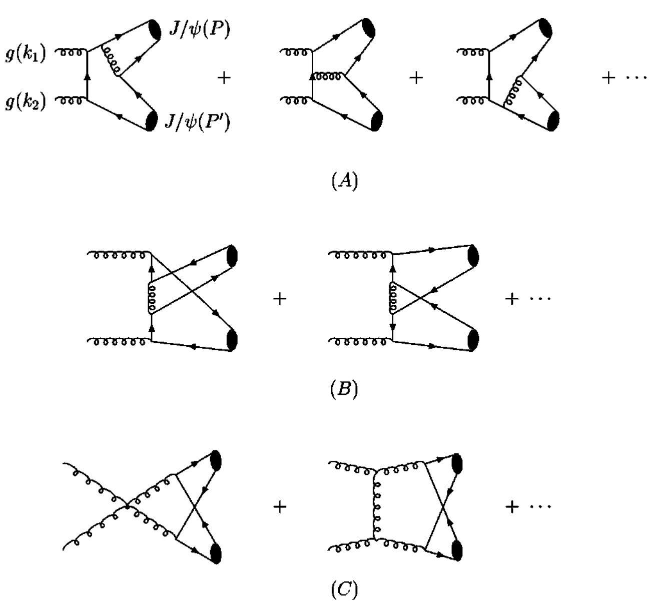

FIG. 1. Typical Feynman diagrams of J/ψ pair production in $p\bar{p}$ collision at leading order.

To manipulate the trace and matrix-element square of those tens of diagrams, the computer algebra system MATHEMATICA is employed with the help of the package FEYNCALC [11].

The values of input parameters used in our numerical calculations are

$$m_c = 1.5\ \mathrm{GeV}, \quad |R(0)|^2 = 0.8\ \mathrm{GeV}^3, \tag{3}$$

and the nonrelativistic relation $m = 2m_c$ is adopted. The typical scale is set to be at m_T, and hence the strong coupling is running with transverse momentum.

With the formulas and input parameters given above, the magnitude of direct J/ψ pair production rate at the Tevatron can be immediately obtained. Applying the pseudorapidity cuts on both produced charmonia, i.e., $|\eta(\psi_1)|,|\eta(\psi_2)| < 0.6$, we get the integrated cross section $\sigma(p\bar{p} \to \psi_{\mu^+\mu^-}\psi_{\mu^+\mu^-})$ for $p_T(\psi) > 4$ GeV to be 0.09 pb. Here, the notation $\psi_{\mu^+\mu^-}$ means that the branching ratio of $B(\psi \to \mu^+\mu^-) = 0.06$ of the practical measuring mode to reconstruct the charmonium state is included. For an integrated luminosity of 100 pb^{-1} achieved in the past run of the Tevatron, there will be about ten J/ψ pair events, coming from the conventional production mechanism, to be detected, which is about the same in magnitude as what was obtained in Ref. [10], where half of the predicted events came from higher excited state feed down and rough approximations on pseudorapidity and p_T cuts were taken. In our numerical cal-

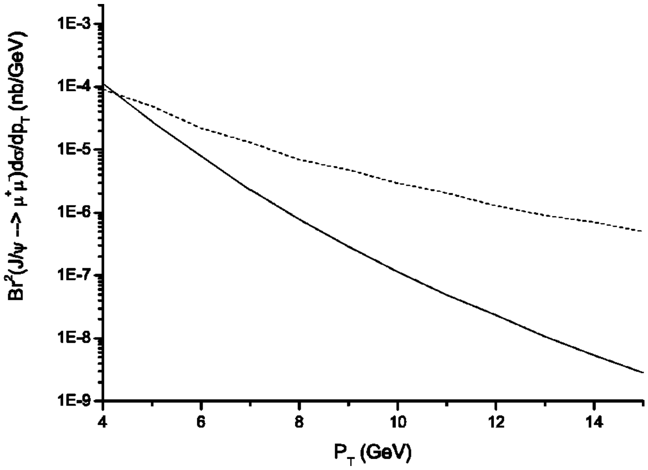

FIG. 2. The differential cross section of J/ψ pair production versus p_T at the Tevatron. Solid line comes from the color-singlet calculation of this paper; the dashed line from the color-octet calculation read from Ref. [10].

culation, the parton distribution of CTEQ5L [12] is used, and both renormalization scale and factorization scale are evolved to the same point m_T; the integration limits of x_a in Eq. (1) are truncated in accordance with the pseudorapidity cuts on both produced charmonia.

The color-singlet double-J/ψ production cross section as a function of transverse momentum p_T is shown in Fig. 2 as a solid line. For comparison, the result from the color-octet process obtained in Ref. [10] is presented in the same figure as a dashed line. From the plot we see that the differential cross section obtained in the conventional production mechanism falls off much more rapidly with the increase of p_T than the one obtained in the color-octet mechanism. This feature indicates that in principle the color-octet mechanism can definitely be tested in the large transverse momentum region, although, unfortunately, there is not enough available data for such a purpose at the moment. Provided we lower the transverse momentum cut to 2 GeV, the concerned color-singlet process will give a cross section of 2.4 pb, which means hundreds of J/ψ pairs could be found from the accumulated data. In this case, no matter if the double gluon fragmentation mechanism still works well or not, it is negligible compared to the singlet process. Therefore, a measurement of J/ψ pair production rate with $p_T>2$ GeV and $|\eta(\psi_1)|,|\eta(\psi_2)|<0.6$ can give information on the magnitudes of higher order corrections and normalization of J/ψ wave function.

In the above analysis, we take the charmonium state J/ψ as an object. Nevertheless, the results can be readily applied to some other charmonium and bottomonium states. For example, the ψ' pair production rates in color-singlet model can be obtained by multiplying the constant

$$\frac{|R'(0)|^4}{|R(0)|^4}\frac{B^2(\psi'\to\mu^+\mu^-)}{B^2(J/\psi\to\mu^+\mu^-)}\approx\frac{B^4(\psi'\to\mu^+\mu^-)}{B^4(J/\psi\to\mu^+\mu^-)} \tag{4}$$

with the J/ψ results.

In conclusion, we calculated the J/ψ pair production rate at the Fermilab Tevatron by taking the conventional heavy quarkonium production treatment, the color-singlet model. The calculation is carried out at leading order in the strong coupling constant. However, higher order corrections should not be too large due to the relatively high interaction scale we are considering. In addition, the relativistic correction, which is not always too small to be negligible in the study of charmonia, is also doubly suppressed since we are considering the pair production; and for the same reason, the higher excited states feed down is suppressed as well. From our analysis, together with previous investigations, 20–30 J/ψ pair events with transverse momentum $p_T>4$ GeV can be found in the accumulated data at the Fermilab Tevatron detectors. Among them at least 40% is produced via the conventional quarkonium production scheme, considering the uncertainties existing in the estimation in Ref. [10]. This finding tells us that analyzing the previously accumulated data for the double J/ψ production process is not useful for chasing the color-octet signature, but can give information on the normalization and higher order corrections in J/ψ color-singlet production. Moreover, the transverse momentum distributions show that with high enough luminosity in present and future runs of the Tevatron or LHC, the discussed process does provide a crucial test for quarkonimum production mechanisms.

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