High-$p_T$ $\psi\psi$ production as signals for Double Parton scattering at hadron colliders

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Abstract

We present an analysis of the $\psi\psi$ production from double parton (DP) scattering and single parton (SP) scattering in the large $p_T$ region via color-octet gluon fragmentation. We find that at the Tevatron the DP $\psi\psi$ production is at the edge of the detectability at present, and at the LHC the DP cross section will dominate over the SP cross section in the lower $p_T$(min) region (i.e., $p_T$(min) < 7GeV). We also conclude that the color-octet mechanism is of crucial importance to the double $J/\psi$ production at high energy hadron colliders.

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The multiple parton (MP) interactions, in which two or more pairs of partons scatter off each other, might become important parts of the structure of typical collisions at very high energy hadron colliders, mostly because of the rapidly increase of the cross section for production of jets with transverse momentum $p_T \geq p_T(\text{min}) \approx 2\,\text{GeV}$. Also, the Double Parton scattering (DP) processes, where two parton-parton hard scattering takes place within one $p\bar{p}$ (or $pp$) collision, have always been a topic to study possible parton-parton correlations in the proton [1]. In experiment, to search for the DP signals, one must subtract the background signals from the single parton (SP) scattering. Any possible process to study the DP signals must have a large enough ratio of signal to background events. This is important to theoretical investigations. The mostly considered DP process is the production of four high-$p_T$ jets via double parton scattering within a single hadronic collision [4] (4 → 4 reactions). In such process, two pairs of jets are produced in the final states and each pair has equal and opposite transverse momentum. Various hadron collider experiments have searched for this signature [4–7]. However, the four jets production from the SP processes (2 → 4 reactions) has a large background. For example, the CDF collaboration at the Fermilab Tevatron found evidence that 4 → 4 reactions contribute only about 5% to the production of four jets with $p_T \geq 25\,\text{GeV}$ [5]. Another sort of the DP signals is the double Drell-Yan processes [6], in which double lepton-pair production may provide a cleaner signature than that of four-jets process. However, such processes which are due to quark and anti-quark annihilations are much less important compared to gluon-induced processes in higher energy hadron collisions. More recently, the production of one-photon + three-jets as signals for the DP interactions has been studied [7], and a strong signal is observed by the CDF collaboration at the Fermilab Tevatron [8].

In this note, we discuss the probability of double $J/\psi$ production at large $p_T$ as signals for DP scattering. $J/\psi$ production at hadron colliders is of special significance because it has extremely clean signature through its leptonic decay modes. In recent years, $J/\psi$ production at large $p_T$ is well studied both in theoretical and experimental sectors. $J/\psi$ production at large $p_T$ has two main sources. One is from $b$ decays, and the other is from so-called “prompt” production. The contributions from $b$ decays can be isolated by using a secondary vertex detector, then the prompt $J/\psi$ production can be studied in experiment [9]. At high energy hadron colliders, unlike the Drell-Yan production mostly coming from the quark and
antiquark annihilations, prompt $J/\psi$ production dominantly comes from gluon-gluon fusion process ($gg \rightarrow \psi X$). This gluon-induced process would provide much larger cross section for the production, and then can be used to study other interesting physics, such as the DP scattering process. By triggering four-$\mu$ final states to measure the double $J/\psi$ production at large $p_T$, we can search for the DP signals in high energy hadronic collisions.

In [10], the authors have calculated $\psi\psi$ production by considering the single $J/\psi$ production at the leading-order within the conventional Color-Singlet Model. However, as pointed out by Braaten and Yuan [11], the fragmentation contributions will dominate over those from leading-order processes at sufficiently large $p_T$, although the fragmentation processes are of higher order in strong coupling constant $\alpha_s$. Explicit calculations of the contributions to $\psi$ production at the Tevatron from fragmentation of gluons and charm quarks revealed that fragmentation dominates over the leading-order gluon-gluon fusion mechanism for $p_T$ greater than $6 GeV$ [12]. More recently, the CDF collaboration have reported their measurement of charmonia production at large $p_T$. They found a large excess of direct production (excluding the contribution from $b$ decays and the feeddown from $\chi c$) both for $J/\psi$ and $\psi'$ [9] [13]. The experimental measurement is a factor of $30 \sim 50$ larger than the theoretical prediction of the Color-Singlet Model. Motivated by this “surplus” problem, a new mechanism for heavy quarkonium production at large $p_T$, named as Color-Octet gluon fragmentation has been proposed [14], which is based on the factorization formalism of non-relativistic quantum chromodynamics (NRQCD) [15]. In this approach, the production process is factorized into short and long distance parts, while the latter is associated with the nonperturbative matrix elements of four-fermion operators. This factorization formalism provides a new production mechanism, the color-octet mechanism, in which the heavy quark and antiquark pair is produced at short distance in a color-octet configuration and subsequently evolves nonperturbatively into physical quarkonium state. In the past few years, applications of the NRQCD factorization formalism to $J/\psi$($\psi'$) production at various experimental facilities have been studied [16].

Single $J/\psi$ production at large $p_T$ may dominantly come from gluon fragmentation contributions. According to NRQCD factorization formalism, the gluon fragmentation to $J/\psi$ production can be factorized as,

\[
D_{g \rightarrow J/\psi}(z, \mu^2) = \sum_n d_{g \rightarrow n}(z, \mu^2) \langle \mathcal{O}^{J/\psi}_n \rangle,
\]  

(1)
where $z$ is the longitudinal momentum fraction carried by the produced $J/\psi$ in gluon fragmentation, $\mu = 2m_c$ is the fragmentation scale. $d_{g \to n}$ represent the short-distance coefficients associated with the perturbative subprocesses in which a $c\bar{c}$ pair is produced in a configuration denoted by $n$ (angular momentum $2S+1L_J$ and color index 1 or 8). $\langle O_n^{J/\psi} \rangle$ are the long distance nonperturbative matrix elements demonstrating the probability of a $c\bar{c}$ pair evolving into the physical state $J/\psi$. The short-distance coefficients $d_{g \to n}$ can be obtained from perturbative calculations in powers of coupling constant $\alpha_s$. $\langle O_n^{J/\psi} \rangle$ consist of two kinds of matrix elements, i.e., the color-singlet and color-octet matrix elements (according to the color index 1 or 8). The color-singlet matrix elements may be related to the quarkonium radial wave function or its derivatives at the origin, and may be calculated by potential models or estimated by leptonic decay widths of quarkonium states. Whereas the color-octet matrix elements can only be determined by fitting the theoretical prediction of quarkonium production rates to the experimental data. The relative sizes of these matrix elements can be determined by their scale properties with $v^2$ according to the NRQCD velocity scaling rules, where $v$ is the typical relative velocity of the heavy quark in the bound state. The fragmentation function in Eq.(1) is a double expansion in $\alpha_s$ and $v$.

For $J/\psi$ production in gluon fragmentation, the color-octet matrix element $\langle O_8^{J/\psi}(3S_1) \rangle$ is smaller than the color-singlet matrix element $\langle O_1^{J/\psi}(3S_1) \rangle$ by a factor of order $v^4$ according to the NRQCD velocity scaling rules. However, the short-distance coefficient for the color-octet term in Eq.(1) is larger than that for the color-singlet term by a factor of order $1/\alpha_s^2$. Numerical results show that color-octet contributions are 50 times larger than color-singlet contributions. In the following calculations, we neglect the color-singlet term in gluon fragmentation in Eq.(1), and only consider the color-octet gluon fragmentation. The leading-order color-octet gluon fragmentation to $J/\psi$ production gives

$$D_{g \to J/\psi}(z, \mu^2) = \frac{\pi \alpha_s (2m_c)}{24} \frac{\langle O_8^{J/\psi}(3S_1) \rangle}{m_c^3} \delta(1 - z).$$  \hspace{1cm} (2)$$

In our calculations, the effects of the evolution of gluon fragmentation function with scale $\mu^2$ are neglected, which may introduce some error. However, as argued in [17], including evolution would not necessarily be an improvement, since naive Altarelli-Parisi equations do not respect the phase-space constraint $D_{g \to J/\psi}(z, \mu^2) = 0$ for $z < m_{J/\psi}^2/\mu^2$ [18].

We plot in Fig.1 the typical Feynman diagrams for double $J/\psi$ production at large $p_T$ via color-octet gluon fragmentation at the Fermilab Tevatron. Fig.1(a) is one of the
Feynman diagrams of the gluon-gluon fusion processes for the DP interactions, and Fig. 1(b) for the SP interactions. In our calculations of the DP cross section for the large $p_T \psi \psi$ production, we only consider the relevant single $J/\psi$ production at large $p_T$ via color-octet gluon fragmentation. For the double $J/\psi$ production from the SP interactions, we also calculate the contributions only from color-octet gluon fragmentation [17], which dominate over the color-singlet contributions both from the leading-order processes [10] and other fragmentation processes [12] at large $p_T$ due to the same reason as pointed out in [14].

In the DP interaction processes, the two partonic interactions occur independently of each other [1,6,7,10]. So, the cross section for $\psi \psi$ production from the DP processes can be related to the cross section for single $J/\psi$ production from the SP processes by

$$\sigma_{DP}(\psi \psi) \approx \frac{\sigma_{SP}(\psi)^2}{2\sigma_{eff}},$$

where the effective cross section $\sigma_{eff}$ represents the possible correlation effects of the parton distributions in the proton (antiproton). If parton correlations are negligible, $2\sigma_{eff}$ should approximately be equal to the total inelastic cross section of 44mb at the Tevatron [19]. This implies $\sigma_{eff} \approx 22mb$. Parton correlations tend to reduce the effective cross section (i.e., increase the double parton scattering cross section) relative to the uncorrelated case. In the following calculations, we use the value $\sigma_{eff} = 14.5mb$ according to the measurement by the CDF [8]. In the literature, some modifications to the above formula have been introduced for the calculation of the DP cross section, which may more correctly represent the correlations between the two partons in one proton such as the energy-momentum conservation effects [6,10]. In our calculations, we do not consider these modifications, because they only cause a little change to the total cross section and can then be neglected [6,10].

To calculate the single $J/\psi$ production rate, we consider $q\bar{q}/gg \rightarrow gg$ and $q(\bar{q})g \rightarrow q(\bar{q})g$ subprocesses, and then gluon fragmentation to $J/\psi$. In gluon fragmentation, the input parameters are taken to be

$$m_c = 1.5GeV, \quad \alpha_s(2m_c) = 0.26, \quad \langle O_{8}^{J/\psi}(3S_1) \rangle = 0.0106GeV^3. \quad (4)$$

The value of the color-octet matrix element $\langle O_{8}^{J/\psi}(3S_1) \rangle$ follows the fitted value in [20] by comparing the theoretical prediction to the experimental data at the Tevatron. We use the MRS(A) parton distribution functions [21] to generate the production cross section, and set
the renormalization scale and the factorization scale both equal to the transverse momentum of the fragmenting gluon $\mu = p_T(g) \approx p_T(\psi)$. A pseudorapidity cut of $|\eta(\psi)| < 0.6$ was also performed on the produced $\psi$s. We obtain the integrated cross section for single $J/\psi$ production (over $p_T$) as a function of the minimum $p_T(\psi)$. In the calculations of gluon fragmentation, we also include the contributions from the $\chi_c$ and $\psi'$ feeddowns through $g \rightarrow \chi_c$ and $g \rightarrow \psi'$ followed by $\chi_c \rightarrow \psi \gamma$ and $\psi' \rightarrow \psi X$. This means that the calculated cross section is for the prompt production (excluding the contributions from $b$ decays). The feeddown contributions give the same $p_T$ distribution of $J/\psi$ and increase the total rate by a factor $\approx 1.6$. We estimate this factor from the measured fraction of direct production in the prompt production [13] (which is 64%). The leptonic decay branching ratio $Br(J/\psi \rightarrow \mu^+ \mu^-) = 0.0597$ is also multiplied in the cross section.

Substituting the integrated cross section for single $J/\psi$ production into Eq.(3), we can estimate the cross section for double $J/\psi$ production coming from the DP processes. The final results are plotted in Fig.2 and Fig.3 for the experiments at the Fermilab Tevatron and at the CERN LHC respectively. The curves represent the integrated cross sections for double $J/\psi$ production (over $p_T$) $\sigma(p\bar{p}(p) \rightarrow \psi \psi + X) \times Br(J/\psi \rightarrow \mu^+ \mu^-)^2$ as the functions of the minimum $p_T(\psi)$. For comparison, we also plot the contributions from the SP interactions via double gluon fragmentation within a single parton-parton scattering. We calculate these contributions by using $q\bar{q}/gg \rightarrow gg$ subprocesses followed by the two gluons fragmentation into two $J/\psi$s [17]. Considering the dominance of the gluon-gluon fusion subprocess in single $J/\psi$ production, as a rough estimate, we can also write the SP $\psi \psi$ production cross section as [17]

$$\sigma_{SP}(\psi \psi) \approx \frac{1}{2} \sigma_{SP}(\psi) \times f_{g \rightarrow \psi},$$

where $f_{g \rightarrow \psi}$ is the gluon fragmentation probability to $J/\psi$ at large $p_T$. In these two figures, the solid lines represent the contributions from the DP interactions, and the dotted lines correspond to the contributions from the SP interactions.

As for the DP processes, suitable kinematic cuts can be used to detect the signals. The SP processes, $gg \rightarrow \psi \psi$ produce the $J/\psi$ pair back-to-back in transverse momentum, whereas the DP processes produce the $J/\psi$ pair unrelated to each other but balanced in $p_T$ by a hard gluon (quark) jet.

From Fig.2, we can see that at the Tevatron the DP cross section is smaller than the SP
cross section in all $p_T$(min) region. Prompt single $J/\psi$ production rate at the Tevatron has been measured with $p_T(\psi) > 4 GeV$ and $|\eta(\psi)| < 0.6$, and the integrated cross section is

$$\sigma(p\bar{p} \rightarrow J/\psi + X) \times Br(J/\psi \rightarrow \mu^+\mu^-) \approx 24 nb.$$ (6)

Substituting the above value of the single $J/\psi$ production cross section into Eq.(3), we obtain the double $J/\psi$ production cross section from the Double Parton processes,

$$\frac{\sigma(p\bar{p} \rightarrow \psi\psi + X) \times Br(\psi \rightarrow \mu^+\mu^-)^2}{\sigma(p\bar{p} \rightarrow \psi + X) \times Br(\psi \rightarrow \mu^+\mu^-)} = \frac{20 fb}{24 nb} = 0.83 \times 10^{-6}.$$ (7)

which shows that there will be about one $\psi\psi$ event among every $10^6$ single $\psi$ events. The fraction of double $J/\psi$ events from the DP processes to single $J/\psi$ events is an order of magnitude smaller than that from the SP process [17] (where it is $7.6 \times 10^{-6}$). The cross section for double $J/\psi$ production from the DP processes is estimated to be about 20fb with $p_T(\psi) > 4 GeV$ and $|\eta(\psi)| < 0.6$. This indicates that the DP $\psi\psi$ signal is at the edge of the detectability of the Tevatron at present (considering the integrated luminosity of 100pb$^{-1}$ now accumulated by each of the Tevatron detectors and the possible inclusion of both the $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ modes), and future increases in luminosity could possibly make it measurable.

However, the DP cross section for double $J/\psi$ production is proportional to the square of the single $J/\psi$ production cross section (see Eq.(3)), whereas the SP cross section for double $J/\psi$ production is proportional to single $J/\psi$ production cross section (see [17]). The relative importance of the DP contributions to $\psi\psi$ production against the SP contributions will be changed with the single $J/\psi$ production rate. At high enough energies, the DP contributions may dominate over the SP contributions because the single $J/\psi$ production rate increases with the collider energy. To see this more clearly, we give the explicit expression for the ratio

$$\frac{\sigma_{DP}(\psi\psi)}{\sigma_{SP}(\psi\psi)} \approx \frac{\sigma_{SP}(\psi)}{\sigma_{eff} \times f_{g \rightarrow \psi}},$$ (8)

which is obtained from Eqs.(3) and (8). At the Tevatron the ratio is about 0.11. But the ratio will increase as $\sigma_{SP}(\psi)$ increases with the collider energies. At the LHC, we find the single $J/\psi$ production rate will be over an order of magnitude higher than that at the Tevatron (see also [22]). So, the DP contributions to the double $J/\psi$ production will be more important at the LHC, which is shown in Fig.3. This figure shows that in the lower $p_T$(min)
region \((i.e., p_T(\text{min}) < 7\text{GeV})\) the DP contributions dominate over the SP contributions. For \(p_T(\text{min}) = 5\text{GeV}\), the DP cross section is

\[
\sigma_{DP}(\psi\psi) = 1.45\text{pb}, \tag{9}
\]

while the SP cross section is

\[
\sigma_{SP}(\psi\psi) = 0.63\text{pb}. \tag{10}
\]

In the above calculations, we choose the effective cross section at the LHC as the same as that at the Tevatron. In fact, the value of \(\sigma_{\text{eff}}\) may change its value while the collider energy \(\sqrt{s}\) increases. However, we notice that the total cross section increases slowly as \(\sqrt{s}\) increases, \((e.g., \sigma_{\text{tot}} \approx 100\text{mb} \text{ at the LHC while } \sigma_{\text{tot}} \approx 80\text{mb} \text{ at the Tevatron})\). So, we expect that \(\sigma_{\text{eff}}\) will not change much at the LHC.

For a typical integrated luminosity \(\sim 10^4\text{pb}^{-1}\) at the LHC, we would expect the order of \(10^4\) events of DP \(\psi\psi\). This indicates that we can detect the DP signals and also measure the \(\sigma_{\text{eff}}\) to investigate the possible correlations between partons in the proton.

It should be emphasized that the color-octet production mechanism is of crucial importance to the double \(J/\psi\) production from the DP interactions at the Fermilab Tevatron and the CERN LHC, just as it is to the single \(J/\psi\) production at Tevatron \([14,20]\). Within the color-singlet model, the DP contribution is much smaller than that from the SP interaction, \((i.e., \sigma_{DP}(\psi\psi) \ll \sigma_{SP}(\psi\psi))\) \([10]\). However, after including the color-octet mechanism, the DP contribution can dominate over the SP contribution for lower \(p_T(\text{min})\) region at the LHC. So, double \(J/\psi\) production at large \(p_T\) can also provide another important test for the color-octet production mechanism.

In conclusion, we have calculated double \(J/\psi\) production at hadron colliders. We find that the DP \(\psi\psi\) production is at the edge of the detectability of the Tevatron at present, and at the LHC the DP cross section will dominate over the SP cross section in the lower \(p_T(\text{min})\) region \((i.e., p_T(\text{min}) < 7\text{GeV})\). We also find the new production mechanism, \((i.e.,\) the color-octet mechanism is of crucial importance to the double \(J/\psi\) production at high energy hadron colliders. Therefore, the measurement of the double \(J/\psi\) production rate would provide an important test for both the DP scattering and the color-octet production mechanism.
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Figure Captions

Fig.1. The typical Feynman Diagrams for double $J/\psi$ production at large $p_T$ via color-octet gluon fragmentation at the Fermilab Tevatron. One of the diagrams of the gluon-gluon fusion subprocesses for (a) the double parton interactions, and for (b) the single parton interactions.

Fig.2. The integrated cross section of $\psi\psi$ production $\sigma_{\psi\psi} \times Br(\psi \rightarrow \mu^+ \mu^-)^2$ for $p_T \geq p_T(\text{min})$ as a function of minimum $p_T(\psi)$ at the Fermilab Tevatron. The dotted line represents the contributions from the SP processes via double gluon fragmentation, and the solid line corresponds to contributions from the DP processes.

Fig.3. The integrated cross section of $\psi\psi$ production at the CERN LHC. Here the curves are defined as those in Fig.2.
Fig.1

(a) 

(b)
Fig. 2
Fig. 3