Charm-sea Contribution to High-$p_T$ $\psi$ Production at the Fermilab Tevatron

Cong-Feng Qiao

Department of Physics, Faculty of Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan

The direct production of $J/\psi(\psi')$ at large transverse momentum, $p_T \gg M_{J/\psi}$, at the Fermilab Tevatron is revisited. It is found that the sea-quark initiated processes dominate in the high-$p_T$ region within the framework of color-singlet model, which is not widely realized. We think this finding is enlightening for further investigation on the charmonium production mechanism.

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Quarkonium production and decays have long been taken as an ideal means to investigate the nature of Quantum Chromodynamics (QCD) and other phenomena. Due to the approximately non-relativistic nature, the description of heavy quark and antiquark system stands as one of the simplest applications of QCD. The rich spectrum of its radial and orbital excitations provides a suitable play ground for testing QCD based models. The heavy, but not very heavy, quark mass enables one to get knowledge of both perturbative and nonperturbative QCD via investigating quarkonium production and decays. The clean signals of quarkonium leptonic decays render the experiment detection with a high precision, and therefore, quarkonium may play an unique role in the study of other phenomena as well, e.g. in detecting the parton distribution, the QGP signal, and even new physics. However, only with a theory which can precisely describe heavy quarkonium production and decays, may these advantages come true.

During the past decade, intrigued by the discovery of $J/\psi(\psi')$ surplus production at high $p_T$ at the Fermilab Tevatron [1,2], our understanding on the natures of quarkonium production and decays has experienced dramatic changes.

Conventionally, the so-called color-singlet model (CSM) was widely employed in the study of heavy quarkonium production and decays [3]. In CSM, it is assumed that the $Q\bar{Q}$ pair produced in a high energy collision will bind to form a given quarkonium state only if the $Q\bar{Q}$ pair is created in color-singlet state with the same quantum numbers as the produced bound states; as well, in the quarkonium decays the annihilating $Q\bar{Q}$ pair will be in short distance and singlet with the same quantum numbers as its parent bound states. It is assumed in CSM that the production amplitudes can be factorized into short distance and long distance parts. The short distance sector is perturbative QCD applicable, while all the long distance nonperturbative effects are attributed to a single parameter, the wave function. That is, e.g.,

$$d\sigma(\psi_n + X) = d\sigma(e\bar{c}(1S_1) + X)|R_{\psi_n}(0)|^2.$$  \hspace{1cm} (1)

The wavefunctions can be either determined phenomenologically through experiment measurement of quarkonium leptonic decay rates, like

$$\Gamma(\psi_n \to l\bar{l}) \approx \frac{4\alpha^2}{9m_{\psi_n}^2}|R_{\psi_n}(0)|^2,$$  \hspace{1cm} (2)

or calculated from potential models.

CSM provides a prescription for calculations of not only the inclusive production rate of quarkonium states, but also their inclusive decay rates into light hadrons, leptons, and photons. Based on it many investigations had been carried out in past more than two decades, and at least qualitative description of quarkonium production and decays were achieved. Nevertheless, color-singlet factorization is only an ad hoc hypothesis. There are no general arguments to guarantee such a naive model may still work up to higher order radiative corrections. In fact people got know for quite long time it does not. Furthermore, the attempt to incorporate relativistic corrections also met difficulties [4]. Although this kind of shortcomings of CSM had been known for many years, and some disagreements between theoretical predictions and experiment data existed, there was no big breakthrough in theory until the CDF group released [1] the data on large-$p_T$ $J/\psi$ production collected in the 1992-1993 run. The new data, which benefited from the advanced technology of vertex detector were free of the large background from $B$ decays, put the CSM in an awkward situation, as the data differ very much from the leading order (LO) CSM predictions in both normalization and $p_T$ scaling.

In 1993, Braaten and Yuan [5] noticed that at sufficiently high $p_T$ the dominant charmonium production mechanism is the production of a parton with large transverse momentum followed by its fragmenting into a charmonium state. With including the contribution by fragmentation mechanism, the prompt $J/\psi$ data can be explained within a small amount of error [6,7], where the

* JSPS Research Fellow. E-mail: qiao@theo.phys.sci.hiroshima-u.ac.jp
charm quark splitting into $\chi_c$ states and then feeding down to $J/\psi$ contributes overwhelmingly. Nevertheless, one can merely get a similar $p_T$ asymptotic behavior for $\psi'$ production with the same scenario, and large discrepancy in normalization remained as well. This phenomenon was referred as the so-called "$\psi'$-surplus" production or "anomaly".

In 1997, a measurement of direct $J/\psi$ production exposed [2], in which the higher excited states feeddown were stripped off. To one’s surprise the new experiment result excesses the CSM prediction by a factor of $\sim 30$, the same as in $\psi'$ production. Nowadays, the former "$\psi'$-surplus" problem turns to be the generic "$\psi$-surplus" problem terminologically.

A general factorization formalism [8] developed from the non-relativistic QCD(NRQCD) [9], which describes the inclusive heavy quarkonium production and decays, were established by Bodwin, Braaten and Lepage(BBL). NRQCD is formulated from first principles and the BBL approach allows relativistic and radiative corrections to be performed safely to any desired order. One of the striking advancements of the new development from CSM is that within the BBL framework the intermediate states, which subsequently evolves into quarkonium states nonperturbatively, can be in both color-singlet and -octet configurations. At first order in $v$, the relative velocity of heavy quark, BBL and CSM are coincident in describing the S-wave quarkonium production.

Based on the BBL formalism, Braaten and Fleming suggested to solve the $\psi'$ surplus production puzzle via color-octet mechanism(COM) [10]. They proposed that the dominant $\psi'$ production at high $p_T$ is through the fragmentation of a gluon into a $c\bar{c}$ pair in color-octet configuration, which will evolve into $\psi'$ nonperturbatively. Indeed they gave a well-fitted curve to the data and from which the non-perturbative matrix element $<O_{\psi'}^{(3S_1)}> \approx 1$ was extracted with a magnitude being consistent with the estimation from NRQCD "velocity scaling rules". After their pioneer work, hundreds of investigations have been performed in order to find either the signatures of color-octet states or any implication of the new proposal to other phenomena [11].

The present situation is that on one hand the COM stands as the most plausible approach, up to now, in explaining the $J/\psi(\psi')$ production "anomaly"; on the other hand, this scenario encounters some difficulties in confronting with other phenomena [11]. The most striking crisis is the absence of high-$p_T$ transversely polarized $J/\psi$ and $\psi'$ at the Tevatron in the first measurement from CDF [12]. According to NRQCD spin-symmetry, and the prescription that the dominant charmonium production mechanism at high $p_T$ is of a gluon splitting into a color-octet $3S_1$ charm quark pair, such polarized states should appear [13]. Therefore, to what degree the COM plays the role in quarkonium production is still an open question to my understanding. To find distinctive color-octet signatures and to eliminate the large errors remaining in different fits for corresponding matrix elements are currently urgent tasks in this research realm, for both theory and experiment.

In order to overcome the difficulties COM met, people tried to attribute large amount of high-$p_T$ events to intrinsic transverse momentum of the interacting partons, suppose that the large uncertainties existed in the $k_t$-factorization are manageable and the $k_t$ would still manifest itself in not very small-$x$ [14]. To be noted that in the $k_t$-factorization formalism, the analyses suggest that the direct $J/\psi$ production is still dominated by color-octet contributions, but from $1S_0^{(8)}$ and $3P_1^{(8)}$, up to large transverse momenta of the order $p_T \leq 20$ GeV.

Now that the difficulties for direct $J/\psi$ and its radial excitation $\psi'$ production at the Tevatron are the same within a small amount of error, as aforementioned, one may reasonably infer that the origins accounting for the large discrepancies between experimental data and the color-singlet description for both states would be the same. On this premise our investigation in this work will be restricted to $J/\psi$ for simplicity. The results and conclusions are applicable to $\psi'$.

We notice that within the framework of collinear factorization, quarkonium production processes initiated by the sea-quark interactions have been paid less attention in previous investigations in color-singlet prescription. In Ref. [15] the sea initiated processes were considered, indirectly, for the large-$p_T J/\psi(\psi')$ production, where the relative importance of valence and sea parton interacting processes was not distinguished. The leading order(LO) charm-sea interacting process was investigated in ref. [16], and found that it contributes negligibly to the large-$p_T \psi$ production as expected, since CDF data indicates that the $\sigma/dp_T^2$ scaling favors fragmentation process behaving like $1/p_T^4$ which happens beyond the LO. Therefore, in order to estimate the sea quark contributions we need to consider the possible processes beyond the LO. It is well-known that the source of the charm-sea distribution can be traced back to higher order gluon-gluon processes. And, because of the large logarithmic term remaining in the NLO result of gluon-gluon to charm pair [17], the evolution effects of summing up all the large logs to any order tend to be important for the processes we are interested in here. Indeed, following evaluation shows that the naive NLO gluon-gluon to charm pair partonic process, which was considered in the calculations of [6,7], can not simply substitutes the charm-sea induced processes of our concern.

On the other hand, although superficially the sea-quark interacting processes seems to be negligible, since the sea distribution probabilities are pretty small comparing to those of valence quarks and gluons. Due to being in high energy and at high, but not very high, $p_T$
region, the $s/\hat{t}$, the ratio of Mandelstam variables of the total center-of-mass energy squared in $s$ and $t$-channels, kinematically suppresses the valence-quark and gluon initiated processes relative to the sea interacting ones. And in the meantime high energy and large $p_T$ enhance the sea quark densities inside the incident hadrons. To see this picture more clearly, let us have a close look at the fragmentation prescription for quarkonium production. Generally, quarkonium fragmentation production, $A + B \rightarrow \psi + X$, can be expressed as

$$d\sigma(A + B \rightarrow H(p_T) + X) = \sum_{a,b,c} \int_0^1 dx_a J_{a/A}(x_a)$$

$$\times \int_0^1 dx_B f_{b/B}(x_b) \int_0^1 dz \hat{d}\sigma(a + b \rightarrow c(p_T/z) + X) \times D_{c\rightarrow H}(z, \mu),$$

where $c$ is the fragmenting parton, either a gluon or (an)anticharm quark, and the sum runs over all possible partons. $D(z, \mu)$ is the fragmentation function and $z$ is the momentum fraction of the the fragmenting parton carried by quarkonium state. The evolution of the fragmentation function $D_{c\rightarrow H}(z, \mu)$ with scale $\mu$ in Eq.(3) is accomplished by the utilization of Alterelli-Parisi(AP) equations

$$\mu \frac{d}{d\mu} D_{c\rightarrow \psi}(z, \mu) = \sum_{j} \int_0^1 dy \frac{dy}{y} P_{ij}(z/y, \mu)D_{j\rightarrow \psi}(y, \mu),$$

where the $P_{ij}$ are the splitting functions of a parton $j$ into a parton $i$.

To show the importance of the sea quark interacting processes in the fragmentation approach (3), we do a simple comparison, for example, of the hard-scattering processes

$$g + g \rightarrow C + \bar{C}$$

with

$$g + C(\bar{C}) \rightarrow g + C(\bar{C}),$$

where the $C$ and $\bar{C}$ stand for charm and anticharm quarks, which are produced slightly off-shell and in high energy with large $p_T$. In LO and massless limit, the differential cross sections for processes (5) and (6) are:

$$\frac{d\sigma}{dT}(s, \hat{t}) = \frac{\alpha_s^2}{s^2} \left\{ \frac{1}{6} \left( \frac{\hat{u}^2 + \hat{t}^2}{\hat{u} \hat{t}} \right) - \frac{3}{8} \left( \frac{\hat{u}^2 + \hat{t}^2}{s^2} \right) \right\}$$

and

$$\frac{d\sigma}{dT}(s, \hat{t}) = \frac{\alpha_s^2}{s^2} \left\{ \left( \frac{\hat{u}^2 + s^2}{t^2} \right) - \frac{4}{9} \left( \frac{\hat{u}^2 + s^2}{\hat{u}} \right) \right\},$$

respectively. Since we are interested in large-$p_T$ $J/\psi(\psi')$ hadroproduction at high energy, obviously in a certain scope of phase space, the process (5) is suppressed with respect to process (6) by the factor of $s/\hat{t}$. However, this is just a schematic argument. To be more strict, we need to convolute the hard scattering cross section with parton distribution and fragmentation functions. Without losing qualitative correctness, for simplicity we do a comparison for the subsets $g + g \rightarrow C + \bar{C}$ and $g + C(\bar{C}) \rightarrow g + C(\bar{C})$ induced processes in $p\bar{p}$ collision by convoluting the hard part with only the parton densities, or in other words, by integrating out the common fragmentation probability $\int D_{\psi}$. Direct numerical calculation shows that the cross section induced by hard process (6) overtakes what induced by (5) by a factor of 7 at $p_T = 15$ GeV.

For completeness, we consider processes

$$q_i(\bar{q}_i) + C(\bar{C}) \rightarrow q_i(\bar{q}_i) + C(\bar{C}),$$

in our numerical calculation as well. Here, the $q_i(\bar{q}_i)$ represents partons of both valence and sea quarks(antiquarks) of the colliding nucleons. Practical exercise, similar as performed in preceding paragraph, shows that this kind of hard interaction processes also contributes more to $J/\psi$ large-$p_T$ production than via subprocess $g + g \rightarrow C + \bar{C}$. And, to be noted that the latter was taken to be the dominant process in many of previous analyses within CSM.

In the numerical calculation of the differential cross section, we need to choose a set of parton distributions. In this work we take CTEQ5M [18] parameterization as our input. We have also tried another set of parton distributions, the MRST99 [19], and found that different parton distribution functions give similar results within tens of percent. That means the conclusions given in this paper will not be spoiled by taking a different set of parton distributions for convolution in Eq.(4).

![FIG. 1. Fragmentation Contributions to the differential cross section for direct $J/\psi$ production at the Fermilab Tevatron, compared with the CDF experiment data read from [2]. The upper curve corresponds to $\mu_R = \mu_F = \mu_{frag} = p_T/2$, while the lower curve to $\mu_R = \mu_F = \mu_{frag} = 2p_T$.](image-url)
In figure 1, various fragmentation contributions to direct $J/\psi$ production are shown, and the sum of them is confronted to the CDF data. Since we merely want to sketch the importance of sea-quark contributions to the large-$p_T$ charmonium production, the lowest order hard scattering cross sections and fragmentation function are employed. We also neglect the effect from non-diagonal splitting function, $F_{e\gamma}$, in Eq. (4), which, as pointed out in Ref. [6,7], may give a factor of as large as $1.5$ to the charm fragmentation process. We estimate the uncertainties of higher order corrections by varying the scale, given that a lower value of scale will account for, in a certain degree, the contributions from higher order corrections and non-diagonal splitting functions. The upper and lower lines in the figure are obtained by varying the scales of factorization, renormalization and fragmentation. The upper curve corresponds to $\mu_R = \mu_F = \mu_{\text{frag}} = p_T/2$, while the lower curve to $\mu_R = \mu_F = \mu_{\text{frag}} = 2p_T$. In drawing the diagram we use the fragmentation function given in Ref. [5] and values quoted thereof ($R_0 = 0.8\text{GeV}^3$, $\alpha_s = 0.26$, $m_c = 1.5$ GeV). The symmetry of a sea quark and its antiquark in hard scattering and fragmentation processes is invoked. In addition, we perform our calculation in the $p_T \geq 10$ GeV region, where contributions from lowest order parton fusion processes can be safely neglected.

From figure 1 we see that the discrepancy between direct $J/\psi$ production data and the CSM prediction (the sum of different processes) is less than an order in optimal case (the upper solid line), rather than the common belief of 30 or more. The finding that the charm-sea initiated processes contribute dominantly to high $p_T$ charmonium production, as shown in figure 1, within CSM looks surprise, whereas, it is not really an unthinkable thing. Similar cases exist in some other quarkonium high energy production processes as well. For example, in photon-photon collision, quarkonium production via resolved processes is not always minor to the direct one. In addition, it should be noted that although the charm sea originates from the high order valence quark and gluon interactions, the naive NLO QCD result for $J/\psi(\psi')$ hadroproduction can not simply substitutes the result from sea-quark initiated processes. In the latter case we are considering the production via fragmentation mechanism, which is already beyond LO in $\alpha_s$.

To conclude, in this work we study the relative importance of the sea quark initiated processes with respect to the valence quark and gluon initiated ones for large-$p_T$ $J/\psi(\psi')$ production within the CSM. It is found that the former may contribute more than the latter by a factor of six. We notice that to many people within the community the gluon initiated processes are still taken to be the dominant ones for the high-$p_T$ $J/\psi(\psi')$ production from CSM calculations. We hope this work may elucidate it somehow. With including the new production scheme, the total cross section from CSM prediction fall off the experiment data by less than an order in extreme situation. Therefore, to explain the CDF data, COM is still necessary and essential. Nevertheless, the increase of the contribution from CSM means a shrinkage of the contribution from COM, which might be as large as twenty percent. Furthermore, the result in this work gives us a strong hint that the $J/\psi(\psi')$-surplus production at the Fermilab Tevatron might still be explained within CSM after including the NLO calculation, like the charmonium photoproduction at HERA [20][21]. At least the color-octet contribution will be much less than previously thought. Finally, we would like to point out that since the (anti)charm quark is taken to be massless in our calculation, some uncertainties will be induced by this measure to order of $O(M_{J/\psi}/p_T)$. For detailed estimations of the uncertainties by taking zero mass scheme see Refs. [22][23]. In all, the error would be within a factor of two in our analysis, which will not change the conclusions of this work.

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