Dissociation of Large-$p_T$ Prompt $J/\psi$
Produced in Pb-Pb Collisions at the LHC

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Abstract

A collision of a light meson and a charmonium produces quarks and antiquarks first, then the charm quark fragments into a charmed hadron, and finally three or more mesons are produced. This is the mechanism that we consider and propose to understand the decreasing prompt-$J/\psi$ nuclear modification factor with increasing $J/\psi$ transverse momentum from 10 GeV/$c$, as measured by the CMS Collaboration. Unpolarized cross sections are derived and calculated for the reactions $\pi + \text{charmonium} \rightarrow Hт + X$ with $Hт$ being $D^+$, $D^0$, $D_s^+$, $D^{*+}$, or $D^{*0}$. Numerical cross sections are parametrized and used to calculate the dissociation rate of charmonium in the interaction with pions in hadronic matter. The momentum dependence of the rate obtained is so as to lead to a decreasing charmonium nuclear modification factor with increasing transverse momentum.

Keywords: Charmonium dissociation, Dissociation rate, Quark potential model

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Charmonium dissociation causes the nuclear modification of charmonia. The change of the nuclear modification of $J/\psi$ as a function of its transverse momentum is very interesting in relativistic heavy-ion collisions. For nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV the prompt-$J/\psi$ transverse momentum measured by the PHENIX Collaboration $[1]$ and the STAR Collaboration $[2]$ is well below 10 GeV/$c$. The dissociation of $J/\psi$ with
such a momentum is attributed to collisions with gluons in a quark-gluon plasma \cite{3} and with mesons in hadronic matter \cite{1}. For Pb-Pb collisions at the Large Hadron Collider (LHC) the prompt-$J/\psi$ transverse momentum measured by the CMS Collaboration \cite{5} can be beyond 10 GeV/$c$. The prompt-$J/\psi$ nuclear modification factor is about 0.33 at the transverse momentum $p_T = 11.3$ GeV/$c$ and 0.28 at $p_T = 16.5$ GeV/$c$. The decreasing nuclear modification factor with increasing $p_T$ cannot be interpreted as correlated with the $J/\psi$ dissociation in collisions with gluons in the quark-gluon plasma \cite{6,7} or the meson-charmonium dissociation induced by quark interchange in hadronic matter \cite{8}. Now, we have to mention that the suppression of the prompt $J/\psi$ receives a contribution from nuclear shadowing \cite{9} because partons that produce the prompt $J/\psi$ in initial Pb-Pb collisions are in the nuclear shadowing region \cite{10}. Nevertheless, calculations based on the parametrization of nuclear parton distributions given by Eskola et al. \cite{11} or the parametrization given by Li and Wang \cite{12} show that the nuclear parton shadowing leads to an increasing nuclear modification factor with increasing transverse momentum \cite{9}. In addition, recombination of charm quarks and charm antiquarks in the quark-gluon plasma does not contribute to the nuclear modification factor beyond 10 GeV/$c$ \cite{9,13}. Therefore, we need to search for a new mechanism that gives a decreasing nuclear modification factor with increasing transverse momentum from 10 GeV/$c$ on. This is the subject of the present work.

We consider the reaction $A(q\bar{q}) + B(c\bar{c}) \rightarrow q + \bar{q} + c + \bar{c} \rightarrow H_c + X$, which means that a collision of meson $A$ and meson $B$ produces quarks and antiquarks ($q$, $\bar{q}$, $c$, and $\bar{c}$), the charm quark fragments into hadron $H_c$, and $q$, $\bar{q}$, and $\bar{c}$ give rise to two or more mesons. The symbol $X$ actually represents two or more mesons of which one meson contains $\bar{c}$. The reaction breaks the charmonium, i.e., meson $B$. The differential cross section for the reaction is

$$
\frac{d\sigma}{dzD_{H_c}(z,\mu^2)} = \frac{(2\pi)^4|M_{H_c}|^2}{4\sqrt{(P_A \cdot P_B)^2 - m_A^2 m_B^2}} \frac{d^3p_q'}{(2\pi)^3} \frac{d^3p_{\bar{q}}'}{(2\pi)^3} \frac{d^3p_c'}{(2\pi)^3} \frac{d^3p_{\bar{c}}'}{(2\pi)^3} \times d\vec{z} D_{H_c}^H(z,\mu^2) \delta^4(P_A + P_B - p_q' - p_{\bar{q}}' - p_c' - p_{\bar{c}}'),
$$

where $p_i' = (E_i', \vec{p}_i')$ ($i = q, \bar{q}, c, \bar{c}$) are the four-momenta of $q$, $\bar{q}$, $c$, and $\bar{c}$; $m_A$ ($m_B$) and
\( P_A (P_B) \) are the mass and four-momentum of meson \( A (B) \), respectively; \( D^H_c (z, \mu^2) \) is the \( c \to H_c \) fragmentation function at the factorization scale \( \mu \); \( z \) is the fraction of energy passed on from quark \( c \) to hadron \( H_c \); \( \mathcal{M}_\text{fi} \) is the transition amplitude for \( A + B \to q + \bar{q} + c + \bar{c} \).

With the Mandelstam variable \( s = (P_A + P_B)^2 \), integration over \( \vec{p}'_q \) and \( |\vec{p}'_q| \) yields

\[
d\sigma = \frac{1}{32(2\pi)^8 \sqrt{|s - (m_A + m_B)^2|}} d\Omega'_q d^3p'_c d^3p'_\bar{c} \\
\times dz D^H_c (z, \mu^2) \frac{|\vec{p}'_q|^2 |\mathcal{M}_\text{fi}|^2}{|\vec{p}'_q|_0^2} \left( |\vec{p}'_q|_0 - |\vec{P}_A + \vec{P}_B - \vec{p}'_c - \vec{p}'_{\bar{c}}| \cos \Theta \right) E'_q,
\]

where \( \Theta \) is the angle between \( \vec{p}'_q \) and \( \vec{P}_A + \vec{P}_B - \vec{p}'_c - \vec{p}'_{\bar{c}} \), and \( d\Omega'_q \) is the solid angle centered about the direction of \( \vec{p}'_q \). \( |\vec{p}'_q|_0 \) is determined by the energy conservation,

\[
E_A + E_B - E'_q - E'_c - E'_\bar{c} = 0,
\]

where \( E_A \) and \( E_B \) are the energies of mesons \( A \) and \( B \), respectively.

We calculate the cross section in the center-of-momentum frame of mesons \( A \) and \( B \). Denote the maxima of \( |\vec{p}'_c| \) and \( |\vec{p}'_{\bar{c}}| \) by \( p'_{c_{\text{max}}} \) and \( p'_{\bar{c}_{\text{max}}} \), respectively. We obtain \( p'_{c_{\text{max}}} \) and \( p'_{\bar{c}_{\text{max}}} \) by setting \( \vec{p}'_q = \vec{p}'_0 = 0 \), and they satisfy

\[
\sqrt{s} - \frac{\sqrt{m^2_c + p'^2_{c_{\text{max}}}}}{\sqrt{m^2_{\bar{c}} + p'^2_{\bar{c}_{\text{max}}}}} + m_q + m_{\bar{c}} + m_c + m_{\bar{c}}
\]

\[
= \sqrt{m^2_c + p'^2_{c_{\text{max}}}} + \sqrt{m^2_{\bar{c}} + p'^2_{\bar{c}_{\text{max}}}} + m_q + m_{\bar{c}} + m_c + m_{\bar{c}}.
\]

where \( m_i \) (\( i = q, \bar{q}, c, \bar{c} \)) are the masses of \( q, \bar{q}, c, \) and \( \bar{c} \). The maxima are

\[
p'_{c_{\text{max}}} = p'_{c_{\text{max}}} = \frac{1}{2(\sqrt{s} - m_q - m_{\bar{q}})} \left( \frac{\sqrt{s} - m_q - m_{\bar{q}} - m_c - m_{\bar{c}}}{\sqrt{s} - m_q - m_{\bar{q}} + m_c - m_{\bar{c}}} \right) \\
\times \frac{1}{2(\sqrt{s} - m_q - m_{\bar{q}})} \left( \frac{\sqrt{s} - m_q - m_{\bar{q}} - m_c - m_{\bar{c}}}{\sqrt{s} - m_q - m_{\bar{q}} + m_c - m_{\bar{c}}} \right) \frac{1}{2}.
\]

Denote the minimum of \( |\vec{p}'_c| \) by \( p'_{c_{\text{min}}} \). The fragmentation of the charm quark into hadron \( H_c \) requires \( \sqrt{m^2_c + p'^2_{c_{\text{min}}}} = m_{H_c} \), which gives

\[
p'_{c_{\text{min}}} = \sqrt{m^2_{H_c} - m^2_c},
\]

where \( m_{H_c} \) is the mass of hadron \( H_c \).
The cross section for \( A(q \bar{q}) + B(c \bar{c}) \rightarrow q + \bar{q} + c + \bar{c} \rightarrow H_c + X \) via \( c \rightarrow H_c \) is

\[
\sigma(\sqrt{s}, T) = \frac{1}{32(2\pi)^8 \sqrt{|s - (m_A + m_B)^2|}} \int dQ' \int_{p_{\text{min}}^c}^{p_{\text{max}}^c} \frac{d^3 p_c'}{E_c'} \times \int_0^{p_{\text{max}}^c} \frac{d^3 p_B'}{E_B'} \int_{m_{H_c}/E_c'}^{1} dz D^H_{c}(z, \mu^2) \times \left| \vec{p}_q'_{x_0} E_q' + (|\vec{p}_q'|_0 - |\vec{P}_A + \vec{P}_B - \vec{p}_c' - \vec{p}_A'\cos \Theta)|E_q' \right| .
\] (7)

In Eq. (7) the transition amplitude is given by

\[
\mathcal{M}_{fi} = \sqrt{2E_A 2E_B 2E_c 2E_c'} 2E_c 2E_c' \\
\times \left[ V_{q\bar{c}}(\vec{Q})\psi_A(\vec{p}_{q\bar{c}}) - \frac{m_q}{m_q + m_{\bar{c}}} \vec{Q}\psi_B(\vec{p}_{\bar{c}c}) - \frac{m_c}{m_c + m_{c}} \vec{Q} \right] + V_{q\bar{c}}(\vec{Q})\psi_A(\vec{p}_{q\bar{c}}) + \frac{m_q}{m_q + m_{\bar{c}}} \vec{Q}\psi_B(\vec{p}_{\bar{c}c}) + \frac{m_c}{m_c + m_{c}} \vec{Q} \\
+ V_{q\bar{c}}(\vec{Q})\psi_A(\vec{p}_{q\bar{c}}) - \frac{m_q}{m_q + m_{\bar{c}}} \vec{Q}\psi_B(\vec{p}_{\bar{c}c}) - \frac{m_c}{m_c + m_{c}} \vec{Q} \\
+ V_{q\bar{c}}(\vec{Q})\psi_A(\vec{p}_{q\bar{c}}) + \frac{m_q}{m_q + m_{\bar{c}}} \vec{Q}\psi_B(\vec{p}_{\bar{c}c}) - \frac{m_c}{m_c + m_{c}} \vec{Q} \right],
\] (8)

where \( \vec{Q} \) is the gluon three-dimensional momentum; \( \vec{p}_{ij} \) \((i, j = q, \bar{q}, c, \bar{c})\) is the relative quark momentum; \( \psi_A (\psi_B) \) represents the product of color, spin, flavor, and relativemotion wave functions of the quark and antiquark inside meson \( A (B) \), and satisfies

\[
\int \frac{d^3 p_A^{\pm}}{(2\pi)^3} \psi_A^{\pm} (\vec{p}_{q\bar{c}}) \psi_A (\vec{p}_{q\bar{c}}) = \int \frac{d^3 p_B^{\pm}}{(2\pi)^3} \psi_B^{\pm} (\vec{p}_{\bar{c}c}) \psi_B (\vec{p}_{\bar{c}c}) = 1,
\]

where \( \vec{p}_{q\bar{c}} \) (\( \vec{p}_{\bar{c}c} \)) is the relative momentum of the quark and antiquark inside meson \( A (B) \).

Denote the orbital angular momentum and the spin of meson \( A (B) \) by \( L_A (L_B) \) and \( S_A (S_B) \), respectively. Let \( L_{Bz} \) be the magnetic projection quantum number of \( L_B \). The unpolarized cross section is

\[
\sigma^{\text{unpol}}(\sqrt{s}, T) = \frac{1}{(2S_A + 1)(2S_B + 1)(2L_B + 1)} \sum_{L_{Bz}S_{q\bar{q}}S_{c\bar{c}}} (2S + 1) \sigma(\sqrt{s}, T),
\] (9)

which holds true for the three cases: \( L_A = 0, L_B = 0; L_A = 0, L_B \neq 0, S_A = 0; L_A = 0, L_B = 1, S_A = 1, S_B = 1 \). The total spin \( S \) of mesons \( A \) and \( B \) satisfies \( |S_A - S_B| \leq S \leq S_A + S_B \) and \( |S_{q\bar{q}} - S_{c\bar{c}}| \leq S \leq |S_{q\bar{q}} + S_{c\bar{c}}| \), where \( S_{q\bar{q}} (S_{c\bar{c}}) \) is the total spin of \( q \) and \( \bar{q} \) (\( c \) and \( \bar{c} \)).
The potential $V_{ab}$ used in the transition amplitude is the Fourier transform of the following potential in coordinate space \cite{13},

$$V_{ab}(\vec{r}) = V_{si}(\vec{r}) + V_{ss}(\vec{r}),$$

(10)

where $\vec{r}$ is the relative coordinate of constituents $a$ and $b$, $V_{si}$ the central spin-independent potential, and $V_{ss}$ the spin-spin interaction. The spin-independent potential depends on temperature $T$ and below the critical temperature $T_c = 0.175$ GeV is given by

$$V_{si}(\vec{r}) = -\frac{\lambda_a}{2} \cdot \frac{\lambda_b}{2} \cdot \frac{3}{4} D \left(1.3 - \left(\frac{T}{T_c}\right)^4\right) \tanh(4r) + \frac{\lambda_a}{2} \cdot \frac{\lambda_b}{2} \cdot \frac{6\pi v(\lambda r)}{25r} \exp(-E r),$$

(11)

where $D = 0.7$ GeV, $A = 1.5[0.75 + 0.25(T/T_c)^{0.6}]$ GeV, $E = 0.6$ GeV, and $\lambda = \sqrt{3b_0/16\pi^2\alpha'}$ in which $\alpha' = 1.04$ GeV$^{-2}$ and $b_0 = 11 - \frac{2}{3}N_f$ with the quark flavor number $N_f = 4$. $\lambda_a$ are the Gell-Mann matrices for the color generators of constituent quark or antiquark labeled as $a$. The dimensionless function $v(x)$ is given by Buchmüller and Tye \cite{15}. The short-distance part of the spin-independent potential originates from one-gluon exchange plus perturbative one- and two-loop corrections. The intermediate-distance and large-distance part of the spin-independent potential fits well the numerical potential obtained in the lattice gauge calculations \cite{16}. At large distances the spin-independent potential is independent of the relative coordinate and obviously exhibits a plateau at $T/T_c > 0.55$. The plateau height decreases with increasing temperature. This means that confinement becomes weaker and weaker.

Denote by $\vec{s}_a$ the spin of constituent $a$. The spin-spin interaction with relativistic effects \cite{17,18} is \cite{14,19}

$$V_{ss}(\vec{r}) = -\frac{\lambda_a}{2} \cdot \frac{\lambda_b}{2} \cdot \frac{16\pi^2}{25} \frac{d^3}{\pi^{3/2}} \exp(-d^2 r^2) \frac{\vec{s}_a \cdot \vec{s}_b}{m_am_b} + \frac{\lambda_a}{2} \cdot \frac{\lambda_b}{2} \cdot \frac{4\pi}{25} \frac{1}{r} \frac{d^2 v(\lambda r)}{dr^2} \frac{\vec{s}_a \cdot \vec{s}_b}{m_am_b},$$

(12)

of which the flavor dependence is relevant to quark masses as shown in $1/m_am_b$ and $d$,

$$d^2 = \sigma_0^2 \left[\frac{1}{2} + \frac{1}{2} \left(\frac{4m_am_b}{(m_a + m_b)^2}\right)^4\right] + \sigma_1^2 \left(\frac{2m_am_b}{m_a + m_b}\right)^2,$$

(13)

where $\sigma_0 = 0.15$ GeV and $\sigma_1 = 0.705$.

Solving the Schrödinger equation with the central spin-independent potential plus the spin-spin interaction, we obtain meson masses and quark-antiquark relative-motion wave
functions with the charm-quark mass, the up-quark mass, and the strange-quark mass being 1.51 GeV, 0.32 GeV, and 0.5 GeV, respectively. The experimental masses of \( \pi, \rho, K, K^*, \eta, \phi, J/\psi, \psi', \chi_c, D, D^*, D_s, \) and \( D_s^* \) mesons \[20\] and the experimental data of \( S \)-wave \( I = 2 \) elastic phase shifts for \( \pi\pi \) scattering in vacuum \[21\] are reproduced with \( V_{ab}(\vec{r}) \) at \( T = 0 \) and the quark-antiquark relative-motion wave functions.

We consider the charmonium dissociation \( \pi + J/\psi \to H_c + X \), \( \pi + \psi' \to H_c + X \), and \( \pi + \chi_c \to H_c + X \) with \( H_c = D^+, D^0, D_s^+, D_s^{*+}, \) or \( D_s^{*0} \). This amounts to 15 reaction channels. We solve the Schrödinger equation with the potential in Eq. (10) to get temperature-dependent quark-antiquark relative-motion wave functions of \( \pi, J/\psi \), \( \psi' \), and \( \chi_c \), calculate the transition amplitude with the wave functions and the potential, and obtain unpolarized cross sections from the transition amplitude and the charm-quark fragmentation functions provided in Ref. \[22\]. The unpolarized cross sections for \( \pi + J/\psi \to H_c + X \) at the temperatures \( T/T_c = 0, 0.65, 0.75, 0.85, 0.9, \) and 0.95 are shown in Figs. 1-4. Because the \( D_s^{*0} \) fragmentation function is unknown, we assume that it is the same as the \( D_s^{*+} \) fragmentation function. The cross section for \( \pi + J/\psi \to D_s^{*0} + X \) then equals the cross section for \( \pi + J/\psi \to D_s^{*+} + X \) and is not shown.

All the reactions are endothermic as shown in Figs. 1-4. When the difference between \( \sqrt{s} \) and the threshold energy is less than 1 GeV, the unpolarized cross section is negligible. With increasing \( \sqrt{s} \), the cross section increases slowly. Given a temperature and a difference between \( \sqrt{s} \) and the threshold energy, the cross section for the production of \( D^0 \) is largest, the cross section for the production of \( D_s^+ \) is smallest, and the cross section for \( \pi + \psi' \to H_c + X \) or \( \pi + \chi_c \to H_c + X \) is larger than the one for \( \pi + J/\psi \to H_c + X \). Since the cross-section curves for \( \pi + \psi' \to H_c + X \) and \( \pi + \chi_c \to H_c + X \) look similar to the ones for \( \pi + J/\psi \to H_c + X \), the former are not shown here.

For the convenience of use of the unpolarized cross sections shown in Figs. 1-4, they are parametrized as

\[
\sigma^{\text{unpol}}(\sqrt{s}, T) = a_1 \left( \frac{\sqrt{s} - \sqrt{s_0}}{b_1} \right)^{c_1} \exp \left[ c_1 \left( 1 - \frac{\sqrt{s} - \sqrt{s_0}}{b_1} \right) \right] + a_2 \left( \frac{\sqrt{s} - \sqrt{s_0}}{b_2} \right)^{c_2} \exp \left[ c_2 \left( 1 - \frac{\sqrt{s} - \sqrt{s_0}}{b_2} \right) \right],
\]

(14)
where $\sqrt{s_0}$ is the threshold energy and equals the sum of the $H_c$ mass, the $\bar{D}$ mass, and 2 times the up-quark mass. The values of the parameters, $a_1$, $b_1$, $c_1$, $a_2$, $b_2$, and $c_2$, are listed in Tables 1-3. The parametrization as a function of $\sqrt{s}$ at a given temperature has a peak. In the three tables we also give the quantities $d_0$ and $\sqrt{s_x}$, where $d_0$ is the separation between the peak’s location on the $\sqrt{s}$-axis and the threshold energy, and $\sqrt{s_x}$ is the square root of the Mandelstam variable at which the cross section is 1/100 of the peak cross section. We note that Eq. (14) is valid for $\sqrt{s_0} \leq \sqrt{s} \leq 11$ GeV.

Having obtained the unpolarized cross sections for the 15 reaction channels, we need to evaluate their influence on the charmonium nuclear modification factor. We thus calculate the dissociation rate of charmonium in the interaction with a pion in hadronic matter, $n_\pi < v_{rel}\sigma^{unpol} >$, where the pion number density $n_\pi$ and the thermal average $< v_{rel}\sigma^{unpol} >$ are obtained from the meson distribution function [23]. The dissociation rates are plotted in Figs. 5-7 as functions of charmonium momentum. The rate shown in Fig. 5 is gotten from the sum of the cross sections for $\pi + J/\psi \rightarrow D^+ + X$, $\pi + J/\psi \rightarrow D^0 + X$, $\pi + J/\psi \rightarrow D_s^+ + X$, $\pi + J/\psi \rightarrow D^{*+} + X$, and $\pi + J/\psi \rightarrow D^{*0} + X$. The rate shown in Fig. 6 (7) is obtained from the cross section for $\pi \psi' \rightarrow D^+ X + D^0 X + D_s^+ X + D^{*+} X + D^{*0} X$ ($\pi \chi_c \rightarrow D^+ X + D^0 X + D_s^+ X + D^{*+} X + D^{*0} X$). Given a charmonium momentum, the rate increases with increasing temperature. Given a temperature, the rate increases with increasing charmonium momentum. At $T/T_c = 0.95$ the rate is about 0.0108, 0.0142, and 0.0149 for the $\pi + J/\psi$, $\pi + \psi'$, and $\pi + \chi_c$ reactions, respectively, when the charmonium momentum is 20 GeV/c. Because the nuclear modification factor is the inverse of the exponential function of the dissociation rate [19], the reactions give a decreasing charmonium nuclear modification factor with increasing transverse momentum.

In summary, we have presented a mechanism for large-$p_T$ charmonium dissociation. In this mechanism the collision between a light meson and a charmonium produces two quarks and two antiquarks; the charm quark fragments into a charmed meson, and the other three constituents give rise to two or more mesons. The cross section for the reaction obeying the mechanism is derived from the transition amplitude and is calculated from the temperature-dependent quark potential. The temperature dependence of the potential,
the meson masses, and the mesonic quark-antiquark relative-motion wave functions lead to the temperature dependence of the cross section. From the cross section the dissociation rate of charmonium in the interaction with pions increases with increasing temperature and/or increasing charmonium momentum. The pion-charmonium reactions governed by the mechanism cause decreasing charmonium nuclear modification factor with increasing charmonium transverse momentum.

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Figure 1: Cross sections for $\pi + J/\psi \rightarrow D^+ + X$ at various temperatures.
Figure 2: Cross sections for $\pi + J/\psi \rightarrow D^0 + X$ at various temperatures.
Figure 3: Cross sections for $\pi + J/\psi \rightarrow D_s^+ + X$ at various temperatures.
Figure 4: Cross sections for $\pi + J/\psi \rightarrow D^{*+} + X$ at various temperatures.
Figure 5: Dissociation rate of $J/\psi$ with $\pi$ versus $J/\psi$ momentum at various temperatures.
Figure 6: Dissociation rate of $\psi'$ with $\pi$ versus $\psi'$ momentum at various temperatures.
Figure 7: Dissociation rate of $\chi_c$ with $\pi$ versus $\chi_c$ momentum at various temperatures.
Table 1: Quantities relevant to the cross sections for the $\pi J/\psi$ dissociation reactions. $a_1$ and $a_2$ are in units of mb; $b_1$, $b_2$, $d_0$, and $\sqrt{s_z}$ are in units of GeV; $c_1$ and $c_2$ are dimensionless.

| Reactions               | $T/T_c$ | $a_1$ | $b_1$ | $c_1$ | $a_2$ | $b_2$ | $c_2$ | $d_0$ | $\sqrt{s_z}$ |
|-------------------------|---------|-------|-------|-------|-------|-------|-------|-------|-------------|
| $\pi + J/\psi \rightarrow D^+ + X$ | 0       | 0.02  | 2.8   | 4.9   | 0.26  | 7.4   | 4.7   | 7.36  | 27.43       |
|                         | 0.65    | 0.01  | 2.7   | 4.8   | 0.26  | 7.4   | 4     | 7.38  | 29.19       |
|                         | 0.75    | 0.01  | 2.5   | 5.9   | 0.25  | 7.3   | 3.8   | 7.29  | 29.39       |
|                         | 0.85    | 0.021 | 2.9   | 4.6   | 0.24  | 7.4   | 3.9   | 7.33  | 29.26       |
|                         | 0.9     | 0.07  | 3.7   | 4.1   | 0.21  | 8.5   | 4.6   | 7.87  | 30.53       |
|                         | 0.95    | 0.04  | 2.7   | 4.5   | 0.2   | 7.2   | 3.8   | 7.05  | 28.54       |
| $\pi + J/\psi \rightarrow D^0 + X$ | 0       | 0.015 | 2.16  | 6.3   | 0.69  | 7.68  | 3.9   | 7.68  | 30.54       |
|                         | 0.65    | 0.03  | 2.7   | 5.2   | 0.68  | 7.6   | 4     | 7.59  | 29.86       |
|                         | 0.75    | 0.06  | 3.2   | 4.6   | 0.67  | 7.9   | 4     | 7.81  | 30.77       |
|                         | 0.85    | 0.028 | 2.5   | 6.4   | 0.61  | 7.2   | 3.6   | 7.19  | 29.59       |
|                         | 0.9     | 0.064 | 2.93  | 4.5   | 0.57  | 7.38  | 3.8   | 7.27  | 29.38       |
|                         | 0.95    | 0.08  | 2.5   | 4.7   | 0.53  | 6.9   | 3.9   | 6.83  | 27.22       |
| $\pi + J/\psi \rightarrow D_s^+ + X$ | 0       | 0.02  | 3.5   | 4.7   | 0.15  | 6.9   | 4.1   | 6.61  | 27.34       |
|                         | 0.65    | 0.02  | 2.7   | 5.2   | 0.15  | 6.1   | 4.9   | 5.98  | 22.99       |
|                         | 0.75    | 0.05  | 4     | 4.5   | 0.12  | 7.5   | 3.9   | 6.22  | 29.36       |
|                         | 0.85    | 0.018 | 3.1   | 6.5   | 0.132 | 6.2   | 3.9   | 5.98  | 25.25       |
|                         | 0.9     | 0.04  | 3.5   | 5.3   | 0.11  | 6.8   | 4.5   | 5.93  | 25.47       |
|                         | 0.95    | 0.05  | 3.3   | 5.3   | 0.1   | 7.1   | 4.9   | 6.11  | 25.41       |
| $\pi + J/\psi \rightarrow D^{*+} + X$ | 0       | 0.027 | 3.5   | 4.9   | 0.31  | 7.5   | 5.3   | 7.39  | 26.63       |
|                         | 0.65    | 0.04  | 3.3   | 5.4   | 0.3   | 7     | 6     | 6.86  | 23.93       |
|                         | 0.75    | 0.01  | 2.6   | 8     | 0.31  | 7.2   | 4     | 7.2   | 28.51       |
|                         | 0.85    | 0.01  | 1.7   | 14    | 0.29  | 6.3   | 3.9   | 6.3   | 25.57       |
|                         | 0.9     | 0.06  | 3     | 4.5   | 0.25  | 7     | 4.2   | 6.67  | 26.88       |
|                         | 0.95    | 0.06  | 2.58  | 4.5   | 0.232 | 6.7   | 3.8   | 6.48  | 26.81       |
Table 2: The same as Table 1 except for $\pi\psi'$.  

| Reactions       | $T/T_c$ | $a_1$ | $b_1$ | $c_1$ | $a_2$ | $b_2$ | $c_2$ | $d_0$ | $\sqrt{s_{z}}$ |
|-----------------|---------|-------|-------|-------|-------|-------|-------|-------|---------------|
| $\pi + \psi' \to D^+ + X$ | 0       | 0.013 | 1.8   | 8.9   | 0.44  | 6.6   | 3.9   | 6.6   | 26.86         |
|                 | 0.65    | 0.209 | 4     | 13.1  | 0.76  | 9.2   | 4.7   | 9.18  | 32.97         |
|                 | 0.75    | 0.13  | 3.4   | 16    | 0.6   | 7.3   | 5.5   | 7.29  | 25.4          |
|                 | 0.85    | 0.11  | 3.4   | 9     | 0.4   | 7.1   | 5.5   | 6.92  | 24.65         |
|                 | 0.9     | 0.067 | 3.2   | 6.7   | 0.3   | 7     | 4.5   | 6.78  | 26.16         |
|                 | 0.95    | 0.04  | 2.9   | 5     | 0.24  | 7     | 3.1   | 6.78  | 30.48         |
| $\pi + \psi' \to D^{0} + X$ | 0       | 0.03  | 1.6   | 15    | 1.16  | 6.8   | 3.8   | 6.8   | 27.84         |
|                 | 0.65    | 0.001 | 0.7   | 5     | 1.8   | 6     | 6.8   | 6     | 20.21         |
|                 | 0.75    | 0.7   | 4.1   | 11    | 3.22  | 14.4  | 4.1   | 14.4  | 52.08         |
|                 | 0.85    | 0.12  | 2.9   | 12.7  | 1.06  | 6.3   | 5.5   | 6.29  | 22.35         |
|                 | 0.9     | 0.13  | 3     | 7.5   | 0.81  | 6.9   | 4.4   | 6.82  | 26.1          |
|                 | 0.95    | 0.13  | 3     | 4     | 0.61  | 6.9   | 3.9   | 6.54  | 27.14         |
| $\pi + \psi' \to D_{s}^{+} + X$ | 0       | 0.012 | 2.2   | 8.4   | 0.27  | 5.9   | 3.8   | 5.9   | 24.84         |
|                 | 0.65    | 0.27  | 3.9   | 17    | 0.42  | 9     | 4.5   | 8.99  | 32.99         |
|                 | 0.75    | 0.15  | 3.3   | 27    | 0.34  | 6     | 6.7   | 5.98  | 20.3          |
|                 | 0.85    | 0.1   | 3.2   | 20    | 0.249 | 6     | 6.7   | 5.95  | 20.18         |
|                 | 0.9     | 0.071 | 3.2   | 14.5  | 0.175 | 6     | 6.2   | 5.8   | 20.6          |
|                 | 0.95    | 0.06  | 3.1   | 8.7   | 0.13  | 6.3   | 4.9   | 5.7   | 23.08         |
| $\pi + \psi' \to D^{*+} + X$ | 0       | 0.009 | 1.7   | 12.1  | 0.52  | 6.8   | 4.2   | 6.8   | 26.87         |
|                 | 0.65    | 0.4   | 4.3   | 18    | 1.98  | 14.4  | 4.4   | 14.4  | 50.68         |
|                 | 0.75    | 0.23  | 3.8   | 19    | 0.73  | 7.8   | 6     | 7.78  | 26.09         |
|                 | 0.85    | 0.116 | 3.1   | 15    | 0.5   | 6.1   | 5.9   | 6.05  | 21.28         |
|                 | 0.9     | 0.1   | 2.8   | 7.4   | 0.37  | 6     | 5.9   | 5.83  | 20.81         |
|                 | 0.95    | 0.12  | 3.2   | 4     | 0.25  | 7     | 3.8   | 5.67  | 27.55         |
Table 3: The same as Table 1 except for $\pi \chi_c$.

| Reactions               | $T/T_c$ | $a_1$ | $b_1$ | $c_1$ | $a_2$ | $b_2$ | $c_2$ | $d_0$ | $\sqrt{s_z}$ |
|-------------------------|---------|-------|-------|-------|-------|-------|-------|-------|-------------|
| $\pi + \chi_c \rightarrow D^+ + X$ | 0       | 0.07  | 3     | 4.3   | 0.41  | 7.6   | 4.8   | 7.45  | 27.8        |
|                         | 0.65    | 0.03  | 3.4   | 14    | 0.53  | 7.2   | 4.2   | 7.19  | 27.95       |
|                         | 0.75    | 0.11  | 3.8   | 9.6   | 0.5   | 7.7   | 4.4   | 7.48  | 28.92       |
|                         | 0.85    | 0.12  | 3.4   | 7.8   | 0.39  | 6.8   | 6.6   | 6.51  | 22.27       |
|                         | 0.9     | 0.1   | 3.5   | 5.7   | 0.29  | 7.3   | 5.2   | 6.75  | 25.54       |
|                         | 0.95    | 0.1   | 3.7   | 4     | 0.25  | 9.6   | 3     | 8.59  | 40.94       |
| $\pi + \chi_c \rightarrow D^0 + X$ | 0       | 0.06  | 2.3   | 5     | 1.04  | 7.2   | 3.8   | 7.19  | 29.22       |
|                         | 0.65    | 0.14  | 4     | 9     | 1.39  | 7.9   | 4     | 7.76  | 30.85       |
|                         | 0.75    | 0.42  | 4.1   | 8.6   | 1.58  | 10.1  | 3.9   | 10.02 | 38.6        |
|                         | 0.85    | 0.2   | 3.2   | 8.7   | 1.05  | 6.7   | 5.6   | 6.59  | 23.35       |
|                         | 0.9     | 0.25  | 3.6   | 5.9   | 0.81  | 8     | 4.4   | 7.56  | 29.57       |
|                         | 0.95    | 0.12  | 3     | 4     | 0.64  | 6.8   | 3.7   | 6.46  | 27.41       |
| $\pi + \chi_c \rightarrow D_s^+ + X$ | 0       | 0.04  | 2.6   | 5.2   | 0.25  | 6.5   | 4.3   | 6.4   | 25.59       |
|                         | 0.65    | 0.1   | 4.1   | 7     | 0.27  | 6.5   | 4.5   | 5.52  | 24.64       |
|                         | 0.75    | 0.11  | 3.5   | 15    | 0.3   | 6.3   | 5.1   | 5.89  | 23.16       |
|                         | 0.85    | 0.13  | 3.4   | 13.3  | 0.23  | 6.3   | 7.5   | 5.88  | 20.2        |
|                         | 0.9     | 0.11  | 3.4   | 11.3  | 0.17  | 6.4   | 8.3   | 5.82  | 19.7        |
|                         | 0.95    | 0.065 | 3     | 9.9   | 0.14  | 6.1   | 5.6   | 5.78  | 21.42       |
| $\pi + \chi_c \rightarrow D^{*+} + X$ | 0       | 0.03  | 2.6   | 6.1   | 0.49  | 7.2   | 4.5   | 7.19  | 27.42       |
|                         | 0.65    | 0.13  | 4.4   | 10.8  | 0.6   | 7.8   | 4.6   | 7.29  | 28.87       |
|                         | 0.75    | 0.2   | 4.1   | 12    | 0.62  | 8.1   | 4.8   | 7.85  | 29.26       |
|                         | 0.85    | 0.21  | 3.5   | 9     | 0.47  | 6.7   | 7.5   | 6.25  | 21.12       |
|                         | 0.9     | 0.11  | 3.1   | 7     | 0.36  | 6.6   | 4.6   | 6.26  | 24.66       |
|                         | 0.95    | 0.13  | 3.2   | 4     | 0.27  | 7.5   | 3.7   | 6.22  | 29.69       |