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# THERMAL CHARM PRODUCTION AT LHC[*] [**]

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We report results from our recent study on charm and anticharm quark pair production in the next-to-leading order in QCD from the quark-gluon formed in heavy ion collisions at the Large Hadron Collider (LHC) and its dependence on the number of charm quark pairs produced from initial hard scattering, the charm quark mass, and the temperature and formation time of the quark-gluon plasma.

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Studying the production of hadrons consisting of heavy charm quarks has been of great interest in relativistic heavy ion collisions. This includes charmonium suppression as a possible signature for the quark–gluon plasma [1], the charm elliptic flow and quenching as a probe of the charm quark interactions in the quark–gluon plasma [2–4], and the production of exotic tetraquark and pentaquark charmed hadrons [5, 6]. For quantitative studies of these phenomena, it is essential to understand the production mechanism of charm quarks in these collisions. Recently, we have studied, in the next-to-leading order in QCD, thermal charm and anticharm quark pair production from the quark–gluon plasma produced in relativistic heavy ion collisions at LHC [7]. Specifically, we have included the processes $q+\bar{q}\to c+\bar{c}$ and $g+g\to c+\bar{c}$ and their virtual corrections as well as the processes

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$q+\bar{q} \to c+\bar{c}+g$ and $g+g \to c+\bar{c}+g$. The amplitudes for these processes were taken from Refs. [8,9] using massless quarks and gluons, the QCD coupling constant $\alpha_s(m_c) \approx 0.37$, and a charm quark mass $m_c = 1.3$ GeV. The charm quark production rate in the quark–gluon plasma was then evaluated by integrating over the thermal quark and gluon distributions in the quark–gluon plasma. Both thermal quarks and gluons were taken to have thermal masses given by $m_q = m_g = gT/\sqrt{6}$, where $T$ is the temperature of the quark–gluon plasma and $g$ is related to the thermal QCD coupling constant $\alpha_s(2\pi T) = g^2/4\pi$, which has values ranging from $\sim 0.23$ for $T = 700$ MeV to $\sim 0.42$ for $T = 170$ MeV. As shown in Fig. 1, for both quark–antiquark annihilation and gluon–gluon fusion, charm quark pair production cross sections (left two windows), given as functions of center-of-mass energy, and their thermal averages (right two windows), shown as functions of temperature, are generally larger in the next-to-leading order than in the leading order.

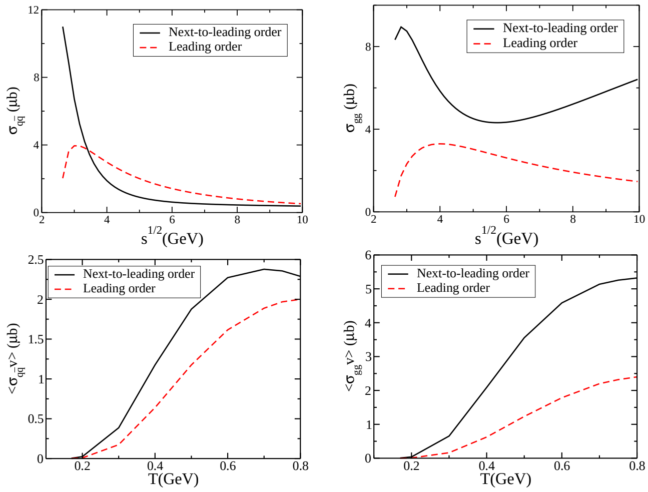


Fig. 1. (Color online) Charm quark pair production cross sections as functions of center-of-mass energy (left two windows) and their thermal averages as functions of temperature (right two windows) from quark–antiquark annihilation and gluon–gluon fusion in the leading and the next-to-leading order.

For the dynamics of formed quark–gluon plasma in central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at LHC, we have assumed that it evolves boost invariantly in the longitudinal direction but with an accelerated transverse expansion. Specifically, its volume expands in the proper time $\tau$ according to $V(\tau) = \pi R^2(\tau)\tau c$, where $R(\tau) = R_0 + a(\tau-\tau_0)^2/2$ is the transverse radius with an initial value $R_0 = 7$ fm, the quark–gluon plasma formation time $\tau_0$, and the transverse acceleration $a = 0.1\ c^2/\text{fm}$. Starting with an initial temperature $T_0 = 700$ MeV at $\tau_0 = 0.2$ fm/$c$, the time dependence of the temperature is obtained from entropy conservation, leading to the critical temperature $T_{\rm C} = 170$ MeV at proper time $\tau_{\rm C} = 6.4$ fm$/c$. The initial number of charm pairs is taken to be $dN_{c\bar{c}}/dy = 20$ at midrapidity, which is of similar magnitude as that estimated from initial hard nucleon-nucleon collisions based on the next-to-leading order pQCD calculations.

In the left window of Fig. 1, we show the temperature dependence of the charm quark pair production rates from the leading order (dashed line) and the next-to-leading order (solid line). Both are appreciable at high temperatures with the latter larger than the former, and their ratio varies from $\sim 4.5$ at low temperatures to $\sim 1.8$ at high temperatures as shown in the inset in the figure. The total number of charm pairs as a function of the proper time $\tau$ is shown in the right window of Fig. 2. As shown by the dashed line, including only the leading-order contribution from two-body processes increases the number of charm pairs by about 10% during the evolution of the quark–gluon plasma, reaching a final value of about 22. Adding the next-

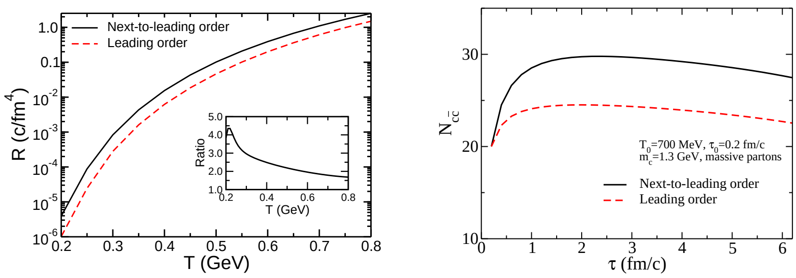


Fig. 2. (Color online) Left window: Production rates of charm quark pairs as functions of temperature. The inset gives the ratio between charm production rates in the next-to-leading and the leading order. Right window: Time evolution of charm quark pair numbers in central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

leading-order contribution through virtual corrections to two-body precesses as well as the $2 \to 3$ processes further increases the charm quark pair number by about 25% to about 27 as shown by the solid line. The number of charm quark pairs reaches its peak value at $\tau \sim 2$ fm$/c$ and then deceases with the proper time as a result of larger charm annihilation than creation rates when the temperature of the quark–gluon plasma drops. At the end of the quark–gluon plasma phase, it remains greater than both its initial value and the chemically equilibrium value of about 5 at $T_{\rm C} = 170$ MeV. We have also found that thermal production of charm quarks from the quark–gluon plasma becomes more important as the initial number of charm quark pairs is smaller, *e.g.*, the final numbers are about 19, 27, and 45, respectively, for initial numbers of charm quark pairs of 10, 20 and 40. The number of charm quark pairs produced from the quark–gluon plasma would be reduced by a factor of about 3 if a larger charm quark mass of 1.5 GeV or a lower initial temperature of $T_0 = 630$ MeV is used. The latter corresponds to an initial energy density similar to those predicted by the AMPT model [10] and the Color Glass Condensate [11], although both have considerable uncertainties. It is, however, not much affected by using massless gluons and quarks due to increase in their densities. On the other hand, increasing the initial temperature to 750 MeV would enhance the thermally produced charm quark pairs by about a factor of 2. Using a larger quark–gluon formation time of $\tau_0 = 0.5$ fm/$c$, similar to that in heavy ion collisions at RHIC, reduces the initial temperature of the quark–gluon plasma but not much the final number of charm quark pairs, compared to the case of a formation time $\tau_0 = 0.2$ fm/$c$.

Although our results have indicated that charm and anticharm quark pair production depends sensitively on the initial temperature of the quark–gluon plasma, it is likely to be enhanced in heavy ion collisions at LHC. Studying charmed hadron production at LHC is thus expected to lead to many exciting phenomena.

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