

# Charmonium production from secondary collisions at LHC energy

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**Abstract.** We consider the charmonium production in the thermalized hadronic medium created in ultrarelativistic heavy ion collisions at LHC energy. The calculations for secondary  $J/\psi$  and  $\psi'$  production by  $D\bar{D}$  annihilation are performed within a kinetic model taking into account the space-time evolution of a longitudinally and transversely expanding medium. We show that secondary charmonium production appears almost entirely during the mixed phase, and that it is very sensitive to the charmonium dissociation cross section with co-moving hadrons. Within the most likely scenario for the dissociation cross section of the  $J/\psi$  mesons their regeneration in the hadronic medium will be negligible. The secondary production of  $\psi'$  mesons however, due to their large cross section above the threshold, can substantially exceed the primary yield.

## 1 Secondary charmonium production

The initial energy density in ultrarelativistic heavy ion collisions at LHC energy exceeds by a few order of magnitudes the critical value required for quark–gluon plasma formation. Thus, according to Matsui and Satz [1,2], one expects the formation of charmonium bound states to be severely suppressed due to Debye screening. The initially produced  $c\bar{c}$  pairs in hard parton scattering, however, due to charm conservation will survive in the deconfined medium until the system reaches the critical temperature where the charm quarks hadronize, forming predominantly  $D$  and  $\bar{D}$  mesons. An appreciable fraction of  $c\bar{c}$  pairs and consequently  $D\bar{D}$  mesons produced in Pb–Pb collisions at LHC energy can lead to an additional production of charmonium bound states due to reactions such as  $D\bar{D}^* + D^*\bar{D} + D^*D^* \rightarrow \psi + \pi$  and  $D^*D^* + D\bar{D} \rightarrow \psi + \rho$  as first indicated in [3]. In the present work we give a quantitative description of secondary  $J/\psi$  and  $\psi'$  production due to the above processes associated with the thermal hadronic medium created in Pb–Pb collisions at LHC energy.

## 2 Thermal production kinetics

The charmonium production cross section  $\sigma_{D\bar{D} \rightarrow \psi h}$  can be related to the hadronic absorption of charmonium  $\sigma_{\psi h \rightarrow D\bar{D}}$ , through the detailed balance relation,

$$\sigma_{D\bar{D} \rightarrow \psi h} = d_{D\bar{D}} \left( \frac{k_{\psi\pi}}{k_{D\bar{D}}} \right)^2 \sigma_{\psi h \rightarrow D\bar{D}}, \quad (1)$$

where  $k_{ab}^2 = [s - (m_a + m_b)^2][s - (m_a - m_b)^2]/4s$  denotes the square of the center of mass momentum of the correspond-

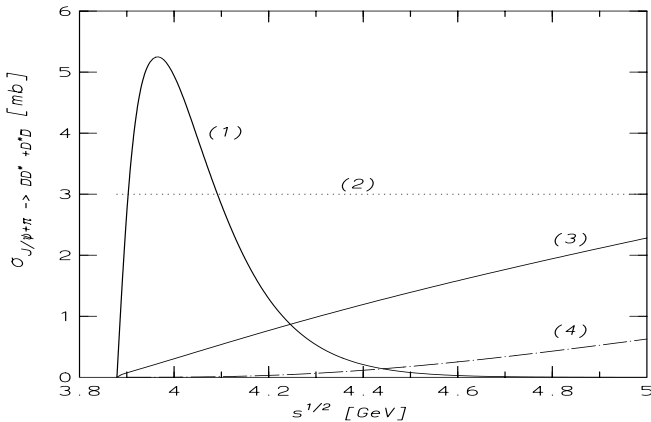
ing reaction and  $h$  stands for  $\rho$  or  $\pi$ , whereas  $\psi$  stands for  $J/\psi$  or  $\psi'$  mesons. The degeneracy factor  $d$  takes the values  $d_{D\bar{D}^*} = d_{D^*\bar{D}} = 3/4$ ,  $d_{D^*D^*} = d_{D^*\bar{D}} = 1/4$  with the pions in the final state and  $d_{D\bar{D}^*} = d_{D^*\bar{D}} = 9/4$ ,  $d_{D\bar{D}} = 27/4$ ,  $d_{D^*D^*} = 3/4$ , for the processes with  $\rho$  mesons.

The magnitude of the charmonium absorption cross section on hadrons is still, however, theoretically not well under control. There are four models which have been proposed to give an estimate for the  $J/\psi$  dissociation cross section on pions:

- (1) the constituent quark model [4],
- (2) the co-mover model [5,6],
- (3) an effective hadronic Lagrangian [7], and
- (4) a short distance QCD approach [8].

In the framework of the constituent quark model the  $J/\psi$  absorption on a pion is viewed as a quark exchange process where the charm quark is changed for a light quark. The cross section for the  $\pi + J/\psi \rightarrow D^*\bar{D} + D\bar{D}^* + D^*\bar{D}^*$  process, in this approach, was calculated in the non-relativistic quark model in terms of the first Born approximation [4]. The energy dependence of the above cross section for the final state  $D^*\bar{D} + D\bar{D}^*$  is shown in Fig. 1. One sees that the cross section abruptly increases just above threshold and reaches a peak value of about 6 mb. The large value of the cross section is mostly due to the particular modeling of the confining interaction between the quarks which is taken as attractive, independent of the color quantum number of the affected quark pair.

The large charm quark mass,  $m_c \sim 1.2\text{--}1.8$  GeV and the  $J/\psi$  binding energy,  $2M_D - M_{J/\psi} \sim 640$  MeV in comparison to  $\Lambda_{\text{QCD}}$ , as well as the small size of  $J/\psi$ ,  $r_{J/\psi} \sim 0.2$  fm  $\ll \Lambda_{\text{QCD}}^{-1}$ , have been used as an argument to cal-



**Fig. 1.** The cross section for  $J/\psi + \pi \rightarrow \bar{D}D^* + \bar{D}^*D$  absorption as a function of energy: curve (1) is calculated within a non-perturbative quark exchange model [4]; curve (2) corresponds to the constant cross section of 3 mb [5,6]; curve (3) was obtained within the framework of a meson exchange model [7]; curve (4) is derived in the context of perturbative QCD [8]

calculate the charmonium dissociation for light hadrons in terms of a QCD approach [8,9]. The  $J/\psi$ - $h$  cross section in this approach is expressed in terms of hadronic gluon distribution functions, making use of the short distance QCD method based on sum rules derived from the operator product expansion. The resulting energy dependence of the  $J/\psi$  absorption cross section on pions calculated within QCD [8] is shown in Fig. 1. The hadronic gluon distribution functions are strongly suppressed at high gluon momenta. Thus, since the dissociation of  $J/\psi$  requires hard gluons, the absorption cross section  $J/\psi\pi \rightarrow D\bar{D}$  becomes very small; just above threshold as seen in Fig. 1. Recent analysis of  $J/\psi$  photoproduction data confirms the relation between the charmonium-hadron interactions and the hadronic gluon structure [8,10,11] indicating a small value of the  $J/\psi$  absorption cross section on hadrons.

The scattering of  $J/\psi$  on a  $\pi$  or  $\rho$  meson can also be described as the exchange of open charm mesons between the charmonium and the incident particle. Near the kinematical threshold this exchange was modeled in terms of an effective meson Lagrangian [7]. In Fig. 1 we show the energy dependence of the cross section for  $J/\psi$  dissociation in this approach. The result for the cross section should be considered here as an upper limit, since in the model the hadronic form factor was taken to be unity.

In phenomenological models describing charmonium production in  $pA$  and light nucleus-nucleus collisions, the dissociation cross section of charmonium on light mesons was assumed to be energy independent [5,6]. Using a value of  $\sigma_{\psi N} \sim 4.8$  mb, which was shown to be consistent with the  $pA$  data, and the quark structure of hadrons one could fix  $\sigma_{\psi(\pi,\rho)} \sim 2\sigma_{\psi N}/3 \sim 3$  mb.

The differences between these various models for the energy dependence of the  $J/\psi$ - $\pi$  cross section are particularly large near threshold. The theoretical uncertainties of the cross section seen in Fig. 1 will naturally influence the yield of the secondary charmonium production.

In the following, we shall calculate and compare the yield of the secondary  $J/\psi$  with all these cross sections.

The  $\psi'$  absorption cross section has not been evaluated in the quark exchange and effective Lagrangian model. The application of the short distance QCD is not possible in this case due to the very low binding energy of the  $\psi'$  (of the order of 60 MeV) and the correspondingly large size of the  $\psi'$ .

For a first estimate of the  $\psi'$  dissociation on light mesons we assume that the absorption cross section is energy independent and attains its geometric value of about 10 mb very near the threshold. This assumption was shown to give a quite good description of the  $\psi'$  suppression observed in S-U collisions [12].

## 2.1 Rate equation for the charmonium production in a hadron gas

In a thermal hadronic medium the rate of charmonium production from  $D\bar{D}$  annihilation is determined by the thermally averaged cross section and the densities of incoming and outgoing particles. The thermal average of the charmonium production cross section  $\langle\sigma_{D\bar{D}\rightarrow\psi h}v_{D\bar{D}}\rangle$  is given by the following expression [13]:

$$\langle\sigma_{D\bar{D}}v_{D\bar{D}}\rangle = \frac{\beta}{8} \times \frac{\int_{t_0}^{\infty} dt \sigma_{D\bar{D}}(t) [t^2 - (m_{D\bar{D}}^+)^2] [t^2 - (m_{D\bar{D}}^-)^2] K_1(\beta t)}{m_D^2 m_{\bar{D}}^2 K_2(\beta m_D) K_2(\beta m_{\bar{D}})}, \quad (2)$$

where  $K_1$ ,  $K_2$  are the modified Bessel functions of the second kind,  $m_{D\bar{D}}^+ \equiv m_D + m_{\bar{D}}$  and  $m_{D\bar{D}}^- \equiv m_D - m_{\bar{D}}$ ,  $t \equiv (s)^{1/2}$  is the center of mass energy,  $\beta$  the inverse temperature,  $v_{ab}$  is the relative velocity of incoming mesons and the integration limit is taken to be  $t_0 = \max[(m_D + m_{\bar{D}}), (m_{\psi} + m_h)]$ .

The thermal cross section for the production and absorption of charmonium convoluted with the densities of incoming particles describes the rate equation for charmonium production in a hadron gas per unit of rapidity by

$$\frac{dR}{d\tau} = \sum_{i,j} \langle\sigma_{D_i \bar{D}_j \rightarrow \psi h} v_{D_i \bar{D}_j}\rangle n_{D_i} n_{\bar{D}_j} - \sum_{i,j} \langle\sigma_{\psi h \rightarrow D_i \bar{D}_j} v_{\psi h}\rangle n_{\psi} n_h, \quad (3)$$

where  $i = \{D, D^*\}$ ,  $h$  denotes a  $\pi$  or  $\rho$  meson and  $\psi$  stands for  $\psi'$  or  $J/\psi$ .

In the hadronic medium we include the following secondary charmonium production processes:

$$D^* \bar{D} + D \bar{D}^* + D^* \bar{D}^* \rightarrow \pi + \psi, \quad (4)$$

$$D^* \bar{D}^* + D \bar{D} \rightarrow \rho + \psi, \quad (5)$$

where  $\psi$  stands for  $J/\psi$  or  $\psi'$ .

The solution of the rate equation requires additional assumptions on the space-time evolution of the hadronic medium and the initial number of  $D$  and  $\bar{D}$  mesons.

## 2.2 Model for expansion dynamics

We have adopted a model for the expansion dynamics assuming an isentropic cylindrical expansion of the thermal fireball. To account for transverse expansion we assume a linear increase of the radius of a cylinder with proper time. Thus, at a given proper time  $\tau$  the volume of the system is parameterized by

$$V(\tau) = \pi R^2(\tau)\tau, \quad \text{with } R(\tau) = R_A + 0.15(\tau - \tau_0), \quad (6)$$

where  $\tau_0$  is the initial proper time when the system is created as a thermally equilibrated quark–gluon plasma and  $R_A$  is an initial radius being determined by the atomic number of colliding nucleus. For central Pb–Pb collisions  $R_A \sim 6.7$ , and we fixed  $\tau_0 \sim 0.1$  fm.

The initially produced quark–gluon plasma cools during the expansion until it reaches the critical temperature  $T_c$  at the time  $\tau_q^c$  where it starts to hadronize. The system stays in the mixed phase until the time  $\tau_h^c$  where the quark–gluon plasma is totally converted to a hadron gas. The purely hadronic gas can still expand until it reaches the chemical freeze-out temperature  $T_f$  at the time  $\tau_f$  where all inelastic particle scattering ceases and the particle production stops.

The most recent results of lattice gauge theory (LGT) give an upper limit for the critical temperature in QCD of  $T_c \sim 0.17$  GeV [14]. The analysis of presently available data for different particle multiplicities and their ratios measured in heavy ion collisions at SPS energy suggests that the chemical freeze-out temperature at LHC should be in the range  $0.16 < T_f < 0.18$  [15–18], that is very close to  $T_c$ .

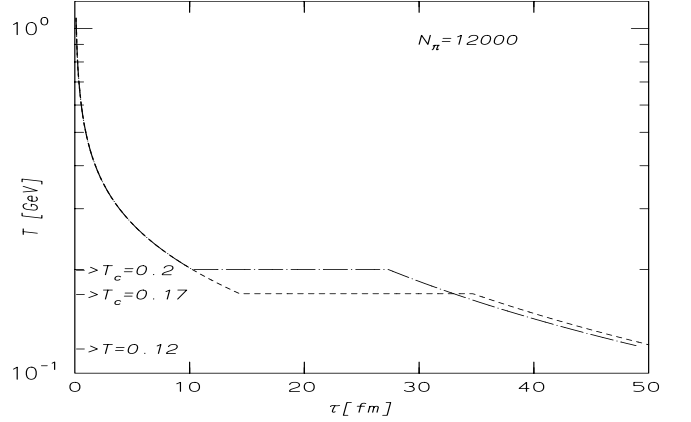
To make a quantitative description of the space-time evolution of a thermal medium one still needs to specify the equation of state. The quark–gluon plasma is considered as an ideal gas of quarks and gluons whereas the hadron gas is described as an ideal gas of hadrons and resonances. We have included the contributions of all baryonic and mesonic resonances with a mass of up to 1.6 GeV into the partition function. To approximately take into account the repulsive interactions between hadrons at short distances we apply excluded volume corrections. Here we use the thermodynamically consistent model proposed in [17, 19] where the thermodynamical observables for extended particles are obtained from the formulas for pointlike objects but with the shift of the chemical potential. In particular, the pressure is described by

$$P^{\text{extended}}(T, \mu) = P^{\text{pointlike}}(T, \bar{\mu}), \quad (7)$$

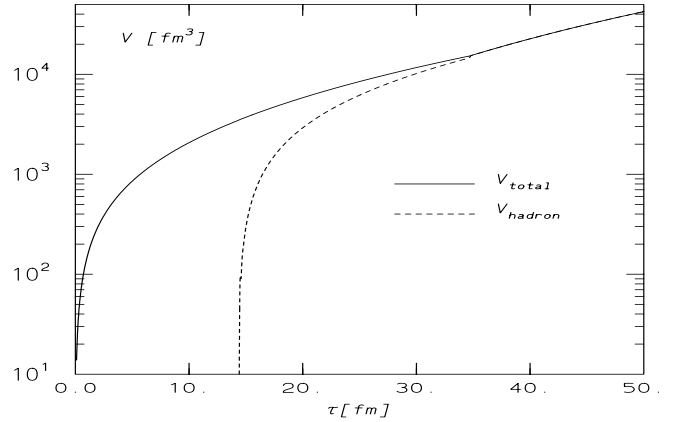
$$\text{with } \bar{\mu} = \mu - v_{\text{eigen}} p^{\text{extended}}(T, \mu),$$

where the particle eigenvolume  $v_{\text{eigen}} = 4(4/3)\pi r^3$  simulates repulsive interactions between the hadrons. Following the detailed analysis in [17, 20] we have assigned the value  $r = 0.3$  fm for all mesons and baryons.

In Fig. 2 we show the time evolution of the temperature for Pb–Pb collisions at LHC energy for two different values of  $T_c$ . The initial temperature of the chemically



**Fig. 2.** Model for the time evolution of temperature in the expanding QCD medium created in Pb–Pb collisions at LHC energy



**Fig. 3.** As in Fig. 1 but for the volume of the system:  $V_{\text{hadron}}$  is the fraction of the volume occupied by the confined hadronic medium;  $V_{\text{total}}$  is the total volume of the system

equilibrated plasma was fixed requiring entropy conservation:

$$s_q(T_0)V_0 \sim N_\pi/3.6 \quad \text{with } N_\pi \equiv (dN_\pi/dy)_{y=0}, \quad (8)$$

where  $N_\pi$  described the final number of pions at midrapidity,  $V_0$  is the initial volume and  $s_q(T_0)$  the initial entropy density of the thermalized quark–gluon plasma. For  $N_\pi = 12,000$  and  $\tau_0 = 0.1$  fm we get the initial thermalization temperature  $T_0 \sim 1.07$  GeV for Pb–Pb collisions at LHC.

The result in Fig. 2 shows that for  $T_c \sim 0.17$  GeV the QGP starts to hadronize after 14 fm and stays in the mixed phase by 20 fm. Taking the lowest expected freeze-out temperature  $T_f \sim 0.16$  GeV the system exists only for a very short time of a few fm in a hadronic phase<sup>1</sup>. Thus, the contribution of the purely hadronic phase to the overall secondary charmonium multiplicity can be neglected. The secondary charmonium bound states are produced almost

<sup>1</sup> We do not count the isentropic expansion phase towards thermal freeze-out, since no appreciable particle production takes place there

entirely during the mixed phase. This is in contrast to [3]. In Fig. 3 we show the time evolution of the total volume  $V$  as well as the fraction of the volume  $V_h$  occupied by hadrons during the mixed phase. The total volume is calculated following (6), whereas  $V_h$  can be obtained from the condition of entropy conservation in the following form:

$$V_h(\tau) = \frac{V(\tau) - V_q^c}{1 - (s_h^c/s_q^c)}, \quad V_q^c = \frac{N_\pi}{3.6s_q^c}, \quad V_h^c = \frac{N_\pi}{3.6s_h^c}, \quad (9)$$

where  $s_q^c$  and  $s_h^c$  are the entropy density in the quark–gluon plasma and the hadron gas at the critical temperature. For the equation of state described above and  $T_c = 0.17$  GeV we have  $s_q^c \sim 11.9$  and  $s_h^c/s_q^c \sim 0.22$ .

The time evolution of the hadronic medium during the mixed phase is totally determined by the number of pions in the final state and the entropy density of the quark–gluon plasma and the hadron gas at the critical temperature. Our default parameters for the expansion dynamics are as follows:

$$\begin{aligned} T_c &= 0.17 \text{ GeV}, & T_f &\sim T_c, & \tau_0 &\sim 0.1 \text{ fm}, \\ s_q^c &\sim 12/\text{fm}^3, & s_h^c/s_q^c &\sim 0.22. \end{aligned} \quad (10)$$

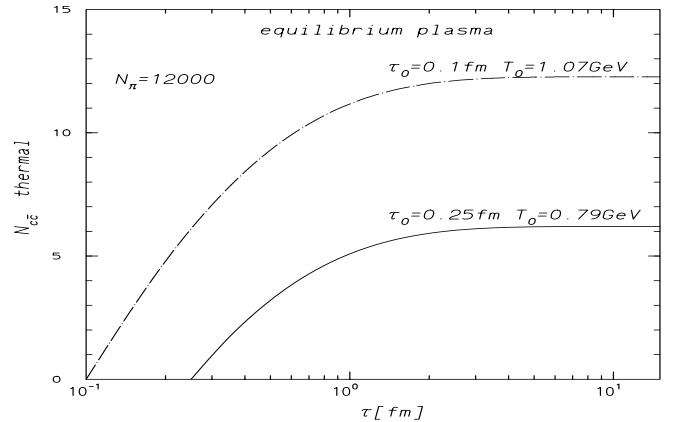
We will study, however, how deviations from the above values influence the final multiplicity of the secondary charmonium produced during the evolution of the hadronic medium.

### 2.3 Charm density

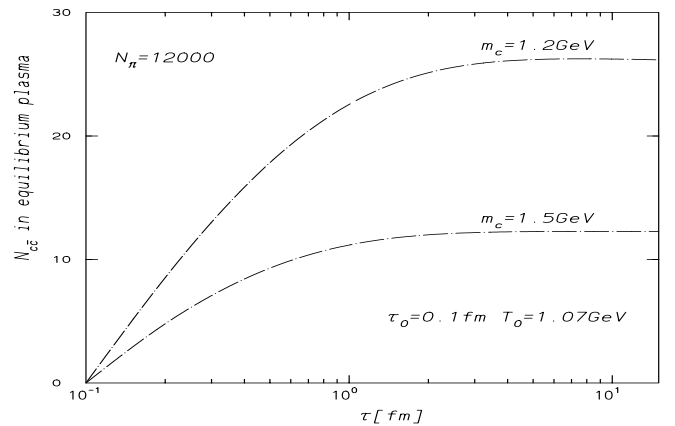
The initial number of open charm mesons at the critical temperature  $N_{D\bar{D}}$  can be related to the number of primary  $c, \bar{c}$  quarks  $N_{c\bar{c}}$  produced in  $A$ – $A$  collisions. Neglecting the possible absorption and production of  $c\bar{c}$  pairs during the evolution and hadronization of a quark–gluon plasma we can put  $N_{D\bar{D}} \sim N_{c\bar{c}}$ . Due to charm conservation the number of  $D$ 's should be equal to the number of  $\bar{D}$  mesons. Charm conservation also implies that during the mixed phase the number of  $D\bar{D}$  mesons in the hadronic phase  $N_{D\bar{D}}^m$  is given by the fraction of the volume occupied by the hadrons, that is  $N_{D\bar{D}}^m = N_{c\bar{c}}V_h/V$ , where  $V$  and  $V_h$  are described by (6) and (9). We further assume that during hadronization of the quark–gluon plasma the open charm mesons are in a local thermal equilibrium with all other hadrons; however, the yield of  $D$  and  $\bar{D}$  exceeds their chemical equilibrium value. The ratio of the number of  $D$  to  $D^*$  mesons at the temperature  $T$  is obtained from the relative chemical equilibrium condition:

$$\frac{N_D}{N_{D^*}} = 3 \frac{m_{D^*}^2 K_2(\beta m_{D^*})}{m_D^2 K_2(\beta m_D)}. \quad (11)$$

The initial number of  $c\bar{c}$  pairs in Pb–Pb collisions at LHC energy was obtained by scaling the  $p$ – $p$  result with the geometrically allowed number of nucleon–nucleon collisions. The cross section for charm production at LHC in  $p$ – $p$  collisions was calculated by leading order perturbative QCD using the code PYTHIA with  $\langle k_t^2 \rangle = 1 \text{ GeV}^2$  [21]. Typical



**Fig. 4.** Time evolution of the number of  $c\bar{c}$  produced in an equilibrium QGP for two different values of the initial thermalization time and the initial temperature calculated with 12,000 pions in the final state

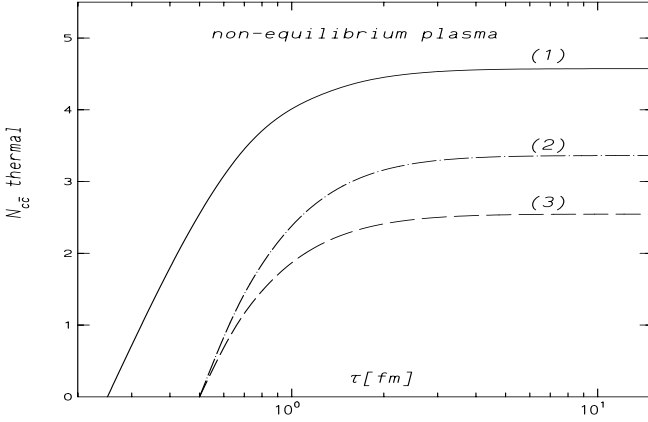


**Fig. 5.** Time evolution of the number of  $c\bar{c}$  produced in an equilibrium QGP for two different values of the charm quark mass

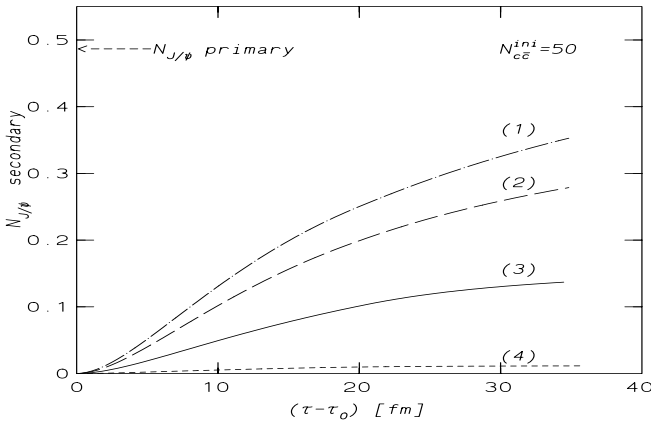
values of the 50  $c\bar{c}$  pairs and 0.5  $J/\psi$  were obtained in central Pb–Pb collisions at midrapidity.

The  $c\bar{c}$  pairs can also be produced and absorbed during the evolution of thermally equilibrated quark–gluon plasma. In lowest order in  $\alpha_s$  the charm quark pairs are produced by gluon and quark pair fusion. Solving a similar rate equation as in (3) [22] but with the appropriate QCD cross sections we calculated in Fig. 4 the time evolution of the number of thermal  $c\bar{c}$  pairs. The thermal production is seen in Fig. 4 not to be negligible as compared with the pre-equilibrium production. Dependent on the thermalization time there are an additional 5–10  $c\bar{c}$  pairs produced during the evolution of the thermally and chemically equilibrated plasma. This number, however, depends crucially on the value of the charm quark mass  $m_c$  and the strong coupling constant  $\alpha_s$ . In Fig. 5 we compare the thermal  $c\bar{c}$  multiplicity calculated with  $m_c = 1.5$  GeV and  $m_c = 1.2$  GeV with  $\alpha_s = 0.3$ .

Dynamical models for parton production and evolution like HIJING [23,24] or SSPC [25] confirmed that indeed, after a very short time of the order of 0.1–0.5 fm,



**Fig. 6.** Time evolution of the number of  $c\bar{c}$  produced in out-of-chemical equilibrium QGP calculated with the initial conditions from SSPC and HIJING



**Fig. 7.** Time evolution of  $J/\psi$  production from the hadron gas due to the  $\bar{D}D^* + DD^* \rightarrow J/\psi\pi$  process calculated for Pb–Pb collisions at LHC energy for four different parameterizations of the  $J/\psi$ – $\pi$  absorption cross sections as described in Fig. 1

the partonic medium can reach the thermal equilibrium. However, both quarks and gluons may appear far below their chemical saturation values. Thus, discussing thermal  $c\bar{c}$  production one should take into account deviations of gluon and light quark yields from their equilibrium values. These deviations can be parameterized by the fugacity parameters  $\lambda_q$  and  $\lambda_g$  modifying the Boltzmann distribution function of quarks and gluons [26].

In Fig. 6 we calculated the time evolution of  $c\bar{c}$  pairs within the kinetic model derived in [26,23] for a non-equilibrium quark–gluon plasma. The following initial conditions for the thermalization time  $\tau_0$ , the initial temperature  $T_0$  and the values for quark ( $\lambda_q$ ) and gluon ( $\lambda_g$ ) fugacities were fixed for Pb–Pb collisions at LHC from SSPC [25] and HIJING [24,27]:

- (1)  $\tau_0 = 0.25$  fm,  $T_0 = 1.02$  GeV,  $\lambda_q^0 = 0.43$ ,  $\lambda_g^0 = 0.082$  [25];
- (2)  $\tau_{in} = 0.5$  fm,  $T_{in} = 0.82$  GeV,  $\lambda_q^{in} = 0.496$ ,  $\lambda_g^{in} = 0.08$  [24];
- (3)  $\tau_{in} = 0.5$  fm,  $T_{in} = 0.72$  GeV,  $\lambda_q^{in} = 0.761$ ,  $\lambda_g^{in} = 0.118$  [27].

In a non-equilibrium plasma, dependent on the initial conditions, there are 3–5  $c\bar{c}$  pairs produced during the evolution of plasma as seen in Fig. 6. One should also note that at the time when the temperature reaches the critical value of 0.17 GeV, the quark and gluon fugacities are very close to unity, which indicates the chemical equilibration of an ideal quark–gluon plasma.

From the results presented in Figs. 4–6 one concludes that, dependent on the initial conditions as well as on the amount of chemical equilibration of the plasma, one expects 5–10  $D\bar{D}$  pairs at  $T_c$  in addition to the 50  $D\bar{D}$  from the hadronization of the initially produced  $c\bar{c}$  pairs.

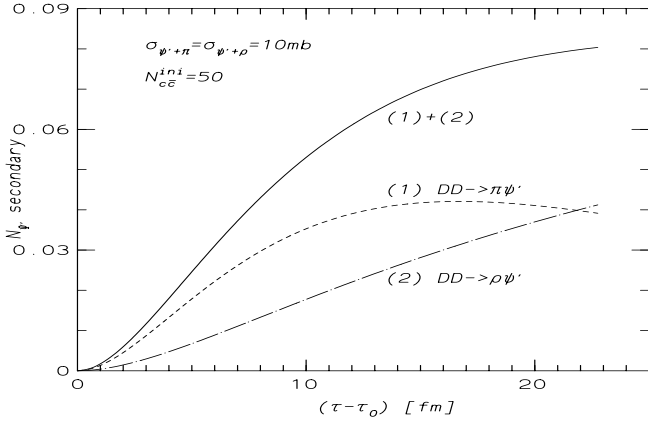
### 3 Time evolution of the charmonium abundances

The number of produced charmonium bound states from  $D\bar{D}$  scattering is obtained by multiplying the rate equation (3) by the volume of the hadron gas (9), and then performing the time integration. In Fig. 7 we show the time evolution of the abundance of  $J/\psi$  from Pb–Pb collisions at LHC energy obtained by solving the rate equation. The calculations were done with the four different models for  $J/\psi$ – $\pi$  absorption cross section described in Fig. 1 and assuming initially 50  $D\bar{D}$  and 12,000 pions at midrapidity. The results in Fig. 7 show a very strong sensitivity of the  $J/\psi$  production on the absorption cross section. The largest number of secondary  $J/\psi$  is obtained with the cross section predicted by the quark exchange model. Here the number of  $J/\psi$  is only by 1/2 smaller than the primary value. If, however, the absorption cross section is described by short distance QCD, the secondary  $J/\psi$  production is lower by more than two orders of magnitude.

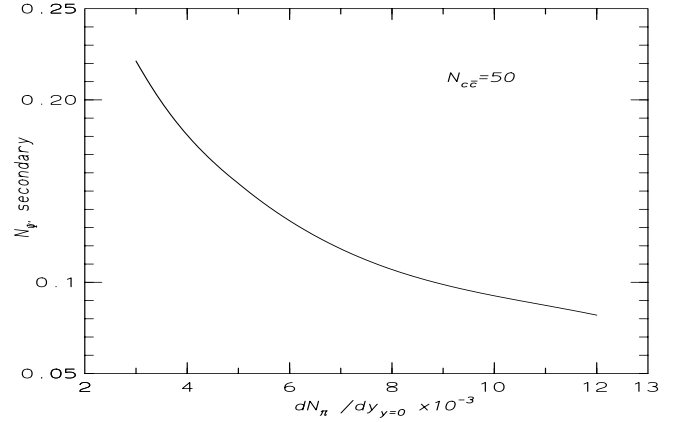
Recent analysis of  $J/\psi$  photoproduction data confirms the relation between the energy dependences of the  $J/\psi$  cross section and the Feynmann  $x$ -dependence of the gluon distribution function of the nucleon [8,10]. This could be used as an indication that the short distance QCD approach is a consistent way to calculate the  $J/\psi$  cross section. Thus, the secondary production of  $J/\psi$  from the hadronic gas can be entirely neglected in this case. The situation can, however, change when discussing the production of  $\psi'$

The time evolution of the abundance of  $\psi'$  is presented in Fig. 8 with the same basic parameters as used for  $J/\psi$  in Fig. 7. We show in Fig. 8 the separate contributions of the production processes for the secondary  $\psi'$  with  $\pi$  and  $\rho$  mesons in the final state. Following the arguments of the previous section the absorption cross section for  $\psi'$  on  $\pi$  and  $\rho$  mesons were taken to be energy independent and equal to its geometric value of 10 mb. The produced  $\psi'$  during the mixed phase from  $D\bar{D}$  annihilation is seen in Fig. 8 to saturate at the large value 0.08, which is almost 1/5 of the primary number of  $J/\psi$  expected for Pb–Pb collisions at LHC energy.

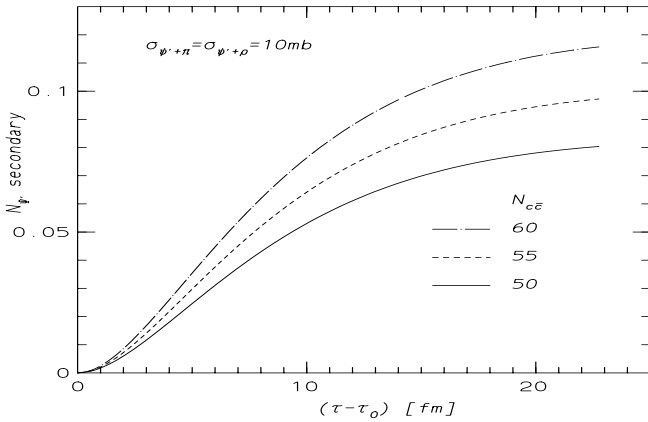
The yield of secondary charmonium summarized in Figs. 7 and 8 depends on the parameters used in the calculations. In the following we study the modification of the



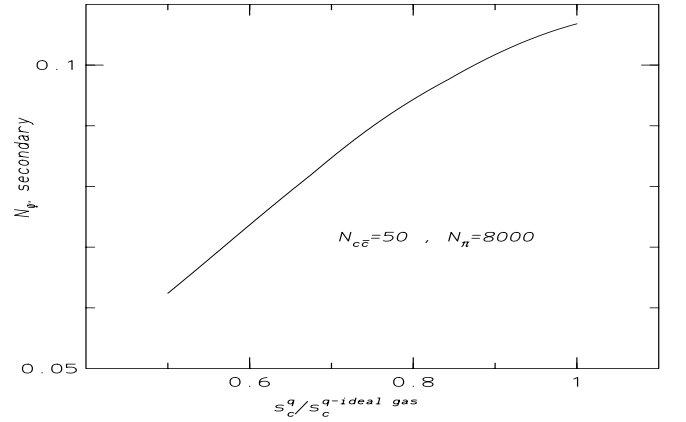
**Fig. 8.** Time evolution of the abundance of  $\psi'$  from Pb-Pb collisions at LHC using constant absorption cross sections for  $\psi'-\pi$  and  $\psi'-\rho$  of 10 mb



**Fig. 10.** Total  $\psi'$  yield produced during the mixed phase as a function of pion multiplicity



**Fig. 9.** As in Fig. 8, but for different values of the number of  $D\bar{D}$  mesons



**Fig. 11.** Total  $\psi'$  yield produced during the mixed phase as a function of the fractions of the critical entropy density of the non-interacting quark-gluon plasma

results on the secondary  $\psi'$  by changing the initial number of  $D\bar{D}$  mesons as well as the values of the relevant thermal parameters.

In Fig. 9 we discuss the yield of  $\psi'$  for different multiplicities of  $D\bar{D}$  mesons by including the contribution of thermal  $c\bar{c}$  pairs. From the rate equation (3) it is clear that this dependence is quadratic. The increase of  $D\bar{D}$  by 10–20% implies the 20–40% increase of the  $\psi'$  yield.

In the space-time evolution model all parameters were fixed assuming  $N_\pi = 12,000$ . This number, however, is still not well established and deviations for  $N_\pi$  in the range  $5000 < N_\pi < 12,000$  are not excluded. In Fig. 10 we show the sensitivity of the results for  $\psi'$  production on  $N_\pi$ . Keeping the same number of  $D\bar{D}$  mesons and decreasing  $N_\pi$  the number of secondary  $\psi'$  increases as seen in Fig. 10. This is mostly because by decreasing  $N_\pi$  the initial density  $n_{D\bar{D}}$  of  $D\bar{D}$  increases leading to a larger production of the charmonium bound states.

Modeling the equation of state we have fixed the critical entropy density  $s_q^{c-ideal}$  in the quark-gluon plasma by the ideal gas equation of state. From the lattice gauge theory we know, however, that, due to interactions, the entropy density  $s_q^c$  could be smaller by a significant factor.

A deviation of the momentum distribution of quarks and gluons from chemical saturation also reduces the critical entropy density of the quark-gluon plasma. To establish the influence of a decreasing critical entropy density we calculated the total number of  $\psi'$  as a function of the ratio  $s_q^c / s_q^{c-ideal}$  in Fig. 11. Decreasing the entropy density of a quark-gluon plasma by a factor of two reduces the yield of  $J/\psi$  by 70%. This is mostly because the time the system spends in the mixed phase is shorter. However, even with this reduction of the entropy density the secondary production of  $\psi'$  is not negligible. The influence of the result on the critical entropy density in a hadron gas  $s_h^c$  is less important. Increasing  $s_h^c$ , by a factor of two reduces the total number of  $\psi'$  by only 10%.

Secondary  $\psi'$  production in a mixed phase is also sensitive to the parameterization of the time evolution of the system size in transverse direction. Increasing the transverse expansion parameter from 0.15 to 0.45 in (6) decreases the total number of  $\psi'$  produced during the mixed phase by 40%. Taking a quadratic dependence of  $R(\tau)$  on proper time as proposed in [3] decreases the yield of  $\psi'$  from 0.08 to 0.036, which is still comparable with the number of primary  $\psi'$ .

## 4 Conclusions

We have considered the possibility of secondary charmonium production in ultrarelativistic heavy ion collisions at LHC energy. Admitting thermalization of a partonic medium created in a collision and the subsequent first order phase transition to hadronic matter, we have shown that secondary charmonium production appears almost entirely during the mixed phase. The yield of secondarily produced  $\psi$  mesons is very sensitive to the hadronic absorption cross section. Within the context of the short distance QCD approach this leads to negligible values for  $J/\psi$  regeneration. The  $\psi'$  production, however, can be large and may even exceed the initial yield from primary hard scattering. Thus it is conceivable that at LHC energy the  $\psi'$  charmonium state can be seen in the final state whereas  $J/\psi$  production can be entirely suppressed. The appearance of the  $\psi'$  in the final state could thus be considered as an indication for charmonium production from secondary hadronic rescattering.

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