

## Statistical hadronization of charm quarks in ultra-relativistic nucleus-nucleus collisions

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We discuss the production of charmonium and open charm in nuclear collisions at SPS/FAIR energies within the framework of the statistical hadronization model. The increasing importance at lower energies of  $\Lambda_c$  production is discussed and provides a challenge for future experiments. We also show that possible modifications of charmed hadrons in the hot hadronic medium do not lead to measurable changes in the cross sections for D-meson production. A possible influence of medium effects can be seen, however, in yields of charmonium. These effects are visible at all energies and results will be presented for the energy range between charm threshold and RHIC energy.

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## 1. Introduction

Charmonium production is considered, since the original proposal more than 20 years ago about its suppression in a Quark-Gluon Plasma (QGP) [1], as an important probe to determine the degree of deconfinement reached in the fireball produced in ultra-relativistic nucleus-nucleus collisions. In the original scenario of  $J/\psi$  suppression via Debye screening [1] it is assumed that the charmonia are rapidly formed in initial hard collisions but are subsequently destroyed in the QGP (see an update of this picture in ref. [2]).

In a recent series of publications [3, 4, 5] we have demonstrated that, in the energy range from top SPS energy ( $\sqrt{s_{NN}} \approx 17$  GeV) on, the data on  $J/\psi$  and  $\psi'$  production in nucleus-nucleus collisions can be well described within the statistical hadronization model proposed in [6]. This includes the centrality and rapidity dependence of recent data at RHIC ( $\sqrt{s_{NN}}=200$  GeV) published by the PHENIX collaboration [7]. We note that the extrapolation of these results to LHC energy ( $\sqrt{s_{NN}}=5.5$  TeV) yields a rather striking centrality dependence [4, 5]. Depending on the magnitude of the  $\bar{c}c$  cross section in central Pb-Pb collisions [8], even an enhancement of  $J/\psi$  production compared to pp collisions ( $R_{AA}^{J/\psi} > 1$ ) is expected due to hadronization (at chemical freeze-out) of uncorrelated (at these high energies) charm quarks thermalized in QGP.

Here we explore the lower energy range (from near threshold,  $\sqrt{s_{NN}} \approx 6$  GeV), which can be investigated in the CBM experiment [9] at the future FAIR facility. One of the motivations for such studies was the expectation [9, 10] to provide, by a measurement of D-meson production near threshold, information on their possible in-medium modification near the phase boundary. However, the cross section  $\sigma_{c\bar{c}}$  is governed by the mass of the charm quark  $m_c \approx 1.3$  GeV, which is much larger than any soft Quantum Chromodynamics (QCD) scale such as  $\Lambda_{QCD}$ . Therefore we expect no medium effects on this quantity.<sup>1</sup> The much later formed D-mesons, or other charmed hadrons, may well change their mass in the hot medium. The results of various studies on in-medium modification of charmed hadrons masses [10, 11, 12, 13, 14, 15, 16, 17, 18] are sometimes contradictory. Whatever the medium effects may be, they can, because of the charm conservation,  $\sigma_{c\bar{c}} = \frac{1}{2}(\sigma_D + \sigma_{\Lambda_c} + \sigma_{\Xi_c} + \dots) + (\sigma_{\eta_c} + \sigma_{J/\psi} + \sigma_{\chi_c} + \dots)$ , only lead to a redistribution of charm quarks [19]. This argument is essentially model-independent and applies equally well at all energies. Here we will consider various types of scenarios for medium modifications and study their effect within the statistical hadronization framework in the energy range from charm threshold to collider energies. In this context, we note that excellent fits of the common (non-charmed) hadrons to predictions of the thermal model have been obtained using vacuum masses (see ref. [20] and references therein). An attempt to use modified masses for the RHIC energy [21] has not produced a conclusive preference for any mass or width modifications of hadrons in medium. On the other hand, some evidence for possible mass modifications was presented in the chiral model of [22].

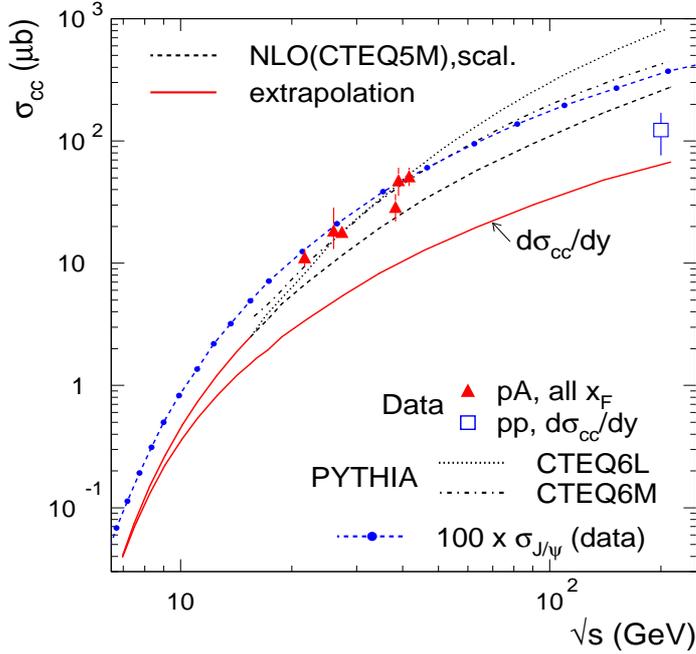
## 2. Assumptions and ingredients of the statistical hadronization model

The statistical hadronization model (SHM) [6, 4] assumes that the charm quarks are produced in primary hard collisions and that their total number stays constant until hadronization. Another

<sup>1</sup>Such a separation of scales is not possible for strangeness production, and the situation there is not easily comparable.

important factor is thermal equilibration in the QGP, at least near the critical temperature,  $T_c$ . We neglect charmonium production in the nuclear corona [4], since we focus in the following on central collisions ( $N_{part}=350$ ), where such effects are small.

In the following we briefly outline the calculation steps in our model [6, 4]. The model has the following input parameters: i) charm production cross section in pp collisions; ii) characteristics at chemical freeze-out: temperature,  $T$ , baryochemical potential,  $\mu_b$ , and volume corresponding to one unit of rapidity  $V_{\Delta y=1}$  (our calculations are for midrapidity). Since, in the end, our main results will be ratios of hadrons with charm quarks normalized to the  $c\bar{c}$  yield, the detailed magnitude of the open charm cross section and whether to use integrated yield or midrapidity yields is not crucial.

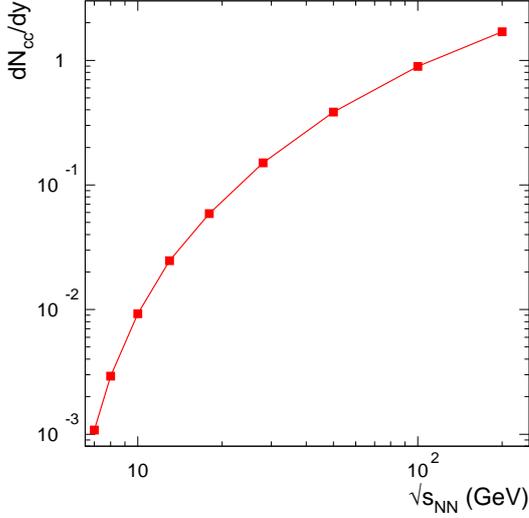


**Figure 1:** Energy dependence of the charm production cross section in pp collisions. The NLO pQCD values [24] are compared to calculations using PYTHIA and to data in pA collisions, taken from ref. [25]. Our extrapolations for low energies are shown with continuous lines, for total and midrapidity ( $d\sigma_{c\bar{c}}/dy$ ) cross section. The open square is a midrapidity measurement in pp collisions [26]. The dashed line with dots indicates a parameterization of the measured energy dependence of the  $J/\psi$  production cross section [27].

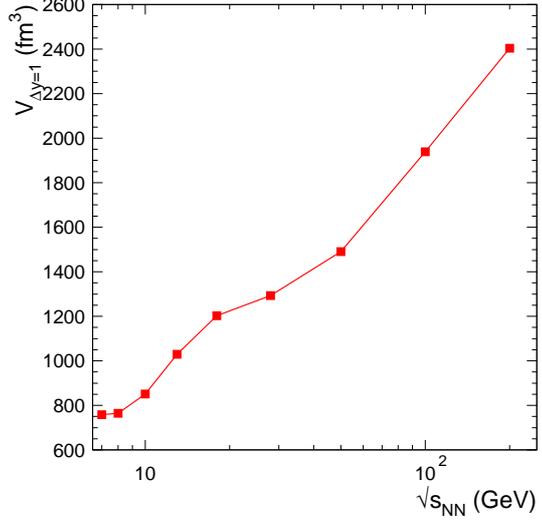
The charm balance equation [6], which has to include canonical suppression factors [23] whenever the number of charm pairs is not much larger than 1, is used to determine a fugacity factor  $g_c$  via:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}. \quad (2.1)$$

Here  $N_{c\bar{c}}^{dir}$  is the number of initially produced  $c\bar{c}$  pairs and  $I_n$  are modified Bessel functions. In the fireball of volume  $V$  the total number of open ( $N_{oc}^{th} = n_{oc}^{th} V$ ) and hidden ( $N_{c\bar{c}}^{th} = n_{c\bar{c}}^{th} V$ ) charm hadrons is computed from their grand-canonical densities  $n_{oc}^{th}$  and  $n_{c\bar{c}}^{th}$ , respectively. This charm balance equation is the implementation within our model of the charm conservation constraint. The densities of different particle species in the grand canonical ensemble are calculated following the statistical model [20]. The balance equation (2.1) defines the fugacity parameter  $g_c$  that accounts for deviations of heavy quark multiplicity from the value that is expected in complete chemical equilibrium. The yield of charmonia of type  $j$  is obtained as:  $N_j = g_c^2 N_j^{th}$ , while the yield of open charm hadrons is:  $N_i = g_c N_i^{th} I_1(g_c N_{oc}^{th}) / I_0(g_c N_{oc}^{th})$ .



**Figure 2:** Energy dependence of the number of initially produced charm quark pairs ( $N_{part}=350$ ).



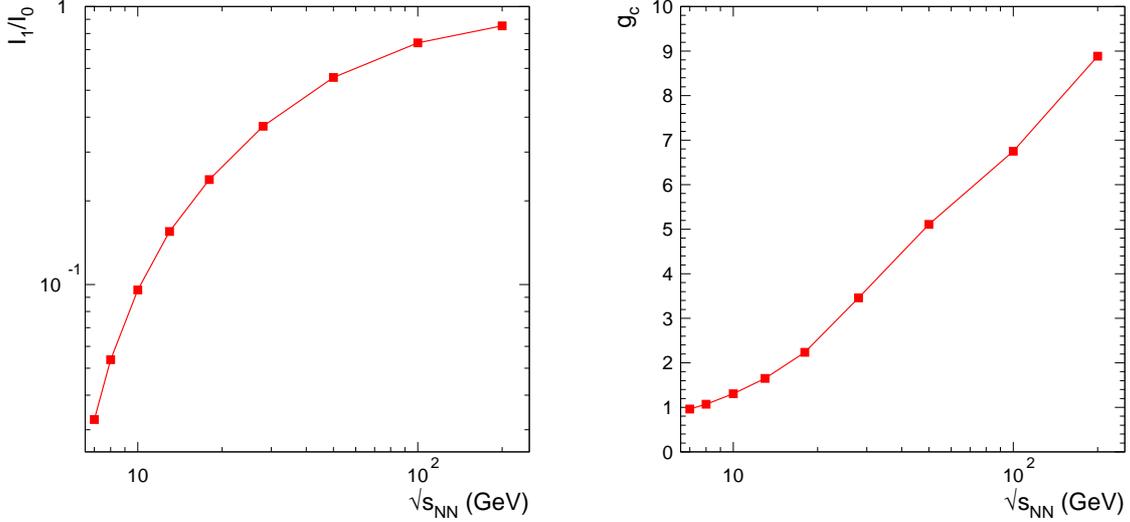
**Figure 3:** Energy dependence of the volume at midrapidity,  $V_{\Delta y=1}$ , for central collisions [20].

As no information on the charm production cross section is available for energies below  $\sqrt{s}=15$  GeV, we have to rely on extrapolation. The basis for this extrapolation is the energy dependence of the total charm production cross section calculated in ref. [24] for the CTEQ5M parton distribution functions in next-to-leading order (NLO), as shown in Fig. 1. We have scaled these calculations to match the more recent values calculated at  $\sqrt{s}=200$  GeV in ref. [28]. We employ a threshold-based extrapolation using the following expression:

$$\sigma_{c\bar{c}} = k(1 - \sqrt{s_{thr}}/\sqrt{s})^a (\sqrt{s_{thr}}/\sqrt{s})^b \quad (2.2)$$

with  $k=1.85 \mu\text{b}$ ,  $\sqrt{s_{thr}}=4.5$  GeV (calculated assuming a charm quark mass  $m_c=1.3$  GeV [29]),  $a=4.3$ , and  $b=-1.44$ . The parameters  $a$ ,  $b$ ,  $k$  were tuned to reproduce the low-energy part of the (scaled) NLO curve. The extrapolated curves for charm production cross section are shown with continuous lines in Fig. 1. Also shown for comparison are calculations with PYTHIA [25]. To obtain the values at midrapidity we have extrapolated to lower energies the rapidity widths (FWHM) of the charm cross section known to be about 4 units at RHIC [28] and about 2 units at SPS [30]. With these cross section values, the rapidity density of initially produced charm quark pairs, shown in Fig. 2 strongly rises from  $1.1 \cdot 10^{-3}$  to 1.7 for the energy range  $\sqrt{s_{NN}}=7-200$  GeV. We note that the so-obtained charm production cross section has an energy dependence similar to that measured for  $J/\psi$  production, recently compiled and parametrized by the HERA-B collaboration [27]. For comparison, this is also shown in Fig. 1. The extrapolation procedure for the low-energy part of the cross section obviously implies significant uncertainties. We emphasize, however, that the most robust predictions of our model, i.e. the yields of charmed hadrons and charmonia relative to the initially produced  $c\bar{c}$  pair yield are not influenced by the details of this extrapolation.

For the studied energy range,  $\sqrt{s_{NN}}=7-200$  GeV,  $T$  rises from 151 to 161 MeV from  $\sqrt{s_{NN}}=7$  to 12 GeV and stays constant for higher energies, while  $\mu_b$  decreases from 434 to 22 MeV [20].



**Figure 4:** Energy dependence of the canonical suppression for charm,  $I_1/I_0$  (left panel) and of the charm quark fugacity,  $g_c$  (right panel).

The volume  $V_{\Delta y=1}$  at midrapidity, shown in Fig. 3 [20] continuously rises from 760 to 2400 fm<sup>3</sup>. Due to the strong energy dependence of charm production, Fig. 2, the canonical suppression factor ( $I_1/I_0$ ) varies from 1/30 to 1/1.2. Correspondingly, the charm fugacity  $g_c$  increases from 0.96 to 8.9, see Fig. 4.

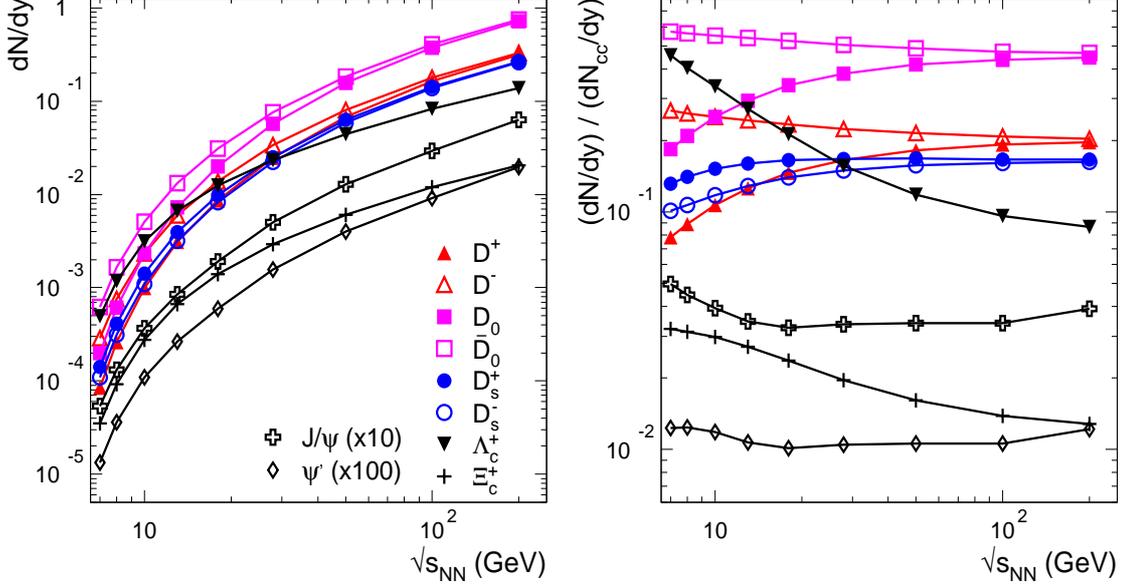
Before proceeding to discuss our results, we would like to emphasize some peculiar aspects of charm at low energies. First, the assumption of charm equilibration can be questionable. In this exploratory study we have nevertheless assumed full thermalization. At SPS and lower energies collision time, plasma formation time, and charmonium (or open charm hadrons) formation time are all of the same order [31]. Furthermore, the maximum plasma temperature may not exceed the  $J/\psi$  dissociation temperature,  $T_D$ , although recent results [32] indicate that  $T_D$  can be very close to  $T_c$ . Charmonia may be broken up by gluons and by high energy nucleons still passing by from the collision. In this latter case cold nuclear suppression needs to be carefully considered (as discussed, e.g., in [33, 34]). Consequently, our calculations, in which both charmonium formation before QGP production and cold nuclear suppression are neglected, may somewhat underestimate the charmonium production yield at SPS energies [4] and below.

We note that models that combine the 'melting scenario' with statistical hadronization have been proposed [35]. Alternatively, charmonium formation by coalescence in the plasma [36, 37, 38, 39] as well as within transport model approaches [40, 41] has been considered.

### 3. Energy dependence of charmed hadrons yield

Our main results are presented in Fig. 5. The left panel shows our predictions for the energy dependence of midrapidity yields for various charmed hadrons. Beyond the generally decreasing trend towards low energies for all yields one notices first a striking behavior of the production of  $\Lambda_c^+$  baryons: their yield exhibits a weaker energy dependence than observed for other charmed hadrons.

In our approach this is caused by the increase in baryochemical potential towards lower energies (coupled with the charm neutrality condition). A similar behavior is seen for the  $\Xi_c^+$  baryon. These results emphasize the importance of measuring, in addition to D-meson production, also the yield of charmed baryons to get a good measure of the total charm production cross section. In detail, the production yields of D-mesons depend also on their quark content.



**Figure 5:** Energy dependence of charmed hadron production at midrapidity. Left panel: absolute yields, right panel: yields relative to the number of  $c\bar{c}$  pairs. Note, in both panels, the scale factors of 10 and 100 for  $J/\psi$  and  $\psi'$  mesons, respectively.

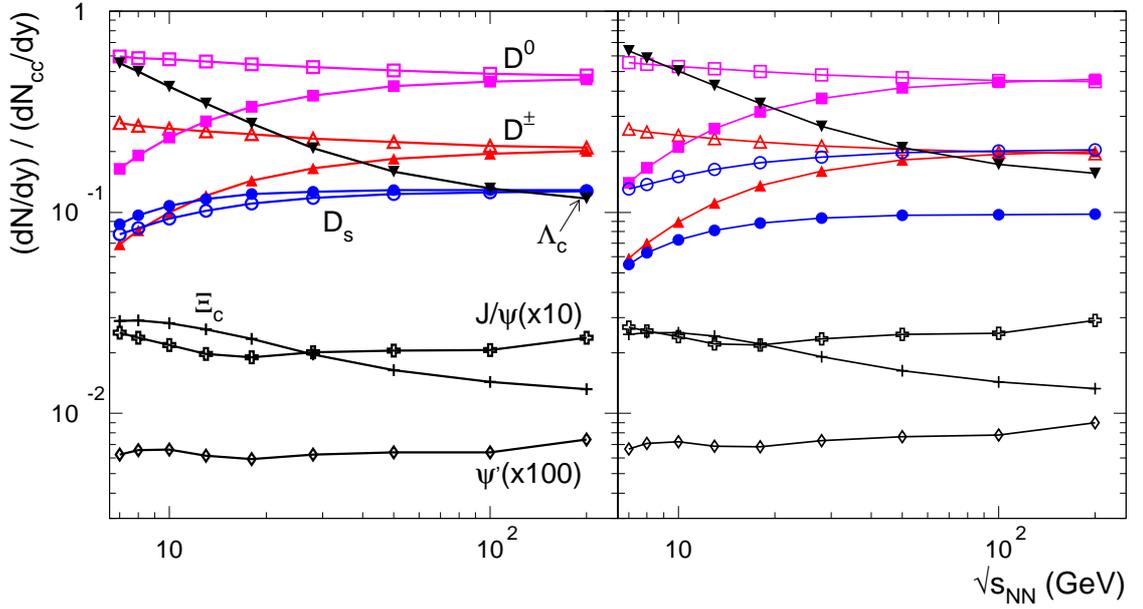
The differing energy dependences of the yields of charmed hadrons are even more evident in the right panel of Fig. 5, where we show the predicted yields normalized to the number of initially produced  $c\bar{c}$  pairs. Except very near threshold, the  $J/\psi$  production yield per  $c\bar{c}$  pair exhibits a slow increase with increasing energy. This increase is a consequence of the quadratic term in the  $J/\psi$  yield equation discussed above. At LHC energy, the yield ratio  $J/\psi/c\bar{c}$  approaches 1% [4], scaling linearly with  $\sigma_{c\bar{c}}$  (for details see [19]). The  $\psi'$  yield shows a similar energy dependence as the  $J/\psi$ , except for our lowest energies, where the difference is due to the decrease of temperature (see above). We emphasize again that this model prediction, namely yields relative to  $c\bar{c}$  pairs, is a robust result, as it is in the first order independent on the charm production cross section. Due to the expected similar temperature, the relative abundance of open charm hadrons at LHC is predicted [8] to be similar to that at RHIC energies.

#### 4. Effects of in-medium modification of charmed hadrons masses

We consider two scenarios<sup>2</sup> for a possible mass change  $\Delta m$  of open charm hadrons containing light,  $u$  or  $d$ , quarks: i) a common decrease of 50 MeV for all charmed mesons and their antiparti-

<sup>2</sup>The scenarios are constructed by modification of the constituent quark masses of light ( $u$  and  $d$ ) quarks in the

cles and a decrease of 100 MeV for the  $\Lambda_c$  and  $\Sigma_c$  baryons (50 MeV decrease for  $\Xi_c$ ); ii) a decrease of 100 MeV for all charmed mesons and a 50 MeV increase for their antiparticles, with the same (scaled with the number of light quarks) scenario as in i) for the baryons. Scenario i) is more suited for an isospin-symmetric fireball produced in high-energy collisions and was used in [15], while scenario ii) may be realized at low energies. In both scenarios, the masses of the  $D_s$  mesons and of the charmonia are the vacuum masses. We also note that if one leaves all D-meson masses unchanged but allows their widths to increase, the resulting yields will increase by 11% (2.7%) for a width of 100 MeV (50 MeV). If the in-medium widths exhibit tails towards low masses, as has been suggested by [10], to first order the effect on thermal densities is quantitatively comparable with that from a decrease in the pole mass.



**Figure 6:** Energy dependence of the yield of charmed hadrons relative to the charm quark pair yield for two scenarios of the mass change (left panel for scenario i), right panel for scenario ii), see text). For the D mesons, the full and open symbols are for particles and antiparticles, respectively. Note the factors 10 and 100 for the  $J/\psi$  and  $\psi'$  mesons, respectively.

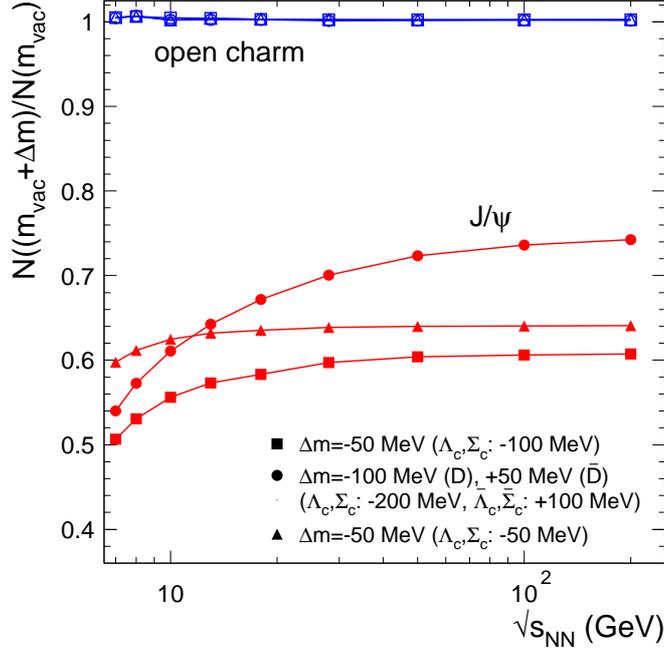
The results for the two cases are presented in Fig. 6 as yields relative to the number of initially-produced  $c\bar{c}$  pairs. As a result of the redistribution of the charm quarks over the various species, the relative yields of charmed hadrons may change. For example, in scenario i) the ratios of D-mesons are all close to those computed for vacuum masses (Fig. 5), while for scenario ii) the changes in the relative abundances of the  $D$  and  $\bar{D}$  mesons are obvious. In both cases the  $\Lambda_c/D$  ratio is increased.

As a result of the asymmetry in the mass shifts for particles and antiparticles assumed in scenario ii), coupled with the charm neutrality condition, the production yields of  $D_s^+$  and  $D_s^-$  mesons are very different compared to vacuum masses. Overall, however, charm conservation leads to

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charmed hadrons by fixed amounts. Reducing, for example, the light quark masses by 50 MeV will lower D-meson masses by 50 MeV and the  $\Lambda_c(\Xi_c)$  mass by 100 (50) MeV.

rather small changes in the total yields. We emphasize that, although the charm conservation equation is strictly correct only for the total cross section we expect within the framework of the statistical hadronization model, also little influence due to medium effects on distributions in rapidity and transverse momentum. This is due to the fact that the crucial input into our model is  $dN_{cc}^{AuAu}/dy$  and there is no substantial D-meson rescattering after formation at the phase boundary.



**Figure 7:** Energy dependence of the relative change in the production yield of open charm hadrons and of  $J/\psi$  meson considering different scenarios for in-medium mass modifications (see text).

In Fig. 7 we demonstrate that the total open charm yield (sum over all charmed hadrons) exhibits essentially no change if one considers mass shifts, while the effect is large on charmonia. This is to be expected from eq. 2.1: as the masses of open charm mesons and baryons are reduced, the charm fugacity  $g_c$  is changed accordingly to conserve charm. Consequently, since the open charm yields vary linearly with  $g_c$ , one expects little change with medium effects in this case. In contrast, the yields of charmonia vary strongly, since they are proportional to  $g_c^2$ . To demonstrate this we plot, in Fig. 7, the relative change of the yields with in-medium masses compared to the case of vacuum masses. For this comparison, we have added a third case, namely considering that the mass change of charmed baryons is the same as for the mesons. Because of total charm conservation, with lowering of their masses the open charm hadrons eat away some of the charm quarks of the charmonia but, since the open charm hadrons are much more abundant, their own yield will hardly change.

Note that the reduction of the  $J/\psi$  yield in our model is quite different from that assumed in [40, 38, 14, 13, 16], where a reduction in D-meson masses leads to the opening up of the decay of  $\psi'$  and  $\chi_c$  into  $D\bar{D}$  and subsequently to a smaller  $J/\psi$  yield from feed-down from  $\psi'$  and  $\chi_c$ . In all

the previous work the in-medium masses are considered in a hadronic stage, while our model is a pure QGP model, with in-medium mass modifications considered at the phase boundary.

## 5. Conclusions

We have investigated charmonium production in the statistical hadronization model at lower energies. An interesting result is that the yield of charmed baryons ( $\Lambda_c$ ,  $\Xi_c$ ) relative to the total  $c\bar{c}$  yield increases strongly with decreasing energy. Below  $\sqrt{s_{NN}}=10$  GeV, the relative yield of  $\Lambda_c$  exceeds that of any D meson except  $\bar{D}_0$ , implying that an investigation of open charm production at low energies needs to include careful measurements of charmed baryons, a difficult experimental task. The charmonium/open charm yield rises only slowly from energies near threshold to reach  $\sim 1\%$  at LHC energy. Note that this ratio depends on the magnitude of the charm cross section, further underlining the importance to measure this quantity with precision. We have also investigated the effect of possible medium modifications of the masses of charmed hadrons. Because of a separation of time scales for charm quark and charmed hadron production, the overall charmed meson and baryon cross section is very little affected by in-medium mass changes, if charm conservation is taken into account. Measurable effects are predicted for the yields of charmonia. These effects are visible at all beam energies and are more pronounced towards threshold.

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