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Charmonium Production and Corona Effect

S. Digal^{1,2}, H. Satz² and R. Vogt^{3,4}

¹The Institute of Mathematical Sciences, Chennai, India

²Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

³Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

⁴Physics Department, University of California, Davis, CA 95616, USA

Abstract

We study the centrality dependence to be expected if only charmonium production in the corona survives in high energy nuclear collisions, with full suppression in the hot, deconfined core. To eliminate cold nuclear matter effects as far as possible, we consider the ratio of charmonium to open charm production. The centrality dependence of this ratio is found to follow a universal geometric form, applicable to both LHC and RHIC in collisions at both central and forward rapidities.

The behavior of charmonium production in high energy nuclear collisions was proposed quite some time ago as probe of color deconfinement [1]. The basic idea was that color screening in the hot primary medium prevents the binding of $c\bar{c}$ pairs produced in the early stages of nucleon-nucleon collisions. As a result, the ratio of hidden to open charm production should vanish when the energy densities of the medium produced in the collision are sufficiently high. Since the observed J/ψ production rate is partially due to feed-down from higher mass excited states, the suppression should occur in a sequential fashion, first for the decay products from ψ' and χ_c production, then for directly produced $J/\psi(1S)$ [2–4].

In subsequent work [5–7], it was argued that, at the hadronisation point, statistical combination of the charm quarks present in the deconfined medium could lead to regeneration of charmonia. Even if the “primary” charmonium states produced in individual nucleon-nucleon collisions are dissociated through color screening, the abundance of charm production at high collision energy could provide enough charm quarks to result in “secondary” charmonium formation through the binding of combinatorial pairs of c and \bar{c} quarks produced in different initial nucleon-nucleon collisions. Since the charm production rate grows with collision energy and centrality, this would imply a corresponding increase in the ratio of hidden to open charm. In Fig. 1, we schematically compare the statistical recombination prediction to that of the sequential color screening scenario. The ratio of hidden to open charm in nuclear collisions is normalized to the pp value, scaled by the number of binary nucleon-nucleon collisions. The increase of this ratio above unity in central collisions for high charm production rates is a crucial prediction of the statistical recombination model. On the other hand, the sequential suppression scenario predicts

that the ratio should decrease to values well below the central SPS results at high energy density when direct $J/\psi(1S)$ suppression sets in.

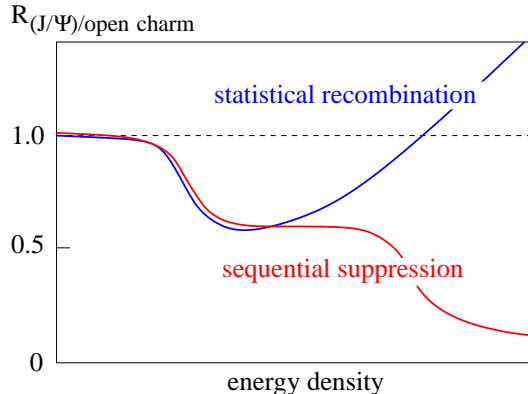


Figure 1: The schematic ratio of J/ψ to open charm production in nuclear collisions, normalized to the scaled pp value, as a function of the energy density.

The first RHIC results on charmonium production, after a decade of SPS data, showed a rather striking feature. While it seemed clear that the energy density of the produced medium should be much higher at RHIC than at the SPS (typical values are 5 - 6 GeV/fm³ at RHIC relative to 2 - 3 GeV/fm³ at the SPS), the magnitude of J/ψ suppression in central RHIC collisions was compatible with the SPS data within the measured uncertainties, as was the overall centrality dependence. Both the sequential suppression and statistical recombination scenarios could explain this behavior with different sets of assumptions:

- In the sequential suppression approach, full suppression of the excited ψ' and χ_c states is expected, with complete survival of the directly-produced $J/\psi(1S)$ states, after cold nuclear matter effects are accounted for;
- The statistical recombination approach predicts a monotonically decreasing survival probability for all $c\bar{c}$ states, coupled with secondary regeneration increasing with energy density.

Predictions for the new data from the LHC in the two scenarios, at still higher energy density (at least 8 - 10 GeV/fm³), lead to relatively distinct outcomes: vanishing measured J/ψ yield with sequential suppression and considerably enhanced J/ψ production with secondary regeneration. In both cases, the predictions are cleanest for the ratio of charmonium to open charm since, in this case, initial-state effects (shadowing, parton energy loss) largely cancel [8]. Because such data are not yet available, the centrality dependence of the cold nuclear matter effects introduces some uncertainty. However, the presently available data do not rule out the possibility that once all corrections (J/ψ feed-down from B -decay, comparable rapidity and transverse momentum ranges) are made, the J/ψ production rates at the LHC, relative to open charm production, will be quite comparable to the corresponding ratios in central RHIC and SPS collisions.

The aim of this note is to argue that, if indeed the fraction of charmonia surviving in nuclear collisions is essentially independent of the collision energy, then the survival probability at high energy density appears to be a geometric effect due to charmonium

production in the corona of the collision where the density is too low for dissociation of primary charmonium production.

The so-called corona effect in nuclear collisions has been discussed in quite some detail for various observables [9–16]. Its role in heavy quark production has also been considered [15]. The basic feature is that, even in a completely central collision, there is a rim region in the transverse plane in which the density of wounded nucleons is low, or in which each nucleon undergoes very few collisions, perhaps only a single one. In this region, there is no produced medium so that, in the corona, all observed effects should be similar to those in pp or pA collisions. While in central collisions of heavy nuclei, the ratio of the rim area to the total overlap area can be quite small (depending on how the corona region is defined), the fraction of the collision region attributable to the corona increases with increasing peripheralty until, in the most peripheral collisions, there are effectively just single nucleon-nucleon interactions (see Fig. 2). In the aforementioned studies [9–16], the aim was typically to remove or correct for the corona effect. Here we take the opposite approach: we assume that the core completely suppresses all charmonium production, so that only the corona structure and the resulting centrality distribution are relevant.

Our aim here is to consider a geometrically-defined corona in order to study the possible role of collision geometry on charmonium suppression. Other previous work defined the corona based on the average energy density produced by the collision in specific regions of nuclear overlap. In this case, the extent of the corona depends on the collision energy.

In this paper, we first identify the collision-energy independent behavior that can be expected if collision geometry alone determines charmonium survival. Later, we will discuss differences between this approach and the assumption that the corona depends on collision energy. The data should be able to distinguish between these approaches.

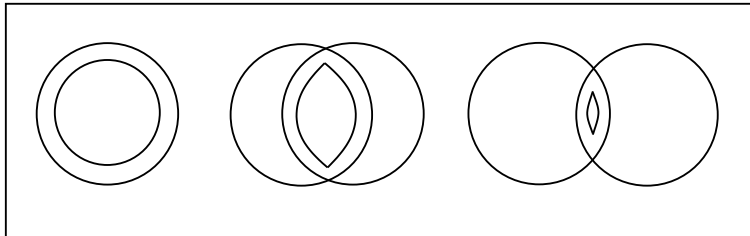


Figure 2: Corona contributions for decreasing centrality, as seen in the transverse profiles of the colliding nuclei.

Before proceeding, we briefly recall the definitions of the relevant geometric quantities. We use the formulation given in a recent survey [17], to which we refer for further details. We consider a collision of two nuclei A and B . For a nucleus of mass number A , the nucleon density projected onto a plane orthogonal to the collision axis is given by

$$\mathcal{T}_A(\mathbf{s}) = \int dz_A \rho_A(\mathbf{s}, z_A) . \quad (1)$$

Here ρ_A is the probability, normalized to unity, to find a nucleon from nucleus A at the location (\mathbf{s}, z_A) , where z_A denotes the longitudinal position and \mathbf{s} is the position in the transverse plane. For an impact parameter \mathbf{b} , the density of the number of collisions in the transverse plane is given by

$$n_c(\mathbf{s}, \mathbf{b}) = AB\mathcal{T}_A(\mathbf{s})\mathcal{T}_B(\mathbf{s} - \mathbf{b})\sigma_{\text{inel}}^{NN} , \quad (2)$$

where $\sigma_{\text{inel}}^{NN}$ is the nucleon-nucleon inelastic cross section. The integral over \mathbf{s} then gives the total number of collisions at impact parameter \mathbf{b} . Similarly, the wounded nucleon density is given by

$$n_w(\mathbf{s}, \mathbf{b}) = A\mathcal{T}_A(\mathbf{s}) \left\{ 1 - \left[1 - \mathcal{T}_B(\mathbf{s} - \mathbf{b})\sigma_{\text{inel}}^{NN} \right]^B \right\} \\ + B\mathcal{T}_B(\mathbf{s} - \mathbf{b}) \left\{ 1 - \left[1 - \mathcal{T}_A(\mathbf{s})\sigma_{\text{inel}}^{NN} \right]^A \right\} . \quad (3)$$

The integral of n_w over \mathbf{s} , $N_{\text{part}}(\mathbf{b}) = \int d^2s n_w(\mathbf{s}, \mathbf{b})$, gives the total number of wounded nucleons (or participants) for a given centrality \mathbf{b} .

The ultimate magnitude of the ratio of contributions from the corona region to those from the overall interaction region depends both on the variables used to distinguish between the rim and the central core regions (density of wounded nucleons, collision density, energy density) and on the chosen thickness used, *i.e.*, on the definition of the corona. Since the radius of a nucleus is generally defined as that distance from the center at which the matter density distribution, ρ_A , has decreased by a factor of two, we use a similar definition to specify the edge of the corona in nuclear collisions. The resulting transverse profiles of the density of wounded nucleons and of the collision density, both for central Au+Au collisions, are shown in Fig. 3 for $\sigma_{\text{inel}}^{NN} = 42$ mb. For this system, $n_w = n_w(R = 0)/2 = 2.16 \text{ fm}^{-2}$ at $R = 5.4$ fm while $n_c = n_c(R = 0)/2 = 9.6 \text{ fm}^{-2}$ at $R = 4.4$ fm.

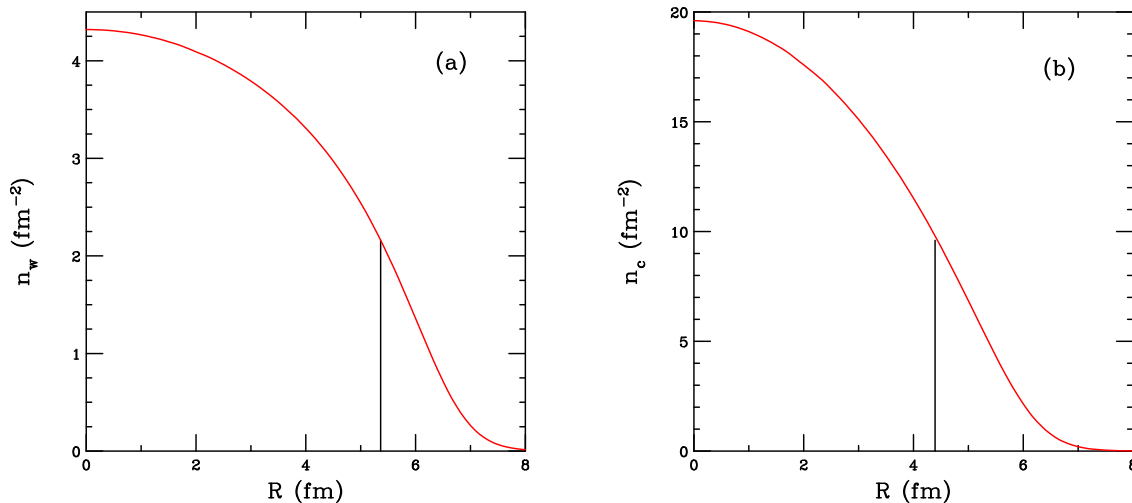


Figure 3: Transverse profiles in central Au-Au collisions, showing (a) the density of wounded nucleons, n_w , and (b) the density of collisions, n_c , in the transverse plane as a function of the radius R , calculated with $\sigma_{\text{inel}}^{NN} = 42$ mb. In both cases, the corona is defined as that region in which the density (n_w or n_c respectively) has decreased by a factor of two or more.

A general feature emerges from the geometry of the collision: for a considerable range of impact parameters from central through mid-peripheral collisions, the fraction of the transverse collision area in the corona relative to the total transverse overlap is small and relatively constant. Only in very peripheral collisions, roughly corresponding to $b > 1.2R$, does the fraction increase quite suddenly to unity. To show this more quantitatively, we present the ratio of the contribution to the overlap area from the corona relative to the

total area as a function of collision centrality in Au+Au collisions in Fig. 4. Here Fig. 4(a) gives the ratio, R_w , of the number of wounded nucleons in the corona to the total number of wounded nucleons while Fig. 4(b) gives the ratio, R_c , of the number of collisions in the corona relative to the total number of collisions. In both cases, the centrality dependence is shown as function of $N_{\text{part}}/N_{\text{max}}$, where N_{part} is the number of wounded nucleons and $N_{\text{max}} = N_{\text{part}}(b = 0)$.

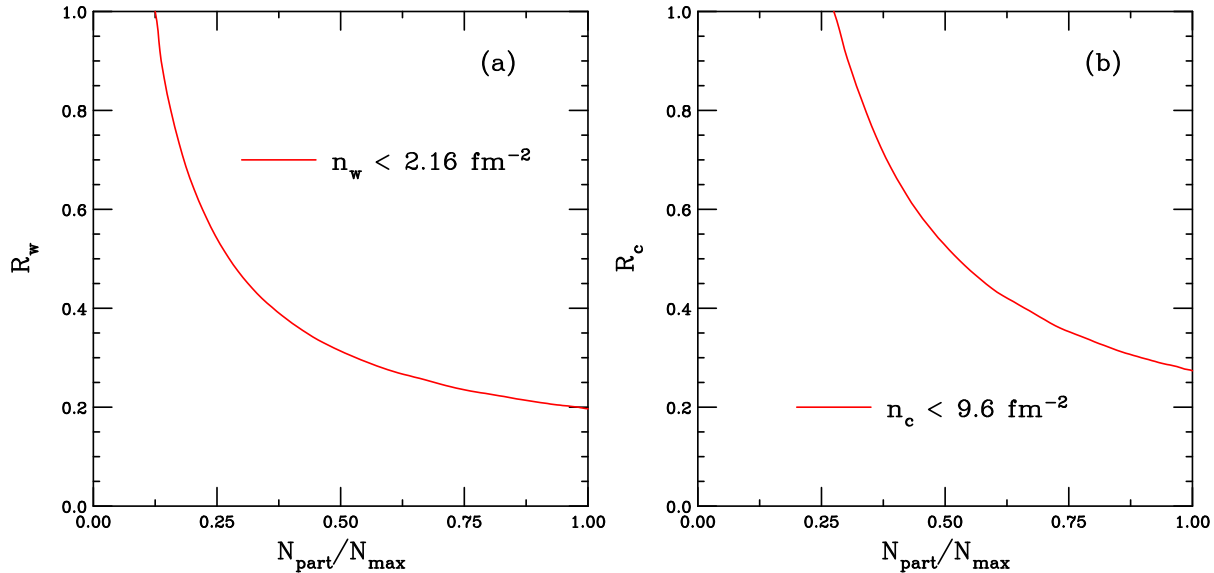


Figure 4: (a) Ratio of wounded nucleons in the corona region to the total number of wounded nucleons. Here the corona region is defined as the region where the density of wounded nucleons, n_w , has decreased by a factor of two or more relative to the value at $b = 0$, $n_w < 2.16 \text{ fm}^{-2}$. (b) Same as (a) for collision density with $n_c < 9.6 \text{ fm}^{-2}$. Both calculations are for Au+Au collisions with $\sigma_{\text{inel}}^{NN} = 42 \text{ mb}$.

The results shown in Fig. 4 employ $\sigma_{\text{inel}}^{NN} = 42 \text{ mb}$, appropriate for $\sqrt{s_{NN}} = 200 \text{ GeV}$ collisions at RHIC. For AA collisions at the LHC, a larger cross section is more appropriate. We choose $\sigma_{\text{inel}}^{NN} = 81 \text{ mb}$. Increasing $\sigma_{\text{inel}}^{NN}$ by nearly a factor of two has only a relatively small effect on the behavior of R_w and R_c , as shown in Fig. 5. The value of n_w is independent of $\sigma_{\text{inel}}^{NN}$, see Eq. (4). However, the value of R at which $n_w(R)/n_w(0) < 0.5$ increases marginally, causing R_w to shift to slightly higher values of $N_{\text{part}}/N_{\text{max}}$ in Fig. 5(a). The origin of this shift is thus not due to $n_w(R)$ but to the increase in N_{part} overall since, at $\sigma_{\text{inel}}^{NN} \rightarrow \infty$, $N_{\text{max}} \rightarrow 2A$ while finite values of $\sigma_{\text{inel}}^{NN}$ reduce N_{max} relative to this asymptotic value. Note that the value of n_c defining the corona is linearly dependent on $\sigma_{\text{inel}}^{NN}$, see Eq. (2), so that for $\sigma_{\text{inel}}^{NN} = 81 \text{ mb}$, the value of $n_c = n_c(0)/2$ is 18.9 fm^{-2} . The value of R when $n_c = n_c(0)/2$ is independent of $\sigma_{\text{inel}}^{NN}$. The same shift in N_{max} described above for R_w manifests itself as a steepening of R_c with $N_{\text{part}}/N_{\text{max}}$ for the larger cross section. Note that the value of R_c for the two NN cross section values coincide for $N_{\text{part}} = N_{\text{max}}$.

The definition of the corona is clearly model dependent and can therefore be given in terms of either n_w or n_c . However, charmonium production is a hard process and, as such, its rate will be governed by the number of binary collisions. Excluding all other possible effects, Fig. 4(b) can therefore be directly compared to centrality profiles of production data. If we define the corona in terms of wounded nucleons, we have to calculate the

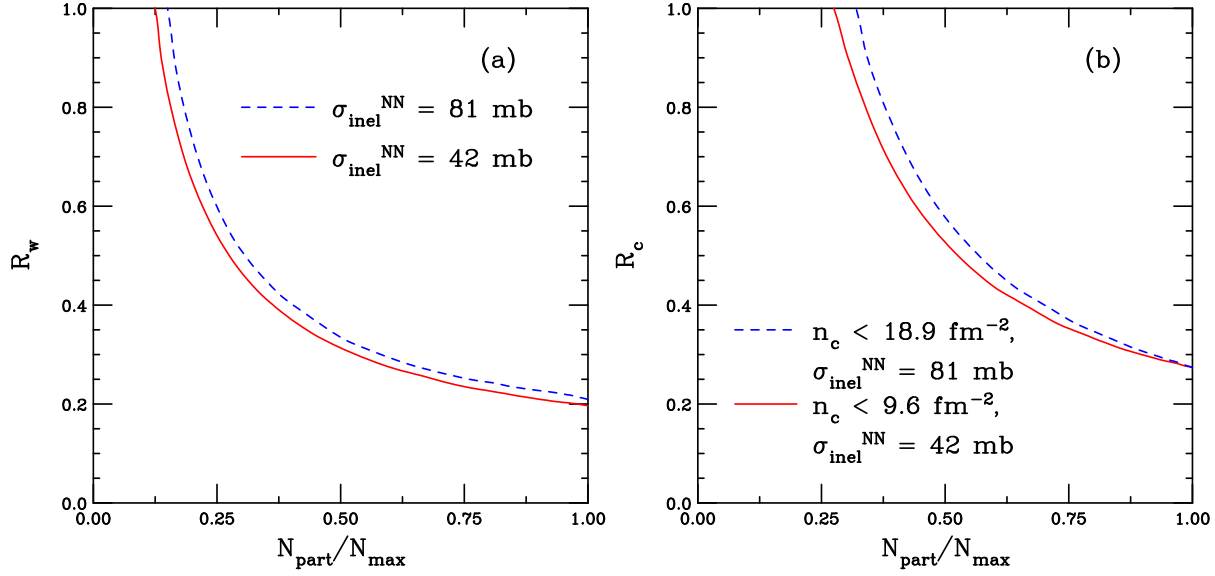


Figure 5: Same as Fig. 4 except that now $\sigma_{\text{inel}} = 81$ mb is also shown.

number of collisions in the corona and core regions defined by n_w in order to compare to the data. The resulting ratio, R_{cw} , of the number of collisions in the corona to the total number of collisions is shown in Fig. 6 for both values of $\sigma_{\text{inel}}^{NN}$.

We note that changing the collision system from Au+Au to Pb+Pb also has only a small effect on R_w , R_c and R_{cw} . The central values of n_w and n_c will change somewhat. In addition, the values of R at which $n_w/n_w(0) < 0.5$ and $n_c/n_c(0) < 0.5$ are slightly higher for the larger A .

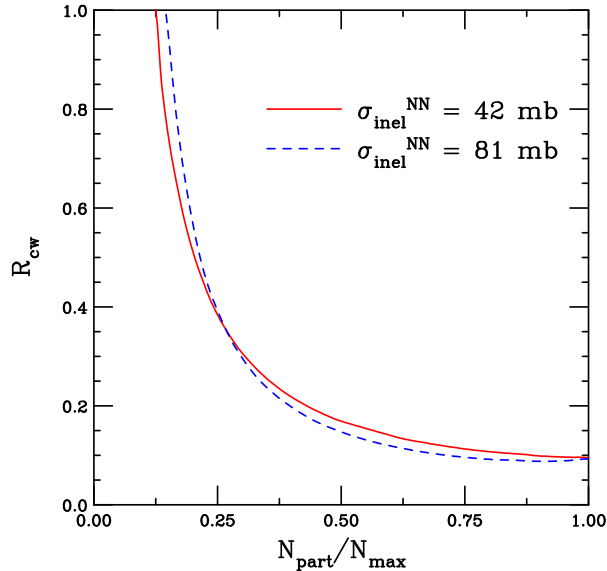


Figure 6: Ratio of collisions in the corona relative to the total number of collisions for Au+Au collisions, using n_w to define the corona. The result is shown for $\sigma_{\text{inel}}^{NN} = 42$ and 81 mb.

Recall that we have been studying the limiting extreme of a purely geometric corona, defined in terms of wounded nucleons or nucleon-nucleon collisions. As previously men-

tioned, the energy density of the produced medium is generally argued to determine the fraction of surviving charmonia [1–3, 18–20]. In this case, in an interior, or core, region of sufficiently high energy density, charmonia would dissociate, while those produced in the cooler outer rim of the collision region would survive. Since the energy density increases with collision energy, the suppression also increases with energy while the region of $N_{\text{part}}/N_{\text{max}}$ within the core becomes more prominent, as schematically illustrated in Fig. 7(a) for densities that might be appropriate for SPS, RHIC and LHC energies.

In contrast, Figs. 4 and 5 showed that a geometric corona results in an energy-independent suppression, as long as the pattern is presented as a function of a geometric variable such as $N_{\text{part}}/N_{\text{max}}$. However, if the suppression pattern in a geometric corona is shown as function of an energy-dependent variable, such as dN_{ch}/dy , the pattern changes, as shown in Fig. 7(b). Now the same maximum suppression is obtained for all energies although the maximum dN_{ch}/dy shifts to higher values as a function of collision energy.

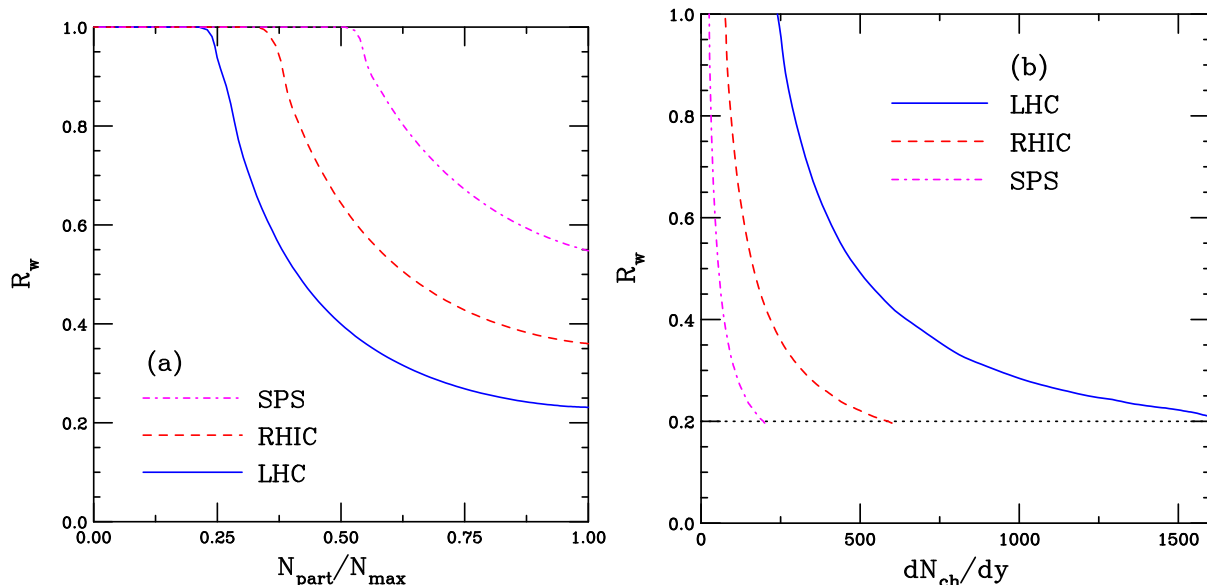


Figure 7: (a): Charmonium survival probability as determined by the energy density profile of the produced medium. (b) The charmonium survival probability obtained by plotting R_w (left-hand side of Fig. 5) as a function of the produced charged particle multiplicity, dN_{ch}/dy , instead of $N_{\text{part}}/N_{\text{max}}$.

Before any comparison to data, we have to address the role of cold nuclear matter effects. In the usual treatments, where the charmonium production in nuclear collisions is compared to that in pp or pA interactions to determine “anomalous” behavior, the role of cold nuclear matter effects on charmonium production in both the initial and final state has to be taken into account. If one considers instead, as suggested in Ref. [8], the ratio of charmonium to open charm, initial-state effects should largely cancel. In this context, a first test would be to compare production at central and forward rapidities. At RHIC, the AA/pp ratios show differences for the two rapidities. If the hidden to open charm ratios are measured as a function of centrality, would the results in the different rapidity regions coincide? Final-state effects on the charmonium resonances will certainly be reduced in the corona. However, it is not clear if they can be neglected entirely. In particular, at the SPS, there are indications that nuclear absorption of the produced charmonia in the

nuclear medium is not negligible. Analysis of J/ψ production at central rapidity over the range of fixed-target energies shows that the effective absorption cross section decreases with $\sqrt{s_{NN}}$ [21]. This result is not unexpected since, as $\sqrt{s_{NN}}$ increases, the traversal time of the nascent charmonium states through the nuclear medium will become very short, diminishing the role of absorption. While absorption could still play a role in the comparison between central and forward rapidities, the hidden to open charm rates should clarify the situation considerably.

If we assume that at sufficiently high $\sqrt{s_{NN}}$, the central core of the transverse collision region is hot enough to dissolve all charmonium bound states, so that only those produced in the corona region survive, then we obtain two immediate predictions for the ratios of charmonium to open charm production after the B -decay contributions have been removed. These predictions are the main result of this paper.

- The J/ψ survival probabilities in central AA collisions for fixed A should be essentially the same at the SPS, RHIC and the LHC.
- The centrality profiles for J/ψ production at RHIC and the LHC should overlap. Some differences may be possible for SPS energy if the dissociation in the core is incomplete for more peripheral interactions.

Here we have defined survival as the ratio of ratios: we divide the charmonium to open charm production ratio in AA collisions as function of centrality by the corresponding single-valued production ratio in pp collisions. No scaling is needed, but if the pp ratio is not independent of rapidity, the AA and pp ratios should be compared at the same rapidity.

We can make an additional prediction for the expected transverse momentum distribution. Nuclear effects due to initial-state scattering and final-state flow generally broaden the p_T distributions relative to pp interactions. If only corona production remains in high energy AA collisions, the p_T distribution should converge to that in pp interactions. Such a convergence would discriminate against recombination models of J/ψ production which would predict narrower p_T distributions [22]. However, charm flow has been observed in nuclear collisions [23] which, in the case of statistical recombination, should be reflected as p_T broadening of the J/ψ produced by recombination.

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