View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by CERN Document Server

(Non)Thermal Aspects of Charmonium Production and a New Look at J/ψ Suppression

P. Braun-Munzinger[a], J. Stachel[b] *

[a]Gesellschaft für Schwerionenforschung, D 64291 Darmstadt, Germany

[b] Physikalisches Institut der Universität Heidelberg, D 69120 Heidelberg, Germany

To investigate a recent proposal that J/ψ production in ultra-relativistic nuclear collisions is of thermal origin we have reanalyzed the data from the NA38/50 collaboration within a thermal model including charm. Comparison of the calculated with measured yields demonstrates the non-thermal origin of hidden charm production at SPS energy. However, the ratio $\psi'/(\mathrm{J}/\psi)$ exhibits, in central nucleus-nucleus collisions, thermal features which lead us to a new interpretation of open charm and charmonium production at SPS energy. Implications for RHIC and LHC energy measurements will be discussed.

The suppression of J/ψ mesons (compared to what is expected from hard scattering models) was early on predicted [1] to be a signature for color deconfinement. Data for S-induced collisions exhibited a significant suppression but systematic studies soon revealed that such suppression exists already in p-nucleus collisions and is due to the absorption in (normal) nuclear matter of a pre-resonant state consisting, e.g., of a color singlet $c\bar{c}g$ state that is formed on the way towards J/ψ production. The situation has been summarized in [2–4].

The newest data for Pb+Pb collisions now exhibit clear evidence for anomalous absorption beyond the standard nuclear absorption expected for such systems. The most recent results are summarized in [5–7]. The observed anomalous suppression is not explained in conventional models where the charmonia are broken up by interactions with co-movers as discussed in [5]. For a discussion of the present status of J/ψ suppression and its understanding in terms of phenomenological models see [8].

However, it was recently conjectured [9,10] that J/ψ production is of thermal origin and exhibits no direct connection to color deconfinement. Since the charmonia are heavy mesons with masses much larger than any conceivable temperature, thermal production would be a big surprize. On the other hand, substantial evidence now exists [11–17] that hadron production (other than charmonia) in ultra-relativistic nuclear collisions proceeds through a state of chemical equilibrium near or at the phase boundary between hadron

---

*The authors are grateful to the US Department of Energy's Institute for Nuclear Theory at the University of Washington for generous hospitality and support during a stay there where part of this work was done.

matter and quark-gluon plasma. For a review of the implications for quark-matter physics see [18–20].

To shed more light on the situation we have modified the thermal model used in [11] to include charmed hadrons. We will first present an overview of the relevant modifications along with a comparison of resulting thermal yields for J/ψ mesons and of the $\psi^{'}/(\mathrm{J}/\psi)$ ratio with experimental results from the NA38/50 collaboration. These results and a comparison to charm production in hard scattering models suggest a new approach towards understanding charmonium production in ultra-relativistic nuclear collisions, which is discussed in the following. The implications for collider experiments at RHIC and LHC will also be summarized.

The present statistical model [11] is based on the use of a grand canonical ensemble to describe the partition function and hence the density of the particles of species i in an equilibrated fireball:

$$n_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\,\mathrm{d}p}{e^{(E_i(p)-\mu_i)/T} \pm 1} \tag{1}$$

with n_i = particle density, g_i = spin degeneracy, $\hbar$ = c = 1, p = momentum, and E = total energy. The chemical potential including charm degrees of freedom is written as $\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3 + \mu_C C_i$. The quantities B_i, S_i, I_i^3, and C_i are the baryon, strangeness, three-component of isospin, and charm quantum numbers of the particle of species i. The temperature T and the baryochemical potential μ_B are the two independent parameters of the model, while the strangeness chemical potential μ_S, the charm chemical potential μ_C, and the isospin chemical potential μ_{I_3} are fixed by strangeness, charm, and charge conservation. In addition, the volume V of the fireball is determined by baryon conservation via the relation $n_{baryon}\mathrm{V} = \mathrm{N}_{part}$, where N_{part} denotes the number of nucleons participating in the collision and n_{baryon} is the net baryon density computed in the thermal model.

In addition to the standard hadronic mass spectrum of 191 hadrons as used in [11] we have added mesons and baryons with open and hidden charm. Specifically, open charm particles included are: D^+, D^-, D^0, $\bar{\mathrm{D}}^0$, Λ_c, Σ_c, Λ_c^*, $\bar{\Lambda}_c$, $\bar{\Sigma}_c$, $\bar{\Lambda}_c^*$, along with the charmonia η_c, J/ψ, χ_0, χ_1, χ_2, ψ', ψ'', ψ'''.

Since the inclusion of these hadrons will modify the rest of the hadron yields only at the sub-percent level, we will use, for the following investigations, the temperature T= 168 MeV and baryon chemical potential μ_B = 266 MeV as established for central Pb+Pb collisions at SPS energy in [11]. This leads to μ_S = 71 MeV, μ_{I_3} = - 5 MeV, (both as in [11]), and μ_C = - 65 MeV. Using a volume of 3085 fm^3 determined by baryon conservation for central Pb+Pb collisions corresponding to 400 participants, we have compared, in Fig. 1, the predictions of this thermal model with the data from NA50 [21,22], as recently analyzed by J. Gosset et al. [23] . Here the data for J/ψ multiplicities are plotted *vs* N_{part}. For this conversion we used the relation between transverse energy and impact parameter as given for the 1995 NA50 data in [23,22] and the connection between impact parameter and N_{part} as established in [24].

The predictions of the thermal model are represented by the dashed line, where we have made use of the fact that, within the range of applicability of the thermal model, all yields scale proportional to the volume, i.e. proportional to the number of participants. We note that, even for the most central collisions (where J/ψ production should be most suppressed [1,8]), the measured J/ψ yield is underpredicted by the thermal model calculations by more than a factor of 2 and the discrepancy is about a factor of 3 for $N_{part} = 200$. To compensate this factor of 3 discrepancy by an increase in temperature[2] would require a temperature of T = 180 MeV, a value not compatible with that determined from hadron production yields [11], where a temperature range of 168 ±4 MeV (including systematic uncertainties) was established.

We further note that it is highly doubtful that full chemical equilibration can be reached for charmed hadrons at SPS energies, either in a hadronic or a quark-gluon plasma scenario. Cross sections for open charm production among hadrons are in the sub-μb level for relevant (thermal) energies, as is estimated from [25]. At such cross section levels the equilibration times for charm should exceed those for strangeness, where production cross sections exceed 100 μb, by more than 2 orders of magnitude. Taking into account that strangeness equilibration times in a hadronic fireball exceed 50 fm/c [26], chemical equilibrium for charm in the hadronic sector can be ruled out. Even in a quark-gluon plasma, where cross sections for charm production are much larger, thermal production is small. Assuming a charm quark mass of 1.5 GeV and an initial temperature of 300 MeV, very high for SPS energies, Redlich has estimated in a parton cascade approach [27,28] that, at hadronization (with $T_c = 160$ MeV), the number of thermal c$\bar{\text{c}}$ pairs is less than 0.01 in central Pb+Pb collisions, lower by a factor of 40 of what would be needed to explain the data. Furthermore, at T = 160 MeV, before the start of the mixed phase, we estimate the volume of the plasma phase to be $V_{plasma} = \pi R^2 \tau = 950$ fm^3, assuming as in [27] a lifetime of the plasma phase of 6.7 fm. The number of charm quark pairs in chemical equilibrium is then $N^{eq}_{c\bar{c}} = 0.47$, implying that in the cascade approach the parton gas is undersaturated in charm by about a factor of 50!

In Table 1 we present a summary of the results from the thermal model calculation for mesons and baryons with open and hidden charm[3]. It is interesting to compare these numbers with predictions for the production of hadrons with open charm in hard collisions. Results obtained by PYTHIA calculations following [25] are shown in Table 2. We note that, somewhat surprizingly, the yield of directly (via hard collisions) produced charm is slightly larger than that produced if charm is in full chemical equilibrium at T= 168 MeV. This implies that one cannot, under any circumstances, neglect direct production. On the other hand, ratios of charmed meson yields differ significantly from the thermal to the direct scenario, as is obvious from Table 1 and Table 2.

Another interesting point concerns the $\psi^{'}/(J/\psi)$ ratio. As is well known [29], this ratio is, in hadron-proton and p-nucleus collisions, close to 12 %, independent of collision system, energy, transverse momentum etc. In the thermal model, the ratio is 3.7 %, including feeding of the J/ψ from heavier charmonium states. A temperature of about 280 MeV would be necessary to explain the ratio found in pp and p-nucleus collisions in a thermal approach. Clearly, J/ψ and $\psi^{'}$ production in pp and p-nucleus collisions are manifestly

---

[2] From T = 168 MeV to T=178 MeV, the J/ψ yield increases by a factor 2.7, the $(J/\psi)/\pi^-$ yield increases by a factor of 2, and the $\psi^{'}/(J/\psi)$ ratio by a factor 1.2.

[3] The thermal fluctuations about these mean values n^{therm} are Poisson distributed. This implies that per collision the variance equals n^{therm}. For 10^6 Pb+Pb collisions, the thermal prediction is, consequently, that 200 ±14 J/ψ mesons will be produced.

non-thermal. This was previously realized by Gerschel [30]. Similar considerations apply for the χ states. In fact, feeding from χ_1 to J/ψ is less than 3 % if the production ratios are thermal.

The evolution with participant number of the $\psi'/(\mathrm{J}/\psi)$ ratio in nucleus-nucleus collisions is presented in Fig. 2. The data are from the NA38/50 collaboration [31–34]. With increasing N_{part} the $\psi'/(\mathrm{J}/\psi)$ ratio drops first rapidly (away from the value in pp collisions) but seems to saturate for high N_{part} values at a level very close to the thermal model prediction, both for S+U and Pb+Pb collisions

This surprizing fact along with the previous observations leads us to propose a new scenario for J/ψ production. We assume that **all** $\mathrm{c\bar{c}}$ pairs are produced in direct, hard collisions, i.e. in line with previous considerations we neglect thermal production. For a description of the hadronization of the c and $\bar{\mathrm{c}}$ quarks, i.e. for the determination of the relative yields of charmonia, and charmed mesons and baryons, we employ the statistical model, with parameters as determined by the analysis of all other hadron yields [11]. The picture we have in mind is that all hadrons form within a narrow time range at or close to the phase boundary.

Since the number of directly produced charm quarks deviates from the value determined by chemical equilibration, we introduce a charm enhancement factor g_c by the requirement of charm conservation. This leads to:

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}) + \frac{1}{2} g_c^2 V (\sum_i n_{\psi_i}^{therm}) + ... \quad (2)$$

Via this equation the thermal yields (thermal densities times volume V) are adjusted to the yield of directly produced charm quark pairs. The remaining terms in eq. (2) of second order and third order in g_c are completely negligible. Of course this equation makes only sense as long as $\mathrm{N}_{c\bar{c}}^{direct}$ is much less than the number of up, down, and strange quarks in the fireball, a relation which is well fulfilled up to the highest (LHC) energies considered here.

The number of D and J/ψ mesons are then enhanced relative to the thermal model prediction by factors g_c and g_c^2, i.e.

$$N_D = g_c V n_D^{therm} \qquad \text{and} \qquad \mathrm{N_{J/\psi} = g_c^2 V n_{J/\psi}^{therm}}. \quad (3)$$

Using this approach of direct production and statistical hadronization we have recalculated the yield for J/ψ mesons. For $\mathrm{N}_{part} = 400$ in Pb+Pb collisions the directly produced number of charm quark pairs is $N_{c\bar{c}}^{direct} = 0.173$ per collision, using the PYTHIA parameters of [25]. This implies $\mathrm{g}_c = 1.38$. The resulting J/ψ yield per participant is plotted, in Fig. 3 as a function of N_{part}.

Without introduction of new parameters this approach describes the measured yield for J/ψ mesons very well for those collision centralities where also the $\psi'/(\mathrm{J}/\psi)$ ratio is well described (see Fig. 2). The interpretation of these results is as follows: at SPS energies charm is produced directly in nuclear collisions at the rate expected by straight extrapolation from what is known about charm in pp collisions [25]. We find no need to enhance open charm production, as has been conjectured in [24]. Furthermore, in the present approach all J/ψ mesons result, for the most central collisions, from the statistical hadronization of the directly produced charm quarks. Directly produced J/ψ mesons are (i) not formed before the reaction proceeds into a plasma phase or (ii) effectively destroyed during the plasma phase by, e.g., a color screening mechanism as proposed in [1]. In either case the current interpretation requires the existence of a deconfined phase during the collision. We remark here that Kabana [35] has recently argued that coalescence of charm quarks is the source of J/ψ mesons in nuclear collisions. While in spirit this is similar to our approach, this scenario assumes an enhancement of open charm which increases with N_{part}, very different from the present conclusions. In the context of the above arguments it would be very important to get a direct measurement of open charm production in nucleus-nucleus collisions.

If the present scenario is correct, the consequences for quarkonium production at collider energies could be significant. For RHIC energies near central rapidity, e.g., the number of directly produced charm quark pairs per unit rapidity is [36] $dN_{c\bar{c}}^{direct}/dy = 1.0$, leading to $g_c = 6.8$ and $dN_{J/\psi}^{therm}/dy = 10^{-2}$, close to the unsuppressed value expected from hard collisions [37]. If the directly produced charm quarks hadronize statistically, as is implied at SPS energy, we would predict no J/ψ suppression at all at RHIC energies, even though there are no J/ψ mesons during the plasma phase. At LHC energy, the current approach would actually predict a significant enhancement of charmonia over the value expected for direct production. Of course, the underlying assumption is that the momenta of the charm quarks are close to thermal near the critical temperature, i.e. thermal (but not chemical) equilibration is required. Present SPS data are not at variance with such a scenario, since the measured transverse momentum spectra for J/ψ mesons [38,33] exhibit thermal shapes with inverse slope constants around 230 MeV, as expected for a heavy particle which participates little in the transverse flow build-up during hadronic expansion. Whether this thermalization will also take place at collider energies is an interesting open question.

We finally note the difference of the present approach with that described in [28], where secondary charmonium production during the mixed phase is calculated under the assumption that all charm quark pairs end up in D mesons after hadronization. Since, even in the present approach, the yield of charmonia is small compared to the yield of D mesons, the calculations reported in [28] concerning secondary charmonium production should still be valid. In fact, the charmonium production yields considered there should be added to the present predictions.

In summary, we have shown that assuming chemical equilibration of charm does not lead to a successful thermal description of available data for p-nucleus and nucleus-nucleus collisions. However, the experimental data at SPS energy for the ratios $\psi'/(J/\psi)$ and $(J/\psi)/N_{part}$ exhibit thermal features for the most central Pb+Pb collisions. Coupled with the fact that direct production of charm quarks in hard scattering exceeds the value obtained by assuming full chemical equilibrium these observations lead to a new interpretation of charmonia production in nucleus-nucleus collisions in terms of a direct production and statistical hadronization approach. This describes the SPS data well and suggests a possible revision of the scenario for charmonium production at collider energies.

REFERENCES

1. T. Matsui and H. Satz, Phys. Lett. **B178** (1986) 416.
2. C. Lourenço, Nucl. Phys. **A610** (1996) 552c.
3. D. Kharzeev, Nucl. Phys. **A638** (1998) 279c.
4. H. Satz, hep-ph/0007069.
5. M.C. Abreu et al., NA50 collaboration, Phys. Lett. **B477** (2000) 28.
6. M.C. Abreu et al., NA50 collaboration, Phys. Lett. **B450** (1999) 456.
7. C. Cicalo for the NA50 collaboration, Proc. Quark Matter 99 conference, Torino, June 1999, Nucl. Phys. **A661** (1999) 93c.
8. J.P. Blaizot, M. Dinh, J.Y. Ollitrault, nucl-th/0007020.
9. M. Gazdzicki, Phys. Rev. **C60** (1999) 054903.
10. M. Gazdzicki and M. Gorenstein, Phys. Rev. Lett. **83** (1999) 4009.
11. P. Braun-Munzinger, I. Heppe, J. Stachel, Phys. Lett **B465** (1999) 15.
12. P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B365** (1996) 1.
13. P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B344** (1995) 43.
14. R. Stock, Phys. Lett. **B456** (1999) 277.
15. U. Heinz, Nucl. Phys. **A661** (1999) 140c.
16. F. Becattini, M. Gazdzicki, J. Sollfrank, Eur. Phys. J. **C5** (1998) 143.
17. J. Cleymans, K. Redlich, Phys. Rev. **C60** (1999) 054908.
18. P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A638** (1998) 3c.
19. J. Stachel, Proc. INPC, Paris, August 1998, Nucl. Phys. **A654** (1999) 119c.
20. P. Braun-Munzinger, Proc. PANIC, Uppsala, June 1999, Nucl. Phys. **A663-664** (2000) 183.
21. F. Bellaiche, dissertation, Univ. Claude Bernard, Lyon 1, 1997.
22. M. C. Abreu et al., NA50 collaboration, Phys. Lett. **B410** (1997) 337.
23. J. Gosset, A. Baldisseri, H. Borel, F. Staley, Y. Terrien, Eur. Phys. J. **C13** (2000) 63.
24. M. C. Abreu et al., NA50 collaboration, Eur. Phys. J. **C14** (2000) 443.
25. P. Braun-Munzinger, D. Miskowiec, A. Drees, C. Lourenço, Eur. Phys. J. **C1** (1998) 123.
26. J. Sollfrank and U. Heinz in: Quark Gluon Plasma 2, R.C. Hwa, editor, World Scientific 1996, p. 555.
27. K. Redlich, private communication.
28. P. Braun-Munzinger and K. Redlich, hep-ph/0001008 and Eur. Phys. J **C** (in print).
29. M.C. Abreu et al., NA50 collaboration, Phys. Lett. **B438** (1998) 35, and references therein.
30. C. Gerschel, Acta Phys. Pol. **B30** (1999) 3585.
31. M.C. Abreu et al., NA38 collaboration, Phys. Lett. **B449** (1999) 128.
32. M. Gonin et al., NA50 collaboration, Proc. 3rd Conf. on Physics and Astrophysics of Quark-Gluon Plasma, Jaipur, India, March 1999, B. C. Sinha, D.K Srivastava, Y.P. Viyogi, editors, Narosa Publ. House 1998, p. 393.
33. L. Ramello et al., NA50 collaboration, Nucl. Phys. **A638** (1998) 261c.
34. M.C. Abreu et al., NA38 collaboration, Phys. Lett. **B466** (1999) 408.
35. S. Kabana, hep-ph/0004138.
36. V. Emel'yanov, A. Khodinov, S.R. Klein, R. Vogt, Phys. Rev. Lett. **81** (1998) 1801.

37. V. Emel'yanov, A. Khodinov, S.R. Klein, R. Vogt, Phys. Rev. **C61** (2000) 044904.
38. M.C. Abreu et al., NA38 collaboration, Phys. Lett. **B423** (1998) 207.

Table 1

Yields for particles with open and hidden charm at mid-rapidity for central Pb+Pb collisions as predicted by the thermal model calculation. Chemical freeze-out takes place at T=168 MeV in a volume of 3085 fm^3 corresponding to 400 participants. The chemical potentials are: $\mu_B = 266$ MeV, $\mu_S = 71$ MeV, $\mu_C = -65$ MeV, $\mu_{I_3} = -5$ MeV. The effect of feeding of the J/ψ meson from heavier charmonia, including the relevant decay branching ratios, is shown in the last row.

particle species	yield/π^-	total
$\mathrm{D}^+ = \mathrm{D}^0$	$5.8{\cdot}10^{-5}$	0.034
$\mathrm{D}^- = \overline{\mathrm{D}^0}$	$1.3{\cdot}10^{-4}$	0.073
Λ_c	$6.4{\cdot}10^{-5}$	0.036
$\overline{\Lambda_\mathrm{c}}$	$5.8{\cdot}10^{-6}$	$3.3 \cdot 10^{-3}$
J/ψ	$3.45\ 10^{-7}$	$2.0 \cdot 10^{-4}$
χ_1	$3.5\ 10^{-8}$	$2.0{\cdot}10^{-5}$
ψ'	$1.3\ 10^{-8}$	$7.6 \cdot 10^{-6}$
$\mathrm{J}/\psi + \chi'\mathrm{s} + \psi'$	$3.6\ 10^{-7}$	$2.1 \cdot 10^{-4}$

Table 2
Yields for particles with open charm for central Pb+Pb collisions as predicted by PYTHIA calculations [25] for N-N collisions and scaled to central ($N_{part} = 400$) Pb+Pb collisions using the nuclear thickness function.

particle species	total yield
D^+	0.032
D^-	0.036
D^0	0.093
$\overline{D^0}$	0.12
Λ_c	0.034
D_s^-	0.011
D_s^+	0.015

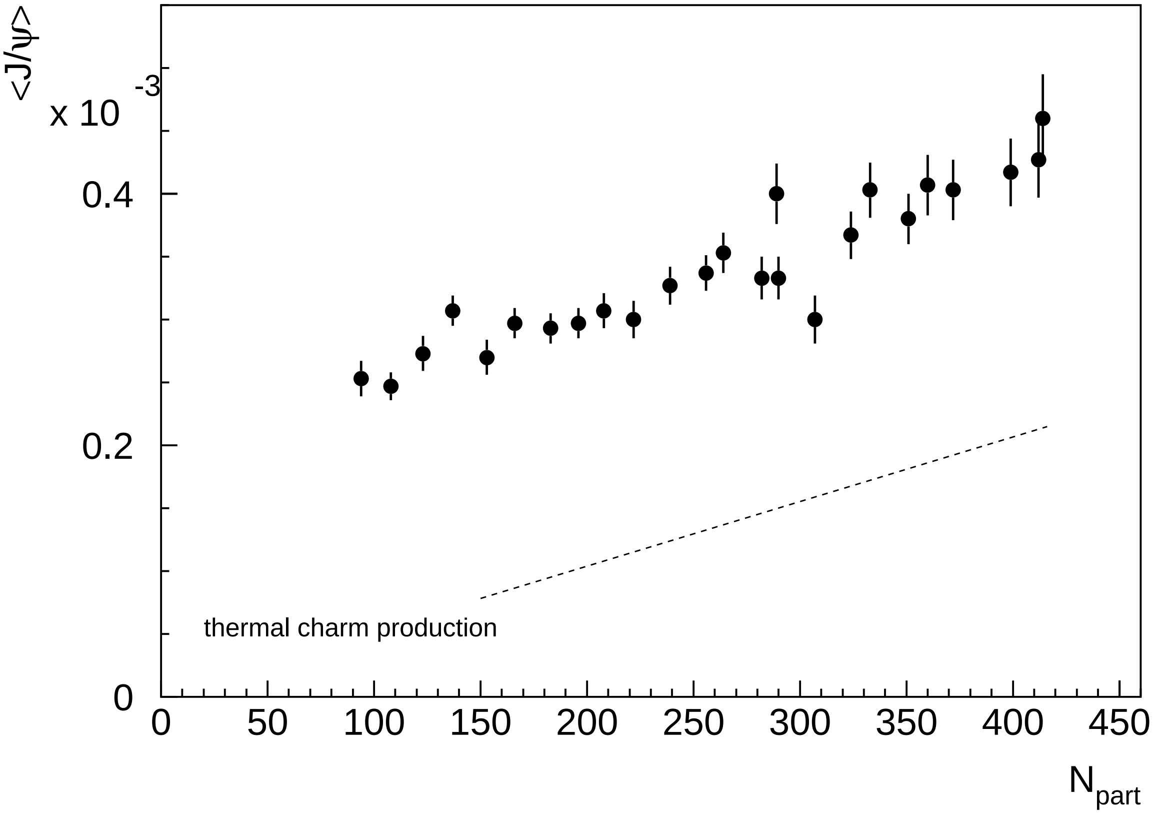

Figure 1. Comparison of measured J/ψ yield per Pb+Pb collision as a function of centrality with the predictions of the thermal model (dashed line). The data are from [21,22] as analyzed in [23]. For details see text

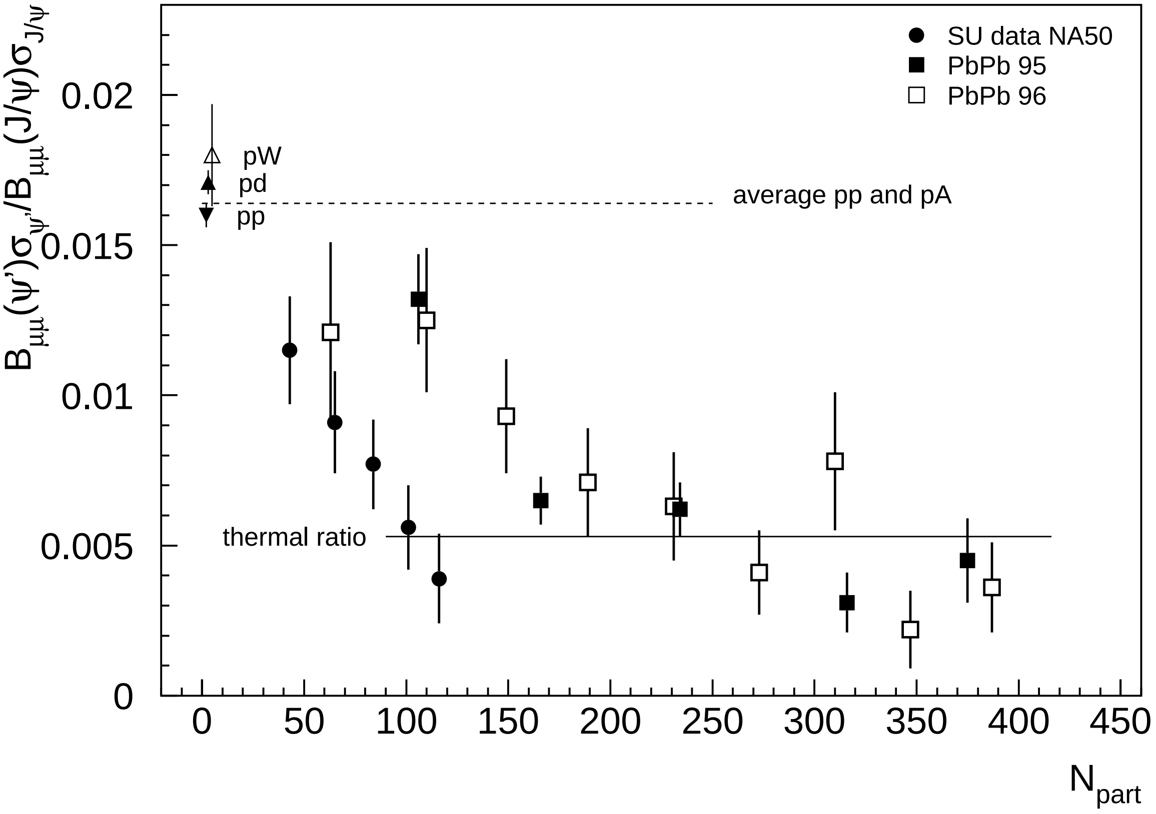

Figure 2. Comparison of the dependence of the measured $\psi'/(J/\psi)$ ratio on the number of participating nucleons with the prediction of the thermal model. The data are from the NA38/50 collaboration [31–34]. See text for more details.

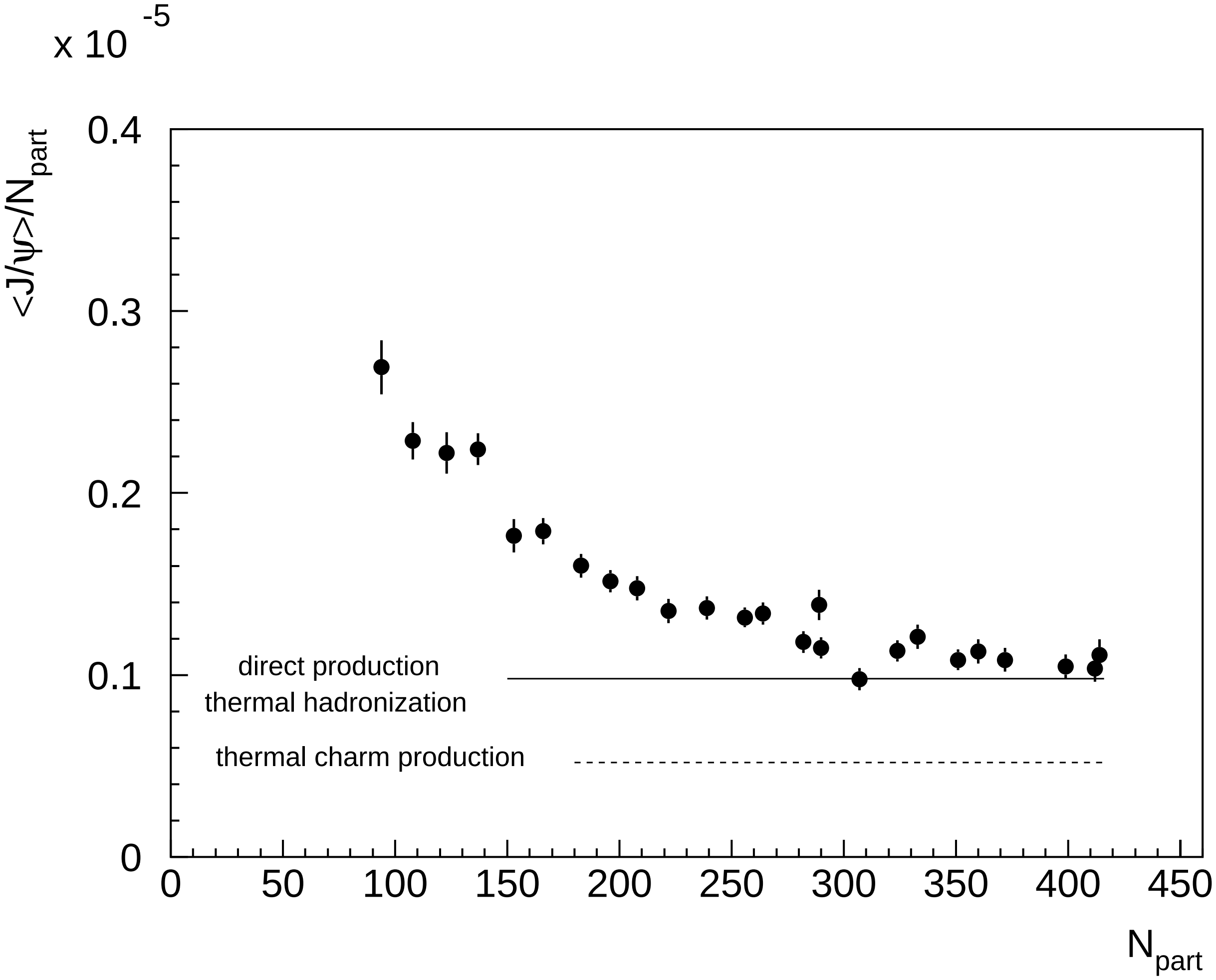

Figure 3. Comparison of the dependence of the measured $(\mathrm{J}/\psi)/\mathrm{N}_{part}$ ratio on the number of participating nucleons with the predictions of the thermal model (dashed line) and of the direct/statistical model (solid line) The data are from [23,21,22]. For details see text.