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New J/ψ suppression data and the comovers interaction model

A. Capella[1], D. Sousa[2]

[1] Laboratoire de Physique Théorique[a], Université de Paris XI, Bâtiment 210, 91405 Orsay Cedex, France
[2] ECT[a], Villa Tambosi, Strada delle Tabarelle 286, 38050 Villazzano (Trento), Italy

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Abstract. New data on the J/ψ suppression both in proton–nucleus and in lead–lead interactions have been presented recently by the NA50 collaboration. We show that these data, together with the final ones on sulfur–uranium interactions, can be described in the framework of the comovers interaction model with a unique set of three parameters: the nuclear absorption cross-section, the comovers interaction cross-section and a single (rescaled) absolute normalization. Expectations for J/ψ suppression at RHIC are also discussed.

1 Introduction

Before the Quark Matter conference of 2002, the NA50 interpretation of the data on J/ψ suppression was as follows [1–3]. The pA, S–U and peripheral Pb–Pb data (up to $E_T \sim 35 \div 40$ GeV) can be described with nuclear absorption alone, with an absorptive cross-section $\sigma_{abs} = 6.4 \pm 0.8$ mb. At $E_T \sim 40$ GeV there is a sudden onset of anomalous suppression, followed by a steady fall-off at larger E_T. However, at variance with this view, the most peripheral points in Pb–Pb collisions lay above the NA50 nuclear absorption curve, which extrapolates the pA and S–U data.

Two important sets of new data have been presented recently [4,5]. The new NA50 data on pA reactions at 450 GeV/c indicate a smaller value of σ_{abs} than the one given above. However, within errors, pA and S–U data can still be described with a single value of the absorptive cross-section $\sigma_{abs} = 4.4 \pm 0.5$ mb, substantially lower than the previous one [5]. The new, preliminary, Pb–Pb data [4], taken in 2000 with a target under vacuum, are consistent with the previous ones except for the most peripheral ones, which are now lower and consistent with the nuclear absorption curve [4]. In this way, the NA50 interpretation remains valid. However, the new data lend support to the interpretation based on comovers interaction, according to which some anomalous suppression is already present in S–U collisions. Indeed, in the comovers approach[1] the sudden onset of anomalous suppression due to deconfinement is replaced by a smooth anomalous suppression due to the comovers interaction. The effect of the comovers turns out to be negligibly small in pA but it is sizable in S–U interactions. With the smaller value of σ_{abs} from the new pA data, there is more room for comovers in S–U.

The purpose of this work is to study the consistency of the new data on pA and Pb–Pb interactions, together with the final S–U ones, with the comovers interaction model [8, 9]. We proceed as follows. Since the effect of the comovers suppression is sizable in S–U, but negligibly small in pA, σ_{abs} has to be determined from the pA data alone. In previous works [8,9] we have used a value $\sigma_{abs} = 4.5$ mb, as a compromise between NA38/NA51 [10] and E537 [11] pA data. Actually, it has been shown in [12] that the old pA data are also consistent with $\sigma_{abs} = 4.5$ mb. As mentioned above, this value has now been confirmed by the recent NA50 data [5], and will be used throughout this paper. The second parameter in the model, the comovers interaction cross-section σ_{co}, can then be determined from the centrality dependence of the J/ψ suppression in Pb–Pb collisions. Obviously its value is correlated with that of the third parameter of the model, the absolute normalization. This normalization, in turn, is strictly related to the one in S–U. The ratio of the Pb–Pb to the S–U normalizations is equal to 1.051 ± 0.026 [5]. This is a rescaling factor which takes into account both isospin and energy corrections. In this way, with σ_{abs} fixed, the model is strongly constrained.

The main drawback of the comovers model [8,9] was precisely a mismatch of about 30% between the absolute normalizations in S–U and Pb–Pb [12]. The origin of this mismatch is the following. The high values of the most peripheral Pb–Pb data in the former NA50 analysis required a value of $\sigma_{co} = 1$ mb. As stated above, in the new data the most peripheral Pb–Pb points are substantially lower and require a lower value of $\sigma_{co} = 0.65$ mb. Indeed, a smaller value of σ_{co} (with σ_{abs} fixed) leads to a flatter centrality dependence of the J/ψ suppression. This change in σ_{co} induces a change in the absolute normalization, which is

[a] Unité Mixte de Recherche UMR no. 8627 - CNRS

[1] For reviews on deconfining and comover interaction models see [6]. Alternative models have also been proposed [7]

now in good agreement with the (rescaled) one obtained in S–U.

The plan of this paper is as follows. In Sect. 2 we present a short summary of the comovers interaction model [8,9]. In Sect. 3 we apply it to Pb–Pb collisions, where the data allow an accurate determination to be made of both the comovers cross-section and the absolute normalization. We also compute the correlation between E_{T} and E_{ZDC}, the energy of the zero degree calorimeter, and discuss the J/ψ suppression in the E_{ZDC} analysis. In Sect. 4 we show that the pp, pA and S–U data can be described using the same values of σ_{abs} and σ_{co} as in Pb–Pb and a single (rescaled) normalization, obtained from either the S–U or the Pb–Pb data. Section 5 contains our conclusions and expectations for J/ψ suppression at RHIC.

2 Comovers interaction in the dual parton model

The cross-section of minimum bias (MB), lepton pair (DY) and J/ψ event samples are given by

$$I_{\mathrm{MB}}^{AB}(b) \propto \sigma_{AB}(b) \ , \quad (1)$$

$$I_{AB}^{DY}(b) \propto \int \mathrm{d}^2 s \ \sigma_{AB}(b) \ n(b,s) \ , \quad (2)$$

$$I_{AB}^{J/\psi}(b) \propto \int \mathrm{d}^2 s \ \sigma_{AB}(b) \ n(b,s) \ S_{\mathrm{abs}}(b,s) S_{\mathrm{co}}(b,s) \ . \quad (3)$$

Here $\sigma_{AB}(b) = \{1 - \exp[-\sigma_{pp} \ AB \ T_{AB}(b)]\}$, where $T_{AB}(b) = \int \mathrm{d}^2 s T_A(s) \ T_B(b-s)$, and $T_A(b)$ are profile functions obtained from the Woods–Saxon nuclear densities [13]. Upon integration over b we obtain the AB total cross-section, σ_{AB}. $n(b,s)$ is given by

$$n(b,s) = AB \ \sigma_{pp} \ T_A(s) \ T_B(b-s)/\sigma_{AB}(b) \ . \quad (4)$$

Upon integration over s we obtain the average number of binary collisions $n(b) = AB \ \sigma_{pp} \ T_{AB}(b)/\sigma_{AB}(b)$.

The factors S_{abs} and S_{co} in (3) are the survival probabilities of the J/ψ due to nuclear absorption and comovers interaction, respectively. They are given by [8,9]

$$S^{\mathrm{abs}}(b,s) = \frac{[1-\exp(-AT_A(s) \ \sigma_{\mathrm{abs}})][1-\exp(-B \ T_B(b-s) \ \sigma_{\mathrm{abs}})]}{\sigma_{\mathrm{abs}}^2 \ AB \ T_A(s) \ T_B(b-s)} \ , \quad (5)$$

$$S^{\mathrm{co}}(b,s) = \exp\left[-\sigma_{\mathrm{co}} \frac{3}{2} N_{y_{DT}}^{\mathrm{co}}(b,s) \ln\left(\frac{\frac{3}{2} N_{y_{DT}}^{\mathrm{co}}(b,s)}{N_f}\right)\right] \ . \quad (6)$$

In (6), $N_{y_{DT}}^{\mathrm{co}}(b,s)$ is the density of charged comovers (positives and negatives) in the rapidity region of the dimuon trigger and $N_f = (3/\pi R_p^2)(\mathrm{d}N/\mathrm{d}y)_{y^*=0} = 1.15\,\mathrm{fm}^{-2}$ [8, 9,14] is the corresponding density in pp. The factor 3/2 in (6) takes care of the neutrals. In the numerical calculations we use $\sigma_{\mathrm{abs}} = 4.5\,\mathrm{mb}$. The value of σ_{co} and the absolute normalization will be determined from the data.

In order to compute the density of comovers we use the DPM formalism described in [15]. It turns out that the density of charged particles is given by a linear superposition of the density of participants and the density of binary collisions with coefficients calculable in DPM. All details can be found in [8,15].

Equations (1) to (6) allow one to compute the impact parameter distributions of the MB, DY and J/ψ event samples. Experimental results are plotted as a function of observable quantities such as E_{T}, the energy of neutrals deposited in the calorimer. Using the proportionality between E_{T} and multiplicity, we have

$$E_{\mathrm{T}}(b) = \frac{1}{2} \ q \ N_{y_{\mathrm{cal}}}^{\mathrm{co}}(b) \quad . \quad (7)$$

Here the multiplicity of the comovers is determined in the rapidity region of the E_{T} calorimeter. The factor 1/2 is introduced because N^{co} is the charged multiplicity whereas E_{T} refers to neutrals. In this way q is close to the average transverse energy per particle, but it also depends on the calibration of the calorimeter. The E_{T}–b correlation is parametrized in the form [3,14]

$$P(E_{\mathrm{T}},b) = \frac{1}{\sqrt{2\pi qaE_{\mathrm{T}}(b)}} \ \exp\left\{-(E_{\mathrm{T}} - E_{\mathrm{T}}(b))^2/2qaE_{\mathrm{T}}(b)\right\} \ . \quad (8)$$

The E_{T} distributions of MB, DY and J/ψ are then obtained by folding (1)–(3) with $P(E_{\mathrm{T}},b)$, i.e.

$$I_{AB}^{\mathrm{MB},DY,J/\psi}(E_{\mathrm{T}}) = \int \mathrm{d}^2 b \ I_{AB}^{\mathrm{MB},DY,J/\psi}(b) \ P(E_{\mathrm{T}},b) \ . \quad (9)$$

The parameters q and a are obtained from a fit of the E_{T} distribution of the MB event sample[2]. Note that since $N_{y_{\mathrm{cal}}}^{\mathrm{co}}(b)$ is nearly proportional to the number of participants (see Fig. 1 of [8]), our fit is practically identical to the one obtained [14] using the wounded nucleon model. Actually, we obtain identical curves to the ones in Fig. 1 of [3], where the E_{T} distributions of MB events of 1996 and 1998 are compared with each other. The values of the parameters for the 1996 data are $q = 0.62\,\mathrm{GeV}$ and $a = 0.825$. For the 1998 data, the tail of the E_{T} distribution is steeper, and we get $q = 0.62\,\mathrm{GeV}$ and $a = 0.60$ [3].

[2] Note that the same value of the parameter a is used in the MB, DY and J/ψ event sample. A priori there could be some differences in the fluctuations for hard and soft processes. Actually, it has been claimed in [8] that there is a small shift in E_{T} between minimum bias, on the one hand, and J/ψ or Drell–Yan pair production on the other hand, induced by the dimuon trigger. However, this is of no relevance for the present work, since, so far, the only 2000 data available have been obtained in the so-called standard analysis, in which the genuine ratio of J/ψ and DY cross-sections is measured

[3] At first sight these sets of values look very different from the ones used by the NA50 collaboration. Nevertheless, they reproduce the same E_{T} distribution. This is due to the fact that the product qa, which, according to (8), determines the width of the distribution, is very similar in the two cases. As for the difference in the values of q it is just due to its definition, which is different in the two approaches ((7), in our case)

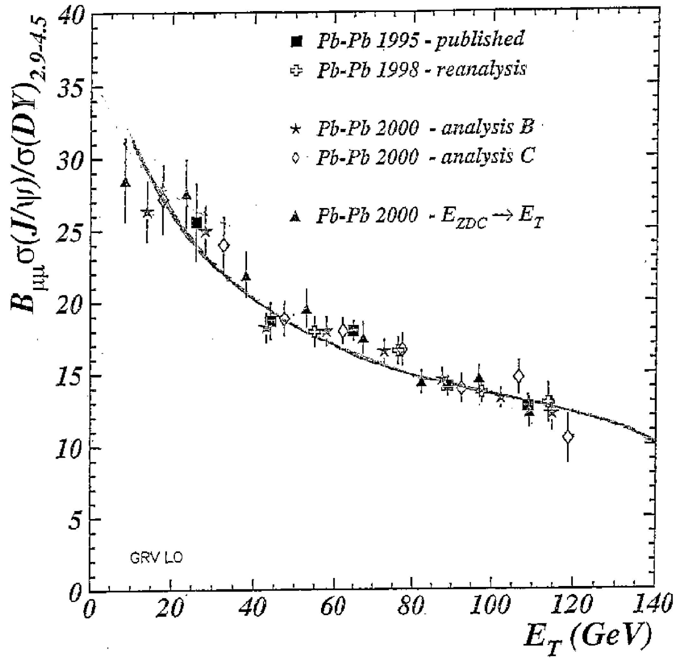

Fig. 1. Ratio of J/ψ to DY cross-sections versus $E_{\rm T}$ in Pb–Pb collisions at 158 GeV/c per nucleon (solid line). The preliminary data are from [4]. GRVLO parton distribution functions have been used in order to calculate the DY cross-section in the mass range 2.9 to 4.5 GeV

In the following we shall use the latter values. Indeed, according to the NA50 collaboration [2], the 1996 data (thick target) at large $E_{\rm T}$ are contaminated by rescattering effects, and only the 1998 data should be used beyond the knee.

The model described above allows us to compute the $E_{\rm T}$ distribution of MB, DY and J/ψ event samples between peripheral AB collisions and the knee of the $E_{\rm T}$ distribution. Beyond it, most models, based on either deconfinement or the comovers interaction, give a ratio of J/ψ to DY cross-sections which is practically constant, in disagreement with NA50 data. A possible way out was suggested in [9]. The idea is that, since $E_{\rm T}$ increases beyond the knee due to fluctuations, one can expect that this is also the case for the density of comovers. Since $N^{\rm co}_{y_{DT}}$ does not contain this fluctuation, it has been proposed in [9] to introduce the following replacement in (6):

$$N^{\rm co}_{y_{DT}}(b,s) \to N^{F{\rm co}}_{y_{DT}}(b,s) = N^{\rm co}_{y_{DT}}(b,s)\ F(b)\ , \qquad (10)$$

where $F(b) = E_{\rm T}/E_{\rm T}(b)$. Here $E_{\rm T}$ is the measured value of the transverse energy and $E_{\rm T}(b)$ is its average value given by (7), which does not contain the fluctuations.

3 J/ψ suppression in Pb Pb

3.1 E_T analysis

The new data [4] for the ratio of J/ψ over DY cross-sections versus the energy of the $E_{\rm T}$ calorimeter are shown in Fig. 1. They are compared with the results of the comovers interaction model described in Sect. 2. As explained there, there are two free parameters in the model ($\sigma_{\rm abs} = 4.5$ mb has been fixed): the comovers interaction cross-section $\sigma_{\rm co}$ (which controls the centrality dependence of the ratio) and the absolute normalization. A good description of the data is obtained using $\sigma_{\rm co} = 0.65$ mb and an absolute normalization of 47.

The only difference between our result and the one in [8] resides in the value of $\sigma_{\rm co}$. Since the effect of the comovers increases with centrality, a larger (smaller) value of $\sigma_{\rm co}$ leads to a larger (smaller) variation of the ratio of J/ψ over DY cross-sections between peripheral and central collisions. As mentioned in the Introduction, in the new NA50 analysis the values of this ratio for peripheral collisions are smaller. In order to describe the new data, the value of $\sigma_{\rm co}$ has to be reduced. The curve in Fig. 1 corresponds to a reduction of $\sigma_{\rm co}$ from 1 mb (used in [8]) to 0.65 mb.

Since the values of $\sigma_{\rm co}$ and of the absolute normalization are correlated, the decrease of $\sigma_{\rm co}$ induces, in turn, a decrease of the absolute normalization. While in [8] the value of the absolute normalization was about 30% higher [12] than in S–U, the one in Fig. 1 is in good agreement with the S–U one. This will be shown in the next section. It is interesting that almost the same value of $\sigma_{\rm co}$ ($\sigma_{\rm co} = 0.7$ mb) was obtained in [16] from an analysis of S–U data and former Pb–Pb data [1] which covered a much smaller centrality range. In [16] the absolute normalizations in S–U and Pb–Pb were in good agreement with each other.

The DY cross-section in Fig. 1 has been integrated in the dimuon mass range 2.9 to 4.5 GeV. Since the J/ψ peak is inside this range, a model is needed in order to determine the DY cross-section. In the S–U analysis, the GRV parton distribution functions at leading order (LO) have been used. Therefore, in order to use the (rescaled) absolute normalization of the S–U data in Pb–Pb (or vice versa), the same GRVLO distributions have to be used in the latter. This is the case in Fig. 1. In Pb–Pb collisions, NA50 has also analyzed the data using, instead, MRS 43 distributions. They have found [4] that in this case the absolute normalization is lower by about 10%. The comparison of the comovers model with the data is presented in Fig. 2. The absolute normalization is 43. The values of $\sigma_{\rm abs}$ and $\sigma_{\rm co}$ are, of course, unchanged.

3.2 $E_{\rm ZDC}$ analysis

The NA50 collaboration has also measured the J/ψ suppression in Pb–Pb as a function of the energy of the zero degree calorimeter ($E_{\rm ZDC}$). In Fig. 1, the results of this analysis have been plotted as a function of $E_{\rm T}$, using the measured correlation between average values of $E_{\rm T}$ and $E_{\rm ZDC}$. We see from Fig. 1 that the data obtained in the two analyses are consistent with each other, even for very central events, beyond the knee of the $E_{\rm T}$ and $E_{\rm ZDC}$ distributions. This important result has been predicted in [12]. Its physical origin is the following.

The energy of the zero degree calorimeter is given by

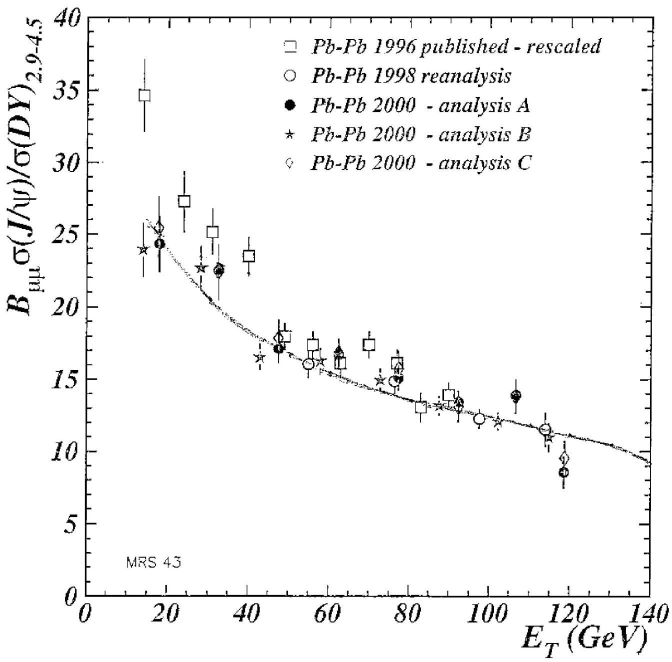

Fig. 2. Same as in Fig. 1, using MRS 43 parton distribution functions

$$E_{\rm ZDC}(b) = [A - n_A(b)]E_{\rm in} + \alpha\ n_A(b)\ E_{\rm in}\ . \qquad (11)$$

Here $n_A(b)$ is the average number of participants at fixed b:

$$n_A(b) = \qquad (12)$$
$$A \int {\rm d}^2 s\ T_A(s)\,[1 - \exp\{-\sigma_{pp}\ B\ T_B(b-s)\}]\,\sigma_{AB}(b)\ .$$

$A - n_A(b)$ is the number of spectator nucleons of A and $E_{\rm in} = 158$ GeV is the beam energy. While the first term in the r.h.s. of (11) gives the bulk of $E_{\rm ZDC}$, the latter corresponds to the contamination by secondaries emitted very forward [17], assumed to be proportional to the number of participants, $n_A(b)$. Here also the value of α can be precisely determined from the position of the "knee" of the $E_{\rm ZDC}$ distribution of the MB event sample measured by NA50 [17]. We obtain $\alpha = 0.076$ [12].

Equations (7) and (11) give the relation between b and $E_{\rm T}$ and b and $E_{\rm ZDC}$, respectively. These relations refer to average values and do not contain any information about the tails of the $E_{\rm T}$ or $E_{\rm ZDC}$ distributions. Equations (7) and (11) also lead to a correlation between (average values of) $E_{\rm T}$ and $E_{\rm ZDC}$. This correlation [12] gives a good description of the experimental one [3]. It is practically a straight line[4] and therefore can be accurately extrapolated beyond the knee of the $E_{\rm T}$ and $E_{\rm ZDC}$ distributions. It turns out that this extrapolation describes the measured $E_{\rm T}$–$E_{\rm ZDC}$ correlation quite well[5], even for values of $E_{\rm T}$ and $E_{\rm ZDC}$ in the tails of the distributions. This result suggests a correlation between b and $E_{\rm ZDC}$ of the form

$$P(E_{\rm ZDC}, b) = P(E_{\rm T}, b)\delta\left(E_{\rm T} - E_{\rm T}(E_{\rm ZDC}\right)\ . \qquad (13)$$

Folding (1) and (13) we obtain the $E_{\rm ZDC}$ distribution of MB events. It describes [12] the one measured by NA50, not only up to the knee, but also in the tail of the distribution. This result shows that the J/ψ supression versus $E_{\rm ZDC}$ is just obtained from the corresponding one versus $E_{\rm T}$ by applying the $E_{\rm ZDC}$–$E_{\rm T}$ correlation, even for very central events beyond the knee of the distributions. In the 1996 and 1998 NA50 data, the J/ψ suppression versus $E_{\rm ZDC}$ indicated some features ("snake shape") not present in the ones versus $E_{\rm T}$. Such differences are no longer present in the new data.

[4] This is due to the fact that $N^{\rm co}_{yca}(b)$ in (7) is practically proportional to $n_A(b)$ (see Fig. 1 of [8])

[5] One can understand the physical origin of this extrapolation if one assumes that a fluctuation in $E_{\rm T}$ is essentially due to a fluctuation in n_A, which, in turn, produces a corresponding fluctuation in $E_{\rm ZDC}$, via (11)

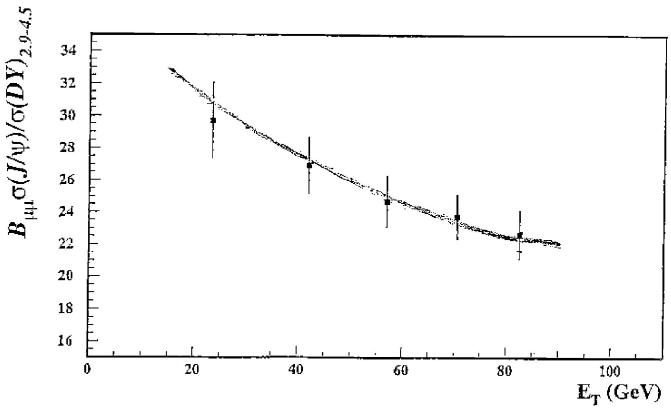

Fig. 3. The ratio of J/ψ to DY cross-sections as a function of $E_{\rm T}$ in S–U collisions at 200 GeV/c per nucleon. The data are from [18]

4 J/ψ suppression in pA and S–U

Let us compute next the ratio R of J/ψ over DY cross-sections in S–U at 200 GeV/c per nucleon in our model. We use, of course, the same values of the parameters as in Pb–Pb: $\sigma_{\rm abs} = 4.5$ mb and $\sigma_{\rm co} = 0.65$ mb. To get this ratio versus b, the only new ingredient is the multiplicity of comovers, which is again computed in DPM, in the way described in Sect. 2. To compute $R(E_{\rm T})$, we also need the $E_{\rm T}$–b correlation in S–U, which is parametrized as in (8). The parameters q and a have been obtained from a fit of the $E_{\rm T}$ distribution of DY given in [18]. We obtain $q = 0.69$ GeV and $a = 1.6$. ($R(E_{\rm ZDC})$ has not been measured in S–U). In S–U, the data do not extend beyond the knee of the $E_{\rm T}$ distribution. Therefore, effects such as $E_{\rm T}$ fluctuations, (10), are not relevant here.

Our results are shown in Fig. 3. We see that the $E_{\rm T}$ dependence of the suppression is reproduced. This indicates that there is, indeed, room in S–U for the (comparatively small) suppression by comovers. As discussed above this could also be inferred from the different central values of $\sigma_{\rm abs}$ obtained in pA and S–U. The absolute normalization of the curve in Fig. 3 is 45. Thus, the normalizations in Pb–Pb and S–U are consistent with each other. This normalization is 4% smaller than the one obtained from the Pb–Pb data, in perfect agreement with the rescaling factor discussed in the Introduction.

In pA collisions, the effect of the comovers is negligible and, therefore, the description of the pA data is the same as in the NA50 analysis [5], since, as discussed above, the value of σ_{abs} they obtain is practically identical to ours. The corresponding normalization is 20% higher than the one we have obtained in S–U. This is also consistent with the expected rescaling factor between the two systems, which takes into account the difference in energy as well as in the rapidity regions covered by the dimuon trigger.

5 Conclusions and outlook

The NA50 deconfining scenario has been described in the Introduction. In this work we have presented a different scenario in which the sudden onset of anomalous suppression due to deconfinement is replaced by a smooth one resulting from comovers interaction. This anomalous suppression is already present in S–U and peripheral Pb–Pb collisions.

We have presented a description of the NA38/NA50 data on the J/ψ suppression in pp, pA, S–U and Pb–Pb interactions in a comovers model. The model is strongly constrained by the existing data. This can be seen in the following way. In S–U, the effect of the comovers is rather small and, thus, once the value of $\sigma_{\mathrm{abs}} = 4.5\,\mathrm{mb}$ is fixed, the absolute normalization depends little on the exact value of σ_{co}. Since the normalizations in S–U and Pb–Pb are strictly related, we are left with a single free parameter, σ_{co}, to determine the J/ψ suppression in Pb–Pb (both in absolute value and centrality dependence). The model is, thus, strongly constrained and provides a unified description of the data in the various systems. On the other hand, it is not possible to describe the former NA50 data on Pb–Pb collisions for peripheral events in a consistent way. Indeed, these data require a value $\sigma_{\mathrm{co}} = 1\,\mathrm{mb}$. As shown in [12], this, in turn, leads to a mismatch of about 30% between the absolute normalizations in the S–U and the Pb–Pb systems. Furthermore, with equal normalizations in S–U and in Pb–Pb, the J/ψ suppression is always larger in the latter than in the former, even for very peripheral events (see Fig. 7 of [12]).

Let us discuss briefly the expectations for J/ψ suppression at RHIC in the comovers interaction model. The calculation of the survival probability S_{co} is quite safe. Indeed, since σ_{co} is a cross-section near threshold, the same value obtained at SPS should be used at RHIC. The situation is quite different for S_{abs}. Many authors assume that σ_{abs} is the same at RHIC and at SPS. It has also been suggested that it can be significantly larger at RHIC. However, it seems plausible that at mid-rapidities, nuclear absorption at RHIC is small due to the fact that, contrary to SPS, the $c\bar{c}$ pair is produced outside the colliding nuclei. It is therefore crucial to have data on J/ψ production in pA interactions at RHIC. If $S_{\mathrm{abs}} \sim 1$, the J/ψ suppression at RHIC and SPS will be comparable, since the smallness of the nuclear absorption will be approximately compensated by the increase of the comovers suppression, due to a larger comovers density at RHIC. Very preliminary data tend to indicate that this is indeed the case. Detailed calculations will be presented elsewhere.

A quantitative analysis of the new NA50 data in the deconfining scenario is still missing. On the other hand, the centrality dependence of the average p_{T} of J/ψ is better described in the comovers approach than in a deconfining scenario [19]. At RHIC energies, a small nuclear absorption in pA collisions (i.e. $S_{\mathrm{abs}} \sim 1$), would be a very interesting situation in order to discriminate between the comovers interaction model and a deconfining scenario. Indeed, in the latter, the shape of the centrality dependence would be almost flat for peripheral collisions (below the deconfining threshold) and would decrease above the threshold. Such a behavior would be a clear signal of deconfinement. On the contrary, in the comovers scenario, the fall-off would be continuous, from peripheral to central collisions, and determined by the same value of σ_{co} obtained from CERN SPS data.

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