New $J/\psi$ suppression data and the comovers interaction model

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Abstract

New data on the $J/\psi$ 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 $J/\psi$ suppression at RHIC are also discussed.

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1 Introduction

Before the Quark Matter conference of 2002, the NA50 interpretation of the data on $J/\psi$ suppression was as follows [1-3]. The $pA$, $SU$ and peripheral $Pb Pb$ data (up to $E_T \sim 35\div40$ 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 lied above the NA50 nuclear absorption curve – which extrapolates $pA$ and $SU$ 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 $\sigma_{abs}$ than the one given above. However, within errors, $pA$ and $SU$ 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 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 $SU$ collisions. Indeed, in the comovers approach the sudden onset of anomalous suppression due to deconfinement is replaced by a smooth anomalous suppression due to comovers interaction. The effect of the comovers turns out to be negligibly small in $pA$ but it is sizable in $SU$ interactions. With the smaller value of $\sigma_{abs}$ from the new $pA$ data, there is more room for comovers in $SU$.

The purpose of this work is to study the consistency of the new data on $pA$ and $Pb Pb$ interactions, together with the final $SU$ ones, with the comovers interaction model [8] [9]. We proceed as follows. Since the effect of the comovers suppression is sizable in $SU$, but negligibly small in $pA$, $\sigma_{abs}$ 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,

\footnote{For reviews on deconfining and comover interaction models see [6]. Alternative models have also been proposed [7].}
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 \( \sigma_{co} \), can then be determined from the centrality dependence of the \( J/\psi \) 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 \( SU \). The ratio of the \( Pb \ Pb \) to the \( SU \) normalizations is equal to 1.051 \( \pm \) 0.026 [5]. This is a rescaling factor which takes into account both isospin and energy corrections. In this way, with \( \sigma_{abs} \) 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 \( SU \) 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 \( \sigma_{co} = 1 \) 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 \( \sigma_{co} \) (with \( \sigma_{abs} \) fixed) leads to a flatter centrality dependence of the \( J/\psi \) suppression. This change in \( \sigma_{co} \) induces a change in the absolute normalization – which is now in good agreement with the (rescaled) one obtained in \( SU \).

The plan of this paper is as follows. In Section 2 we present a short summary of the comovers interaction model [8-9]. In Section 3 we apply it to \( Pb \ Pb \) collisions, where the data allow an accurate determination 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 \( J/\psi \) suppression in the \( E_{ZDC} \) analysis. In Section 4 we show that the \( pp \), \( pA \) and \( SU \) data can be described using the same values of \( \sigma_{abs} \) and \( \sigma_{co} \) as in \( Pb \ Pb \) and a single (rescaled) normalization – obtained from either \( SU \) or \( Pb \ Pb \) data. Section 5 contains our conclusions and expectations for \( J/\psi \) suppression at RHIC.

## 2 Comovers interaction in the dual parton model

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

\[ I_{MB}^{AB}(b) \propto \sigma_{AB}(b) \]  \hspace{1cm} (1)

\[ I_{DY}^{AB}(b) \propto \int d^2 s \sigma_{AB}(b) n(b, s) \]  \hspace{1cm} (2)

\[ I_{J/\psi}^{AB}(b) \propto \int d^2 s \sigma_{AB}(b) n(b, s) S_{abs}(b, s)S_{co}(b, s) \]  \hspace{1cm} (3)

Here \( \sigma_{AB}(b) = \{1 - \exp[-\sigma_{pp} AB T_{AB}(b)]\} \) where \( T_{AB}(b) = \int d^2sT_A(s) T_B(b - s) \), 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, \( \sigma_{AB} \). \( n(b, s) \) is given by

\[ n(b, s) = AB \sigma_{pp} T_A(s) T_B(b - s)/\sigma_{AB}(b) \]  \hspace{1cm} (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 \( J/\psi \) due to nuclear absorption and comovers interaction, respectively. They are given by [8, 9]

\[ S_{abs}(b, s) = \frac{[1 - \exp(-A T_A(s) \sigma_{abs})][1 - \exp(-B T_B(b - s) \sigma_{abs})]}{\frac{\sigma_{abs}^2}{4} AB T_A(s) T_B(b - s)} \]  \hspace{1cm} (5)

\[ S_{co}(b, s) = \exp\left[-\sigma_{co} \frac{3}{2} N_{yDT}^{co}(b, s) \ell n\left(\frac{\frac{3}{2} N_{yDT}^{co}(b, s)}{N_f}\right)\right] \]  \hspace{1cm} (6)

In [6], \( N_{yDT}^{co}(b, s) \) is the density of charged comovers (positives and negatives) in the rapidity region of the dimuon trigger and \( N_f = (3/\pi R_p^2)(dN/dy)_{y^* = 0} = 1.15 \text{ fm}^{-2} \) is the corresponding density in \( pp \). The factor 3/2 in (6) takes care of the neutrals. In the numerical calculations we use \( \sigma_{abs} = 4.5 \text{ mb} \). The value of \( \sigma_{co} \) 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] and [15].

Eqs. (1) to (3) allow to compute the impact parameter distributions of the \( MB, DY \) and \( J/\psi \) event samples. Experimental results are plotted as a function of
observable quantities such as $E_T$ – the energy of neutrals deposited in the calorimeter. Using the proportionality between $E_T$ and multiplicity, we have

$$E_T(b) = \frac{1}{2} q N_{\text{coal}}^o(b).$$  

(7)

Here the multiplicity of comovers is determined in the rapidity region of the $E_T$ calorimeter. The factor 1/2 is introduced because $N_{\text{coal}}^o$ 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 correlation $E_T - b$ is parametrized in the form [3] [14]

$$P(E_T, b) = \frac{1}{\sqrt{2\pi qaE_T(b)}} \exp \left\{-(E_T - E_T(b))^2/2qaE_T(b) \right\}.$$  

(8)

The $E_T$ distributions of $MB$, $DY$ and $J/\psi$ are then obtained by folding Eqs. (1)-(3) with $P(E_T, b)$, i.e.

$$I_{AB}^{MB,DY,J/\psi}(E_T) = \int d^2b I_{AB}^{MB,DY,J/\psi}(b) P(E_T, b).$$  

(9)

The parameters $q$ and $a$ are obtained from a fit of the $E_T$ distribution of the $MB$ event sample. Note that since $N_{\text{coal}}^o(b)$ 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 ref. [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 $q = 0.62$ GeV and $a = 0.825$. For the 1998 data, the tail of the $E_T$ distribution is steeper, and we get $q = 0.62$ GeV and $a = 0.60$. In the following we shall use

3Note that the same value of the parameter $a$ is used in the $MB$, $DY$ and $J/\psi$ event sample. A priori there could be some differences in the fluctuations for hard and soft processes. Actually, it has been claimed in Ref. [8] that there is a small shift in $E_T$ between minimum bias, on one hand, and $J/\psi$ 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 $J/\psi$ and $DY$ cross-sections is measured.

4At 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 Eq. [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 (Eq. [7], in our case).
the latter values. Indeed, according to the NA50 collaboration [2], the 1996 data (thick target) at large $E_T$ are contaminated by rescattering effects – and only the 1998 data should be used beyond the knee.

The model described above allows to compute the $E_T$ distribution of $MB$, $DY$ and $J/\psi$ event samples between peripheral $AB$ collisions and the knee of the $E_T$ distribution. Beyond it, most models, based on either deconfinement or comovers interaction, give a ratio of $J/\psi$ 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 $E_T$ increases beyond the knee due to fluctuations, one can expect that this is also the case for the density of comovers. Since $N_{yDT}^{co}$ does not contain this fluctuation, it has been proposed in [9] to introduce the following replacement in Eq. (6):

$$N_{yDT}^{co}(b, s) \rightarrow N_{yDT}^{Fco}(b, s) = N_{yDT}^{co}(b, s) F(b)$$  \hspace{1cm} (10)

where $F(b) = E_T/E_T(b)$. Here $E_T$ is the measured value of the transverse energy and $E_T(b)$ is its average value given by Eq. (7) – which does not contain the fluctuations.

3 J/\psi suppression in Pb Pb

a) $E_T$ analysis

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

The only difference between our result and the one in [8] resides in the value of $\sigma_{co}$. Since the effect of the comovers increases with centrality, a larger (smaller) value of $\sigma_{co}$ leads to a larger (smaller) variation of the ratio of $J/\psi$ 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.
order to describe the new data, the value of $\sigma_{co}$ has to be reduced. The curve in Fig. 1 corresponds to a reduction of $\sigma_{co}$ from 1 mb (used in [8]) to 0.65 mb.

Since the values of $\sigma_{co}$ and of the absolute normalization are correlated, the decrease of $\sigma_{co}$ 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 $SU$, the one in Fig. 1 is in good agreement with the $SU$ one. This will be shown in the next section. It is interesting that almost the same value of $\sigma_{co}$ ($\sigma_{co} = 0.7$ mb) was obtained in [16] from an analysis of $SU$ data and former $Pb Pb$ data [1] which covered a much smaller centrality range. In [16] the absolute normalizations in $SU$ 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 $J/\psi$ peak is inside this range, a model is needed in order to determine the $DY$ cross-section. In the $SU$ analysis, the GRV parton distribution functions at leading order (LO) have been used. Therefore, in order to use the (rescaled) absolute normalization of the $SU$ 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 $\sigma_{abs}$ and $\sigma_{co}$ are, of course, unchanged.

b) $E_{ZDC}$ analysis

The NA50 collaboration has also measured the $J/\psi$ suppression in $Pb Pb$ as a function of the energy of the zero degree calorimeter ($E_{ZDC}$). In Fig. 1, the results of this analysis have been plotted as a function of $E_T$, using the measured correlation between average values of $E_T$ and $E_{ZDC}$. We see from Fig. 1 that the data obtained in the two analysis are consistent with each other, even for very central events, beyond the knee of the $E_T$ and $E_{ZDC}$ 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

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

(11)
Here $n_A(b)$ is the average number of participants at fixed $b$:

$$n_A(b) = A \int d^2 s \ T_A(s) \left[ 1 - \exp \left\{ -\sigma_{pp} \ \ T_B(b - s) \right\} \right] \sigma_{AB}(b) \quad (12)$$

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

Eqs. (7) and (11) give the relation between $b$ and $E_T$ and $b$ and $E_{ZDC}$, respectively. These relations refer to average values and do not contain any information about the tails of the $E_T$ or $E_{ZDC}$ distributions. Eqs. (7) and (11) also lead to a correlation between (average values of) $E_T$ and $E_{ZDC}$. This correlation \cite{12} gives a good description of the experimental one \cite{3}. It is practically a straight line\footnote{This is due to the fact that $N^{co}_{yca}(b)$ in Eq. (7) is practically proportional to $n_A(b)$ (see Fig. 1 of \cite{8}).} and therefore can be accurately extrapolated beyond the knee of the $E_T$ and $E_{ZDC}$ distributions. It turns out that this extrapolation describes the measured $E_T - E_{ZDC}$ correlation quite well\footnote{One can understand the physical origin of this extrapolation if one assumes that a fluctuation in $E_T$ is essentially due to a fluctuation in $n_A$ – which, in turn, produces a corresponding fluctuation in $E_{ZDC}$, via Eq. (11).} – even for values of $E_T$ and $E_{ZDC}$ in the tails of the distributions. This result suggests a correlation between $b$ and $E_{ZDC}$ of the form

$$P(E_{ZDC}, b) = P(E_T, b) \delta (E_T - E_T(E_{ZDC})) \quad (13)$$

Folding (11) and (13) we obtain the $E_{ZDC}$ distribution of $MB$ events. It describes \cite{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 $J/\psi$ suppression versus $E_{ZDC}$ is just obtained from the corresponding one versus $E_T$ by applying the $E_{ZDC} - E_T$ correlation, even for very central events beyond the knee of the distributions. In the 1996 and 1998 NA50 data, the $J/\psi$ suppression versus $E_{ZDC}$ indicated some features (“snake shape”) not present in the ones versus $E_T$. Such differences are no longer present in the new data.
4 \( J/\psi \) suppression in \( pA \) and \( SU \)

Let us compute next the ratio \( R \) of \( J/\psi \) over \( DY \) cross-sections in \( SU \) at 200 GeV/c per nucleon in our model. We use, of course, the same values of the parameters as in \( Pb Pb \): \( \sigma_{\text{abs}} = 4.5 \text{ mb} \) and \( \sigma_{\text{co}} = 0.65 \text{ mb} \). 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 Section 2. To compute \( R(E_T) \), we also need the \( E_T - b \) correlation in \( SU \), which is parametrized as in Eq. (8). The parameters \( q \) and \( a \) have been obtained from a fit of the \( E_T \)-distribution of \( DY \) given in [18]. We obtain \( q = 0.69 \text{ GeV} \) and \( a = 1.6 \). \( R(E_{ZDC}) \) has not been measured in \( SU \). In \( SU \), data do not extend beyond the knee of the \( E_T \)-distribution. Therefore, effects such as \( E_T \) fluctuations, Eq. (10), are not relevant here.

Our results are shown in Fig. 3. We see that the \( E_T \) dependence of the suppression is reproduced. This indicates that there is, indeed, room in \( SU \) for the (comparatively small) suppression by comovers. As discussed above this could also be inferred from the different central values of \( \sigma_{\text{abs}} \) obtained in \( pA \) and \( SU \). The absolute normalization of the curve in Fig. 3 is 45. Thus the normalizations in \( Pb Pb \) and \( SU \) 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 [9], since, as discussed above, the value of \( \sigma_{\text{abs}} \) they obtain is practically identical to ours. The corresponding normalization is 20 \% higher than the one we have obtained in \( SU \). 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 $SU$ and peripheral $Pb Pb$ collisions.

We have presented a description of the NA38/NA50 data on the $J/\psi$ suppression in $pp$, $pA$, $SU$ 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 $SU$, the effect of the comovers is rather small and, thus, once the value of $\sigma_{abs} = 4.5$ mb is fixed, the absolute normalization depends little on the exact value of $\sigma_{co}$. Since the normalizations in $SU$ and $Pb Pb$ are strictly related, we are left with a single free parameter, $\sigma_{co}$, to determine the $J/\psi$ 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 $\sigma_{co} = 1$ mb. As shown in [12], this, in turn, leads to a mismatch of about 30 % between the absolute normalizations in $SU$ and $Pb Pb$ systems. Furthermore, with equal normalizations in $SU$ and in $Pb Pb$, the $J/\psi$ 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 $J/\psi$ suppression at RHIC in the comovers interaction model. The calculation of the survival probability $S_{co}$ is quite safe. Indeed, since $\sigma_{co}$ 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 $\sigma_{abs}$ 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 $J/\psi$ production in $pA$ interactions at RHIC. If $S_{abs} \sim 1$, the $J/\psi$ 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 $J/\psi$ 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. \( S_{abs} \sim 1 \)), 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 \( \sigma_{co} \) obtained from CERN SPS data.

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Figure Captions

**Fig. 1**: Ratio of $J/\psi$ to $DY$ cross-sections versus $E_T$ 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.

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

**Fig. 3**: The ratio of $J/\psi$ to $DY$ cross-sections as a function of $E_T$ in $SU$ collisions at 200 GeV/c per nucleon. The data are from [18].
Figure 1
