

# An alternative way of plotting the data and results of models of $J/\psi$ suppression

Ján Pišút<sup>a)</sup> and Neva Pišútová<sup>b)</sup>

<sup>a)</sup> *Theory Division, CERN, CH-1211 Geneva 23, Switzerland,  
on leave of absence from <sup>b)</sup>*

<sup>b)</sup> *Department of Physics, Comenius University,  
SK-84248 Bratislava, Slovakia*

## Abstract

We propose an alternative way of looking at data on anomalous  $J/\psi$  suppression. The proposed method is in principle equivalent to the one used by the NA50 Collaboration, but it permits to visualize separate contributions of individual processes responsible for the disintegration of  $J/\psi$ 's produced by a hard process in nuclear collisions. The method can be used provided that the time sequence of contributing mechanisms is known or assumed. It offers an alternative graphical presentation of the onset of anomalous  $J/\psi$  suppression in Pb–Pb interactions observed by the NA50 Collaboration at the CERN SPS and might contribute to explain why different mechanisms, such as  $J/\psi$  suppression by the Quark–Gluon Plasma and by co–movers in the Dual Parton Model or in Monte Carlo microscopic approaches, all lead to an approximate description of anomalous  $J/\psi$  suppression.

# 1 Introduction

The anomalous  $J/\psi$  suppression observed by the NA50 Collaboration [1, 2] in Pb–Pb collisions at the CERN SPS can be naturally interpreted as  $J/\psi$  dissolution by the Quark–Gluon Plasma (QGP). This phenomenon was predicted by Matsui and Satz [3] more than 15 years ago. The interpretation of the anomalous  $J/\psi$  suppression is somewhat complicated by the fact that there are also other contributions to  $J/\psi$  suppression. Nuclear absorption (NA) (sometimes referred to as "pre-resonance absorption" or "Gerschel–Hüfner mechanism") [4]–[6] is probably responsible for most of  $J/\psi$  suppression in nuclear collisions induced by lighter ions. Disintegration of  $J/\psi$  by collisions with secondary hadrons [7]–[13] (also referred to as "co-mover" interaction) is another possible contribution. In order to make the  $J/\psi$  suppression by the gas of secondary hadrons sufficiently large, in some approaches [10, 12] cross-section ( $\sigma_{co}$ ) for the process  $\text{hadron}+J/\psi \rightarrow D\bar{D} + X$  has to be of about 5 mb, depending also on the value of the cross-section ( $\sigma_a$ ) for nuclear absorption. In the approach based on the Dual Parton Model (DPM) [11] one needs  $\sigma_{co} = 0.6$  mb, for  $\sigma_a = 6.7$  mb and [13]  $\sigma_{co} = 1$  mb for  $\sigma_a = 4.5$  mb. It has been argued [14] that, at energies corresponding to the thermal motion of hadrons, the cross-sections for the disintegration of  $J/\psi$  by hadrons are in fact an order of magnitude smaller. The issue is not yet definitely clarified.

There is one key difference between the suppression of  $J/\psi$  by the QGP and by other mechanisms. For  $J/\psi$  dissolution by QGP a rapid onset of the anomalous suppression is expected or at least possible, whereas for other mechanisms one expects a smooth dependence of  $J/\psi$  suppression on the impact parameter  $b$  and on the total transverse energy  $E_T$  of a nuclear collision. Models by Blaizot and Ollitrault (BO) [15] and by Kharzeev, Lourenço, Nardi and Satz (KLNS) [16, 17] do show a rather rapid onset of the dependence of the anomalous  $J/\psi$  suppression on  $E_T$  or on  $b$ . Plots of experimental data on  $J/\psi$  suppression, in particular those with the nuclear absorption "subtracted" [18] do show such an abrupt onset.

Although the anomalous  $J/\psi$  suppression is a rather spectacular Phenomenon, indicating a rapid onset of a new mechanism of  $J/\psi$  Suppression, there are a few mechanisms that are able to obtain some agreement with the basic features of the data. Apart from the suppression by QGP [15, 16, 17] these include the disintegration of  $J/\psi$  by co-movers [11, 13] and Monte Carlo microscopic models [10]. In order to see why it is possible that rather differ-

ent models lead to a similar overall  $J/\psi$  suppression, it would be interesting to see not only the resulting total  $J/\psi$  suppression but also contributions of individual mechanisms involved in this total suppression. The purpose of the present paper is to propose an alternative way of looking at the data on  $J/\psi$  suppression, and in particular on the onset of anomalous  $J/\psi$  suppression. Our approach is based on the additive decomposition of contributions of different mechanisms responsible for the disintegration of  $J/\psi$ 's produced by a hard process in nuclear collisions. The method can be used provided that the time sequence of contributing mechanisms is known or assumed. In some cases there are good reasons to believe that two mechanisms are at work in the same time period. This would concern, for instance, the nuclear absorption and possible depletion of gluon structure functions [19] during the first part of the nuclear collision. In such a case both mechanisms should be considered as one stage.

In the next section we shall describe the method; in Sect. 3 we shall present a few illustrative examples. In Sect. 4 we shall discuss the relationship of the proposed way of looking at the data with the standard procedure used by the NA50 Collaboration, and comments and conclusions will be presented in Sect. 5.

## 2 Separation of different contributions to $J/\psi$ disintegration

We shall consider here for simplicity the case when only two mechanisms of  $J/\psi$  suppression are present: the nuclear absorption and the dissolution of  $J/\psi$  by QGP, the latter taken from a point of view very close to that of the BO [15] and KLNS [16, 17] models.

We shall use the following notation

$N_{prod}^{J/\psi}(E_T)$  = the total number of  $J/\psi$  produced in collisions at given  $E_T$ ,

$N_{NA}^{J/\psi}(E_T)$  = the number of  $J/\psi$ 's disintegrated by NA,

$N_{QGP}^{J/\psi}(E_T)$  = the number of  $J/\psi$ 's dissolved by QGP,

$N_{exp}^{J/\psi}(E_T)$  = the number of surviving  $J/\psi$ 's, measured in experiment

$N_{other}^{J/\psi}(E_T)$  = the numbers of  $J/\psi$ 's disintegrated by other mechanisms.

The balance between input and output requires

$$N_{prod}^{J/\psi}(E_T) = N_{exp}^{J/\psi}(E_T) + N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T) + N_{other}^{J/\psi}(E_T). \quad (1)$$

We suggest that all terms in Eq. (1) be calculated and plotted separately, or in combinations, for a given A-B collision, for all values of  $E_T$ . In this sense our approach tries to give an answer to the question "Where are all the  $J/\psi$ 's gone?" or corresponds to "an accountant's look at the data on  $J/\psi$  suppression".

Admittedly, the suggestion we are making is rather trivial, but we do hope that looking at the data in this way can make the results of a particular model more transparent and can help to avoid some inconsistencies.

In specific applications Eq.(1) can be rewritten in such a way that more reliably known terms are put on one side, thus providing constraints for the more model-dependent and less reliably known ones. We can for instance put on one side the best known terms  $N_{prod}^{J/\psi}(E_T) - N_{exp}^{J/\psi}(E_T)$  or even  $N_{prod}^{J/\psi}(E_T) - N_{exp}^{J/\psi}(E_T) - N_{NA}^{J/\psi}(E_T)$ , and try to describe or fit these expressions by a particular model. For instance in the latter case by  $N_{QGP}^{J/\psi}(E_T) + N_{other}^{J/\psi}(E_T)$ .

The purpose of the present paper is not to attempt a detailed analysis of the data. We wish just to describe the method and to give a few examples as illustrations. For that purpose we shall take nuclei as homogeneous hard spheres with radii  $R_A = 1.2A^{1/3}\text{fm}$ , we shall neglect the energy fluctuations, including the "knee" in multiplicity distribution at  $E_T \approx 100\text{GeV}$  and we shall assume here a strong correlation between  $b$  and  $E_T$ :

$$E_T(b) = 0.325\text{GeV}N_w(b), \quad (2)$$

where  $N_w(b)$  is the number of interacting ("wounded") nucleons. With these simplifications the quantities entering Eq. (1) can be expressed in the following way:

$$N_{prod}^{J/\psi}(E_T) = \sigma_{nn}^{J/\psi} N_{coll}(E_T), \quad (3)$$

where  $\sigma_{nn}^{J/\psi}$  is the  $J/\psi$  production cross-section in the average nucleon–nucleon collision and  $N_{coll}(E_T)$  is the number of nucleon–nucleon collisions at a given value of  $E_T$ . In a rather simplified case we have

$$N_{coll}(E_T) = \int_0^{R_A} \frac{sd s}{\sigma_{nn}} \int_0^{2\pi} d\theta \rho_A \sigma_{nn} 2L_A(s) \rho_A \sigma_{nn} 2L_B(b, s, \theta) =$$

$$\int_0^{R_A} \frac{s ds}{\sigma_{nn}} \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} \rho_A \sigma_{nn} dz_A \int_{-L_B(s,\theta)}^{L_B(b,s,\theta)} \rho_B \sigma_{nn} dz_B, \quad (4)$$

where

$$L_A(s) = \sqrt{R_A^2 - s^2}, \quad L_B(b, s, \theta) = \sqrt{R_B^2 - b^2 - s^2 + 2bs\cos(\theta)},$$

when the expression under the square-root in  $L_B$  is negative, there is no tube-on-tube collision and the contribution vanishes. Nuclear densities are denoted as  $\rho_A, \rho_B$  (we are working in the approximation of nuclei as hard spheres, therefore  $\rho_A, \rho_B$  are constants),  $b$  is the impact parameter,  $s$  is the distance from the centre of the A-nucleus and  $\theta$  is the angle between  $\vec{b}$  and  $\vec{s}$ . A nuclear collision is taken as the sum of tube-on-tube collisions, with lengths of tubes  $2L_A$  and  $2L_B$ , and  $z_A, z_B$  specifying the coordinate of nucleons within both colliding tubes:  $z_A$  varies from  $-L_A$  to  $L_A$ ,  $z_B$  from  $-L_B$  to  $L_B$ , and both  $z_A$  and  $z_B$  increase in the direction of motion of the tubes in the c.m. frame of the nucleon-nucleon collision. The nucleon-nucleon non-diffractive cross-section  $\sigma_{nn}$  is taken as 30mb. Experimental results on the survival probability  $S(E_T)$  of  $J/\psi$  enter the expression

$$N_{exp}^{J/\psi}(E_T) = S(E_T) N_{prod}^{J/\psi}(E_T). \quad (5)$$

Nuclear absorption of  $J/\psi$  is given by the expression

$$N_{NA}^{J/\psi}(E_T) = \sigma_{nn}^{J/\psi} \int_0^{R_A} \frac{s ds}{\sigma_{nn}} \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} \rho_A \sigma_{nn} dz_A \int_{-L_B(s,\theta)}^{L_B(b,s,\theta)} \rho_B \sigma_{nn} dz_B \\ (1 - e^{-\rho_A \sigma_a [z_A + L_A(s)]} e^{-\rho_B \sigma_a [z_B + L_B(b,s,\theta)]}), \quad (6)$$

where  $\sigma_a$  is the cross-section describing the absorption of  $J/\psi$  by nucleons.

The integral in Eq. (6) can be decomposed into two separate integrals, the former giving the total number of  $J/\psi$ 's produced and the latter being equal to the number of  $J/\psi$ 's that survive the nuclear absorption. The term  $N_{QGP}^{J/\psi}(E_T)$  gives the number of  $J/\psi$ 's destroyed by the QGP; it is given as

$$N_{QGP}^{J/\psi}(E_T) = \sigma_{nn}^{J/\psi} \int_0^{R_A} \frac{s ds}{\sigma_{nn}} \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} \rho_A \sigma_{nn} dz_A \int_{-L_B(s,\theta)}^{L_B(b,s,\theta)} \rho_B \sigma_{nn} dz_B \\ e^{-\rho_A \sigma_a [z_A + L_A(s)]} e^{-\rho_B \sigma_a [z_B + L_B(b,s,\theta)]} \Theta(\kappa - \kappa_{crit}). \quad (7)$$

Following KLNS [16], see also Ref.[20], we have introduced

$$\kappa = \frac{\rho_A \sigma_{nn} 2L_A(s) \cdot \rho_B \sigma_{nn} 2L_B(b, s, \theta)}{\rho_A \sigma_{nn} 2L_A(s) + \rho_B \sigma_{nn} 2L_B(b, s, \theta)}. \quad (8)$$

The parameter  $\kappa_{crit}$  specifies the onset of the QGP formation. This parameter has to be determined by the data in such a way that

$$N_{prod}^{J/\psi}(E_T) = N_{exp}^{J/\psi}(E_T) + N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T), \quad (9)$$

where we have assumed that the contribution  $N_{other}^{J/\psi}$  can be neglected. Equation (9) simply says that out of all  $J/\psi$ 's produced some survived, others were disintegrated by the nuclear absorption and others by QGP.

The multiplicative factor  $\sigma_{nn}^{J/\psi}$  is present in all of the terms in Eq. (9) and in what follows we shall leave it out.

The time ordering of the different processes enters Eq. (7). It is most likely that the QGP is formed after the colliding nuclei have passed through one another and the QGP can thus destroy only those  $J/\psi$ 's that survived the nuclear absorption.

### 3 Illustrative examples

Figures showing the experimental data in the way they were used by NA50 Collaboration [1, 2] are well known. In these figures they plot the survival probability of  $J/\psi$  as

$$S(E_T) = \frac{J/\psi_{measured}}{J/\psi_{produced}}, \quad (10)$$

inferred from direct data on  $J/\psi$  over Drell–Yan pair production. The coefficient  $S(E_T)$  contains in a multiplicative way probabilities that  $J/\psi$  has survived nuclear absorption, QGP dissolution and other possible mechanisms of  $J/\psi$  disintegration. In the way of looking at data proposed here we plot separately the surviving  $J/\psi$ 's (as given by experiment), those disintegrated by nuclear absorption, and those dissolved by the QGP and possibly also by other mechanisms.

In Fig. 1 we plot as an illustration the terms  $N_{prod}^{J/\psi}$ ,  $N_{exp}^{J/\psi}$  (survivors), and  $N_{NA}^{J/\psi}$ , leaving out the common factor  $\sigma_{nn}^{J/\psi}$  in Eqs. (3)–(7). The anomaly is

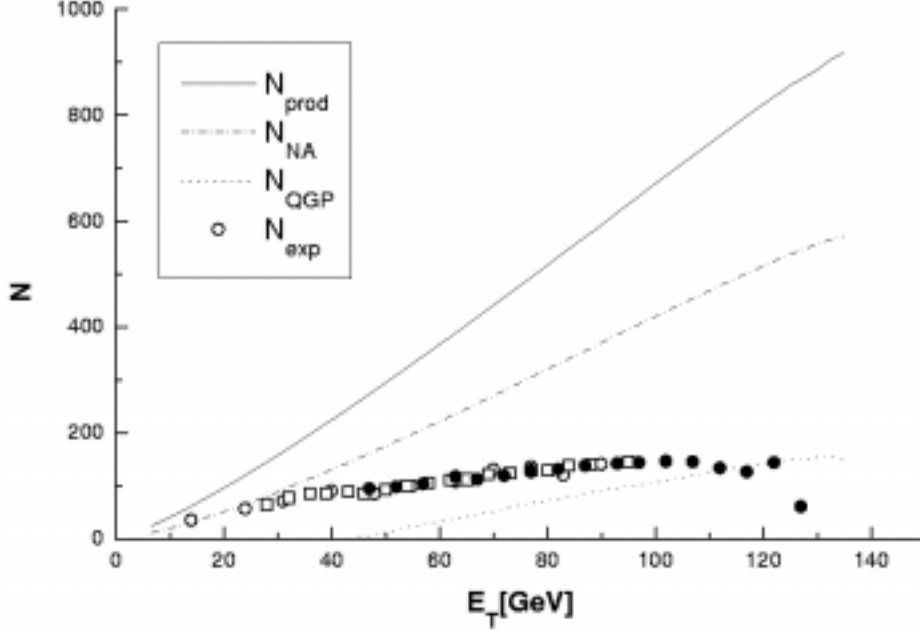


Figure 1: Results on  $N_{prod}^{J/\psi}$  as calculated by Eq.(3) with  $\sigma_{nn} = 3\text{fm}^2$ , the data of NA50 Collaboration [1, 2] used to calculate  $N_{exp}^{J/\psi}$  by Eq. (5) and the  $N_{NA}^{J/\psi}$  calculated by Eq.(6) with  $\sigma_a = 0.7\text{fm}^2$ , and  $N_{QGP}^{J/\psi}$  evaluated by Eq. (7).

not easily visible, since it appears as a rapidly growing difference  $N_{prod}^{J/\psi} - N_{exp}^{J/\psi}$ . In order to make the anomaly visible, we plot in Fig. 2 the expression  $\Delta N = N_{prod}^{J/\psi} - N_{exp}^{J/\psi} - N_{NA}^{J/\psi}$  with a nuclear absorption cross-section  $\sigma_a = 0.7\text{fm}^2$ . The shape of  $\Delta N$  indicates a presence of a  $J/\psi$  dissolving mechanism with threshold between  $E_T = 30\text{GeV}$  and  $E_T = 40\text{GeV}$ . Note that values of  $\Delta N$  are slightly negative for the lowest three  $E_T$  points, which is connected with the fact that in the standard presentation of data calculations based on the NA mechanism are below the lowest  $E_T$  data.

In Fig. 3 we show the opening of the space for other contributions, most

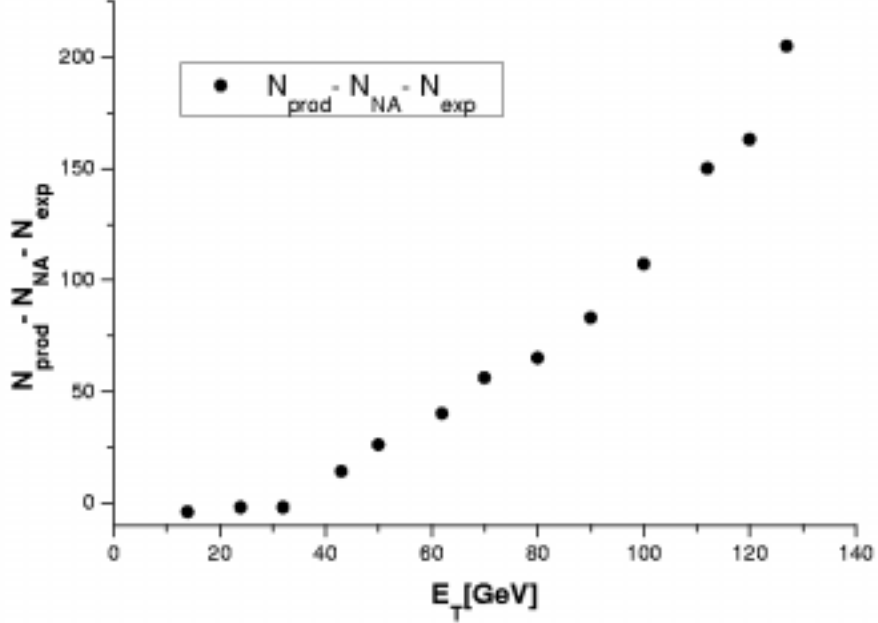


Figure 2: The expression  $\Delta N = N_{prod}^{J/\psi} - N_{exp}^{J/\psi} - N_{NA}^{J/\psi}$  as a function of  $E_T$ . The term  $N_{NA}^{J/\psi}$  has been calculated with  $\sigma_a = 0.7 \text{fm}^2$ .

probably for  $J/\psi$  suppression by a hadron gas, when  $\sigma_a$  in nuclear absorption becomes smaller.

The true consistency check of the phenomenological description of data is provided by Eq. (1) with  $N_{exp}^{J/\psi}$  given by Eq. (5) and  $S(E_T)$  taken from experimental data on  $J/\psi$  survival. In the illustrative case discussed above we have  $N_{other}^{J/\psi} = 0$  and Eq. (1) reduces to

$$N_{prod}^{J/\psi}(E_T) = \Sigma(E_T) \equiv N_{exp}^{J/\psi}(E_T) + N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T). \quad (11)$$

In Fig. 4 we compare  $N_{prod}^{J/\psi}(E_T)$  and  $\Sigma(E_T)$ . The agreement is quite reasonable, in view of simplifying assumptions that we made. Agreement



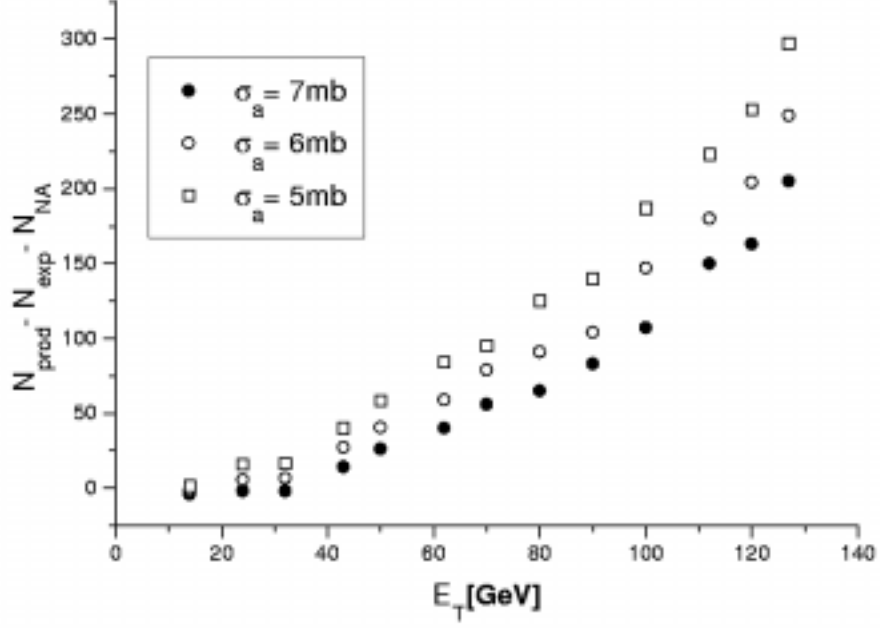


Figure 3: The expression  $\Delta N = N_{prod}^{J/\psi} - N_{exp}^{J/\psi} - N_{NA}^{J/\psi}$  as a function of  $E_T$ . The term  $N_{NA}^{J/\psi}$  has been calculated with  $\sigma_a = 0.7\text{fm}^2$ ,  $\sigma_a = 0.6\text{fm}^2$ , and  $\sigma_a = 0.5\text{fm}^2$ .

with data is worse for the points with the highest values of  $E_T$  where a large part of  $E_T$  is given by fluctuations [13] and our simplified model is not applicable. Note that the agreement visible in Fig. 4 is non-trivial since  $N_{exp}^{J/\psi}(E_T) = S(E_T)N_{prod}^{J/\psi}$  is given by experimental data on  $S(E_T)$ .

The information contained in Fig. 1 and Fig. 4 can be compressed into a single Fig. 5, where we plot  $N_{NA}^{J/\psi}(E_T)$ ;  $N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T)$  and  $N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T) + N_{exp}^{J/\psi}(E_T)$ ; and for comparison with the last expression also  $N_{prod}^{J/\psi}(E_T)$ .

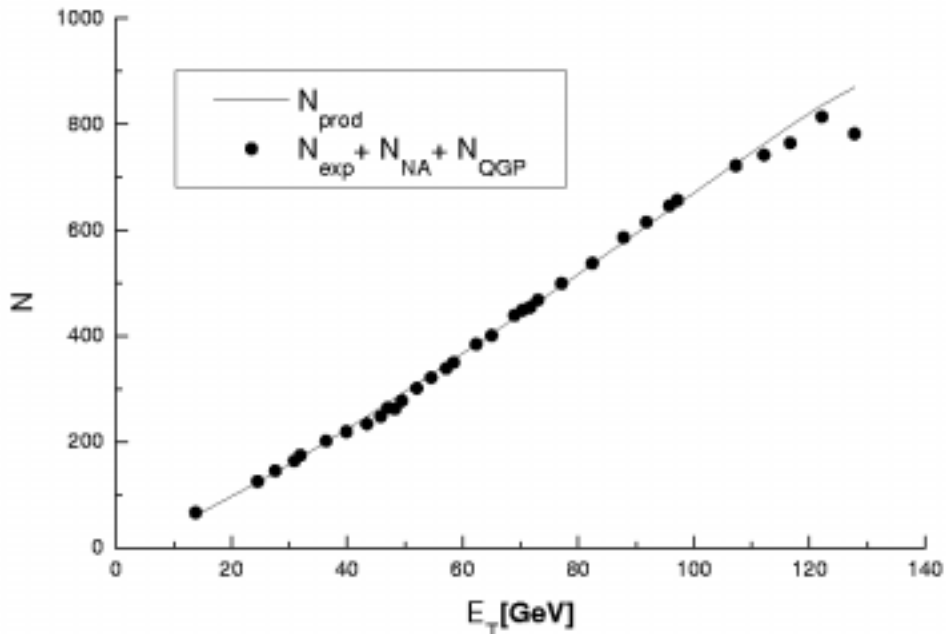


Figure 4: The comparison of  $N_{\text{prod}}^{J/\psi}$  (solid line) and  $\Sigma(E_T)$  (open circles).

## 4 Common points of the new way of looking at data and the standard procedure

We shall first show that the way of plotting experimental data and results of phenomenological calculations is in some aspects equivalent to the standard way introduced and used by the NA50 Collaboration.

To make the argument transparent, suppose that a certain number  $N_0$  of  $J/\psi$ 's is passing successively through three obstacles (media) and can be disintegrated by each of them. The probability that it passes (survives) through the first obstacle is denoted as  $P_1$ . The number of  $J/\psi$ 's passing through is  $N_0 P_1$ , the number of those that fail to pass is  $N_{F1} = N_0(1 - P_1)$ . In the same way the number of  $J/\psi$ 's passing through the second obstacle

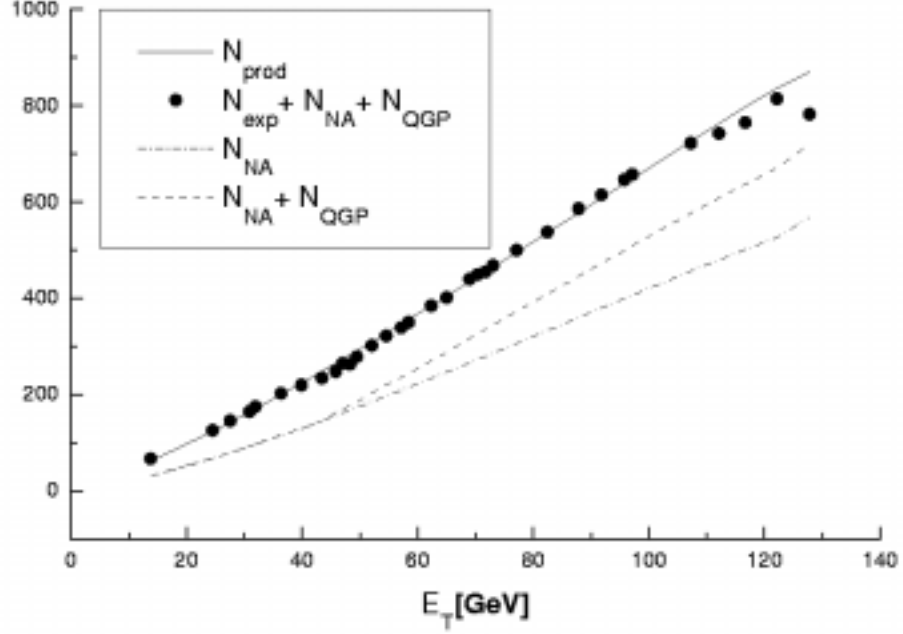


Figure 5: The compressed information from Figs. 1 and 4.  $N_{NA}^{J/\psi}(E_T)$  (dash-dotted line);  $N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T)$  (dashed line);  $N_{NA}^{J/\psi}(E_T) + N_{QGP}^{J/\psi}(E_T) + N_{exp}^{J/\psi}(E_T)$  (open circles) and  $N_{prod}^{J/\psi}(E_T)$  (solid line).

is  $N_0 P_1 P_2$  and the number of those that passed the first obstacle, but failed to pass the second one is  $N_{F2} = N_0 P_1 (1 - P_2)$ . Finally, the number of  $J/\psi$ 's passing through the third obstacle is  $N_0 P_1 P_2 P_3$  and the number of those that failed to pass the third obstacle is  $N_{F3} = N_0 P_1 P_2 (1 - P_3)$ . The obvious identity

$$N_0 = N_0(1 - P_1) + N_0 P_1(1 - P_2) + N_0 P_1 P_2(1 - P_3) + P_1 P_2 P_3 N_0 \quad (12)$$

can be rewritten as

$$N_0 = N_{F1} + N_{F2} + N_{F3} + S N_0. \quad (13)$$

where

$$S = P_1 P_2 P_3 = \frac{N_0 - N_{F1} - N_{F2} - N_{F3}}{N_0} \quad (14)$$

gives the overall survival probability. When comparing the results of the calculations with the data in the usual way the comparison is between experimentally measured values of  $S$  and the probability  $P_1 P_2 P_3$  calculated from phenomenological models. The alternative way used here consists in proceeding according to Eq. (12), plotting individual terms  $N_{F1}, N_{F2}, N_{F3}, S N_0$ , with  $S$  taken from experiment and verifying the validity of Eq.(12).

In a real situation, each  $J/\psi$  is born at a certain value of the parameters  $s, \theta$  (when considering nuclear collisions at a fixed value of  $b$ , and at a certain value of  $b, s, \theta$  when integrating also over  $b$ ). The probability of passing through different media depends on values of these parameters. Equations (11–13) change only a little. Lumping  $s, \theta$ , or  $b, s, \theta$  into a single parameter  $x$  and introducing probabilities  $P_1(x), P_2(x)$  and  $P_3(x)$ , we have in an obvious notation:

$$\begin{aligned} N_0 &= \int n_0(x) dx \\ N_{P1} &= \int n_0(x) P_1(x) dx, & N_{F1} &= \int n_0(x) [1 - P_1(x)] dx \\ N_{P2} &= \int n_0(x) P_1(x) P_2(x) dx, & N_{F2} &= \int n_0(x) P_1(x) [1 - P_2(x)] dx \\ N_{P3} &= \int n_0(x) P_1(x) P_2(x) P_3(x) dx, & N_{F3} &= \int n_0(x) P_1(x) P_2(x) [1 - P_3(x)] dx \end{aligned}$$

and one can write again Eqs. (11)–(13).

When calculating the total  $J/\psi$  suppression via an expression corresponding to Eq. (14), we get:

$$S(E_T) = \frac{N_{prod}^{J/\psi} - N_{GH}^{J/\psi} - N_{QGP}^{J/\psi}}{N_{prod}^{J/\psi}}. \quad (15)$$

Using Eqs. (4)–(6) and the identity  $1 - \Theta(\kappa - \kappa_{crit}) = \Theta(\kappa_{crit} - \kappa)$ , we obtain from Eq. (15) the standard expression valid for  $J/\psi$  suppression by nuclear absorption and by the QGP

$$\begin{aligned} S^{J/\psi}(E_T) &= \int_0^{R_A} \frac{sd s}{\sigma_{nn}} \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} \rho_A \sigma_{nn} dz_A \int_{-L_B(s,\theta)}^{L_B(b,s,\theta)} \rho_B \sigma_{nn} dz_B \\ &e^{-\rho_A \sigma_a [z_A + L_A(s)]} e^{-\rho_B \sigma_a [z_B + L_B(b,s,\theta)]} \Theta(\kappa_{crit} - \kappa). \end{aligned} \quad (16)$$

## 5 Comments and conclusions

We have described here an alternative way of plotting the data and model calculations on  $J/\psi$  suppression and presented a few illustrative examples. A more detailed analysis of  $J/\psi$  suppression along this path would certainly require using more realistic Woods–Saxon nuclear densities, a more realistic relationship between  $b$  and  $E_T$ , detailed analysis of  $J/\psi$  suppression in collisions induced by lighter ions at 200GeV per nucleon and a detailed evaluation of experimental errors. We are of the opinion that such an undertaking, although rather tedious, might help us to understand why models based on rather different assumptions lead to roughly similar results.

For models considering only nuclear absorption and  $J/\psi$  interaction with co-movers, as in Refs. [9, 11, 12, 13] the present scheme requires only minimal modifications. Equation (9) should be rewritten as

$$N_{prod}^{J/\psi}(E_T) = N_{exp}^{J/\psi}(E_T) + N_{NA}^{J/\psi}(E_T) + N_{co}^{J/\psi}(E_T). \quad (17)$$

where the last term corresponds to the number of  $J/\psi$ 's suppressed by the interaction with co-movers (with the gas of secondary hadrons). The term  $N_{prod}^{J/\psi}(E_T)$  is given by Eqs. (3) and (4),  $N_{exp}^{J/\psi}(E_T)$  by Eq.(5),  $N_{NA}^{J/\psi}(E_T)$  by Eq. (6) and  $N_{co}^{J/\psi}(E_T)$  is calculated, in analogy to Eq. (7), as

$$N_{co}^{J/\psi}(E_T) = \sigma_{nn}^{J/\psi} \int_0^{R_A} \frac{s ds}{\sigma_{nn}} \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} \rho_A \sigma_{nn} dz_A \int_{-L_B(s,\theta)}^{L_B(s,\theta)} \rho_B \sigma_{nn} dz_B \\ e^{-\rho_A \sigma_a [z_A + L_A(s)]} e^{-\rho_B \sigma_a [z_B + L_B(s,\theta)]} \left( 1 - \exp\left(- \int d\tau \langle v \sigma_{co} \rho_{co} \rangle \right) \right). \quad (18)$$

In Eq.(18),  $\sigma_{co}$  is the cross-section for the disintegration of  $J/\psi$  by the interaction with co-movers,  $\rho_{co}(\tau)$  is the density of co-movers as a function of the proper time  $\tau$  of  $J/\psi$ . For more details see Refs. [8, 9, 11, 12, 13, 21].

For Monte Carlo microscopic models such as the one in Ref.[10], an analytic recipe for separating different contributions cannot be written down, but the separation is most likely possible as well.

The alternative way of plotting and looking at data might be useful, but it will not resolve the physics problems. The question of whether the QGP is responsible for anomalous  $J/\psi$  suppression observed by the NA50 Collaboration will probably and hopefully be resolved in one of the following ways (or by combination of some of them):

- Accurate determination of  $\sigma_a$  by data on  $J/\psi$  suppression at  $E_{Lab} = 160\text{GeV}$  per nucleon. Using this value of  $\sigma_a$  together with data on  $S(E_T)$  in Pb–Pb interactions might reveal a threshold of "missing contribution", when plotted as in Fig. 2 above.
- Combining data on anomalous  $J/\psi$  suppression with information on other signatures, including the data [23] on transverse momenta of surviving  $J/\psi$ 's and their analyses [24, 25, 26] and possible future data on nucleon number dependence on anomalous  $J/\psi$  suppression. In this respect see e.g. Ref.[20]. The explanation of data on anomalous  $J/\psi$  suppression by QGP will only be generally accepted provided that the explanation will lead to experimentally verified predictions concerning the onset as function of A,B and  $E_T$ .
- Additional information on pre-resonance interaction with nucleons, see e.g. Refs.[7, 17, 27, 28] ("inverse experiment" and antiproton interactions in nuclei).
- Making use of recent results of lattice calculations [29], which are becoming more and more accurate and lead to the critical temperature for the phase transition of about 173MeV. This represents a constraint for models with  $J/\psi$  suppression by a gas of hadrons, since the energy density of the hadron gas higher than  $\epsilon_{QGP}(T_c)$  indicates the transition of the hadron gas into the QGP.

### Acknowledgements

One of the authors (J.P.) is indebted to the CERN Theory Division for the hospitality extended to him. We would like to thank F. Karsch, C.Salgado and B. Tomášik for comments and helpful discussions.

## References

- [1] M. Gonin et al., NA50 Collab., Nucl. Phys. **A610** (1996) 404c; C. Lourenco et al., NA50 Collab., Nucl. Phys. **A610** (1996) 552c
- [2] M. C. Abreu et al., NA50 Collab., Phys. Lett. **B410** (1997) 337
- [3] T. Matsui and H. Satz, Phys. Lett. **B178** (1986) 416
- [4] C. Gerschel and J. Hüfner, Phys.Lett. **B207** (1988) 253; A. Capella, J. A. Casado, C. Pajares, A. V. Ramallo, and J. Tran Thanh Van, Phys.

- Lett. **B206** (1988) 354; A. Capella, C. Merino, J. Tran Thanh Van, C. Pajares, and A. V. Ramallo, Phys. Lett. **B243** (1990) 144
- [5] C. Gerschel and J. Hüfner, Zeit.f. Phys. **C56** (1992) 171
- [6] C. Gerschel and J. Hüfner, Annu. Rev. Nucl. Part. Sci. **49** (1999) 255
- [7] S. J. Brodsky, and A. H. Mueller, Phys. Lett. **B206** (1988) 685
- [8] J. Ftáčnik, P. Lichard, and J. Pišút, Phys. Lett. **B208** (1988) 194, S. Gavin, M. Gyulassy, and A. Jackson, Phys. Lett. **B208** (1988) 257, R. Vogt, M. Prakash, P. Koch, and T. H. Hansen, Phys. Lett. **B208** (1988) 263, J. P. -Blaizot, and J.-Y. Ollitrault, Phys. Rev. **D39** (1989) 232, J. Ftáčnik, P. Lichard, N. Pišútová, and J. Pišút, Zeit. f. Phys. **C42** (1989) 132
- [9] R. Vogt, Phys. Reports, **310** (1999) 197, R. Vogt, and S. Gavin, Nucl. Phys. **B345** (1990) 104
- [10] C. Spieles, R. Vogt, L. Gerland, S. A. Bass, M. Bleicher, and H. Stöcker, Phys. Rev. **C60** (1999) 054901
- [11] N. Armesto, A. Capella, and E. C. Ferreiro, Phys. Rev. **C59** (1999) 315,
- [12] R. Vogt, Phys. Lett. **B430** (1998) 15
- [13] A. Capella, E. G. Ferreiro, and A. B. Kaidalov, Phys. Rev. Lett. **85** (2000) 2080
- [14] D. Kharzeev, and H. Satz, Phys. Lett. **B334** (1994) 155
- [15] J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. Lett. **77** (1996) 1703
- [16] D. Kharzeev, C. Lourenço, M. Nardi, and H. Satz, Zeit. f. Phys. **C74** (1997) 307, D. Kharzeev, Nucl. Phys. **A638** (1998) 219c
- [17] H. Satz, Repts. Progr. Phys. **63** (2000) 1511
- [18] M. C. Abreu et al., NA50 Collab., Phys. Lett. **B447** (2000) 28
- [19] R. C. Hwa, J. Pišút, and N. Pišútová, Phys. Rev. **C56** (1997) 432, Phys. Rev. **C58** (1998) 434
- [20] A. Nogová, N. Pišútová and J. Pišút Phys. Lett. **500** (2001) 59
- [21] R. Vogt, and S. Gavin, Phys. Rev. Lett. **78** (1997) 1006
- [22] D. Kharzeev, Nucl. Phys. **A558** (1993) 331c; K. K. Seth, Nucl. Phys. **A629** (1998) 358c

- [23] M. C. Abreu et al., NA50 Collaboration, Phys. Lett. **B499** (2001) 85
- [24] D. Kharzeev, M. Nardi, and H. Satz, Phys. Lett. **B405** (1997) 14
- [25] J. Hüfner, and P. Zhang, Phys. Lett. **B515** (2001) 115
- [26] P. Zhang, and J. Hüfner, nucl-th/0109037
- [27] D. Kharzeev, H. Satz, Phys. Lett. **B356** (1995) 365
- [28] D. Kharzeev, and H. Satz, Phys. Lett. **B344** (1994) 155; D. Kharzeev, and H. Satz, Zeit. f. Phys, **C60** (1993) 389
- [29] F. Karsch, E. Laermann, and A. Peikert, Nucl. Phys. **B605** (2001) 579