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Absorption and percolation in the production of J/ψ in heavy ion collisions

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Abstract. We present a simple model with string absorption and percolation to describe the J/ψ suppression in heavy ion collisions. The model qualitatively agrees with the NA50 data, and makes precise predictions for RHIC and LHC.

It was recently argued that in multicollision models, when measuring central region distributions like the one of the transverse energy E_{T} or the distributions of the multiplicity n, these are dominated by fluctuations in the number ν of elementary collisions. This effect should occur in nucleus–nucleus interactions and even in hadron–hadron interactions at very high energy and should be fairly model independent [1]. In fact, away from energy conservation and flavour quantum number flow constraints, one expects statistical aspects to become important.

In that general framework, if the total number of events with ν elementary collisions is $N(\nu)$ and $N_C(\nu)$ is the number of events with the rare event C occurring, then [2]

$$N_C(\nu) = \alpha_C \nu N(\nu), \tag{1}$$

where α_C is the probability of event C occurring in an elementary collision. An event is rare if, in good approximation, it only occurs once.

Relation (1) is correct as far as event C is free from absorption [3], or from quark–gluon plasma formation [4]. This is directly seen in the observed linear relation between E_{T} distributions associated to Drell–Yan production, $N_{\mathrm{D.Y.}}(E_{\mathrm{T}})$, and minimum bias E_{T} distributions, $N(E_{\mathrm{T}})$ [2,5].

However, in the case of J/ψ production, the J/ψ formed may be destroyed by subsequent interactions, as it moves through the interacting medium [6], or it may happen that it is not really formed, as a result of quark–gluon plasma Debye screening preventing the $c\bar{c}$ binding.

In the standard multicollision model – the dual parton model [7], for instance – in every elementary collision two coloured strings are originated. These strings constitute the medium that may absorb a created J/ψ (see also [8]). They may also fuse (percolate) and form the quark–gluon plasma, thus inhibiting J/ψ creation.

We shall consider that when ν collisions occur they occupy an interaction volume $V(\nu)$ characterised by a transverse area $A(\nu)$ and a mean longitudinal length $L(\nu)$,

$$V(\nu) \equiv A(\nu)L(\nu). \tag{2}$$

As nuclear matter density is uniform, we expect the string density ρ_{s} defined as

$$\rho_{\mathrm{s}} \equiv \frac{2\nu}{A(\nu)L(\nu)}, \tag{3}$$

where 2ν is the number of formed strings, to be uniform as well. Note that ρ_{s} in (3) is, in general, independent of the interacting nuclei, but may be energy dependent.

In order to take care of J/ψ absorption we introduce the survival probability $P_{\mathrm{s}}(\nu)$ in the conventional form

$$P_{\mathrm{s}}(\nu) = \exp(-L(\nu)\rho_{\mathrm{s}}\sigma), \tag{4}$$

σ being the J/ψ–string ($q\bar{q}$) absorption cross section.

Next, we include the probability of quark–gluon plasma formation in a very simple two-dimensional percolation model [9,10]. In a ν elementary collision event there is a probability $P_{\mathrm{np}}(\nu)$ of percolation not occurring and a probability $1 - P_{\mathrm{np}}(\nu)$ of percolation to occur. As percolation means here quark–gluon plasma formation, we make the strong assumption that the J/ψ is formed only in events in which there is no percolation. This means that in (1) we shall multiply $N_C(\nu)$ by $P_{\mathrm{np}}(\nu)$:

$$N_C(\nu) \longrightarrow N_C(\nu)P_{\mathrm{np}}(\nu). \tag{5}$$

This probability $P_{\mathrm{np}}(\nu)$ is in fact a function of the scaling variable η, the dimensionless density of strings in the transverse plane,

$$\eta \equiv \pi r_{\mathrm{s}}^2 \frac{2\nu}{A(\nu)}, \tag{6}$$

where πr_{s}^2 is the transverse area of a string. Because of (3), we can also write

$$\eta = \pi r_{\mathrm{s}}^2 \rho_{\mathrm{s}} L(\nu). \tag{7}$$

Recently, in [11], the probability P_{np} was studied for S–U and Pb–Pb collisions at $s^{1/2} = 19.4\,\mathrm{AGeV}$. This can be written in the form

$$P_{\mathrm{np}}(\eta) = \frac{1}{\exp\left(\frac{\eta-\eta_{\mathrm{c}}}{a}\right) + 1}, \tag{8}$$

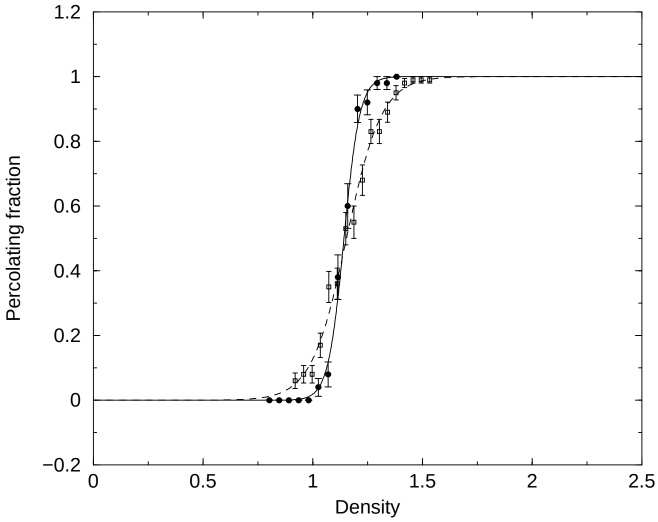

Fig. 1. Percolation probability as a function of the transverse density η for S–U (open squares) and Pb–Pb (filled circles) collisions geometry as obtained from Monte Carlo simulations [11]. The curves show fits with $P_{\mathrm{p}}(\eta) = 1 - P_{\mathrm{np}}(\eta)$, see (8); we obtain $a = 0.07 \pm 0.01$ for S–U (dashed line) and $a = 0.04 \pm 0.01$ for Pb–Pb (solid line); $\eta_{\mathrm{c}} = 1.15 \pm 0.02$

where η_{c} is the critical density, $\eta_{\mathrm{c}} \approx 1.15$ for a uniform distribution of strings in the transverse plane, and a is a parameter which depends only on the geometry of the colliding nuclei (see Fig. 1).

We can now write our final formula for J/ψ production, normalised to Drell–Yan production, $R \equiv (J/\psi)/$(D.Y.), as

$$R(\nu) = K P_{\mathrm{s}}(\nu) P_{\mathrm{np}}(\nu), \tag{9}$$

where K is a normalisation constant, which should be close to 50 based on *pp* collisions [12]. This corresponds to the small ν, small E_{T} limit, with $P_{\mathrm{s}}(\nu) \to 1$, $P_{\mathrm{np}}(\nu) \to 1$. In fact, in this limit, all the models should reproduce *pp* collisions. Note that the validity of (9) requires J/ψ and Drell–Yan production being treated as rare events.

Now we note that, from (4) and (7), R is in fact a function of the mean length L only,

$$R = K \exp(-L\rho_{\mathrm{s}}\sigma) \left[\exp\left(\frac{\pi r_{\mathrm{s}}^2 \rho_{\mathrm{s}} L - \eta_{\mathrm{c}}}{a} \right) + 1 \right]^{-1}. \tag{10}$$

For small values of L, away from percolation, the ratio R in (10) is universal, i.e., does not depend on the colliding nuclei, but it depends, in our approach, on the c.m. energy, through ρ_{s}.

We are naturally aware of the crudeness of our model. On the one hand, saying that percolation necessarily implies J/ψ suppression may be too strong a statement, only valid at very high temperature. On the other hand, the J/ψ may be normally produced in a several stage process, and different kinds of absorption mechanisms may be present (with comovers, for instance), which implies possible additional structures and different absorption cross sections. For a discussion see, for instance, [13]. Equation (10) is certainly oversimplified, but it seems to be able to reproduce the general behaviour of R as a function of L (or E_{T}), in the full range of L (or E_{T}), and it may be useful in estimating the centre of mass energy dependence of R, as a consequence of the energy dependence of ρ_{s}.

Results were presented by the NA50 Collaboration [5] on S–U and Pb–Pb collisions as functions of the average interaction distance L computed in a geometrical model [14,15]. In Fig. 2a we compare (10) with the NA50 data. The string radius was fixed at the value $r_{\mathrm{s}} = 0.2\,\mathrm{fm}$ [10], which places η for S–U somewhat below the percolation threshold, and the parameter a at the Pb–Pb value, 0.04. In Fig. 2a we have included the 1998 data on the ratio R as a function of E_{T}, and transformed to L using the NA50 E_{T} versus L plot [14] in the approximate form (valid for Pb–Pb at 19.4 AGeV)

$$L \approx 2.07 \ln E_{\mathrm{T}}, \tag{11}$$

with E_{T} in units of GeV.

The curve shown in Fig. 2a corresponds to the following values of the parameters in (10): $\rho_{\mathrm{s}} = 0.9\,\mathrm{fm}^{-3}$, $\sigma = 1.5\,\mathrm{mb}$ and $K = 58$. The string density ρ_{s} is, as expected [16], much larger than the nuclear density ($\rho \approx 0.17\,\mathrm{fm}^{-3}$) and the absorption cross section agrees with what is measured in J/ψ–hadron collisions at intermediate energies.

In Fig. 2b we present the ratio R as a function of E_{T} in comparison with data, by making use of (11). The agreement is mostly qualitative.

The essential point is that at small E_{T} the behaviour is typical of absorption – with positive curvature – at higher values of E_{T} the approach to the percolation transition produces a change in the sign of the curvature.

We present in Fig. 3 our predictions for RHIC and LHC energies, compared with the curve for SPS. Figure 3a displays (10) with the expected change in ρ_{s} determined by the change in the number of strings given in [10], and with the other parameters (σ, r_{s}) held constant. In Fig. 3b we transformed the curve from the L variable to E_{T} with the conservative assumption that the proportionality between E_{T} and the number ν of elementary collisions is independent of $s^{1/2}$, i.e., the average E_{T} per collision remains constant. This implies that

$$E_{\mathrm{T}}(L;\sqrt{s}) = \frac{\rho_{\mathrm{s}}(\sqrt{s})}{\rho_{\mathrm{s}}(\sqrt{s_0})} E_{\mathrm{T}}(L;\sqrt{s_0}), \tag{12}$$

and we use (11) for $s_0^{1/2} = 19.4\,\mathrm{GeV}$. We see that, as $s^{1/2}$ grows, absorption gets stronger and the change of curvature, denoting percolation, sets in at a much smaller value of E_{T}.

Finally, we would like to mention that the inclusion of mini-jets (semi-hard physics) may substantially change our results.

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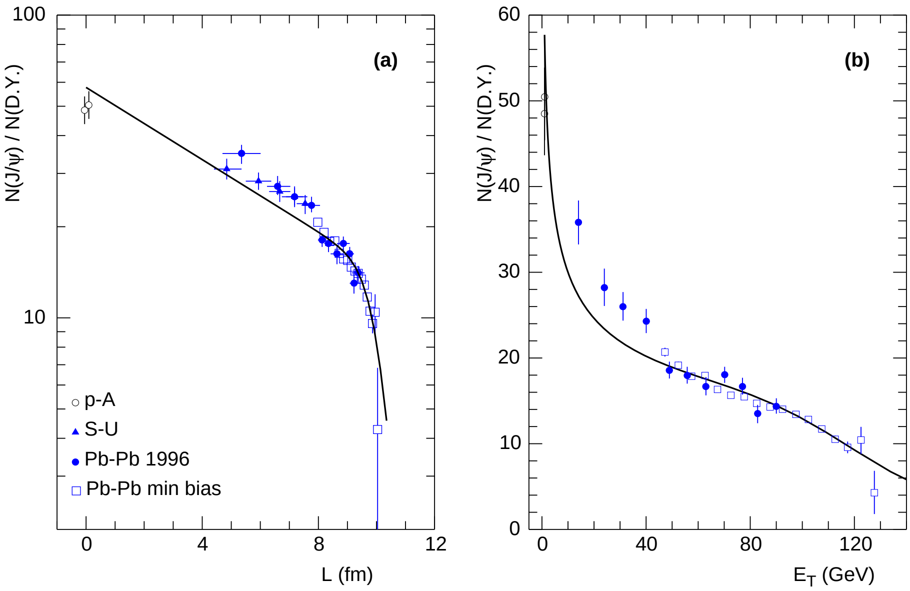

Fig. 2a,b. The ratio of J/ψ to Drell–Yan events as predicted by (9), compared to experimental data as published by NA50 Collaboration [5,17]

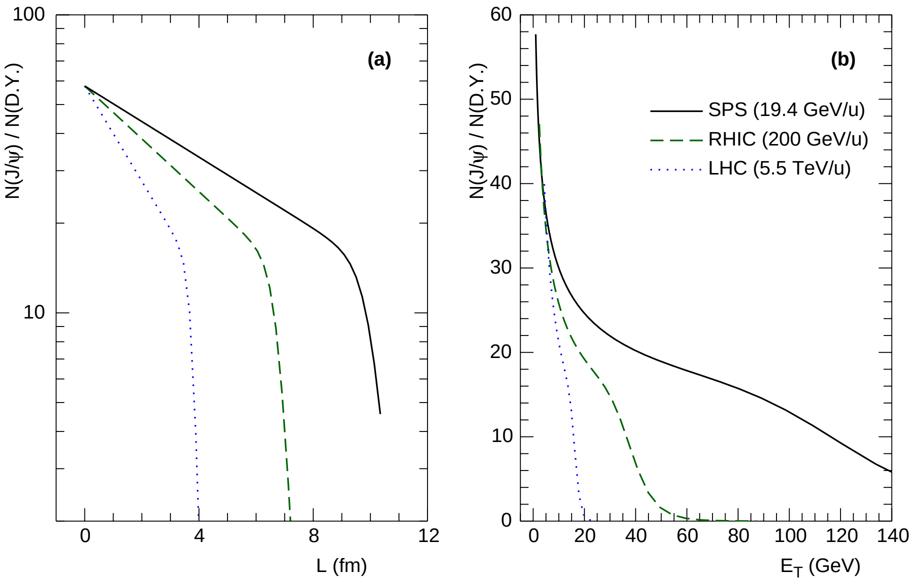

Fig. 3a,b. The ratio of J/ψ to Drell–Yan events as predicted by (9) at RHIC energy (dashed lines) and at LHC energy (dotted lines), compared with SPS energy (solid lines)

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