Charmonium suppression in lead-lead collisions: Is there a break in the J/ψ cross section?

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In the framework of a model based on nuclear absorption plus comover interaction, we compute the E_T distribution of the J/ψ in PbPb collisions at SPS and compare it with available NA50 data. Our analysis suggests that the existence of new physics (deconfinement phase transition) in the region $E_T \lesssim 100$ GeV is unlikely and that signals of new physics should rather be searched in the region $E_T \gtrsim 100$ GeV. The E_T dependence of the J/ψ transverse momentum has been computed. At large E_T it turns out to be much flatter in the comover approach than in a phase transition framework. Estimates of the J/ψ suppression at RHIC and LHC energies are also given. [S0556-2813(99)01001-8]

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I. INTRODUCTION

The 1995 data from the NA50 Collaboration [1] show an anomalous J/ψ suppression, i.e., a suppression larger than the one expected in a nuclear absorption model. This model describes the J/ψ suppression both in proton-nucleus interactions and in nucleus-nucleus interactions with a light projectile [1]. Following the original proposal of Ref. [2], the anomalous J/ψ suppression has been interpreted as a signal of a deconfining phase transition [3–6]. However, an explanation by a more conventional mechanism, namely, the interaction of the J/ψ (or the $c\bar{c}$ pair) with comovers, is also possible [7–10].

A very spectacular feature of the 1996 data by the same collaboration [11], is the presence of a break in the ratio $R(E_T)$ of J/ψ over Drell-Yan (DY) cross sections at $E_T \sim 55$ GeV. It has been argued [12,6] that this break is a signal of deconfinement—although there is no general consensus on this point [13,3–6]. It is, however, fully recognized that a break in the J/ψ cross section would rule out any conventional model, such as the one based on comover interaction. (Other approaches to J/ψ suppression can be found in Ref. [14].)

At present, the evidence for this break is weakened by the presence of fluctuations in the ratio $R(E_T)$ [see Eq. (16) for a precise definition] at large values of E_T [11], which are generally regarded as spurious. Also, it is necessary to assess whether this break, if confirmed, is due to a genuine break in the J/ψ cross section or rather to fluctuations in the J/ψ and DY ones. Of course, a definitive answer to these questions can only come from data. However, in view of the interest of the subject, it is important to examine the available data in a theoretical framework in order to gain some insight on these questions, while waiting for a complete analysis of the 1996 NA50 data, and above all, for the 1998 results.

The aim of the present work is to perform such an analysis in the framework of a model based on nuclear absorption plus comover interaction. This work is a continuation of the one in Ref. [9]. We use the same formalism and the same values of the parameters which were determined in Ref. [9] from the best fit to the ratio $R(E_T)$ in pA, SU, and PbPb collisions. The plan of the paper is the following. In Sec. II we describe the model. In Sec. III we compute the E_T distributions of minimum bias DY and J/ψ and compare them with available data. In Sec. IV we compute the ratio $R(E_T)$ and compare it with the NA50 data. In Sec. V we compute the E_T dependence of the average p_T^2 of the J/ψ and compare it with recent NA50 data. Section VI contains our conclusions and prospects at higher energies.

II. THE MODEL

Our model is formulated in a conventional framework [7–10] based on two different mechanisms of J/ψ suppression: nuclear absorption of the pre-resonant $c\bar{c}$ pair with nucleons of the colliding nuclei and absorption by comoving partons or hadrons produced in the collision. For completeness we recall its main ingredients.

Nuclear absorption. In nucleus-nucleus collisions, the survival probability of the J/ψ at impact parameter b and transverse position s is given by [15,9]

$$S^{\rm abs}(b,s) = \frac{\{1-\exp[-AT_A(s)\sigma_{\rm abs}]\}\{1-\exp[-BT_B(b-s)\sigma_{\rm abs}]\}}{\sigma_{\rm abs}^2 ABT_A(s)T_B(b-s)}. \quad (1)$$

Here $T_{A(B)}(b)=\int_{-\infty}^{+\infty} dz \rho_{A(B)}(b,z)$ are the nuclear profile functions normalized to unity. The nuclear densities $\rho_{A(B)}(b,z)$ are determined from a three-parameter Fermi distribution with parameters given in Ref. [16]. [In Ref. [9] a different parametrization of the nuclear density is used; this introduces differences in $R(E_T)$ of less than 4% in PbPb collisions.] For the absorptive cross section we take $\sigma_{\rm abs}=6.7$–7.3 mb, consistent with a fit to the proton-nucleus data [5]. Note that $S^{\rm abs}=1$ for $\sigma_{\rm abs}=0$.

Absorption by comovers. This absorption is due to the interaction of the $c\bar{c}$ pair (or of the J/ψ itself) in the dense medium produced in a nucleus-nucleus collision—which results in the production of a $D\bar{D}$ pair. The J/ψ survival probability is given by [5,9]

$$S^{\rm co}(b,s)=\exp\left[-\sigma_{\rm co}N_y^{co}(b,s)\ln\left(\frac{N_y^{\rm co}(b,s)}{N_f}\right)\times\theta[N_y^{\rm co}(b,s)-N_f]\right]. \quad (2)$$

Here $N_y^{\rm co}(b,s)$ is the initial density of comovers per unit transverse area d^2s and per unit rapidity at impact parameter b, and N_f is the corresponding freeze-out density. In order to have a smooth onset of the comovers, it is natural to take for N_f the density of hadrons per unit rapidity in a pp collision, i.e., $N_f=[3/(\pi R_p^2)]dN^-/dy|_{y^*=0}=1.15\ \text{fm}^{-2}$. This coincides with the value introduced in Ref. [5]. With this choice of N_f, the θ function in Eq. (2) is numerically irrelevant. The effect of the comovers in pA turns out to be negligibly small. $\sigma_{\rm co}$ is the comover cross section properly averaged over the momenta of the colliding particles (the relative velocity of the latter is included in its definition). The logarithmic factor in Eq. (2) is the result of an integration in the proper time τ from the initial time to freeze-out time. (One assumes [17,18] a decrease of densities with proper time in $1/\tau$.) A large contribution to this integral comes from the few first fm/c after the collision—where the system is in a prehadronic stage. (In this respect, see the last paper of Ref. [10].) Actually, Brodsky and Mueller [19] introduced the comover interaction as a coalescence phenomenon at the partonic level. In view of that, there is no precise connection between $\sigma_{\rm co}$ and the physical $J/\psi-\pi$ or $J/\psi-N$ cross section, and $\sigma_{\rm co}$ has to be considered as a free parameter. We take $\sigma_{\rm co}=0.6$ mb [9].

Cross-sections. The J/ψ production cross section in nuclear collisions is given by

$$\sigma_{AB}^{\psi}(b)=\frac{\sigma_{pp}^{\psi}}{\sigma_{pp}}\int d^2s\, m(b,s)S^{\rm abs}(b,s)S^{\rm co}(b,s), \quad (3)$$

where

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

We take $\sigma_{pp}=30$ mb. With the definition (3), the Drell-Yan cross section [obtained from (3) with $\sigma_{\rm abs}=\sigma_{\rm co}=0$] is proportional to AB.

The cross section for minimum bias (MB) events is given by

$$\sigma_{AB}(b)=1-\exp[-\sigma_{pp}ABT_{AB}(b)], \quad (5)$$

with $T_{AB}(b)=\int d^2sT_A(s)T_B(b-s)$.

In order to compute these cross sections we need to know the comover density $N_y^{\rm co}(b,s)$ in the NA50 dimuon spectrometer. Moreover, comparison with experiment requires to compute the above cross section at a given transverse energy E_T—measured in the NA50 calorimeter. This requires the knowledge of the E_T-b correlation function $P(E_T,b)$. In the following we proceed to calculate these two quantities.

Density of comovers. It is commonly assumed in the literature that the density of comovers is proportional to that of participating (or wounded) nucleons [5,20]. This is the so-called wounded nucleon model (WNM); for a review see Ref. [21]. In asymmetric systems and, in particular, in pA collisions, this model provides a reasonable description of the data but only for the average multiplicity—or at $y^*\sim 0$. At $y^*>0$ ($y^*<0$) it overestimates (underestimates) the multiplicity. For symmetric AA collisions, the model seems to be valid in a broader rapidity range. (This can be understood from the arguments in Ref. [22]; see p. 26.) However, for central PbPb collisions (and also for other central nucleus-nucleus collisions at SPS) there is experimental evidence of a violation of this scaling law at midrapidities [23,24]. Moreover, models such as the dual parton model (DPM) [22], in which unitarity is fully implemented, contain an extra term proportional to the average number of collisions. This term is small at present energies but its relative size increases with energy. Moreover, it contributes mostly at midrapidities. The origin of this term is the following. In DPM one has both baryonic strings of type diquark-quark and bosonic ones of type q-$\bar{q}$. The latter contribute mainly at midrapidities. Since the number of diquarks available is equal to the number of participating nucleons, the number of baryonic strings is equal to the number of participants. On the other hand, the total number of strings is proportional to the number of collisions. Therefore, the number of q-$\bar{q}$ strings increases, with increasing centrality, much faster than the number of participants. The WNM is obtained from DPM by neglecting the contribution of the q-$\bar{q}$ strings.

In the following calculations we will use the density of comovers given by DPM. We will also discuss how the J/ψ suppression is modified when using a density of comovers proportional to the number of participants.

In DPM, $N_y^{\rm co}(b,s)$ is given by [9,22]

$$\begin{aligned}N_y^{\rm co}(b,s)=&[N_1m_A(b,s)+N_2m_B(b,b-s)\\&+N_3m(b,s)]\theta[m_B(b,b-s)-m_A(b,s)]\\&+[N_1'm_A(b,s)+N_2'm_B(b,b-s)\\&+N_3'm(b,s)]\theta[m_A(b,s)-m_B(b,b-s)]. \quad (6)\end{aligned}$$

Here m is given by Eq. (4) and m_A, m_B are the well known geometric factors [25,18]

$$m_{A(B)}(b,s)=A(B)T_{A(B)}(s)\times\{1-\exp[-\sigma_{pp}B(A)T_{B(A)}(b-s)]\}. \quad (7)$$

The coefficients N_i and N_i' are obtained in DPM by convoluting momentum distribution functions and fragmentation functions [22]. Their values (per unit rapidity) for the rapidity window and energies of the NA38 and NA50 experiments are given in Table I of Ref. [9]. The rapidity density of hadrons is given by

$$\frac{dN^{\rm co}}{dy}=\frac{1}{\sigma_{AB}}\int d^2b\int d^2s\, N_y^{\rm co}(b,s), \quad (8)$$

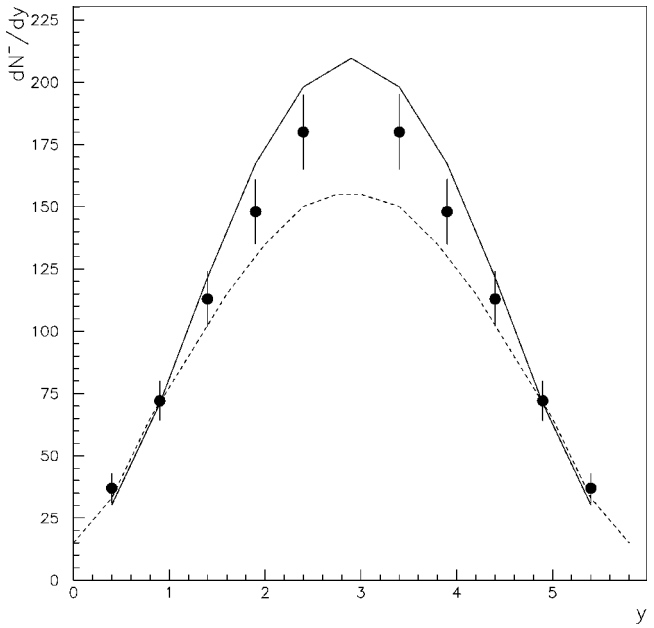

FIG. 1. Rapidity distribution of negative hadrons in central PbPb collisions at 158A GeV/c. Preliminary data of the NA49 Collaboration [23] (black circles) are compared with the DPM results (solid line) using the same centrality criterium, and with the scaling in the number of participants (dashed line [23]).

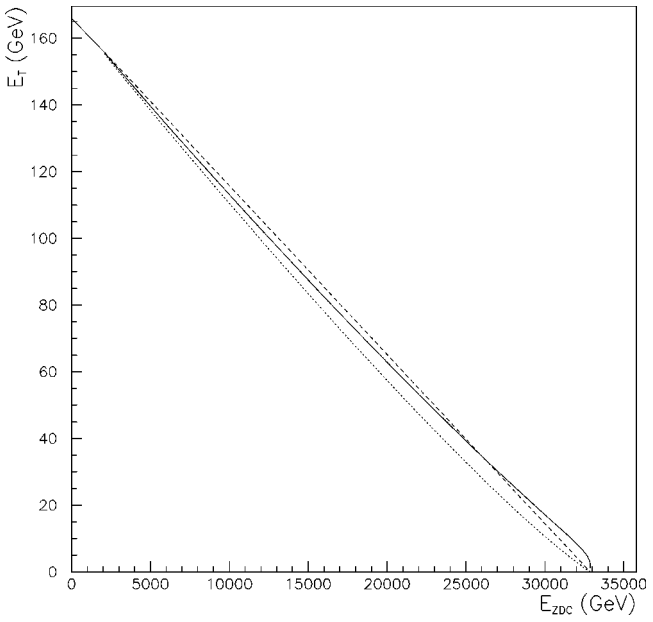

FIG. 2. E_T-E_{ZDC} correlation: the full line is obtained in DPM from Eqs. (11) and (12) and gives a very good description of the NA50 Collaboration data [11]. The dotted line is obtained in DPM from Eqs. (10) and (12). The dashed line is obtained in the WNM with $E_T(b)=0.4[m_A(b)+m_B(b)]$ GeV [5].

with $\sigma_{AB}=\int d^2b\sigma_{AB}(b)$. Note that at fixed b in the range of interest, $\sigma_{AB}(b)\simeq 1$.

The obtained densities of negative hadrons at $y^*=0$ for pp, SS, SAu, and PbPb are compared in Table II of Ref. [9] with available data, using in each case the centrality criteria (in percentage of total events) given by the experimentalists. In Fig. 1 we compare the predictions of both the DPM and the WNM with the NA49 data [23] for the rapidity distribution of negative particles in central PbPb collisions at 158A GeV/c.

E_T-b correlation. The experimental results are given as a function of E_T. This is the total transverse energy of neutrals measured by the NA50 calorimeter in the rapidity window $-1.8<y^*<-0.6$. The correspondence between average values of b and E_T is given by the proportionality between E_T and multiplicity:

$$E_T(b)=qN_y^{\mathrm{co}}(b), \tag{9}$$

where $N_y^{\mathrm{co}}(b)=\int_{-1.8}^{-0.6}dy\int d^2sN_y^{\mathrm{co}}(b,s)$, with $N_y^{\mathrm{co}}(b,s)$ given by Eq. (6). The parameter q is closely connected to the average transverse energy per particle. However, it contains extra factors due to the fact that N_y^{co} corresponds to the multiplicity of negatives whereas E_T is the transverse energy of neutrals. Moreover, a calibration factor of the NA50 calorimeter (which has an estimated systematic error of about 40%) is also included in q.

A precise determination of q comes from the measured correlation between E_T and E_{ZDC}—the energy measured at the zero-degree calorimeter. The latter is defined as

$$E_{\mathrm{ZDC}}(b)=[A-m_A(b)]E_{\mathrm{in}}, \tag{10}$$

where $m_A(b)=\int d^2sm_A(b,s)$, i.e., the average number of participants of A at fixed impact parameter, and AE_{in} is the beam energy ($E_{\mathrm{in}}=158$ GeV/c). A fit to the experimental E_T-E_{ZDC} correlation using Eqs. (9) and (10) allows a precise determination of q. From the NA50 data [11] we obtain $q=0.78$ GeV. It follows from Eqs. (9) and (10) that with the WNM ansatz [5] $E_T(b)=0.4[m_A(b)+m_B(b)]$ GeV, the E_T- E_{ZDC} correlation is a straight line. Experimentally, it is indeed found to be close to a straight line but shows a clear concavity. In DPM this correlation has a concavity due to the contribution of the q-$\bar{q}$ strings. However, in the acceptance region of the NA50 E_T calorimeter, the contribution of the q-$\bar{q}$ strings is rather small (see Fig. 1) and the concavity is also small. Actually, DPM describes well the data in the upper half of the E_T region but falls too fast at low E_T, while the WNM describes the data better in the low E_T region (see Fig. 2). One could think that the difference between the two correlation functions is too small to have any significant effect on the shape of the E_T distributions. It turns out that this is not the case and, therefore, a more accurate description of the E_T-E_{ZDC} correlation is needed.

The failure of the DPM at low E_T can be attributed to the effect of the intranuclear cascade, which is not included in Eq. (6). This well known phenomenon consists in the production of extra particles in the fragmentation regions of the two colliding nuclei due to the rescattering of slow secondaries (in the rest frames of the two nuclei) with spectator nucleons. Obviously this effect has to vanish for central collisions when no spectator nucleons are left. It is also absent at midrapidities. However, the rapidity region of the E_T calorimeter $-1.8<y^*<0.6$ is affected by the intranuclear cascade (which is known to have an extension of about 1.5 rapidity units). In order to incorporate the intranuclear cascade in a phenomenological way, we replace Eq. (9) by

$$E_T(b)=qN_y^{\mathrm{co}}(b)+kE_{\mathrm{ZDC}}(b). \tag{11}$$

With the values of the parameters we use, $q=0.78$ GeV and $k=1/4000$, the relative contribution of the second term in Eq. (11) is comparatively small (about 30% for a very peripheral collision with $E_{\rm ZDC}=30\,000$ GeV and less than 2% for $E_{\rm ZDC}\lesssim 10\,000$ GeV). The only drawback of this extra term is that it does not vanish at $E_{\rm ZDC}=E_{\rm ZDC}^{\rm max}=AE_{\rm in}$. However, this can be easily cured by replacing Eq. (11) by

$$E_T(b)=qN_y^{\rm co}(b)+0.95\left(\frac{E_{\rm ZDC}(b)}{4000}\right)^{1.2}\left(\frac{E_{\rm ZDC}^{\rm max}-E_{\rm ZDC}(b)}{E_{\rm ZDC}^{\rm max}}\right)^{0.2}. \tag{12}$$

The corresponding E_T-$E_{\rm ZDC}$ correlation, shown in Fig. 2 (full line), is practically identical to the one obtained from Eq. (11) for $E_T<30\,000$ GeV and gives an excellent description of the experimental data [11]. Moreover, both correlations lead to the same E_T distributions for J/ψ and DY in the region $E_T\gtrsim 15$ GeV, where data are available. Eq. (12) will be used in all DPM calculations.

In order to obtain the E_T-b correlation, and not only the relation between the average values of these two quantities, we have to determine the E_T distributions at a given b. A good description of the experimental E_T distributions is obtained [20,5,26] using a Gaussian distribution at fixed impact parameter, with squared dispersion $D^2(b)\equiv\langle[N_y^{\rm co}(b)]^2\rangle-\langle N_y^{\rm co}(b)\rangle^2=a\langle N_y^{\rm co}(b)\rangle$, i.e.,

$$P(E_T,b)=\frac{1}{\sqrt{2\pi q^2 a\overline{N}_y(b)}}\exp\left[-\frac{[E_T-q\overline{N}_y(b)]^2}{2q^2a\overline{N}_y(b)}\right], \tag{13}$$

where $\overline{N}_y(b)=E_T(b)/q$, with $E_T(b)$ given by Eq. (12), and a is a free parameter (see Sec. III).

III. E_T DISTRIBUTIONS

The E_T distributions of J/ψ, DY, and minimum bias (MB) are obtained by folding the corresponding cross sections at fixed b [Eqs. (3) and (5)] with the E_T-b correlation function

$$\frac{d\sigma^{\psi}}{dE_T}=\int d^2b\,\sigma_{AB}^{\psi}(b)P(E_T,b), \tag{14}$$

$$\frac{d\sigma^{MB}}{dE_T}=\int d^2b\,\sigma_{AB}(b)P(E_T,b). \tag{15}$$

The corresponding expression for DY is obtained from (14) with $\sigma_{\rm abs}=\sigma_{\rm co}=0$.

The most precise determination of the parameter a is obtained from a fit of (the tail of) the MB E_T distribution. Using the 1995 data of Ref. [26] we obtain $a=0.73$. This value will be used in all DPM calculations. With the WNM we use the parameters in Ref. [26]: $q=0.4$ GeV and $a=1.43$. Note that the product aq is the same in both cases. (It turns out that the ratio of J/ψ over DY is very insensitive to the value of a.)

The comparison of $d\sigma^{DY}/dE_T$ with the 1995 data [26] is shown in Fig. 3. The agreement is satisfactory but the error bars are quite large. Also shown is the distribution obtained using the WNM. This distribution has a stronger increase with increasing E_T —but both are consistent with the data within errors.

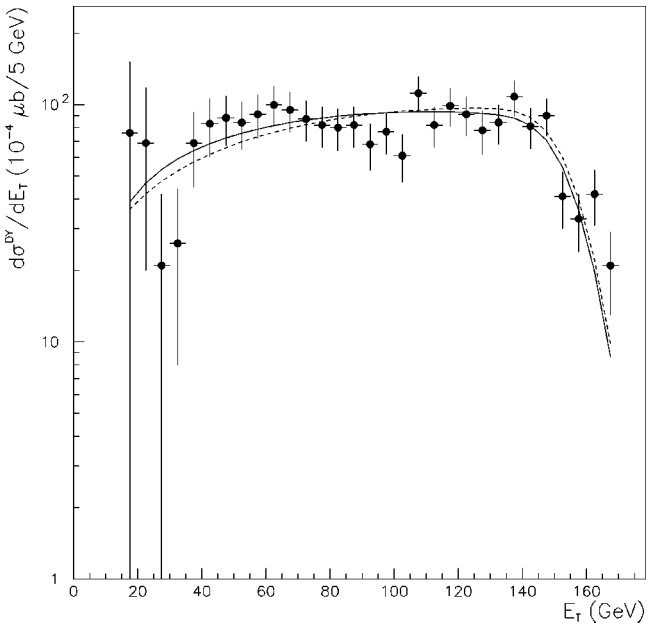

FIG. 3. Inclusive cross section $d\sigma^{DY}/dE_T$ for DY pair production with $M_{\mu\mu}>4.2$ GeV/c^2 from the 1995 NA50 data [26] compared to the results obtained from Eq. (14) with $\sigma_{\rm abs}=\sigma_{\rm co}=0$. The full curve is obtained in DPM and the dashed one in the WNM. The normalization constant $\sigma_{pp}^{DY}/\sigma_{pp}$ in Eq. (3) is 9×10^{-10}. Note that, in order to compare with the experimental value of $\sigma_{pp}^{DY}/\sigma_{pp}$, this normalization factor should be divided by 5 due to the E_T binning in Fig. 3.

The comparison with the 1996 E_T distribution is shown in Fig. 4. Again the (statistical) error bars are quite large. More-

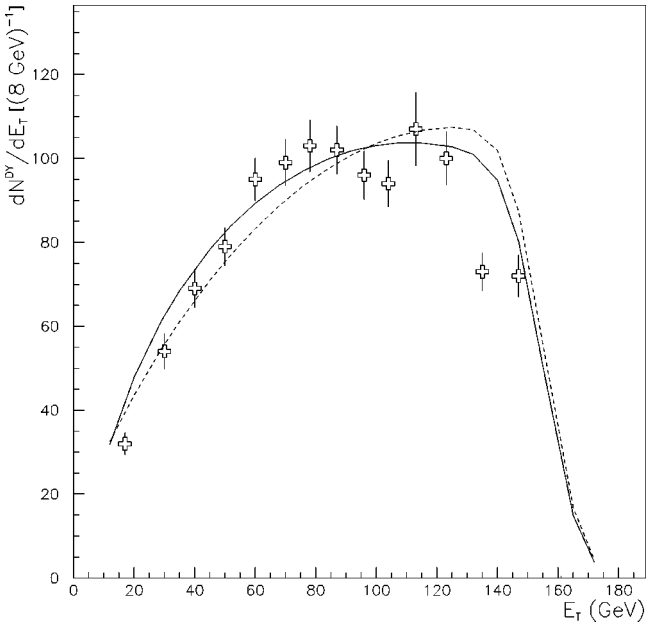

FIG. 4. Preliminary E_T distribution dN^{DY}/dE_T for DY pair production with $M_{\mu\mu}>4.2$ GeV/c^2 for the 1996 NA50 data [11] compared to the theoretical curves of Fig. 3 normalized to the data. The common normalization factor is 0.10 fm^{-2}.

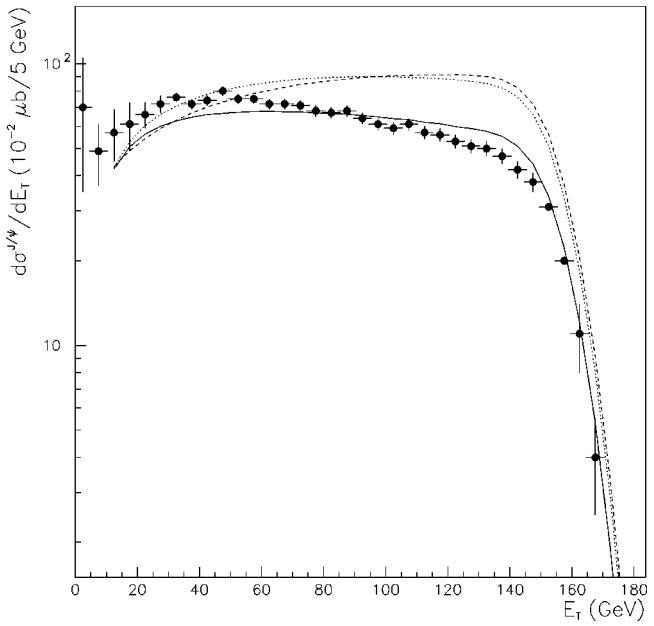

FIG. 5. Inclusive cross section $d\sigma^{J/\psi}/dE_T$ for J/ψ production from the 1995 NA50 data [26] compared with the results obtained from Eq. (14). The normalization constant $B_{\mu\mu}\sigma_{pp}^{J/\psi}/\sigma_{pp}$ in Eq. (3) is 2.4×10^{-7}. The dotted line is obtained with nuclear absorption alone ($\sigma_{\rm abs}=7.3$ mb, $\sigma_{\rm co}=0$), while the solid line contains the effect of comovers with $\sigma_{\rm abs}=6.7$ mb and $\sigma_{\rm co}=0.6$ mb. The dashed line is obtained in the WNM with nuclear absorption alone ($\sigma_{\rm abs}=7.3$ mb, $\sigma_{\rm co}=0$).

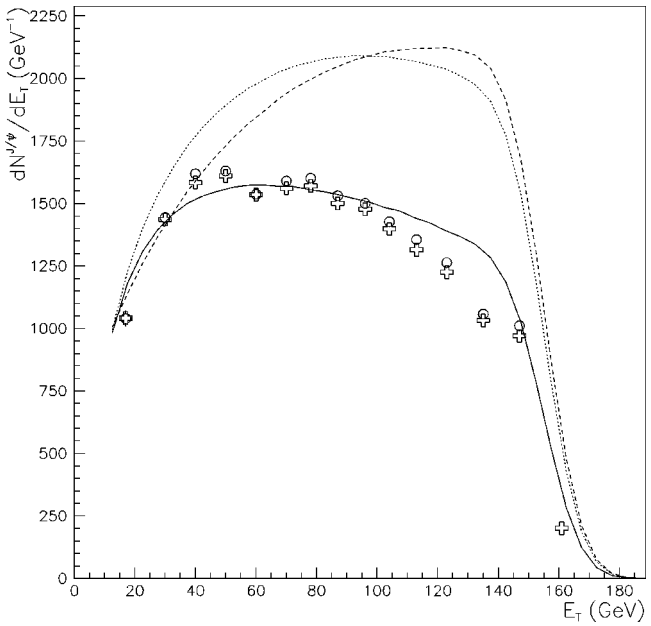

FIG. 6. Preliminary E_T distribution $dN^{J/\psi}/dE_T$ for J/ψ production from the 1996 NA50 data [11], compared with the theoretical curves of Fig. 5 normalized to the data. The common normalization factor is 5.57 fm^{-2}. The circles and the crosses correspond to two different experimental methods [11]: fitting and counting procedures.

over, there is a significant disagreement both with DPM and WNM at $E_T\sim135$ GeV which was not present when comparing with the 1995 data. There is also a significant difference in shape between DPM and WNM. Note that the only ingredients in the calculation are the b dependence of the DY,$ABT_{AB}(b)$, which is common to all models, plus the E_T-b or E_T-$E_{\rm ZDC}$ correlation. Thus all models which reproduce the latter correlation should lead to the same DY distribution. Since the DPM [with Eqs. (10) and (12)] gives an excellent description of the latter, the full curve in Fig. 4 should be regarded as the theoretical DY distribution—which can be used as a reference when considering the J/ψ one. Any significant discrepancy with this distribution, such as the one occurring at large E_T, should be regarded as a possible experimental inconsistency between the measured DY E_T distribution and the E_T-$E_{\rm ZDC}$ correlation.

We turn next to the E_T distribution of the J/ψ. We have computed it using $\sigma_{\rm abs}=6.7$ mb, $\sigma_{\rm co}=0.6$ mb. The result of our calculation is compared with the 1995 data [26] of the NA50 Collaboration in Fig. 5. The agreement between theory and experiment is reasonable. However, the data seem to decrease slightly faster than the theoretical curve. Note that these data show no break in the J/ψ cross section at any value of E_T. Figure 5 shows also the E_T distribution obtained with nuclear absorption alone ($\sigma_{\rm abs}=7.3$ mb) both for DPM [Eq. (11)] and for the WNM. We see that the shape of the E_T distribution is very sensitive to the effect of the comovers. Thus, a slightly steeper decrease of the J/ψ cross section, if confirmed, could possibly be obtained with a small increase in the absorption parameters. (The constraint on these parameters coming from the SU data is now significantly smaller due to an increase by a factor 2.8 of the statistical errors; see Sec. VI.) Note also that, with nuclear absorption alone, the WNM has a faster increase with E_T than the DPM. Therefore the extra J/ψ suppression required in order to reproduce a given shape of the J/ψ distribution, must be considerably stronger in the WNM than in DPM. This is even more clearly seen in Fig. 6 where we compare the theoretical predictions with the J/ψ E_T distribution from the 1996 data in a linear scale. In this comparison we observe some deviations at $E_T\gtrsim100$ GeV. This region should be studied with great care in the 1998 high statistics run. In our opinion, this is a most interesting region to look for eventual signs of new physics, i.e., for the onset of a truly anomalous suppression at $E_T\gtrsim100$ GeV. On the contrary, in the region $E_T<100$ GeV [where the break in the ratio $R(E_T)$ occurs], there is no strong disagreement between theory and experiment. However, there is no perfect agreement either and, therefore, it is not possible to draw a clear conclusion at present. In particular a sudden drop of the J/ψ cross section at $E_T\simeq55$ GeV has been claimed [11]. Even if further data show that this drop is statistically significant, our analysis suggests that it cannot be easily attributed to a sudden increase of J/ψ suppression due to deconfinement. Indeed, in the next four E_T bins the measured J/ψ cross section is consistent with the predictions of a model which does not have deconfinement.

IV. J/ψ OVER DY RATIO

The J/ψ suppression is described by the ratio $R(E_T)$ of J/ψ and DY cross sections in different E_T bins. The advantage of taking this ratio is that systematic errors common to

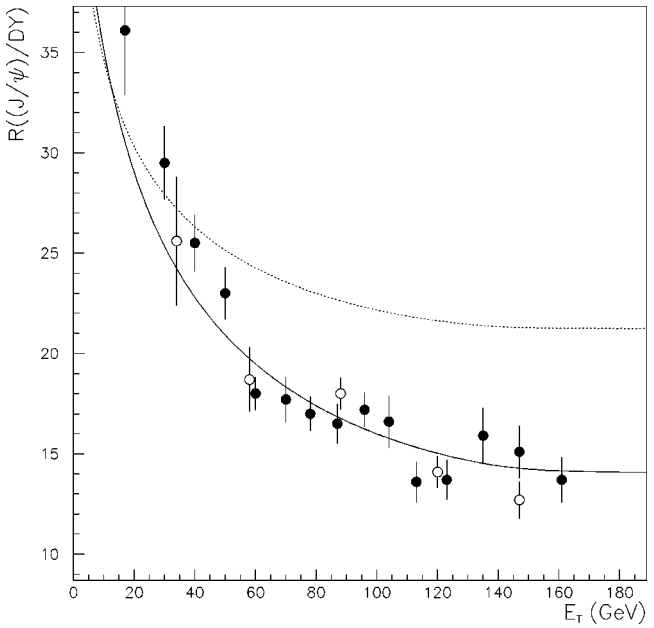

FIG. 7. The ratio $R(E_T)$ of J/ψ over DY versus E_T both from the 1995 [1] (open symbols) and preliminary 1996 [11] (black symbols) NA50 data compared to the ratio of theoretical curves (solid lines) in Figs. 4 and 6 (with comovers, solid line). The dotted line is obtained in DPM with nuclear absorption alone ($\sigma_{\rm abs}=7.3$ mb, $\sigma_{\rm co}=0$). The normalization factor (61.2) is the one obtained in Ref. [9] from a fit to the pA, SU, and PbPb data. This normalization coincides with the one obtained from the normalizations of the individual E_T distributions in Figs. 4 and 6 after correcting the latter for the different E_T binnings, the experimental acceptances and the different DY mass range—which is $2.9<M<4.5$ GeV/c^2 in the ratio $R(E_T)$ and $M>4.2$ GeV/c^2 in Fig. 4.

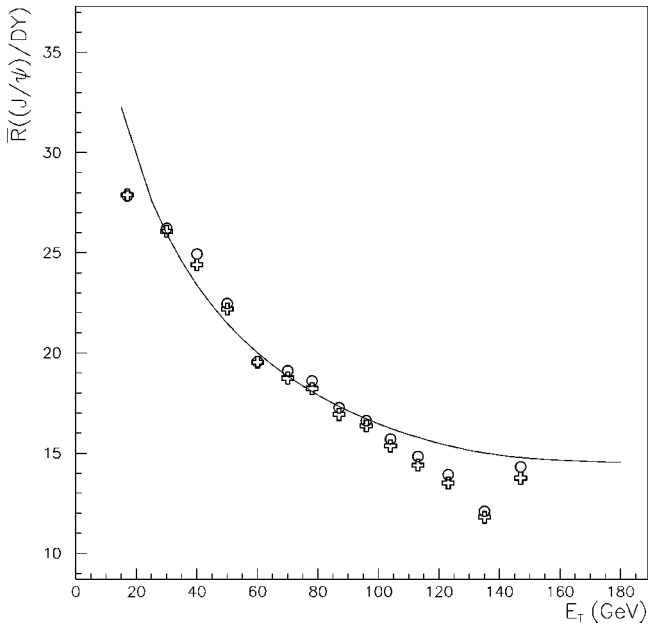

FIG. 8. The theoretical curve of Fig. 7 (solid line) is compared to the ratio $\overline{R}(E_T)$ of the experimental E_T distribution of Fig. 6 over the theoretical DY distribution of Fig. 4 (solid line). Here the normalization of $\overline{R}(E_T)$ is arbitrary since we are only interested in the change in the shape of $R(E_T)$ when smoothing the DY E_T distribution.

both systems do not appear in this ratio. The inconvenience, however, is that the results are sensitive to the shape of the DY E_T distribution. In our opinion, it is of utmost importance to have good data on the E_T distribution of the J/ψ—as illustrated by the analysis of the previous section. The ratio $R(E_T)$ is given by

$$R(E_T)=\frac{\int d^2b\,\sigma_{AB}^{\psi}(b)P(E_T,b)}{\int d^2b\,\sigma_{AB}^{DY}P(E_T,b)}. \tag{16}$$

This ratio has been calculated, within the present model, in Ref. [9], where the values of the parameters [the same ones used here, including the absolute normalization but excepting the value of a which, as discussed in the previous section, has practically no effect on $R(E_T)$] were determined from the best fit to $R(E_T)$ in pA,SU, and PbPb collisions. At that time, however, the 1996 data were not available. The comparison of the model results with both the 1995 and 1996 data [11] is shown in Fig. 7.

The model reproduces the qualitative behavior of the ratio R. However, there are disagreements at a quantitative level. The overall suppression, both from the 1995 and the 1996 data, is somewhat larger than the theoretical one. More important, the 1996 data seem to show a break at $E_T\sim 55$ GeV which is not present in the model calculation. Here, several comments are in order. First, as seen in Fig. 7, the experimental data for the first E_T bin is higher than the one obtained with nuclear absorption alone (with a normalization extracted from a fit to pA and SU data [1,9]). This is difficult to explain in any model. Second, the relevance of the break at $E_T\sim 55$ GeV is weakened by the existence of fluctuations in $R(E_T)$ at large E_T of a comparable size. These fluctuations, which are generally regarded as spurious, are an example of systematic errors that do not cancel when taking the ratio of J/ψ and DY cross sections and have to be understood. Third, the failure of the model to describe quantitatively the ratio $R(E_T)$ in the region $E_T\lesssim 100$ GeV is in sharp contrast with the conclusions reached in Sec. III from a direct comparison of the model results with the E_T distribution of the J/ψ which showed reasonable agreement in this E_T region. In order to understand the origin of this contradiction we have plotted in Fig. 8 the theoretical curve of Fig. 7 (full curve), and compared it with the J/ψ suppression obtained from the ratio $\overline{R}(E_T)$ of the experimental E_T distribution of the J/ψ (for the 1996 NA50 data) over the theoretical one for the DY (full curve of Fig. 5). We see that the agreement in shape between theory and experiment has considerably improved in the region $E_T<100$ GeV—except for the first E_T bin. Moreover, in the ratio $\overline{R}(E_T)$ the break at $E_T\sim 55$ GeV has practically disappeared. Figure 8 indicates that the ratio $R(E_T)$ is very sensitive to the shape of the DY distribution. We would like to stress that Fig. 8 contains no new information. However, it is useful since its comparison with Fig. 7 shows the effect on the ratio $R(E_T)$ of smoothing out the DY cross section. Again, the interest of a careful study of the large E_T region is seen in Fig. 8.

Before concluding this section we would like to comment on the modifications in the ratio $R(E_T)$ when using the comover density computed in the WNM, rather than the one

based on DPM, Eq. (9). As discussed in Sec. II, the WNM underestimates the number of negative particles in a central PbPb collision at $y^* \sim 0$ by 15–30 %. The corresponding DPM value is 30% larger than the WNM one and in better agreement with the NA49 data (see Sec. II). If we would decrease the density of comovers by 30% for the most central E_T bin, the value of $R(E_T)$ would decrease by about 10%. Actually, the net effect would be significantly smaller, since the WNM multiplicity is smaller than the DPM one also in SU, and this can be compensated by a corresponding increase of $\sigma_{\rm co}$. Although a difference would remain, it would not basically change the conclusions of the present analysis. On the contrary, our results would be changed if we were to use the WNM in the calorimeter rapidity region, in order to determine the E_T-$E_{\rm ZDC}$ correlation. In this case we would obtain an E_T distribution for the J/ψ which would be too large in the upper half of the E_T interval.

V. TRANSVERSE MOMENTUM BROADENING

A mechanism producing an increase of the $\langle p_T \rangle$ of any type of particle produced in pA or AB collisions with increasing nuclear sizes or centrality has been known for a long time [27,28]. It is due to initial state rescattering. More precisely, for J/ψ production this increase is due to rescattering of the projectile and target gluons, before fusion, with target and projectile nucleons, respectively, encountered in their path through the nuclei. The average broadening of the intrinsic gluon distribution in each collision is denoted by δ_0. In Ref. [28] it has been shown that the p_T broadening of the J/ψ is affected by J/ψ absorption. In particular the suppression in PbPb collisions in a deconfining approach [5], produces a maximum in the E_T dependence of $\langle p_T^2 \rangle_{J/\psi}$ at $E_T \sim 100$ GeV followed by a decrease with increasing E_T. This peculiar behavior has been considered as a signature of quark-gluon plasma formation.

In this section, we follow the formalism of p_T broadening of the J/ψ in Ref. [28], but using absorption by comovers instead of the one due to deconfinement.

The broadening of p_T is given by

$$\delta_{AB}(b) \equiv \langle p_T^2 \rangle_{AB}(b) - \langle p_T^2 \rangle_{pp} = N_{AB}(b)\,\delta_0 . \tag{17}$$

N_{AB} is the average number of collisions of the projectile and target gluons with target and projectile nucleons, respectively, up to the formation point of the $c\bar{c}$ pair, at fixed b. This point is specified by the impact parameter b and the positions (s,z) and $(b-s,z')$ in the two nuclei. One has

$$N_{AB}(b,s,z,z') = \sigma_{gN} A \int_{-\infty}^{z} dz_A \rho_A(s,z_A) + \sigma_{gN} B \int_{-\infty}^{z'} dz_B \rho_B(b-s,z_B). \tag{18}$$

Here σ_{gN} is the gluon-nucleon cross section. This expression (18) has to be averaged over all positions of the $c\bar{c}$ formation point with a weight given by the product of nuclear densities and survival probabilities:

$$W(b,s,z,z') = \rho_A(s,z)\rho_B(b-s,z') S_A(s,z) \times S_B(b-s,z') S^{\rm co}(b,s), \tag{19}$$

where

$$S_A(b,z) = \exp\left(-A\sigma_{\rm abs} \int_z^{\infty} d\tilde{z}\, \rho_A(b,\tilde{z}) \right) \tag{20}$$

is the survival probability due to nuclear absorption [15] and $S^{\rm co}(b,s)$ is the survival probability due to interaction with comovers, Eq. (2). The latter does not depend on the $c\bar{c}$ formation point.

We obtain in this way

$$N_{AB}(b) = \frac{\int d^2s \int_{-\infty}^{+\infty} dz \int_{-\infty}^{+\infty} dz'\, W(b,s,z,z') N_{AB}(b,s,z,z')}{\int d^2s \int_{-\infty}^{+\infty} dz \int_{-\infty}^{+\infty} dz'\, W(b,s,z,z')} . \tag{21}$$

This expression can be written after some transformations as

$$N_{AB}(b) = \sigma_{gN} \frac{\int d^2s\, S^{\rm co}(b,s)[N_A(s) D_B(b-s) + N_B(b-s) D_A(s)]}{\int d^2s\, S^{\rm co}(b,s) D_A(s) D_B(b-s)}, \tag{22}$$

where

$$D_A(s) = \frac{1}{A\sigma_{\rm abs}} \{1 - \exp[-A\sigma_{\rm abs} T_A(s)]\} \tag{23}$$

and

$$N_A(s) = \frac{1}{A\sigma_{\rm abs}^2} \{\sigma_{\rm abs} A T_A(s) - 1 + \exp[-A\sigma_{\rm abs} T_A(s)]\}, \tag{24}$$

$D_B = D_A(A \to B)$ and $N_B = N_A(A \to B)$.

Finally, the corresponding quantity at fixed transverse energy can be obtained as

$$N_{AB}(E_T)=\frac{\int d^2b\,P(E_T,b)\sigma_{AB}(b)N_{AB}(b)}{\int d^2b\,P(E_T,b)\sigma_{AB}(b)}, \qquad (25)$$

where $P(E_T,b)$ is the E_T-b correlation function, Eq. (13), and $\sigma_{AB}(b)$ is given by Eq. (5).

The values of $\langle p_T^2\rangle_{pp}$ and $\sigma_{gN}\delta_0$ at 158A GeV/c are obtained from a fit to the NA50 data [11]. One obtains $\langle p_T^2\rangle_{pp}=1.03$–$1.10(\mathrm{GeV}/c)^2$ and $\sigma_{gN}\delta_0=0.39$–$0.47 \simeq 10.0$–$12.1(\mathrm{GeV\ fm})^2$ (depending on whether the effect of comovers is included or not). The value of $\sigma_{gN}\delta_0=0.39$ we obtain for nuclear absorption with $\sigma_{\mathrm{abs}}=7.3$ mb and no comovers, agrees with that obtained in Ref. [28], 9.4 ± 0.7 $(\mathrm{GeV\ fm})^2$, from a fit to pA and SU data [29,30]. As suggested in Ref. [31], we should take different values of $\langle p_T^2\rangle_{pp}$ in SU and PbPb, since this value increases with energy. Using the values measured [32] in $\pi^- p$ collisions at 150 and 200 GeV/c, the value $\langle p_T^2\rangle_{pp}=1.07$ $(\mathrm{GeV}/c)^2$ would correspond to $\langle p_T^2\rangle_{pp}=1.23(\mathrm{GeV}/c)^2$ at 200 GeV/c. This last value coincides with the one measured in Ref. [32], $1.23\pm 0.05(\mathrm{GeV}/c)^2$, in pp collisions at 200 GeV/c. (From a fit to DY data in pA,OCu,OU, and SU [29], a value of $\sigma_{gN}\delta_0=0.13$ is obtained, whose ratio over the values for J/ψ is ~ 0.33, smaller than the value $4/9\simeq 0.44$ suggested [27] by the difference of coupling between gluons and quarks or gluons.)

Our results for nuclear absorption plus comovers with $\sigma_{\mathrm{abs}}=6.7$ mb and $\sigma_{\mathrm{co}}=0.6$ mb (nuclear absorption alone with $\sigma_{\mathrm{abs}}=7.3$ mb), for SU with $\langle p_T^2\rangle_{pp}=1.23$ $(\mathrm{GeV}/c)^2$ and $\sigma_{gN}\delta_0=0.42$ (0.40), and for PbPb collisions with $\langle p_T^2\rangle_{pp}=1.10$ $(\mathrm{GeV}/c)^2$ (in agreement with the mentioned rescaling between 200 and 158 A GeV/c) and the same $\sigma_{gN}\delta_0$ as in SU, are shown in Fig. 9 and compared with experimental data [11,33]. We see that, in PbPb collisions with comovers, there is a small maximum at $E_T\sim 125$ GeV. However, after this maximum, $\langle p_T^2\rangle_{AB}$ is practically constant and only slightly smaller than the one obtained with nuclear absorption alone. This is in contrast with the sharper decrease at large E_T found in a deconfining scenario [28]. The physical origin of this decrease is the same in both approaches. At large E_T, corresponding to large comover or energy density, the J/ψ, with large $\langle p_T^2\rangle$ due to a large number of initial gN collisions, is suppressed by either the comover or the deconfining mechanisms. However, this effect turns out to be numerically much smaller in the former approach. Unfortunately, with the present data it is not possible to clearly discriminate between these two predictions.

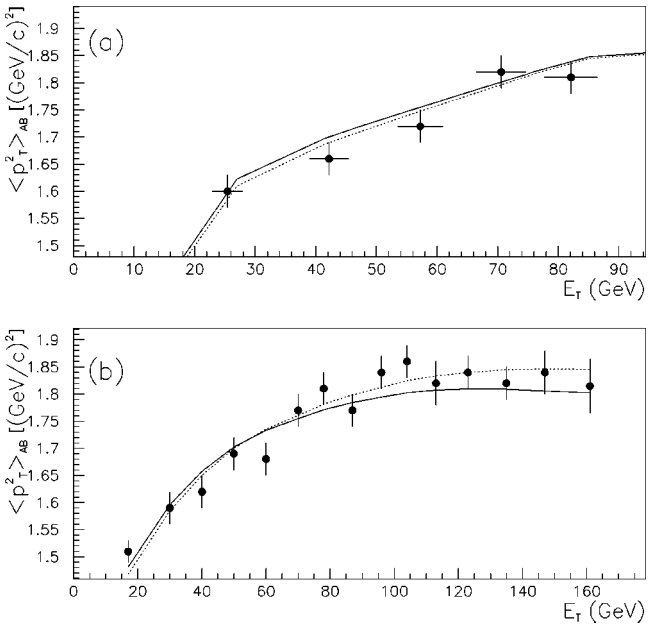

FIG. 9. $\langle p_T^2\rangle_{AB}$ in (a) SU and (b) PbPb collisions at SPS. Solid line: nuclear absorption plus comovers; dotted line: nuclear absorption alone (see text for the values of the corresponding parameters). Black circles are experimental data from Refs. [11,33].

VI. CONCLUSIONS AND PROSPECTS

We have presented a direct comparison of the available NA50 data for the E_T distribution of the J/ψ with the results obtained in a conventional framework based on nuclear absorption plus comover interaction. Our analysis suggests that the presence of new physics in the region $E_T<100$ GeV is unlikely. On the contrary, the region $E_T>100$ GeV is very interesting and should be studied with great care in the 1998 high statistics run. Agreement of the J/ψ cross section with the comovers results for $E_T\lesssim 100$ GeV together with a significantly sharper decrease for $E_T>100$ GeV (for which there might be some hint in the 1996 data), would signal the onset of a truly anomalous J/ψ suppression.

Is it possible with the present data to distinguish a deconfining phase transition scenario from the more conventional one described here? In order to answer this question we have to distinguish between deconfining scenarios producing sharp breaks in the ratio $R(E_T)$ [12,6] from others leading to a smooth behavior of this ratio [3–6]. For the former, a clear-cut answer will probably come from the 1998 data. On the contrary, it will be more difficult to distinguish the second type of deconfining models from the comover approach presented here.

A very clear way to do so would be to show that the onset of the anomalous suppression is abrupt, i.e., it is not present below some critical density—for instance, the maximal one reached in SU collisions [3]. Up to a recent date, there was some evidence for that [11]. Indeed, the effect of the comovers in SU produced a somewhat larger suppression [8,9] than the measured one. At present, however, the experimental errors in the ratio $R(E_T)$ in SU collisions have been increased by a factor 2.8 (see Ref. [34]; also the experimental errors for PbPb have increased, by a factor 1.4, which has been taken into account in this work). In view of that, it is no longer possible to claim that the J/ψ suppression in SU is too large in the comover approach [9] or that the onset of the anomalous suppression is an abrupt one.

As we have shown in Sec. V, there is a difference between comovers and deconfining scenarios regarding the behavior of $\langle p_T^2\rangle$ versus E_T. According to Ref. [28], in a deconfining scenario this quantity has a maximum at $E_T\sim 100$ GeV and decreases at larger E_T values. In the comover ap-

proach presented here, this drop is practically absent and the E_T dependence is close to the one obtained with nuclear absorption alone. Although no such drop is seen in the data, the present experimental errors are rather large and a clear conclusion is not possible.

A promising possibility is the measurement of the J/ψ suppression at higher energies. The J/ψ suppression due to either comover interactions or deconfinement, is expected to increase substantially with increasing energy. In the first case, this is due to the increase of the density of comovers with increasing energy. In the second case, it is due to the corresponding increase of energy density—while the critical value of this quantity is unchanged. Therefore, it is important to make predictions at higher energies in both approaches, using the values of the parameters determined from present data. One can hope that the differences in the predictions of the two approaches will be sufficiently large to be experimentally measurable.

The main uncertainty in the determination of the absolute value of the suppression at high energies resides in the value of dN/dy at $y^* \sim 0$. For instance, in central PbPb collisions, at RHIC energies, one expects in DPM a value [35] for negative particles $dN^-/dy|_{y^* \sim 0} = 1000$, and 3500 at $\sqrt{s_{NN}} = 5.5$ TeV. On the contrary, from the scaling in the number of participants (WNM) one expects a value $dN^-/dy|_{y^* \sim 0} = 400$ at $\sqrt{s_{NN}} = 200$ GeV and 800 at $\sqrt{s_{NN}} = 5.5$ TeV. In the first case, there is an increase by roughly a factor 5 at RHIC (17.5 at LHC) with respect to the value at $\sqrt{s_{NN}} = 17$ GeV. In the second case, there is only an increase by a factor 2 at RHIC (4 at LHC), which is due to the corresponding increase of $dN/dy|_{y^* \sim 0}$ in pp collisions. An estimate at RHIC (LHC) of the J/ψ survival probability in central PbPb collisions is given in Table I. The numbers in this table, for comover absorption alone, are obtained from Eq. (2) by rising the comover absorption, computed at $\sqrt{s_{NN}} = 17$ GeV for a central E_T bin ($E_T \sim 145$ GeV), to a power 2 (4) in the case of the WNM and to a power 5 (17.5) in the case of DPM. The corresponding numbers for the total J/ψ suppression are obtained by multiplying the ones for comovers alone given in Table I, by the nuclear absorption. The latter is expected to depend little on energy [36].

TABLE I. Comover and total J/ψ suppression at SPS, RHIC, and LHC, for central PbPb collisions, in the WNM and the DPM (see text for an explanation).

	SPS Comover	SPS Total	RHIC Comover	RHIC Total	LHC Comover	LHC Total
WNM	0.62	0.23	0.38	0.14	0.14	0.06
DPM	0.62	0.23	0.09	0.03	2×10^{-4}	8×10^{-5}

These estimates illustrate the important increase of the J/ψ suppression with energy and also the dramatic uncertainties associated to the value of $dN/dy|_{y^* \sim 0}$. Clearly, a more detailed calculation is needed which takes into account the modifications of parton densities inside nuclei (usually neglected at SPS energies) and also the changes in the Glauber formulas due to the increase with energy of σ_{pp}. However, it is obvious that the J/ψ suppression will increase strongly with increasing energies and it is very unlikely that the results will be the same in the comover and in the deconfining frameworks.

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