

# Role of parton shadowing in the comparison of $p$ - $A$ and $A$ - $A$ results on $J/\psi$ suppression at energies available at the CERN Super Proton Synchrotron

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The observation of an anomalous  $J/\psi$  suppression in nucleus-nucleus collisions is one of the most important results of the Super Proton Synchrotron (SPS) heavy-ion program. An essential ingredient in this result is the determination, obtained by studying  $p$ - $A$  collisions, of effects not related with the formation of a deconfined medium. These effects are extrapolated to  $A$ - $A$  collisions, determining a reference  $J/\psi$  yield that is then compared with the measurements. In this article we investigate the role of parton shadowing on the determination of such a reference, and we calculate its effect for  $In$ - $In$  and  $Pb$ - $Pb$  collisions as a function of rapidity and centrality.

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## I. INTRODUCTION

The suppression of charmonium states was proposed a long time ago as a signature of the production of a deconfined state in nucleus-nucleus collisions [1]. However, it was very soon realized that nuclear effects not related to deconfinement or, more generally, to the production of a hot medium may influence the observed charmonia suppression [2,3]. Such effects were investigated through the study of charmonia production in  $p$ - $A$  collisions. In these reactions, the produced  $c\bar{c}$  pair may interact with the cold nuclear medium of the target nucleus, hindering the formation of a bound state.

Several  $p$ - $A$  data samples exist today for  $J/\psi$  production at fixed target energies, in particular from NA50 at the Super Proton Synchrotron (SPS) [4–6], from E866 at FNAL [7], and from the HERA-B Collaboration at HERA [8]. Nuclear effects are usually parametrized by comparing the yields for various nuclear targets in a certain kinematical region, and then fitting their  $A$  dependence in terms of the simple power law  $A^\alpha$ . Alternatively, the data are analyzed in the framework of the Glauber model [9], and their  $A$  dependence expressed as an effective “absorption” cross section  $\sigma_{J/\psi}^{\text{eff}}$ . The interpretation of  $J/\psi$  results in  $p$ - $A$  collisions is the object of a rather strong theory effort. Nowadays, it is clear that not only the nuclear dissociation of the  $c\bar{c}$  pair plays a role, but also effects like shadowing, initial- and final-state parton energy loss, and possibly the intrinsic charm component of the projectile should be taken into account in a realistic description of the results [10].

When studying  $J/\psi$  suppression in  $A$ - $A$  collisions, a precise knowledge of nuclear effects is an essential requisite to disentangle genuine hot-medium effects. In the approach commonly used up to now [3], the effective quantity  $\sigma_{J/\psi}^{\text{eff}}$  is obtained analyzing  $p$ - $A$  data taken in the same kinematic domain of  $A$ - $A$  collisions under study. Then, it is assumed that in both  $p$ - $A$  and  $A$ - $A$  collisions nuclear effects, parameterized through the quantity  $\sigma_{J/\psi}^{\text{eff}}$ , scale with  $L$ , the mean thickness of nuclear matter seen by the  $c\bar{c}$  pair in its way through the projectile and target nuclei. In this way it is possible to determine the expected  $J/\psi$  yield for nuclear collisions as a function of centrality [5]. With this approach, a significant

anomalous suppression (i.e., a suppression that goes beyond the estimated contribution from nuclear effects) has been detected at SPS energies [11,12].

In this article, we go a step further by taking explicitly into account parton shadowing in the determination of the cold nuclear matter effects in  $A$ - $A$  collisions. Shadowing of partons in nuclei is a depletion of their population at small momentum fraction of the nucleon,  $x$ , compared to that in a free nucleon, with a corresponding enhancement at moderate  $x$  (antishadowing). Contrarily to final-state dissociation of the  $c\bar{c}$  pair, shadowing is not expected to scale with  $L$ , because in  $p$ - $A$  collisions only partons in the target are affected by shadowing, whereas in  $A$ - $A$  the projectile is also involved. Therefore, a different approach to the evaluation of nuclear effects is required.

## II. SHADOWING EFFECTS: $p$ - $A$ COLLISIONS

To give an estimate of shadowing effects on  $J/\psi$  production, we use the color evaporation model (CEM) at leading order (LO) [13]. In this approach the charmonium production cross section for  $p$ - $A$  collisions is obtained by integrating the free  $c\bar{c}$  cross section from energy threshold to the open charm threshold. In absence of final-state interactions of the produced  $J/\psi$  one has [14]

$$\frac{1}{A} \frac{d\sigma_{J/\psi}}{dx_F} = 2F \int_{2m_c}^{2m_D} m dm \frac{H_{pA}(x_1, x_2, m^2)}{\sqrt{s} \sqrt{x_F^2 s + 4m^2}}, \quad (1)$$

where  $F$  is the fraction of  $c\bar{c}$  pairs which gives a  $J/\psi$  in the final state and  $H_{pA}$  is given by

$$H_{pA}(x_1, x_2, m^2) = f_g^p(x_1, m^2) f_g^A(x_2, m^2) \sigma_{gg}(m^2) + \sum_{q=u,d,s} f_q^p(x_1, m^2) f_q^A(x_2, m^2) \sigma_{q\bar{q}}(m^2), \quad (2)$$

$H_{pA}$  is the sum of two terms, corresponding to the elementary  $c\bar{c}$  production by gluon fusion and  $q\bar{q}$  annihilation, convoluted with the parton densities  $f_i^A(x, Q^2)$  and  $f_i^p(x, Q^2)$

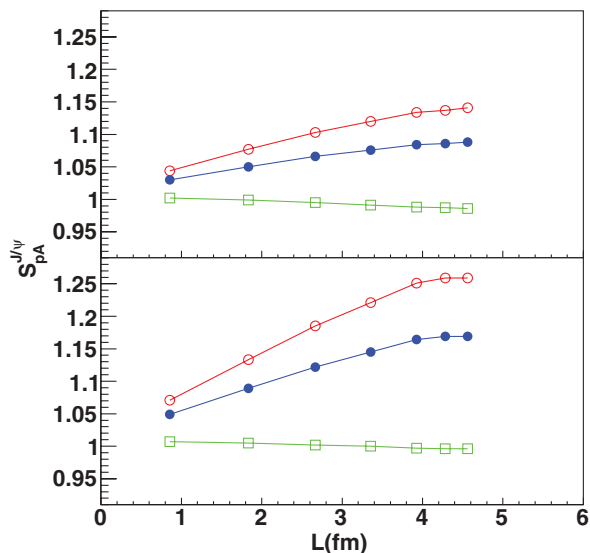


FIG. 1. (Color online) Shadowing factors for  $p$ - $A$  collisions at 158 GeV, at midrapidity. Open circles refer to the  $gg$  fraction of the cross section, open squares to  $q\bar{q}$ , and solid circles to the total cross section. The top plot has been obtained with the EKS98 set, the bottom plot with EPS08.

in the target and projectile nucleons, evaluated at  $Q = m_{x_1(x_2)}$  is the fraction of the nucleon momentum carried by the parton of the projectile (target) which interacts. We have used in our calculation the GRV98LO [15] set of parton distribution functions (PDF). The PDF for nucleons inside nuclei are modified with respect to the free ones according to the following expression:

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i^N(x, Q^2). \quad (3)$$

Various parametrizations of the PDF modifications from nuclear effects exist. We have used the EKS98 [16] and EPS08 [17] sets, which are available for all mass numbers and have been implemented in the frame of the commonly used LHAPDF interface [18]. The calculation has been performed for several  $A$  values, corresponding to Be, Al, Cu, In, W, Pb, and U target nuclei. For each target the ratio between the  $J/\psi$  production cross section (per nucleon-nucleon collision) in  $p$ - $A$  and  $p$ - $p$ , which we refer to as shadowing factor in the following, is given by

$$S_{pA}^{J/\psi}(x_F) = \frac{1}{A} \frac{d\sigma_{J/\psi}^{pA}/dx_F}{d\sigma_{J/\psi}^{pp}/dx_F}. \quad (4)$$

In Fig. 1 we present the result of the calculation of the shadowing factors for  $p$ - $A$  collisions at 158 GeV, the energy used in the  $A$ - $A$  data taking at the SPS. The plots refer to midrapidity, and we separately show the shadowing factors for the  $gg$  and  $q\bar{q}$  fraction of the production cross section. We plot the results as a function of the  $L$  variable [19], computed for each nucleus using the Glauber model with realistic nuclear density distributions [20].

It can be noted that both EKS98 and EPS08 sets give shadowing factors larger than 1, and that such an antishadowing is more pronounced when using EPS08. The  $q\bar{q}$  fraction of the cross section exhibits a small shadowing, which is

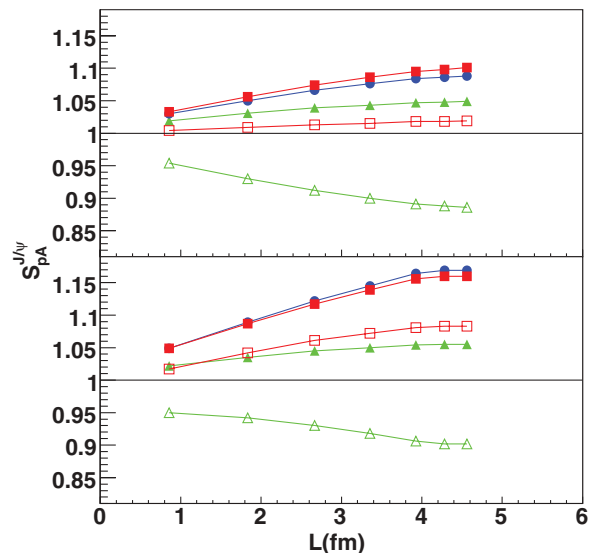


FIG. 2. (Color online) Shadowing factors for  $J/\psi$  production in  $p$ - $A$  collisions at 158 GeV, using EKS98 (top plot) and EPS08 (bottom plot). Solid and open triangles refer to  $y = 1$  and  $y = -1$  respectively, solid and open squares to  $y = 0.5$  and  $y = -0.5$ , and circles to  $y = 0$ .

more than counterbalanced by the dominant  $gg$  production process. We have also verified by choosing another set of PDFs (MRST2001LO [21]) that our results do not depend, within at most 2%, on the specific choice of the PDF set. The flattening of  $S_{pA}^{J/\psi}$  for heavy nuclei when using EPS08 is because of the fact that a constant shadowing is assumed beyond  $A = 208$  [22]. In Fig. 2 we present the results of a similar calculation at slightly forward ( $y = 0.5$ ,  $y = 1$ ) and backward ( $y = -0.5$ ,  $y = -1$ ) rapidity. We also plot the  $y = 0$  result for comparison. We recall that the region  $0 < y < 1$  is the one where  $J/\psi$  results are available at SPS energies for  $A$ - $A$  collisions. The shadowing factors are found to depend on  $y$ , as expected, because  $x_2$  is directly related to this quantity. We recall that  $x_2 = (m_{J/\psi}/\sqrt{s}) \exp(-y)$  for  $J/\psi$  production in the CEM at LO. In Fig. 3 we plot the EKS98 and EPS08 parametrizations of nuclear effects on PDFs for the Pb nucleus, relative to  $Q = m_{J/\psi}$ . The arrows indicate the  $x_2$  values corresponding to the rapidities where we have performed the shadowing factor calculation of Fig. 2. It can be clearly seen that from  $y = -1$  toward  $y = 1$  one goes from a shadowing to an antishadowing regime, reaching a maximum of the antishadowing effect at  $x_2 \sim 0.10$  for the EKS98 set ( $\sim 0.13$  for EPS08), which then decreases going toward smaller  $x_2$  (corresponding to more forward rapidities). Such an evolution can clearly be identified looking, at fixed  $L$ , to the shadowing factors shown in Fig. 2, which are  $< 1$  at  $y = -1$ , then increase and finally decrease at forward rapidity.

We note that the shadowing factors calculated for  $y = -0.5$ ,  $-1$  are identical, for symmetry reasons, to those for  $A$ - $p$  collisions at  $y = 0.5$ ,  $1$ . Results on  $A$ - $p$  collisions are interesting in order to study effects from PDF modifications in the projectile, which will be important when studying  $A$ - $A$  interactions. We see, for example, that at  $y = 1$  the shadowing effects in  $A$ - $p$  are very different with respect to  $p$ - $A$ .

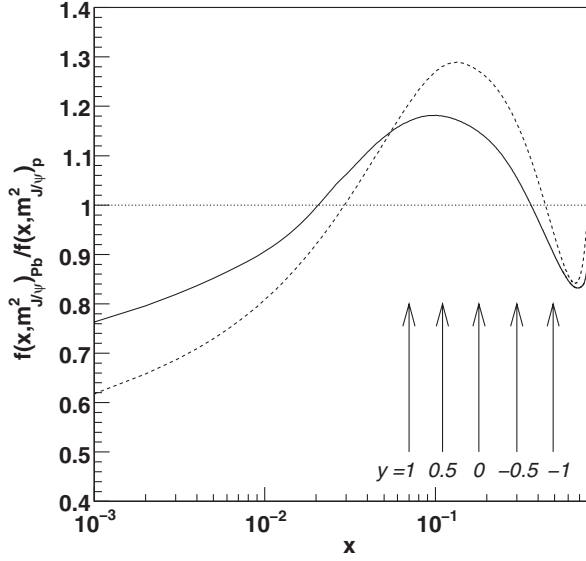


FIG. 3. The EKS98 (continuous line) and EPS08 (dashed line) parametrizations of nuclear modifications to the PDFs for the Pb nucleus, calculated at  $Q = m_{J/\psi}$ . The arrows correspond to the rapidity values where the calculation of Fig. 2 has been performed.

### III. SHADOWING EFFECTS: A-A COLLISIONS

When moving to  $A$ - $A$  collisions, the cross section and the shadowing factors, integrated over centrality, can be calculated with an expression similar to Eq. (1), by replacing  $H_{pA}(x_1, x_2, m^2)$  with  $H_{AA}(x_1, x_2, m^2)$ , taking now into account that shadowing affects both projectile and target nuclei. The problem becomes more complicated if shadowing factors have to be calculated for various centrality intervals. Clearly, for various geometries of the collision, either the halo or the core of the nuclei will be mainly involved, and the shadowing effects will be more important in the core than in the halo. Various parametrizations of the local shadowing inside the nucleus have been proposed. We have used two of them [23]:

$$R_{i,\rho}^A(x, Q^2, \vec{r}, z) = 1 + N_\rho^A [R_i^A(x, Q^2) - 1] \frac{\rho_A(\vec{r}, z)}{\rho_0}, \quad (5)$$

and

$$R_{i,L}^A(x, Q^2, \vec{r}, z) = 1 + N_L^A [R_i^A(x, Q^2) - 1] \frac{\int dz \rho_A(\vec{r}, z)}{\int dz \rho_A(0, z)}. \quad (6)$$

In the first one, shadowing in a certain location  $(\vec{r}, z)$  inside the nucleus is proportional to the local nuclear density  $\rho_A(\vec{r}, z)$ , whereas in the second it is proportional to the length  $L$  of nuclear matter crossed by the parton on its way through the nucleus. The normalization  $N_\rho^A$  is fixed to ensure that  $\int d\vec{r} dz R_{i,\rho}^A(x, Q^2, \vec{r}, z) = R_i^A(x, Q^2)$  (and similarly for  $N_L^A$ ).

The study of the shadowing factors in  $A$ - $A$  collisions as a function of centrality has been performed for In-In and Pb-Pb at 158 GeV/nucleon (see also [24] for a previous investigation of the influence of shadowing on the centrality dependence of  $J/\psi$  and Drell-Yan cross sections). A large number of events has been generated for centrality values

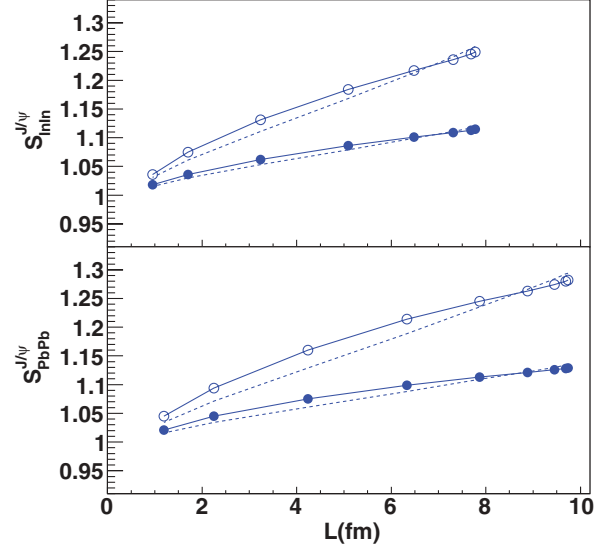


FIG. 4. (Color online) Shadowing factors for In-In (top) and Pb-Pb collisions at 158 GeV, at  $y = 0.5$ , obtained with EKS98. Solid circles refer to the EKS98 parametrization, and open circles to EPS08. The symbols connected by a continuous line have been calculated using Eq. (5), whereas the dashed lines have been obtained using the parametrization of Eq. (6) for the local dependence of shadowing.

in the interval  $0 < b < 12$  fm for In-In and  $0 < b < 16$  fm for Pb-Pb, in steps of 2 fm, with a Glauber Monte Carlo approach. We have used  $\sigma_{\text{inel}}^{pp} = 30$  mb and the measured nuclear density distributions for In and Pb [20]. For every  $N$ - $N$  collision in each  $A$ - $A$  interaction, we calculate  $\rho_A(\vec{r}, z)$  and  $L(\vec{r})$  for the two colliding nucleons, and the product of the two corresponding shadowing factors, according to Eqs. (5) and (6). By averaging the shadowing factors over all the  $N$ - $N$  collisions in each  $A$ - $A$  interaction, we get the centrality dependence of the shadowing factors. In Fig. 4 we show, as a function of  $L$ , the calculated shadowing factors for In-In and Pb-Pb collisions at  $y = 0.5$ . For the SPS data at 158 GeV, this is the rapidity where the acceptance reaches its maximum. The symbols, connected by the continuous lines, have been calculated using Eq. (5) for the local dependence of shadowing inside the nucleus, whereas the dashed line has been obtained using the parametrization of Eq. (6). We note that the two parametrizations give similar results, their difference not exceeding 2%–3%. In absence of other nuclear effects, this result implies an  $\sim 10\%$  antishadowing effect for central nucleus-nucleus collisions. When using EPS08, the effect increases up to  $\sim 25\%$ .

### IV. COMPARISON OF COLD NUCLEAR MATTER EFFECTS IN $p$ - $A$ AND $A$ - $A$ COLLISIONS

We now want to discuss the extrapolation of cold nuclear matter effects measured in  $p$ - $A$  to  $A$ - $A$  collisions, taking into account shadowing effects together with final-state absorption of the created  $c\bar{c}$  pair. To do that, we model final-state absorption effects using the simple law  $\exp(-\rho \sigma_{J/\psi}^{\text{abs}} L)$ , which has been shown to reproduce, at first order, data on  $J/\psi$

production at fixed target energies. In this approach, the  $J/\psi$  production cross section per  $N$ - $N$  collision in  $p$ - $A$  is given by

$$\frac{1}{A} \sigma_{J/\psi}^{pA} = \sigma_{J/\psi}^{NN} \times S_{pA}^{J/\psi} \times \exp(-\rho \sigma_{J/\psi}^{\text{abs}} L). \quad (7)$$

We then fit the  $p$ - $A$  cross section per  $N$ - $N$  collision, obtained through Eq. (7) with the simple  $\exp(-\rho \sigma_{J/\psi}^{\text{eff}} L)$  law (i.e., neglecting the existence of shadowing). This is the procedure usually followed at SPS energies to extract the so-called “normal nuclear absorption.” Clearly this approach, when shadowing factors are not negligible, leads to two main consequences. On one hand the obtained  $\sigma_{J/\psi}^{\text{eff}}$  values do not represent anymore the size of final-state absorption, but an effective quantity which, due to the presence of shadowing [25,26], may be quite different from  $\sigma_{J/\psi}^{\text{abs}}$ . On the other hand, because shadowing effects do not necessarily have the same  $L$  dependence of final-state absorption,  $\exp(-\rho \sigma_{J/\psi}^{\text{eff}} L)$  may not give a reasonable fit anymore of the  $p$ - $A$  data. However, given the size of the shadowing corrections, their deviation from the exponential behavior is difficult to observe in the existing data samples.

The  $J/\psi$  cross section per  $N$ - $N$  collision in  $A$ - $A$ , as a function of centrality, is then obtained using Eq. (7), replacing  $S_{pA}^{J/\psi}$  with  $S_{AA}^{J/\psi}$  and  $1/A$  with  $1/N_{\text{coll}}$ , where the shadowing factor and the number of  $N$ - $N$  collisions are calculated for the various centrality bins. We can now compare the extrapolation of the exponential fit of the  $p$ - $A$  calculation with what has been obtained for  $A$ - $A$  collisions. When doing that, we may expect significant deviations from such an extrapolation. First of all, in  $A$ - $A$  shadowing affects not only the target nucleus but also the projectile, leading to an extra effect that is clearly not present in the naive extrapolation of the exponential fit of  $p$ - $A$ . Furthermore, these deviations may heavily depend on rapidity because when moving away from  $y = 0$  the  $x$  region probed in the projectile becomes different from that of the target.

To illustrate the procedure, we show in Fig. 5, for 158-GeV energy and  $y = 0.5$ , the expected behavior for  $p$ - $A$  collisions, including shadowing and having assumed  $\sigma_{J/\psi}^{\text{abs}} = 4$  mb. We also show the result of an exponential fit to  $p$ - $A$  data, which gives  $\sigma_{J/\psi}^{\text{eff}} = 3.0$  mb, a value smaller than  $\sigma_{J/\psi}^{\text{abs}}$ , because of the presence of an antishadowing effect. In the same plot we compare this exponential fit with the calculated cross section values per  $N$ - $N$  collision for In-In and Pb-Pb, as a function of centrality. We clearly see that  $A$ - $A$  cross sections deviate from the extrapolation of  $p$ - $A$  results. In particular, at fixed  $L$ , the  $J/\psi$  cross section per  $N$ - $N$  collision is systematically lower in  $A$ - $A$  with respect to  $p$ - $A$ . However, we note that the relative behavior of  $A$ - $A$  results with respect to  $p$ - $A$ , at a certain  $L$ , cannot be easily deduced by a simple inspection of the  $p$ - $A$  (and  $A$ - $p$ ) shadowing factors. In fact, from the geometry of the interaction, it can be shown that the same  $L$  for  $p$ - $A$  ( $A$ - $p$ ) and  $A$ - $A$  corresponds to very different average nuclear densities probed in the collision and therefore to a different average strength of the shadowing effects. (To give a numerical example, the  $L$  value corresponding to  $p$ -Pb collisions is obtained with Pb-Pb collisions at  $b = 12$  fm. The average nuclear densities probed are  $0.76\rho_0$  and  $0.48\rho_0$ , respectively, where  $\rho_0$  is the core nuclear density). Therefore, the  $A$ - $A$  shadowing factors cannot be obtained as a simple product of  $p$ - $A$  and  $A$ - $p$  shadowing at the same  $L$ .

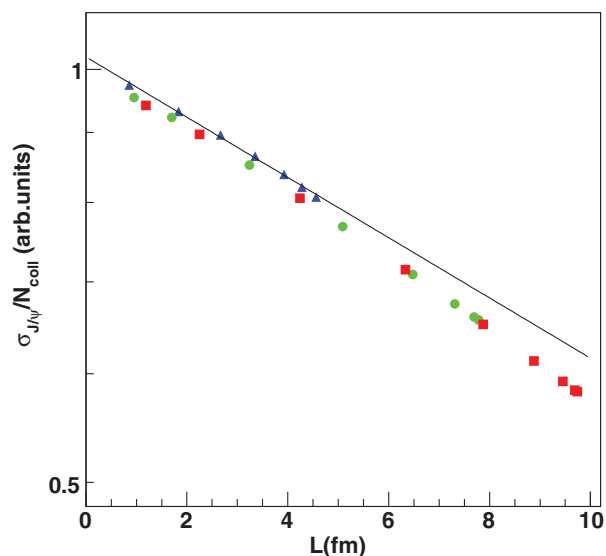


FIG. 5. (Color online) Comparison of  $p$ - $A$  and  $A$ - $A$  cross sections for  $J/\psi$  at 158 GeV, for  $y = 0.5$ , including shadowing and final-state absorption, in arbitrary units. The  $p$ - $A$  cross sections per  $N$ - $N$  collisions are shown as triangles. The line represents an exponential fit to  $p$ - $A$  data. In-In and Pb-Pb cross sections are shown as circles and squares, respectively.

A deviation of  $A$ - $A$  results from the  $p$ - $A$  extrapolations was indeed found at SPS energies, and it was called “anomalous  $J/\psi$  suppression” [11,12]. Usually this effect was connected to hot nuclear matter effects, including the production of a deconfined state [27]. The result of Fig. 5 shows that at least a fraction of this effect can be attributed to having neglected the influence of shadowing in the determination of the “nuclear absorption” reference. In Fig. 6 we present the ratio between the  $J/\psi$  cross sections for In-In and Pb-Pb and the exponential extrapolation of  $p$ - $A$  results, for three rapidity values ( $y = 0, 0.5$ , and  $1$ ), using EKS98 and Eq. (5) for the local dependence of shadowing. This kinematical range corresponds to the region where  $J/\psi$  production has been studied by the NA50/NA60 experiments in nuclear collisions. The values of these ratios do not depend on the specific  $\sigma_{J/\psi}^{\text{abs}}$  value used in the calculation, because, at fixed  $L$ , the factors  $\exp(-\rho \sigma_{J/\psi}^{\text{abs}} L)$  cancel out in the ratio of the cross sections between  $A$ - $A$  and  $p$ - $A$ .

The values plotted in Fig. 6 show that a simple extrapolation of  $p$ - $A$  results, obtained through a fit of the  $A$  dependence that parametrizes all nuclear effects under a single parameter  $\sigma_{J/\psi}^{\text{eff}}$ , is not in agreement with  $A$ - $A$   $J/\psi$  cross sections as a function of centrality. This is basically because of the presence in  $A$ - $A$  of shadowing effects in the projectile that are of course not present in  $p$ - $A$ . Although the effect remains rather small at midrapidity, it increases fast when moving away from  $y = 0$ , reaching a discrepancy of  $\sim 20\%$  between the extrapolation of  $p$ - $A$  data and the central  $A$ - $A$  results for  $y = 1$ . This effect must clearly be taken into account when looking for hot nuclear matter effects in  $A$ - $A$  data. In particular, the anomalous suppression values observed at the SPS must be rescaled by the values shown in Fig. 6 at the corresponding rapidities, resulting in an  $\sim 10\%$  average reduction of this

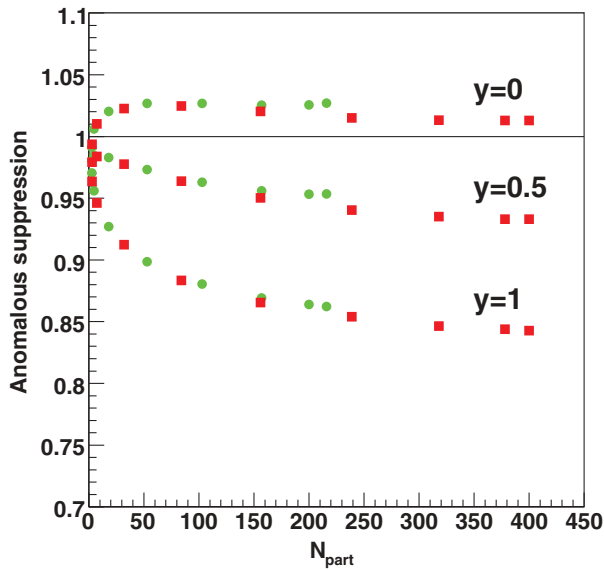


FIG. 6. (Color online) Ratio between the  $A$ - $A$  cross section per  $N$ - $N$  collision and the extrapolation of  $p$ - $A$  results, for three rapidity values, using the EKS98 parametrization. The results for In-In and Pb-Pb are shown as circles and squares, respectively.

effect in the interval  $0 < y < 1$  where data were taken. When using the EPS08 parametrization, similar values to those of Fig. 6 were obtained, with relative discrepancies not larger than  $\sim 2\%$ . However, it is well known that the uncertainties on the modification of gluon PDFs are quite large, and very recent analyses (EPS09) are now starting to systematically address this issue [30]. The LO set of EPS09 gluon PDF modification has an average value, in the  $x$  region corresponding to SPS data, quite similar to the EKS98 one, with an error of the order of  $\pm 15\%$ . By injecting such an uncertainty in our calculation, it turns out that the values shown in Fig. 6 vary by about 5%. Finally, other sets of nuclear modifications to gluon PDFs exist in the literature that exhibit either no (or little) antishadowing in our  $x$  region ( $n\text{DS}/n\text{DSg}$  [28]) or an antishadowing very strongly increasing with  $x$  (HKN

[29]). The use of such sets in our analysis gives almost no difference between the extrapolation of  $p$ - $A$  results and  $A$ - $A$  for  $n\text{DS}/n\text{DSg}$  (ratios  $\sim 1$  in Fig. 6), or higher values, increasing with  $y$ , for  $A$ - $A$  with respect to  $p$ - $A$  for HKN (i.e., ratios larger than 1 in Fig. 6). However, it was pointed out [30] that such analyses might be less constrained in the  $x$  region under study because they do not make use of data from high- $p_T$   $\pi$  production in  $d$ -Au collisions from the BNL Relativistic Heavy-Ion Collider (RHIC) [31,32], which are relevant for the determination of the large  $x$ -region gluon contribution.

## V. CONCLUSIONS

We have investigated in this article the role of shadowing for  $J/\psi$  production in  $p$ - $A$  and  $A$ - $A$  collisions at SPS energies. In particular, we have shown that an extrapolation of cold nuclear matter effects measured in  $p$ - $A$ , which does not take explicitly into account shadowing, cannot reproduce in a correct way such effects for  $A$ - $A$ . In the frame of an LO color evaporation model calculation, performed using the EKS98 and EPS08 parametrizations, we have shown that neglecting shadowing, the  $p$ - $A$  extrapolation is biased by  $\sim 10\%$  at  $y = 0.5$  for central In-In and Pb-Pb collisions. Such a bias must be taken into account in analysis that aim at determining effects from hot nuclear matter in  $J/\psi$  production in  $A$ - $A$  collisions at SPS energies (the so-called ‘‘anomalous suppression’’). In particular it may be quantitatively important for lighter systems, such as In-In, where the deviations from  $p$ - $A$  extrapolations are relatively small.

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