Charmed mesons have captured our attention for decades. Due to the high scale provided by their large masses, they are considered to be outstanding probes of Quantum Chromodynamics (QCD). The interest in this field concerns the issue of their production mechanisms in proton-proton collisions together with their interaction with the nuclear matter created in ultrarelativistic heavy-ion collisions.

This is so since lattice QCD calculations predict that, at sufficiently large energy densities, hadronic matter undergoes a phase transition to a plasma of deconfined quarks and gluons, the so-called quark gluon plasma (QGP), where the QCD binding potential is screened. Given the existence of several quarkonium states, each of them with different binding potentials, they are expected to sequentially melt into open charm or bottom mesons above certain energy density thresholds. Moreover, puzzling features in proton(deuteron)-nucleus collision data, where the deconfinement cannot be reached, reveal new aspects of charmonium physics in nuclear reactions, namely the role of cold nuclear matter effects.

In fact, unexpected results on \( \psi(2S) \) production in proton(proton)-nucleus collisions from PHENIX [1] and ALICE [2, 3] collaborations have shown an important suppression of its yield with respect to proton-proton production. Furthermore, this suppression is stronger than the one previously obtained for the \( J/\psi \) production. Usual explanations, based on nuclear parton shadowing or \( c\bar{c} \) break-up in interactions with nucleons cannot be invoked here, the first one being indistinguishable between \( \psi(2S) \) and \( J/\psi \) and the second being negligible at the present RHIC and LHC energies [4].

Here, we wish to explore the possibility that the final state interactions of the \( c\bar{c} \) pair with the dense medium created in the collision cause the puzzling anomalies seen in quarkonium production, i.e. the stronger \( \psi(2S) \) suppression relative to the \( J/\psi \), within the so-called comover scenario. In a comover framework, the suppression arises from scattering of the nascent \( \psi \) with produced particles—the comovers—that happen to travel along with the \( c\bar{c} \) pair [5, 6].

Let us remain two common features of the comover approaches. First, the comovers dissociation affects strongly the \( \psi(2S) \) relative to the \( J/\psi \), due to the larger size of the first. Second, the comover suppression is stronger there where the comover densities are larger, i.e. it increases with centrality and, for asymmetric collisions as proton(proton)-nucleus, it will be stronger in the nucleus-going direction.

On the other hand, one cannot forget an additional effect that will be at play here. This is the nuclear modification of the parton distribution functions. It will produce a common decrease of the \( J/\psi \) and the \( \psi(2S) \) yields in the mid and forward rapidity regions both at RHIC and LHC energies. It can induce an increase of both yields in the backward rapidity region.

In the following, we will show that taking into account the above features we obtain a surprisingly good and coherent quantitative description of the available deuteron-nucleus and proton-nucleus data at RHIC and LHC energies. We will apply the well established comover interaction model (CIM) [6–11]. In this model, the rate equation that governs the density of charmonium at a given transverse coordinate \( s \), impact parameter \( b \) and rapidity \( y \), \( \rho^\psi(b, s, y) \), obeys the simple expression

\[
\tau \frac{d\rho^\psi}{dt}(b, s, y) = -\sigma^{co-\psi} \rho^{co}(b, s, y) \rho^\psi(b, s, y),
\]

where \( \sigma^{co-\psi} \) is the cross section of charmonium dissociation due to interactions with the comoving medium of transverse density \( \rho^{co}(b, s, y) \).

To obtain the survival probability \( S^\psi_{\psi}(b, s, y) \) \( \psi \) interacting with comovers, this equation is to be integrated between initial time \( \tau_0 \) and freeze-out time \( \tau_f \). We consider longitudinal boost invariance and neglect transverse expansion. Assuming a dilution in time of the densities due to longitudinal motion which leads to a \( t^{-1} \) dependence on proper time the equation can be solved analytically. The result depends only on the ratio \( \tau_f/\tau_0 \) of final over initial time. Using the inverse proportionality between proper time and densities, we put \( \tau_f/\tau_0 = \rho^{co}(b, s, y)/\rho_{pp}(y) \), i.e. we assume that the interaction stops when the densities have diluted, reaching the value of the p+p density at the same energy. Thus, the solution of eq. (1) is given by

\[
S^\psi_{\psi}(b, s, y) = \exp\left(-\sigma^{co-\psi} \rho^{co}(b, s, y) \ln \left[ \frac{\rho^{co}(b, s, y)}{\rho_{pp}(y)} \right] \right),
\]
where the argument of the log is the interaction time of the $\psi$ with the comovers. 

The main ingredient in order to compute the survival probability $S^{co}_{\psi}$ of the quarkonium due to interactions with the comoving medium is the density of comovers $\rho^{co}$. This density is not a free parameter, since it has the constraint that the total rapidity distribution $dN/dy$ of the observed particles must be reproduced. We take it as proportional to number of collisions,

$$\rho^{co}(b, s, y) = n(b, s) S_{co}^{ch}(b, s) \frac{3}{2} (dN^{pp}_{ch}/dy),$$

where $n(b, s)$ corresponds to the number of binary nucleon-nucleon collisions per unit transverse area at given impact parameter, $S_{co}^{ch}$ refers to the shadowing of the parton distribution functions in a nucleus that affects the comover multiplicity, $ch$ refers to the charged particle density in p+p and the factor 3/2 takes into account the neutral comovers. In order to compute the comover densities in nuclear collisions we have introduced the shadowing corrections that affects the comover multiplicities [12–14]. Within this approach, a good description of the centrality dependence of charged multiplicities in nuclear collisions is obtained both at RHIC [15] and LHC energies [12].

Finally, the comover density in p+p collisions is given by $\rho_{pp}(y) = \frac{3}{2}(dN^{pp}_{ch}/dy)/\pi R_{p}^{2}$, where $R_{p}$ is the proton radius. We apply the experimental values and theoretical extrapolations [12] for the charged particle multiplicities in proton-proton collisions. We get, at mid rapidity, the values $\rho_{pp}(0) = 2.24 \text{ fm}^{-2}$ at $\sqrt{s} = 200 \text{ GeV}$ [10] and $\rho_{pp}(0) = 3.37 \text{ fm}^{-2}$ at $\sqrt{s} = 5.02 \text{ TeV}$, which correspond to the values of charged particle multiplicities $dN^{ch}_{pp}/dy = 2$ at $\sqrt{s} = 200 \text{ GeV}$ and $dN^{ch}_{pp}/dy = 4.5$ at $\sqrt{s} = 5.02 \text{ TeV}$.

Note that, together with the comover interaction, another important effect that plays a role in quarkonium nuclear production is the shadowing of the heavy pairs due to the modification of the gluon parton distribution functions in the nucleus. It can be calculated analytically in the above mentioned framework or using any of the available parametrizations for the nuclear parton distribution functions [16, 17]. Note also that this effect is to be taken identical for the states $1S$ and $2S$ [4], i.e. for the $J/\psi$ and $\psi'$. 

The only adjustable parameter of the comover interaction model is the cross section of charmonium dissociation due to interactions with the comoving medium, $\sigma^{co-\psi}$. It was fixed [7] from fits to low-energy experimental data to be $\sigma^{co-J/\psi} = 0.65 \text{ mb}$ for the $J/\psi$ and $\sigma^{co-\psi(2S)} = 6 \text{ mb}$ for the $\psi(2S)$. Reliable theoretical calculations of this cross section show that it increases very slowly with energy from threshold [18]. Moreover, note that an invariant dissociation cross section of charmonium on light mesons, assumed to be energy independent, is a common feature to various comover models [19]. Thus, we have chosen to keep them fixed to their low energy values. These values have been also successfully applied at higher energies to reproduced the RHIC [20] and LHC [21] data on $J/\psi$ from nucleus-nucleus collisions.

It is now straightforward to calculate the nuclear modification factor, i.e. the ratio of the $\psi$ yield in proton(deuteron)-nucleus collisions to the $\psi$ yield in proton-proton collisions multiplied by the average number of binary nucleon-nucleon collisions:

$$R^{co}_{pp}(b) = \frac{dN_{pA}/dy}{n(b) dN^{pp}_{pp}/dy} = \frac{\int d^{2}s \sigma_{pA}(b) n(b, s) S_{\psi}^{ch}(b, s) S^{co}_{\psi}(b, s)}{\int d^{2}s \sigma_{pA}(b) n(b, s)},$$

$S^{co}_{\psi}$ refers to the survival probability due to the medium interactions, while $S_{\psi}^{ch}$ takes into account the shadowing of the parton distribution functions in a nucleus that affects the $\psi$ production. Any nuclear effect affecting quarkonium production leads to a deviation of $R_{pp}$ from unity.

Figure 1 shows the nuclear modification factor $R_{dAu}$ as a function of the number of collisions $N_{coll}$ for the $J/\psi$ and $\psi(2S)$ production in d+Au collisions at $\sqrt{s} = 200 \text{ GeV}$ compared to PHENIX experimental data [1]. The suppression due to the shadowing corrections (discontinuous line) is also shown. The suppression due to the shadowing corrections (discontinuous line) is also shown.

We proceed now with the analysis of $J/\psi$ and $\psi(2S)$ production in p+Pb collisions at $\sqrt{s} = 5.02 \text{ TeV}$, that offers an excellent opportunity to verify the role of comovers on quarkonium suppression. According to available experimental data [2, 3], the suppression of the $J/\psi$ shows a strong difference between the forward and backward rapidity regions, while the $\psi(2S)$ shows astonishing similar suppression in both rapidity intervals.
Note that any effect related to nuclear shadowing would produce an slight antishadowing in the backward region while it would induce a suppression in the forward region, these effects being identical for the \( J/\psi \) and \( \psi(2S) \).

In fact, the experimental finding of a different suppression for the \( \psi(2S) \) relative to the \( J/\psi \), in particular in the backward rapidity region, is a clear indication of comover interactions. Actually, the density of comovers is smaller in the forward region–p-going direction– than in the backward region–Pb-going direction–, the difference increasing with centrality, which is easily confirmed by experimental data on charged particle multiplicities [23]. As a consequence, the effect of comovers–which differs on the \( J/\psi \) and \( \psi(2S) \) case– will be strong in the backward region, while the suppression found in the forward region will be mainly due to the initial shadowing of the nuclear parton distribution functions, identical in both cases. Thus, one should expect a much similar \( J/\psi \) and \( \psi(2S) \) suppression in the forward than in the backward region.

This is illustrated in Figure 2, where experimental data [2] on \( J/\psi \) and \( \psi(2S) \) production in p-Pb collisions at \( \sqrt{s} = 5.02 \text{ TeV} \) is compared to our results. We have considered a common EPS09 LO shadowing [16, 22] for both the \( J/\psi \) and \( \psi(2S) \). The interaction with comovers, mostly at play in the backward region, is able to explained the stronger \( \psi(2S) \) suppression.

Our results for \( J/\psi \) and \( \psi(2S) \) production versus centrality in p-Pb collisions at \( \sqrt{s} = 5.02 \text{ TeV} \) are shown in Figure 3. Two rapidity intervals are studied, the p-going direction, \( 2.03 < y < 3.53 \) and the Pb-going direction, \( -4.46 < y < -2.96 \). The effect of the EPS09 LO shadowing is completely different depending on the rapidity interval considered. While it induces an increase–antishadowing– in the backward region, it produces a suppression–shadowing– in the forward region. On the other hand, the interaction with comovers introduces a suppression, stronger in backward region due to the higher comover density. Their effect will be more important on the \( \psi(2S) \) than on the \( J/\psi \) production, due to the higher \( \sigma_{\text{pp}}^{\psi(2S)} \) of the first. In fact, we obtain a nuclear modification factor \( R_{\text{pp}}^{\psi(2S)} \) compatible with one for the \( J/\psi \) in the backward region resulting for the the combined effect of EPS09 LO nuclear modification together with the comover suppression, while the total suppression of the \( J/\psi \) in the forward region achieves almost 50%, mainly due to the shadowing effect.

Concerning the \( \psi(2S) \) production, we obtain a similar suppression for the backward and forward rapidity regions. Note, nevertheless, that the origin of this decrease corresponds to different effects depending of the region of consideration: in the backward region, there is an antishadowing identical to one previously found for the \( J/\psi \) which is hidden by the strong effect of comover suppression in this region; on the other side, in the forward region, both the shadowing and a limited comover effect contribute to the suppression.

FIG. 2: (Color online) The \( J/\psi \) (blue line) and \( \psi(2S) \) (red line) nuclear modification factor \( R_{\text{pp}} \) as a function of rapidity compared to the ALICE data [2]. The suppression due to the shadowing corrections (discontinuous line) is also shown.

FIG. 3: (Color online) The \( J/\psi \) (upper figure) and \( \psi(2S) \) (lower figure) nuclear modification factor \( R_{\text{pp}} \) as a function of the number of collisions in the backward \( -4.46 < y < -2.96 \) (blue continuos line) and forward \( 2.03 < y < 3.53 \) (red continuos line) rapidity intervals. The modification due to the antishadowing corrections in the backward region (blue discontinuous line) and to the shadowing corrections in the forward region (red discontinuous line) is also shown.
The ratio of both nuclear modification factors, i.e. \( R^{(2S)}_{pPb}/R^{(1S)}_{pPb} \), also defined as the double ratio \( \frac{R^{(2S)}_{pPb}/R^{(1S)}_{pPb}}{R^{(2S)}_{\psi}\psi pPb/R^{(1S)}_{\psi}\psi pPb} \), is shown in Figure 4 for the backward and forward rapidity regions. In this double ratio the corrections due to the modification of the nuclear parton distribution functions cancel, and only comover interaction is at play.

We obtain a double ratio lower than one in both rapidity regions, due to the stronger effect of the comovers on the \( \psi(2S) \). Moreover, this decrease below one is more pronounced in the backward rapidity region due to higher comover density which produces stronger dissociation on the \( \psi(2S) \), due to its higher interaction cross section.

In conclusion, we have performed a detailed study of the \( \psi(2S) \) and \( \psi(2S) \) production in \( d+Au \) and \( p+Pb \) collisions at \( \sqrt{s} = 200 \) GeV and \( \sqrt{s} = 5.02 \) TeV respectively. From our point of view, the available data constitute experimental confirmation of the interaction of fully formed physical quarkonia with the produced particles –the comovers– that happen to travel along with the \( cc \) pair.

In particular, the comover suppression can explain the relative modification of the \( \psi(2S) \) to the \( \psi(1S) \), \( R^{(2S)}_{pPb}/R^{(1S)}_{pPb} \), in proton(deuteron)-nucleus collisions at RHIC and LHC energies. Other cold nuclear matter effects, as the nuclear absorption of the \( cc \) pairs with the nucleons or the nuclear modification of the parton distribution functions, cannot account for this difference since they impact similarly the \( J/\psi \) and the \( \psi(2S) \).

The comover effect, found to be of the order of 10% in proton-nucleus collisions at SPS energy, increases with the total particle multiplicity and achieves significant influence in proton(deuteron)-nucleus collisions at RHIC and LHC energies, in particular in the A-going direction.

While in nucleus-nucleus collisions at RHIC and LHC energies the dynamics of \( cc \) quarks can be expected to be dominated by partonic or ‘pre-hadronic’ comover interactions due to the high densities involved, we find that in proton-nucleus collisions a hadronic comover dissociation scenario is compatible with the experimental data.

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\[ \text{FIG. 4: (Color online) The ratio of the } \psi(2S) \text{ over } J/\psi \text{ nuclear modification factors } R^{(2S)}_{pPb}/R^{(1S)}_{pPb} \text{ as a function of the number of collisions in the backward } 2.03 < y < 3.53 \text{ (red continuos line) rapidity intervals.} \]

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