Theory status of quarkonium production in proton-nucleus collisions

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Abstract. I give a brief overview of the recent theoretical progress in the study of quarkonium production in proton-nucleus collisions in view of the recent LHC and RHIC results. A special emphasis is put on the excited states such as the $\psi'$, $\Upsilon(2S)$ and $\Upsilon(3S)$.

1. On the importance of understanding conventional nuclear effects: the CMS $\Upsilon(nS)$ sequential suppression example.

One of the highlights of the Run1-LHC heavy-ion results is admittedly the observation made by the CMS collaboration of a relative suppression of the $n = 2, 3 \Upsilon$ states with respect to the $n = 1 \Upsilon$ state in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Such an observation was expected and even awaited for by the supporters of the phenomenon of “sequential quarkonium suppression” according to which the excited states with larger radii should suffer more from the colour screening in the deconfined matter [1].

Actually, CMS published a set of two papers [2, 3] describing this observation, the second reinforcing the first by quoting measurements of individual nuclear modification factor. In discussing their results, they had in mind that other nuclear-matter effects than the creation of a quark-gluon plasma (QGP) could suppress the $\Upsilon(nS)$, yet noting:

[...] such effects should have a small impact on the double ratios reported here. Initial-state nuclear effects are expected to affect similarly each of the three $\Upsilon$ states, thereby canceling out in the ratio. Final-state nuclear absorption becomes weaker with increasing energy and is expected to be negligible at the LHC.

At this point, it is fair to say that nobody claimed the contrary and that this assertion was supported by a number of theoretical studies, e.g. [4, 5, 6], where the excited states were expected to be suppressed as much as the $n = 1$ state. In particular, such expectations were in line with the idea that any phenomenon taking place into the very fast moving lead nucleus (the nuclear matter in question) and which would impact differently the $\Upsilon$ states would de facto violate the Heisenberg principle. Indeed, the time they take to escape this nuclear matter is way smaller, given the huge boost between their rest frame and the nucleus rest frame, than the time they

1 For minimum bias $AB$ collisions, such factors are defined such that $R_{AB} = \sigma_{AB}/(A\sigma_{pp})$; they equal unity in absence of nuclear effects, that is when the nucleus-nucleus collision is like an incoherent superposition of nucleon-nucleon collisions.
Table 1. Double ratios expressing the relative nuclear suppression of the excited $\Upsilon(2S, 3S)$ states with respect to the $\Upsilon(1S)$ state as observed by CMS [3, 7] in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in $p$Pb collisions at $\sqrt{s_{NN}} = 5$ TeV.

|       | $2S$                          | $3S$                          |
|-------|-------------------------------|-------------------------------|
| PbPb  | $0.21 \pm 0.07$ (stat.) $\pm 0.02$ (syst.) | $0.06 \pm 0.06$ (stat.) $\pm 0.06$ (syst.) |
| $p$Pb | $0.83 \pm 0.05$ (stat.) $\pm 0.05$ (syst.) | $0.71 \pm 0.08$ (stat.) $\pm 0.09$ (syst.) |

need to form and to be distinguished. The situation is obviously different if one considers effects resulting from a nucleus-nucleus collision, such as that of a QGP which is produced at small velocities/rapidities in the center-of-mass frame of the nucleus-nucleus reaction. This is precisely the region covered the LHC detectors which are used to detect quarkonia.

However, in 2013, the CMS collaboration carried out the corresponding analysis in proton-nucleus collisions at 5 TeV [7]. At the great surprise of many, they uncovered a significant relative suppression of the $2S$ and $3S$ states with respect to the $1S$ state. Quantitatively speaking, if the effects responsible for the relative $nS/1S$ suppression in $p$Pb collisions quoted in Table 1 factorise (and is thus squared in the PbPb case), they could be responsible for half of the PbPb relative suppression strongly contradicting all previous expectations! This illustrates how important state-of-the-art and dedicated studies in $p$Pb collisions are.

In addition to be of crucial importance to correctly interpret nucleus-nucleus observations – as just illustrated, such proton-nucleus reactions involve many physics effects, which are of high interest on their own, and which can certainly tell us much about QCD at the interface between its perturbative and nonperturbative domain. They indeed provide means to study:

- the nuclear modification of the parton distributions of nucleons inside nuclei, also referred as to shadowing, antishadowing, EMC and Fermi-motion effects;
- the phenomenon of gluon saturation and the high-energy limit of QCD, the so-called low-$x$ physics;
- the time-evolution of a $Q\bar{Q}$ pair and the dynamics of its hadronisation;
- the propagation of quarks and gluons in a dense medium, the process of energy loss and the Cronin effect;
- the quarkonium-production mechanisms, in particular the colour octet vs. singlet contributions;
- the nonperturbative charm content of the proton;
- the collinear-factorisation framework in the nuclear medium;
- the quarkonium-hadron interactions;
- the mechanisms underlying single-spin asymmetries, …

In this proceedings contribution, I briefly review the current knowledge of quarkonium production in proton-nucleus collisions at ultra-relativistic energies, with a specific focus on quarkonium radially-excited states.

2. A baseline to understand the basics

Let us start by discussing a simple picture where only two effects are accounted for, namely (i) the inelastic scattering of the quarkonia with some nucleons in the nuclear matter, sometimes also called the nuclear absorption and (ii) the modification of the partonic densities in nucleons embedded in nuclei, historically referred to as the EMC effect.
The differential cross section as a function, for instance, of \( y, P_T \) and \( \vec{b} \) for the production of a quarkonium in a proton-nucleus collision can be assumed to be obtained from the partonic one via the following convolution:

\[
\frac{d\sigma_{pA \rightarrow Q\bar{Q}}}{dy \, dP_T \, d\vec{b}} = \int dx_1 \, dx_2 \, g(x_1, \mu_F) \int dz_A \, F_A^g(x_2, \vec{b}, z_B, \mu_F) \times 2\hat{s}P_T \frac{d\sigma_{gg \rightarrow Q\bar{Q} \; pA}}{dt} \delta(\hat{s} - \hat{t} - \hat{u} - M^2)S_A(\vec{b}, z_A)
\] (1)

The partonic differential cross section \( \frac{d\sigma_{gg \rightarrow Q\bar{Q} \; pA}}{dt} \) can in principle be evaluated from any model (Colour Singlet, Colour Octet or Colour Evaporation Model for instance. See [8, 9, 10] for reviews.) provided that it satisfactorily describes the spectra under scrutiny, i.e. \( y \) or \( P_T \). To do so, we have developed a probabilistic Glauber Monte Carlo code, JIN, which can handle any expression for \( \frac{d\sigma_{gg \rightarrow Q\bar{Q} \; pA}}{dt} \) [11, 12, 13], yet accounting for the impact-parameter \( \vec{b} \) dependence of any nuclear effect.

Since theoretical predictions are usually compared to experimental measurements in the form of \( R_{pA} \), the absolute normalisation of \( \frac{d\sigma_{gg \rightarrow Q\bar{Q} \; pA}}{dt} \) cancels out. In general, its normalisation uncertainty (from the heavy-quark mass, the scales and nonpertubative inputs), which can easily be on the order of a factor of 2 or 3, is significantly larger than the expected nuclear effects, up to 50% at best. It makes sense to keep looking at \( R_{pA} \) rather than at \( \sigma_{pA} \) not to be misguided by normalisation issues unrelated to nuclear effects.

2.1. The so-called nuclear break-up

The first basic effect and ingredient entering this simple approach is the survival probability for a \( Q\bar{Q} \) produced at the point \((\vec{r}_A, z_A)\) to escape the nuclear medium unscathed. It is usually parametrised as

\[
S_A(\vec{r}_A, z_A) = \exp \left(-A \sigma_{\text{break-up}} \int_{z_A}^{\infty} \rho_A(\vec{r}_A, \tilde{z}) \, d\tilde{z} \right),
\] (2)

by introducing \( \sigma_{\text{break-up}} \) as the cross section for inelastic collisions between a nucleon in the nuclear matter—the nucleus—and the quarkonium (\( \rho_A(\vec{r}_A, z) \) is the nuclear density). Although it is sometimes meant to account for any effect beyond those of the nuclear PDF (see below), \( \sigma_{\text{break-up}} \) is nevertheless considered to be somehow connected to the size of the propagating object. In particular, if the meson is formed when it traverses the nuclear matter, one expects \( \sigma_{\text{break-up}} \propto r_{\text{meson}}^2 \). In particular, 2\( S \) (and 3\( S \)) states should significantly be more suppressed owing to their significantly larger radius.

In principle, \( \sigma_{\text{break-up}} \) is also connected to the meson-photonproduction cross section on nuclear target. This connection is however not always trivial [14]. Both charmonia and bottomonia typically need 0.3 ÷ 0.4 fm/c to form – in other words for one to be able to distinguish the 1\( S \) – 2\( S \) energy levels in the meson rest frame. If the quarkonium momentum in the nucleus rest frame increases, this time gets boosted and the states form way outside the nuclear matter. In such a case, they are less suppressed and such a break-up mechanism should act on the same way on any state of a family. What propagates in the nuclear matter is a sort of pre-resonant state whose quantum numbers are not yet determined.

To fix the idea, in the case of a quarkonium produced at \( y = 0 \) in a \( dAu \) collision at RHIC at \( \sqrt{s_{NN}} = 200 \) GeV, the boost between the quarkonium rest frame and that of the gold nucleus\(^2 \) is \( \gamma = E_{\text{beam, cms}}/m_N \simeq 107 \). It thus takes 30 fm/c for a quarkonium to form and to

\(^2 \gamma(y = 0) = \cosh(\gamma_{\text{beam}} = 5.36)\).
become distinguishable from its excited states. At the LHC (5 TeV), still for a particle with 
\( y = 0, \gamma \simeq 2660 (y_{beam} = 8.58) \). The quarkonium-formation time seen from the nuclear-matter 
viewpoint is now 800 \( \div \) 1000 fm/c. No nuclear-matter effect taking place over the size of the 
nucleus, \textit{i.e.} less than 15 fm, can in principle act differently on a \( J/\psi \) or \( \Upsilon \) and its excited 
states. The boost at \( y = 0 \) increases when one increases the collision energies, and obviously 
does so when one increases \( y \) in the colliding nucleon direction. This formation-time effect has 
for instance been invoked to explain the disappearance of the different \( \psi' \) vs \( J/\psi \) suppression 
measured by E866 [15] at Fermilab when moving from \( y \simeq 0 (x_F \simeq 0) \) to forward rapidities 
\((x_F \rightarrow 1)\).

For extremely large values of \( \gamma \), what propagates in the nucleus is probably a mere \( Q\bar{Q} \) pair–
whose colour state is however not known–and, in such a case, one could assume a naive high 
energy limit, \( \sigma_{\text{break-up}} \propto \pi/m_Q^2 \), that is on the order of 0.5 mb for the charmonia. The situation 
is however much more complex, not only because of the suppression of the gluon densities, which 
I discuss below, but also because of non-linear coherent effects [16] arising at high energies.

In general, one admits that the “conventional” nuclear break-up is not among the dominant 
effects at LHC energies-except perhaps in the backward edge of the LHCb acceptance–and can 
even be neglected. According to the above discussion about the formation time, what should 
matter to determine if \( \sigma_{\text{break-up}} \) is large or not is \( \sqrt{s_{NN}} \), or the energy of the quarkonium in the 
nucleus rest frame, rather than the collision energy, \( \sqrt{s_{NN}} \). A global survey of data at \( x_F \simeq 0 \) 
however showed [17] that \( \sigma_{\text{break-up}} \) seemed to scale and to decrease with \( \sqrt{s_{NN}} \). However, I 
stress that a scaling and a decrease with \( \sqrt{s_{NN}} \) was not ruled out in presence of a strong gluon 
shadowing (see Fig. 11 (d) of [17]) as I discuss now.

### 2.2. Implementing nuclear PDFs and their impact-parameter dependences

In addition to final-state interactions-once the meson is produced-in the nuclear matter, one 
should indeed account for the nuclear modification of the initial parton densities. To do so, 
the nuclear gluon PDF and its spatial dependence, \( F_g^A(x_1, \tilde{r}_A, z_A, \mu_F) \), are assumed to be 
factorisable [18] in terms of the nucleon gluon PDFs:

\[
F_g^A(x_1, \tilde{r}_A, z_A; \mu_F) = \rho_A(\tilde{r}_A, z_A) \times g(x_1; \mu_F) \times \left( 1 + \left[ R_g^A(x, \mu_F) - 1 \right] N_{\rho_A} \int \frac{dz \rho_A(\tilde{r}_A, z)}{dz \rho_A(0, z)} \right)
\]

where \( R_g^A(x, \mu_F) \) is the ratio of the gluon density per nucleon in a nucleus \( A \) by that in a free 
proton at a momentum fraction \( x \) and a factorisation scale \( \mu_F \). When discussing \( R_g^A(x, \mu_F) \), 
four regions are distinguished depending on the value of \( x \), namely the (i) Fermi-motion region 
\((x > 0.7)\), (ii) the EMC region \((0.3 < x < 0.7)\), (iii) the anti-shadowing region \((0.05 < x < 0.3)\), 
(iv) the shadowing region \((x < 0.05)\). Regarding the gluons, I stress that only the shadowing 
depletion is established, but its magnitude is still discussed. The gluon antishadowing has not 
yet been observed although assumed in many studies. For instance, it is absent in some nPDF 
fits [19]. The gluon EMC effect is even less known. We have claimed in [5] that the backward 
\( \Upsilon \) data at RHIC may hint at a significant gluon EMC effect, perhaps stronger than for quarks.

### 2.3. Overall

Typical comparisons at LHC energies when the break-up is neglected are shown on Figure 1.
A few comments are in order: (i) as discussed in [20, 5], such evaluations do depend on the 
factorisation scale as well as on the nPDF set chosen\(^4\); The corresponding uncertainties are not

\(^3\) \( N_{\rho_A} \) is fixed such that \( A^{-1} \int d^2 \tilde{r}_A \int dz \rho_A(\tilde{r}_A, z_A) \left( 1 + \left[ R_g^A(x, \mu_F) - 1 \right] N_{\rho_A} \int \frac{dz \rho_A(\tilde{r}_A, z)}{dz \rho_A(0, z)} \right) = R_g^A(x, \mu_F) \).

\(^4\) In addition to EPS09 [21] and nDSg [19] used here, other common nPDFs sets which could have been used are nCTEQ15[22], HKN [23], DSSZ[24], FSG[25], ...
Figure 1. $R_{pPb}$ at $\sqrt{s_{NN}} = 5$ TeV: typical comparisons between the ALICE and LHCb data and the effect induced by the gluon shadowing only (see text).

shown and can be as large as of a given nPDF set; (ii) the global normalisation uncertainties of the data due to the absence of $pp$ data at 5 TeV are also not shown. These however cancel in $R_{FB}$ (see [20]). (iii) such a computation accounts for a $2 \to 2$ parton scattering. Evaluations with a simplified $2 \to 1$ kinematics and based on the colour evaporation model give similar results [4, 26] (See [13] for a detailed discussion).

RHIC results have been discussed at length within this simple picture in e.g. [12, 13, 27, 28]. $\sigma_{break-up}$ was fitted to the PHENIX data. In general, this method works except in some parts of the phase space: a counter-intuitive increase of $\sigma_{break-up}$ at forward rapidities, a slight $p_T$ enhancement difficult to explain at backward rapidites, a hint at a different centrality dependence as compared to nPDFs proportional to the local nuclear density, etc. For more details, I refer the interested reader to the recent review [8] and references therein.

3. Going further by adding some nuclear effects

Whereas the simple model discussed above probably accounts reasonably well for initial state effects via nuclear PDFs, the treatment of the final state effects is indeed rather empirical for $\sigma_{break-up}$ is fitted to the data and its value $a posteriori$ confronted to qualitative expectations. As just said, it works, but some “anomalies” have lately been observed.

This has motivated more advanced theoretical studies. In particular, it was argued [29] that a coherent energy loss, scaling like the projectile energy, could explain well the data from fixed-target to LHC energies. In presence of such an energy loss, arising from interferences between initial and final state radiations, no additional break-up is needed. In a sense, it accounts for it. However, it is not clear if gluon shadowing is needed when such an energy loss is “switched on.”

The treatment of small-$x$ effects like the gluon saturation, which were initially predicted [30] to be stronger than the expected gluon-shadowing suppression from global nPDF fits, have been improved. Current postdictions [31] are in better agreement with data. They are thus on the same order as nPDF predictions, and it is legitimate to wonder if different physics is really at work.

Finally, it was recently noted in [8] that the nuclear suppression seen in the data seems not to show an increase from RHIC to LHC energies as most of the models had predicted it: higher

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5 except in presence of a strong gluon shadowing [13].

6 It has also recently been claimed that the suppression may essentially depend on the quantum state of propagating pair [32], emphasising that such a small-$x$ suppression is not merely an initial state effect.
energy, smaller $x$ and stronger shadowing. Yet, it seems that the nuclear suppression decreases when progressively going to heavier systems, i.e. from $J/\psi$ to $\Upsilon$, passing by $b(\to J/\psi)$.

4. The excited state puzzle(s)

As I have reported in the introduction, CMS uncovered an unexpected relative suppression of the $\Upsilon(2S, 3S)$ state to the $\Upsilon(1S)$. As it can be read on Table 1, it is on the order 20% for the $\Upsilon(2S)$ and 30% for the $\Upsilon(3S)$. Along the lines of the discussion of section 2.1, it is extremely counter-intuitive because of the very large boost between the quarkonia and the nucleus at LHC energies.

In fact, a similar observation was also made by the PHENIX experiment at 200 GeV. They reported [33] a relative suppression of the $\psi'$ to the $J/\psi$ increasing with the centrality (but with a large ($\approx 25\%$) global systematical uncertainty). Integrating over centrality, the ratio $[\psi'/J/\psi]_{dAu}/[\psi'/J/\psi]_{pp} = 0.68 \pm 0.14^{+0.13}_{-0.08} \pm 0.16$, i.e. smaller than unity but with significant uncertainties. Following this analysis, we confirmed [34] that the theoretical uncertainties in the nPDF impact evaluation (mass in the kinematics, scale) is at most 2 %, i.e. much smaller. ALICE also performed an analysis [35] in $p$Pb collisions at 5 TeV (see Figure 2 (right panel)) and also uncovered a relative suppression of larger magnitude in the backward region than that in the forward region.

As for now, the only approach, which can describe these results without tuning parameters$^7$, is the comover interaction model (CIM) (see [38] and references therein). Such an approach accounts for final-state scatterings with comoving hadrons along the quarkonium trajectory. These can occur over times long enough for the quarkonium to be formed; differences between the $1S$ and $2S$ suppression can thus occur. As for the break-up cross section, one introduces an empirical comover-quarkonium inelastic cross section, which is however fixed to reproduce $AA$ data where the comover density is very large. Such a picture also naturally explains a larger relative suppression in the nucleus rapidity region (negative $y$ at the LHC) where the comover density—connected to the charged particle multiplicity—is larger. Comparisons between the CIM results and data from PHENIX and ALICE are shown on Figure 2.

$^7$ In [37], Du and Rapp studied the impact of some of their model parameters on the dAu RHIC relative suppression, which is then used to study the PbPb LHC relative suppression.
5. Conclusions and outlooks

As I argued, the study of quarkonium production in proton-nucleus collisions is of fundamental importance, if one wishes to properly interpret—quantitatively but even also qualitatively—the physics underlying the quarkonium suppression in nucleus-nucleus collisions. The case of the sequential suppression of $\Upsilon$ measured by CMS is a prime example. Just measuring quarkonium production in nucleus-nucleus collisions is not enough!

Moreover, such studies are of highest relevance for themselves. It is very important to identify the mechanisms responsible for the relative suppression of quarkonium excited states seen at RHIC and the LHC. Indeed, at high energies, final-state interactions within the nucleus—as the ones included in the conventional models discussed here—occur too early to impact differently the different energy levels. One of the mechanisms, which can naturally explain such a relative suppression is the possibility of scatterings over "long" times with comoving hadrons. This is included in the comover interaction model, which was introduced long ago to explain part of the anomalous quarkonium suppression in $AA$ collisions.

As outlooks, let us stress that LHCb recently reported preliminary results on $\psi'$ production in $pPb$ collisions [39]. Their measurement confirms the ALICE one reported above. It also has the potential to extend it with the extraction of the (relative) suppression of non-prompt $\psi'$. On general grounds, $\psi'$ from $b$ come from a process at a higher scale where some nuclear effect may be smaller but, more importantly, such $\psi'$ are produced a fraction of a millimeter—as opposed to femtometers—after the collisions. As such, it is hard to believe that they would suffer from any nuclear final-state effect. As for now, the LHCb uncertainty is somewhat too large to draw any strong conclusion, the non-prompt $\psi'$ suppression is both compatible with that of non-prompt $J/\psi$—which would be compatible with the absence of final-state interactions—also with that of prompt $\psi'$, which would be another stunning result. As stunning as it could be, such a possibility should, however, not be ruled out given the previous surprising observations reported here which clearly challenged the established ideas.

In the longer run, let us add that ATLAS has also recently reported $J/\psi$ measurements in $pPb$ collisions [40] at finite $p_T$ and could also probably add some information on the excited state sector. Along these lines, the $p_T$ dependence of the relative $\psi'$ over $J/\psi$ suppression has still to be addressed theoretically and experimental uncertainties can certainly be reduced. Complementary measurements by LHCb in $pPb$ collisions bearing on Drell-Yan and open charm production may also shed some light on some nuclear-matter effects at work in the same kinematical region as for quarkonia. The same also holds for measurements in the fixed-target mode at the LHC, in the energy range of RHIC, but at negative $x_F$ and with unprecedented luminosities [41, 42, 43]. For an overview, I guide the reader to [44, 45].

To complete the picture, let us mention the importance of looking at quarkonium-associated production in $pPb$ collisions which could uncover a new geometric scaling regime $A^{3/2}$ vs $A^1$ [46, 47]. Recent theoretical [48, 49, 50, 51, 52, 53, 54] and experimental [55, 56, 57, 58, 59] studies in $pp$ collisions paved the way for such studies.

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