We study the effect of nuclear matter in $\Upsilon$ production in $d$Au collisions at RHIC and $p$Pb collisions at the LHC. We find that the nuclear modification factor, $R_{dAu}^{\Upsilon}$, measured at RHIC is not satisfactorily reproduced by the conventional effects used in the literature, namely the modification of the gluon distribution in bound nucleons and an effective survival probability for a bound state to escape the nucleus. In particular, we argue that this probability should be close to 1 as opposed to the $J/\psi$ case. We note that, at backward rapidities, the unexpected suppression of $R_{dAu}^{\Upsilon}$ observed by PHENIX hints at the presence of a gluon EMC effect, analogous to the quark EMC effect – but likely stronger. Further nuclear matter effects, such as saturation and fractional energy loss, are discussed, but none of them fit in a more global picture of quarkonium production. Predictions for $\Upsilon(nS)$ for the forthcoming $p$Pb run at 5 TeV at the LHC are also presented.

1 Introduction

Quarkonium bound states, especially the $\Upsilon$’s, offer a solid ground to probe the short distances behaviour of Quantum Chromodynamics (QCD), due to the relatively high scale provided by the large mass of the heavy quarks. In addition to the production mechanisms in the vacuum [1, 2], the properties of production and absorption of quarkonium in a nuclear medium [2, 3] provide quantitative inputs for the study of Cold Nuclear Matter (CNM) effects in proton-nucleus collisions and for the understanding of QCD at high density and temperature in nucleus-nucleus collisions.

We show that the conventional nuclear modifications of the gluon distribution in heavy ions – known as shadowing and anti-shadowing – as well as the possible break up of the $b\bar{b}$ pair along its way off the nucleus are shown to have a limited impact on the $\Upsilon$ production in $d$Au collisions at RHIC at $\sqrt{s_{NN}} = 200$ GeV. Without additional effects, the nuclear modification of
the yield available from the PHENIX experiment [4] in the backward region is not satisfactorily reproduced.

This motivated us to study in detail other effects: (a) the impact of Fermi motion on the gluon distribution in nuclei from unity down to rather low \( x \approx 0.2 \), (b) a suppression of the gluon distribution in nuclei for intermediate \( x \), \( 0.35 \leq x \leq 0.7 \), analogous to the quark EMC effect [5], unobserved until now, (c) the possible effect of the saturation of gluon dynamics at low \( x \) and finally (d) a fractional energy loss [6] proportional to the projectile parton energy and caused by medium-induced radiations associated to the quarkonium hadroproduction provided that the heavy quark pair remains in a coloured state for some time\(^1\).

We have compared our results –from our Monte-Carlo framework JIN [8]– to the \( dAu \) \( \Upsilon \) data available from RHIC experiments [4, 7] and we have predicted the trend of the nuclear modification factor for the forthcoming \( pPb \) run at the LHC only using the effect of nPDF. We have then discussed whether gluon saturation and fractional energy loss could be applied within a coherent picture of \( \Upsilon \) production.

The structure of the paper is as follows. In section 2, we discuss the propagation of the (pre-resonant) \( \Upsilon \) state in the nuclear matter and we explain why we believe that its survival probability is close to unity. In section 3, we discuss all the possible nuclear modifications of the gluon-momentum distribution in a nucleon embedded in a large nucleus which can impact on \( \Upsilon \) production in \( pA \) collisions at RHIC and LHC energies. In section 4, we present our results for \( dAu \) collisions at RHIC and compare with existing data. In section 5, we briefly sketch the expected trend for the \( \Upsilon \) nuclear modification factor in \( pPb \) collisions at 5 TeV at the LHC for a mild gluon shadowing and antishadowing. In section 6, we discuss on the possibility of the presence of a fractional energy loss at forward rapidities. Section 7 gathers our conclusions.

\section{Propagation in cold nuclear matter: \( \Upsilon \) vs \( J/\psi \)}

The first effect to be discussed is the probability for the heavy-quark pair to survive the propagation through the nuclear medium, usually parametrised by an effective cross section \( \sigma_{\text{eff}} \). It is sometimes referred to as the nuclear absorption or break-up probability.

A priori, the smaller size of the \( b\bar{b} \) pair when compared to \( c\bar{c} \) pair implies that \( b\bar{b} \) states should suffer less break-up than \( c\bar{c} \). Yet, the ratio of their size depends on the evolution stage of the heavy-quark pair. At the production time, this ratio is expected to be \( m_b/m_c \), hence a size 3 times smaller for \( b\bar{b} \) than for \( c\bar{c} \). When they are fully formed, it is rather \( \alpha_s(2m_b)/\alpha_s(2m_c) \times m_b/m_c \) as expected from their Bohr radii, hence a size 2 times smaller. The relevant timescale to analyse the pair evolution is its formation time. According to the uncertainty principle, it is related to the time needed – in their rest frame – to distinguish the energy levels of the \( 1S \) and \( 2S \) states [9]: \( t_f = \frac{2M_{g_{1S}}}{(M_{2S} - M_{1S})^2} = 2 \times 10 \text{ GeV} / 10.5 \text{ GeV}^2 = 0.4 \text{ fm} \) for the \( \Upsilon \).

For our purpose, \( t_f \) has to be considered in the rest frame of the target nucleus, \( i.e. \) the Au beam at RHIC. The relevant \( \gamma \) factor is then obtained from the rapidity of the pair corrected by the Au beam rapidity \( \gamma = \cosh(y - y_{\text{beam}}^\text{Au}) \) where \( y_{\text{beam}}^\text{Au} = -5.36 \) for RHIC. At the LHC, for a lead

\footnote{As we argue later, such effect would be in contradiction with the satisfactory [29] description of low \( P_T pp \) data by the Colour-Singlet Model [1, 2].}
beam of 1.57 TeV in pPb mode, $y_{beam} = -8.11$. The formation time for the different rapidities reached by RHIC and LHC experiments are given in Table. 1 and Table. 2. $t_f$ is significantly larger than the Au and Pb radii – except in the most backward region. This implies that the b$b$ is nearly always in a pre-resonant state when traversing the nuclear matter in both experimental set-ups.

| $y$  | $\gamma(y)$ | $t_f(y)$ | $y$  | $\gamma(y)$ | $t_f(y)$ |
|------|-------------|---------|------|-------------|---------|
| -2.0 | 14.4        | 5.8 fm  | 0.0  | 106         | 42 fm   |
| -1.5 | 23.7        | 9.5 fm  | +1.5 | 476         | 190 fm  |
| -1.0 | 39          | 16 fm   | +2.0 | 786         | 310 fm  |

Table 1: Boost and formation time in the Au rest frame of the $\Upsilon$ as a function of its rapidity at $\sqrt{s_{NN}} = 200$ GeV.

| $y$  | $\gamma(y)$ | $t_f(y)$ | $y$  | $\gamma(y)$ | $t_f(y)$ | $y$  | $\gamma(y)$ | $t_f(y)$ |
|------|-------------|---------|------|-------------|---------|------|-------------|---------|
| -4.0 | 20          | 8 fm    | -0.5 | $10^3$      | $4.0 \times 10^4$ fm | 1.5  | $7.5 \times 10^4$ | $3.0 \times 10^4$ fm |
| -3.5 | 50          | 20 fm   | 0.0  | $1.7 \times 10^3$ | $7.0 \times 10^2$ fm | 2.5  | $2.0 \times 10^4$ | $8.0 \times 10^2$ fm |
| -2.5 | 140         | 60 fm   | 0.5  | $2.7 \times 10^3$ | $1.1 \times 10^3$ fm | 3.5  | $5.5 \times 10^4$ | $2.2 \times 10^4$ fm |
| -1.5 | 370         | 150 fm  |      |             |         | 4.5  | $1.5 \times 10^5$ | $6.0 \times 10^4$ fm |

Table 2: Boost and formation time in the Pb rest frame of the $\Upsilon$ at $\sqrt{s_{NN}} = 5$ TeV in pPb collisions ($E_{Pb}^N = 1.57$ TeV and the Pb has a negative rapidity).

For the forward and mid rapidity regions, this has two consequences: first, the break-up probability is expected to be small, of the order of a tenth of that of $J/\psi$ ($(m_c/m_b)^2 \sim 0.1$), following the early-time scaling $m_b/m_c$; and second, it ought to be the same for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states, since these states cannot be distinguished at the time they traverse the nucleus. At the LHC (Table. 2), $t_f$’s are even larger in the mid and forward-rapidity regions; the relative suppression of the excited $\Upsilon$ states in PbPb collisions seen by CMS [10] can thus only be explained by hot nuclear effects.

The backward region at RHIC as well as the most backward one at the LHC require a closer look. Indeed, for the same $t_f$, of the order of 15 fm, the E866 experiment at Fermilab [11] observed a different suppression of $J/\psi$ and $\psi(2S)$ produced with Feynman $x_F$ up to 0.2 at $\sqrt{s_{NN}} = 38.8$ GeV. We might thus expect different absorption cross-section for the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states for $y < -1$. However, the E772 experiment at Fermilab [12] has measured the $\Upsilon(1S)$ and $\Upsilon(2S + 3S)$ separately at $\sqrt{s} = 38.8$ GeV down to negative $x_F$ – with even smaller $t_f$ – and it observed a similar suppression for the 1S and the (2S + 3S) states. The only explanation for such a result is that the absorption of the bottomonium is actually very small, preventing us to see any difference of absorption between the 3 states. In the following,

2As it was discussed later on (see e.g. [11]), the E772 experiment suffered from a $P_T$ dependent acceptance, especially in the backward region. For instance, the $J/\psi$ suppression was subsequently shown to be less marked than initially thought. Yet, such a correction should equally apply for the 3 $\Upsilon$ states [13].

3
we will consider a range of $\sigma_{\text{eff}}$ from 0 to 1 mb even though 1 mb has to be seen as a conservative upper bound.

3 Gluon momentum distribution in the nucleus

3.1 Gluon shadowing and antishadowing

At high energy (small $x_B$), the nuclear Parton Distribution Functions (nPDF) differ from those of free nucleons due to non-linear QCD effects. Nucleons shadow [14, 15] each other and the nPDFs are expected to be lower than for free nucleons. At $0.01 \leq x_B \leq 0.3$, some experimental data hint [16] at an excess of partons with regards to unbound nucleons, referred to as anti-shadowing. For $0.35 \leq x_B \leq 0.7$, the distribution is depleted again. This suppression is known as the EMC effect.

These nuclear modifications are usually expressed in terms of the ratios $R_A$ of the nPDF of a nucleon bound in a nucleus $A$ to the free nucleon PDF. The numerical parametrisation of $R_A(x_B, Q^2)$ is usually given for all parton flavours. Here, we limit our study to gluons since, at RHIC and the LHC, $\Upsilon$ is essentially produced through gluon fusion [1, 2]. To best explore the possible impact of $R_A$, we have considered 3 sets: EKS98 [17], EPS08 [18] and nDSg [19] at LO. Recently, a new set with fit uncertainties, EPS09 [20], has been made available. Yet, in the case of gluons, nDS and EPS08 match –except for $x_B \geq 0.3$– the extreme values of EPS09LO$^3$. Besides EKS98 is very close to EPS09LO central values. We thus consider more illustrative to use EKS98, EPS08 and nDSg. The spatial dependence of the PDF nuclear modification has been included with a modification proportional to the local density [21]. Following the common practice, we label $x_1$ ($x_2$) the gluon momentum fraction in the proton/deuteron (nucleus).

To account for the nuclear effects on $\Upsilon$ production in nucleus collisions, we use our Monte-Carlo framework JIN [8], based on the probabilistic Glauber model, used to describe $J/\psi$ production at RHIC [22, 23]. It allows to consider improved kinematics corresponding to a $2 \rightarrow 2$ ($g+g \rightarrow b\bar{b}+g$) partonic process for the $\Upsilon$ production (as in the Colour-Singlet Model (CSM) at LO [25], but also at higher-orders in $\alpha_S$ with 2 or 3 coloured partons in the final state [26, 27]). In earlier studies of nuclear matter effects on $\Upsilon$ production [28], the $b\bar{b}$ pair was assumed to be produced by a $2 \rightarrow 1$ partonic process ($g+g \rightarrow b\bar{b}$). It would only apply if Color-Octet Mechanism (COM) at LO were the relevant production mechanism at low transverse momenta. This is disfavoured in view of the recent comparisons between the CSM predictions and the experimental data [29], which leave little room for any COM contributions for $P_T \lesssim 5$ GeV.

3.2 The EMC effect and the gluons

Thirty years ago, the European Muon Collaboration (EMC) [5] observed a depletion of the quark densities in nucleons bound in nuclei, when compared to the ones of free nucleons, in the range of $0.35 < x_B < 0.7$. To date, there is no consensus [30] about the origin of this

$^3$Note, however, that the central curves for the LO and NLO EPS09 fits are different. This difference is particularly large at low $Q^2$. 

4
suppression, referred to as the EMC effect. It is still the subject of vivid activities. It has been
attributed to local nuclear density effects, to properties of the bulk nuclear system, and recently
[31] to Short Range Correlations (SRC) in the nucleus. Up to now, this effect has not been
confirmed for gluons, even if it is allowed in some of the shadowing fits.

![Figure 1: The EPS09 uncertainty for the gluon density for Au at mid and large x and the 3 gluon
nPDF sets we have used to single out the EMC effect.](image)

While gluon shadowing in the existing constrained fits of nPDFs, especially in EPS 08 & 09,
is the subject of intense on-going debates, the gluon EMC suppression is usually overlooked.
Indeed, very little is known about gluons in this region and few data constrain their distribution
at $x_B$ larger than 0.3. The amount of the gluon EMC suppression is actually pretty much
unknown [20] (see Fig. 1), except for a loose constrain set by momentum conservation. We also
note that another effect [32] arising from momentum conservation within the nucleons could be
at play at larger $x$, $x \geq 0.7$, i.e. at larger $y$ or smaller $\sqrt{s_{NN}}$, and hence it is not applicable here.

In the following discussion, in order to single out a possible impact of the gluon EMC
suppression on the $\Upsilon$ production at RHIC, we will use three of the EPS09 LO sets: one with a
quark-like EMC gluon suppression, and the two limiting curves in the region $0.35 < x_B < 0.7$
(Fig. 1). As the data-theory comparison will show, its magnitude indeed seems stronger than
what has been previously supposed in most of the existing nPDF sets (which assumed a quark-
like EMC gluon suppression) and disagrees with a Fermi-motion enhancement down to $x_B \approx 0.5$
as expected in [33].

### 3.3 Fermi-motion and the gluons in the EMC region

Beside the scarce information on the gluon in the EMC region which can be obtained from
global fits of nPDFs, some theoretical ideas have been put forward. For instance, it has been
suggested [33] that the stronger falloff at large-\(x\) of the gluon PDF \(((1 - x)^5)\) vs the quark one \(((1 - x)^3)\) would have as consequence that the nPDF enhancement due to the Fermi-motion would manifest itself in gluon densities down to smaller \(x\) than in quark ones.

In practice, the Fermi-motion effect can simply be taken into account by convoluting the nucleon PDF of a given flavour with a gaussian distribution encoding the effect of the Fermi momentum, \(p_F\). Following [33], one has for the gluon density in a nucleus \(A\):

\[
g_A(x) = \int_x^1 dz N(z) \frac{1}{z} g\left(\frac{x}{z}\right), \text{ with } N(z) = \frac{1}{\sqrt{2\pi\gamma}} \exp\left(-\frac{(z - 1)^2}{2\gamma}\right),
\]

where \(z\) corresponds to the light cone momentum fraction of the nucleon in the nucleus \((z = Ap_N/p_A)\), \(g(x)\) is the gluon distribution in the nucleon, \(\gamma = \langle p_z^2 \rangle/M_N^2 = \frac{1}{5p_F^2}/M_N^2\) and \(p_F = 0.27\) GeV [34].

![Figure 2: Comparison between the nuclear modification of the gluon and \(u\)-quark distributions in a lead nucleus at large \(x\) only due to the Fermi motion following [33] (blue double dot, red dot-dash) and those encoded in EPS09LO (green long-dash, yellow small dash) and nDSg (pink dot, purple dot-long dash).](image)

Fig. 2 shows our result for the \(u\)-quark and the gluon densities in a Pb nucleus modified by the Fermi motion\(^4\) compared to those from EPS09LO and from nDSg. The impact of the Fermi motion is larger for the gluon than for the \(u\)-quark in the region of applicability of the model of [33]. This arises uniquely from the different behaviour of the nucleon PDF at large \(x\). One also observes that the gluon distribution is still enhanced at \(x \approx 0.4\) whereas the \(u\)-quark one is then nearly unmodified. As can be seen on Fig. 2, the trend of the nDSg fit follows the behaviour expected from the Fermi motion. nDSg can thus be seen as a realisation of this simple model. On the contrary, the EPS09LO fit shows a different behaviour since it incorporates additional effects from antishadowing and from EMC suppression.

\(^4\)using, as initial proton PDF, the MSTW LO set [35].
3.4 Gluon saturation and $\Upsilon$ production at RHIC and LHC energies

In order to evaluate the saturation scale from which one expects effects beyond collinear factorisation to be important in $\Upsilon$ production in $pA$, we have employed the following formula [36, 37]:

$$Q_{sA}^2 = A^{\frac{2}{3}} \times 0.2 \times \left(\frac{x_0}{x}\right)^{\lambda} \text{(in unit of GeV}^2),$$

with $\lambda \sim 0.2 \pm 0.3$ and with $x_0 = 0.01$ which sets the minimum momentum fraction below which one expects non-linear effects to be significant in the evolution of the parton distribution. In the previous formula, we have set $x$ equal to $\langle x_2 \rangle$ computed with our Monte Carlo framework for a given rapidity. The values which we have obtained for $Q_{sA}$ are given in Table 3 and Table 4 along with the ratio of $Q_{sA}$ to the $\Upsilon$ mass. For the rapidities where $\langle x_2 \rangle$ was found to be above $x_0$, the saturation scale in a proton is of the order of $\Lambda_{QCD}$. Even in a large nucleus, it is still below 1 GeV. In such a case, one thus does not expect any new phenomenon beyond collinear factorisation—i.e. beyond those encoded in the nPDFs— to be significant in hard processes such as heavy-quark and quarkonium production.

| $y$   | $Q_{s\text{Au}}$(GeV) | $Q_{s\text{Au}}/m_{\Upsilon}$ | $y$   | $Q_{s\text{Au}}$(GeV) | $Q_{s\text{Au}}/m_{\Upsilon}$ |
|-------|----------------------|--------------------------------|-------|----------------------|--------------------------------|
| -2.0  | $\leq 1$             | $-$                            | 0.0   | $\leq 1$             | $-$                            |
| -1.5  | $\leq 1$             | $-$                            | +1.5  | 1.0 $\div$ 1.1      | 0.1                            |
| -1.0  | $\leq 1$             | $-$                            | +2.0  | 1.1 $\div$ 1.2      | 0.1                            |

Table 3: Evaluation of the saturation scale (for $x \leq x_0$) in the Au nucleus, $Q_{s\text{Au}}$, and of its ratio to $m_{\Upsilon}$ for the kinematics of the $\Upsilon$ production at $\sqrt{s_{NN}} = 200$ GeV in $d\text{Au}$ collisions as a function of the $\Upsilon$ rapidity (in the $d\text{Au}$ CMS, i.e. the laboratory system at RHIC).

| $y$   | $Q_{s\text{Pb}}$(GeV) | $Q_{s\text{Pb}}/m_{\Upsilon}$ | $y$   | $Q_{s\text{Pb}}$(GeV) | $Q_{s\text{Pb}}/m_{\Upsilon}$ |
|-------|----------------------|--------------------------------|-------|----------------------|--------------------------------|
| -4.0  | $\leq 1$             | $-$                            | +2.0  | 1.6 $\div$ 1.9      | 0.2                            |
| -2.0  | $\leq 1$             | $-$                            | +4.0  | 1.9 $\div$ 2.5      | 0.2 $-$ 0.25                    |
| 0.0   | 1.3 $\div$ 1.4      | 0.15                           |

Table 4: Same as Table 3 at $\sqrt{s_{NN}} = 5$ TeV in $p\text{Pb}$ collisions as a function of the $\Upsilon$ rapidity (in the CM).

Following the values displayed on Table 3 and Table 4, one does not expect any specific saturation effect on $\Upsilon$ production in $p(d)A$ collisions at RHIC and the LHC since the saturation scale is always well below the typical energy scale of the process, namely $m_{\Upsilon}$ or even $m_b$. In particular, the shadowing of the gluons as encoded in the nPDF fits based on the collinear factorisation should give a reliable account of the possible low-$x$ physics in the forward region.
4 Results for \(dAu\) collisions at RHIC

Experimentally, the nuclear effects on \(\Upsilon\) production in \(dAu\) is studied by measuring a nuclear modification factor \(R_{dAu}\), the ratio of the yield in \(dAu\) collisions to the yield in \(pp\) collisions at the same energy, times the average number of binary inelastic nucleon-nucleon collisions, \(N_{\text{coll}}\), in a \(dAu\) collision:

\[
R_{dAu} = \frac{dN_{dAu}}{\langle N_{\text{coll}} \rangle dN_{pp}}.
\]

Any nuclear effect affecting the \(\Upsilon\) production leads to \(R_{dAu} \neq 1\).

From the data from STAR and PHENIX [4, 7], only the rapidity dependence of \(R_{dAu}\) is known. For now, the 3 \(\Upsilon\) resonances are not resolved but are measured together. Since the nuclear absorption has to be small and since the nPDF effects are very likely similar for these 3 states, we can safely consider them on the same footage. However, it is worth noting that a future measurement of \(R_{dAu}\) focusing only on \(\Upsilon(1S)\) would be very precious to confirm this assumption.

![Figure 3: Theoretical uncertainties on \(R_{dAu}^{\Upsilon}\) due to usual nPDFs (coloured lines) and \(\sigma_{\text{eff}}\) (purple band). Data for \(\Upsilon\) are from [4, 7].](image)

Fig. 3 shows the uncertainties on \(R_{dAu}^{\Upsilon}\) vs \(y\) due to the lack of knowledge on the gluon nPDF and due to a variation of \(\sigma_{\text{eff}}\) between 0 and 1 mb. The nuclear absorption (purple band) shows a very mild effect – despite the likely exaggerated upper value we have taken. It is in any case insufficient to reproduce the available data in the backward rapidity region. At mid \(y\), the STAR data do not show any hint of antishadowing. In fact, the nDSg nPDF –without any antishadowing– gives the best account of the data. If this was to be confirmed, this would be an extremely important constrain for further fits of gluon nPDFs. A measurement bearing on the sole \(\Upsilon(1S)\) and possibly with a binning in \(y\) which would allow one to see if the suppression is getting even stronger for more negative \(y\) or not, would therefore be invaluable.
At forward $y$, the shadowing encoded in the three usual nPDF fits we have used (EKS98, EPS08 and nDSg) agrees with the present PHENIX data.

As one can see on Fig. 4 for backward $y$, a gluon EMC effect stronger than that of quarks (dashed blue lines), such as the one provided by the EPS09 lower bound –or stronger–, would be provide a convincing account of the backward data. A strong gluon EMC effect is perfectly legitimate given the current knowledge of the gluon nPDF in this region. The current experimental uncertainties are large and the observation of such a strong EMC gluonic effect would only be confirmed once we have data with reduced errors. The data however already visibly disfavour the case with no gluon EMC effect in EPS09LO (orange solid bars on Fig. 4) with an excess\(^5\) of the gluons all the way from the antishadowing region up to the Fermi motion one (see Fig. 1).

In the absence of any antishadowing, let us also recall that the behaviour of nDSg for $x > 0.1$ would be very close to what is expected from the Fermi motion effect and would disagree with the PHENIX value (Fig. 3). As already mentioned, the current data are not precise enough to draw further conclusions.

5 Results for $pPb$ collisions at the LHC

We have extended our study to the $\Upsilon$ production for $pPb$ collisions at $\sqrt{s_{NN}} = 5$ TeV. In Fig. 5, the effect of the shadowing as encoded in EPS09 LO is shown to be important, in particular in

\(^5\)Such excess of the gluon density in large nuclei would be in line with the expected enhancement due to the Fermi motion and the steep large-$x$ falloff of $g(x)$. 
the forward rapidity region. Taking into account that in PbPb collisions at mid rapidities the shadowing effect is squared compared to pPb, we can expect, in minimum bias PbPb collisions, a typical suppression due to shadowing of the order of 20%.

In addition, we suggest to analyse the forward-to-backward ratio of the nuclear modification factor, \( R_{FB}(\mid y_{CM}) \equiv R_{pPb}(y_{CM})/R_{pPb}(-y_{CM}) \) which has the advantage to be independent of a pp reference and in which some systematic experimental uncertainties would cancel. Our predictions for such a quantity are presented on Fig. 6 for the LHC kinematics. Such a forward-backward asymmetry is quite large (up to 45%) and should be measurable.

Provided that the only nuclear effect on the \( \Upsilon \) production at the LHC would come from the modification of the PDFs, it is interesting to figure out how similar the suppression/enhancement of the 3 \( \Upsilon \) states would be. Two effects can enter: a shift in \( x_2 \) and a difference in the scale of the process, \( Q^2 \). We have checked, using EPS09LO [20], EPS09NLO [20], nDSgLO [19], HKN04LO [39] and with conservative choices of the \( Q^2 \), that the nuclear modification factors of \( \Upsilon(nS) \) are expected to be equal to a precision of 2%.

Yet, new effects might come into play. One of these is the fractional energy loss discussed in the next section, which shows a magnitude inversely proportional to the mass state. This is, however, not sufficient to produce any visible difference within the \( R_{pPb} \) of the 3 \( \Upsilon \) states. In fact, the difference would also be of the order of a few percents. As a reminder, conventional nuclear absorption can neither be an effect impacting differently on the 3 states, simply because only a single type of pre-resonant state propagates in the nuclear matter at the LHC.

Unfortunately, as long as one does not have at our disposal a pp reference at 5 TeV, the uncertainties in the normalisation of the nuclear modification factor would of course not allow
to reach precision of a few percents. It will thus be expedient to analyse differences in central-to-peripheral nuclear modification factors, $R_{CP}$ or forward-to-backward nuclear modification factors, $R_{FB}$ for $3\Upsilon$ states.

## 6 Energy loss and production mechanism

It has recently [6] been pointed out that, in the case of small angle quarkonium production, the spectrum of the gluon radiation induced by the nuclear medium can scale as the quarkonium energy $E$. The main reason for such a fact is that the gluon radiation arises from large formation times $t_f \gg L$ and it is not subject to the bound derived in [40] preventing any parton energy loss to scale like the projectile energy and thus to impact quarkonium production at RHIC and LHC energies.

This fractional energy loss may however only act on octet-like mechanisms\(^6\) where the heavy-quark pair is produced at short distances in a colour-octet state and where the latter has thus a long enough time to radiate. This is a priori so in the Colour-Evaporation Model (CEM) and the Color-Octet Mechanism (COM) (see [1, 2]). For singlet-like mechanisms –such as the CSM which is favoured by the low $P_T \pp$ data [29]– for which the heavy-quark pair is produced at short distances (or at short production times, $t_{prod}$) in a colour-singlet state, such an energy loss is not expected to occur –at least as a fractional energy loss, scaling in $E$.

\(^6\)Along the same lines, it would not have any effect on DY pair production for instance.
Following [6], one finds that for forward angle Υ production in pA collisions via a long-lived color-octet pair, the fraction of medium-induced radiated energy is given by

\[ \frac{\Delta E}{E} \approx N_c \alpha_s \sqrt{\Delta \langle p_T^2 \rangle / M_T}, \]

where \( \Delta \langle p_T^2 \rangle \) is the broadening of the radiated gluon from the proton and \( M_T \) is the transverse mass of the final-state coloured object. \( \Delta \langle p_T^2 \rangle \) can be indirectly fit from the data as in [41]. Its size can also be guessed from the Υ broadening, \( \Delta \langle P_T^{\Upsilon^2} \rangle \equiv \langle P_T^{\Upsilon^2} \rangle(A) - \langle P_T^{\Upsilon^2} \rangle(2H) \), proportional to the length of nuclear matter seen by the incoming parton. This broadening of \( P_T^{\Upsilon^2} \) is consistent with a dependence on \( A^{1/3} \), as expected in multiple scattering models. Taking the E772 value\(^7\) with W target [42, 12], \( \Delta \langle P_T^{\Upsilon^2} \rangle = 0.410 \text{ GeV}^2 \), one can thus write

\[ \Delta \langle P_T^{\Upsilon^2} \rangle = 0.072 \text{ GeV}^2 A^{1/3}. \]

For \( N_c = 3 \) and \( \alpha_s = 0.2 \), we estimate a maximum loss of the order of \( \Delta E_{\text{max}} / E \approx 4\% \). It is important to note that \( \Upsilon \) production at LO does not involve the emission of a coloured heavy quark pair, both in the CSM and the COM. Any feed-down from it would not be affected by such an energy loss. For forward Υ produced at RHIC, this energy loss implies a suppression of the order 10-15 % when implemented in the PDFs (see Fig. 7).

\[ R_{dAu}^{\Upsilon} \text{ Expected range for the effect of a fractional energy loss for a yield up to 100% from an octet-like mechanism (e.g. COM, CEM)} \]

![Figure 7: Expected range for the energy loss on \( R_{dAu}^{\Upsilon} \) for a production mechanism where the heavy-quark remains in a coloured state for a long time. Data for Υ are from[4, 7].](image)

Moreover, this suppression by an energy loss undergone by the heavy-quark pair before its hadronisation is in apparent conflict with the convincing account of the \( P_T \)-integrated yields by the CSM approach –see for instance [29] for a recent account of the comparison between the CSM prediction and the results at RHIC, the Tevatron and the LHC. It is worth mentioning that the computation in the CSM does not involve any adjustable parameter and that any

\[ \text{We note a discrepancy between the published value of Ref. [12] and that subsequently published in a review by members of E772 [42]. We prefer to use the latter since "[T]his difference was due to the use of earlier parameterisations of the } P_T \text{ dependence, derived by E605 for } pCu \text{ collisions, rather than the new function based on } p^3H \text{ data"} \ [43]. \]
contribution from colour-octet transitions would be additive. We would face an excess of the theoretical prediction in $pp$ as compared to the existing measurements if we were to invoke a significant fraction of the yield to be suppressed in $pA$ since from a colour-octet like production mechanism.

In fact, for the time being, there is no up-to-date study of $\Upsilon$ production at low $P_T$ (below 5 GeV) incorporating in a consistent way the contributions from the leading colour-octet transitions. The most recent $\Upsilon$ analysis with CO at NLO did not even attempt to consider $P_T$’s below 7 GeV [44]. In any case, to clear up the situation, at least at RHIC energy, it is of paramount importance to have at our disposal experimental measurements of the $\Upsilon(1S)$ yield integrated and differential in $P_T$ as well as in rapidity. Hopefully, such measurements would be available soon with the data accumulated at RHIC.

7 Conclusion

We have investigated the $\Upsilon$ suppression in $dAu$ collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and in $pPb$ collisions at $\sqrt{s_{NN}} = 5$ TeV at the LHC. The rapidities covered by the RHIC experiments allow for a unique study of cold nuclear matter effects and revealed unexpected features presented here. Backward rapidities correspond to the largest $x_2$, above 0.2, where one can expect an EMC suppression – at least for quark PDFs. For mid and slightly backward rapidities, one expects anti-shadowing, i.e. an excess of partons inducing an excess of $\Upsilon$. Finally, the forward domain – where $x_2$ becomes small – should be subject to parton shadowing, giving a reduction of the yield.

We have first argued that, for bottomonia, as opposed to charmonia, the survival probability for the pre-resonant state to escape a large nucleus should be large and close to unity. In turn, the use of a small effective absorption cross section is mandatory.

Then, we have discussed the different effects which can be expected from the modification of the gluon densities in a nucleon bound in a heavy nucleus, namely from high $x$ to low $x$: the Fermi motion, the EMC effect, the antishadowing, the shadowing and then the saturation.

We have confronted these expectations with the existing data and our findings were as follows: in the most backward region, studied by PHENIX, the suppression of the $\Upsilon$ yield in the $dAu$ data may be a first hint of an EMC suppression of the gluon PDF, possibly stronger than the quark one. It is one of the first observations of such an effect, whose quantitative understanding may in the future provide us with fundamental information on the internal dynamics of heavy nuclei such as those studied at RHIC, especially if the EMC gluon effect is stronger than the quark one. In the central rapidity region, the existing STAR data does not exhibit any excess which would pin down anti-shadowing.

In addition, due to the large scale set in by the $\Upsilon$ mass, shadowing is found to be small and it reproduces the present PHENIX data [4] at $y > 0$. As we discussed, additional effects sometimes claimed to apply to $J/\psi$ production –such as saturation or fractional energy loss– are not relevant here and, in fact, are not needed. We have indeed demonstrated that –at variance with the $J/\psi$ case [23, 24]– gluon shadowing has, for any nPDF fit, a small effect at the $x_2$ and $Q^2$ of forward-$\Upsilon$ production at RHIC.

13
We have finally concluded that additional data at RHIC energies both in $pp$ and $dAu$ collisions are eagerly awaited as well as the forthcoming LHC data in $pPb$ collisions at 5 TeV.

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