# Υ production in *pp* and *pA* collisions: from RHIC to the LHC

J. P. Lansberg

*IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France*

## Abstract

I discuss Υ production in *pp* collisions at RHIC, Tevatron and LHC energies, in particular the behaviour of the differential cross section in rapidity and the impact of QCD corrections on the $P_T$ differential cross section. I also emphasise the very good agreement between the parameter-free predictions of the Colour-Singlet Model (CSM) and the first LHC data, especially in the region of low transverse momenta, which is the most relevant one for heavy-ion studies. I also show that the CSM predicts Υ cross-section ratios in agreement with the most recent LHC data. I then briefly discuss the nuclear-matter effects on Υ production at RHIC and the LHC in $p(d)A$ collisions and, by extension, in *AA* collisions. I argue that a) the Υ break-up probability can be neglected, at RHIC and the LHC, b) gluon shadowing –although non-negligible– is not strong enough to describe forward RHIC data, c) backward RHIC data hints at a gluon EMC effect, possibly stronger than the quark one. Outlooks for the LHC *p*Pb run are also presented.

*Keywords:* Υ production, proton-proton collisions, cold nuclear matter effects, heavy-ion collisions

## 1. Introduction

With the advent of the LHC, the study of Υ production has become more accessible than ever. First results [1–4], in *pp* and PbPb collisions, have already been obtained and the Υ production pattern at the LHC differs from that of the lighter $\psi$'s. Υ's are thus complementary probes of the QCD dynamics in *pp* and PbPb collisions besides the charmonia [5]. It is therefore important to achieve a good understanding of their production mechanism in the vacuum as well as of how different the nuclear effects in proton-nucleus collisions are when they act on Υ and on $J/\psi$.

I first discuss *pp* collisions. I show that the $P_T$-integrated yields obtained at LO in $\alpha_S$ and $v$ (the *b*-quark velocity in the Υ) agree with the data at different $\sqrt{s}$ and $y$. In turn, I briefly mention the impact of QCD corrections on the $P_T$ spectrum. In particular, a comparison with the LHCb data is shown and it demonstrates that the NLO CSM describes very well the Υ yield up to 5 GeV. The CSM also provides with parameter-free predictions for Υ cross-section ratios in agreement with the most recent LHC data. Finally, the NNLO leading-$P_T$ contributions seem to be required to account for the data at larger $P_T$ as the comparison with the NNLO$^\star$ yield shows. In a second section, I discuss the effect of (cold) nuclear matter as probed in Υ production in *d*Au collisions at RHIC and *p*Pb collisions at the LHC.

## 2. Υ production in *pp* collisions: from RHIC to LHC energies

### 2.1. Total and differential cross sections

I discuss first the total number of Υ produced in *pp* collisions as predicted by the CSM at LO in $\alpha_S$ and irrespective of their transverse momenta. Contrary to what is sometimes claimed in the literature (see *e.g.* [6]) the yield from colour-singlet transitions agrees with the experimental measurements. There is a slight discrepancy at RHIC energy

with the STAR data [7], which is nevertheless less precise[1] than that of the Tevatron [8, 9] and LHC [1–3], with which the LO CSM evaluations are in good agreement.

Fig. 1 (a) and (b) nicely illustrate the situation. Both the energy and the rapidity dependences of the $P_T$-integrated cross section are well reproduced by the LO band. The theory uncertainty at LO is unfortunately large due to the presence of three powers of $\alpha_S$ in the LO cross-section, hence one finds a significant renormalisation-scale dependence. The experimental measurements at the Tevatron and the LHC are in fact more precise than the theory. Yet, it has to be noted that, at the LHC (Fig. 1 (b)), the experimental points tend to lie in the lower part of the theory band.



(a) Energy dependence of the $\Upsilon(1S)$ yield at $y = 0$

(b) Rapidity dependence of the $\Upsilon(1S)$ yield at 7 TeV

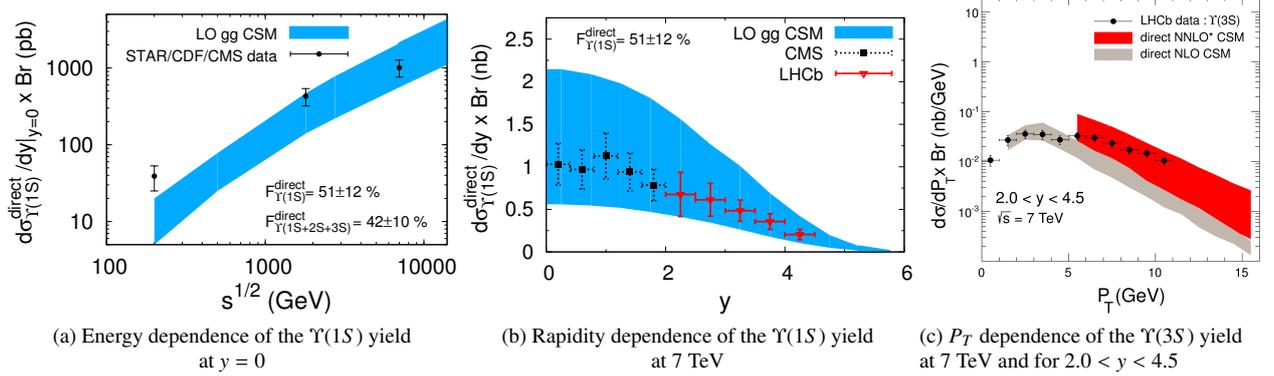(c) $P_T$ dependence of the $\Upsilon(3S)$ yield at 7 TeV and for $2.0 < y < 4.5$

Figure 1: (a) and (b): comparison between the CSM predictions for the direct $\Upsilon(1S)$ yield and various experimental data [1, 3, 7] for the prompt $\Upsilon(1S)$ yield multiplied by $F^{\text{direct}}_{\Upsilon(1S)}$ [10] or $F^{\text{direct}}_{\Upsilon(1S+2S+3S)}$ [14] for the STAR data. (c): comparison between the $\Upsilon(3S)$ LHCb data [3] and the NLO and NNLO$^\star$ CSM predictions for the direct yield.

The situation is nevertheless more intricate when the $P_T$ dependence of the yield is concerned [11]. The main reason is that the leading-$P_T$ contributions to $\Upsilon$ hadroproduction only appear at NNLO in the CSM. For the time being, only the NLO cross section [12] is fully known along with a partial evaluation of the NNLO yield, dubbed NNLO$^\star$ [13]. As expected from the discussion of the $P_T$ integrated yields, the cross section at low $P_T$ is well reproduced by the NLO yield; it only differs from the LO yield by a harder $P_T$ spectrum. The partial NNLO yield is even harder and it matches the data at higher $P_T$. Yet, a full NNLO computation is needed before drawing final conclusions. This is illustrated on Fig. 1 (c) by a comparison between the LHCb data for $\Upsilon(3S)$ compared to the NLO and NNLO$^\star$ CSM predictions for the direct yield. The full NLO evaluation –without any ajustable parameter– perfectly matches the LHCb data up to 5 GeV. The comparison is equally good with the $1S$ and $2S$ states [3] provided that one subtracts the part of the yield from feed downs. At larger $P_T$, the leading-$P_T$ contributions of the NNLO seem to be required to describe the data. Overall, this confirms that this sole CS channel contribution seems to be sufficient to convincingly reproduce the total yield [14] *as well as* the cross section differential in $P_T$ [11] as measured at RHIC [7], the Tevatron [8, 9] and the LHC [1–3] –once $P_T^{-6}$ (NLO) and $P_T^{-4}$ (NNLO) contributions are included.

## 2.2. Cross-section ratios at LO

Despite the rather large theoretical uncertainties of the CSM predictions, these are free of any adjustable parameter. The overall normalisation or the $P_T$ and $y$ dependence cannot be tuned by fitting non-perturbative parameters, for instance. In particular, at LO in $v$, ratios of cross sections for *direct* $\Upsilon(nS)$ are obtained straightforwardly. These are in fact simple ratios of Schrödinger's wave function at the origin, $\psi^{nS}(0)$. We have:

$$\frac{\sigma(\text{direct } \Upsilon(3S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi^{3S}(0)|^2}{|\psi^{1S}(0)|^2} \sim 0.34, \quad \frac{\sigma(\text{direct } \Upsilon(2S))}{\sigma(\text{direct } \Upsilon(1S))} = \frac{|\psi^{2S}(0)|^2}{|\psi^{1S}(0)|^2} \sim 0.45. \tag{1}$$

As we mentioned, these numbers hold for the *direct* yields. From an early CDF study [10] at the Tevatron (1.8 TeV), we know that roughly 50% of the inclusive $\Upsilon(1S)$'s are directly produced. We will make the reasonable

---

[1]The number of events is lower, the 3 $\Upsilon$ states are not resolved and the feed-down from $\chi_b$ has never been measured at this energy.

assumption that a similar fraction holds at the LHC, with the drawback that CDF did not measure low-$P_T$ $\chi_b$'s. From the recent CMS measurement [1] ($\sigma(\Upsilon(1S)(|y| < 2))Br_{\ell\ell} \simeq 7.4$ nb), we can thus obtain an evaluation of the direct $\Upsilon(1S)$ yield: $\sigma(\text{direct }\Upsilon(1S)) \sim 150$ nb. In turn, it is straightforward to get what is expected from the CSM for the direct $\Upsilon(3S)$ yield at 7 TeV: $0.34 \times 150$ nb $\sim 50$ nb. This is surprisingly close to the value measured[2] by CMS [1], 45 nb, assuming that 100% of the $\Upsilon(3S)$ are directly produced. The latter assumption was perfectly sound until recently. However, ATLAS has made the first observation [15] of a candidate for the $\chi_b(3P)$ which is likely to decay into $\Upsilon(3S)$. The $\Upsilon(3S)$ yield may not be 100% direct.

From the above arguments, one would not expect any $P_T$ dependence of these cross-section ratios. Two effects should nevertheless be kept in mind. At low $P_T$, the $P_T$ dependence of the cross section is known to be affected by mass effects. Indeed, it does not follow a simple power-law falloff in $P_T$. We should be aware that the ratio predicted above hold in the limit where $M_{\text{NRQCD}}^{\Upsilon(nS)} = 2m_b$ for all the states. Such an approximation is not ideal for the $3S$ states for instance. Another effect comes from a simple kinematical effect of the feed-down: the transverse momentum of a daughter particle is always smaller than that of the parent (the excited state here). Quantitatively, we can write the approximate relation: $P_T^{\text{daughter}} \sim (M^{\text{daughter}}/M^{\text{mother}}) \times P_T^{\text{mother}}$.

Such a rescaling of the $P_T$ spectrum does not matter if $\frac{d\sigma}{dP_T} \propto P_T^{-n}$ with $n$ fixed –we would always keep the cross-section ratio independent of $P_T$ (with a smaller feed-down for higher $n$, though). However, if $n$ changes, which is especially true at low $P_T$, this induces a $P_T$ dependence of the feed-down, even if both the direct production cross sections of the lower-lying state and of the excited state have the same $P_T$ dependence. The feed-down fraction is expected to increase when the $P_T$ dependence is mild and to decrease when it is steep. From the usual shape of $\frac{d\sigma}{dP_T}$, one expects a decrease of the feed-down with $P_T$. In turn, the cross-section ratio, $\Upsilon(mS)/\Upsilon(nS)$ with $m > n$ would increase with $P_T$ until the differential cross section gets the behaviour of a power law ($P_T^{-n}$). A detailed Monte Carlo simulation is required to quantify this increase. Yet, it is instructive to keep in mind that $(M_{\Upsilon(3S)}/M_{\Upsilon(1S)})^6 \simeq 1.7$. Such kinematical effects up to 50% would not be surprising. This provides a reasonable explanation of the ratio increase observed by CMS [1] and LHCb [3] on Figs. 2.
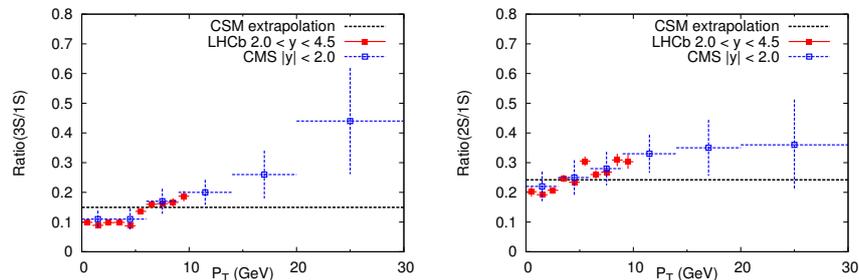


Figure 2: $\Upsilon$ cross-section ratios "$3S/1S$" and "$2S/1S$" as measured by LHCb [3] and CMS [1] and as predicted by the CSM without the kinematical effect mentioned in the text. The systematic experimental uncertainties from the unknown polarisation are not shown.

## 3. $\Upsilon$ production in *pA* collisions: from RHIC to LHC energies

### 3.1. dAu collisions at RHIC

As we discussed in [16], the survival probability of the $\Upsilon$ (or its pre-resonant state) in the nuclear matter is significantly larger than for $J/\psi$ – or conversely its "absorption" is small. This is due to its smaller size. On the contrary, the impact of (anti)shadowing is not necessarily small. When compared to $J/\psi$ results (see *e.g.* [17]), two effects should be kept in mind. First, the energy scale of the scattering entering the nuclear-PDF evaluation ($Q$ or $\mu_F$) is expected to be three times larger for the $\Upsilon$ than for the $J/\psi$. A priori, we do not expect any saturation effect of the gluon densities [16]. Second, and more importantly, the average momentum fractions of the partons in both colliding

---

[2]$\sigma(\Upsilon(3S)(|y| < 2))Br_{\ell\ell} \simeq 1.0$ nb $\overset{100\%direct}{\longrightarrow} \sigma(\text{direct }\Upsilon(3S)) \sim 45$ nb

particles are three times larger in the $\Upsilon$ case compared to that of $J/\psi$'s for a fixed quarkonium rapidity. This explains, for instance, why anti-shadowing could show up at a given rapidity for $\Upsilon$ and not for $J/\psi$.

At RHIC, $\Upsilon$ production allows one to probe the gluon densities in a wide momentum-fraction range: at forward $y$, it probes the shadowing region; at mid $y$, the anti-shadowing region; and, at backward $y$, the EMC region. The latter is pretty much unknown for gluons and we emphasised in [16] that $\Upsilon$ production in $d$Au collisions at RHIC energies can be an invaluable probe of the unexplored large-$x$ dynamics of gluons in bound nucleon inside heavy nucleus (see also [18]). As a matter of fact, the slight $\Upsilon$ suppression at backward $y$ observed by PHENIX [19] nearly rules out a gluon excess from Fermi motion for $x$'s close to 0.3 as predicted in [20] and it may even be the first hint of gluon EMC suppression.

At mid $y$, an update of the STAR data [21] is awaited to confirm the absence of a significant anti-shadowing. On the contrary, the forward PHENIX data [19] are already precise enough to indicate that an ingredient is missing in the existing analyses since the conventional shadowing is far from being enough [16] to explain the large suppression of the $\Upsilon$ yield. Fractional parton energy loss for forward-angle quarkonium production might explain this anomalous suppression, along the same lines as the analysis of Ref. [22] for the $J/\psi$ production in proton-nucleus collisions.

### 3.2. Outlooks for pPb collisions at the LHC

Taking into account the rapidity shift between the lab system and the c.m.s. of the colliding particles due to the imbalance in their energies at the LHC at $\sqrt{s_{NN}} = 5$ TeV, one expects an excess of $\Upsilon$ between 5 and 15% due to the anti-shadowing in Pb$p$ collisions in the acceptance of the ALICE detector. In $p$Pb collisions, for which the LHCb detector will also take data, one expects a suppression ranging from 20 to 25% in the forward rapidity region.

Such numbers are not to be overlooked: remember that in PbPb collisions, such nuclear effects act roughly speaking quadratically compared to in $p$Pb collisions ! Cold nuclear effects on the $\Upsilon$ yield can thus be up to 20-30% in PbPb collisions. This calls for a detailed $\Upsilon$ analysis in the forthcoming $p$Pb/Pb$p$ runs at the LHC.

Along these lines, let us keep in mind that, at RHIC energies, the suppression of $\Upsilon$ in $d$Au collisions is of the same size as that of $J/\psi$. Novel effects such as fractional energy loss might be at work and need be subtracted for a proper analysis of the $\Upsilon$ behaviour in the deconfined matter created in central heavy-ion collisions at the LHC.

## References

[1] V. Khachatryan *et al.* [CMS Coll.], Phys. Rev. D **83** (2011) 112004.
[2] G. Aad *et al.* [ATLAS Coll.], Phys. Lett. B **705** (2011) 9.
[3] R.Aaij, *et al.* [LHCb Coll.], Eur. Phys. J. C **72** (2012) 2025.
[4] S. Chatrchyan *et al.* [CMS Coll.], Phys. Rev. Lett. **107** (2011) 052302.
[5] J. P. Lansberg, Int. J. Mod. Phys. A **21**, 3857 (2006); N. Brambilla, *et al.* Eur. Phys. J. C **71** (2011) 1534; R. Rapp, D. Blaschke and P. Crochet, Prog. Part. Nucl. Phys. **65** (2010) 209; Z. Conesa del Valle, *et al.* Nucl. Phys. (Proc. Suppl.) **214** (2011) 3.
[6] F. Cooper, M. X. Liu and G. C. Nayak, Phys. Rev. Lett. **93** (2004) 171801 [hep-ph/0402219].
[7] B. I. Abelev *et al.*, [STAR Coll.], Phys. Rev. D **82** (2010) 012004; A. Kesich, [STAR Coll.], arXiv:1207.7166 [nucl-ex].
[8] D. Acosta *et al.* [CDF Coll.], Phys. Rev. Lett. **88** (2002) 161802.
[9] V. M. Abazov *et al.* [D0 Coll.], Phys. Rev. Lett. **94** (2005) 232001 [Erratum-ibid. **100** (2008) 049902].
[10] T. Affolder *et al.* [CDF Coll.], Phys. Rev. Lett. **84** (2000) 2094.
[11] J. P. Lansberg, Eur. Phys. J. C **61** (2009) 693.
[12] J. Campbell, F. Maltoni and F. Tramontano, Phys. Rev. Lett. **98** 252002 (2007);
     P. Artoisenet, J.P. Lansberg and F. Maltoni, Phys. Lett. B **653** 60 (2007)
[13] P. Artoisenet, J. Campbell, J. P. Lansberg, F. Maltoni and F. Tramontano, Phys. Rev. Lett. **101** (2008) 152001.
[14] S. J. Brodsky and J.P. Lansberg, Phys. Rev. D **81** (2010) 051502; J. P. Lansberg, PoS ICHEP **2010** (2010) 206.
[15] G. Aad *et al.* [ATLAS Coll.], Phys. Rev. Lett. **108** (2012) 152001.
[16] E. G. Ferreiro, F. Fleuret, J. P. Lansberg, N. Matagne and A. Rakotozafindrabe, arXiv:1110.5047 [hep-ph].
[17] E. G. Ferreiro *et al.*, Eur. Phys. J. C **61** (2009) 859; E. G. Ferreiro *et al.*, Phys. Lett. B **680** (2009) 50; *Ibid.*, Phys. Rev. C **81** (2010) 064911;
     E. G. Ferreiro *et al.*, Nucl. Phys. A **855** (2011) 327; *Ibid.*, Few Body Syst. **53** (2012) 27.
[18] J.P. Lansberg, S.J. Brodsky, F. Fleuret and C. Hadjidakis, Few Body Syst. **53** (2012) 11;
     S.J. Brodsky, F. Fleuret, C. Hadjidakis and J.P. Lansberg, Phys. Rept. (2012), 10.1016/j.physrep.2012.10.001[arXiv:1202.6585 [hep-ph]].
[19] K. B. Lee, *et al.*, [PHENIX Coll.] PoS **DIS2010** (2010) 077.
[20] H. Merabet, J. F. Mathiot, J. Dolejsi and H. J. Pirner, Phys. Lett. B **307** (1993) 177.
[21] R. Reed *et al.*, [STAR Coll.] Nucl. Phys. A **855** (2011) 440.
[22] F. Arleo, S. Peigne and T. Sami, Phys. Rev. D **83** (2011) 114036.