γ production in hadron collisions at forward rapidity with ALICE at the LHC

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Abstract. Ultrarelativistic heavy-ion collisions produce strongly interacting matter at high temperature and energy density. Under these extreme conditions, a deconfined partonic state, called Quark-Gluon Plasma, is formed. The measurement of charmonia and bottomonia in AA collisions is expected to provide essential information about the QGP properties. In pp collisions high precision data serve as crucial test for several competing models of quarkonium hadroproduction and provide the reference for the measurements in heavy-ion collisions, while pA collisions are useful to disentangle hot and cold nuclear matter effects. In the ALICE Muon Spectrometer, bottomonium production can be measured at forward rapidity (2.5 < y < 4) and down to \( p_T = 0 \) via the dimuon decay channel. The latest results on Υ production in pp, Pb–Pb and p–Pb collisions are discussed and compared to various theoretical predictions.

1. Introduction
ALICE [1] is the LHC experiment dedicated to the study of heavy-ion collisions, but it has also a strong physics program in pp and p–Pb collisions. At forward rapidity (2.5 < y < 4) the quarkonia (c\( \bar{c} \) and b\( \bar{b} \) mesons) are reconstructed with the Muon Spectrometer down to a transverse momentum \( p_T \) equal to zero, exploiting their decay into two muons.

The study of bottomonium production in hadron collisions is important for several reasons. New measurements in pp collisions help to constrain the various models describing the quarkonium production mechanisms and the theoretical calculations for bottomonium are more robust than those of charmonium due to the higher mass. Furthermore, according to the colour-screening model [2], the dissociation probability due to the Quark-Gluon Plasma (QGP) of the different quarkonium states is expected to provide essential information about the properties of the system produced in AA collisions. A competing effect such as the quarkonium regeneration is much smaller for the bottomonium than for the charmonium [3]. Other important mechanisms are the cold nuclear matter (CNM) effects, which can modify the quarkonium production even in absence of the QGP [4]. Data from pA collisions are necessary to disentangle these effects from the hot ones.

2. Υ production in pp collisions
The \( \Upsilon(1S) \) and \( \Upsilon(2S) \) inclusive cross sections have been measured at forward rapidity in pp collisions at an energy of \( \sqrt{s} = 7 \) TeV [5].

The \( \Upsilon(1S) \) and \( \Upsilon(2S) \) rapidity differential cross sections presented in Fig. 1 (left) show a good agreement with the values reported by LHCb [6] in the same rapidity range and complement
the results obtained by CMS at midrapidity [7, 8].

In Fig. 1 (right) the inclusive $\Upsilon(1S)$ differential production cross section as a function of $p_T$ is compared to three Color Singlet Model (CSM) calculations which account for the feed down from higher mass states [9]. The LO calculation underestimates the data for $p_T > 4$ GeV/c and falls too rapidly with increasing $p_T$. The $p_T$ dependence of the NLO calculation is closer to the measurements, but the prediction still underestimates the cross section over the full $p_T$ range. A good agreement is achieved at NNLO* (it includes the leading-$p_T$ contributions appearing at NNLO [10]), but over a limited $p_T$ range and with large theoretical uncertainties.

**Figure 1.** On the left, rapidity differential cross sections of $\Upsilon(1S)$ and $\Upsilon(2S)$ measured by ALICE [5], LHCb [6] and CMS [7, 8]. On the right $p_T$ differential cross section of $\Upsilon(1S)$ compared to three theoretical calculations [9].

### 3. $\Upsilon$ production in Pb–Pb collisions

The effects of the hot and dense medium on the $\Upsilon(1S)$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are quantified by means of the nuclear modification factor $R_{AA} = \frac{Y_{\Upsilon}^{\text{Pb-Pb}}}{Y_{\Upsilon}^{\text{pp}}}$

The $R_{AA}$ shown in Fig. 2 (left) shows a more pronounced suppression in central collisions. Moreover, the rapidity dependence in the right panel suggests a stronger suppression at forward than at midrapidity as it appears from the comparison with the CMS measurement in $|y| < 2.4$ [12].

In the same figures, the measurements are also compared to the predictions of a dynamical model which does not include CNM nor regeneration effects [13]. The predictions are made assuming two possible initial temperature profiles in rapidity: a boost-invariant plateau and a Gaussian profile. For each of them, three values of QGP shear viscosity over entropy density ($\eta/s$) are used in the calculations. The predictions underestimate the measured suppression, for every temperature profiles and $\eta/s$ values considered. All sets used in the model predicts a rapidity dependence opposite to the measured one.

Predictions from a transport model are shown in Fig. 3. These calculations are based on a kinetic rate-equation approach in an evolving QGP and include both suppression and regeneration effects [14]. CNM effects are calculated by varying an effective absorption cross section between 0 and 2 mb, resulting in an uncertainty band. This model underestimates the observed suppression, even if the centrality dependence is fairly reproduced. The model predicts also an almost constant $R_{AA}$ as a function of the rapidity which is in disagreement with the trend observed by ALICE and CMS.
Figure 2. Inclusive $\Upsilon(1S)$ $R_{AA}$ as a function of the average number of participants (left) and rapidity (right) compared to predictions from a dynamical model [13]. Horizontal bars represent the uncertainty associated to $\langle N_{\text{part}} \rangle$ (from a Glauber model) in the former plot and the rapidity bin width in the latter.

Figure 3. Inclusive $\Upsilon(1S)$ $R_{AA}$ as a function of the average number of participants (left) and rapidity (right) compared to predictions from a transport model [14].

4. $\Upsilon$ production in p–Pb collisions

The nuclear modification factor $R_{\text{pPb}} = \frac{\sigma_{\text{pPb}}}{\sigma_{\text{pp}}}$ (i.e. the ratio between the $\Upsilon$ production cross sections in p–Pb and pp collisions, normalized to the Pb mass number) is used to determine the CNM effects in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [15]. It is equivalent to the $R_{AA}$ used to investigate the QGP effects in Pb–Pb collisions.

As shown in Fig. 4, the inclusive $\Upsilon(1S)$ production is suppressed at forward rapidity (p-going direction), while at backward rapidity (Pb-going direction) the measurement is compatible with unity within uncertainties, disfavoring a strong gluon anti-shadowing.

In the left plot, the ALICE results are compared to a NLO Color Evaporation Model (CEM) calculation with shadowing parametrized by EPS09 at NLO [16] which tends to overestimate the observed $\Upsilon(1S)$ $R_{\text{pPb}}$. Coherent parton energy loss calculations [17] with or without EPS09 are also shown: the former reproduces the data at forward rapidity, while the latter is in better agreement with our measurements at backward rapidity.

In the right panel, the results are compared to a LO calculation of a $gg \to \Upsilon g$ production with shadowing parametrization [18]. The two bands show the uncertainties related to EPS09 LO in the shadowing region and in the EMC region. A calculation based on the CGC framework coupled with a CEM production is also shown for positive values of $y_{\text{cms}}$ [19]. Although this prediction only slightly underestimates the $\Upsilon(1S)$ $R_{\text{pPb}}$, it is not able to reproduce the analogous $J/\psi$ measurement in the same rapidity range [20].
Figure 4. Nuclear modification factor of inclusive $\Upsilon(1S)$ in p–Pb collisions as a function of rapidity compared to several model calculations: CEM with EPS09 shadowing at NLO [16] and parton energy loss with and without EPS09 shadowing at NLO [17] on the left; CSM with EPS09 shadowing at LO [18] and CGC [19] on the right.

5. Conclusions
The measured inclusive production cross sections of $\Upsilon(1S)$ and $\Upsilon(2S)$ at forward rapidity in pp collisions are in good agreement with measurements by LHCb and complement those by CMS at midrapidity. Both CSM LO and NLO calculations underestimate the data at large transverse momentum, while the addition of the leading-$p_T$ NNLO contributions helps to reduce this disagreement, but with larger theoretical uncertainties.

The observed suppression of inclusive $\Upsilon(1S)$ in Pb–Pb collisions is stronger in central than in semiperipheral collisions and shows a pronounced rapidity dependence over the large domain covered by ALICE and CMS. The suppression, larger than that predicted by the models considered, might point to a significant dissociation of direct $\Upsilon(1S)$.

Finally, the $\Upsilon(1S)$ production in p–Pb collisions is suppressed at forward rapidity, while it is consistent with unity at backward rapidity. Models including the nuclear modification of the gluon PDF or a contribution from coherent parton energy loss tend to overestimate the measured $R_{pPb}$ and cannot simultaneously describe the forward and backward rapidity measurements.

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