Preliminary Physics Summary:
Inclusive $\Upsilon$ production in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

ALICE Collaboration

Abstract

The inclusive $\Upsilon$ production in p–Pb interactions at the centre-of-mass energy per nucleon-nucleon collision $\sqrt{s_{NN}} = 8.16$ TeV is studied with the ALICE detector at the CERN LHC. The measurement has been performed reconstructing $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons via their dimuon decay channel, in the centre-of-mass rapidities $2.03 < y_{\text{cm}} < 3.53$ and $-4.46 < y_{\text{cm}} < -2.96$, down to zero transverse momentum. Preliminary results on the inclusive $\Upsilon(1S)$ nuclear modification factors ($R_{\text{pPb}}$) as a function of rapidity, transverse momentum ($p_T$) and centrality of the collisions will be presented. The results will be compared with those obtained by ALICE in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and with theoretical model calculations. The inclusive $\Upsilon(2S)$ $R_{\text{pPb}}$ will also be discussed and compared to the corresponding $\Upsilon(1S)$ measurement.
1 Introduction

The production of quarkonium resonances, bound states of heavy Q and ¯Q quarks, is a well-known probe of the formation of a plasma of quarks and gluons (QGP). The high colour-charge density reached in such a medium can, in fact, screen the binding force among the Q and ¯Q quarks, leading to a temperature-depending melting of the quarkonium states according to their binding energies [1].

At LHC energies, for charmonium resonances (i.e. the quarkonium states formed by c and ¯c quarks) such a sequential melting is masked by the presence of additional (re)combination processes due to the large abundance of c and ¯c quarks produced in high energy nucleus–nucleus collisions. On the contrary, the approximately twenty times smaller beauty production cross section with respect to the charm one [2] implies a significantly smaller (re)combination probability for bottomonia, i.e. bound states of b and ¯b quarks. A sequential suppression of bottomonium states has indeed been observed in Pb–Pb collisions at √s_{NN} = 2.76 TeV and √s_{NN} = 5.02 TeV [3, 4]. All the Υ resonances show, in fact, a reduction in their production compared to pp interactions at the same centre-of-mass energy, scaled by the number of nucleon–nucleon collisions. Since the binding energies of the Υ states range between ∼1 GeV for the Υ(1S) to ∼0.2 GeV for the Υ(3S) [5], the size of the suppression is significantly different for the three resonances, being larger for the more loosely bound Υ(3S).

More quantitative conclusions on the observed Υ sequential suppression require the precise knowledge of the feed-down contributions from the higher excited Υ states, which are measured to be ∼40% for the Υ(1S) [6, 7], albeit in a slightly different kinematic range with respect to the ALICE and CMS measurements in Pb–Pb collisions [8–12]. Furthermore, since modifications to the bottomonium production might also be induced by cold nuclear matter (CNM) mechanisms not related to the formation of the QGP, a precise assessment of these effects is also needed. The modification of the parton distribution functions in a nucleus compared to free nucleons, the formation of a Colour Glass Condensate in the nuclei or the coherent energy loss of the Q ¯Q pair during its path through the medium, are examples of cold nuclear matter mechanisms which can influence quarkonium production [13]. The size of these effects is usually investigated in proton–nucleus collisions.

ALICE results from the 2013 p–Pb data taking at √s_{NN} = 5.02 TeV have shown a modification of the Υ(1S) production yields as a function of rapidity (y_{cms}) [14]. The size of the observed suppression is similar in the forward (2.03 < y_{cms} < 3.53) and in the backward (−4.46 < y_{cms} < −2.96) rapidity intervals. Theoretical calculations based on the aforementioned CNM mechanisms fairly describe the forward-y_{cms} measurements, while they slightly overestimate the results obtained in the backward-y_{cms} range. Furthermore, the ALICE measurement of the cross section ratio Υ(2S)/Υ(1S) shows no evidence for different CNM effects on the two states at forward and backward rapidities, albeit within large uncertainties [14].

In 2016 the LHC delivered p–Pb collisions at √s_{NN} = 8.16 TeV. The higher integrated luminosity, about a factor 2 larger than the one achieved in 2013, allows a more detailed study of the bottomonium production in p–Pb collisions. In this note, preliminary results on the inclusive Υ(1S) production as a function of rapidity, transverse momentum (p_T) and centrality of the collisions will be discussed and compared to the results obtained in p–Pb collisions at √s_{NN} = 5.02 TeV and to theory calculations. A comparison of the Υ(1S) and Υ(2S) nuclear modification factors, integrated over y_{cms}, p_T and centrality, will also be presented.

2 Experimental apparatus, data sample and event selection

The detailed description of the ALICE set-up can be found in [15, 16]. The Muon Spectrometer [17] is the main detector used in this analysis. It tracks muons in the pseudo-rapidity range −4 < η < −2.5, in the laboratory reference frame, and provides a dimuon trigger based on the simultaneous detection of two unlike-sign muons in a dedicated trigger detector system. Both muons must have an online-
Inclusive $\Upsilon$ production in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

Estimated $p_T^\mu > 0.5$ GeV/$c$. The V0 detector $[18]$, composed by two scintillator hodoscopes covering the pseudo-rapidity intervals $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, is used to define the minimum-bias (MB) trigger and to remove beam-induced background. The trigger condition used in this analysis ($\mu\mu - \text{MB}$) is based on the coincidence of the MB trigger and the dimuon one. The primary interaction vertex is reconstructed with the two innermost layers of the Inner Tracking System (Silicon Pixel Detector, SPD) $[19]$, covering the pseudo-rapidity intervals $|\eta| < 2$ and $|\eta| < 1.4$, respectively. Finally, two sets of Zero Degree Calorimeters (ZDC) $[20]$ placed 112.5 m from the interaction point, are used for the centrality estimate and to reject events where interactions occurred out of the nominal bunches. Events where two or more interactions occur in the same colliding bunch (in-bunch pile-up) or during the readout time of the SPD (out-of-bunch pile-up) are removed using the information from SPD and V0.

Further selection criteria, commonly adopted in the ALICE quarkonium analyses, are applied, namely:

- both muons forming the dimuon should have a pseudo-rapidity value in the range $-4 < \eta_\mu < -2.5$ to reject tracks at the edges of the Muon Spectrometer acceptance;
- the radial transverse position of each muon track at the end of the absorber ($R_{\text{abs}}$) should be within $17.6 < R_{\text{abs}} < 89.5$ cm, to remove muons crossing the thicker part of the absorber;
- both muons forming the dimuon should have a pseudo-rapidity value in the range $-3 < \eta_\mu < -2.5$ to reject tracks at the edges of the Muon Spectrometer acceptance;
- tracks reconstructed in the tracking chambers of the Muon Spectrometer should match the track segment reconstructed in the trigger system.

Data were collected with two beam configurations by inverting the directions of the proton and Pb beams circulating inside the LHC. Hence, it was possible to access both a forward ($2.03 < y_{\text{cms}} < 3.53$) and a backward ($-4.46 < y_{\text{cms}} < -2.96$) rapidity interval, where the positive and negative $y_{\text{cms}}$ refers to the p-going and Pb-going direction, respectively. The corresponding data samples, referred to as p–Pb and Pb–p in the following, have an integrated luminosity $L_{\text{int}}^{\text{Pb}} = 8.4 \pm 0.2$ nb$^{-1}$ and $L_{\text{int}}^{\text{Pb}} = 12.8 \pm 0.3$ nb$^{-1}$, respectively $[21]$.

3 Data Analysis

The results presented in this note are based on an analysis procedure similar to the one described in $[14]$ for the former studies of $\Upsilon$ production in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The same approach is followed for both the p–Pb and Pb–p data samples.

The $\Upsilon$ production in p–Pb collisions is compared to the production measured in pp interactions at the same centre-of-mass energy, scaled by the number of binary nucleon–nucleon collisions, through the so-called nuclear modification factor $R_{\text{pPb}}$ (or $Q_{\text{pPb}}$ for the study of the centrality dependence, to be distinguished from $R_{\text{pPb}}$ since potential biases from the centrality estimation, unrelated to nuclear effects, might be present $[22]$), defined as

$$R_{\text{pPb}} = \frac{N_{\Upsilon}}{B.R.\Upsilon \rightarrow \mu^+\mu^- \cdot N_{\text{MB}} \cdot (A \cdot \varepsilon) \cdot (T_{\text{pPb}}) \cdot \sigma_{\Upsilon}^{\text{pp}}}. \quad (1)$$

$N_{\Upsilon}$ is the number of $\Upsilon$ in a given $p_T$, $y_{\text{cms}}$ or centrality bin. B.R.$\Upsilon \rightarrow \mu^+\mu^-$ is the branching ratio in the dimuon channel, B.R.$\Upsilon \rightarrow \mu^+\mu^- = (2.48 \pm 0.05)\%$ for $\Upsilon$(1S), B.R.$\Upsilon \rightarrow \mu^+\mu^- = (1.93 \pm 0.17)\%$ for $\Upsilon$(2S), and B.R.$\Upsilon \rightarrow \mu^+\mu^- = (2.18 \pm 0.21)\%$ for $\Upsilon$(3S) $[23]$. The number of collected minimum-bias events is $N_{\text{MB}}$, while $(A \cdot \varepsilon)$ is the $\Upsilon$ acceptance times efficiency in the kinematical interval under study. $(T_{\text{pPb}})$ is the
centrality-dependent average nuclear thickness function, computed in the Glauber framework \[24\]. Finally, \( \sigma_{\gamma}^{pp} \) is the production cross section of the \( \Upsilon \) state at the same centre-of-mass energy and in the same \( \gamma_{\text{cms}} \) and \( p_{\text{T}} \) interval as the \( \text{p–Pb} \) collisions.

The number of \( \Upsilon(1S) \) and \( \Upsilon(2S) \) was obtained by fitting the unlike-sign dimuon invariant mass spectra in each \( p_{\text{T}}, \gamma_{\text{cms}} \) or centrality interval under study and an example of fits, for both the \( \text{p–Pb} \) and \( \text{Pb–p} \) samples, is shown in Fig. 1.

![Fig. 1: Fits to the invariant mass spectra of unlike-sign dimuons, integrated over \( p_{\text{T}} \) and centrality. The left plot corresponds to the \( \text{Pb–p} \) sample, while the right one to the \( \text{p–Pb} \) one. The shapes of the \( \Upsilon(1S), \Upsilon(2S) \) and \( \Upsilon(3S) \) resonances are shown (red continuous lines), together with the background function (blue dashed line) and the global fit (blue continuous line).](image)

Fits were performed adopting various choices of signal functions to describe the \( \Upsilon(1S), \Upsilon(2S) \) and \( \Upsilon(3S) \) resonances and empirical functions for the background shape. More in detail, the background was described by several combinations of exponential and polynomial functions or by a Gaussian function with a mass-dependent width. For the resonance shapes an extended Crystal Ball function, with non-Gaussian tails on the right and left side of the resonance peak was used. Alternatively, a pseudo-Gaussian function, with a mass-dependent width was also adopted \[25\]. The mass of the \( \Upsilon(1S) \) was a free parameter of the fit. The width of the \( \Upsilon(1S) \) state \( (\sigma_{\Upsilon(1S)}) \) was also kept free in the fits, since a dependence on the resonance \( p_{\text{T}} \) and \( \gamma_{\text{cms}} \) is expected. On the contrary, no significant variation of \( \sigma_{\Upsilon(1S)} \) is foreseen as a function of the collision centrality. Hence for centrality studies, the \( \Upsilon(1S) \) width was fixed to the value obtained in the fit to the centrality-integrated invariant mass spectrum. The uncertainty associated to the width was accounted for in the evaluation of the systematic uncertainty on the signal extraction. The mass and the width of the \( \Upsilon(2S) \) and \( \Upsilon(3S) \) were bound to those of the \( \Upsilon(1S) \) in the following way: \( m_{\Upsilon(nS)} = m_{\Upsilon(1S)} + (m_{\text{PDG}}^{\Upsilon(nS)} - m_{\Upsilon(1S)}^{\text{PDG}}) \) and \( \sigma_{\Upsilon(nS)} = \sigma_{\Upsilon(1S)} \times \sigma_{\Upsilon(nS)}/\sigma_{\Upsilon(1S)}^{\text{PDG}} \) where \( m_{\text{PDG}}^{\Upsilon(nS)} \) is the mass value from Ref. \[23\] and \( \sigma_{\Upsilon(nS)}^{\text{MC}} \) is the width of the resonance as obtained from a Monte Carlo (MC) simulation. The number of \( \Upsilon \) signals was evaluated as the average of the \( \Upsilon \) values obtained varying the signal and background functions as well as the fitting ranges. Alternative descriptions of the signal tails were also tested and included in the determination of the signal yields. The statistical uncertainties were calculated as the average of the statistical uncertainties over the various fits and the standard deviation of the \( \Upsilon \) distribution provided the systematic uncertainties on the signal extraction. The total number of \( \Upsilon(1S) \), integrated over \( \gamma_{\text{cms}}, p_{\text{T}} \) and centrality, amounts to \( N_{\Upsilon(1S)} = 984 \pm 66(\text{stat.}) \pm 37(\text{syst.}) \) for the \( \text{p–Pb} \) configuration and \( N_{\Upsilon(1S)} = 973 \pm 58(\text{stat.}) \pm 34(\text{syst.}) \) for the \( \text{Pb–p} \) one. Corresponding figures for the \( \Upsilon(2S) \) are \( N_{\Upsilon(2S)} = 197 \pm 43(\text{stat.}) \pm 15(\text{syst.}) \) and \( N_{\Upsilon(2S)} = 201 \pm 37(\text{stat.}) \pm 16(\text{syst.}) \) for the \( \text{p–Pb} \) and \( \text{Pb–p} \) samples, respectively. Even if the \( \Upsilon(3S) \) resonance was included in the fits to the unlike-sign dimuon mass spectra, its significance is limited, hence the results presented in this note will focus only on \( \Upsilon(1S) \) and \( \Upsilon(2S) \).

The acceptance times detection efficiency \((A \cdot \varepsilon)\) was calculated in Monte Carlo (MC) simulations, based
on the GEANT3 transport code [26]. The MC was performed on a run-by-run basis, to closely follow the evolution of the performance of the detectors during the data taking. \( \Upsilon(1S) \) were generated using, as input shapes, rapidity and transverse momentum distributions directly tuned on p–Pb or Pb–p data at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV, through an iterative procedure. Since the limited statistics did not allow for the tuning on the data of the \( \Upsilon(2S) \) and \( \Upsilon(3S) \) \( \sigma_T \) and \( \gamma_{\text{cms}} \) distributions, the same shapes of the \( \Upsilon(1S) \) were adopted.

The \( \sigma_T \) and \( \gamma_{\text{cms}} \) integrated \( (A \cdot \varepsilon) \) amounts to 0.31 ± 0.02 for the \( \Upsilon(1S) \) and to 0.30 ± 0.01 for the \( \Upsilon(2S) \) in p–Pb collisions. In Pb–p collisions the \( \Upsilon(1S) \) \( (A \cdot \varepsilon) \) is 0.28 ± 0.01 and the \( \Upsilon(2S) \) one is 0.28 ± 0.01. No significant centrality dependence is expected, hence the same \( (A \cdot \varepsilon) \) values were used in the study of the \( \Upsilon \) production as a function of the collision centrality. The systematic uncertainty associated to the \( (A \cdot \varepsilon) \) includes contributions related to the uncertainty on the MC input distributions (4% for p–Pb and 2.3% for Pb–p), on the tracking and trigger efficiencies (1% for both data taking configurations). While these systematic uncertainties depend on the \( \gamma_{\text{cms}} \) and on the matching efficiency between the tracking and triggering systems (1% for both data taking configurations). When the \( \gamma_{\text{cms}} \) and \( \sigma_T \) interval under study, no significant centrality dependence has been observed. The statistical uncertainties on \( (A \cdot \varepsilon) \) are negligible.

\( N_{\text{MB}} \) is the number of equivalent minimum-bias events and it was evaluated by multiplying the number of events corresponding to the \( \mu \mu - \text{MB} \) triggers by a factor \( F_{\text{norm}} \), corresponding to the inverse of the probability of having a triggered dimuon in a MB event. This quantity, computed from the event trigger-input information and the level-0 trigger mask, amounts to 679 ± 7 in p–Pb and 371 ± 4 in Pb–p. The associated systematic uncertainty (1%) accounts for differences coming from an alternative evaluation method, based on the information provided by the trigger scalers, as detailed in [27]. In each centrality bin \( i \), \( F_{\text{norm}}^i \) was obtained from the corresponding centrality integrated value scaled by \( (N_{\text{MB}}/N_{\text{MB}})/(N_{\mu\mu-\text{MB}}/N_{\mu\mu-\text{MB}}) \). Alternatively, \( F_{\text{norm}}^i \) was computed directly for each centrality class and a further 1% difference between the two approaches was included in the systematic uncertainty. The statistical uncertainty on \( F_{\text{norm}}^i \) is negligible.

\( \langle T_{p\text{Pb}} \rangle \) represents the average nuclear thickness function and it depends on the collision centrality. The systematic uncertainties on \( \langle T_{p\text{Pb}} \rangle \) vary between \( \sim 3 \) and \( \sim 5.8\% \) depending on the centrality interval.

Finally, the reference \( \Upsilon(1S) \) and \( \Upsilon(2S) \) cross sections in pp collisions were obtained from the LHCb measurements at \( \sqrt{s} = 8 \) TeV [28] applying a correction factor to account for the slightly different centre-of-mass energy of the collisions. This correction factor, which amounts to 1.02 ± 0.01 in p–Pb and 1.03 ± 0.01 in Pb–p was evaluated extrapolating the \( \Upsilon \) cross section at \( \sqrt{s} = 8.16 \) TeV, according to the energy dependence obtained from the LHCb \( \Upsilon(1S) \) measurements at \( \sqrt{s} = 2.76, 7 \) and 8 TeV [28][29], as detailed in Ref. [30]. This factor shows a negligible \( \gamma_{\text{cms}} \) dependence and it varies by \( \sim 1\% \) from low to high \( \sigma_T \). A systematic uncertainty on the determination of this factor (\( \sim 1\% \)), due to the choice of the different extrapolating functions, was included. The values of the B.R. \( \times \sigma_{\Upsilon(1S)}^{pp} \) reference cross sections used in this analysis are 2.495 ± 0.003(stat.) ± 0.068(syst.) nb in the range \( 2.03 < \gamma_{\text{cms}} < 3.53 \) and 1.548 ± 0.002(stat.) ± 0.043(syst.) nb in the range \( -4.46 < \gamma_{\text{cms}} < -2.96 \). The corresponding cross sections for the \( \Upsilon(2S) \) are B.R. \( \times \sigma_{\Upsilon(2S)}^{pp} = 0.616 ± 0.002 \) (stat.) ± 0.017 (syst.) nb at forward rapidity and \( \sigma_{\Upsilon(2S)}^{pp} = 0.385 ± 0.001 \) (stat.) ± 0.011 (syst.) nb at backward rapidity.

In Tab. I the values of the systematic uncertainties entering the nuclear modification factor evaluation are summarised. When the \( K_{p\text{Pb}} \) is computed as a function of \( \sigma_T \) or \( \gamma_{\text{cms}} \), all the systematic uncertainties are considered as bin-by-bin uncorrelated. The only global uncertainties, within the p–Pb or Pb–p system, are the one on \( F_{\text{norm}} \) and the correlated uncertainty on the pp reference. When the \( Q_{p\text{Pb}} \) is evaluated, the uncertainties on signal extraction and on \( \langle T_{p\text{Pb}} \rangle \) have a dependence on the centrality of the collisions, while the other uncertainties are common to all centralities and, therefore, considered as global. As described earlier, the pile-up contribution has been removed in the event selection procedure. However, a conservative 2% systematic uncertainty is assigned to the \( Q_{p\text{Pb}} \) values, to account for residual pile-up which might still affect the measurement.
For the $\Upsilon(2S)$ studies, the same values of the systematic uncertainties should be considered, the only difference being the larger signal extraction uncertainties which amount to 7.6% in p–Pb and 8% Pb–p collisions.

<table>
<thead>
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<th>Source</th>
<th>p–Pb (%)</th>
<th>Pb–p (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal extr.</td>
<td>3.8 (2.8–17.0)</td>
<td>3.5 (3.0–6.0)</td>
</tr>
<tr>
<td>Trigger</td>
<td>2.6 (1.4–4.1)</td>
<td>3.1 (1.4–4.1)</td>
</tr>
<tr>
<td>Tracking</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Matching</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MC inputs</td>
<td>4 (1.6–4)</td>
<td>2.3 (1.1–4)</td>
</tr>
<tr>
<td>pp reference</td>
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<td>1</td>
</tr>
<tr>
<td>pp reference (global)</td>
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</tr>
<tr>
<td>$F_{\text{norm}}$</td>
<td>1 (2)</td>
<td>1 (2)</td>
</tr>
<tr>
<td>Pile-up</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Systematic uncertainties on the $\Upsilon(1S)$ nuclear modification factor ($R_{p\text{Pb}}$ and $Q_{p\text{Pb}}$) for both p–Pb and Pb–p collisions. The values not in parenthesis refer to the integrated results, while ranges refer to the maximum variation as a function of centrality, $y_{\text{cms}}$ or $p_T$. When no ranges are specified, the quoted values are valid for both the integrated and the differential measurements. Details on the degree of correlation of the uncertainties, over $y_{\text{cms}}$, $p_T$ or centrality, are given in the text. It should be noted that the pile–up systematic uncertainty applies only to the $Q_{p\text{Pb}}$ determination.

4 Results

The inclusive $\Upsilon(1S)$ nuclear modification factor, computed according to Eq. [1] is shown in Fig. [2] as a function of rapidity.

The numerical values, in the forward and backward rapidity intervals, are

$$R_{p\text{Pb}}(\Upsilon(1S))(2.03 < y_{\text{cms}} < 3.53) = 0.78 \pm 0.05(\text{stat.}) \pm 0.06(\text{syst.})$$

$$R_{p\text{Pb}}(\Upsilon(1S))(-4.46 < y_{\text{cms}} < -2.96) = 0.87 \pm 0.05(\text{stat.}) \pm 0.06(\text{syst.})$$

The measured $R_{p\text{Pb}}$ values indicate a reduction of the $\Upsilon(1S)$ yields in p–Pb collisions, both at forward and backward rapidities, with a hint for a stronger suppression at forward-$y_{\text{cms}}$. The suppression is about 2.8$\sigma$ and 1.7$\sigma$ in p–Pb and Pb–p, respectively. Results are compatible with the $R_{p\text{Pb}}$ values measured in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, as shown in Fig. [2] where an improvement in the precision of the results obtained at $\sqrt{s_{\text{NN}}} = 8.16$ TeV can also be appreciated.

The larger statistics collected in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV allows us to measure the $\Upsilon(1S)$ $R_{p\text{Pb}}$ in 3 $y_{\text{cms}}$ bins or in 5 $p_T$ bins. The rapidity dependence of the $R_{p\text{Pb}}$, explored in narrower $y_{\text{cms}}$ bins, is shown in Fig. [5] While the suppression already observed in the $y_{\text{cms}}$-integrated case is confirmed, the size of the uncertainties do not allow us to draw more detailed conclusions on the rapidity dependence.

The $p_T$-dependence of the $\Upsilon(1S)$ $R_{p\text{Pb}}$ is shown in Fig. [4] A slight decrease of the $\Upsilon(1S)$ nuclear modification factor, with decreasing $p_T$ is observed. A similar behaviour is observed at both backward and forward rapidities.

The $y_{\text{cms}}$ and $p_T$ dependence of the $\Upsilon(1S)$ $R_{p\text{Pb}}$ are compared, in Fig. [5] and Fig. [4] with a pure nuclear shadowing theory calculation based on EPS09 NLO set of nuclear parton distribution functions (nPDFs) [13, 31]. It can be observed that, while the shadowing calculation describes the $p_T$ and $y_{\text{cms}}$ dependence of the results in $2.03 < y_{\text{cms}} < 3.05$, it slightly overestimates the results obtained in $-4.46 <$
$y_{\text{ cms}} < -2.96$. The $y_{\text{ cms}}$-dependence of the $R_{pPb}$ is also compared to a model which includes the effects of parton coherent energy loss with or without the contribution of the EPS09 nuclear shadowing [13,12]. Also in this case, the model describes the forward-rapidity results, while it slightly overestimate the backward-rapidity $R_{pPb}$, in particular when the nuclear shadowing contribution is included.

The $\Upsilon(1S)$ nuclear modification factor has been also evaluated as a function of the collision centrality, shown as average number of binary nucleon–nucleon collisions, $\langle N_{\text{coll}} \rangle$. The centrality selection is based on a hybrid approach, as discussed in [22] and $\langle N_{\text{coll}} \rangle$ is computed via a Glauber model [24]. The $Q_{pPb}$ results are shown in Fig. 3 in 4 centrality intervals corresponding to 2–20%, 20–40%, 40–60% and 60–90% of the measured MB cross section. The most central events, corresponding to 0–2% are not included, since they might still be sensitive to residual pile-up contamination, whose contribution is elsewhere negligible.

Both at forward- and backward-rapidity the $\Upsilon(1S)$ centrality dependence is rather flat, confirming the stronger suppression at forward-$y_{\text{ cms}}$, already observed in the centrality integrated $R_{pPb}$.

The smaller $\Upsilon(2S)$ statistics does not allow us similar differential studies, hence only results integrated over $p_T$, $y_{\text{ cms}}$ and centrality will be discussed. Given the relatively small mass difference between the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances, most of the systematic uncertainties, except those on the signal extraction and on the choice of the $p_T$ and $y_{\text{ cms}}$ inputs used in the MC, cancel out in the ratio $[\Upsilon(2S)/\Upsilon(1S)]$ of the resonances yields defined as $[\Upsilon(2S)/\Upsilon(1S)] = \frac{N_{\Upsilon(2S)}/(A\varepsilon)_{\Upsilon(2S)}}{N_{\Upsilon(1S)}/(A\varepsilon)_{\Upsilon(1S)}}$.

The $[\Upsilon(2S)/\Upsilon(1S)]$ values at forward and backward rapidities are:

$[\Upsilon(2S)/\Upsilon(1S)](2.03 < y_{\text{ cms}} < 3.53) = 0.20 \pm 0.05\text{(stat.)} \pm 0.02\text{(syst.)}$

$[\Upsilon(2S)/\Upsilon(1S)](-4.46 < y_{\text{ cms}} < -2.96) = 0.21 \pm 0.04\text{(stat.)} \pm 0.02\text{(syst.)}$

Finally, the $\Upsilon(2S)$ $R_{pPb}$ has been evaluated in the forward and backward $y_{\text{ cms}}$ ranges, as shown in Fig. 6.

![Fig. 2: Inclusive $\Upsilon(1S)$ $R_{pPb}$ as a function of $y_{\text{ cms}}$. The $R_{pPb}$ values at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (red circles) are compared to those obtained at $\sqrt{s_{\text{NN}}} = 5.02$ TeV (blue squares) in the same $y_{\text{ cms}}$ interval [14]. Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity. All uncertainties are considered as uncorrelated between the results at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The horizontal error bars reflect the width of the rapidity bins. The $R_{pPb}$ values at the two energies are slightly displaced to improve visibility.](image-url)
Fig. 3: Inclusive $\Upsilon(1S)$ $R_{pPb}$ as a function of $y_{\text{cms}}$. The $R_{pPb}$ values at $\sqrt{s_{\text{NN}}} = 8.16$ TeV (red circles) are compared to theoretical calculations based on EPS09 NLO nuclear shadowing [13, 31] and on parton coherent energy loss predictions, with or without the inclusion of the EPS09 shadowing contribution [13, 32]. Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity. The horizontal bars correspond to the width of the $y_{\text{cms}}$ bins.

Fig. 4: Inclusive $\Upsilon(1S)$ $R_{pPb}$ as a function of $p_T$ for Pb–p (left panel) and p–Pb collisions (right panel). The $R_{pPb}$ values are compared to a theoretical calculation based on EPS09 NLO shadowing [13, 31]. Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity and horizontal bars reflect the $p_T$ bin width.

The $\Upsilon(2S)$ $R_{pPb}$ values at backward and forward rapidities are:

$$R_{pPb}(\Upsilon(2S))(2.03 < y_{\text{cms}} < 3.53) = 0.62 \pm 0.13(\text{stat.}) \pm 0.06(\text{syst.})$$
$$R_{pPb}(\Upsilon(2S))(-4.46 < y_{\text{cms}} < -2.96) = 0.72 \pm 0.13(\text{stat.}) \pm 0.07(\text{syst.})$$

The difference in the $R_{pPb}$ of the $\Upsilon(2S)$ and $\Upsilon(1S)$ amounts to $1\sigma$ at forward rapidity and $0.9\sigma$ at backward rapidity.
Inclusive $\Upsilon$ production in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Fig. 5: Inclusive $\Upsilon$(1S) $Q_{\text{pPb}}$ as a function of the average number of binary nucleon–nucleon collisions, $\langle N_{\text{coll}} \rangle$, for Pb–p (left panel) and p–Pb collisions (right panel). Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. Global uncertainties are represented as boxes around unity.

Fig. 6: Inclusive $\Upsilon$(1S) and $\Upsilon$(2S) $R_{\text{pPb}}$ as a function of $y_{\text{cms}}$. The $\Upsilon$(1S) $R_{\text{pPb}}$ values at $\sqrt{s_{NN}} = 8.16$ TeV (red circles) are compared to the $\Upsilon$(2S) ones (blue squares) in the same $y_{\text{cms}}$ intervals. Systematic uncertainties are shown as boxes around the symbols, while statistical ones are shown as bars. The gray box around unity represents the uncertainties on the pp reference and on $\langle T_{\text{pPb}} \rangle$ which are common to the $\Upsilon$(1S) and $\Upsilon$(2S) resonances. The $R_{\text{pPb}}$ values of the two resonances are slightly displaced to improve visibility. Horizontal error bars refer to the $y_{\text{cms}}$ bin width.

5 Conclusions

The ALICE measurements of the rapidity, transverse momentum and centrality dependence of the inclusive $\Upsilon$(1S) nuclear modification factor in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV have been presented. Preliminary results show a suppression of the $\Upsilon$(1S) yields, with respect to pp collisions at the same centre-of-mass energy. The $R_{\text{pPb}}$ values are similar at forward and backward rapidities with a hint for a stronger suppression at low $p_T$. In both rapidity intervals there is no evidence for a centrality dependence of the $\Upsilon$(1S) $Q_{\text{pPb}}$. The results obtained at $\sqrt{s_{NN}} = 8.16$ TeV are compatible with those measured by ALICE in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Models based on nuclear shadowing and coherent...
parton energy loss fairly describe the data at forward rapidity, while they tend to overestimate the $R_{pPb}$ at backward-$y_{\text{cms}}$. Finally, the $\Upsilon(2S)R_{pPb}$ has also been measured, showing a similar suppression in the two investigated rapidity ranges. The $\Upsilon(2S)$ and $\Upsilon(1S)$ suppressions are compatible within one sigma.

References


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