Nuclear modification of \( \Upsilon \) states in pPb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV

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Abstract

Production cross sections of \( \Upsilon(1S) \), \( \Upsilon(2S) \), and \( \Upsilon(3S) \) states decaying into \( \mu^+\mu^- \) in proton-lead (pPb) collisions are reported using data collected by the CMS experiment at \( \sqrt{s_{NN}} = 5.02 \) TeV. Nuclear modification factors \( R_{\text{pPb}} \) for all three \( \Upsilon \) states are obtained using measured proton-proton (pp) cross sections at the same collision energy. All \( \Upsilon \) states are found to be suppressed in pPb collisions compared to pp collisions. The \( \Upsilon \) \( R_{\text{pPb}} \) show a sequential ordering, with \( \Upsilon(1S) \) least suppressed and \( \Upsilon(3S) \) most suppressed, indicating presence of final-state modification of \( \Upsilon \) states in pPb collisions. When presented as a function of transverse momentum \( p_T \) and center-of-mass rapidity \( y_{\text{CM}} \), the \( R_{\text{pPb}} \) of individual \( \Upsilon \) states are found to be consistent with constant values; although there is slight indication of higher separation of the suppression level of excited states for low-\( p_T \) \( \Upsilon \) in the lead-going direction, where more nuclear matter is present. The final-state comover interaction model, which predicts sequential suppression of bottomonia in pPb, is found to be in better agreement with \( R_{\text{pPb}} \) versus \( y_{\text{CM}} \) than initial-state models. The nuclear modification observed in pPb collisions is less pronounced than the strong modification observed in lead-lead collisions, suggesting presence of additional quark gluon plasma effects in the latter. Forward-backward production ratios \( R_{\text{FB}} \) of \( \Upsilon \) states are reported as functions of event activity variables, obtained from midrapidity as well as forward and backward rapidity regions. The \( R_{\text{FB}} \) for all \( \Upsilon \) states are found to be consistent with unity and constant with increasing event activity, irrespective of the rapidity region used to measure activity.
Heavy ion experiments can be used to study thermal properties of the quark gluon plasma (QGP) [1–6]. Debye screening and gluo-dissociation [7–9] in the QGP produced in lead-lead (PbPb) collisions is understood to modify quarkonium yields. The modified heavy-quark potential in the QGP causes in-medium spectral functions of quarkonia to broaden and shift to lower masses in a hierarchical pattern according to their vacuum binding energies. The result is observed as hierarchical suppression of quarkonium yields in PbPb collisions compared to collisions in vacuum. Thus, measured yields of various quarkonium states, which have a short formation time in their rest frames but survive long enough to outlive the QGP, may be used to determine its early-stage temperature [1, 2, 4, 6, 10, 11]. In particular, because of the high mass of bottomonia compared to collision temperatures, bottomonium production is dominated by initial scattering of partons, primarily via gluon-gluon fusion [10, 12–14]. Previous studies have measured nuclear modification of bottomonium states decaying via the dimuon channel in PbPb collisions compared to proton-proton (pp) collisions using data collected by the CMS experiment at $\sqrt{s_{NN}} = 2.76$ TeV [15] and $\sqrt{s_{NN}} = 5.02$ TeV [16, 17]. The sequential pattern of $\Upsilon$ suppression measured in these studies allows the inference of model-dependent QGP temperatures. However, along with the formation of the hot, dense plasma in heavy ion collisions, cold nuclear matter (CNM) effects due to the involvement of non-deconfined nuclei [10, 12, 18–21] also affects measured yields of bottomonium mesons produced. Understanding CNM effects can help distinguish quarkonium suppression in heavy ion collisions due to color deconfinement alone.

In contrast to the PbPb case, modifications to quarkonium yields in proton-lead (pPb) collisions are expected to be dominated by CNM effects. Initial-state CNM effects include gluon saturation [22] and modification of gluon parton distribution functions (PDFs), known as shadowing, before the $Q\overline{Q}$ is formed [12, 23]. Once the $Q\overline{Q}$ is produced, but before it hadronizes to a quarkonium state, it may be affected by coherent parton energy loss [14, 20, 24]. Since both shadowing and energy loss affect the pre-hadronized $Q\overline{Q}$, they should modify all $\Upsilon$ states in the same way [25, 26]. Mechanisms that affect hadronized $\Upsilon$ states, and may therefore modify each state to a different extent, are known as final-state effects. In the final-state, $\Upsilon$ states may be modified by comover interaction, where they are broken up by particles traveling with similar rapidities. In its own rest frame, the $Q\overline{Q}$ hadronizes quickly and the $\Upsilon$ can interact with comoving particles well outside the nuclear volume. The cross section of comover interaction depends on the quarkonium radius, thus varying with each $\Upsilon$ state [25, 26]. Therefore, any observed differences in production yields of the three bottomonium states in pPb collisions at the LHC would be indicative of final-state comover interaction effects. Comparing $\Upsilon$ nuclear modification across collision systems helps not only to disentangle hot and cold nuclear matter effects but also to investigate various CNM mechanisms.

Nuclear modification factors $R_{pPb}$ and $R_{AA}$ are a useful way to compare bottomonium yields produced in pp, pPb, and PbPb collisions. Theoretical uncertainties associated with the choice of renormalization and factorization scales, as well as the choice of $b$ quark mass, affect $\Upsilon$ cross section calculations in the same way for each collision system, and thus cancel in the nuclear modification factors. Calculations incorporating shadowing, parton energy loss, and comover interaction are able to isolate such effects in the $R_{pPb}$, while canceling some of the uncertainties of quarkonium production models. Experimentally, many systematic uncertainties that affect the measurement of absolute yields and cross sections cancel to a large extent in the measurement of $R_{pPb}$.

Whereas pp collisions have center of mass at rest in the lab frame, the center of mass in pPb collisions is shifted with respect to lab-frame rapidity $y_{lab}$ because of the difference in energy-
per-nucleon between incident proton and lead beams. The asymmetry of pPb collisions with respect to the lab frame allows us to investigate the difference in production of bottomonia in the proton-going (defined as forward rapidity) and lead-going (backward rapidity) directions. The forward-backward production ratio $R_{FB}$ versus event activity helps in investigating different CNM effects in regions with more nuclear matter, even when event activity is held constant. Similar to the $R_{p\bar{p}}$ case, many systematic uncertainties cancel in the $R_{FB}$.

Using pPb and pp collision data at center-of-mass (CM) energy of $\sqrt{s_{NN}} = 5.02$ TeV collected with the CMS detector in 2013 and 2015 respectively, we present the first measurements of Y production cross sections in pPb collisions as functions of transverse momentum $p_T$ and CM rapidity $y_{CM}$. Using Y cross sections in pp collisions in the same kinematic regions (reported in Appendix A), we determine the $R_{p\bar{p}}$ of the three states. We study the kinematic dependence of the $R_{p\bar{p}}$ on $p_T$ and $y_{CM}$. Investigating the $R_{p\bar{p}}$ of all three Y states allows for the separation of initial-state versus final-state mechanisms for CNM modification. Moreover, we make comparisons to the Y $R_{AA}$ results [17] using PbPb data from 2015, also collected at $\sqrt{s_{NN}} = 5.02$ TeV, allowing a direct comparison of bottomonia in hot and cold nuclear matter. We further study the $R_{FB}$ in pPb collisions as a function of event activity measured in two different ways. Event activity is measured in the midrapidity region $|\eta_{lab}| < 2.4$ using the number of reconstructed tracks, $N_{tracks}$, and in the forward and backward rapidity regions $4 < |\eta_{lab}| < 5.2$ using the sum of deposited transverse energy $E_T$.

The main feature of the CMS detector is a superconducting solenoid with a 6 m internal diameter which produces a 3.8 T field and houses the silicon pixel and strip tracker. Muons are detected in the pseudorapidity range $|\eta_{lab}| < 2.4$ in the detector frame in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes based on drift tube, cathode strip chamber, and resistive plate chamber technologies. Matching muons to tracks measured in the silicon tracker leads to a relative transverse momentum resolution between 1–2% for a typical muon in this analysis [27]. Event activity in the midrapidity region is estimated using $N_{tracks}$ in the silicon tracker, which extends to $|\eta_{lab}| < 2.5$. In the forward and backward rapidity regions, activity is measured using $E_T^{HF}$, the $E_T$ measured in two hadron forward (HF) calorimeters, which cover the range $2.9 < |\eta_{lab}| < 5.2$. All recorded events in pPb collisions are required to have at least 1 tower above 3 GeV in the HF on each side of the interaction point, while in pp collisions, at least 3 such towers are required. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28].

Since the Y mesons are identified via their decay to dimuons, this analysis uses a fast hardware-based algorithm (trigger) that selects events with two muons. The trigger sampled an integrated luminosity of 28.0 pb$^{-1}$ in pp collisions and 34.6 nb$^{-1}$ in pPb collisions. We select single muons in the kinematic range $p_T^{\mu} > 4$ GeV/$c$, $|\eta_{lab}^{\mu}| < 2.4$ in the lab frame. The muon tracks are required to have at least 6 hits in the silicon tracker, with at least one hit in the silicon pixel detector, and match with at least one segment in any station of the muon system. The muon’s momentum is derived from a fit to its trajectory using the tracker hits. The distance of the track from the closest primary vertex (from which the majority of tracks in an event originate) must be less than 20 cm in the longitudinal direction and 0.3 cm in the transverse direction. When forming a muon pair, the two muons are required to match the dimuon trigger object and to originate from a common vertex with a $\chi^2$ probability larger than 1% as obtained by a Kalman vertex algorithm [29].

Since the center of mass in pPb collisions is boosted relative to the detector, the rapidity range
The mass parameter of the Υ state in a given fit. The mass parameter of the Υ state is left free to account for possible systematic shifts in the momentum scale of the reconstructed tracks. The masses of the excited states are constrained to be consistent with the ratio of the PDG world-average mass values $m(nS) = \frac{m(1S)}{m(1S)}_{\text{PDG}}$. The three parameters governing the CB tail shapes and ratio of CB widths are allowed to float in an interval around their mean values from a group of preliminary fits. An additional Gaussian penalty is incorporated to prevent large deviations.
from the mean. In the case of pPb, a Gaussian constraint on the parameter determining the relative contributions of the two CBs to the overall peak shape is additionally derived from the value of this parameter in the corresponding pp fit. The appropriate parameter phase space is found by iteratively restricting more stable parameters to their mean values and allowing less stable parameters to vary freely in the preliminary fits. The mean values from preliminary fits are obtained separately in the midrapidity region and very forward or backward rapidity regions, to allow for differences in Y reconstruction region and very forward or backward rapidity regions, to allow for differences in Y reconstruction and very forward or backward rapidity regions, to allow for differences in Y reconstruction and very forward or backward rapidity regions, to allow for differences in Y reconstruction in the barrel and end-cap regions of the detector. The background is modeled with a shifted and scaled error function multiplied by an exponential. The use of an error function is motivated by the effect of the \( p_T > 4 \text{ GeV}/c \) selection applied to single muons, which produces an enhancement in combinatorial background at low invariant masses and at low dimuon \( p_T \). For dimuon \( p_T > 6 \text{ GeV}/c \), this feature lies outside our analysis window and we model the background solely with an exponential function.

The systematic uncertainty due to incomplete knowledge of the parameterization of the signal is estimated using an alternative function consisting of a single CB in combination with a Gaussian, which arrives at a comparable goodness-of-fit. The alternative function used in the case of background depends on the region of dimuon \( p_T \) probed. We use a power law function for dimuons with \( p_T > 6 \text{ GeV}/c \) or in the most extreme regions of the detector. For all other kinematic regions, we use a compound probability density function constructed using a linear combination of invariant mass fits to a Monte Carlo (MC) simulation of rapidity-shifted dimuon decays with mass and kinematic distributions weighted according to data. The MC dimuon mass distributions are fitted separately in the four \( p_T \) intervals \([0, 1.5], [1.5, 3], [3, 4.5], \) and \([4.5, 30] \text{ GeV}/c \). In the first three \( p_T \) intervals, the fit function used is the sum of an error function and an inverted exponential function with an overall exponential decay. A power law function is used in the fourth \( p_T \) interval.

In order to validate the nominal fit and determine systematic uncertainties in the choices of signal and background models, we generate MC events by sampling the overall fitted shape of the dimuon invariant mass spectra in each analysis bin. Invariant mass distributions from such pseudo-experiments are fit with nominal and alternative signal models, using the nominal background model in both cases. Similarly, additional pseudo-experiments are performed to test the background models. The systematic uncertainty is the mean of absolute values of relative differences between yields extracted using the nominal and alternative methods. The choice of background model is the dominant source of systematic uncertainty in the analysis. Additionally, we estimate systematic uncertainty due to the reduction of phase-space for the signal model parameters discussed above. We use the value of the parameter obtained in the preliminary free-parameter fit to data as an alternate value for the mean of the penalizing Gaussian. The largest deviation of the yield extracted using this method for each constrained parameter from the nominal extracted yield is assigned as the systematic uncertainty. The uncertainties due to the signal fitting procedure are determined by combining the uncertainties in the choice of signal model and in parameter restrictions.

Dedicated MC simulations are used to determine detector acceptance and efficiency corrections to be applied to the extracted yields to convert them to cross sections. Two million decays each for Y(1S), Y(2S), and Y(3S) are generated at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) using PYTHIA 8.209 [31] for pp collisions. These samples are also used for pPb collisions, once particles are boosted by \( \delta \eta = 0.465 \) in the lead-going direction to simulate the \( \eta_{\text{CM}} \) shift in data. The transverse momentum distributions of the Y states in MC samples are reweighted using a fit to the ratio of the \( p_T \) spectra in data and MC. The reweighted MC samples are used to determine acceptance corrections as the fraction of generated Y mesons in a given kinematic bin that decay to muons satisfying the kinematic requirements of the analysis. The relative systematic uncertainty in
acceptance correction due to the parameterization of $p_T$ reweighting is determined. In order to determine the efficiency of various dimuon reconstruction steps, the CMS detector response to generated MC samples is simulated using GEANT4 [32]. Possible effects of non-cancellation of reconstruction, trigger, and muon identification efficiencies in $R_{pPb}$ and $R_{FB}$ are studied using these MC samples along with additional data-driven corrections. Systematic uncertainties in efficiency corrections are estimated by combining two sources in quadrature: the uncertainty in reweighting MC $p_T$ spectra, which is estimated using MC with and without reweighting, and the uncertainty in the data-driven corrections.

The product of the branching fraction of $\Upsilon(nS)$ to muon pairs, $B(\Upsilon(nS) \rightarrow \mu^+\mu^-)$, and the double-differential production cross section, $d^2\sigma/dp_Tdy_{CM}$, is obtained experimentally as:

$$B(\Upsilon(nS) \rightarrow \mu^+\mu^-) \frac{d^2\sigma}{dp_Tdy_{CM}} = \frac{N_{\text{Fit}}^{\Upsilon(nS)}}{L_{\text{int}}\Delta p_T\Delta y_{CM}},$$

where $N_{\text{Fit}}^{\Upsilon(nS)}$ is the extracted raw yield of $\Upsilon$ mesons in a given ($p_T, y_{CM}$) bin, $(a \cdot \varepsilon)$ represents the product of dimuon acceptance and efficiency, and $L_{\text{int}}$ is the integrated luminosity. Figure 2 shows the cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ depicted using filled red circles, blue squares, and green diamonds, respectively, in pPb collisions in the kinematic regions probed. This color convention is maintained throughout the note, except when comparisons to the $R_{AA}$ results [17] are made, where all $R_{pPb}$ results are shown as red circles. The error bars on the points represent statistical and fit uncertainties in the pPb data, and the filled boxes around the points represent the combined systematic uncertainties in acceptance and efficiency corrections as well as in the yield extraction process due to the choice of signal and background models.

![Figure 2: Cross section times dimuon branching fraction of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as a function of $p_T$ (left) and rapidity (right) in pPb collisions. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties.](image)

Figure 3 shows the $\Upsilon(nS) R_{pPb}$ as a function of $p_T$ and $y_{CM}$, obtained as

$$R_{pPb}(p_T, y_{CM}) = \frac{(d^2\sigma/dp_Tdy_{CM})_{pPb}}{A(d^2\sigma/dp_Tdy_{CM})_{pp}},$$

where $A$ is the atomic mass number.
where $A = 208$ is the mass number of the Pb nucleus. The uncertainties are represented as in Fig. 2, with an additional gray box drawn around the line at unity depicting combined uncertainties in the pp and pPb luminosity normalizations, which are applicable to all points. We observe that all three $\Upsilon$ states are suppressed in pPb collisions relative to pp collisions throughout the kinematic region explored, indicating modification by CNM effects in pPb. Furthermore, the $\Upsilon$ states show a sequential pattern of suppression, with $\Upsilon(1S)$ the least suppressed and $\Upsilon(3S)$ the most suppressed, suggesting active final-state CNM mechanisms. Similar to the PbPb case [17], the level of suppression for each $\Upsilon$ state in pPb collisions is consistent with a constant value in the kinematic region studied. However, a much stronger level of suppression is seen in PbPb throughout the kinematic range, due to deconfinement effects. The ATLAS collaboration reported an increasing $R_{pPb}$ with $p_T$ for $\Upsilon(1S)$ [33] in a midrapidity region similar to CMS. However, the overall $p_T$ dependence of $\Upsilon(1S)$ $R_{pPb}$ in the two experiments are consistent within uncertainties. In the charmonium sector, a similar sequential suppression pattern as we present here was observed by CMS, with the $R_{pPb}$ of $\psi(2S)$ being smaller [34] than that of $J/\psi$ [35] in pPb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ over the entire kinematic region studied.

![Figure 3: $R_{pPb}$ of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) as a function of $p_T$ for $|y_{CM}| < 1.93$ (left) and versus $y_{CM}$ for $p_T < 30 \text{ GeV}/c$ (right). Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization. All three $\Upsilon$ states are suppressed in pPb collisions compared to pp collisions throughout the kinematic region explored. For each $\Upsilon$ state, the measured $R_{pPb}$ is consistent with a constant value across the kinematic range. The $\Upsilon$ states show a sequential pattern of suppression, with $\Upsilon(1S)$ the least suppressed.](image-url)
only (green) and energy loss with shadowing (blue) [24]. These models predict $R_{\text{pPb}}$ values that are slightly higher than our measured $\Upsilon(1S) R_{\text{pPb}}$. Slightly closer agreement with data is observed when the energy loss model is combined with shadowing effects from EPS09.

These initial- and intermediate-state effects modify all $\Upsilon$ states similarly. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization.

In contrast to shadowing and energy loss models, the CIM predicts different amounts of modification for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states in nuclear collisions. In the comover framework, higher excited states experience stronger comover dissociation rates due to their larger size, and modification of quarkonium states is stronger in regions where the comover densities are larger, such as in the nucleus-going direction in asymmetric proton-nucleus collisions [25, 26].

Figure 5 shows comparisons of predicted $R_{\text{pPb}}$ in the CIM by E. Ferreiro and J. Lansberg [26], along with our measured $R_{\text{pPb}}$ for $\Upsilon(1S)$ (top left), $\Upsilon(2S)$ (top right), and $\Upsilon(3S)$ (bottom). CIM predictions for all three states are illustrated with shadowing corrections using nCTEQ15 (brown) and EPS09 (pink). The CIM $R_{\text{pPb}}$ predictions show significant overall suppression for all $\Upsilon$ states with both shadowing corrections. Moreover, sequential suppression of the $\Upsilon$ states is predicted, with the least suppression expected for $\Upsilon(1S)$. The final-state effect of hadronic comovers yields predictions in stronger agreement with our data for all three states.

By exploring the $Y R_{\text{pPb}}$ in the forward and backward directions, we can investigate the dependence of bottomonium suppression on the amount of nuclear matter present. Figure 6 shows the $R_{\text{pPb}}$ of $Y$ states for $-1.93 < y_{\text{CM}} < 0$ and $0 < y_{\text{CM}} < 1.93$ in the low $p_T$ (left) and high $p_T$ (right) regions. These results reinforce the indication of sequential suppression of $Y$ states in the entire kinematic region explored. We find indication of slightly greater separation of the suppression levels of low-$p_T Y(nS)$ in the lead-going versus the proton-going $y_{\text{CM}}$ directions. A similar, albeit more significant, observation was made by CMS in the charmonium sector [34], where $\psi(2S)$ was found to be more suppressed in the backward region than $J/\psi$ while both states experienced similar suppression in the forward region.

We study the forward-backward production ratio of $Y$ mesons in pPb, defined as follows,
Figure 5: $R_{pPb}$ versus $y_{CM}$ with comover effect predictions from E. Ferreiro and J. Lansberg [26] with shadowing corrections using nCTEQ15 and EPS09 for $\Upsilon(1S)$ (top left), $\Upsilon(2S)$ (top right) and $\Upsilon(3S)$ (bottom). The final-state comover effect is seen to modify the $\Upsilon$ states sequentially. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization.
Figure 6: $R_{pPb}$ of $\Upsilon(1S)$ (red circles), $\Upsilon(2S)$ (blue squares), and $\Upsilon(3S)$ (green diamonds) at forward and backward rapidity for $0 < p_T < 6$ GeV/c (left) and $6 < p_T < 30$ GeV/c (right). The points are shifted horizontally for better visibility. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization.

\begin{equation}
R_{FB}(p_T, y_{CM} > 0) = \frac{(d^2\sigma(p_T, y_{CM})/dp_Tdy_{CM})}{(d^2\sigma(p_T, -y_{CM})/dp_Tdy_{CM})},
\end{equation}

where $y_{CM}$ is positive. Figure 7 shows the $R_{FB}$ as a function of event activity measured in the midrapidity region ($|\eta_{lab}| < 2.4$), where $\Upsilon$ mesons are measured, using $N_{\text{tracks}}$ (Fig. 7 left), and in forward and backward rapidity regions ($|\eta_{lab}| > 4$), at large rapidity gaps from the measured $\Upsilon$, using $E_T^{HF}$ (Fig. 7 right). The measured $R_{FB}$ remains constant at unity at all levels of event activity for all three $\Upsilon$ states. This observation is independent of the rapidity region used to measure activity. In the very forward and backward $y_{CM}$ regions, integrated $\Upsilon(1S)$ $R_{FB}$ values consistent with unity and slightly less than unity were reported by the ALICE [38] and LHCb [39] collaborations, respectively. By contrast to $\Upsilon$ results, the $R_{FB}$ for prompt and nonprompt $J/\psi$ were found by CMS to diminish with increasing $E_T^{HF}$ [35].

Figure 8 shows the integrated $R_{pPb}$ of $\Upsilon$ states (red circles) as well as the $R_{AA}$ (blue squares) observed in PbPb collisions [17] at $\sqrt{s_{NN}} = 5.02$ TeV for comparison. The 95% confidence level on the $\Upsilon(3S)$ $R_{AA}$ is depicted using a blue arrow. Uncertainties on the measured data points are represented as before, while global uncertainties in the pPb, PbPb, and pp data are depicted by red, blue, and gray boxes around unity, respectively. The data indicate a sequential ordering of nuclear modification for the $\Upsilon$ family with $R_{pPb}(1S) > R_{pPb}(2S) > R_{pPb}(3S)$:

\begin{align*}
\Upsilon(1S) & \ R_{pPb} = 0.773 \pm 0.023\text{(stat)} \pm 0.074\text{(syst)}, \\
\Upsilon(2S) & \ R_{pPb} = 0.673 \pm 0.039\text{(stat)} \pm 0.083\text{(syst)}, \\
\Upsilon(3S) & \ R_{pPb} = 0.514 \pm 0.056\text{(stat)} \pm 0.094\text{(syst)}.
\end{align*}

We determine the $p$-values of the observed suppression in pPb collisions relative to pp collisions, under the hypothesis of $A$-scaling, to be $1.70 \times 10^{-3}$, $1.81 \times 10^{-4}$, and $4.45 \times 10^{-6}$ for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively. The corresponding significances (z-scores) are 2.9, 3.6,
Figure 7: $R_{FB}$ vs. midrapidity $N_{\text{tracks}}$ (left) and forward/backward rapidity $E_{T}^{FB}$ (right) of $\Upsilon$(1S) (red circles), $\Upsilon$(2S) (blue squares), and $\Upsilon$(3S) (green diamonds) for $p_T < 30$ GeV/$c$ and $|y_{CM}| < 1.93$. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties.

and 4.4 standard deviations, respectively. Furthermore, the $p$-values of additional suppression of excited states compared to the ground state are found to be $1.45 \times 10^{-1}$ for $\Upsilon$(2S) and $1.03 \times 10^{-2}$ for $\Upsilon$(3S), corresponding to significances of 1.1 and 2.3 standard deviations, respectively. The differences in suppression level of the three states can be explained by the presence of final-state effects in pPb, such as the comover effect previously discussed. The measured differences in $\Upsilon$(nS) production in pPb are much more modest than the sequential suppression seen in PbPb [17]. A direct comparison of the $R_{AA}$ to the $R_{pPb}$ requires appropriate scaling of the $R_{pPb}$ to reflect modification by two lead nuclei instead of one in PbPb collisions. Such a direct comparison is needed in order to determine whether hot nuclear matter effects in the QGP result in additional suppression of bottomonia in PbPb. Additional modification in PbPb collisions compared to pPb collisions can be caused by the presence of color deconfinement as predicted by Refs. [2, 3, 5, 10, 18], and possibly even enhanced comover interaction effects also present in the dense medium [26].

In summary, the $\Upsilon$ family has been studied in pPb collisions at 5.02 TeV and the production cross sections presented. Together with pp data obtained at the same center-of-mass energy, we measured the nuclear modification factors for the three $\Upsilon$ states decaying in the dimuon channel. We observe a suppression of the $\Upsilon$ yields relative to the hypothesis of $A$-scaling for all three states, in the full kinematic range studied. No significant trend is seen for the suppression as functions of $p_T$ or $y_{CM}$, although there is slight indication of higher separation of the suppression level of excited states in the lead-going direction for low-$p_T$ $\Upsilon$. The forward-backward production ratios $R_{FB}$ of $\Upsilon$ states were studied separately as functions of event activity recorded near to and far away from the rapidity region where $\Upsilon$ mesons were measured. The $R_{FB}$ values are consistent with unity for all states, independent of the rapidity region used to measure activity. The integrated nuclear modification factors for $\Upsilon$ were compared to those obtained in PbPb collisions. The $R_{AA}$ values are much smaller than the corresponding $R_{pPb}$ value for each state, as expected in the presence of deconfinement effects in PbPb. A modest sequential suppression, consistent with predictions from hadronic comover effects, is observed in pPb, indicating the presence of final-state effects in pPb collisions. These results will help to elucidate
Figure 8: $R_{p\text{Pb}}$ of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ (red circles) for the integrated kinematic range $0 < p_T < 30$ GeV/$c$ and $|y_{CM}| < 1.93$. The $R_{p\text{Pb}}$ results are compared to the CMS results on $Y$ $R_{AA}$ (blue squares for $\Upsilon(1S)$ and $\Upsilon(2S)$ and blue arrow for $\Upsilon(3S)$ at 95% confidence level) for $0 < p_T < 30$ GeV/$c$ and $|y_{CM}| < 2.4$ at the same energy [17]. Error bars represent statistical and fit uncertainties and filled boxes around points represent systematic uncertainties. The gray and red boxes around the line at unity depict the uncertainty in the pp and pPb luminosity normalizations, respectively. The blue box around unity depicts the global uncertainty pertaining to PbPb data.
the contributions of cold and hot nuclear matter effects to the modification of bottomonia in heavy ion collisions.

References


A. \( \Upsilon \) cross sections in pp collisions for \( y_{\text{CM}} < 1.93 \)

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Figure 9: Cross section times dimuon branching fraction of \( \Upsilon(1S) \) (red circles), \( \Upsilon(2S) \) (blue squares), and \( \Upsilon(3S) \) (green diamonds) as a function of \( p_T \) (left) and rapidity (right) in pp collisions. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties.