Understanding sequential quarkonium suppression with Υ(nS) measurements in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the CMS detector

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The production cross sections of the Υ(1S), Υ(2S), and Υ(3S) states were measured separately using the CMS experimental apparatus, in proton-proton (pp) and lead-lead (PbPb) collisions at 5.02 TeV. The final results of the nuclear modification factors, R_{AA}, are reported for the three upsilon states as a function of transverse momentum (p_T), rapidity (y) and PbPb collision centrality. The data show a significant suppression of all three states following a sequential ordering, $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$. The suppression of Υ(1S) is larger than that seen at $\sqrt{s_{NN}} = 2.76$ TeV, though the two are compatible within uncertainties. The Υ(3S) was not observed in PbPb collisions, being suppressed by more than a factor 10 at 95% confidence level.

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1. Introduction

A strongly interacting medium of deconfined quarks and gluons, the quark-gluon plasma (QGP), is predicted to be formed in relativistic heavy ion collisions. The measurement of bottomonium production is one of the most promising ways to understand the properties of such a strongly interacting matter. Bottomonia are produced at the early stages of collisions via hard scattering and their spectral functions are modified as a consequence of Debye screening of the heavy-quark potential at finite temperatures [1, 2], as well as by thermal broadening of their widths due to interactions with gluons [3, 4]. One of the most remarkable signatures of these in-medium effects is the sequential suppression of the bottomonium states in heavy ion collisions compared to the production in proton-proton (pp) collisions. This scenario follows from the expectation that the suppression of bottomonia is stronger for states with smaller binding energy. The yield of the bottomonium states can also increase from the recombination of uncorrelated quarks [5]. However this process is expected to be negligible for bottomonia compared to other quarkonium species such as charmonia, because of less abundance of heavy-quark pairs in a single event for beauty than for charm. The dissociation temperatures for the Υ states, above which suppression occurs, are expected to be correlated with their binding energies, and are predicted to be $T_{dissoc} \approx 2T_c$, $1.2T_c$ and $1T_c$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states, respectively, where T_c is the critical temperature for deconfinement [6]. Therefore, measurements of the yields of each Υ state can provide information about the thermal properties of the medium during its hot early phase. In this conference proceedings, the final results of the R_{AA} measurement will be described for all three Υ states in lead-lead (PbPb) and pp collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$.

2. Data selection

In this analysis, the Υ mesons are identified via the dimuon decay channel. Muons are detected in the pseudorapidity interval of $|\eta| < 2.4$ and the dimuon events are selected by a fast hardware-based trigger system, which requires two muon candidates in a given bunch crossing with no explicit requirement on the muon momentum. The detailed description of the CMS detector can be found in Ref. [7]. In pp collisions, the dimuon event selection trigger recorded an integrated luminosity of 28 pb^{-1}. The PbPb data were taken with two triggers based on the same algorithm used for pp data. The first trigger introduced an additional collision centrality selection, 30-100%, in order to enhance the peripheral event counts. This trigger registered a total of 464 μb^{-1} integrated luminosity. The second mode, without a centrality selection, was prescaled during part of the run and sampled the full integrated luminosity of 368 μb^{-1}. The second trigger was used to analyze the PbPb data in the 0-30% and 0-100% centrality bins. Muons are selected in the kinematic range of $p_T^\mu > 4$ GeV and $|\eta^\mu| < 2.4$, and are also required to be reconstructed using the combined information of the tracker and muon detectors (so-called "global muons" defined in Ref. [8]). The studied dimuon kinematic range is limited to $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$. The dimuons in this p_T range comprise 99% of those passing all of the analysis selection criteria.

3. Signal extraction

The yields of the Υ states are extracted using an unbinned maximum-likelihood fit to the in-

variant mass distribution using a signal PDF and a background PDF on each pp and PbPb data. The sum of two Crystal Ball (CB) functions was used for the signal PDF and an error function multiplied by an exponential function for the background PDF. For $p_T^{\mu^+\mu^-} > 6$ GeV an exponential without the error function for the background PDF provides the best fit, and was used for the nominal results. The dimuon mass window was 8-14 GeV, and a p_T cut ($p_T^{\mu} > 4$ GeV) was applied to the single muons. Figure 1 shows the dimuon invariant mass spectrum in pp and PbPb collisions along with the fits using the signal PDF and background PDF described above, for the kinematic range $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$.
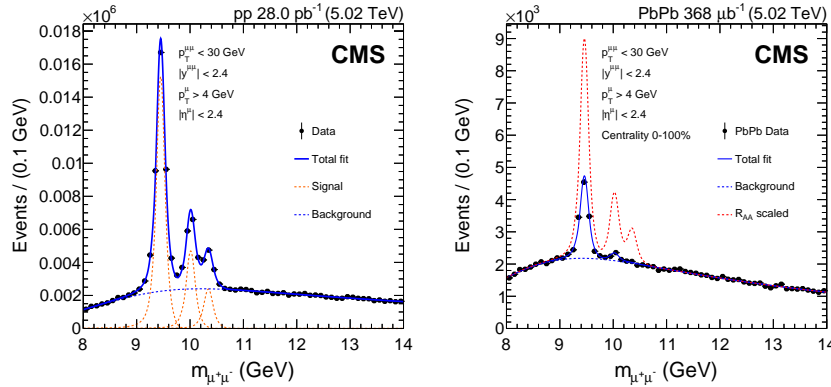

Figure 1: Invariant mass distribution of muon pairs in pp (left) and PbPb (right) collisions, for the kinematic range $p_T^{\mu^+\mu^-} < 30$ GeV and $|y^{\mu^+\mu^-}| < 2.4$ at 5.02 TeV [9]. In both figures, the results of the fits to the data are shown as solid blue lines. The separate yields for each Υ state in pp are shown as dashed red lines in the left panel. The dashed red lines in the right panel are the results of the fits in PbPb (blue solid line) but with the fitted Υ yield for each state scaled by the inverse of its measured R_{AA}.

4. Results

The modification of the bottomonium production for each Υ state in PbPb collisions compared to pp collisions, quantified as the nuclear modification factor R_{AA}, is the ratio of the yield measured in PbPb collisions to that in pp collisions scaled by the mean number of binary NN collisions. The R_{AA} can be obtained by dividing the normalized yields in PbPb collisions with the pp cross sections and nuclear overlap function T_{AA} as in Eq 1.

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N^{AA}/dp_T dy}{d^2 \sigma^{pp}/dp_T dy} \tag{1}$$

$\langle T_{AA} \rangle$ is the average value of T_{AA} computed in each centrality interval. The quantities N^{AA} and σ^{pp} refer to the normalized yield of Υ states in PbPb collisions and the pp cross section. Figure 2 shows the nuclear modification factor of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ as a function of p_T and $|y|$. Within the systematic uncertainties, the R_{AA} values show no clear dependence on p_T or rapidity while the excited Υ states are found to have a larger suppression than the ground state.

The centrality dependent R_{AA} is shown in figure 3 as a function of average $\langle N_{part} \rangle$, with a comparison of two models of bottomonium suppression from Krouppa and Strickland [10], and
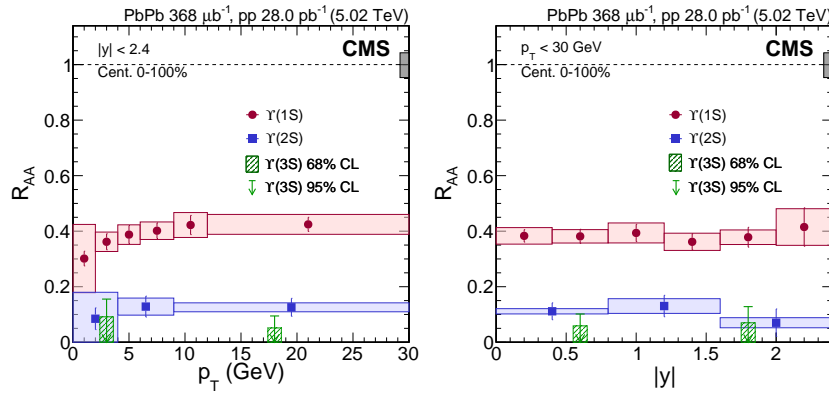
Figure 2: Nuclear modification factors for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as functions of p_T (left) and rapidity (right) [9].

from Du, He, and Rapp [5]. The R_{AA} decreases with increasing PbPb collision centrality for $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons. The strong suppression of the $\Upsilon(3S)$ meson is observed in the studied centrality bins, 0-30% and 30-100%. The two models both incorporate color-screening effects on the bottomonium family and feed-down contributions from decays of heavier quarkonia. No regeneration in QGP or cold nuclear matter effects are considered by the first model, but are included in the second. In Krouppa and Strickland model, the evolution of the medium is described using anisotropic hydrodynamics, where the initial conditions are changed by the variation of the viscosity to entropy ratio, η/s, and the initial momentum-space anisotropy. The model of Du, He, and Rapp uses a kinetic-rate equation to simulate the time evolution of bottomonium abundances and considering the medium effects with temperature-dependent binding energies, and lattice-QCD-based equation of state of the QGP. Within the current theoretical and experimental uncertainties, both models are in agreement with the data.
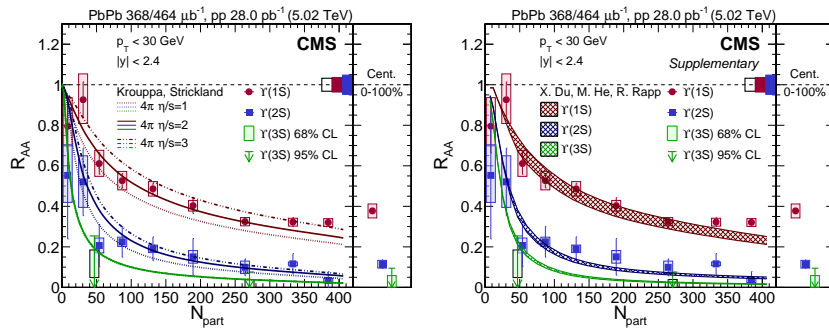

Figure 3: Nuclear modification factors for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of $\langle N_{part} \rangle$ [9] with comparison of the calculations from Krouppa and Strickland (left) [10] and Du, He, and Rapp (right) [5].

The comparison of the centrality-integrated R_{AA} values at $\sqrt{s_{NN}} = 2.76$ TeV to those at 5.02 TeV is shown in figure 4. The suppression of the $\Upsilon(1S)$ meson at 5.02 TeV is larger by a factor of 1.20 ± 0.15, although the two R_{AA} values are compatible within the uncertainties. The centrality-integrated results show similar suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons between the two different collision energies.
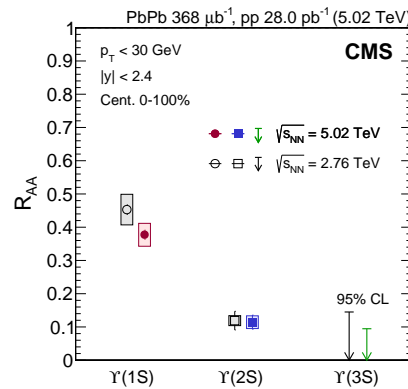
Figure 4: Comparison of R_{AA} values for the Υ(1S), Υ(2S) and Υ(3S) mesons at $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 2.76 TeV [11] for integrated centrality in the full kinematic range. The error bars represent the statistical uncertainties and the boxes the systematic uncertainties, including global uncertainties.

5. Summary

The nuclear modification factors of Υ(1S), Υ(2S) and Υ(3S) are measured as functions of Υ transverse momentum (p_T) and rapidity (y), as well as PbPb collision centrality. A gradual decrease in R_{AA} with increasing centrality is observed for the Υ(1S) and Υ(2S) mesons, while no significant dependence on p_T or y is found in the measured kinematic range. The suppression of Υ(1S) is larger than that seen at $\sqrt{s_{NN}}$ = 2.76 TeV though the results are compatible within the current uncertainties. The Υ(3S) is suppressed strongly in the overall measured kinematic region and no signal is found in the PbPb data.

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