DETAILED STUDY OF UPSILON SUPPRESSION WITH THE MEASUREMENT OF THE $\Upsilon(3S)$ MESON IN PbPb COLLISIONS AT 5.02 TeV IN CMS*

Soohwan Lee

Department of physics, Korea University, 02841 Seoul, Republic of Korea

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Owing to their different binding energies, bottomonia are particularly useful probes to understand the thermal properties of the quark–gluon plasma (QGP) created in relativistic heavy ion collisions. Previously, the CMS Collaboration measured the sequential suppression of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states in PbPb collisions. However, the $\Upsilon(3S)$ yield was excessively low, thus allowing us to report only statistical upper limits. In this contribution, we report a detailed study of the measurement of excited bottomonium states with improved analysis technique and high-statistics data that enables us to observe the $\Upsilon(3S)$ meson in AA collisions for the first time. The result provides a comprehensive picture of the three Υ states in PbPb collisions.

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1. Introduction

Quarkonium production in a relativistic heavy-ion collisions environment has a rich history as a probe to study the signatures of the quark–gluon plasma (QGP). It was first predicted by Matsui and Satz [1] that J/ψ will dissolve into its constituent quark and anti-quark in the presence of QGP. Experimentally, this prediction has been first studied in high-energy heavy-ion collisions at CERN SPS [2]. The concept of J/ψ suppression was later extended to the idea of sequential quarkonium suppression, due to the stronger suppression for quarkonium states with lower binding energies. Bottomonia, bound states of bottom and anti-bottom quarks, are particularly useful probes because they are created by initial hard scatterings so they experience the whole evolution of the QGP phase. They are thus prone to various in-medium effects such as the Debye color screening,

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gluo-dissociation, quasi-free dissociation [3–6], and different channels of recombination processes [6–11]. These interactions affect the survival rate of bottomonia. In this sense, by measuring the relative suppression of the bottomonium yields, one can, in principle, estimate the temperature of the QGP as a function of the collision impact parameter [12]. Another advantage for studying bottomonia is that the three bound states, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ have comparable hierarchical binding energies. The comparisons among the three states provide crucial constraints in modeling the full dynamics of bottomonia inside the QGP. A previous measurement [13] of the Υ states in PbPb collision data confirmed this sequential suppression, but the yields of the excited states were not sufficient to pin down the precise suppression rate, especially for the $\Upsilon(3S)$ meson. In this report, we present the measurement of the excited Υ states including the first observation of $\Upsilon(3S)$ with data taken in 5.02 TeV PbPb collisions by the CMS experiment.

2. Analysis details

2.1. The CMS detector

This analysis is based on the PbPb collision data collected in 2018. The data sample corresponds to an integrated luminosity of 1.6 nb^{-1} [14], which is more than a fourfold increase relative to the data used in the aforementioned previous analysis [13]. The *pp* collision data taken from 2017 reference run in 5.02 TeV has the total luminosity of 300 pb^{-1} [15]. In this analysis, we use the Υ to dimuon decay channel where the CMS detector can provide high-precision muon reconstruction in large spatial and kinematic range, from $|\eta| < 2.4$ and p_{T} up to $\mathcal{O}(100)$ GeV with great momentum resolution.

2.2. Signal extraction

Even with an increased amount of data, it is still challenging to extract a significant $\Upsilon(3S)$ yield due to the large and structured combinatorial background in the dimuon invariant mass distribution. That is why we adopted the use of machine learning technique to enhance the signal significance. Here, we use the Boosted Decision Tree (BDT) algorithm to select dimuons originating from genuine Υ decay. The BDT algorithm is trained with Monte Carlo generated samples of the excited Υ states for the signal, and with the opposite-sign muon pairs whose invariant masses lie on each side of the Υ mass region for background. The training variables include dimuon- and vertex-related variables, such as the distance to the closest approach, dimuon decay length from the primary vertex, *etc.*, that are not directly correlated with variables such as the centrality or the meson transverse momentum. The BDT selection only applies to the PbPb data since the signal-to-background ratio in the *pp* case is high enough to extract precise Υ yields. The Υ yield is finally extracted from the extended unbinned maximum-likelihood fit with the signal shape modeled with three Crystal Ball functions for each Υ state and background modeled with the error function multiplied with exponential.

As it can be seen in the right panel of Fig. 1, both of the excited Υ states are seen clearly in the PbPb data fit, with a statistical significance above five standard deviations for $\Upsilon(3S)$.

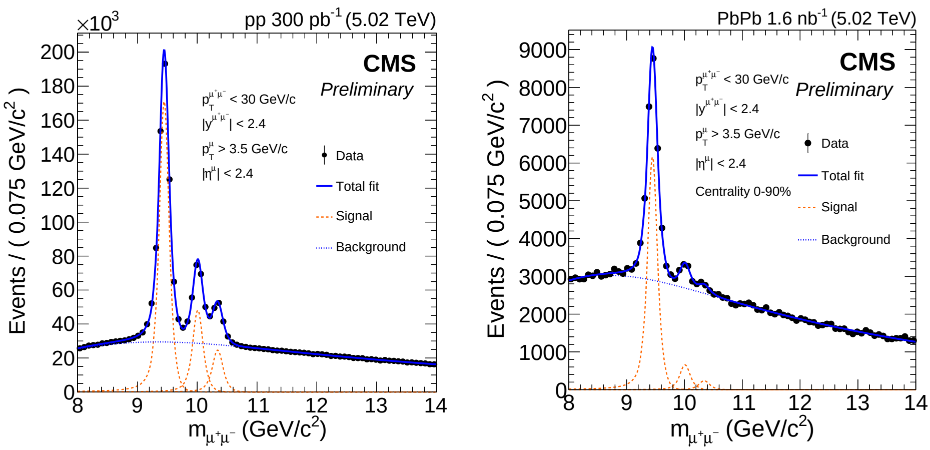

Fig. 1. The dimuon invariant mass distributions of the *pp* and PbPb data, respectively.

3. Results and discussion

The nuclear modification factor (R_{AA}) is defined as

$$R_{AA}(p_{\rm T}, y) = \frac{{\rm d}^2 N^{AA}_{\Upsilon,\rm corr}/{\rm d}p_{\rm T}\,{\rm d}y}{\langle T_{AA}\rangle {\rm d}^2\sigma^{pp}_{\Upsilon}/{\rm d}p_{\rm T}\,{\rm d}y}\,, \tag{1}$$

where $N^{AA}_{\Upsilon,\rm corr}$ is the efficiency and acceptance corrected Υ yield divided by the number of PbPb collision minimum-bias events, and $\langle T_{AA}\rangle$ corresponds to the nuclear overlap function averaged over each centrality interval considered. Figure 2 shows the R_{AA} as a function of the average number of participant nucleons $\langle N_{\rm part}\rangle$. The $\Upsilon(1S)$ data points are taken from the previous study [13]. The stronger suppression towards larger $\langle N_{\rm part}\rangle$, *i.e.* for more central collisions, is consistent with the increase of quarkonium dissociation probability with the QGP temperature. The significantly improved significance of the measurements compared to the previous work [13] allows us to see a clear ordering of the R_{AA} values for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$.

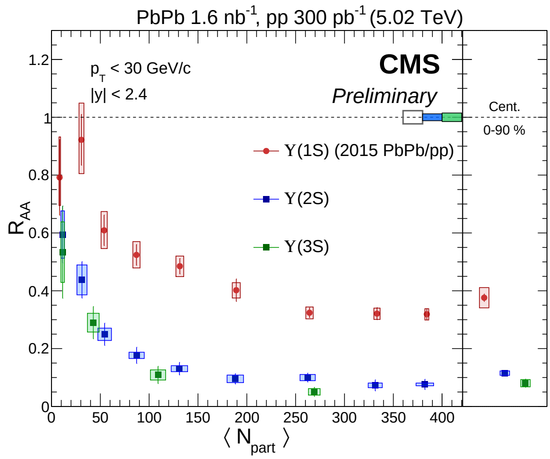

Fig. 2. (Color online) R_{AA} as a function of $\langle N_{\text{part}} \rangle$. The boxes on the right top side of the plot represent global uncertainties. The white box in the left panel shows the uncertainty in the *pp* luminosity and the number of PbPb minimum-bias events, and the colored boxes adjacent to it represent uncertainties of the yields for the corresponding Υ excited states in *pp* collisions. The $\Upsilon(1S)$ data points are taken from previous study [13].

We introduce a variable to quantify the relative suppression among the excited states: the double ratio of $\Upsilon(3S)/\Upsilon(2S)$ in PbPb over *pp*, which is equivalent to the ratios of R_{AA} for $\Upsilon(3S)$ to those for $\Upsilon(2S)$. More specifically, a double ratio lower than unity means that $\Upsilon(3S)$ suppression rate in PbPb collisions is stronger than that of $\Upsilon(2S)$.

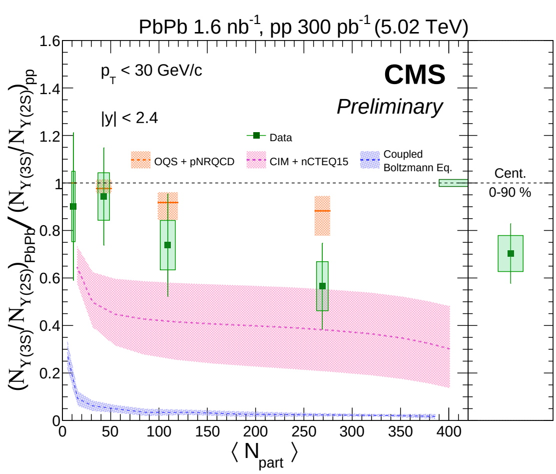

Fig. 3. Double ratio of $\Upsilon(3S)/\Upsilon(2S)$ as a function of average N_{part}. The box on the right top side represents systematic and statistical uncertainties in the *pp* data. Theory calculations [7, 11, 16] are overlaid for comparison.

Figure 3 displays the double ratios as a function of $\langle N_{\rm part}\rangle$ along with theoretical predictions. The double ratio decreases towards central PbPb collisions indicating stronger suppression for $\Upsilon(2S)$ than $\Upsilon(3S)$. The plot shows the discrepancy between predictions and experimental data. It suggests that excited states production in heavy-ion collisions should be considered in the model with good precision by considering contributions from various effects such as a series of in-medium effects. Therefore, this updated measurement provides a more comprehensive picture of the sequential suppression scheme in the bound state Υ family.

4. Summary

Nuclear modification factors and double ratios of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons are measured in PbPb collisions with the CMS detector. The measured values are given as a function of the PbPb collision centrality. The $\Upsilon(3S)$ meson is observed for the first time in PbPb collisions with a significance well above five standard deviations. The amount of suppression for the $\Upsilon(3S)$ meson is found to be stronger than for the $\Upsilon(2S)$ meson, strengthening the evidence of sequential suppression in the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states. The comparison of the results with theory calculations indicates the importance of sophisticated treatment of in-medium effects for $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons. Combined with previous measurements, the results in this study reveal the sequential suppression of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons, which provide new constraints on the understanding of quarkonium suppression in heavy-ion collisions.

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