

# Detailed measurements of bottomonium suppression in PbPb collisions at 2.76 TeV with CMS

Guillermo Breto Rangel (on behalf of the CMS Collaboration)<sup>1</sup>

*CERN, Geneva*

---

## Abstract

The three  $\Upsilon(1S, 2S, 3S)$  states can be separated using the CMS experimental apparatus via their dimuon decays in both pp and heavy-ion collisions. A suppression of the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$  mesons is observed in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, compared to the yield in pp collisions scaled by the number of inelastic nucleon-nucleon collisions. Furthermore, a suppression of the excited  $\Upsilon$  states has been measured with respect to the  $\Upsilon$  ground state, expressed as a double ratio  $[\Upsilon(nS)/\Upsilon(1S)]_{PbPb} / [\Upsilon(nS)/\Upsilon(1S)]_{pp}$  with  $n = 2, 3$ , and  $2 + 3$ . The centrality dependence of the double ratio, as well as the nuclear modification factors ( $R_{AA}$ ) of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states are presented as a function of collision centrality, based on the analysis of the full data sample collected during the 2011 PbPb run, which corresponds to an integrated luminosity of  $150 \mu b^{-1}$ .

---

## 1. Introduction

In high-energy heavy-ion collisions, the properties of the new state of matter known as the quark-gluon plasma (QGP) can be probed studying the suppression of heavy quarkonium states in the hot and dense medium [1]. The suppression is predicted to occur above a critical temperature of the medium, and sequentially, in the order of the  $Q\bar{Q}$  binding energy, making quarkonia a perfect thermometer [2].

The LHC center-of-mass energy allows copious  $\Upsilon$  production in collisions. The bottomonium family is expected to provide additional and theoretically cleaner probes of the deconfined medium when compared to its lower mass counterpart since several competing nuclear and medium effects complicate the prediction of the suppression for charmonium [3]. In addition, due to the larger mass of the bottom quark, the effects of initial state nuclear suppression are expected to be reduced for bottomonium. Moreover, heavier quarks allows for cleaner theoretical treatments based on potential models because these models rely on taking the non-relativistic limit and the heavier the quark the more reliable the treatment is. Furthermore, since bottom  $Q\bar{Q}$  quarks and anti-quarks are relatively rare within the plasma, the probability for regeneration of bottomonium states through recombination is much smaller than for charm quarks.

Finally, the three  $\Upsilon(nS)$  states, characterized by similar decay kinematics and production mechanisms but distinct binding energies, further enable the measurement of relative state sup-

---

<sup>1</sup>A list of members of the CMS Collaboration and acknowledgements can be found at the end of this issue.

pression, where common experimental and theoretical factors and their associated uncertainties, cancel.

A detailed description of the CMS detector can be found elsewhere [4]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Because of the strong magnetic field and the fine granularity of the tracker, the muon  $p_T$  measurement based on information from the tracker alone has a resolution between 1 and 2% for a typical muon in this analysis.

## 2. Relative suppression through a double ratio

Muons are reconstructed by matching tracks in the muon detectors and silicon tracker. The same offline reconstruction algorithm and selection criteria are applied to the PbPb and pp data samples. Only muons with  $p_T > 4$  GeV/c are considered. The dimuon  $p_T$  distribution of the selected candidates extends down to zero and has a mean of about 6 GeV/c, covering a dimuon rapidity range of  $|y| < 2.4$ . The three  $\Upsilon(nS)$  peaks are separated in the PbPb case although the  $\Upsilon(3S)$  state is not prominent above the dimuon continuum.

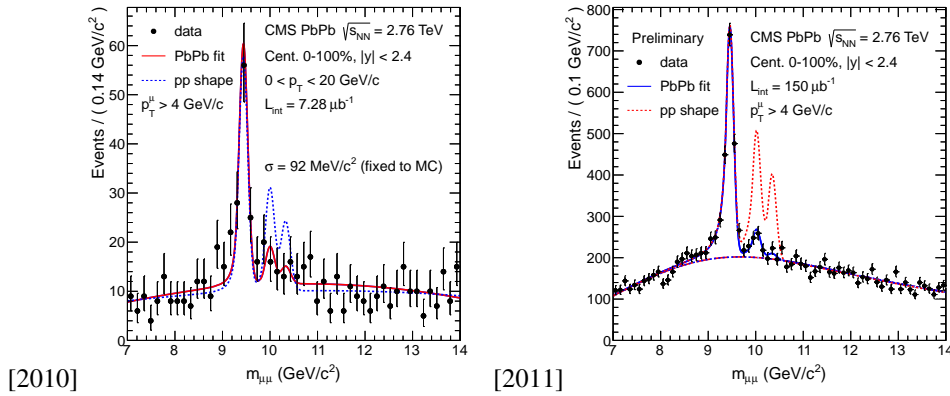


Figure 1: Illustration of the excited to ground states relative  $\Upsilon$  suppression in PbPb compared to pp, and comparison of the effect observed using the 2010 (*left*) and the much larger statistics 2011 (*right*) PbPb datasets. The fit to the PbPb data, shown by the continuous line, is overlaid with the result of the pp fit, represented by the dashed line (shown on top of a common PbPb background shape, for comparison)

An extended unbinned maximum likelihood fit to the invariant mass spectra shown in Fig. 1 (*right*) is performed to extract the  $\Upsilon(nS)$  yields, following the method described in Refs. [5, 6]. The measured mass lineshape of each  $\Upsilon(nS)$  state is parameterized by a “Crystal Ball” (CB) function. The mass differences between the states are fixed to their world average values and the mass resolution is forced to scale with the resonance mass.

The background model for the PbPb dataset consists of an exponential function multiplied by an error function describing the low-mass turn-on due to the kinematics cuts of the analysis. This nominal model accurately describes the mass sidebands in the opposite-sign muon signal sample, as well as the alternative estimates of the shape of the combinatorial background obtained from like-sign muon pairs or via a “track-rotation” method. In the latter method [7] the azimuthal angular coordinate of one of the muon tracks is rotated by 180 degrees. The comprehensive

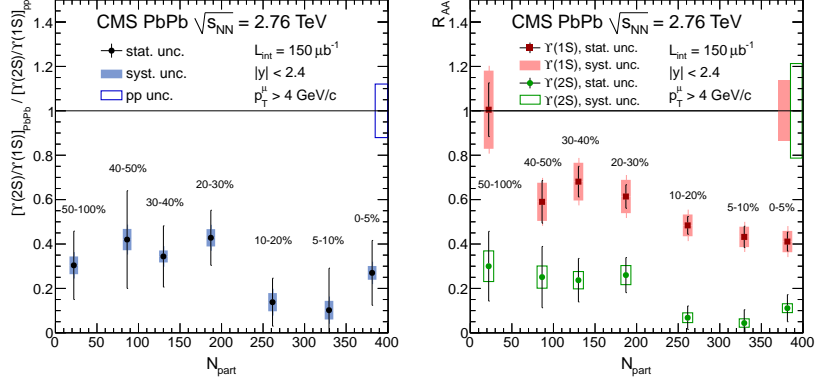


Figure 2: Centrality dependence of the double ratio (*left*) and of the nuclear modification factors (*right*) for the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states. The relative uncertainties from  $N_{\text{part}}$ -independent quantities (pp yields and, for the  $R_{AA}$ , also integrated luminosity) are represented by the boxes at unity, and are not included in the data points as these uncertainties do not affect the point-to-point trend. The event centrality bins used are indicated by percentage intervals.

studies performed on the background described the opposite sign background accurately and the minor differences were added as systematics.

The measurement of the ratio of the  $\Upsilon(nS)/\Upsilon(1S)$  ratios in PbPb and pp collisions benefits from an almost complete cancellation of possible acceptance or efficiency differences among the reconstructed resonances. The simultaneous fit to the PbPb and pp mass spectra gives the double ratios

$$\begin{aligned}
 \Upsilon(2S)/\Upsilon(1S)|_{\text{PbPb}}/\Upsilon(2S)/\Upsilon(1S)|_{\text{pp}} &= 0.21 \pm 0.07 \text{ (stat.)} \pm 0.02 \text{ (syst.)}, \\
 \Upsilon(3S)/\Upsilon(1S)|_{\text{PbPb}}/\Upsilon(3S)/\Upsilon(1S)|_{\text{pp}} &= 0.06 \pm 0.06 \text{ (stat.)} \pm 0.06 \text{ (syst.)} \\
 &< 0.17 \text{ (95\% CL)}.
 \end{aligned}
 \tag{1}$$

The systematic uncertainties from the fitting procedure are evaluated by varying the fit function. An additional systematic uncertainty (1%), estimated from MC simulation, is included to account for possible imperfect cancellations of acceptance and efficiency. For the  $\Upsilon(3S)$  to  $\Upsilon(1S)$  double ratio a 95% confidence level (CL) limit is set, based on the Feldman–Cousins statistical method [8].

The double ratios are expected to be compatible with unity in the absence of suppression of the excited states relative to the  $\Upsilon(1S)$  state. The measured values are, instead, considerably smaller than unity. The significance of the observed suppression exceeds  $5\sigma$ .

In order to investigate the dependence of the suppression on the centrality of the collision, the double ratio is displayed as a function of  $N_{\text{part}}$  in Fig. 2 (*left*). The dependence on centrality is not pronounced.

### 3. Absolute suppression through an $R_{AA}$

Absolute suppressions of the individual  $\Upsilon$  states and their dependence on the collision centrality are studied using the nuclear modification factor,  $R_{AA}$ .

Integrated over centrality, the  $R_{AA}$  values are  $0.56 \pm 0.08$  (stat.)  $\pm 0.07$  (syst.),  $0.12 \pm 0.04$  (stat.)  $\pm 0.02$  (syst.), and lower than 0.10 (at 95% confidence level), for the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  states, respectively. Namely, a significant suppression of the  $\Upsilon(nS)$  states in heavy-ion collisions compared to pp collisions is observed and this suppression is higher for the less strongly bound states. In other words, the  $\Upsilon(1S)$  is the least suppressed and the  $\Upsilon(3S)$  is the most suppressed of the three states. The  $\Upsilon(1S)$  and  $\Upsilon(2S)$  suppressions are observed to increase with collision centrality. The suppression of  $\Upsilon(2S)$  is stronger than that of  $\Upsilon(1S)$  in all centrality ranges, including the most peripheral bin. The observed  $\Upsilon(nS)$  yields contain contributions from decays of heavier bottomonium states and, thus, the measured suppression is affected by the dissociation of these states. This feed-down contribution to the  $\Upsilon(1S)$  state was measured to be of the order of 50% [9], albeit in different kinematic ranges and center of mass energy than used here. These results indicate that the directly produced  $\Upsilon(1S)$  state is not significantly suppressed, however quantitative conclusions will require precise estimations of the feed-down contribution matching the phase space of the suppression measurement.

In addition to QGP formation, differences between quarkonium production yields in PbPb and pp collisions can also arise from cold-nuclear-matter effects. However, such effects should have a small impact on the double ratios reported here. Initial-state nuclear effects are expected to affect similarly each of the three  $\Upsilon$  states, thereby canceling out in the double ratio. Final-state “nuclear absorption” becomes weaker with increasing energy [10] and is expected to be negligible at the LHC [11].

#### 4. Summary

The relative suppression of the  $\Upsilon$  excited states has been measured, based on the first  $150 \mu b^{-1}$  of the 2011 PbPb dataset. The observed results  $2S/1S = 0.21 \pm 0.07 \pm 0.02$  and  $(2S + 3S)/1S = 0.15 \pm 0.05 \pm 0.02$  are considerably more precise than, and found compatible with, the published measurements based on the 2010 PbPb dataset. Profile likelihood based estimations show the significance of the relative excited-to-ground state suppression is larger than  $5\sigma$ . The larger luminosity of the PbPb dataset further allows to carry out the measurement in ranges of the centrality of the collision. No definitive trend is identified with the current precision. A clear dependence on the collision centrality is observed for the nuclear modification factors for the individual  $\Upsilon(1S)$  and  $\Upsilon(2S)$  states. The nuclear modification factors for the three  $\Upsilon$  states follow the sequential suppression hypothesis. Finally, an upper limit on the  $\Upsilon(3S)$  nuclear modification factor was set at 95% C.L. resulting in  $R_{AA}(3S) < 0.1$ .

#### References

- [1] T. Matsui and H. Satz, *Phys. Lett.* **B178** (1986) 416, doi: 10.1016/0370-2693(86)91404-8.
- [2] S. Digal *et al.*, *Phys. Rev. D* **64** (2001) 094015.
- [3] X. Zhao and R. Rapp, *Nucl. Phys. A* **859** (2011) 114, 10.1016/j.nuclphysa.2011.05.001
- [4] CMS Collaboration, *JINST* **0803** (2008) S08004.
- [5] CMS Collaboration, *Phys. Rev. Lett.* **107** (2011) 052302,.
- [6] CMS Collaboration, *Phys. Rev. D* **83** (2011) 112004, arXiv:1012.5545.
- [7] STAR Collaboration, (2012). arXiv:1204.4244. Submitted to *Phys. Rev. D*.
- [8] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57** (1998) 3873.
- [9] CDF Collaboration, *Phys. Rev. Lett.* **84** (2000) 2094.
- [10] C. Lourenco, R. Vogt, and H. K. Woechri, *JHEP* **02** (2009) 014, 10.1088/1126-6708/2009/02/014,
- [11] Z.-W. Lin and C. M. Ko, *Phys. Lett. B* **503** (2001) 104