

Υ suppression in PbPb collisions at the LHC

Torsten Dahms*, for the CMS collaboration

Laboratoire Leprince-Ringuet (LLR), École Polytechnique, 91128 Palaiseau, France

E-mail: torsten.dahms@cern.ch

The Compact Muon Solenoid (CMS) has measured the suppression of the bottomonium states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV relative to pp collisions, scaled by the number of inelastic nucleon–nucleon collisions. CMS observed a stronger suppression for the weaker bound $\Upsilon(2S)$ and $\Upsilon(3S)$ states than for the ground state $\Upsilon(1S)$. Such “sequential melting” has been predicted to be a clear signature for the creation of a quark-gluon plasma. The suppression of the $\Upsilon(1S)$ and $\Upsilon(2S)$ has been measured as a function of collision centrality for Υ in the rapidity interval $|y| < 2.4$ and with transverse momentum (p_T) down to 0. Furthermore, the p_T and rapidity dependence of the $\Upsilon(1S)$ suppression are presented.

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*Speaker.

1. Introduction

The goal of the SPS, RHIC, and LHC heavy-ion programmes is to validate the existence and study the properties of the quark-gluon plasma (QGP), a state of deconfined quarks and gluons. One of its most striking expected signatures is the suppression of quarkonium states [1], both of the charmonium (J/ψ , $\psi(2S)$, χ_c , etc.) and the bottomonium ($\Upsilon(1S, 2S, 3S)$, χ_b , etc.) families. The suppression is predicted to occur above the critical temperature of the medium (T_c) and depends on the $Q\bar{Q}$ binding energy [2]. Since the $\Upsilon(1S)$ is the most tightly bound state among all quarkonia, it is expected to be the one with the highest dissociation temperature. Examples of dissociation temperatures are given in Ref. [3]: $T_{\text{dissoc}} \sim 1 T_c$, $1.2 T_c$, and $2 T_c$ for the $\Upsilon(3S)$, $\Upsilon(2S)$, and $\Upsilon(1S)$, respectively. Similarly, in the charmonium family the dissociation temperatures are $\leq 1 T_c$ and $1.2 T_c$ for the $\psi(2S)$ and J/ψ , respectively. In PbPb collisions at the LHC, Υ mesons are produced at high enough rates to become the prime choice for measuring a possible sequential melting in a QGP: in contrast to charmonia, they are not subject to b-hadron feed down and offer sensitivity to a wider temperature range. As cold-nuclear matter effects [4] and statistical recombination of thermalized heavy-quarks [5, 6] are also expected to be smaller than for charmonia, the interpretation of Υ suppression is less complicated.

In these proceedings, the CMS measurements of the $\Upsilon(1S, 2S, 3S)$ mesons via their $\mu^+\mu^-$ decays in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are discussed. The results are first presented as a double ratio of Υ yields:

$$(N_{\Upsilon(nS)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(nS)}/N_{\Upsilon(1S)})_{\text{pp}}. \quad (1.1)$$

Such double ratio has the advantage that common experimental and theoretical uncertainties cancel. However, since yields are uncorrected for acceptance and efficiency, any deviation from unity will reflect a yield modification of only the bottomonia that are reconstructed in the CMS detector. Furthermore, it only provides information about the suppression of the excited Υ state relative to the $\Upsilon(1S)$ ground state. Hence, the results are also presented as nuclear modification factors (R_{AA}), based on a comparison to the yield measured in a pp reference run at the same $\sqrt{s_{NN}}$, scaled by the number of binary collisions (N_{coll}):

$$R_{AA} = \frac{\mathcal{L}_{\text{pp}}}{T_{AA} N_{\text{MB}}} \frac{N_{\text{PbPb}}(\Upsilon(nS))}{N_{\text{pp}}(\Upsilon(nS))} \cdot \frac{\epsilon_{\text{pp}}}{\epsilon_{\text{PbPb}}}. \quad (1.2)$$

The measured yields in PbPb ($N_{\text{PbPb}}(\Upsilon(nS))$) and pp collisions ($N_{\text{pp}}(\Upsilon(nS))$) are corrected by their respective efficiencies ϵ_{PbPb} and ϵ_{pp} . \mathcal{L}_{pp} is the integrated luminosity of the pp data set, T_{AA} is the nuclear overlap function, which is equal to N_{coll} divided by the elementary nucleon–nucleon cross section, and N_{MB} is the number of minimum bias events in the PbPb sample. While the $\Upsilon(1S)$ results as a function of p_T and rapidity [7] are based on the 2010 sample, corresponding to an integrated luminosity of $\mathcal{L}_{\text{int}} = 7.28 \mu\text{b}^{-1}$, the centrality dependent results [8] were obtained from the twenty times larger 2011 data set with an integrated luminosity of $\mathcal{L}_{\text{int}} = 150 \mu\text{b}^{-1}$. The pp reference, used in all results, has an integrated luminosity of $\mathcal{L}_{\text{int}} = 231 \text{nb}^{-1}$, which for hard-scattering processes is comparable in size to the 2010 PbPb sample ($7.28 \mu\text{b}^{-1} \cdot 208^2 \approx 315 \text{nb}^{-1}$).

The central feature of CMS is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are

measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The muons are measured in the pseudorapidity window $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution better than 1.5% for p_T smaller than 100 GeV/c. A much more detailed description of CMS can be found elsewhere [9].

2. Signal

In Fig. 1, the invariant-mass spectra of $\mu^+\mu^-$ pairs in the Υ mass region are shown: the left panel displays the spectrum measured in pp collisions, the right panel the spectrum in PbPb collisions. Both samples have been reconstructed with the same algorithm. A transverse-momentum cut of $p_T > 4$ GeV/c has been applied to the individual muons, which still allows Υ with $p_T = 0$ to be reconstructed. Only muons with pseudorapidity $|\eta| < 2.4$ have been reconstructed, restricting the Υ rapidity range to $|y| < 2.4$.

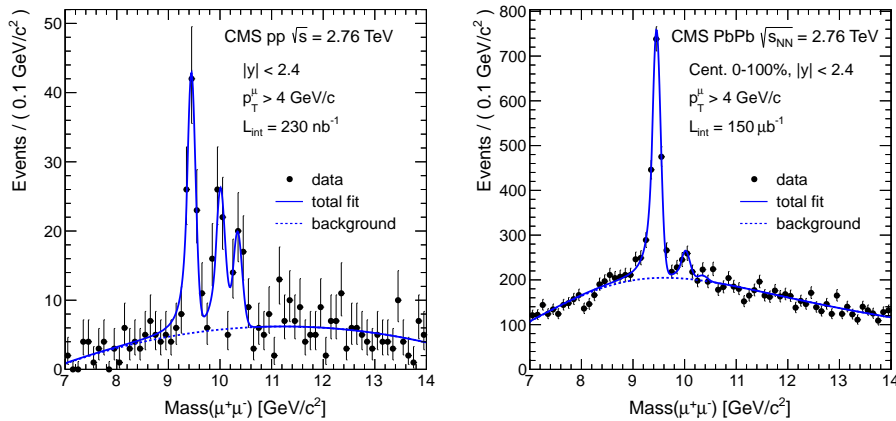


Figure 1: Invariant-mass spectrum of $\mu^+\mu^-$ pairs (black circles) in pp (left) and PbPb collisions (right) at $\sqrt{s_{NN}} = 2.76$ TeV. The solid (signal + background) and dashed (background-only) curves show the results of the simultaneous fit to the two data sets.

The pp data exhibit clear signals of all three Υ states at their expected masses. Also in the PbPb data a clear signal of the $\Upsilon(1S)$ and the $\Upsilon(2S)$ can be seen. However, no clear $\Upsilon(3S)$ peak is visible. Overlaid is the result of a simultaneous fit to pp and PbPb data. The signal is parametrised by the sum of three Crystal-Ball functions. A Crystal-Ball function combines a Gaussian core and a power-law tail at the low side, to account for energy loss due to final-state photon radiation. The mean and the width of the Crystal-Ball function, used to describe the $\Upsilon(1S)$, are left free in the fit, while the mean and the width of the $\Upsilon(2S)$ and $\Upsilon(3S)$ signal shapes are fixed to scale as the mass ratios of the world average [10]. The pp background is described by a parabola, whereas the PbPb background is fitted to the product of an exponential function and an error function, which describes the low-mass turn-on.

3. Results

From the simultaneous fit to pp and PbPb data, centrality integrated double ratios have been measured separately for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states:

$$(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{pp}} = 0.21 \pm 0.07 (\text{stat.}) \pm 0.02 (\text{syst.}),$$

$$(N_{\Upsilon(3S)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(3S)}/N_{\Upsilon(1S)})_{\text{pp}} = 0.06 \pm 0.06 (\text{stat.}) \pm 0.06 (\text{syst.}) \quad (< 0.17 \text{ at } 95\% \text{ CL}).$$

These double ratios are expected to be unity in the absence of suppression. Instead, the measured values are significantly smaller. The $\Upsilon(2S)$ double ratio has been measured as a function of centrality, as shown in Fig. 2. Within uncertainties, no pronounced centrality dependence is observed. Furthermore, the nuclear modification factors of all three states have been measured, integrated over centrality:

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08 (\text{stat.}) \pm 0.07 (\text{syst.}),$$

$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04 (\text{stat.}) \pm 0.02 (\text{syst.}),$$

$$R_{AA}(\Upsilon(3S)) = 0.03 \pm 0.04 (\text{stat.}) \pm 0.01 (\text{syst.}) \quad (< 0.10 \text{ at } 95\% \text{ CL}).$$

The centrality dependence of the nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$ are displayed in the centre panel of Fig. 2. The data show a clear ordering of the suppression with binding energy, the least bound state being the most suppressed. The suppression of the $\Upsilon(1S)$ state is consistent with no suppression of directly produced $\Upsilon(1S)$, but a suppression of feed-down contribution from excited state decays only, which is expected to contribute $\approx 50\%$ at high p_T [11]. However, the uncertainties in the measurement of the feed-down contributions preclude quantitative conclusions about the suppression of directly produced $\Upsilon(1S)$.

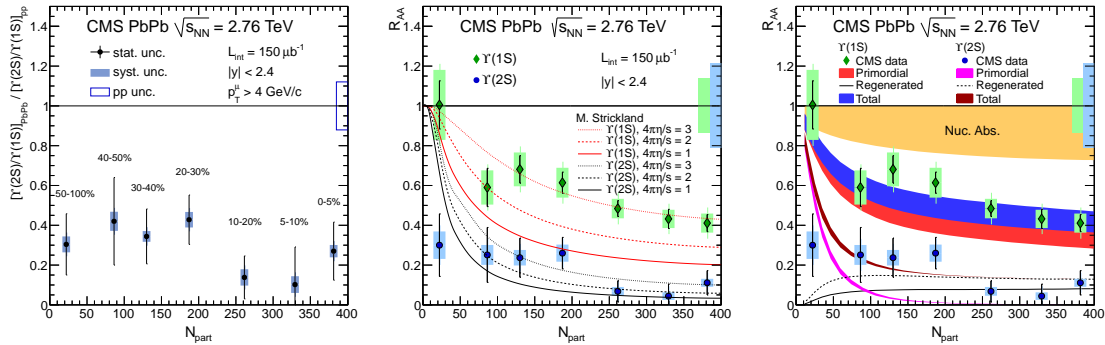


Figure 2: Centrality dependence of the double ratio $(N_{\Upsilon(nS)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(nS)}/N_{\Upsilon(1S)})_{\text{pp}}$ (left) and the nuclear modification factor of $\Upsilon(1S)$ (green diamonds) and $\Upsilon(2S)$ (blue circles). The data are compared to two theoretical models [12] (centre) and [13] (right). Statistical (systematic) uncertainties are shown as bars (boxes). Global uncertainties from the pp yields and, in case of the R_{AA} , luminosity, are shown as boxes at unity.

These results are compared to theoretical models of Υ suppression in a quark-gluon plasma. The first, presented in the centre panel of Fig. 2, combines a complex-valued heavy-quark potential and a dynamic evolution of an anisotropic plasma [12]. The model is presented for three values of

shear viscosity to entropy density ratios η/s . To fix the charged particle multiplicity, for each value of $\eta/s = \{1, 2, 3\}$ a different initial temperature is assumed: $T_0 = \{520, 504, 494\}$ MeV. The $\Upsilon(1S)$ data appear to favour larger values η/s . The second model, compared to CMS data in the right panel of Fig. 2, is based on a rate-equation approach [13]. It is worth to note that this model predicts sizeable cold nuclear matter effects on Υ states produced in PbPb collisions at the level of $\approx 20\%$. The authors also predict a small contribution of Υ production via regeneration of thermalized b quarks, which provides the only source of $\Upsilon(2S)$ in central PbPb collisions. While both models describe the data qualitatively, for a detailed comparison it is crucial to not only decrease the global uncertainty on the R_{AA} measurement, which is currently limited by the available pp data. But it is also mandatory to measure the feed-down contributions with better precision and to low p_T , as these enter directly in the model calculations.

A first attempt to measure the p_T and rapidity dependence of the $\Upsilon(1S)$ suppression has been made with the 2010 PbPb data, as shown in Fig. 3. At this point it is too early to conclude on a p_T and rapidity dependence of the $\Upsilon(1S)$ suppression. However, it is clear that $\Upsilon(1S)$ at low- p_T and midrapidity are suppressed. The data are compared to an earlier prediction of the same model as in the centre panel of Fig. 2 [14]. The model follows the general features of the data, but underpredicts the suppression of $\Upsilon(1S)$ at low p_T .

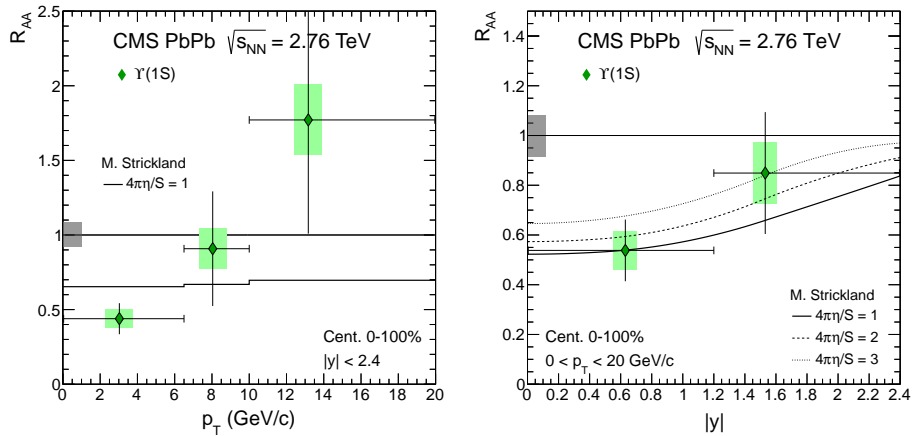


Figure 3: Transverse momentum (left) and rapidity (right) dependence of the nuclear modification factor of $\Upsilon(1S)$ (green diamonds). The data are compared to a theoretical model [14]. Statistical (systematic) uncertainties are shown as bars (boxes). Global uncertainties from the pp yields, T_{AA} , and luminosity are shown as boxes at unity.

4. Summary

In summary, CMS has measured the nuclear modification factors of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons. For $\Upsilon(1S)$ and $\Upsilon(2S)$, these are presented as a function of centrality. Furthermore, the R_{AA} as a function of p_T and rapidity has been measured for the $\Upsilon(1S)$. A sequential melting of the Υ states is observed. Models of Υ suppression in a QGP qualitatively describe the data. New data from pp collisions at $\sqrt{s} = 2.76$ TeV and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, collected at the

beginning of 2013, will enable CMS to study the p_T and rapidity dependence of the ΥR_{AA} in more detail and to quantify cold nuclear matter effects on the double ratio and the R_{AA} .

Acknowledgments

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