

# Bottomonium measurements in pp, pPb and PbPb using the CMS detector

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**Abstract.** Bottomonia are important probes of the quark-gluon plasma since they are produced at early times and propagate through the medium, mapping its evolution. The three  $\Upsilon$  states (1S, 2S, 3S) were measured separately using the Compact Muon Solenoid (CMS) experimental apparatus and observed to disappear sequentially in PbPb collisions at 2.76 TeV. However, recent measurements in pp and pPb collisions, at 2.76 and 5.02 TeV respectively, show a surprising dependence of the excited state (2S or 3S) over the ground (1S) state ratio, as a function of event activity. The three  $\Upsilon$  states are also observed to be individually more produced in events with more activity. We review the latest results from pp, pPb and PbPb collisions and highlight their possible interpretations.

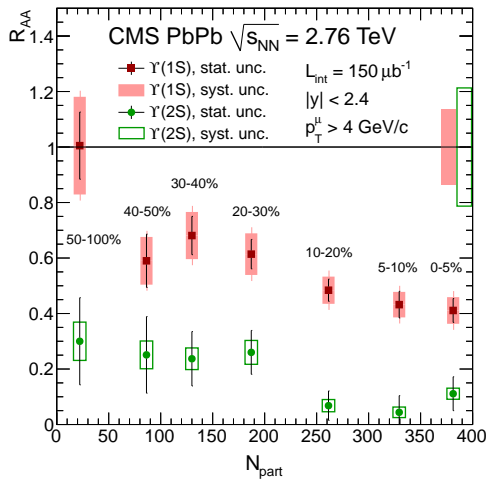
## 1. Introduction

Quarkonium suppression is known to be one of the experimental signatures of the formation of a Quark-Gluon Plasma [1]. Additional forms of modification of a heavy  $q\bar{q}$  pair may arise in nuclear interactions, such as gluon shadowing or absorption in spectator nuclear matter. In 2012, the CMS collaboration has published a centrality-dependent measure of  $\Upsilon$  suppression at  $\sqrt{s_{NN}} = 2.76$  TeV with  $150 \mu\text{b}^{-1}$  of PbPb data [2]. However, the measurement of the nuclear modification  $R_{AA}$  in peripheral events was limited to a wide 50 – 100% centrality range and no transition from cold to hot effects can be established. In a recent paper by CMS [3], the relative production of the excited states  $\Upsilon(2S)$  and  $\Upsilon(3S)$  over the ground  $\Upsilon(1S)$  state is studied with  $5.4 \text{ pb}^{-1}$  of pp data and  $34 \text{ nb}^{-1}$  of pPb data, by the use of single yield ratios and double ratios, as well as self-normalised cross section ratios. These observables are evaluated for various event activities.

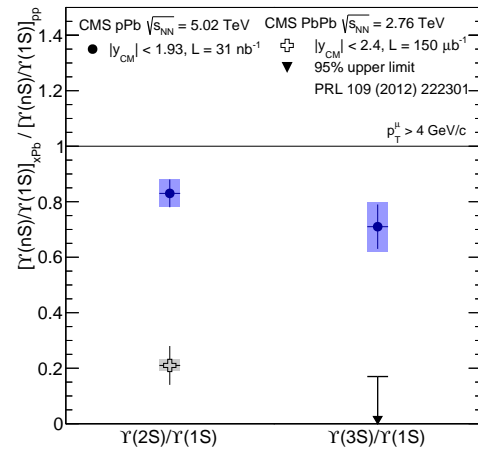
## 2. Sequential suppression of $\Upsilon$ in PbPb

$\Upsilon$  mesons are measured in CMS through their di-muon decay. A description of the CMS detector can be found elsewhere [4]. Muons are reconstructed in CMS using information from the muon chambers and the tracker. Events containing two muon tracks well matched to hits in the muon spectrometer are selected by the hardware level trigger and further filtered offline using the High Level Trigger of CMS [5]. The  $\Upsilon$  yields are then extracted with a fit to the invariant mass spectrum of the di-muon event sample. A first observation of sequential  $\Upsilon$  suppression was reported in [2], by computing the nuclear modification factor  $R_{AA}$ . With the use of PbPb and pp data at the same energy, the centrality-integrated  $R_{AA}$  values for each  $\Upsilon$  state are:  $R_{AA}(1S) = 0.56 \pm 0.08(\text{stat.}) \pm 0.07(\text{syst.})$ ,  $R_{AA}(2S) =$

$0.12 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst.})$ ,  $R_{AA}(3S) < 0.10$  (95%CL). The nuclear modification factor as a function of centrality (number of participating nucleons) is reported in Fig. 1. From these values, one can observe that the excited states are more suppressed than the ground state over all centrality ranges. The ground state yield is suppressed up to a level, which is compatible with the known feed-down fractions, suggesting that its suppression could come from the disappearance of higher energy states only. Comparing the  $R_{AA}$  of excited states to that of the ground state can be done by measuring the double ratio  $\chi^{\text{PbPb}}(2S/1S) = R_{AA}(2S)/R_{AA}(1S) = N(2S)/N(1S)|_{\text{PbPb}}/N(2S)/N(1S)|_{\text{pp}}$ . In this ratio most of the detector effects cancel, as well as parton energy loss and gluon shadowing, which are expected to affect all  $b\bar{b}$  states the same way. A clear suppression of the  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states was measured over all centrality ranges with respect to the  $\Upsilon(1S)$ . The centrality-integrated values of the double ratios are  $\chi^{\text{PbPb}}(2S/1S) = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{syst.})$ ,  $\chi^{\text{PbPb}}(3S/1S) < 0.17$  (95%CL) as reported in Fig. 2.



**Figure 1.** Nuclear modification factor  $R_{AA}$  for  $\Upsilon$  states versus centrality.



**Figure 2.** Double ratios  $\chi(2S/1S)$ ,  $\chi(3S/1S)$  for pPb and PbPb versus pp.

To extend this measurement of suppression to pPb collisions, double ratios are measured in pPb  $\chi^{\text{pPb}}(2S/1S)$ ,  $\chi^{\text{pPb}}(3S/1S)$  in [3] and reported in Fig. 2. The double ratio values are  $\chi^{\text{pPb}}(2S/1S) = 0.83 \pm 0.05 \pm 0.05$ ,  $\chi^{\text{pPb}}(3S/1S) = 0.71 \pm 0.08 \pm 0.09$  where the quoted uncertainties are statistical first and systematic second. This result indicates the excited states are more affected than the ground state. This suggests the presence of final state effects in pPb compared to pp, calling for a differential measurement as a function of event activity.

### 3. Event activity measurements in pPb

#### 3.1. Transverse energy deposits in forward calorimeters: $E_T^{4 < |\eta| < 5.2}$

The CMS detector is equipped at forward pseudorapidities ( $2.9 < |\eta| < 5.2$ ) with hadron forward (HF $^\pm$ ) calorimeters, composed of steel absorbers embedded with quartz fibres emitting Čerenkov light, collected downstream by photomultipliers. The transverse energy deposit is used in PbPb for a measurement of the centrality (impact parameter) of the collision. In the context of pPb collisions, the total transverse energy deposit in the pseudorapidity range  $4.0 < |\eta| < 5.2$  is used to separate the collision data in classes of forward event activity. This sampling at forward

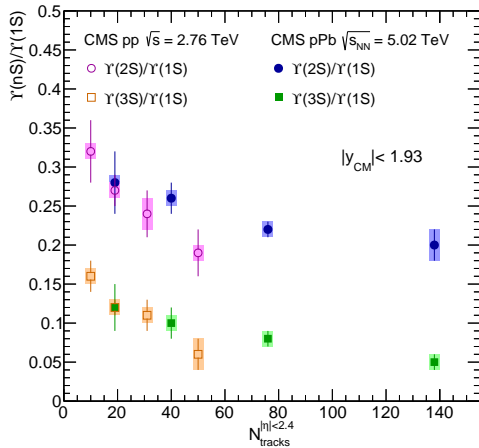
pseudo-rapidities provides an event activity measurement that should be independent of the measurement of the hard probe.

### 3.2. Inner tracker charged particle multiplicity: $N_{\text{Trk}}^{|\eta|<2.4}$

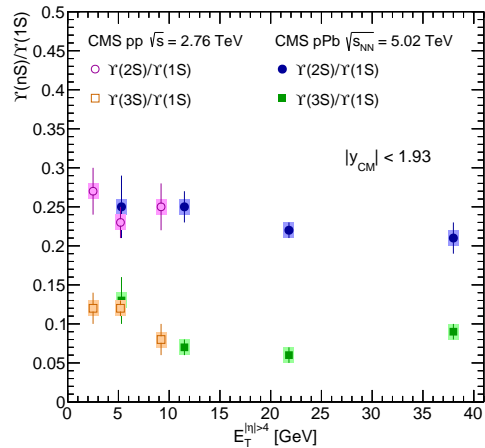
The CMS tracking system is composed of an inner set of 66 million pixel detectors deployed in 3 layers around the beam pipe and silicon microstrips containing 9.9 million channels spread among a variable number of layers, within 4.8 pseudorapidity units around the primary vertex. This high precision device allows a very efficient tracking for charged particles with transverse momentum down to  $p_T < 400$  MeV/ $c$ . The charged particle multiplicity associated with di-muon events is used to separate the data in classes of multiplicity.

## 4. Yield ratios

The single ratios  $\Upsilon(2S)/\Upsilon(1S)$  and  $\Upsilon(3S)/\Upsilon(1S)$  measured in pPb and pp are displayed in bins of charged particle multiplicity  $N_{\text{Trk}}^{|\eta|<2.4}$  in Fig. 3 and in bins of  $E_T^{4<|\eta|<5.2}$  in Fig. 4.



**Figure 3.** Single ratios  $\Upsilon(2S)/\Upsilon(1S)$  and  $\Upsilon(3S)/\Upsilon(1S)$  versus charged particles multiplicity in  $|\eta_{\text{Trk}}| < 2.4$ .

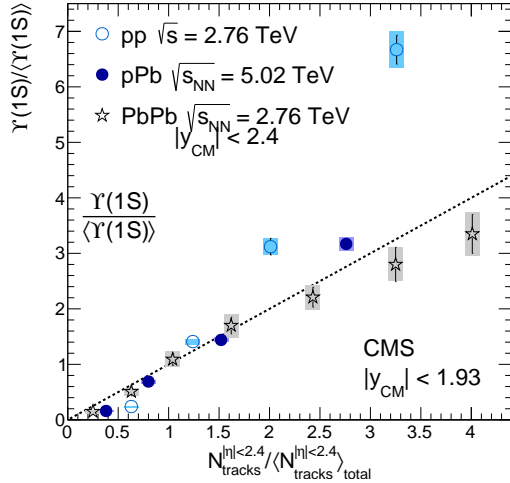


**Figure 4.** Single ratios  $\Upsilon(2S)/\Upsilon(1S)$  and  $\Upsilon(3S)/\Upsilon(1S)$  versus forward transverse energy.

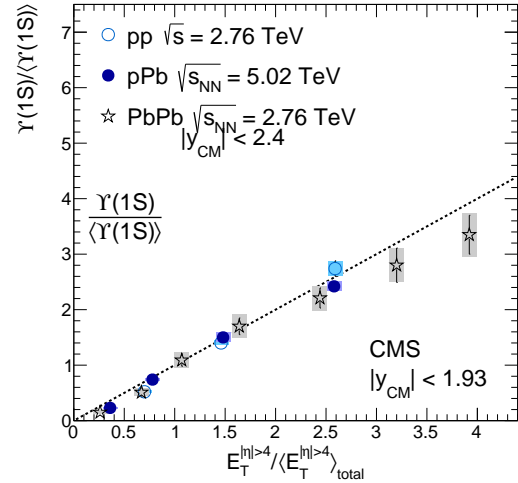
The mean values of event activity observables are  $\langle N_{\text{Trk}}^{|\eta|<2.4} \rangle = (10, 41, 278)$ , and  $\langle E_T^{4<|\eta|<5.2} \rangle = (3.5, 15, 77)$  GeV for pp, pPb and PbPb, respectively. The ratios are fully corrected for detector inefficiencies regarding muon detection as well as event activity estimation. No clear dependence of the single ratios is observed when activity is measured in the forward region, while a variation is seen with increasing multiplicity at mid-rapidity. This dependence is unexpectedly steeper in pp than in pPb. Furthermore, the measured slope is compatible in both collision systems with the presence of two additional tracks on average in  $\Upsilon(1S)$  events compared to  $\Upsilon(2S, 3S)$ . The number of additional charged particles does not vary when lowering the  $p_T$  threshold down to 200 MeV/ $c$  in the  $N_{\text{Trk}}^{|\eta|<2.4}$  computation, or when removing tracks located in a cone of radius  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$  or 0.5 around the  $\Upsilon$  momentum direction [3]. Moreover, the feed-down contribution from P-wave decays to  $\Upsilon$  could not account for the full effect, given the low efficiency for electron pairs from low momentum photon conversion.

## 5. Self-normalised cross section ratios

To further investigate the  $\Upsilon$  production rates, fully corrected cross sections were computed, normalised to their activity-integrated result. In Fig. 5, the horizontal axis displays multiplicity bins divided by the mean multiplicity. A positive correlation is observed with increasing charge-particle multiplicity. The self-normalised cross sections exhibit linear scaling with the forward transverse energy, as can be seen in Fig. 6.



**Figure 5.**  $\Upsilon(1S)$  yield, reconstructed with  $|y_{CM}^{CM}| < 1.93$  versus charged particle multiplicity in  $|\eta| < 2.4$ .



**Figure 6.**  $\Upsilon(1S)$  yield, reconstructed with  $|y_{CM}^{CM}| < 1.93$  versus forward transverse energy.

## 6. Conclusion

We have presented the measurement of event-activity dependent production of  $\Upsilon$  states by the CMS experiment in pp, pPb and PbPb collisions at the LHC. In the case of PbPb collisions, we observe a sequential pattern for suppression. Recent pPb data shows some suppression of the excited states with respect to the ground state, less pronounced than in PbPb collisions.

In the case of pp collisions, the normalised production rates exhibit correlations with associated particle multiplicity, a possible hint of quarkonium production being proportional to multi-parton interactions.

## Acknowledgements

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## References

- [1] Matsui T and Satz H 1986 *Phys. Lett.* **B178** 416
- [2] Chatrchyan S *et al.* (CMS Collaboration) 2012 *Phys. Rev. Lett.* **109** 222301 (*Preprint* 1208.2826)
- [3] Chatrchyan S *et al.* (CMS Collaboration) 2014 *JHEP* **1404** 103 (*Preprint* 1312.6300)
- [4] Adolphi R *et al.* (CMS) 2008 *JINST* **3** S08004
- [5] Adam W *et al.* (CMS Trigger and Data Acquisition Group) 2006 *Eur. Phys. J.* **C46** 605–667 (*Preprint* hep-ex/0512077)