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

Guillermo Breto Rangel (on behalf of the CMS collaboration)
University of California at Davis, One Shields Ave, Davis, CA 95616
E-mail: guillermo.breto.rangel@cern.ch

Abstract. The three $\Upsilon$ 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 $n = 2, 3, 2 + 3$. 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, based on the analysis of the full data sample collected during the 2011 PbPb run and the 2010 pp run, which corresponds to an integrated luminosity of 150 $\mu$b$^{-1}$ and 231 nb$^{-1}$ respectively. The three $\Upsilon$ states suppression pattern is ordered as $R_{AA}^{1(1S)} > R_{AA}^{1(2S)} > R_{AA}^{1(3S)}$.

1. Introduction
Quarkonia, bound states of a heavy quark and its antiquark, are very different kind of hadrons. For the ground states $J/\psi$ and $\Upsilon$ the binding energies are around 0.6 and 1.2 GeV, respectively, and thus much larger than the typical hadronic scale $\Lambda \sim 0.2$ GeV; as a consequence, they are also much smaller, with radii of about 0.1 and 0.2 fm. It is therefore expected that they can survive in a quark-gluon plasma through some range of temperatures above $T_c$. The higher excited quarkonium states are less tightly bound and hence larger. Since deconfinement is related to colour screening [1], the critical quantity for dissociation of a bound state is the relation of binding energy of the state to the Debye screening radius of the medium. We therefore expect that the different quarkonium states have different “dissociation temperatures” in a quark-gluon plasma. Hence the spectral analysis of in-medium quarkonium dissociation should provide a QGP thermometer [2].

In particular, the $\Upsilon$ in heavy-ion collisions was suggested to be a theoretically and experimentally cleaner probe of the deconfined medium due to the larger mass of the bottom quark. For the bottomonium the effects of initial state nuclear suppression are expected to be reduced. Moreover, heavier quarks allow 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 [4]. Furthermore, since bottom $Q\bar{Q}$ pairs are relatively rare within the plasma, the probability for regeneration of bottomonium states through recombination is much smaller than for charm quarks [3].

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 suppression, where common experimental and theoretical factors, and their respective uncertainties, cancel.
2. Muon reconstruction
Quarkonia are identified through their dimuon decay. The silicon pixel and strip tracker measures charged-particle trajectories for the range $|\eta| < 2.5$. The tracker consists of 66M pixel and 10M strip detector channels, providing a vertex resolution of $\sim 15 \mu m$ in the transverse plane. Muons are detected for the $|\eta| < 2.4$ range, with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A detailed description of the CMS detector can be found elsewhere [5]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Due to the strong magnetic field and the fine granularity of the silicon tracker, the transverse momentum measurement based on information from the silicon tracker alone has a resolution between 1 and 2% for a typical muon in this analysis. CMS is therefore very well suited to measure dimuons. In this analysis the pp data was reconstructed using the heavy ion algorithm and the same nominal cuts ( muons with $|\eta| < 2.4$ and $p_T > 4.0$ GeV/c). Incidentally, these muon cuts coincide with the ones used in our previous analysis [6].

3. Quantifying the observation of the relative suppression through the double ratio
In order to extract the $\Upsilon(nS)$ yields we performed an extended unbinned maximum likelihood fit to the invariant mass spectra shown in Fig. 1, similar to our previous analysis described in Refs. [6, 7]. 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.

![Figure 1](image-url) Simultaneous fit to the pp (left) and the much larger statistics 2011 (right) PbPb datasets.

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 [11] the azimuthal angular coordinate of one of the muon tracks is rotated by 180 degrees. The comprehensive studies performed on the background described the opposite sign background accurately and the minor differences were used to estimate systematic uncertainties.

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
The measured number of equivalent minimum bias events in PbPb, \(N_{MB}^{\text{pPb}}\), benefits from an almost complete cancellation of possible imperfect cancellations of acceptance and efficiency.

The measurement of the ratio of the \(3S/N\) ratios in PbPb and pp collisions, referred to as the double ratio \(\frac{\langle \frac{N_{pPb}(\bar{Q})}{N_{pp}(\bar{Q})} \rangle_{\text{PbPb}}}{\langle \frac{N_{pPb}(\bar{Q})}{N_{pp}(\bar{Q})} \rangle_{\text{pp}}}\), 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 ratio \(\frac{Y(3S)/Y(1S)}{Y(nS)/Y(1S)}\) at 95% confidence level (CL), based on the Feldman-Cousins statistical method [12], yielding a double ratio \(\frac{Y(3S)/Y(1S)}{Y(nS)/Y(1S)} < 0.17\).

Assuming the absence of suppression of the excited states relative to the \(Y(1S)\) state hypothesis, the probability of observing a double ratio as discrepant or more to the value measured is very small corresponding to a significance that exceeds 5\(\sigma\) in a one-sided gaussian tail test.

4. Describing the absolute suppression through the nuclear modification factor

Using both data sets, the production measured in PbPb collisions is compared to expectations from an independent superposition of nucleon-nucleon collisions typically expressed in terms of the nuclear modification factor:

\[
R_{AA} = \frac{\mathcal{L}_{pp}^{N_{MB}} N_{pPb}(\bar{Q})}{T_{AA} N_{MB}} \frac{\varepsilon_{pp}}{\varepsilon_{pPb}}. \tag{1}
\]

Here \(T_{AA}\) is the nuclear overlap function (ratio of the number of binary nucleon-nucleon collisions \(N_{coll}\) calculated from a Glauber model of the nuclear collision geometry [8, 9]) and the inelastic nucleonnucleon cross section \(\sigma_{inel}^{NN} = (64 \pm 5)\) mb at \(\sqrt{s} = 2.76\) TeV. \(\varepsilon_{pp}\) is the pp luminosity, \(N_{MB}\) is the measured number of equivalent minimum bias events in PbPb. \(\varepsilon_{pp} N_{pp}(\bar{Q})\) is the raw yield ratio, and \(\varepsilon_{pPb} N_{pPb}(\bar{Q})\) the multiplicity dependent fraction of the efficiency (\(\varepsilon_{pPb}/\varepsilon_{pp} \sim 1.1\) for the most central bin).

The centrality integrated \(R_{AA}\) values are 0.50 \(\pm\) 0.08\((\text{stat.})\) \(\pm 0.07\((\text{syst.})\), 0.12 \(\pm\) 0.04\((\text{stat.})\) \(\pm 0.02\((\text{syst.})\), and lower than 0.10 (at 95% confidence level), for the \(Y(1S)\), \(Y(2S)\), and \(Y(3S)\) states, respectively. A significant suppression of the \(Y(nS)\) 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\% [13], albeit in different kinematic ranges and center of mass energy than used here.

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 [14] and is expected to be negligible for the $\Upsilon(1S)$ at the LHC [15].

5. Summary

In summary, the high statistics accumulated at the LHC allows the detailed studies of bottomonia. CMS has performed the measurements of the $\Upsilon(nS)$ mesons via their decay into dimuon pair in PbPb and pp collisions at 2.76 TeV. Based on a PbPb dataset of 150 $\mu$b$^{-1}$, CMS managed to separate the three $\Upsilon$ resonances and measured the double ratio $\Upsilon(2S)/\Upsilon(1S)$ in PbPb relative to pp collisions. For the $\Upsilon(3S)$ double ratio a 95\% CL upper limit was set. No clear centrality dependence of the double ratios can be inferred from the data, while such a dependence is observed when inspecting the individual $\Upsilon(1S)$ and $\Upsilon(2S)$ nuclear modification factors, $R_{AA}$. The nuclear modification factors for the three $\Upsilon$ states follow the sequential suppression hypothesis $R_{AA}^{\Upsilon(1S)} > R_{AA}^{\Upsilon(2S)} > R_{AA}^{\Upsilon(3S)}$. Additionally, an upper limit on the $\Upsilon(3S)$ nuclear modification factor was set at 95\% CL resulting in $R_{AA}(3S) < 0.1$. Finally, the quarkonia results seem qualitatively consistent with the presence of a deconfining medium. However, a quantitative understanding needs better statistics, in order to correct for possible cold nuclear matter effects (absorption/shadowing) at LHC with data from the upcoming pPb run, and quantitatively take into account the contributions of feed-down from the various higher lying quarkonia resonance states.

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