In this paper we review results on the bottomonium system from the CMS experiment at the Large Hadron Collider. Production measurements, for both cross sections and polarizations, have been carried out at different collision energies in $pp$ collisions and collisions involving heavy ions. The measurements have led to a number of important observations including evidence for sequential suppression in bottomonium production, which is expected in quark-gluon plasma formation. The observation of production of bottomonium pairs is also reported along with searches for new states. We close with a brief outlook of the physics program ahead.

Keywords: quarkonia; bottomonia; $\Upsilon$; LHC; cross section; polarization; suppression; QGP.

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1. Introduction

Bottomonia, bound states of a bottom quark (b) and its antiparticle (¯b), constitute the heaviest meson system (the heavier quark, the top, decays before it can hadronize). They thus provide a valuable system for shedding light on the strong interactions, described in the Standard Model (SM) by the theory of Quantum Chromodynamics (QCD). The Υ(1S) was the first bottomonium state to be observed, and this was found in the $\mu^+\mu^-$ spectrum from proton-nucleus collisions by the E288 experiment at Fermilab in 1977. In the next 40 years, other bottomonium states were discovered and the b ¯b spectroscopy was experimentally established, as shown in Fig. 1.

In general, heavy flavor studies in hadron collider involve many precision measurements. They are not only extremely helpful in testing QCD and the hadron production mechanism, but also have great potential to discover new particles and rare decays. On the one hand, anomalies observed that differ from calculations can be used as a direct search of physics beyond the Standard Model; on the other hand, heavy flavor experiments serve as a probe of the indirect effects associated with new physics well above TeV scale.
Given their high mass, charmonia and bottomonia are approximately nonrelativistic systems, which allows the calculation to be simplified by factorizing the perturbative and nonpertubative terms. The latter can be computed based on the non-relativistic QCD (NRQCD)\(^3\) long-distance matrix element (LDME) approach. Several QCD and NRQCD models\(^3\)–\(^{14}\) predict different cross sections and polarizations. The studies of quarkonium production play a crucial role in testing the theoretical picture.

Heavy flavor quarkonia are also widely used to understand the properties of the deconfined phase of QCD matter, the Quark Gluon Plasma (QGP), created under extreme temperature and density. While charmonium production in a QGP environment has been extensively studied,\(^{15}\) until recently this has not been the case for bottomonium production.

A new era of detailed bottomonium studies has been underway at the Large Hadron Collider (LHC) since 2010,\(^{16}\) as it pushed the collider physics to new energy and intensity frontiers. The center-of-mass energy of the proton-proton (pp) collisions reached 13 TeV in 2015, which is about 7 times higher than that at Tevatron. The \(\sqrt{s_{NN}} = 5\) TeV for lead-lead (PbPb) collisions at the LHC is more than 20 times that of RHIC. A large data set has been collected at the LHC in the past 7 years.

The Compact Muon Solenoid (CMS) is a general purpose detector at the LHC. It explores both pp collisions and collisions involving heavy ions. Taking advantage of its good momentum resolution, CMS can distinguish the three lowest lying \(\Upsilon\) resonances in the dimuon decay channel (Fig. 2), which is difficult at RHIC, ALICE, and ATLAS. A full spectrum of the dimuon invariant mass reconstructed by CMS is also shown in Fig. 2, with many Standard Model particles reconfirmed. Compared to LHCb and the Tevatron, CMS has a complementary and wider kinematic acceptance coverage. These advantages make CMS uniquely suited for heavy quarkonia.
measurements. Heavy-flavor studies at CMS rely on the dimuon triggers; the green area in Fig. 2 illustrates the data collected by the specialized trigger path for $\Upsilon$ studies.

In this review, measurements of S-wave bottomonium ($\Upsilon$) production in $pp$, PbPb, and $p$Pb collisions are summarized and discussed. The P-wave bottomonium production cross section ratio, $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$, and the first observation of $\Upsilon(1S)$ pair production are also discussed.

2. $\Upsilon$ production measured in $pp$ collisions

Quarkonium production has not been well understood. A number of models including the QCD-based color-singlet model (CSM),\textsuperscript{10,11} the NRQCD color-octet mechanism (COM),\textsuperscript{12,13} and the color-evaporation model (CEM)\textsuperscript{14} have been proposed to explain production measurements. The similarities and differences among these models are discussed in detail in Section 4.1 of Ref. 18. These models provide different predictions for the quarkonium production cross sections and polarizations. Bottomonium states are heavier and more non-relativistic than charmonium states, so the comparison between experiment and theory is expected to be cleaner for bottomonium.\textsuperscript{19} Therefore, a precise measurement of $\Upsilon$ production is important to test the above models.

Recently, CDF,\textsuperscript{20} D0,\textsuperscript{21} LHCb, CMS, and ATLAS have reported $\Upsilon$ cross section and $\Upsilon$ polarization results. However, none of the current theoretical models correctly predict both the rate and the polarization in any of these experiments. In this section, we summarize the CMS $\Upsilon$ production measurements, at various center-of-mass regimes.

2.1. $\Upsilon$ cross section

The first measurement\textsuperscript{22} of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production cross sections in $pp$ collisions was made at $\sqrt{s} = 7$ TeV, using the CMS Run 1 data collected in 2010 and corresponding to an integrated luminosity of $3.1 \pm 0.3$ pb$^{-1}$. The $\Upsilon(nS)$ differential cross section $\sigma$ is defined as:\textsuperscript{22}

$$\frac{d^2\sigma(pp \rightarrow \Upsilon(nS)X)}{dp_T dy} \cdot B(\Upsilon(nS) \rightarrow \mu^+ \mu^-) = \frac{N_{\Upsilon(nS)}^{\text{corrected}}(A, \epsilon)}{L \cdot \Delta p_T \cdot \Delta y}$$ (1)

where, $B$ is the dimuon branching fraction, $N$ is the signal yield corrected by detector acceptance $A$ and efficiency $\epsilon$, $L$ is the integrated luminosity, and $\Delta p_T$ and $\Delta y$ are the bin widths of transverse momentum ($p_T$) and rapidity ($y$). The signal yield $N$ before correction is determined using an extended unbinned maximum-likelihood fit to the dimuon invariant-mass spectrum, as shown in the left panel of Fig. 2. The dimuon candidates are required to satisfy $|y| < 2$, while the individual muon candidates must satisfy kinematic thresholds that depend on pseudorapidity $\eta$, to ensure the trigger and reconstruction efficiencies are high and stable.\textsuperscript{22}
\[ p_T^{\mu} > 3.5 \text{ GeV}/c, \text{ if } |\eta^{\mu}| < 1.6, \]
\[ p_T^{\mu} > 2.5 \text{ GeV}/c, \text{ if } 1.6 < |\eta^{\mu}| < 2.4. \]  

This region defined by the \( \eta \) and \( y \) requirements is referred to the fiducial region. The \( \Upsilon \to \mu^+ \mu^- \) acceptance \( A \) is defined as the fraction of \( \Upsilon \)s with both muons in this region of the detector. The acceptance as a function of \( \Upsilon p_T \) is evaluated with Monte Carlo and shown in Fig. 3 (left). Other selection criteria, such as the separation between the two muons, the vertex quality of dimuon candidate, and single muon quality requirements, were also applied. The efficiency \( \epsilon \) of the accepted muon is determined with a data-based tag-and-probe (T&P) technique. An example efficiency turn-on curve is displayed in Fig. 3 (right).\(^{22}\)

Assuming unpolarized \( \Upsilon(nS) \) production, the products of cross sections and dimuon branching fractions in the rapidity region \(|y| < 2\) are: \(^{22}\)

\[
\sigma(pp \rightarrow \Upsilon(1S)X) \cdot B(\Upsilon(1S) \rightarrow \mu^+ \mu^-) = 7.37 \pm 0.13 \text{(stat.}&\text{syst.) } \pm 0.81 \text{(lumi.)} \text{nb},
\]
\[
\sigma(pp \rightarrow \Upsilon(2S)X) \cdot B(\Upsilon(2S) \rightarrow \mu^+ \mu^-) = 1.90 \pm 0.08 \text{(stat.}&\text{syst.) } \pm 0.21 \text{(lumi.)} \text{nb},
\]
\[
\sigma(pp \rightarrow \Upsilon(3S)X) \cdot B(\Upsilon(3S) \rightarrow \mu^+ \mu^-) = 1.02 \pm 0.07 \text{(stat.}&\text{syst.) } \pm 0.11 \text{(lumi.)} \text{nb}.
\]

The measured cross section is about 3 times larger than that measured at the Tevatron. This can be explained by the fact that the \( \Upsilon \) production cross section increases with \( \sqrt{s} \). The differential \( \Upsilon(nS) \) cross sections as functions of \( \Upsilon p_T \) and rapidity are shown in Fig. 4, \(^{22}\) and compared to the LHCb result. \(^{23}\)

Later, the analysis was extended with a more extensive data set, also collected in 2010, \(^{24}\) corresponding to an integrated luminosity of 35.8 \pm 1.4 \text{ pb}^{-1}. In a larger \( \Upsilon \) transverse momentum range, \( p_T < 50 \text{ GeV}/c \), and larger \( \Upsilon \) rapidity range, \(|y| < 2.4\), the products of \( \Upsilon \) production cross sections and dimuon branching fractions are found to be: \(^{24}\)
σ(pp→Υ(1S)X)·B(Υ(1S)→μ⁺μ⁻) = 8.55 ± 0.05(stat.)±0.56(syst.) ± 0.34(lumi.) nb,
σ(pp→Υ(2S)X)·B(Υ(2S)→μ⁺μ⁻) = 2.21 ± 0.03(stat.)±0.16(syst.) ± 0.09(lumi.) nb.(4)
σ(pp→Υ(3S)X)·B(Υ(3S)→μ⁺μ⁻) = 1.11 ± 0.02(stat.)±0.10(syst.) ± 0.04(lumi.) nb.

To compare with the results given in Eq. (3), a selection requirement on rapidity was applied to the data. Both results agreed within uncertainties in the |y| < 2 region. The differential cross sections, corrected by acceptance and efficiency, as a function of Υp_T and y are shown in Fig. 5. The comparisons of the measured results with the CASCADE MC generator, the color-evaporation model without feed-down, NRQCD COM at next-to-leading order (NLO) including feed-down, CSM to NLO, and NNLO* are also shown in the figure.

The total cross section reported above depends on the polarization of the Υ. This has been measured by the CDF, D0, and CMS experiments, but all measurements are in disagreement with theoretical expectations, which make the assignment of a polarization in the cross section calculations problematic. Polarization affects the spatial distribution of the two muons from the Υ decay. In an experiment, only a fraction of the full phase space (fiducial region) is covered by the detector. However, a fiducial cross section, defined as the cross section corrected by only the detector efficiency ϵ but not by the geometric acceptance A, can be used to compare with theoretical models without an assumption for polarization.

The products of the fiducial Υ(nS) cross sections and dimuon branching fractions o are:

σ(pp→Υ(1S)X)·B(Υ(1S)→μ⁺μ⁻) = 3.06 ± 0.02(stat.)±0.20(syst.) ± 0.12(lumi.) nb,
σ(pp→Υ(2S)X)·B(Υ(2S)→μ⁺μ⁻) = 0.910 ± 0.011(stat.)±0.045(syst.) ± 0.036(lumi.) nb.(5)
σ(pp→Υ(3S)X)·B(Υ(3S)→μ⁺μ⁻) = 0.490 ± 0.010(stat.)±0.029(syst.) ± 0.020(lumi.) nb.

As p_T increases, higher-order corrections become more significant in several of the theoretical models. Therefore, cross section measurements in high p_T regions are

![Graph](image-url)
important for distinguishing amongst the models. Consequently, the CMS analysis was further expanded using the full 4.9 fb$^{-1}$ $pp$ collision data taken at $\sqrt{s} = 7$ TeV in 2011 with the $p_T$ coverage increased to 100 GeV/$c$. The three $\Upsilon$ states were again reconstructed through the dimuon decay channel.

Figure 6 (left) shows the differential cross section as a function of $p_T$ from the two groups of data, one integrated over the rapidity range of $|y| < 1.2$ (CMS 2011, black dots) and the other scaled to the same range (CMS 2010, cross-hatched areas). The solid lines are the NLO calculations from Ref. 30, with the range of $p_T$ further extended to $p_T < 100$ GeV by the corresponding authors.

A similar measurement was repeated during Run 2 using the 2.7 fb$^{-1}$ of data collected in 2015; this was the first result of the $\Upsilon$ cross section at $\sqrt{s} = 13$ TeV. An analysis strategy similar to the one previously described was used, but only with data after a selection requirement on the central rapidity region, $|y| < 1.2$. To stay

Fig. 5. $\Upsilon(nS)$ differential cross sections in the rapidity region $|y| < 2$. 
within the flat acceptance region at 13 TeV, the $p_T$ threshold was increased to:

$$p_T^\mu > 4.5 \text{ GeV}/c, \text{ if } 0.0 < |\eta^\mu| < 0.3,$$

$$p_T^\mu > 4.0 \text{ GeV}/c, \text{ if } 0.3 < |\eta^\mu| < 1.4.$$  \hspace{1cm} (6)

A comparison of the $\Upsilon(nS)$ differential cross sections between the 7 and 13 TeV data sets is shown in Fig 7. The cross section of all bottomonium states at 13 TeV is larger than that at 7 TeV by a factor of 2 to 3. This increase factor can be expected from the parton distribution function. The extensions of NRQCD and other theoretical models at 13 TeV are currently pending to be completed.

CMS also measured the $\Upsilon$ cross section in $pp$ collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV, which will be discussed in Section 3, where they are mainly used as references for the heavy ion studies.

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Fig. 6. The $\Upsilon(nS)$ differential $p_T$ cross sections times dimuon branching fractions for $|y| < 1.2.$

Fig. 7. The $\Upsilon(nS)$ differential cross sections for 7 and 13 TeV CMS data for $|y| < 1.2$, assuming isotropic dimuon decays. The inner error bars represent the statistical uncertainty while the total errors show the statistical and systematic uncertainties. The uncertainty on the luminosity measurement is not included.
2.2. Υ polarization

Although the \( J/\psi \) and \( \Upsilon(nS) \) cross sections measured at Tevatron\(^{20,21,34} \) and LHC\(^{22–24,35} \) can be reproduced by NRQCD COM calculations, the corresponding predictions\(^{36} \) for “strong” transverse polarizations are in stark contrast with the negligible polarizations observed in the experiments.\(^{37} \) And although heavy quarkonia from color singlets are expected to be produced with longitudinal polarization,\(^{10,19} \) this is not observed either.

The polarization can be measured through the angular distribution of the two leptons produced in the \( \Upsilon \rightarrow \mu^+ \mu^- \) decay:\(^{8,9} \)

\[
W(\cos \theta, \phi) \propto \frac{1}{3 + \lambda_\theta} (1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi)
\]

where the parameter \( \lambda_\theta \) is 0 or 1 for 100% longitudinal or transverse polarization, and \( \phi \) and \( \theta \) are the azimuthal and polar angles of the outgoing leptons with respect to the quantization axis (z-axis) of the polarization frame. Several polarization reference frames have been proposed. The three most commonly used are the helicity (HX) frame, where the z-axis coincides with the \( \Upsilon \) momentum direction in the collision center-of-mass frame; the Collins-Soper (CS) frame,\(^{38} \) where the z-axis is chosen as the bisector of the two beam directions in the \( \Upsilon \) rest frame; and the perpendicular helicity (PX) frame,\(^{39} \) which is orthogonal to the CS frame. The y-axis is always taken along the direction of the vector product of the two beam directions in the \( \Upsilon \) rest frame.

The bottomonium states are heavier and satisfy the non-relativistic approximation much better than charmonium states. So the \( \Upsilon \) polarization measurement, especially at larger \( p_T \) region, provides a better test of NRQCD. All the existing measurements from the CDF\(^{25} \) and D0\(^{26} \) are in disagreement with the theoretical predictions. Recently, CMS measured all the polarization parameters \( \lambda_\theta, \lambda_\phi, \) and \( \lambda_{\theta\phi} \), as well as the frame-invariant quantity \( \tilde{\lambda} = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi) \), using the pp data sample at \( \sqrt{s} = 7 \) TeV corresponding to an integrated luminosity of 4.9 fb\(^{-1} \).\(^{27} \)

Figure 8\(^{27} \) shows the measured \( \lambda_\theta, \lambda_\phi, \) and \( \lambda_{\theta\phi} \) distributions, for the \( \Upsilon(nS) \) states in the HX frame, in the rapidity range \( |y| < 0.6 \). The polarization parameters in the rapidity range \( 0.6 < |y| < 1.2 \) and in other frames can be found in Ref. 27. The frame-invariant parameter \( \tilde{\lambda} \) for the three \( \Upsilon \) states were also studied as a function of the \( \Upsilon(nS) p_T \) and they are in good agreement in the HX, CS, and PX frames.\(^{27} \) All the polarization parameters are compatible with zero or small values in the three polarization frames. More discussion regarding this measurement can be found in Ref. 27.

In summary, the measurements exclude large longitudinal and transverse polarizations for \( \Upsilon(nS) \), with extended \( p_T \) and \( y \) ranges compared with previous experiments. This result is in disagreement with the theoretical predictions for high-energy hadron collisions, as shown in Fig 9.
Fig. 8. The $\Upsilon(nS)$ differential cross sections for 7 and 13 TeV CMS data for $|y| < 1.2$, assuming isotropic dimuon decays. The inner error bars represent the statistical uncertainty, while the outer bars indicate the combined statistical and systematic uncertainties. The uncertainty on the luminosity measurement is not included.

Fig. 9. The $\Upsilon(3S)$ polarization measurement compared to CDF result and theoretical predictions.$^{27,28}$
3. \( \Upsilon \) suppression in heavy ion collisions

3.1. \( \Upsilon \) suppression in PbPb

Quarks and gluons are normally bound together to form composite particles. However, Quantum Chromodynamics allows for strongly interacting matter to undergo a phase transition to an unbound state (deconfined state), at sufficiently high temperature and density. The unique medium of quarks and gluons in this deconfined state where the partons are no longer confined to hadrons is referred to as a quark-gluon plasma.

This medium can be produced in heavy-ion collisions, where once the heavy quarkonium states are formed, they are expected to unbind due to the strong interactions between quarks and gluons and the high temperature in the medium. At a certain temperature, the weaker bound states, such as \( \Upsilon(3S) \), unbind more completely compared to the stronger bound states such as \( \Upsilon(1S) \). At higher temperature, more of the weaker bond states are expected to dissolve. In the experiment, this sequential unbinding of quarkonium states is observed as a sequential suppression of their yields. For this reason quarkonium states were proposed as a good probe of the phase transition.

The PHENIX experiment\(^{15} \) at the RHIC (Relativistic Heavy Ion Collider) had observed suppression of \( J/\psi \) and \( \psi(2S) \) yields in Au-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV in 2007, but RHIC was not able to perform a \( \Upsilon \) measurement. The \( \Upsilon \) is regarded as a better probe because the \( \Upsilon \) recombination is believed to be less significant than \( J/\psi \). CMS was the first experiment to be able to observe the \( \Upsilon \) sequential suppression.

The first indication of \( \Upsilon \) suppression in heavy ion collisions was reported by CMS in 2011.\(^{32,40,41} \) This result is based on data collected during the first PbPb run in 2010 (\( \sqrt{s_{NN}} = 2.76 \) TeV) and a special \( pp \) run at \( \sqrt{s} = 2.76 \) TeV in 2011. The PbPb and \( pp \) data sets correspond to integrated luminosities of 7.3 \( \mu \)b\(^{-1} \) and 230 nb\(^{-1} \), respectively. Thanks to the good momentum resolution of the CMS detector and the large event samples, the three \( \Upsilon \) resonances observed in the dimuon mass spectrum were well separated for both PbPb and \( pp \). Similar techniques were applied to the two data sets to extract yields and calculate cross sections. As shown in Fig: 10, the blue line represents the fit to the mass spectrum in PbPb; the red dashed line represents the line-shape from the fit to the \( pp \) data. For a better comparison, all three \( \Upsilon(nS) \) peaks were normalized such that the \( \Upsilon(1S) \) yield in the \( pp \) line-shape matches the \( \Upsilon(1S) \) yield in the PbPb fit. The \( \Upsilon(2S) \) and \( \Upsilon(3S) \) resonances in PbPb collisions are clearly more strongly suppressed than the \( \Upsilon(1S) \), comparing with the \( pp \) result. The double ratio, \[ \frac{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{\text{PbPb}}}{[\Upsilon(2S + 3S)/\Upsilon(1S)]_{\text{pp}}} \], is measured to be \( 0.31^{+0.19}_{-0.15} \) (stat.) \( \pm 0.03 \) (syst.),\(^{41} \) in the kinematic region of \( p_T > 4 \) GeV/c and \( |\eta| < 2.4 \).

Besides the hot-nuclear-matter (HNM) effect, i.e., the QGP, the suppression of \( \Upsilon \) production can also be caused by cold-nuclear-matter (CNM) effects.\(^{43} \) But these effects cancel to first order in the double ratio measurements for \( \Upsilon \). For example,
one of the initial-state effects, “shadowing”, is expected to suppress all three Υ resonances by almost the same factor, so it has a small impact on ratio. One of the final-state effects, “nuclear absorption”, is expected to be less important at LHC collision energies. (To further probe the CNM effect, another measurement in the proton-lead (pPb) reference system was performed, and this is described in Section 3.2.) All other biases that could affect the suppression measurements, such as a possible bias from the detector acceptance and efficiency, largely cancel in the double ratio analysis.

The integrated luminosity of the second PbPb run exceeded 150 µb\(^{-1}\) at the end of 2011, which is approximately 20 times larger than the 2010 integrated luminosity. With this large data set, as a follow-up study, the relative suppression of excited Υ states with respect to the Υ(1S) ground state in PbPb was observed with a significance exceeding 5σ.\(^4\) A comparison of the PbPb and pp mass spectra is shown in Fig. 11.\(^4\) The Υ(1S) state is apparently suppressed in PbPb relative to pp, while the Υ(2S) and Υ(3S) states are suppressed to an even greater degree.

The double ratios for Υ(2S) and Υ(3S) are measured as:

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

\[
\frac{[\Upsilon(3S)/\Upsilon(1S)]_{\text{PbPb}}}{[\Upsilon(3S)/\Upsilon(1S)]_{\text{pp}}} = 0.06 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.}) < 0.17(95\%\text{CL}).
\] (8)

In addition to the relative suppression of the two excited Υ states, the absolute suppression of all three individual Υ states was also measured. This study is performed through the \(R_{AA}\) (nuclear modification factor) measurement, which is common in heavy ion studies and is given by

![Dimuon invariant-mass distribution from the 7.3 µb\(^{-1}\) PbPb data. The blue line shows the fit to the PbPb data. The red dashed line shows the shape obtained from the fit to the pp data.](image)
$R_{AA} = \frac{L_{pp} T_{AA} N_{MB} \epsilon_{pp}}{\epsilon_{PbPb}} \frac{\Upsilon(nS)_{PbPb}}{\Upsilon(nS)_{pp}}$  

(9)

$R_{AA}$ is defined as the ratio of the yield per nucleon-nucleon collision in PbPb relative to that in $pp$, corrected for efficiencies and normalized by luminosities. A more detailed explanation of this equation can be found in Ref. 45. When $R_{AA} < 1$, a suppression in PbPb is observed; otherwise, there is no hot nuclear effect. The $R_{AA}$ values for the three individual $\Upsilon$ resonances are:

\begin{align*}
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.)} < 0.10 \text{(95\%CL)}.
\end{align*}

(10)

Subsequently, the $pp$ event sample was increased by about 20 times in 2013 ($5.4 \text{ pb}^{-1}$), which allowed for a better differential $R_{AA}$ study as functions of the $\Upsilon$ rapidity, transverse momentum, and centrality. Figure 12 shows the $\Upsilon(1S)$ and $\Upsilon(2S)$ $R_{AA}$ versus rapidity (left plot) and transverse momentum (middle plot).

Centrality is an important parameter to study the properties of QGP matter because it is directly related to the overlap region of the colliding nuclei. It is common in heavy ion physics to express the centrality of a collision in terms of $N_{\text{part}}$ (the number of participants). In PbPb collisions, $N_{\text{part}}$ is the number of nucleons (at most 208 for a Pb) that collide at least once with nucleons in the other Pb. In Fig. 12 (right), the $R_{AA}$ values for $\Upsilon(1S)$ and $\Upsilon(2S)$ are shown as functions of $N_{\text{part}}$. For $\Upsilon(1S)$, the suppression was observed to increase with the centrality of the collisions. Comparisons with theoretical models are given in Ref. 47.

![Dimuon invariant-mass distribution from the 150 $\mu$b$^{-1}$ PbPb data. The blue solid line shows the fit to the PbPb data. The red dashed line illustrates the corresponding signals in $pp$ data, scaled by the $R_{AA}$ values.](image-url)
The suppression of Υ states in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is expected to be stronger than that measured at 2.76 TeV, because the temperature of the medium is higher due to the higher collision energy. The most recent result from CMS, reported in Quark Matter 2017, confirmed this expectation, as shown in Fig. 13 (left). In Fig. 13 (right), the $\Upsilon(nS) R_{AA}$ versus centrality is compared with models given by Krouppa and Strickland, which contain bottomonia placed in an anisotropic hydrodynamic model. Other comparisons of $R_{AA}$ as functions of $\Upsilon$ rapidity and transverse momentum can be found in Ref. 33,48.
3.2. \( \Upsilon \) suppression in \( pPb \) and in \( pp \)

As discussed above, cold-nuclear-matter (CNM) effects will influence the formation of bottomonium bound state. Some CNM effects could even cause a sequential suppression depending on the binding energy of the \( b\bar{b} \) pairs. The suppression observed in the \( pPb \) collisions is a combined effect caused by both CNM and HNM, while the suppression observed in the proton-lead (\( pPb \)) collisions is thought to be caused by CNM rather than HNM. Consequently, it is essential to study \( \Upsilon \) production in the \( pPb \) reference system, as it is representative of the suppression due to non-HNM effects. This knowledge can be extrapolated into the \( pPb \) system so that the fraction of suppression due to HNM in \( pPb \) collisions can be understood.

The \( pPb \) data set collected by CMS in 2013 corresponds to an integrated luminosity of \( 31 \text{ nb}^{-1} \). The double ratios were measured to be:

\[
\begin{align*}
\frac{\Upsilon(2S)/\Upsilon(1S)}{pPb} & = 0.83 \pm 0.05(\text{stat.}) \pm 0.05(\text{syst.}), \\
\frac{\Upsilon(3S)/\Upsilon(1S)}{pPb} & = 0.71 \pm 0.08(\text{stat.}) \pm 0.09(\text{syst.}).
\end{align*}
\]

Together with the \( pPb \) double ratios in Eq. (8), a comparison is made in Fig. 14. It is noted that the \( pPb \) double ratios in Eq. (8) were derived with the smaller \( pp \) data set (\( 230 \text{ nb}^{-1} \)) collected by CMS in 2011. If the larger \( pp \) data set (\( 5.4 \text{ pb}^{-1} \)) in 2013 were used instead, the \( pPb \) double ratio would increase by a factor 1.6.

The \( \Upsilon(nS)/\Upsilon(1S) \) ratio in the three collision systems also studied as a function of event activity variables. As shown in left panel of Fig. 15, the ratios are plotted...
with respect to the raw transverse energy deposited in the most forward part of
the hadron calorimeters at $4.0 < |\eta| < 5.2$, while in the right panel, the ratios are
plotted with respect to the number of charged particle tracks, excluding the two
muons, with $p_T > 400$ MeV and at $|\eta| < 2.4$. The tracks are required to originate
from the same vertex as the dimuon pairs.

![Fig. 15. The $\Upsilon(2S)/\Upsilon(1S)$ ratio as function of the event activity variables in $pp$, $pPb$, and PbPb
collisions.](image)

The decrease of $\Upsilon(2S)/\Upsilon(1S)$ ratio in Fig. 15 (right) may indicate the presence of
some new phenomena in quarkonium production mechanisms in $pp$ collisions. Other
recently published results by LHC$^{51-56}$ can also be interpreted as hints of collective
effects in the high multiplicity environment at LHC energies.$^{57,58}$ But it is still not
clear whether the medium produced in $pp$ collisions could undergo a phase transi-
tion, as observed in PbPb collisions. As a result, it was suggested to search for possi-
ble new features in the bottomonium yields as the particle multiplicities increase in
$pp$ collisions.$^{59,60}$ Using the $pp$ collision data collected at $\sqrt{s} = 7$ TeV by the CMS
experiment, the ratios of the cross section of the $\Upsilon(nS)$ mesons were investigated,
as shown in Fig. 16.$^{61}$ The production ratios for $\Upsilon(2S)/\Upsilon(1S)$, $\Upsilon(3S)/\Upsilon(1S)$ and
$\Upsilon(3S)/\Upsilon(2S)$ are displayed as a function of the number of charged particles with
$p_T > 0.4$ GeV and $|\eta| < 2.4$. All these ratios clearly decrease with increasing multi-
licity. Figure 17$^{61}$ shows the above production ratios in different $p_T$ regions. The
decline with increasing multiplicities is present again and is stronger in the lower
$p_T$ region. The behavior at higher $p_T$ is flatter, especially in Fig. 17 (left).

Overall, the observed decrease in the production ratios at $\sqrt{s} = 7$ TeV shows a
similar behavior as that at $\sqrt{s} = 2.76$ TeV (Fig. 15).
4.8 fb⁻¹ (7 TeV)

\( p_T(\mu\mu) > 7 \text{ GeV}, |y(\mu\mu)| < 1.2 \)

- \( Y(2S)/Y(1S) \)
- \( Y(3S)/Y(1S) \)

Fig. 16. Production ratios for \( \Upsilon(nS)/\Upsilon(1S) \) (left) and \( \Upsilon(3S)/\Upsilon(2S) \) (right) as a function of \( N_{\text{tracks}} \). The \( \Upsilon(nS) \) mesons are required to satisfy \( p_T > 7 \text{ GeV} \) and \( |y| < 1.2 \). Error bars represent statistical uncertainties, while empty squares show the systematic uncertainties.⁵¹

4.8 fb⁻¹ (7 TeV)

\( p_T(\mu\mu) > 7 \text{ GeV}, |y(\mu\mu)| < 1.2 \)

- \( Y(3S)/Y(2S) \)

Fig. 17. Production ratios vs multiplicity in different regions of \( \Upsilon \) \( p_T \), within \( |y| < 1.2 \). Error bars represent statistical uncertainties, while empty squares show the systematic ones.⁵¹
4. $\chi_b$ production cross section

Measurements of P-wave quarkonium production can be used to help understand the hadron formation mechanism and test NRQCD predictions. The production ratios $\chi_{c2}/\chi_{c1}$ have been measured by CMS, LHCb, and ATLAS, providing valuable insight into the quarkonium production mechanism. The $\chi_{b1,2}$ production cross section measurement is also important since it’s more sensitive to color-octet contributions. However, the measurement is very challenging because of the small separation (only 19.4 MeV) between the $\chi_{b1}(1P)$ and the $\chi_{b2}(1P)$ peaks as well as their small cross sections. The P-wave bottomonium production cross section ratio, $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$, was measured with the 20.7 fb$^{-1}$ pp collision data taken at $\sqrt{s} = 8$ TeV. The $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ states are detected through their radiative decays $\chi_{b1,2}(1P) \rightarrow \Upsilon(1S) + \gamma$, where the $\Upsilon(1S)$ decays to two muons, and the $\gamma$ is reconstructed through its conversion to $e^+e^-$ pair in the inner layers of the tracker. Although the yield of conversion photons is small, the four-momentum of the photon can be precisely determined through a fit to the electron and positron tracks in the tracker. With this strategy, the resulting mass resolution (of the order of 5 MeV) of the $\chi_b$ candidates is sufficient to separate the $\chi_{b1}(1P)$ and $\chi_{b1}(1P)$ peaks.

The $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ ratio was measured in four $\Upsilon(1S)$ $p_T$ bins: (7,11), (11,16), (16,20), and (20,40) GeV. As an example, the invariant mass distribution of the $\mu\mu\gamma$ candidates for the (11,16) GeV bin is shown in Fig. 18(left). Distributions for other bins can be found in Ref. 66.

Figure 18 (right) gives the production cross section ratio as a function of $\Upsilon(1S)$ $p_T$ measured by CMS, and it is compared to the LHCb result and a NRQCD theoretical calculation. Because of the lack of $\chi_b$ measurements, the calculation is based on the previous charmonium measurements of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, but scaled for the case of bottomonium. Neither CMS nor LHCb results agree with the band predicted by the theory. More studies are needed in order to thoroughly test NRQCD predictions in the P-wave bottomonium sector.

5. $\Upsilon$ pair production

The measurement of quarkonium pairs originating from a common vertex in $pp$ collisions provides additional insight into the underlying mechanism of particle production at the LHC. The cross section measurements of quarkonium pair production are essential to understanding contributions of SPS (single-parton scattering) and DPS (double-parton scattering) processes. This in turn forms important inputs in the search for quarkonium pair resonances, which are predicted by several studies. In this section, the first observation and cross section measurement of $\Upsilon(1S)$ pair production by CMS based on 20.7 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV is discussed.

Proton collisions at hadron colliders are described by parton models. Each colliding hadron is characterized as a collection of free elementary constituents. In
a single hadron-hadron collision, two partons often undergo a single interaction (SPS), although the composite nature of hadrons permits multiple distinct interactions (multiple-parton interactions or MPIs) to occur, the simplest case being DPS. The SPS mechanism for heavy-quarkonium pair production can be described by NRQCD COM theory.\textsuperscript{12} However, contributions from the DPS mechanism are not easily addressed within this framework,\textsuperscript{72} and DPS or MPIs are widely invoked to account for the observations that cannot be explained otherwise.\textsuperscript{73} Heavy quarkonium final states are expected to probe the distribution of gluons in the proton since their production is dominated by gluon-gluon interactions.\textsuperscript{74,75} The large event samples at LHC enable a search for exotic states decaying into heavy quarkonium such as tetra-bottom or tetra-charm quark states, and a measurement of the double $\Upsilon$ cross section provides a benchmark measurement for these searches.\textsuperscript{70,76}

In this study,\textsuperscript{71} each $pp$ collision is scanned for a signature of four-muon candidates that do not all have the same electric charge. To ensure a uniform muon acceptance and a well-defined kinematic region, selected muons are required to be within $|\eta^\mu| < 2.4$ and have $p_T > 3.5$ GeV. An $\Upsilon$ candidate is reconstructed by combining two oppositely charged muons that originate from a common vertex. In forming $\Upsilon\Upsilon$ candidates the two pairs of muons are sorted as (i) the $\mu^+\mu^-$ invariant mass of the higher-mass $\Upsilon$ candidate, $M_{\mu\mu}^{(1)}$, (ii) the $\mu^+\mu^-$ invariant mass of the lower-mass $\Upsilon$ candidate, $M_{\mu\mu}^{(2)}$. Figure 19\textsuperscript{71} shows the distribution of $M_{\mu\mu}^{(1)}$ versus $M_{\mu\mu}^{(2)}$ from the four-muon events.
The signal yield of $\Upsilon(1S)$ pair events is extracted by constructing a two-dimensional (2D) unbinned maximum likelihood fit to the invariant mass of the reconstructed $\mu^+\mu^-$ combinations. Figure 2071 shows the projection of the invariant mass distributions of the higher and lower mass muon pairs in the data with a 2D fit superimposed. The efficiency and acceptance of the detector is computed with a data-embedding method that repeatedly substitutes the measured muon four-momenta into different simulated events, which are then subjected to the complete CMS detector simulation and reconstruction chain.

The fiducial cross section of $\Upsilon(1S)$ pair production is determined to be $\sigma_{\text{fid}} = 68.8 \pm 12.7\,\text{(stat)} \pm 7.4\,\text{(syst)} \pm 2.8\,\text{(B)}\,\text{pb}$, where both $\Upsilon(1S)$ mesons are assumed to decay isotropically, and the last uncertainty related to the $\Upsilon(1S) \rightarrow \mu^+\mu^-$ branching fraction. The major uncertainty on the cross section stems from the unknown polarization of the $\Upsilon$ states. Compared to an isotropic $\Upsilon(1S)$ meson decay, the
The measurement of the effective cross section $\sigma_{\text{eff}}$ depends on the fraction of DPS interactions. $\sigma_{\text{eff}}$ is calculated using the fiducial $\Upsilon(1S)$ pair production cross section $\sigma_{\text{fid}}$:

$$
\sigma_{\text{eff}} = \frac{[\sigma(\Upsilon)]^2}{2f_{\text{DPS}}\sigma_{\text{fid}}|B(\Upsilon(1S) \rightarrow \mu^+\mu^-)|^2} = 6.6\text{nb (12)}
$$

where $f_{\text{DPS}} \approx 10\%$ is the fraction of the DPS contribution and $\sigma(\Upsilon) = 7.5\pm0.6\text{nb}$ is the single $\Upsilon(1S)$ production cross section extrapolated to the fiducial region ($|y_{\Upsilon}| < 2.0$). The effective cross section, $\sigma_{\text{eff}}$, is consistent with previous measurements of heavy quarkonium, but smaller than those from multijet studies. The values of $\sigma_{\text{eff}}$ measured in different final states may indicate that the gluons occupy a smaller region in the proton compared to jet-related channels, which are dominated by quark-antiquark and quark-gluon parton interactions. More data at the LHC will improve the calculation of SPS/DPS contributions and will open new opportunities for exotic searches in four b-quark bound states.

### 6. Search for new and exotic states

Quarkonium states are “standard candles” that are used extensively for detector and trigger calibration, for extending measurements and searches down to the limit of the detector kinematic acceptance. The low-mass region is probed directly for new particle states. For example, searches are performed for light pseudoscalar states around the $\Upsilon$ mass, as predicted in scenarios such as next-to-minimal supersymmetric models (Fig. 21 left). In addition, quarkonium states can be explored as final states in the search for new particles and rare processes.

Studies of di-quarkonium production, such as reported in Section 5, open new opportunities to search for possible exotic resonance states decaying to quarkonium pairs. In the bottomonium case, one may probe for four b-quark bound states.

Various unexpected quarkonium-like states have been identified since the discovery of the X(3872) by BELLE more than a decade ago. This exotic charmonium state was discovered in the final state $J/\psi\pi^+\pi^-$, tagged through B meson decays, and its prompt production has been confirmed, by various experiments including CMS. A search is conducted for an exotic bottomonium counterpart. This is done probing the corresponding final state $\Upsilon(1S)\pi^+\pi^-$, as shown in Fig. 21 (right). Besides the excited $\Upsilon$ states that are expected (Fig. 1) and appear prominently in the spectrum, no excess is detected over background, despite the analysis having the sensitivity for detecting such a state if its relative strength were comparable to the corresponding value for the X(3872). The search yielded the first exclusion limits on the production of the exotic bottomonium state at a hadron collider.
7. Conclusion and outlook

The CMS experiment has contributed already a set of most significant results towards an improved understanding of the heavy quarkonium sector at the LHC. The detector acceptance, trigger, and reconstruction capabilities have allowed the prompt collection of large datasets containing dimuon signals, down to low transverse momenta, probing the wide mass spectrum (displayed in Fig. 2). While the muon detectors contribute particle identification and the seeds for online selection, the Silicon tracker allows for precise kinematic and topological reconstruction of particle decays. The precision achieved allows, in particular, for separately identifying all three (light) \( \Upsilon(nS) \) states – a capability that is fully exploited in the measurements here reported.

CMS has contributed the first bottomonium measurements at the LHC. Cross sections are among the results first extracted with initial data, both in LHC’s Run1 and Run2 data taking periods. Measurements in pp collisions at the unprecedented centre-of-mass energies of 2.76, 7, and 13 TeV have been undertaken, within the rapidity window of \( |y| < 2.4 \), and dimuon momenta from down to 0 GeV and up to 100 GeV. Cross sections (and/or ratios thereof) have been measured for S-wave and P-wave states. In addition, the angular distribution of the final-state muons has been analyzed, in complementary reference frames, resulting in detailed measurements of the polarization parameters, that have been reported for all three S-wave states. The cross-sections and the polarizations, combined in global fits, have shed considerable light on the involved QCD production mechanisms, having further contributed towards the resolution of the “quarkonium puzzle”. Analysis of further LHC data being collected will allow to extend the kinematic reach of the measurements and, in particular, to extend the cross section and polarization measurements to the P-wave states. These will be important pieces in the puzzle per se, and will

![Image](https://via.placeholder.com/150)

**Fig. 21.** Left: search for light states near the \( \Upsilon \) mass, showing hypothetical signals from pseudoscalar Higgs bosons at 7 and 12 GeV. Right: Search for an exotic bottomonium state in the \( \Upsilon(1S)\pi^+\pi^- \) invariant mass spectrum. The peaks shown correspond to the \( \Upsilon \) excited states decays \( \Upsilon(nS) \rightarrow \Upsilon(1S)\pi^+\pi^- \).
allow to disentangle the P- to S-wave feed-down contributions, thus granting access to directly produced bottomonia.

Ground breaking results have been achieved further in collisions involving heavy ions. The considerable jump in collision energy and detector capability, with respect to previous heavy-ion experiments, has placed CMS in a privileged position to explore the bottomonium sector in nuclear collisions. In particular, the experiment has delivered the first complete measurements of the individual states of the Υ family in collisions involving heavy ions. Foremost, the ability to separately identify the individual Υ(nS) states has been explored to probe their relative suppression. Such a novel and robust analysis has allowed to experimentally establish the pattern of sequential suppression, wherein the excited states are more suppressed than the smaller, more strongly bound states. The absolute suppression, in PbPb with respect to pp, of the individual states has also been assessed. Detailed measurements of bottomonia, in PbPb but also pPb and pp, have allowed to probe (cold) nuclear and environment effects. Another pPb run at √sNN = 8.16 TeV in 2018 is expected to collect about 5 times more luminosity than that at 5.02 TeV in 2013. The analysis of larger LHC datasets will allow to explore P-wave states, quantifying the suppression of higher-mass states and their feed-down contribution to the inclusive measurements of the lighter ones. It will allow also to explore new observables, such as azimuthal anisotropies and polarizations through angular analyses, and perform further studies of kinematic, angular, and environment dependencies. The continued exploration of the bottomonium sector, through such more precise and new measurements, across different collisions systems and energies, will allow to gain a more complete understanding of the underlying processes contributing to quarkonium production and suppression, and a more complete characterization of the properties of the hot medium attained with LHC collisions.

Production of bottomonium pairs has been observed for the first time, and the cross section of Υ(1S) pair production was reported. Extended and more precise studies of quarkonium pair production will allow to quantify to a better precision the effect of multi-parton interactions at the LHC. Additional studies of bottomonia associated production, involving other quarkonium states and, more generally, other hadrons, jets, and vector bosons, will contribute new perspectives towards a more complete understanding of the mechanisms of hadron production. At the same time, such studies of associated production open an interesting window into the spectroscopy realm, forming the basis for the search and exploration of new and exotic states. Rare decays of heavier particle states, e.g. Z and Higgs, to bottomonium provide interesting channels that ought to be explored as well in future higher luminosity LHC runs.

Precision heavy-flavor measurements with a general purpose detector at the LHC are challenging, required understanding of fine-grain effects and calibration of the detector in a low-p_T regime and in view of corresponding increasing online rate limitations. Building upon the solid achievements already attained, and benefitting from detector and data acquisition systems upgrades, a dedicated and promising
program of heavy-quarkonium physics may continue to be further pursued in the future LHC runs, aiming at contributing to a more complete understanding of the nature of strong interactions and the search for new phenomena.

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