Production of $\Upsilon(nS)$ mesons in Pb+Pb and $pp$ collisions at 5.02 TeV with ATLAS

The ATLAS Collaboration

The measurement of the production of bottomonium states, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$, in Pb+Pb and $pp$ collisions at a center-of-mass energy per nucleon pair of 5.02 TeV is presented. The data correspond to integrated luminosities of 1.38 nb$^{-1}$ of Pb+Pb collisions collected in 2018 and 0.26 fb$^{-1}$ of $pp$ collisions collected in 2017 by the ATLAS detector. The measurements are performed in the dimuon decay channel in transverse momentum $p_T^{\mu\mu} < 30$ GeV, absolute rapidity $|y^{\mu\mu}| < 1.5$, and the event centrality 0 – 80%. The production of three bottomonium states in Pb+Pb is compared to that in $pp$ collisions to extract the nuclear modification factor, $R_{AA}$, as functions of event centrality, $p_T^{\mu\mu}$ and $|y^{\mu\mu}|$. In addition, the relative suppression of the excited states $\Upsilon(nS)$ to the ground state $\Upsilon(1S)$ is studied. The measurements are compared to the previous CMS results and theoretical model predictions.
1 Introduction

Quantum chromodynamics (QCD) predicts that at very high temperature and energy density, hadronic matter can undergo a phase transition and can turn into a state of deconfined quarks and gluons known as Quark-Gluon Plasma (QGP). This state of matter can be created by colliding two heavy nuclei at ultra-relativistic energies. In such collisions, heavy-flavor quarks, especially charm and bottom, are produced at a very early stage by hard scattering and hence can be used to characterize the properties of the QGP.

Due to the large charm and bottom quark masses, many basic quarkonium properties can be calculated using non-relativistic potential theory [1]. The relevant S-wave quarkonium states are summarized in Table 1. The binding energies $\Delta E$ listed there are the differences between the quarkonium masses and the mass threshold for production of a pair of hadrons with open charm or bottom, $r_0$ is the separation of bound quarks while $\Delta M$ is the difference between the calculated mass and the measured mass of the resonance.

<table>
<thead>
<tr>
<th>State</th>
<th>$J/\psi$</th>
<th>$\psi'$</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [GeV]</td>
<td>3.10</td>
<td>3.68</td>
<td>9.46</td>
<td>10.02</td>
<td>10.36</td>
</tr>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.64</td>
<td>0.05</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>$\Delta M$ [GeV]</td>
<td>0.02</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.07</td>
</tr>
<tr>
<td>$r_0$ [fm]</td>
<td>0.50</td>
<td>0.90</td>
<td>0.28</td>
<td>0.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 1: Quarkonium states and their properties from non-relativistic potential theory [1]. $\Delta E$ is the difference between the mass of the meson and the mass threshold for production of a pair of hadrons with open charm or bottom. $\Delta M$ is the difference between the theoretically calculated mass and the experimentally measured mass of the meson [2]. $r_0$ is the separation of bound quarks.

It is predicted that the production of quarkonia (charmonia and bottomonia) in nucleus-nucleus collisions will be suppressed relative to that in proton-proton ($pp$) collisions due to Debye-screening of the quark color charge in the QGP [3]. It is also expected that the modification to the heavy-quark potential will lead to different quarkonium states dissolving at different temperatures of the medium [3]. In particular, a sequential suppression of quarkonia, depending on their binding energies, $\Delta E$, has been proposed as a thermometer of the deconfined medium [4].

While the excited states are dissociated just above the critical temperature $T_c$ needed to form the QGP, the fundamental states melt far above that value; this causes a structure in the measured suppression of quarkonium states. To estimate the sequence and positions of the suppression steps as a function of temperature and energy density, Digal, Petreczky and Satz made use of lattice studies calculating the temperature behavior of the heavy-quark potential in full QCD [5]. It was found that the $\Upsilon(1S)$ persists well above $T_c$ while the $\Upsilon(3S)$ cannot exist for temperatures above $T_c$ and $\Upsilon(2S)$ dissociates at about $1.1T_c$.

If the population of heavy-flavor quarks is large, then it is possible for quarkonia to be regenerated through binding of open heavy-flavor quark(anti-quark) with heavy flavor anti-quark(quark) from a different nucleon-nucleon collision. There can also be a local reformation of an individual bound state due to medium interactions with a rate proportional to the square of the number of heavy-quark pairs in the medium [1]. Given the abundance of charm quarks, the regeneration mechanism is important for low transverse momentum ($p_T < 6$ GeV) charmonia at the Large Hadron Collider (LHC) [6–8], but it is expected to be negligible for bottomonia [9]. This makes the study of bottomonium production in lead-lead (Pb+Pb) collisions a sensitive tool to probe the sequential dissociation [10].
In order to understand quarkonium yields in Pb+Pb collisions it is necessary to disentangle effects due to interaction between quarkonium and the QGP from those that can be ascribed to cold nuclear matter (CNM) such as shadowing, parton energy loss, and interaction with the hadronic medium. In proton-lead ($p$+Pb) collisions, the modification of quarkonium production with respect to $pp$ collisions has traditionally been attributed to CNM effects. ATLAS already measured $\Upsilon(nS)$ production in $p$+Pb collisions [11] and found it to be suppressed at low momentum relative to $pp$ collisions. Also the production of excited bottomonium states was found to be suppressed relative to that of the ground states in central $p$+Pb collisions.

In Pb+Pb collisions, every event is characterized by the centrality which reflects the overlap of the colliding nuclei. The geometrical properties of the collisions are calculated using the Glauber model [12]. The modifications of bottomonium production yields in Pb+Pb collisions with respect to the $pp$ system are quantified by the nuclear modification factor, $R_{AA}$, which can be defined for each centrality bin as

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}},$$

where $N_{AA}$ is the per-event yield of bottomonium states, $\langle T_{AA} \rangle$ is a mean value of the nuclear overlap function, and $\sigma_{pp}$ is the bottomonium production cross section in $pp$ collisions at the same collision energy. If $R_{AA}$ is unity, the production is the same as in $pp$ collisions, and if $R_{AA} < 1$, there is a suppression of bottomonium production in Pb+Pb collisions.

The ALICE [13] and CMS [14] at the LHC and PHENIX [15, 16] at RHIC have studied bottomonium production in various collision systems and at different collision energies. The ATLAS measurement in $pp$ and Pb+Pb collisions will provide complementary information since each experiment has slightly different kinematic coverage.

In the following sections, we will report the details of bottomonium production measurement in $pp$ and Pb+Pb collisions with the ATLAS detector. In Section 2 we describe the ATLAS detector, in Section 3 we summarize the analysis details, in Section 4 we outline the systematic uncertainties and finally in Section 4 we report the results for $\Upsilon(nS)$ production in $pp$ and Pb+Pb collisions.

2 ATLAS detector

The ATLAS detector [17] at the LHC covers nearly the entire solid angle\(^1\) around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit being normally in the insertable B-layer (IBL) installed before Run 2 [18, 19]. It is followed by the silicon microstrip tracker, which usually provides four two-dimensional measurement points per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$.

---

\(^1\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta \eta \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. 
The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) electromagnetic calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillating-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules (FCal) situated at $3.1 < |\eta| < 4.9$, optimized for electromagnetic and hadronic measurements, respectively. The minimum-bias trigger scintillator (MBTS) system detects charged particles over $2.07 < |\eta| < 3.86$ using two hodoscopes of 12 counters positioned at $z = \pm 3.6$ m. The zero-degree calorimeters (ZDC) measure neutral particles at pseudorapidities $|\eta| \geq 8.3$.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detectors. A set of precision chambers covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region, where the background is highest. Resistive plate chambers (RPCs) and thin gap chambers (TGCs) with a coarse position resolution but a fast response time are used primarily to trigger on muons in the ranges $|\eta| < 1.05$ and $1.05 < |\eta| < 2.4$ respectively.

A two-level trigger system is used to select interesting events [20]. The Level-1 (L1) trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 100 kHz. This is followed by the software-based high-level trigger (HLT), which reduces the event rate to about 1–4 kHz. The L1 muon trigger requires coincidences between hits on different RPC or TGC planes, which are used as a seed for the HLT algorithms. The HLT uses dedicated algorithms to incorporate information from both the MS and the ID, achieving position and momentum resolution close to that provided by the offline muon reconstruction, as shown in Ref. [20].

### 3 Analysis

The analysis is based on data collected by ATLAS at the LHC during Pb+Pb collisions at a center-of-mass energy of 5.02 TeV per nucleon pairs in 2018 with an integrated luminosity of 1.38 nb$^{-1}$, and $pp$ collisions at a center-of-mass energy of 5.02 TeV in 2017 with an integrated luminosity of 0.26 fb$^{-1}$. Candidate events in Pb+Pb collisions were collected with a trigger which requires one muon to pass the L1 requirement which must be confirmed at the HLT as a muon with $p_T^\mu > 4$ GeV, and at least one more muon candidate with $p_T^\mu > 4$ GeV must be found in a search over the full MS system (full scan). In $pp$ collisions, the candidate events were collected with a different trigger which requires at least two distinguished L1 muon candidates with $p_T^\mu > 4$ GeV, subsequently confirmed in the HLT.

Muon candidates are reconstructed based on a combination of charged-particle tracks reconstructed in the ID and the MS passing "medium" selection requirements detailed in Ref. [21] without the requirement on the number of TRT hits in Pb+Pb collisions due to the high occupancy in the ID. In addition, muons are selected to have a tight association with a primary vertex: transverse impact parameter significance satisfies $|d_0/\sigma(d_0)| < 3$ and longitudinal impact parameter satisfies $|z_0\sin(\theta)| < 0.5$ mm. The ID tracks of the two muon candidates are fitted to a common vertex with goodness of the vertex fit $\chi^2 < 100$, fully efficient for signal candidates as used in the previous ATLAS measurement [22], and the significance of the refitted vertices transverse displacement with respect to a primary vertex is required to be $|L_{xy}/\sigma(L_{xy})| < 3$. Only events with both muon candidates matching with muons reconstructed by the HLT are used in the analysis.
Muon pairs are selected with invariant mass, $m_{\mu\mu}$, between 7.7 and 12.3 GeV, and are limited to the rapidity range of $|y^{\mu\mu}| < 1.5$ for better muon momentum resolution. Approximately 880k (390k) muon candidates are found in $pp$ ($Pb+Pb$) collisions for the $p_T^{\mu\mu}$, $|y^{\mu\mu}|$, and centrality-integrated bin before separating signal candidates from background components.

Monte Carlo (MC) simulations [23] of $pp$ collision events with and without overlaying with minimum-bias $Pb+Pb$ data are used to study muon trigger and reconstruction efficiencies as well as quarkonium acceptance and signal yields extraction in $pp$ and $Pb+Pb$ collisions. Events were generated using Pythia8 [24] with the CTEQ6L1 [25] parton distribution functions. In each sample, one of the four quarkonium states, $J/\psi$, and $\Upsilon(nS)$ ($n = 1, 2, 3$), was produced unpolarised, and forced to decay via the dimuon channel. The response of the ATLAS detector was simulated using Geant4 [26]. The simulated events were reconstructed with the same algorithms used for data.

The $Pb+Pb$ events are characterized by centrality via the total transverse energy deposited in FCal, $\Sigma E_T^{FCal}$. For the results shown here, the minimum-bias $\Sigma E_T^{FCal}$ distribution is divided into percentiles ordered from the most central (large $\Sigma E_T^{FCal}$, small impact parameter) to the most peripheral (small $\Sigma E_T^{FCal}$, large impact parameter): 0–5%, 5–10%, 10–15%, 15–20%, 20–30%, 30–40%, 40–60%, and 60–80%. The interval 80–100% is excluded to suppress dimuon production from electromagnetic processes [27]. A MC Glauber [12] calculation is used to characterize each centrality class [28]. The above centrality classes have an average number of participating nucleons ($N_{part}$) = 384.5 ± 1.9, 333.1 ± 2.7, 285.2 ± 2.9, 242.9 ± 2.9, 189.2 ± 2.8, 131.4 ± 2.6, 70.5 ± 2.2, and 23.0 ± 1.3, respectively.

Differential $\Upsilon(nS)$ production cross sections in $pp$ collisions are measured according to the relation

$$
\frac{d^2\sigma(\Upsilon(nS))}{dp_T^{\mu\mu}dy^{\mu\mu}} \times Br(\Upsilon(nS) \rightarrow \mu^+\mu^-) = \frac{N_{corr}^{\Upsilon(nS)}}{\Delta p_T^{\mu\mu} \times \Delta y^{\mu\mu} \times \int L dt},
$$

where $Br(\Upsilon(nS) \rightarrow \mu^+\mu^-)$ is the dimuon decay branching fraction, $N_{corr}^{\Upsilon(nS)}$ is $\Upsilon(nS)$ yield corrected for acceptance and detector inefficiency, $\Delta p_T^{\mu\mu}$ and $\Delta y^{\mu\mu}$ are bin widths, and $\int L dt$ is the integrated luminosity.

Determination of $N_{corr}^{\Upsilon(nS)}$ proceeds in several steps. First, a resonance-dependent weight, $w_{total}(\Upsilon(nS))$, is determined for each selected dimuon candidate in bins of $p_T^{\mu\mu}$, $|y^{\mu\mu}|$, and centrality as

$$
w_{total}(\Upsilon(nS)) = \frac{1}{\mathcal{A}(\Upsilon(nS)) \cdot e_{reco}(\mu_1\mu_2) \cdot e_{trig}(\mu_1\mu_2) \cdot \mathcal{E}_{pVasso}(\mu_1\mu_2)},
$$

where $\mathcal{A}(\Upsilon(nS))$ is the acceptance for $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decay, $e_{reco}$ is the muon reconstruction efficiency which also includes muon identification, $e_{trig}$ is the trigger efficiency, and $\mathcal{E}_{pVasso}$ is the efficiency related to the primary vertex association which is found to be 97.7% (98.5%) for $pp$ ($Pb+Pb$) collisions obtained from MC simulations. Next, an unbinned maximum-likelihood fit is performed to the weighted dimuon invariant mass distribution ($m_{\mu\mu}$) to extract $\Upsilon(nS)$ yields.

The nuclear modification factor, $R_{AA}$, is used to compare the production of $\Upsilon(nS)$ in Pb+Pb to the same processes in $pp$ collisions at the same energy, defined as Eq. 1. The per-event yields of $\Upsilon(nS)$ states in Pb+Pb collisions are defined by

$$
N_{AA} = \frac{N_{corr}^{\Upsilon(nS)}}{\Delta p_T^{\mu\mu} \times \Delta y^{\mu\mu} \times N_{evi}}.
$$
where \( N_{\text{evt}} \) is the total number of minimum-bias \( \text{Pb}+\text{Pb} \) collisions probed in each centrality class. For example, \( N_{\text{evt}} = 1.02 \times 10^9 \) for the 10% centrality interval.

In order to reduce experimental uncertainties, the suppression of the excited states can be quantified with respect to the ground state via the double ratio, defined as the production cross sections of the excited states to the ground state, in \( \text{Pb}+\text{Pb} \) to \( pp \) collisions

\[
\rho_{\text{AA}}^{\Upsilon(0S)/\Upsilon(1S)} = \frac{\sigma_{\text{Pb}+\text{Pb}}^{\Upsilon(0S)}/\sigma_{\text{Pb}+\text{Pb}}^{\Upsilon(1S)}}{\sigma_{pp}^{\Upsilon(0S)}/\sigma_{pp}^{\Upsilon(1S)}} = R_{\text{AA}}(\Upsilon(0S))/R_{\text{AA}}(\Upsilon(1S)).
\] (5)

The kinematic acceptance \( \mathcal{A} \) is defined as the probability that both muons from \( \Upsilon(0S) \rightarrow \mu^+\mu^- \) decay pass the fiducial selection (\( p_T^\mu > 4 \text{ GeV} \) and \( |\eta_{\mu}| < 2.4 \)). The kinematic acceptance is calculated from a generator-level simulation separately for different \( \Upsilon(0S) \) states as described in Ref. \[29\]. The acceptance could in principle depend on the spin-alignment of the \( \Upsilon(0S) \) meson. In this analysis, \( \Upsilon(0S) \) mesons are assumed to be produced unpolarized following the previous measurements in \( pp \) collisions \[30–32\].

The dimuon reconstruction efficiency, \( \epsilon_{\text{reco}}(\mu_1\mu_2) \), is determined as the product of two single muon reconstruction efficiencies. The single muon reconstruction efficiency is factorized into ID track reconstruction efficiency and MS reconstruction efficiency with respect to reconstructed ID tracks. For \( pp \) collisions, central values of the reconstruction efficiency are obtained from the \( J/\psi \rightarrow \mu^+\mu^- \text{ PYTHIA8} \) simulation, and additional data-to-MC efficiency scale factors are derived using \( J/\psi \rightarrow \mu^+\mu^- \) tag and probe method from \( pp \) data at \( \sqrt{s} = 13 \text{ TeV} \) \[21\] to account for residual differences between data and simulation. The same \( J/\psi \rightarrow \mu^+\mu^- \) tag and probe method is employed to measure muon reconstruction efficiency in \( \text{Pb}+\text{Pb} \) collisions. The ID reconstruction efficiency is obtained from \( \text{Pb}+\text{Pb} \) data directly with a requirement on the transverse displacement of the \( J/\psi \) vertex to suppress the bias in the ID efficiency determination from displaced muons. The MS reconstruction efficiency is obtained from \( J/\psi \rightarrow \mu^+\mu^- \text{ PYTHIA8} \) simulation overlaid with minimum-bias \( \text{Pb}+\text{Pb} \) data, and additional data-to-MC scale factors are determined in \( \text{Pb}+\text{Pb} \) data to account for the small difference between data and simulation. The ID reconstruction efficiency is found to be larger than 99% in both \( pp \) and \( \text{Pb}+\text{Pb} \) collisions with no obvious centrality dependence in the latter case. The MS reconstruction efficiency at \( p_T^\mu = 4 \text{ GeV} \) is about 65% in the barrel region (\( |\eta_{\mu}| < 1.05 \)) and 75% in the end-cap region (\( 1.05 < |\eta_{\mu}| < 2.4 \)), and the MS efficiency increases with \( p_T^\mu \) and saturates at 95% around \( p_T^\mu = 7 \text{ GeV} \) in both barrel and end-cap regions.

The single muon trigger efficiency is determined in the data and simulation using the \( J/\psi \rightarrow \mu^+\mu^- \) tag and probe method similar to what was used for muon reconstruction efficiency. Two different muon trigger logic schemes are used in this analysis: 1) a full-chain muon trigger which requires the formation of an L1 muon candidate which is subsequently confirmed at the HLT, and 2) a full-scan muon trigger which is only performed at the HLT via a muon candidate search of the full MS system without any requirement at L1. The central values for the full-chain muon trigger efficiency are determined from MC simulation, with data-to-MC scale factors determined from the \( pp \) data to cover the difference in data and simulation. The same central values and scale factors of full-chain trigger efficiency are used for \( pp \) and \( \text{Pb}+\text{Pb} \) collisions, except that an additional centrality-dependent correction is applied to \( \text{Pb}+\text{Pb} \) data. The centrality-dependent correction is determined by comparing trigger efficiency measured in \( \text{Pb}+\text{Pb} \) in different centralities with that in \( pp \) data. The full-chain muon trigger efficiency plateau is found to be 70% in the barrel and 90% in the end-cap. The centrality-dependent correction is about 0.9 (1.0) for 0 – 10% (60 – 80%). The full-scan muon trigger is only used in \( \text{Pb}+\text{Pb} \) collisions and its efficiency is determined from \( \text{Pb}+\text{Pb} \) data directly. The full-scan trigger plateau is found to be 90% in both barrel and end-cap regions. The dimuon trigger efficiency in \( pp \) is factorized as the product of two full-chain muon trigger efficiencies, and the factorization
form consisting of full-chain and full-scan muon trigger efficiency as detailed in Ref. [33] is used in Pb+Pb collisions.

The corrected signal yields of \( \Upsilon(nS) \) mesons are extracted from extended unbinned maximum likelihood fits performed on invariant mass distributions in each \( p_T^{\mu\mu} \), \( |y^{\mu\mu}| \) or centrality interval. The correction weights are calculated according to Eq. 3. The probability distribution function, pdf, for the fit is defined as a normalized sum of three \( \Upsilon \) signals and the background components as

\[
\text{pdf} (m_{\mu\mu}) = N_{\Upsilon(1S)} f_{\Upsilon(1S)}(m_{\mu\mu}) + N_{\Upsilon(2S)} f_{\Upsilon(2S)}(m_{\mu\mu}) + N_{\Upsilon(3S)} f_{\Upsilon(3S)}(m_{\mu\mu}) + N_{\text{bkg}} f_{\text{bkg}}(m_{\mu\mu}).
\]  

The individual line shape components are shown in Table 2. Each of the three \( \Upsilon \) signal shapes is described by a combination of Crystal Ball [34] (CB) and Gaussian (G) functions with a common mean but different widths, where the CB function is introduced to model the final-state radiation (FSR) low-mass tail. The mean and the Gaussian width of the \( \Upsilon(1S) \) signal, \( M_{1S} \) and \( \sigma_{1S} \), are left free for all \( p_T^{\mu\mu} \), \( |y^{\mu\mu}| \) and centrality bins, while the mean and the Gaussian widths of \( \Upsilon(2S) \) and \( \Upsilon(3S) \) in the same bin are fixed to the parameters of \( \Upsilon(1S) \) scaled by the ratio of the mass values as reported by PDG [2]: \( M_{nS} = M_{1S} (M_{nS}^{\text{PDG}} / M_{1S}^{\text{PDG}}) \) and \( \sigma_{nS} = \sigma_{1S} (M_{nS}^{\text{PDG}} / M_{1S}^{\text{PDG}}) \). The widths of the CB functions are set by scaling the corresponding Gaussian widths with a constant factor, \( 1.7\sigma_{nS} \), obtained from fit optimizations in the MC sample. The fraction between CB and Gaussian function \( \omega \) for \( \Upsilon(1S) \) is left free, and \( \omega \) for \( \Upsilon(2S) \) and \( \Upsilon(3S) \) are fixed to the value of \( \Upsilon(1S) \). In the CB function, the \( \alpha \) and \( n \) parameters describe the transition point of the low-edge from a Gaussian to a power-law shape, and the shape of the tail, respectively. Based on the fact that these two parameters are strongly correlated, the \( \alpha \) for the \( pp \) analysis is fixed at the value obtained from fitting signal \( \Upsilon(1S) \) MC samples, and \( n \) is left free. For Pb+Pb, \( n \) is fixed to the \( pp \) value in addition. The nominal signal fit model described above is tested by fitting the signal MC samples in various \( p_T^{\mu\mu} \), \( |y^{\mu\mu}| \), and centrality bins.

The background parameterizations vary with dimuon \( p_T^{\mu\mu} \). At low \( p_T^{\mu\mu} \) bins (\( p_T^{\mu\mu} < 6 \text{ GeV} \)), or integrated over the whole \( p_T^{\mu\mu} \) range (\( p_T^{\mu\mu} < 30 \text{ GeV} \)), an error function multiplied by an exponential function is used to describe the \( m_{\mu\mu} \) turn-on effects due to the single-muon \( p_T^{\mu\mu} \) requirement. The background model parameters are constrained by the background-enriched sample, which contains same-sign charged dimuon pairs and opposite-sign charged dimuon pairs with at least one muon being significantly displaced \((|d_0|/\sigma(d_0)| > 2 \text{ or } |z_0 \sin(\theta)| > 0.2 \text{ mm})\). The background fit model is first fit to the background-enriched sample, and the parameters related to the error function are fixed at this step. Then, the full fit model including signal and background is used to fit the data, while the additional background parameter \( \lambda \) from

<table>
<thead>
<tr>
<th>Signal</th>
<th>pdf (( m_{\mu\mu} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\Upsilon(1S)}(m_{\mu\mu}) )</td>
<td>( \omega G(m_{\mu\mu}; M_{1S}, \sigma_{1S}) + (1 - \omega) CB(m_{\mu\mu}; M_{1S}, 1.7\sigma_{1S}, \alpha, n) )</td>
</tr>
<tr>
<td>( f_{\Upsilon(2S)}(m_{\mu\mu}) )</td>
<td>( \omega G(m_{\mu\mu}; M_{2S}, \sigma_{2S}) + (1 - \omega) CB(m_{\mu\mu}; M_{2S}, 1.7\sigma_{2S}, \alpha, n) )</td>
</tr>
<tr>
<td>( f_{\Upsilon(3S)}(m_{\mu\mu}) )</td>
<td>( \omega G(m_{\mu\mu}; M_{3S}, \sigma_{3S}) + (1 - \omega) CB(m_{\mu\mu}; M_{3S}, 1.7\sigma_{3S}, \alpha, n) )</td>
</tr>
</tbody>
</table>

Table 2: Functional forms of individual components in the central fit model. The composite pdf terms are defined as follows: \( G \) - single Gaussian function, CB - Crystal Ball function, er f - error function, \( E \) - exponential function, \( P \) - 2nd order polynomial function. The parameter \( \omega \) is the normalization factor between the two single Gaussian functions.
the exponential function is left free. At higher $p_T^{\mu\mu}$ ($p_T^{\mu\mu} > 6$ GeV), a second-order polynomial is used to model the background contribution.

Figure 1 shows an example of the fit on the dimuon mass for $pp$ (left) and Pb+Pb (right) collisions for the inclusive $p_T^{\mu\mu}$ and $|y^{\mu\mu}|$ bin. In Pb+Pb collisions, the centrality range is also integrated. The bottom panels show the pull distribution, $(\text{Data-Fit})/\sigma(\text{Data})$.

For some bins, the $N_{AA}$ of $\Upsilon(2S)$ are consistent with zero within the statistical uncertainties. In this case, the upper limits are calculated as follows and presented instead of data points. First, each point in the mass distribution is randomized by the Gaussian distribution, using the central values as means and the statistical uncertainties as widths. The randomization is done for 1000 times, then each of the new mass distributions are fitted individually to get 1000 different results. Next, the distributions of the $R_{AA}$ or $\rho^{\Upsilon(1S)}/\rho^{\Upsilon(1S)}_{AA}$ results are interpreted as a probability density function, and the upper limits are determined by integrating these distributions along the $x$-axis.

### 4 Systematic uncertainties

**Luminosity and $\langle T_{AA} \rangle$ uncertainty**

The uncertainty in the integrated luminosity for the 2017 $pp$ data is 1.6\%, derived using methods described in Ref. [35] using the LUCID-2 detector [36] for the primary luminosity measurements. For Pb+Pb
collisions, the systematic uncertainty on $\langle T_{AA} \rangle$ is estimated by varying the Glauber model parameters as detailed in Ref. [28].

**Acceptance**

The central acceptance maps in $p_{T}^{\mu\mu}$ and $|y^{\mu\mu}|$ are produced by toy MC programs in which the final state radiation (FSR) is not included. The impact of FSR on the acceptance correction is estimated by comparing the acceptance obtained from toy MC to the full MC simulations with FSR at the generator level with the same phase space requirement on muons [11]. The difference observed from $\Upsilon(1S)$ simulation is applied as a correction to $\Upsilon(nS)$ yields as a function of $p_{T}^{\mu\mu}$ for both pp and Pb+Pb collisions, and the correction is fully canceled in $R_{AA}$ and $\rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)}$ measurements. Systematic uncertainty on the FSR correction includes the difference observed for different $\Upsilon(nS)$ states and a small rapidity dependence for a given state. Acceptance values obtained from the toy MC method are derived assuming that $\Upsilon(nS)$ mesons are produced at the center of the detector $(x, y, z) = (0, 0, 0)$. Typical beam spreads in $x$ and $y$ are too small to impact the acceptance corrections. The impact of a spread of $z$ on the acceptance correction is observed to be $8.6 \times 10^{-6} \pm 7.4 \times 10^{-6}$ which is negligible; while the spreads in $x$ and $y$ are even smaller. Therefore, no correction is applied nor systematic uncertainties are assigned to the acceptance correction due to the primary vertex position.

**Efficiency**

The systematic uncertainty on the MS reconstruction efficiency is dominated by the uncertainty of the scale-factor determination. The scale-factor uncertainty is evaluated similarly to Ref. [21] by changing the tag muon selection and varying line-shapes in the efficiency extraction fit procedure in the data. The uncertainty related to the ID reconstruction efficiency is estimated by comparing the results with and without applying the efficiency correction. The systematic uncertainty on the muon trigger efficiency is also dominated by the tag and probe efficiency determination procedure. For Pb+Pb collisions, an additional systematic uncertainty associated with the centrality-dependent correction is included which addresses variations on the correction at different $\eta_{\mu}$ and a small non-closure of the centrality dependence factorization. This uncertainty is evaluated by comparing centrality dependence corrected Pb+Pb efficiency with pp efficiency. The resulting variations on the final $\Upsilon(nS)$ yields due to the MS reconstruction, ID reconstruction and muon trigger systematic variations are combined in quadrature to be assigned as the total systematic uncertainty of the muon efficiency correction.

**Signal extraction**

The uncertainty coming from the selection of a certain fit model is evaluated by varying the line-shape of each component, categorized into three sources. First, for signal resolution, the nominal fit function, CB + G, is replaced by a single CB or triple Gaussian model. Also, the width-scaling constant between CB and Gaussian functions $(f = 1.7)$ is varied up $(2.0)$ and down $(1.5)$. Second, to estimate the uncertainties on the signal FSR tail, the nominal fit function is replaced by a double Gaussian model, or the $\alpha$ parameter of CB is left free which is originally fixed to fit results from MC simulation of $\Upsilon(1S)$ production. Lastly, to vary the background shapes, a fourth-order Chebychev polynomial is used instead of the nominal exponential times error function for low $p_{T}^{\mu\mu}$ bins, and an exponential function is used instead of a second-order polynomial for high $p_{T}^{\mu\mu}$ bins. The maximum variations between the recalculated values and the central value in each source are summed in quadrature to assign the total systematic uncertainty on signal extraction.
**Bin migration**

Given steeply falling $p_T^{\mu\mu}$ spectra, $\Upsilon(nS)$ mesons could migrate from lower to higher $p_T^{\mu\mu}$ bins. The magnitude of bin migration is evaluated by constructing response matrices from signal-only MC for $pp$ and from data-overlay MC samples for Pb+Pb collisions. The deviation of unfolded spectra from raw spectra is observed to be $<1\%$ for $pp$ and $<2\%$ for Pb+Pb collisions in $p_T^{\mu\mu}$. Therefore, no corrections for the bin migration have been applied to the result and the residual effects are considered as a systematic uncertainty. The migration in the $|y^{\mu\mu}|$ bin is observed to be negligible.

**Primary vertex association**

The selected muons and dimuon vertices are required to have tight association with a primary vertex as described in Section 3. To estimate the systematic uncertainty of these requirements, the signal extraction is also performed in the $pp$ and Pb+Pb data after releasing the requirements. The difference in extracted $\Upsilon(1S)$ yields with and without tight association requirements is found to be $2.0\%$ for $pp$ and $3.4\%$ for Pb+Pb collisions and is considered as a systematic uncertainty. The same systematic uncertainty is also applied to excited states.

**Total systematic uncertainties**

Table 3 summarizes each source of the systematic uncertainties on different observables. The dominant source of the systematic uncertainty is the signal extraction. For $\Upsilon(1S)$ mesons, the largest uncertainty is found in $p_T^{\mu\mu} < 2$ GeV where the background shape is sensitive to the muon $p_T^\mu$ requirement of 4 GeV. Without this bin, the uncertainties on the signal extraction for $\Upsilon(1S)$ in Pb+Pb collisions range from 4.4% to 21.3%.

<table>
<thead>
<tr>
<th>Collision type</th>
<th>Sources</th>
<th>$\Upsilon(1S) [%]$</th>
<th>$\Upsilon(nS) [%]$</th>
<th>$\Upsilon(nS)/\Upsilon(1S) [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$ collisions</td>
<td>Luminosity</td>
<td>1.6</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Acceptance</td>
<td>0.3–9.3</td>
<td>0.2–4.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>2.7–7.0</td>
<td>2.8–4.0</td>
<td>0.0–4.1</td>
</tr>
<tr>
<td></td>
<td>Signal extraction</td>
<td>3.2–13.4</td>
<td>5.3–15.0</td>
<td>3.6–12.1</td>
</tr>
<tr>
<td></td>
<td>Bin migration</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Primary vertex association</td>
<td>2.0</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>Pb+Pb collisions</td>
<td>$\langle T_{AA} \rangle$</td>
<td>0.8–8.2</td>
<td>0.8–8.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Acceptance</td>
<td>0.3–9.3</td>
<td>0.2–4.1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>5.0–15.0</td>
<td>2.9–53.2</td>
<td>1.4–53.9</td>
</tr>
<tr>
<td></td>
<td>Signal extraction</td>
<td>4.4–47.1</td>
<td>22.7–73.6</td>
<td>18.7–71.9</td>
</tr>
<tr>
<td></td>
<td>Bin migration</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Primary vertex association</td>
<td>3.4</td>
<td>3.4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: Summary of the sources of systematic uncertainties for each state and excited-to-ground state ratio in $pp$ and Pb+Pb collisions.

The systematic uncertainties on luminosity in $pp$ and $\langle T_{AA} \rangle$ in Pb+Pb collisions are considered uncorrelated between the two systems. The acceptance systematic uncertainties in $pp$ and Pb+Pb collisions are fully correlated because the correction is the same for both collisions. Systematic uncertainties related to the reconstruction efficiency are treated as uncorrelated due to different muon selection criteria in $pp$ and Pb+Pb collisions. The uncertainties of trigger efficiency are also treated as uncorrelated since different
efficiency determination strategies are used in $pp$ and Pb+Pb collisions and the factorization biases originate from different types of trigger correlations.

For the excited-to-ground state ratios ($\Upsilon(nS)/\Upsilon(1S)$) measured in the same data set, uncertainties on luminosity, $\langle T_{AA} \rangle$, and acceptance are totally cancelled. In the case of uncertainties on signal extraction and efficiency, variations on the ratio observable are directly derived instead of estimating variations on each $\Upsilon(nS)$ state. Then, the excited-to-ground state ratios in Pb+Pb and $pp$ data are considered uncorrelated.

Systematic uncertainties arising from luminosity, $\langle T_{AA} \rangle$ (except centrality dependent results) and primary vertex association are fully correlated between bins.

5 Results

The $\Upsilon(nS)$ production cross sections in $pp$ collisions at 5.02 TeV multiplied by the dimuon branching fractions are shown as a function of dimuon $p_T$ on the left panel of Figure 2. For Pb+Pb collisions, per-event yields divided by $\langle T_{AA} \rangle$ are shown on the right panel of Figure 2. The results for $\Upsilon(3S)$ mesons are not shown because of their strong suppression in Pb+Pb collisions. Vertical error bars indicate statistical uncertainties, and the boxes represent systematic uncertainties. Not shown are the correlated systematic uncertainties of 2.6% for luminosity and primary vertex association in $pp$ and 3.7% for $T_{AA}$ and primary vertex association in Pb+Pb collisions, described in Table 3.

Figure 2: Production cross sections of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of $p_T$ in $pp$ (left) and Pb+Pb (right) collisions at 5.02 TeV. The error bars indicate the statistical uncertainties and the boxes represent the systematic uncertainties. Not shown is the correlated systematic uncertainty of 2.6% for luminosity and primary vertex association in $pp$ and 3.7% for $T_{AA}$ and primary vertex association in Pb+Pb collisions.

Figure 3 shows the $R_{AA}$ of $\Upsilon(nS)$ as functions of $N_{\text{part}}$ (top), dimuon $p_T$ (bottom left), and $|y|$ (bottom right). The centrality-integrated results are also shown on the right panel of the top plot. In addition to

$^2$ Dimuon transverse momentum and rapidity are denoted as $p_T$ and $y$ in the rest of the note.
the results for \( \Upsilon(1S) \) and \( \Upsilon(2S) \), the combined results of excited states, \( \Upsilon(2S+3S) \), are presented as \( \Upsilon(3S) \) peaks are barely seen in \( \text{Pb+Pb} \) data. For the top panel, data points for \( \Upsilon(2S+3S) \) are slightly shifted to the right in order to avoid overlap with those for \( \Upsilon(2S) \). The \( \Upsilon(nS) \) states are observed to be suppressed over the whole kinematic range investigated, and the \( R_{AA} \) values of \( \Upsilon(2S) \) and \( \Upsilon(2S+3S) \) are always lower than those of \( \Upsilon(1S) \), which is consistent with the sequential suppression expectation. The \( R_{AA} \) decreases with centrality for all three states. No strong \( p_T \) or \( |y| \) dependence is observed.

Figure 3: The nuclear modification factor \( R_{AA} \) of \( \Upsilon(1S) \), \( \Upsilon(2S) \), and \( \Upsilon(2S+3S) \) as functions of centrality (top), \( p_T \) (bottom left), and \( |y| \) (bottom right) at 5.02 TeV. The error bars indicate the statistical uncertainties and the boxes represent the systematic uncertainties. The grey boxes around \( R_{AA} = 1 \) correspond to the correlated systematic uncertainty. For the top panel, data points for \( \Upsilon(2S+3S) \) are slightly shifted to the right in order to avoid overlap with those for \( \Upsilon(2S) \).

Figure 4 shows the double ratio \( \rho_{AA}^{\Upsilon(nS)/\Upsilon(1S)} \) of \( \Upsilon(2S) \) and \( \Upsilon(2S+3S) \) as functions of \( N_{\text{part}} \) (top), dimuon \( p_T \) (bottom left), and \( |y| \) (bottom right). For the top panel, data points for \( \Upsilon(2S+3S) \) are slightly shifted to the
right in order to avoid overlap with those for $\Upsilon(2S)$. The centrality-integrated results are also shown on the right panel of the top plot. The advantage of measuring the double ratios is that the acceptance and efficiency corrections are partially cancelled, and the systematic uncertainty on the corrections are reduced. The $\rho_{AA}^{\Upsilon(2S)/\Upsilon(1S)}$ values of $\Upsilon(2S)$ and $\Upsilon(2S+3S)$ are always lower than unity, indicating the excited states are more suppressed than the ground state. The centrality-dependent $\rho_{AA}^{\Upsilon(2S)/\Upsilon(1S)}$ shows a slightly decreasing trend, but is also consistent with a flat behavior within uncertainties. No strong $p_T$ or $|y|$ dependence is observed.

Figure 4: The double ratio $\rho_{AA}^{\Upsilon(2S)/\Upsilon(1S)}$ of $\Upsilon(2S)$ and $\Upsilon(2S+3S)$ as functions of centrality (top), $p_T$ (bottom left), and $|y|$ (bottom right) at 5.02 TeV. The error bars indicate the statistical uncertainties and the boxes represent the systematic uncertainties. For the top panel, data points for $\Upsilon(2S+3S)$ are slightly shifted to the right in order to avoid overlap with those for $\Upsilon(2S)$.

Production cross sections of $\Upsilon(1S)$ and $\Upsilon(2S)$ in $pp$ and Pb+Pb collisions are compared in Figure 5 to the CMS results at the same collision energy [37]. The CMS results are obtained in $p_T < 30$ GeV, $|y| < 2.4$, and $|y| < 2$. The acceptance and efficiency corrections are partially cancelled, and the systematic uncertainty on the corrections are reduced.
and centrality 0-100%. Both experiments are in good agreement in \(pp\) collisions, while the CMS results are systematically higher in \(Pb+Pb\) collisions. Figures 6 and 7 show the comparison of \(R_{AA}\) results for \(\Upsilon'(1S)\) and \(\Upsilon'(2S)\), respectively. The CMS results are higher as expected from cross-section results, but both measurements are consistent within uncertainties. It is worth noting that the kinematic ranges and the centrality intervals are different between the two experiments. In Figure 8, the \(p_T^{\Upsilon(nS)/\Upsilon'(1S)}\) results of \(\Upsilon'(2S)\) and \(\Upsilon'(2S+3S)\) are also compared to the CMS results at the same collision energy [38]. The results from both experiments are observed to agree well with each other.

Figure 9 shows the comparison of \(R_{AA}\) of \(\Upsilon'(1S)\) and \(\Upsilon'(2S)\) to the theoretical model prediction by Krouppa and Strickland [10]. The model includes the effect of in-medium dissociation of \(\Upsilon(nS)\), as well as taking into account the late-time feed-down of heavier states, and it uses an anisotropic viscous hydrodynamics background. The presented calculations are made for \(p_T < 40\) GeV, \(|y| < 2.4\) and centrality 0-100%, with three different shear viscosity-to-entropy density ratios, \(4\pi\eta/s = 1, 2, 3\). The measured \(\Upsilon'(1S)\) and \(\Upsilon'(2S)\) \(R_{AA}\) are consistent with the model which predicts sequential suppression due to different dissociation temperatures for the two states. The resulting \(\Upsilon'(1S)\) and \(\Upsilon'(2S)\) \(R_{AA}\) measurements seem to prefer the calculations with \(4\pi\eta/s = 1\), but it is difficult to draw a firm conclusion with the present experimental uncertainties and also due to differences in the centrality and kinematic requirements.

In Figure 10, the \(\Upsilon'(1S)\) \(R_{AA}\) is compared to those of prompt and nonprompt \(J/\psi\) mesons from the previous ATLAS measurement [33]. The resulting \(\Upsilon'(1S)\) \(R_{AA}\) is found to be comparable with prompt \(J/\psi\) \(R_{AA}\) for \(9 < p_T < 30\) GeV, although \(\Upsilon'(1S)\) meson is more tightly bound and expected to be less suppressed than \(J/\psi\) meson according to the sequential suppression scenario. Unlike the clear binding-energy dependence observed in the suppression of three \(\Upsilon(nS)\) states, there might be other effects that affect the production yields of charmonia and bottomonia differently, such as a different amount of regeneration, feed-down fractions, etc. Nonprompt \(J/\psi\) \(R_{AA}\), on the other hand, reflects the suppression of \(b\)-hadron that is driven by a different mechanism from the suppression of quarkonia, e.g., parton energy loss in the medium.
Figure 6: The nuclear modification factor $R_{AA}$ of $\Upsilon(1S)$ as functions of centrality (top), $p_T$ (bottom left), and $|y|$ (bottom right) at 5.02 TeV compared to the CMS results [37].
Figure 7: The nuclear modification factor $R_{AA}$ of $\Upsilon(2S)$ as functions of centrality (top), $p_T$ (bottom left), and $|y|$ (bottom right) at 5.02 TeV compared to the CMS results [37].
Figure 8: The double ratio $\rho_{AA}^{1S}/\rho_{AA}^{(nS)}$ of $\Upsilon(2S)$ as functions of centrality (top), $p_T$ (bottom left), and $|y|$ (bottom right) at 5.02 TeV compared to the CMS results [38].
Figure 9: The nuclear modification factor $R_{AA}$ of $\Upsilon(1S)$ and $\Upsilon(2S)$ as functions of centrality (top), $p_T$ (bottom left), and $|y|$ (bottom right) at 5.02 TeV compared to the theoretical calculations with different shear viscosity-to-entropy density ratios from Krouppa and Strickland [10]. The grey boxes around $R_{AA} = 1$ correspond to the correlated experimental systematic uncertainty.
Figure 10: The nuclear modification factor $R_{AA}$ of $\Upsilon(1S)$ as a function of $p_T$ compared to $R_{AA}$ of prompt and nonprompt $J/\psi$ from the previous ATLAS measurement at the same collision energy [33]. The grey and violet boxes around $R_{AA} = 1$ correspond to the correlated systematic uncertainties for $\Upsilon(1S)$ and $J/\psi$ results, respectively.
6 Conclusion

In summary, a measurement of \( \Upsilon(nS) \) yields for \( n = 1, 2, \) and \( 3 \) in \( pp \) and Pb+Pb data at 5.02 TeV per nucleon-nucleon collision is presented. The measurement uses datasets of \( pp \) collisions collected in 2017 with a total integrated luminosity of 0.26 fb\(^{-1}\) and Pb+Pb collisions collected in 2018 with a total integrated luminosity of 1.38 nb\(^{-1}\) recorded by the ATLAS experiment at the LHC. The \( pp \) and Pb+Pb measurements are combined to obtain the nuclear modification factor of \( \Upsilon(1S) \) and \( \Upsilon(2S) \), and \( \Upsilon(2S) \) to \( \Upsilon(1S) \) double ratio as functions of transverse momentum, rapidity, and centrality. Both \( \Upsilon(1S) \) and \( \Upsilon(2S) \) yields are suppressed with increasing centrality in Pb+Pb compared to those in \( pp \) collisions, and the excited state shows stronger suppression of yields than the ground state resulting in double ratios smaller than unity. The measured nuclear modification factor and double ratio are found to be consistent with the previous CMS measurements and theoretical model predictions. A constraint on \( \Upsilon(3S) \) yields in Pb+Pb collision is provided via a combined measurement of the nuclear modification factor and the double ratio of \( \Upsilon(2S + 3S) \).

References


