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# Indications of Suppression of Excited $\Upsilon$ States in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

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A comparison of the relative yields of $\Upsilon$ resonances in the $\mu^+\mu^-$ decay channel in Pb-Pb and $pp$ collisions at a center-of-mass energy per nucleon pair of 2.76 TeV is performed with data collected with the CMS detector at the LHC. Using muons of transverse momentum above 4 GeV/$c$ and pseudorapidity below 2.4, the double ratio of the $\Upsilon(2S)$ and $\Upsilon(3S)$ excited states to the $\Upsilon(1S)$ ground state in Pb-Pb and $pp$ collisions, $[\Upsilon(2S+3S)/\Upsilon(1S)]_{\text{Pb-Pb}}/[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}$, is found to be $0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst})$. The probability to obtain the measured value, or lower, if the true double ratio is unity, is calculated to be less than 1%.

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Quantum chromodynamics (QCD) predicts that strongly interacting matter undergoes a phase transition to a deconfined state, often referred to as the quark-gluon plasma (QGP), in which quarks and gluons are no longer bound within hadrons. Calculations in lattice QCD [1,2] indicate that the transition should occur at a critical temperature $T_c \simeq 150$–175 MeV, corresponding to an energy density $\varepsilon_c \simeq 1$ GeV/fm$^3$.

If the QGP is formed in heavy-ion collisions, it is expected to screen the confining potential of heavy quark-antiquark pairs [3], leading to the melting of charmonia ($J/\psi$, $\psi'$, $\chi_c \ldots$) and bottomonia ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b \ldots$). The melting temperature depends on the binding energy of the quarkonium state. The ground states $J/\psi$, and $\Upsilon(1S)$, are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. Quenched lattice QCD calculations [4,5] predict that the $\Upsilon(nS)$ states melt at 1.2 $T_c$ ($3S$), 1.6 $T_c$ ($2S$), and above 4 $T_c$ ($1S$), while modern spectral-function approaches with complex potentials [6,7] favor somewhat lower dissolution temperatures. This sequential melting pattern is generally considered a "smoking-gun" signature of the QCD deconfinement transition. However, a large fraction of the observed $\Upsilon(1S)$ yield is due to decays of heavier states (around 50% for the $\Upsilon(1S)$ [8]). Therefore the melting of the excited states is expected to result in a significant suppression of the observed $\Upsilon(1S)$ yield, even if the medium is not hot enough to directly dissolve it.

Observations of a larger $J/\psi$ and $\psi(2S)$ suppression in heavy-ion collisions with respect to proton-nucleus collisions were reported by the NA38 [9], NA50 [10,11], and NA60 [12] fixed-target experiments at the Super Proton Synchrotron (SPS), respectively, in sulfur-uranium, lead-lead, and indium-indium collisions, at center-of-mass energies per nucleon pair ($\sqrt{s_{\mathrm{NN}}}$) of about 20 GeV. The PHENIX experiment, at the Relativistic Heavy Ion Collider (RHIC), extended the $J/\psi$ suppression measurements to Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [13]. Recent results from ATLAS and CMS show $J/\psi$ suppression at LHC [14,15]. At RHIC, bottomonia production becomes measurable [16], though with limited integrated luminosities. PHENIX observed that the dimuon yield in the $\Upsilon$ mass region for minimum bias Au-Au collisions is less than 64%, at the 90% confidence level, of the value expected by extrapolating the proton-proton yields [17].

A new era of detailed studies of the bottomonium family in heavy-ion collisions has started at the Large Hadron Collider (LHC). The measurement reported in this Letter is performed with data recorded by the Compact Muon Solenoid (CMS) experiment during the first lead-lead (Pb-Pb) LHC run, at the end of 2010, and during the proton-proton ($pp$) run of March 2011, both at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The integrated luminosity used in this analysis corresponds to 7.28 $\mu$b$^{-1}$ for Pb-Pb and 225 nb$^{-1}$ for $pp$ collisions, the latter corresponding approximately to the equivalent nucleon-nucleon luminosity of the Pb-Pb run. The momentum resolution of the CMS detector results in well-resolved $\Upsilon$ peaks in the dimuon mass spectrum. The CMS Collaboration has previously studied $\Upsilon$ production in $pp$ data at $\sqrt{s} = 7$ TeV [18], using techniques to extract the $\Upsilon$ yields that are very similar to the ones used in the study reported in this Letter.

A detailed description of the CMS detector can be found in [19]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon (Si) pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition, CMS has extensive

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forward calorimetry, in particular, two steel or quartz-fiber Čerenkov hadron forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < |\eta| < 5.2$.

In this analysis, $\Upsilon$ states are identified through their dimuon decay. The silicon pixel and strip tracker measures charged-particle trajectories in the range $|\eta| < 2.5$. The tracker consists of 66 M pixel and 10 M strip detector channels, providing a vertex resolution of $\sim 15\ \mu$m in the transverse plane. Muons are detected in the $|\eta| < 2.4$ range, with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Because of the strong magnetic field and the fine granularity of the Si tracker, the muon transverse momentum measurement ($p_T$) based on information from the Si tracker alone has a resolution between 1% and 2% for a typical muon in this analysis.

In both the Pb-Pb and $pp$ runs, the events are selected by the CMS two-level trigger. At the first, hardware level, two independent muon candidates are required in the muon detectors. No selection is made on momentum or pseudorapidity, but in the $pp$ case more stringent quality requirements are imposed for each muon in order to reduce the higher trigger rate. In both cases, the software-based higher-level trigger accepts the lower-level decision without applying further criteria. The single-muon trigger efficiencies are measured from reconstructed $J/\psi \rightarrow \mu\mu$ decays, for muons with $p_T > 4$ GeV/$c$. The values of these efficiencies, $(96.1 \pm 1.0)\%$ in the Pb-Pb data set and $(95.5 \pm 0.6)\%$ in the $pp$ data set, are consistent.

For the Pb-Pb data, events are preselected offline if they contain a reconstructed primary vertex made of at least two tracks, and a coincidence in both HF calorimeters of energy deposits larger than 3 GeV in at least three towers. These criteria reduce contributions from single-beam interactions (e.g., beam-gas and beam-halo collisions with the beam pipe), ultraperipheral electromagnetic collisions, and cosmic-ray muons. A small fraction of the most peripheral Pb-Pb collisions is not selected by these requirements, which accept $(97 \pm 3)\%$ of the hadronic inelastic cross section [20]. For the $pp$ run, a similar event filter is applied, relaxing the HF coincidence to one tower in each HF, with at least 3 GeV deposited. This filter removes only 1% of the $pp$ events satisfying the dimuon trigger.

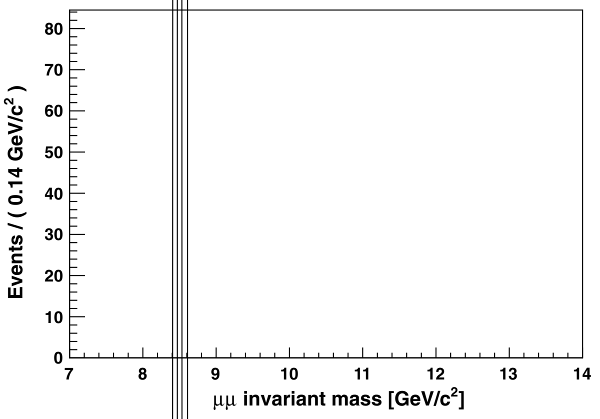
The muon offline reconstruction is seeded with $\simeq 99\%$ efficiency by tracks in the muon detectors, called standalone muons. These tracks are then matched to tracks reconstructed in the Si tracker by means of an algorithm optimized for the heavy-ion environment [21,22]. For muons from $\Upsilon$ decays the Si-tracking efficiency is $\simeq 85\%$. This efficiency is lower than in $pp$, as in Pb-Pb the Si-track reconstruction is seeded by a greater number of pixel hits to reduce the large number of random combinations arising from the high multiplicity of each event. Combined fits of the muon and Si-tracker tracks are used to obtain the results presented in this Letter. The heavy-ion dedicated reconstruction algorithm is applied to the $pp$ data in order to avoid potential biases.

Identical, very-loose selection criteria are applied to the muons in the $pp$ and Pb-Pb data. Their transverse (longitudinal) distance of closest approach from the event vertex is required to be less than 3 (15) cm. Tracks are only kept if they have 11 or more hits in the silicon tracker and the $\chi^2$ per degree of freedom of the combined (tracker) track fit is lower than 20 (4). The two muon trajectories are fit with a common vertex constraint, and events are retained if the fit $\chi^2$ probability is larger than 1%. This removes background arising primarily from the displaced, semileptonic decays of charm and bottom hadrons. As determined from Monte Carlo simulation of the $\Upsilon(1S)$ signal, these selection criteria are found to reduce the efficiency by 3.9%, which is consistent with the signal loss observed in both $pp$ and Pb-Pb data. The available event sample limits to 20 GeV/$c$ the dimuon transverse momentum range probed in this study.

Only muons with a transverse momentum ($p_T^\mu$) higher than 4 GeV/$c$ are considered, resulting in a $\Upsilon$ acceptance of approximately 25% for the $|y^\Upsilon| < 2.4$ rapidity range. This requirement optimizes the significance of the $\Upsilon(1S)$ signal in Pb-Pb data and is applied to both data sets. The acceptance of a $\Upsilon$ state depends on its mass, since the excited states give rise to higher-momenta muons. In consequence, requiring higher $p_T^\mu$ increases the acceptance for the excited states relative to the ground state. In the corresponding analysis performed with the higher statistics ($3.1\ \mathrm{pb}^{-1}$) 7 TeV data [18], looser criteria were applied ($p_T^\mu > 3.5$ GeV/$c$ and $|\eta^\mu| < 1.6$, or $p_T^\mu > 2.5$ GeV/$c$ and $1.6 < |\eta^\mu| < 2.4$), where $\eta^\mu$ is the muon pseudorapidity. The stricter ($p_T^\mu > 4$ GeV/$c$) requirements used here enhance the $\Upsilon(2S+3S)/\Upsilon(1S)$ yield ratio by $\simeq 60\%$ in the $pp$ data at 2.76 TeV. It was checked that, applying identical $pp$ reconstruction algorithms and $p_T^\mu$ requirements, the $\Upsilon(2S+3S)/\Upsilon(1S)$ yield ratio is consistent, within statistical uncertainties, between the 2.76 and 7 TeV $pp$ data sets [15].

The dimuon invariant-mass spectra with the selection criteria applied are shown in Fig. 1 for the $pp$ and Pb-Pb data sets. Within the 7–14 GeV/$c^2$ mass range, there are 561 (628) opposite-sign muon pairs in the $pp$ (Pb-Pb) data set. The three $Y$ peaks are clearly observed in the $pp$ case, but the $\Upsilon(2S)$ and $\Upsilon(3S)$ are not visible over the residual background in Pb-Pb collisions.

An extended unbinned maximum likelihood fit to the two invariant-mass distributions of Fig. 1 is performed to extract the yields, following the method described in [18]. The measured mass line shape of each $\Upsilon$ state is parametrized by a "crystal ball" (CB) function, i.e., a Gaussian resolution function with the lowside tail replaced by a power law describing final-state radiation (FSR). Since the three $\Upsilon$ resonances partially overlap in the measured dimuon mass, they are fit simultaneously. Therefore, the



probability distribution f ction ( [redacted] signal consists of thre three Υ($nS$) yields, t ma left free, to accom possible scale calibratio ass ratios be fixed to thei average values [2 resolution to scale with the re The Υ(1 tion is fixed to the value the si , 92 MeV/$c^2$, which is compatible res tained from both the Pb-Pb and $pp$ data. l parameters are also fixed to the values obtaine mulation. Finally, a second-order polynomial is en to describe the background in the 7–14 GeV/$c^2$ ass-fit range.

The quality of the unbinned fit is checked *a posteriori* by comparing the obtained line shapes to the binned data of Fig. 1. The $\chi^2$ probabilities are 74% and 77%, respectively, for $pp$ and Pb-Pb.

The ratios of the observed (uncorrected) yields of the Υ(2$S$) and Υ(3$S$) excited states to the Υ(1$S$) ground state in the $pp$ and Pb-Pb data are

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02, \qquad (1)$$

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{Pb-Pb}} = 0.24^{+0.13}_{-0.12} \pm 0.02,$$

where the first uncertainty is statistical and the se systematic.

The systematic uncertainties are computed [redacted] the line shape in the following ways: ( parameters are varied randomly accordi ance matrix and within conservative perfect knowledge of the amount o FSR in the underlying process; (2 by ±5 MeV/$c^2$, which is a c the current understanding and reasonable changes Υ-resonance kinemati (3) the background linear while the to 8–12 GeV/ results is tak sum of the uncertai ($pp$)

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Pb- bedding, decays simu simulated with HY as the number of hits a similar distributions in data and s above, the trigger efficiency is evaluat using single-muon-triggered data events, and reco ting $J/\psi$ signal with and without the dimuon trigger requirement. The same exercise is carried out with the simulation and it agrees with the efficiency measured in data at the 2% level. The track efficiency in the silicon detector is measured with standalone muons, applying all selection criteria. The efficiencies in data and simulation agree within the 4% statistical uncertainty of the efficiency determined from data.

The difference in reconstruction and selection efficiencies between the $\Upsilon$ states is less than 5% and the relative variation with charged-particle multiplicity is about 10% from $pp$ to central Pb-Pb collisions, producing a maximum change of 0.5% on the double ratio. The good agreement between single-muon trigger efficiencies extracted from data for the $pp$ and Pb-Pb trigger requirements, applied to the $\Upsilon(1S)$ and $\Upsilon(2S)$ trigger efficiencies derived from simulation, leads to a negligible effect on the double ratio. The single-muon trigger efficiencies extracted from data agree within 1.5% for the $pp$ and Pb-Pb trigger requirements, and the $\Upsilon(1S)$ and $\Upsilon(2S)$ trigger efficiencies agree within 3%, according to simulation: the potential trigger bias on the double ratio is negligible. Even doubling the size of these variations, to take the $\Upsilon(3S)$ into account, leads to a negligible change in the double ratio. The magnitudes of the statistical and systematic uncertainties on the double ratio, respectively, 55% and 9%, are significantly larger than the systematic uncertainties associated with possible imperfect cancellation of acceptance and efficiency effects. Therefore no additional uncertainty from these sources is applied.

Finally, using an ensemble of $1 \times 10^6$ pseudoexperiments, generated with the signal line shape obtained from the $pp$ data [Fig. 1(a)], the background line shapes from both data sets, and a double ratio [Eq. (3)] equal to unity within statistical and systematic uncertainties, the probability of finding the measured value of 0.31 or below is estimated to be 0.9%. In other words, in the absence of a suppression due to physics mechanisms, the probability of a downward departure of the ratio from unity of this significance or greater is 0.9%, i.e., that corresponding to 2.4 sigma in a one-tailed integral of a Gaussian distribution.

Other studies from the CMS experiment show that the $\Upsilon(1S)$ is suppressed by about 40% [15] in minimum bias Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. Since a large fraction of the $\Upsilon(1S)$ yield arises from decays of heavier bottomonium states [8], this $\Upsilon(1S)$ suppression could be indirectly caused by the suppression of the excited states reported in this Letter.

Production yields of quarkonium states can also be modified, from $pp$ to Pb-Pb collisions, in the absence of QGP formation, by cold nuclear matter effects [27]. However, such effects should have a small impact on the $\Upsilon$ double ratio reported here. The nuclear modifications of the parton distribution functions (shadowing) should have an equivalent effect on the three $\Upsilon$ states, because their production involves very similar partons, canceling in the ratio, at least to first order. The same should happen to any other initial-state nuclear effect. In principle, the larger and more loosely bound excited quarkonium states are more likely to be broken up by final-state interactions while traversing the nuclear matter, something extensively studied in the context of charmonium suppression at lower energies [28]. This ''nuclear absorption'' becomes weaker with increasing energy, and should be negligible at the LHC. At RHIC energies, the STAR experiment [29] has reported a $\Upsilon(1S + 2S + 3S)$ yield in $d$-Au collisions of $0.78 \pm 0.28 \pm 0.20$ times the yield expected by scaling $pp$ collisions, compatible with the absence of absorption. Furthermore, the double ratio presented here would only be sensitive to a difference between the nuclear dependencies of the three states and already at much lower energies the Fermilab E772 experiment observed [30], in proton-nucleus collisions, no such difference, within uncertainties, between the $\Upsilon(1S)$ and the sum $\Upsilon(2S + 3S)$.

Future high-statistics heavy-ion and proton-nucleus runs at the LHC will provide further quarkonia measurements, which should help disentangle nuclear from medium effects and aid the interpretation of the result reported in this Letter.

In summary, a comparison of the relative yields of $\Upsilon$ resonances has been performed in Pb-Pb and $pp$ collisions at the same center-of-mass energy per nucleon pair of 2.76 TeV. The double ratio of the $\Upsilon(2S)$ and $\Upsilon(3S)$ excited states to the $\Upsilon(1S)$ ground state in Pb-Pb and $pp$ collisions, $[\Upsilon(2S+3S)/\Upsilon(1S)]_{\text{Pb-Pb}}/[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}$, is found to be $0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst})$, for muons of $p_T > 4$ GeV$/c$ and $|\eta| < 2.4$. The probability to obtain the measured value, or lower, if the true double ratio is unity, has been calculated to be less than 1%.

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