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Observation of sequential Υ suppression in PbPb collisions

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Observation of sequential Υ suppression in PbPb collisions

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Abstract. The sequential suppression of the individual Υ states in PbPb collisions with respect to their yields in *pp* data has been measured. The PbPb and *pp* datasets used in these proceedings correspond to integrated luminosities of 150/μb and 230/nb, respectively, collected by the CMS experiment at the LHC at 2.76 TeV in 2011. The relative suppression of the excited Υ states has been measured with respect to the Υ(1S) ground state, expressed as a double ratio $[\Upsilon(\mathrm{nS})/\Upsilon(\mathrm{1S})]_{\mathrm{PbPb}}/[\Upsilon(\mathrm{nS})/\Upsilon(\mathrm{1S})]_{pp}$. The absolute suppression of the Υ(nS) yields in PbPb relative to the yields in *pp* scaled by the number of nucleon-nucleon collisions, R_{AA}, is measured as a function of the collision centrality. Integrated over centrality, the R_{AA} values for Υ(1S), Υ(2S), and the upper limit of Υ(3S) R_{AA} are reported in this proceeding, which demonstrate the sequential suppression of the Υ(nS) states in PbPb collisions at LHC energies.

1. Introduction

The LHC allows for the detailed studies of the heavy quarkonium states in ultra-relativistic heavy-ion collisions. Suppression of heavy quarkonium states has been proposed as a probe of the properties of the hot and dense medium created in high-energy heavy-ion collisions [1]. 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. If the QGP is formed in heavy-ion collisions, it is expected to screen the confining potential of heavy quark-antiquark pairs [1], leading to the melting of charmonium and bottomonium states: J/ψ, $\psi(2S)$, χ_c, Υ(1S), Υ(2S), Υ(3S), χ_b, etc. The melting temperature depends on the binding energy of the quarkonium state. The ground states, J/ψ and Υ(1S), are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. Quenched lattice QCD calculations [2][3] originally predicted that the Υ 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 [4] favor somewhat lower dissolution temperatures. This sequential melting pattern is generally considered a smoking-gun signature of the QCD deconfinement transition. Given the mass resolution achieved, the CMS detector suits these measurements well.

The indication of the Υ excited states suppression at the LHC was published in [5] in 2011 with the first 7.28/μb PbPb data at $\sqrt{s_{NN}} = 2.76$ TeV. In these proceedings, we report a follow up study revealing the observation of sequential Υ suppression with full 150/μb PbPb data collected in 2011 by the CMS experiment [6].

2. Signal extraction

A detailed description of the CMS detector can be found in [7]. The trigger conditions, offline event selection, and muon reconstruction criteria are discussed in [6]. The same offline reconstruction algorithm and selection criteria are applied to the PbPb and *pp* data samples. In order to reduce the background in the Υ mass region, only muons with a transverse momentum (p_T^μ) higher than 4 GeV/c are considered [5].

An extended unbinned maximum likelihood fit is performed to extract the signal yields, following the method described in [6][8]. The measured mass line shape of each Υ state is parametrized by a Crystal Ball (CB) function, i.e. a Gaussian resolution function with the low-side tail replaced by a power law describing final state radiation (FSR). The mass differences between the states are fixed to their world average values [9] and the mass resolution is forced to scale with the resonance mass. The signal shape parameters are treated as common for both PbPb and *pp* data sets via a simultaneous fit. The background model for the *pp* data set consists of a second-order polynomial, as was used in Ref. [5]. The larger PbPb data set requires a more detailed background model, so an exponential function multiplied by an error function is used to describe its low-mass turn-on effect due to the p_T^μ selection threshold.

The dimuon invariant mass spectra are shown in Fig. 1 for PbPb and in Fig. 2 for *pp*. The solid (signal + background) and dashed (background-only) curves show the simultaneous fit to the two data sets. The three Υ peaks are clearly observed in the *pp* case, but the Υ(3S) peak is not visible over the residual background in PbPb collisions.

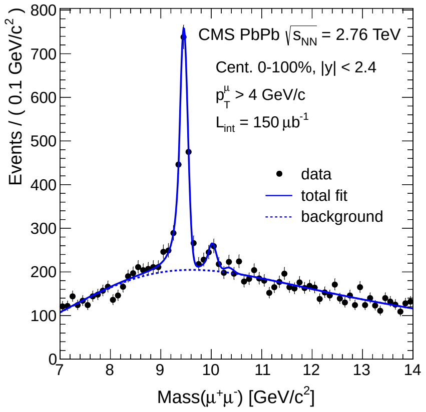

Figure 1. Dimuon invariant-mass distributions in PbPb data at $\sqrt{s_{NN}} = 2.76$ TeV.

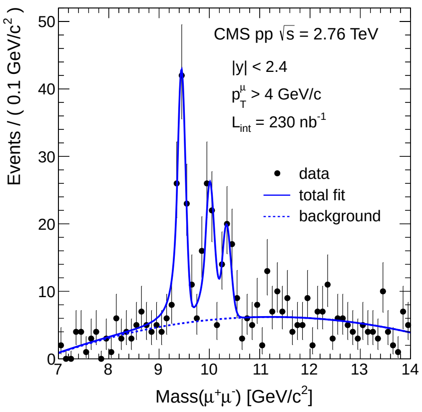

Figure 2. Dimuon invariant-mass distributions in *pp* data at $\sqrt{s} = 2.76$ TeV.

3. Relative suppression of excited Υ states in PbPb collisions

The simultaneous fit to the PbPb and *pp* mass spectra gives the ratio of the Υ(nS)/Υ(1S) ratios in PbPb and *pp* collisions:

$$\begin{aligned}
[\Upsilon(2S)/\Upsilon(1S)]_{\mathrm{PbPb}} \,/\, [\Upsilon(2S)/\Upsilon(1S)]_{pp} &= 0.21 \pm 0.07\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})\,, \\
[\Upsilon(3S)/\Upsilon(1S)]_{\mathrm{PbPb}} \,/\, [\Upsilon(3S)/\Upsilon(1S)]_{pp} &= 0.06 \pm 0.06\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \\
&< 0.17\ (95\%\ \mathrm{CL})\,. \qquad (1)
\end{aligned}$$

This double ratio measurement benefits from an almost complete cancellation of possible efficiency and acceptance differences among the reconstructed resonances. The systematic uncertainties from the fitting procedure are evaluated by varying the fit function. An additional systematic uncertainty (1%), estimated from MC simulation, is included to account for possible imperfect cancellations of efficiency and acceptance.

The double ratios, defined in Eq. (1), are expected to be compatible with unity if there is no suppression of the excited Υ states relative to the $\Upsilon(1S)$ state. Instead, the measured values are considerably smaller than unity. The significance of the observed suppression exceeds $5\,\sigma$.

In order to investigate the dependence of the suppression on the centrality, the double ratio is displayed as a function of N_{part} in Fig. 3. The results are constructed from the single ratio $[\Upsilon(2S)/\Upsilon(1S)]_{\text{PbPb}}$ measured in bins of PbPb centrality, using the *pp* ratio as normalization. The dependence on centrality is not pronounced. More data, in particular more *pp* collisions, are needed to further establish possible dependences on centrality and kinematic variables.

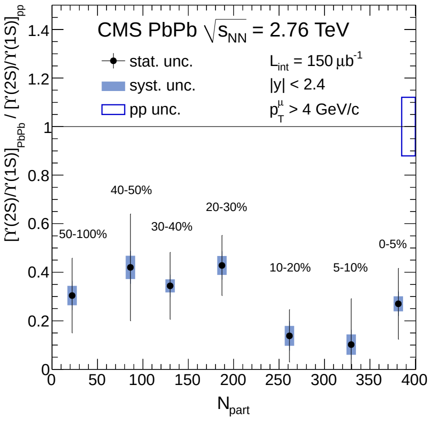

Figure 3. Centrality dependence of the double ratio. The relative uncertainties from N_{part}-independent quantities are represented by the box at unity, and are not included in the data points as these uncertainties do not affect the point-to-point trend. The event centrality bins used are indicated by percentage intervals.

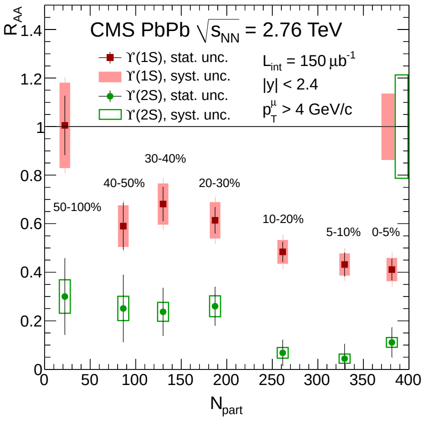

Figure 4. Centrality dependence of the nuclear modification factors for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states. The two relative uncertainties from N_{part}-independent quantities (*pp* yields, efficiency and integrated luminosity) are represented by the boxes at unity. These common uncertainties are not included in the data points.

4. Absolute suppression of the Υ(nS) states in PbPb collisions

Absolute suppressions of the individual Υ states and their dependence on the collision centrality are studied using the nuclear modification factor, R_{AA}, defined as the yield per nucleon-nucleon collision in PbPb relative to that in *pp* [6].

The centrality-integrated (0–100%) R_{AA} values for the three individual Υ states are:

$$\begin{aligned} R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})\,, \\ R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})\,, \\ R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \\ & < 0.10\ (95\%\ \text{CL})\,. \end{aligned} \tag{2}$$

The centrality dependences of the $\Upsilon(1S)$ and $\Upsilon(2S)$ R_{AA} are obtained by performing the measurement in ranges of centrality, as displayed in Fig. 4. The results indicate a significant suppression of the Υ(nS) states in heavy-ion collisions compared to *pp* collisions at the same per-nucleon-pair energy. The data support the hypothesis of increased suppression of less strongly bound states: the Υ(1S) is the least suppressed and the Υ(3S) is the most suppressed of the three states. The Υ(1S) and Υ(2S) suppressions are observed to increase with collision centrality. The observed Υ(nS) yields contain contributions from heavier bottomonium states decays. As a result, the measured suppression is affected by the dissociation of these states. The detailed discussion about the feed-down contribution is in [6]. These results indicate that the directly produced Υ(1S) state is not significantly suppressed, however quantitative conclusions will require precise estimations of the feed-down contribution matching the phase space of the suppression measurement. In addition to QGP formation, cold-nuclear-matter effects can also lead to the differences between quarkonium production yields in PbPb and *pp* collisions [10]. More discussion can be found in [6]. The comparisons to two theoretical models are shown in Fig. 5 and Fig. 6.

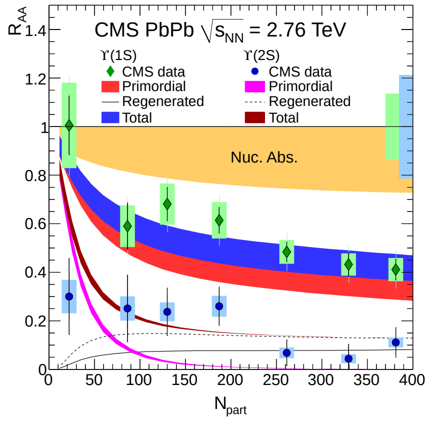

Figure 5. Strong-binding scenario (SBS) prediction, produced using the calculations performed in the paper [11], based upon the approach developed in [12].

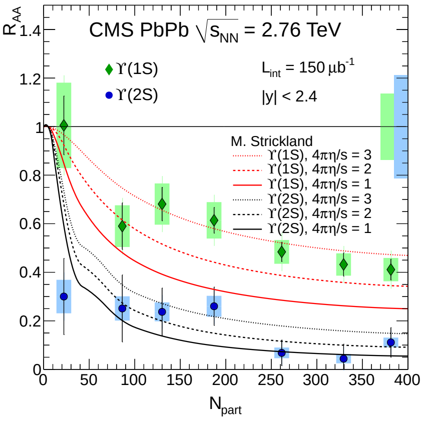

Figure 6. Comparison of the Υ(1S) and Υ(2S) nuclear modification factor R_{AA} centrality dependence result to theory prediction by M. Strickland [13][14].

In conclusion, the nuclear modification factors for the Υ(nS) states have been measured in this analysis. The observation of sequential suppression of the Υ(nS) states in heavy-ion collisions is reported in these proceedings.

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