The Compact Muon Solenoid Experiment

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Bottomonium production measured in PbPb and pp collisions by CMS

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Abstract

The LHC centre-of-mass energy allows copious Υ production in PbPb collisions. Detailed measurements of bottomonium production will help characterize the dense matter produced in heavy-ion collisions. The full spectroscopy of quarkonium states has been suggested as a possible thermometer for the QGP. CMS is well suited to measure Υ decays to muons given the muon identification and charged particle tracking capability. Using muons of transverse momentum above 4 GeV/c and pseudorapidity below 2.4, the double ratio of the $\Upsilon(2S + 3S)$ excited states to the $\Upsilon(1S)$ ground state in PbPb and pp collisions, $[\Upsilon(2S + 3S)/\Upsilon(1S)]_{\text{PbPb}}/[\Upsilon(2S + 3S)/\Upsilon(1S)]_{\text{pp}}$, 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%. $\Upsilon(1S)$ suppression in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV is also presented in this proceeding.

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A First Comparison of Υ production in PbPb and pp collisions at the LHC

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Abstract. The LHC centre-of-mass energy allows copious Υ production in PbPb collisions. Detailed measurements of bottomonium production will help characterize the dense matter produced in heavy-ion collisions. The full spectroscopy of quarkonium states has been suggested as a possible thermometer for the QGP. CMS is well suited to measure Υ decays to muons given the muon identification and charged particle tracking capability. Using muons of transverse momentum above 4 GeV/ c and pseudorapidity below 2.4, the double ratio of the $\Upsilon(2S+3S)$ excited states to the $\Upsilon(1S)$ ground state in PbPb and pp collisions, $[\Upsilon(2S+3S)/\Upsilon(1S)]_{\text{PbPb}}/[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}$, 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%. $\Upsilon(1S)$ suppression in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV is also presented in this proceeding.

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] indicate that the transition should occur at a critical temperature $T_c \sim 175$ MeV, corresponding to an energy density $\epsilon_c \sim 1$ GeV/fm³. If the QGP is formed in heavy-ion collisions, it is expected to screen the confining potential of heavy quark-antiquark pairs [2], leading to the melting of charmonium and bottomonium states: J/ψ , $\psi(2S)$, χ_c , $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b , etc. The melting temperature depends on the binding energy of the quarkonium state. The ground states, J/ψ and $\Upsilon(1S)$, are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. Quenched lattice QCD calculations [3, 4] 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 [5] favour somewhat lower dissolution temperatures. This sequential melting pattern is generally considered a smoking-gun signature of the QCD deconfinement transition.

This analysis presents the first measurements of the $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ mesons via their decay into $\mu^+\mu^-$ pairs in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Differential cross sections and nuclear modification factors for $\Upsilon(1S)$ are reported in bins of rapidity, p_T and centrality of the collision [6]. The $\Upsilon(2S+3S)/\Upsilon(1S)$ ratio of PbPb relative to pp is quantified [7].

A detailed description of the CMS detector can be found in [8]. The trigger conditions, offline event selection, and muon reconstruction criteria are discussed in [7]. 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. An extended unbinned maximum likelihood fit is performed to extract the signal yields, following the method described in [9]. The measured mass lineshape of each Υ state is parameterised 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). In addition to the three $\Upsilon(nS)$ yields, the $\Upsilon(1S)$ mass is the only parameter left free, to accommodate a possible bias in the momentum scale calibration. The mass ratios between the states are fixed to their world average values [10] and the mass resolution is forced to scale with the resonance mass. The $\Upsilon(1S)$ resolution is fixed to the value estimated in the simulation, 92 MeV/ c^2 , which is compatible with the resolution obtained from both the PbPb and pp data. The low-side tail parameters are also fixed to the values obtained via simulation. Finally, a second-order polynomial is chosen to describe the background in the 7–14 GeV/ c^2 mass-fit range. The dimuon invariant mass spectra are shown in Fig. 1 for the pp (left) and PbPb (right) data sets. The three Υ peaks are clearly observed in the pp case, but the $\Upsilon(2S)$ and $\Upsilon(3S)$ are not visible over the residual background in PbPb collisions.

Figure 1: Invariant mass spectrum of $\mu^+\mu^-$ pairs (solid black circles) with $p_T < 20$ GeV/ c and $|y| < 2.4$ in minimum bias collisions, for muons above 4 GeV/ c , for the pp(left) and PbPb(right) data sets.

The differential cross sections are reported in the form:

$$\frac{1}{T_{AA}} \cdot \frac{d^2 N}{dp_T dy} = \frac{1}{T_{AA}} \cdot \frac{1}{\Delta y \Delta p_T} \cdot \frac{N_\Upsilon}{\alpha \varepsilon N_{MB}} \quad (1)$$

where the raw yields of $\Upsilon(1S)$ (N_Υ) are corrected for acceptance (α), efficiency (ε) and the number of minimum bias events (N_{MB}) and converted into an invariant yield divided by the geometric overlap function T_{AA} . This quantity can be directly compared to cross

sections measured in pp collisions. Fig. 2 shows the invariant yield normalized by T_{AA} of $\Upsilon(1S)$ as a function of p_T , rapidity, and N_{part} (the number of nucleons participating in the collisions).

Figure 2: Invariant yield divided by T_{AA} as a function of N_{part} (left), p_T (middle) and rapidity (right) for the $\Upsilon(1S)$. The negative rapidity points (open symbols) are reflections of the positive rapidity points. The green boxes show the systematic uncertainty and the lines illustrate the statistical uncertainty.

Using data from the pp run at $\sqrt{s} = 2.76$ TeV, the nuclear modification factor can be calculated using the following equation:

$$R_{AA} = \frac{L_{pp}}{T_{AA} N_{MB}} \frac{N_{\Upsilon}^{PbPb}}{N_{\Upsilon}^{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}} \quad (2)$$

based on raw yields, correcting only for the multiplicity dependent fraction of the efficiency. All other factors should cancel in the PbPb/pp ratio and possible biases are included in systematic uncertainties.

Fig. 3 shows the R_{AA} of $\Upsilon(1S)$ as function of N_{part} (left), p_T (middle) and rapidity (right). The p_T dependence shows a suppression by a factor ~ 2.3 at low p_T but it is not clear for $p_T > 6.5$ GeV/c due to the large uncertainties. The rapidity dependence indicates a suppression at central rapidity, however the statistical uncertainties are too large for any strong conclusions.

The ratios of the observed yields of the $\Upsilon(2S)$ and $\Upsilon(3S)$ excited states to the $\Upsilon(1S)$ ground state in the pp and PbPb data are:

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

$$\Upsilon(2S + 3S)/\Upsilon(1S)|_{PbPb} = 0.31^{+0.13}_{-0.12} \text{ (stat.)} \pm 0.02 \text{ (syst.)}. \quad (4)$$

The dominant systematic uncertainty arises from imperfect knowledge of the lineshape [7], which results in a relative uncertainty on the ratio of 10% (3%) on the PbPb (pp) data.

The ratio of the $\Upsilon(2S+3S)/\Upsilon(1S)$ ratios in PbPb and pp benefits from an almost complete cancellation of possible acceptance and efficiency differences among the

Figure 3: The nuclear modification factor as function of N_{part} (left), p_T (middle) and rapidity (right) for the $\Upsilon(1S)$. An uncertainty of 7% on the measured integrated luminosity of the pp data sample is a global scale uncertainty. It is indicated by the gray box at $R_{AA} = 1$. The other rectangle boxes represent the systematic uncertainty and the lines show the statistical uncertainty.

reconstructed resonances. A simultaneous fit to the pp and PbPb mass spectra gives the double ratio

$$\frac{\Upsilon(2S + 3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S + 3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} (\text{stat.}) \pm 0.03 (\text{syst.}) \quad (5)$$

where the systematic uncertainty (9%) arises from varying the lineshape in the simultaneous fit, thus taking into account partial cancellations of systematic effects. Using an ensemble of one million pseudo-experiments, generated with the signal lineshape obtained from the pp data (Fig. 1), the background lineshapes from each data set, and a double ratio equal to unity within uncertainties, the probability of finding the measured value of 0.31 or below is estimated to be 0.9%, which corresponds to 2.4σ in a one-tailed integral of a Gaussian distribution. Production yields of quarkonium states can also be modified, from pp to PbPb collisions, in the absence of QGP formation, by cold nuclear matter effects [11]. More discussion can be found in [7].

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