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Open and closed heavy-flavour suppression in heavy-ion collisions with CMS

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Abstract. The Compact Muon Solenoid (CMS) is fully equipped to measure quarkonia in the dimuon decay channel in the high multiplicity environment of nucleus-nucleus collisions. Quarkonia are especially relevant for studying the quark-gluon plasma since they are produced at early times and propagate through the medium, mapping its evolution. CMS has measured the nuclear modification factors of non-prompt J/ψ (from b-hadron decays), prompt J/ψ, inclusive ψ(2S), and the first three Υ states in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A suppression of non-prompt J/ψ, which is sensitive to the in-medium b-quark energy loss, has been measured at relatively high p_T ($6.5 < p_T < 30$ GeV/c) in PbPb collisions, compared to the yield in pp collisions scaled by the number of inelastic nucleon-nucleon collisions. For prompt J/ψ in the same kinematic range, a strong, centrality-dependent suppression is observed. Such strong suppression at high p_T has previously not been observed at RHIC. At mid-rapidity and high p_T, ψ(2S) show an even stronger suppression than J/ψ. Furthermore, CMS has measured the suppression of the three Υ states, separately, down to $p_T = 0$ GeV/c. A clear ordering of the suppression with binding energy is observed, as expected from sequential melting of quarkonium states.

1. Introduction

A deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP), is predicted to be formed at high parton density and medium temperature by lattice Quantum Chromodynamics (QCD) in high energy heavy-ion collisions. Heavy quarks are created at the early stage of collisions thereby they help to study the properties of QGP. The confining potential of quark and anti-quark is expected to be screened in the QGP and the suppression of heavy quarkonium production is predicted [1]. At higher medium temperature, quarkonia with stronger binding energy are expected to be dissociated, hence quarkonium states are melted sequentially.

Partons that are produced in the initial hard scattering process undergo energy loss as they traverse the medium. Gluons, light quarks and heavy quarks lose energy in the medium differently by inelastic and elastic interactions. Especially for heavy quarks, the radiative energy loss by gluon emission at small angle is expected to be reduced [2]. The independent measurement of b-quark is essential for better understanding of these phenomenon and this can be obtained via non-prompt J/ψ which is originated from b-hadron decays.

In these proceedings, the nuclear modification factors, R_{AA}, of Υ(1S), Υ(2S), Υ(3S) [3], prompt J/ψ and non-prompt J/ψ [4] are presented as well as the ψ(2S)/J/ψ ratio [5] as measured with the Compact Muon Solenoid (CMS) [6] detector.

2. Experimental Methods

The measurement of J/ψ, $\psi(2S)$ and Υ via $\mu^+\mu^-$ decays at $\sqrt{s_{NN}} = 2.76$ TeV are performed with PbPb and pp datasets corresponding to integrated luminosities of 150 μb^{-1} and 230 nb^{-1}, respectively. Muons are identified in the range $|\eta| < 2.4$ with the muon system and the p_T measurement is based on the information from tracker system. The forward calorimetry system covers the range $2.9 < |\eta| < 5.2$ and is used for event selection and centrality determination.

Reconstructed $\mu^+\mu^-$ pairs are selected in the range of $|y| < 1.6$ and $6.5 < p_T < 30$ GeV/c, $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c for J/ψ and $\psi(2S)$. Only muons with $p_T > 4$ GeV/c and dimuon pairs in $|y| < 2.4$ are used for Υ(nS).

Invariant mass of J/ψ, $\psi(2S)$, Υ(nS) and lifetime distributions of J/ψ are presented in Fig.1. Invariant mass spectrum of J/ψ is fitted with a sum of Crystal Ball function and a Gaussian to describe the signal and an exponential for the background in the region of $2.6 < m_{\mu^+\mu^-} < 3.5$ GeV/c^2. Non-prompt J/ψ originated from b-hadron decays is identified via the measurement of secondary $\mu^+\mu^-$ vertex [7]. In order to obtain the fraction of non-prompt J/ψ, 2-dimensional simultaneous extended unbinned maximum likelihood fitting with the invariant mass and the pseudo-proper decay length is performed.

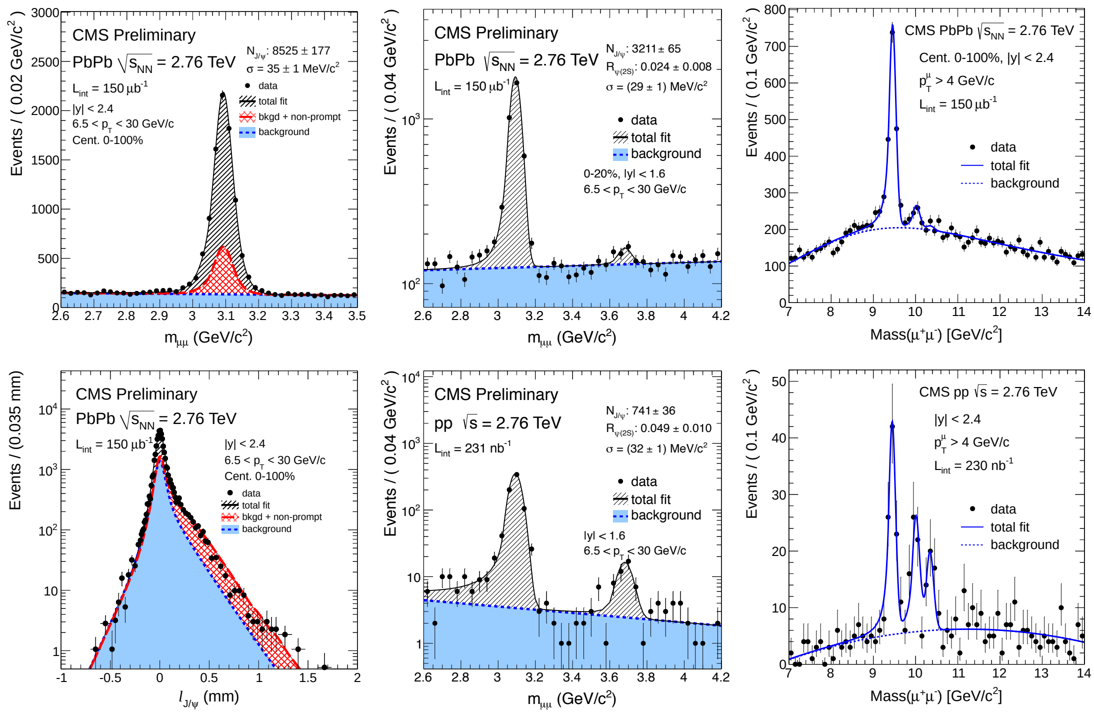

Figure 1. Invariant mass spectrum *(top left)* and pseudo-proper decay length distribution *(bottom left)* of J/ψ by PbPb collisions in $|y| < 2.4$, $6.5 < p_T < 30$ GeV/c, centrality 0-100%. Wider invariant mass spectrum of J/ψ and $\psi(2S)$ in PbPb *(top center)* and in pp *(bottom center)* in $|y| < 1.6$, $6.5 < p_T < 30$ GeV/c, centrality 0-20% for PbPb. Invariant mass spectrum of Υ(nS) in PbPb *(top right)* and in pp *(bottom right)* in $|y| < 2.4$, $p_T^\mu > 4$ GeV/c, centrality 0-100% for PbPb.

The $\psi(2S)/J/\psi$ ratio is obtained by simultaneous unbinned maximum likelihood fitting in the range of $2.6 < m_{\mu^+\mu^-} < 4.2$ GeV/c^2 independently in PbPb and pp datasets. For J/ψ, a Crystal Ball function is used at mid-rapidity while additional a Gaussian function is used at

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forward rapidity. Same shapes were used for ψ(2S). The two width parameters of the Crystal Ball and Gaussian functions are set to the values of J/ψ that are multiplied by Particle Data Group(PDG) mass ratio of ψ(2S) and J/ψ. The mass ratio of ψ(2S) and J/ψ is also fixed to the PDG value. An exponential function is used to describe the background.

The invariant mass spectrum of Υ(nS) is also described by an extended unbinned maximum likelihood fit. The signals consist of three Crystal Ball functions and the mass differences between Υ(nS) are fixed to their PDG values and the widths are scaled with the resonance mass. The shape parameters are common for PbPb and pp datasets via a simultaneous fit. The background model is a second-order polynomial for pp dataset and a exponential for PbPb dataset.

Efficiencies are estimated from Monte-Carlo simulations for all quarkonium states. Data-driven efficiency measurement, Tag and Probe, is also performed as a cross-check. The systematic uncertainties for efficiencies, 1-16% for the J/ψ R_{AA}, 4-8% for the Υ(nS) R_{AA} and 2-10% for the $\psi(2S)/J/\psi$ ratio, are estimated by comparing the efficiencies obtained from data and MC simulations and considering variations of simulated kinematic distributions.

The nuclear modification factor, R_{AA}, is defined in the form

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}}{N_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}} \tag{1}$$

where $\mathcal{L}_{pp}$ is the luminosity of the pp dataset, T_{AA} is the nuclear overlap function, N_{MB} is the number of the sampled minimum bias PbPb events, N is the raw yield of quarkonium, and ε is the efficiency. If the R_{AA} is less(larger) than 1, that means the production of particle is relatively reduced(enhanced) in heavy-ion collisions with respect to proton-proton collisions, respectively.

3. Results

The R_{AA} for Υ(nS) states have been measured as well as the double ratio of Υ(1S) and Υ(2S) in Fig.2. For the minimum bias(0–100%) case, R_{AA} of Υ(nS) are

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

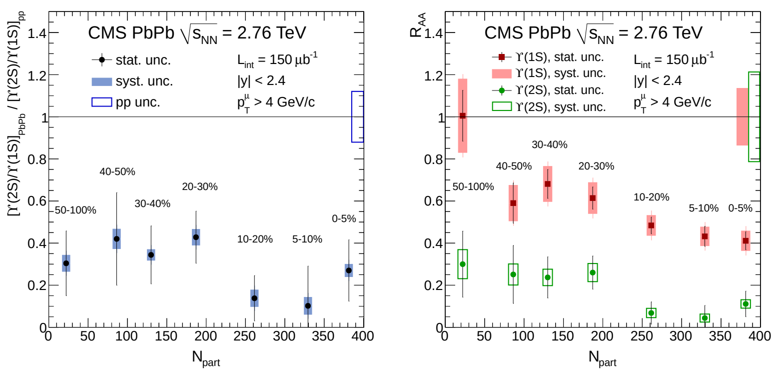

Figure 2. The double ratio *(left)* and the R_{AA} *(right)* of the Υ(2S) and Υ(1S) states are presented as a function of number of participants. The uncertainties that are independent from N_{part} are shown by box at unity.

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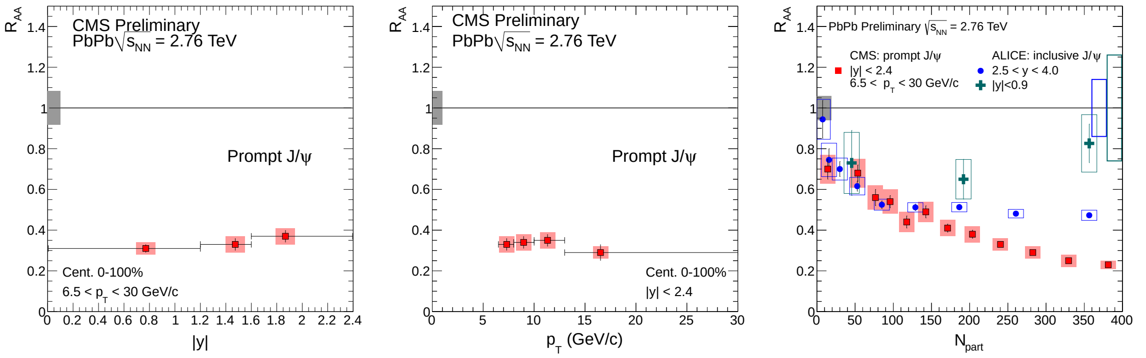

Figure 3. The R_{AA} of prompt J/ψ with respect to rapidity *(left)*, p_T *(center)* and centrality *(right)* are presented. Inclusive J/ψ measurement by ALICE *(blue, green markers)* are compared as a function of centrality.

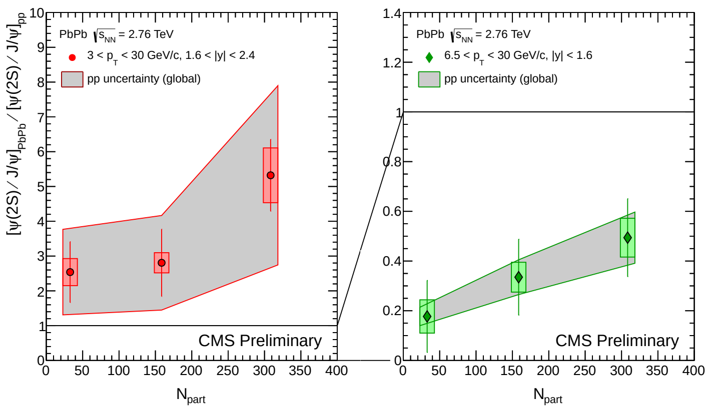

Figure 4. The double ratio of J/ψ and ψ(2S) at lower p_T *(left)*, $3 < p_T < 30$ GeV/c, and higher p_T *(right)*, $6.5 < p_T < 30$ GeV/c, are shown.

A clear suppression of higher Υ states is observed. Different amount of Υ(nS) suppression can be explained by increased suppression of higher order resonances that are more loosely bounded.

The R_{AA} of prompt J/ψ are presented as a function of centrality, p_T and rapidity. Prompt J/ψ is suppressed over all measured p_T and rapidity regions. A clear centrality dependent suppression is observed. In Fig.3, inclusive J/ψ R_{AA} results from ALICE [8] is compared. Note that inclusive J/ψ measured by ALICE consist of particles with $p_T > 0$ GeV/c while CMS measurements start from higher p_T, 6.5 GeV/c.

The first measurement of the $\psi(2S)/J/\psi$ ratio in heavy-ion collisions is presented in Fig.4. At lower p_T and forward rapidity region, the production of ψ(2S) is slightly larger than ψ(2S) however the error driven by lack of pp collision statistics is too large to draw a conclusion. At higher p_T region, ψ(2S) is more suppressed than J/ψ over all measured centrality regions.

The open bottom R_{AA} is measured in p_T, rapidity and centrality via non-prompt J/ψ and presented in Fig.5. Hints of rapidity and p_T dependent suppression are observed. A comparison of the open charm R_{AA} by ALICE [9] shows a slightly less suppression at the most central collisions. Note that non-prompt J/ψ is measured from 6.5 to 30 GeV/c by CMS while D meson measured by ALICE starts from 6 to 12 GeV/c at mid-rapidity, and p_T of open bottom is expected to be higher than that of non-prompt J/ψ.

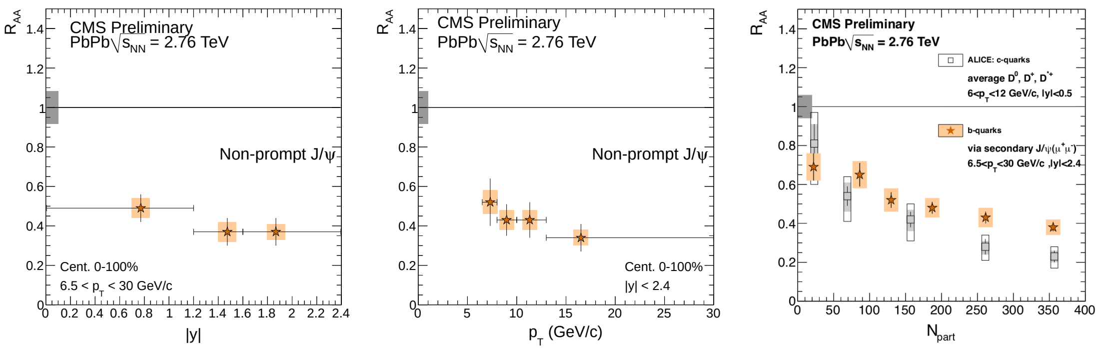

Figure 5. The non-prompt J/ψ R_{AA} with respect to rapidity*(left)*, p_T*(center)* and centrality*(right)* are presented. Centrality dependence of open charm R_{AA} via D meson measurement by ALICE is compared to non-prompt J/ψ.

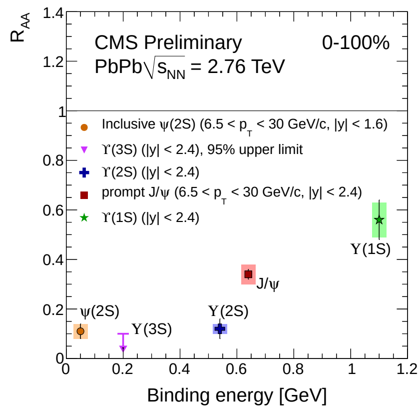

Figure 6. R_{AA} of quarkonia is presented with prompt J/ψ, ψ(2S) and Υ(nS) as a function of their binding energy.

4. Summary

CMS has measured R_{AA} and double ratios of open and closed heavy-flavour with PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Quarkonium states with smaller binding energy are more suppressed than quarkonia with higher binding energy, such as Υ(1S). Quarkonium R_{AA} in various p_T and rapidity regions as a function of the binding energy is presented at Fig.6. The centrality, p_T and rapidity dependent suppression of non-prompt J/ψ from B meson decays has been observed. This reflects the in-medium energy loss of b-quark.

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