Heavy flavor Production and Interactions in Relativistic Heavy-Ion Collisions in CMS Experiment

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Abstract. This paper presents the CMS measurements of quarkonia and open heavy flavor production in *p*-*p* , *p*-Pb , and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. A brief outlook of the near-future CMS heavy flavor physics analyses is provided at the end.

1. Introduction

Measurements of heavy quarkonia and open heavy flavor production may provide further insight in understanding the properties of the strongly coupled Quark-Gluon plasma (sQGP). The quarkonium production is sensitive to the medium's temperature and the state of deconfinement due to different binding energies for different quarkonia. Besides the large suppression of production rate caused by mechanisms like the Debye screening [1], the coalescence process was found to be important for quarkonium production in heavy ion collisions at RHIC and LHC because of the large number of heavy quarks produced [2]. Open heavy flavor measurements not only serve as a good reference in studying quarkonia, but also provide unique inputs in understanding the parton energy loss in the sQGP medium. The interaction between heavy quarks and the medium involves different mechanisms [3–6] from those of light quarks due to the much larger masses and can be studied through measuring open heavy flavor production. Furthermore, cold nuclear matter effects (CNM) [7] can also lead to enhancement or suppression of production yield in heavy-ion collisions. To disentangle all these effects, we need to study a wide variety of species of heavy flavor probes in broad p_T ranges in *p*-*p* , *p*-A , and A-A collisions.

The CMS experiment is a large acceptance, high performance, and multipurpose experiment. In CMS, heavy quarkonium production is measured through dilepton decay channels. The open heavy flavor measurements are done either indirectly through decay daughters or directly through full reconstruction of D, B hadrons, and heavy flavor jets. In this article, Sec. 2 describes the CMS heavy quarkonia measurements including charmonia and bottomonia production in Pb-Pb , *p*-Pb , and *p*-*p* collisions. Sec. 3 presents the measurements of open heavy flavor production, including D^0 , non-prompt J/ψ and heavy flavor jets in in Pb-Pb , *p*-Pb , and *p*-*p* collisions. At the end of this article, a summary and a brief outlook of the CMS heavy flavor physics analyses in the near future is provided.

2. Heavy Quarkonium Measurements

The left panel of Figure 1 shows the prompt J/ψ R_{AA} as a function of N_{part} at high p_T ($6.5<p_T < 30$ GeV/c) measured within three rapidity regions in 2.76 TeV Pb-Pb collisions [8].

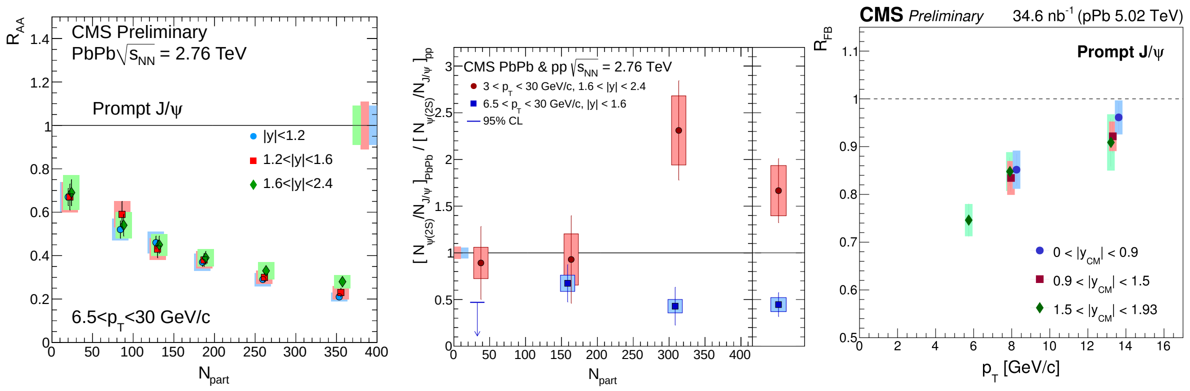

Figure 1. (Left) Prompt J/ψ R_{AA} as a function of N_{part} for $6.5 < p_T < 30$ GeV/c in different rapidity regions. (Middle) Double ratio $[N_{\psi(2S)}/N_{J/\psi}]_{PbPb}/[N_{\psi(2S)}/N_{J/\psi}]_{pp}$ as a function of N_{part} for 3<p_T <30 GeV/c in 1.6 < |y| < 2.4 and for 6.5<p_T <30 GeV/c in |y| < 1.6. (Right) Prompt J/ψ R_{FB} as a function of p_T in different $\mathrm{y_{CM}}$ regions.

Compared to the low p_T measurements at the same energy [9], high p_T J/ψ is more suppressed. This p_T dependence is opposite to what is observed at RHIC in Au-Au collisions at $\sqrt{s_{NN}} =$ 200 GeV [10] and may suggest interplay among suppression, regeneration from coalescence in sQGP medium and CNM effects in different collision energies. The middle panel shows the double ratio $[N_{\psi(2S)}/N_{J/\psi}]_{PbPb}/[N_{\psi(2S)}/N_{J/\psi}]_{pp}$ as a function N_{part} for two different p_T regions. The results indicate $\psi(2S)$ is less suppressed than J/ψ for low p_T (3<p_T <30 GeV/c) and more suppressed for higher p_T region (6.5<p_T <30 GeV/c), which is possibly caused by the coalescence production at different time scale during the medium evolution due to different binding energies [11]. The right panel shows the prompt J/ψ $R_{FB} = \frac{d^2\sigma(\mathrm{y_{CM}}>0)/\mathrm{dp_T dy_{CM}}}{d^2\sigma(\mathrm{y_{CM}}<0)/\mathrm{dp_T dy_{CM}}}$ as a function of p_T in 5.02 TeV p-Pb collisions, where positive $\mathrm{y_{CM}}$ is defined as the proton-going direction. The prompt J/ψ production in $\mathrm{y_{CM}} > 0$ region is found to be less than that in $\mathrm{y_{CM}}$ < 0 region, presumably due to CNM effects. The R_{pA} of prompt J/ψ is needed and is expected to be ready soon to tell how CNM effects play a role in R_{AA} measurements in Pb-Pb collisions. CMS also measured the coherent J/ψ photoproduction in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [12]. The results are consistent with the leading twist approximation which includes nuclear gluon shadowing.

In Figure 2, the left and middle panels show the $\Upsilon(nS)$ R_{AA} as a function of N_{part} and p_T in 2.76 TeV Pb-Pb collisions, respectively [13]. The R_{AA} of $\Upsilon(nS)$ are found to be ordered with the binding energy of each state for all centralities and for all p_T regions. The suppression in Pb-Pb collisions is mostly from the sQGP medium effect since the double ratio $\frac{\Upsilon(nS)/\Upsilon(1S)]_{PbPb}}{\Upsilon(nS)/\Upsilon(1S)]_{pp}}$ observed in p-Pb collisions is much higher than that in Pb-Pb collisions as shown in the right panel. Contrary to what is observed from the $\psi(2S)$ and J/ψ double ratio measurement at low p_T , $\Upsilon(2S)$ is more suppressed than $\Upsilon(1S)$ for all p_T . These different trends may come from the different roles the regeneration contribution plays in Υ and J/ψ production due to their large difference in mass.

The left panel of Figure 3 shows the ratio of $\Upsilon(nS)$ cross section to $\Upsilon(1S)$ cross section, i.e. $\Upsilon(nS)/\Upsilon(1S)$, in p-p and p-Pb collisions as a function of the charged tracks multiplicity in $|\eta| < 2.4$, where the Υ signals are selected in $|\mathrm{y_{CM}}| < 1.93$ [14]. The $\Upsilon(nS)/\Upsilon(1S)$ is found to decrease toward higher multiplicity. Similar trend is observed at RHIC for $\psi(2S)$ and J/ψ production in d-Au collisions [15]. The more suppression of excited states with weaker binding energy indicate final state effects in quarkonia production in high multiplicity p-p and p-Pb or

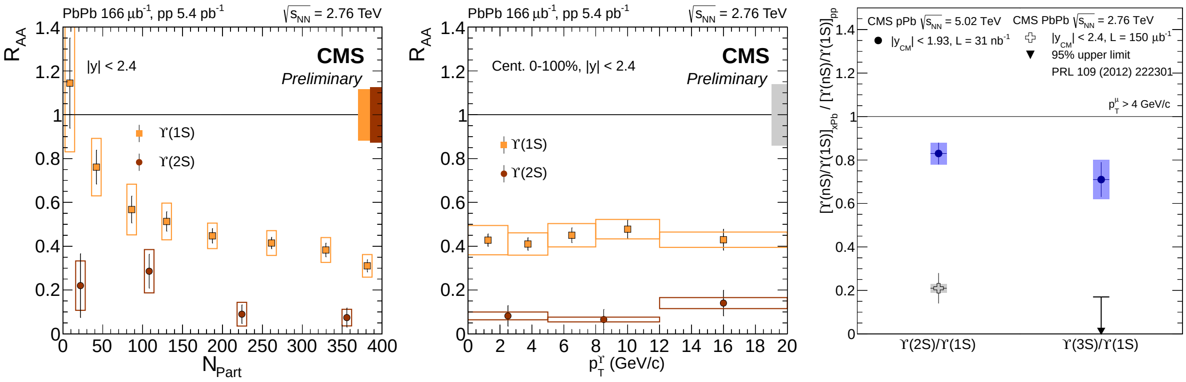

Figure 2. (Left) R_{AA} as a function of N_{part} for $\Upsilon(1S)$ and $\Upsilon(2S)$ in Pb-Pb collisions. (Middle) R_{AA} as a function of p_T for $\Upsilon(1S)$ and $\Upsilon(2S)$ in Pb-Pb collisions. (Right) Double ratio $[\Upsilon(nS)/\Upsilon(1S)]_{PbPb}/[\Upsilon(nS)/\Upsilon(1S)]_{pp}$ for $\Upsilon(2S)$ and $\Upsilon(3S)$ in p-Pb and Pb-Pb collisions.

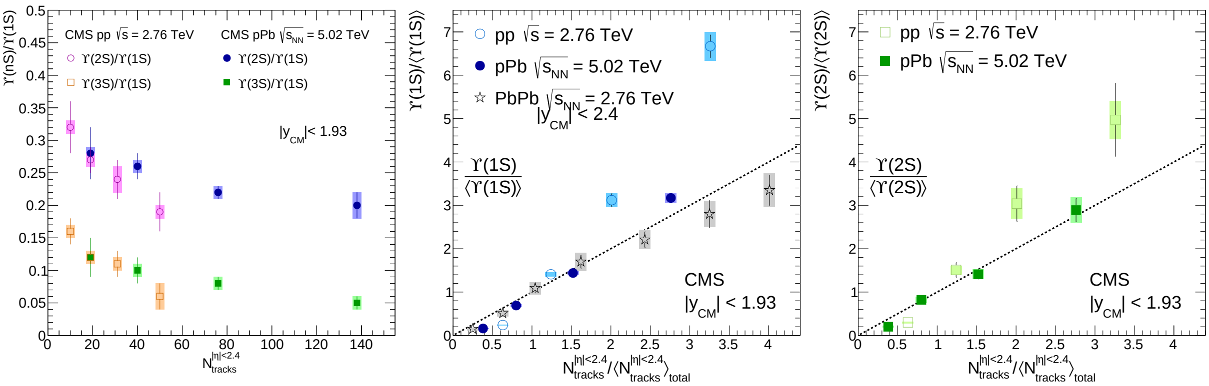

Figure 3. (Left) Ratio $\Upsilon(nS)/\Upsilon(1S)$ as a function of $N_{tracks}^{|\eta|<2.4}$ in 2.76 TeV p-p and 5.02 TeV p-Pb collisions for $\Upsilon(2S)$ and $\Upsilon(3S)$ in $|y_{CM}|$ <1.93. (Middle) Normalized $\Upsilon(nS)$ cross section as a function of the normalized charged track multiplicity for $\Upsilon(1S)$ in 2.76 TeV p-p , 5.02 TeV p-Pb , and 2.76 TeV Pb-Pb collisions for $|y_{CM}|$ < 1.93. (Right) Same as middle panel but for $\Upsilon(2S)$.

d-Au collisions.

Since a $Q\bar{Q}$ interact with the surrounding QCD medium before forming a quarkonium state, it is essential to understand how this interaction may affect quarkonia formation mechanism and thus the production rate in high multiplicity p-A collisions. A measurement of quarkonia polarization as a function of charged particle multiplicity can provide the needed clues and CMS took the first step toward that direction. Figure 4 shows measrements of the frame-invariant parameter $\tilde{\lambda}$, in 7 TeV p-p collisions, as a function of charged particle multiplicity in the center-of-mass helicity frame as well as in Collins-Soper frame for the three Υ states in $10 < p_T < 15$ GeV/c and $15 < p_T < 35$ GeV/c [16]. No significant variation of Υ polarization as a function of charged particle multiplicity is observed for the two high p_T bins.

3. Open Heavy Flavor Measurements

Figure 5 shows the prompt D^0 R_{AA} as a function of p_T within |y| <1.0 in 0-100% and 0-10% centrality selection of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [17]. One significant improvement over the previous measurements at 2.76 TeV [19] is that the reference of the new R_{AA} results

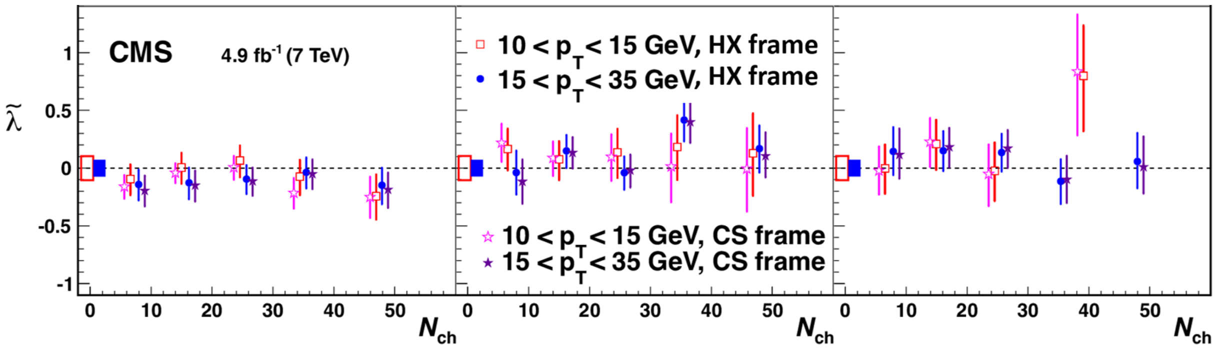

Figure 4. The $\tilde{\lambda}$ parameter for the $\Upsilon(1S)$ (left), $\Upsilon(2S)$ (middle), and $\Upsilon(3S)$ (right) states in the center-of-mass helicity frame (HX) and in Collins-Soper frame (CS) as a function of N_{ch} for p_T = 10-15 GeV/c (open symbols) and 15-35 GeV/c (closed symbols). The boxes at the zero horizontal line represent the global uncertainties.

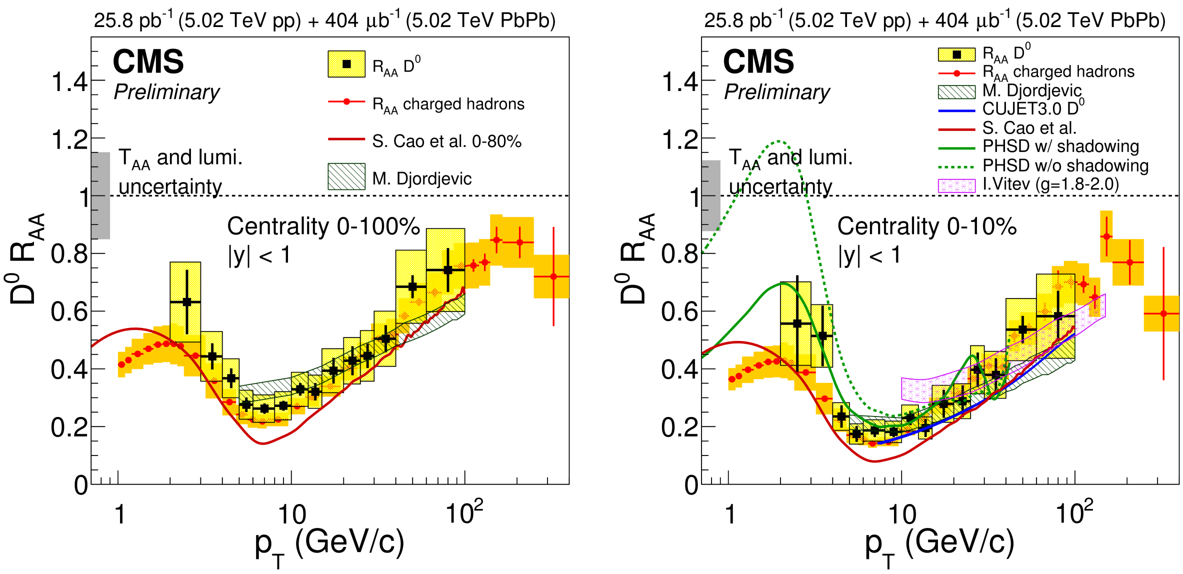

Figure 5. D^0 R_{AA} as a function of p_T in 0-100% (left) and 0-10% (right) centrality selection of Pb-Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV. The charged particle R_{AA} are shown for comparison. The bands and curves are model predictions.

is from the p-p measurement at the same collisions energy. The prompt D^0 R_{AA} is found to decrease with p_T for $p_T < 10$ GeV/c and increase toward higher p_T , which can be qualitatively described by various model calculations [18]. The charged particle R_{AA} is found to be consistent with D^0 R_{AA} within uncertainties for p_T = 2-100 GeV/c despite the much larger charm quark mass.

To further study the mass dependence of energy loss in sQGP medium, the non-prompt J/ψ from B-hadron decays is measured. The left panel of Figure 6 shows non-prompt J/ψ R_{AA} as a function of p_T in 2.76 TeV Pb-Pb collisions in 0-100% centrality region for 6.5 GeV/c $< p_T <$ 30 GeV/c [8]. For non-prompt J/ψ with $p_T >$ 6.5 GeV/c , the parent B-hadron p_T is roughly above 8.0 GeV/c . The D^0 R_{AA} measurement with $p_T >$ 8.0 GeV/c can thus be compared to the non-prompt J/ψ results. With large uncertainties, the comparison indicates larger non-prompt

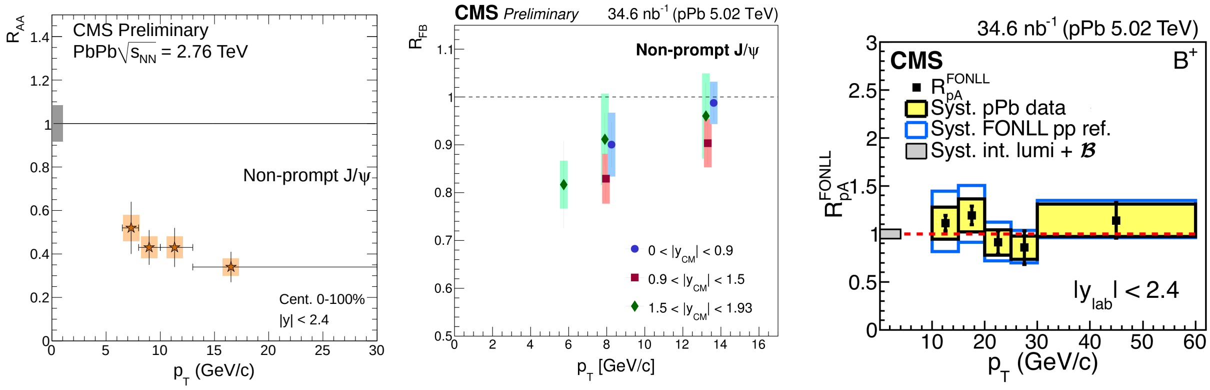

Figure 6. (Left) Non-prompt J/ψ R_{AA} as a function of p_T in 0-100% centrality selection of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. (Middle) Non-prompt J/ψ R_{FB} as a function of p_T in three different $\mathrm{y_{CM}}$ regions in 5.02 TeV p-Pb collisions. (Right) B^+ meson R_{pA}^{FONLL} in $|\mathrm{y_{lab}}| <$ 2.4 as a function of p_T in 5.02 TeV p-Pb collisions.

J/ψ R_{AA} than that of D^0 at $p_T \sim 10$ GeV/c . Further information can be provided when the non-prompt J/ψ at 5.02 TeV becomes available to compare with the more precise D^0 result at 5.02 TeV. The right panel of Figure 6 shows the B^+ R_{pA}^{FONLL} as a function of p_T in 5.02 TeV p-Pb collisions, where B^+ signal is obtained via full reconstruction and the reference is from FONLL calculation [20]. No significant CNM effects are observed within uncertainties in B hadron production. However, the more differential R_{FB} measurements from non-prompt J/ψ in p-Pb shows that the production in the $\mathrm{y_{CM}} > 0$ region is less than that in the $\mathrm{y_{CM}} < 0$ region at $p_T \sim 6$ GeV/c , as observed in the prompt J/ψ measurements.

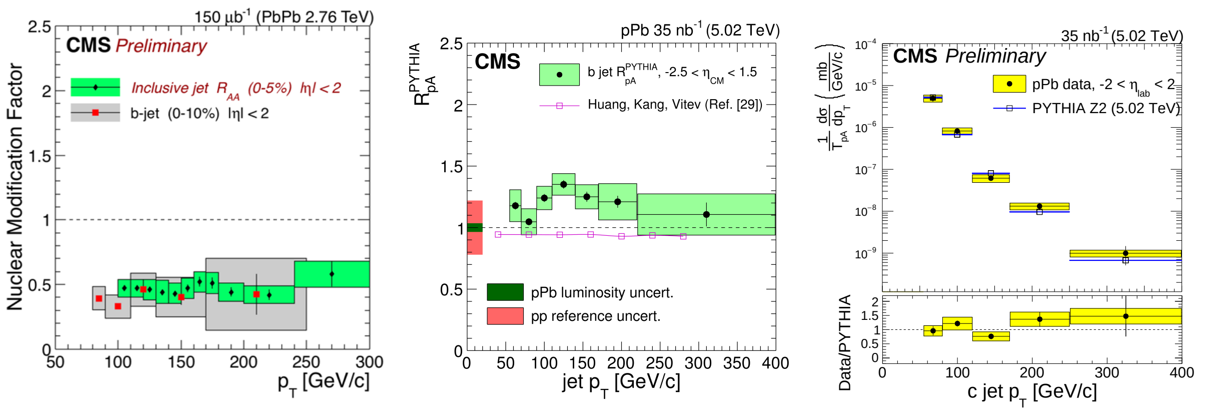

Figure 7. (Left) b-jet R_{AA} as a function of p_T within $|\eta| < 2$ in 0-10% Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The measurement of inclusive jet R_{AA} is also shown for comparison. (Middle) b-jet R_{pA}^{PYTHIA} as a function of p_T in 5.02 TeV p-Pb collisions. (Right) c-jet invariant yield scaled by T_{pA} as a function of p_T 5.02 TeV p-Pb collisions. PYTHIA calculation is shown for comparison.

Figure 7 shows the CMS heavy flavor jets measurements. The b-jet reconstructed in $|\eta| < 2.0$ in Pb-Pb collision is more suppressed in central collisions than in peripheral collisions [21]. In the left panel of the figure the R_{AA} of b-jet and inclusive jet are compared and found to be consistent within uncertainties for $p_T > 80$ GeV/c . The middle panel shows the R_{pA} measurements for b-jet as a function of p_T in 5.02 TeV p-Pb collisions [22]. The result indicates that the b jet suppression measured in Pb-Pb collisions, is not due to CNM effects. In the right panel of the figure, the invariant yield of the first charm-jet measurement normalized by T_{pA} as a function of p_T is compared with PYTHIA [23]. As in the case of b-jet production, the data/PYTHIA ratio indicates no significant CNM effect in charm-jet production.

4. Summary and Outlook

The suppression of the three Υ states is found to be ordered, i.e. R_{AA} $(\Upsilon(1S)) > R_{AA}$ $(\Upsilon(2S)) > R_{AA}$ $(\Upsilon(3S)$, for all centrality and p_T regions. This ordering is consistent with the expectation that a quarkonium state with weaker bounding energy is less likely to survive in the sQGP medium. However, the $\psi(2S)$ is found less suppressed than J/ψ in $3 < p_T < 30$ GeV/c , which may be caused by the coalescence production at different time scale during the medium evolution. The dependence of Υ production on charged particle multiplicity indicates final state effects in p-Pb collisions.

The prompt D^0 R_{AA} is consistent with charged particle R_{AA} in 5.02 TeV Pb-Pb collisions, with the trend that R_{AA} decreases with p_T for $p_T < 10$ GeV/c but increases toward higher p_T , which can be qualitatively described by many models. There are some indications that non-prompt J/ψ is less suppressed than prompt D^0 in intermediate p_T region, while at high p_T the b-jet R_{AA} is consistent with the inclusive jet R_{AA} within uncertainties. The R_{pPb} measurements suggest that CNM effects do not have a large role in open heavy flavor R_{AA} measurements in Pb-Pb . However, R_{FB} measurements show significant CNM effects in non-prompt J/ψ production in p-Pb collisions.

At the time of writing this paper, many new physics results in CMS are expected to be publicly available soon, part of which include R_{AA} of fully reconstructed B meson and non-prompt D^0 meson, di-b-jet correlation, prompt D^0 v_n. These new measurements should provide further inputs in understanding the heavy quark and sQGP medium interaction.

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