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 $J/\psi$ 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 $J/\psi$ $R_{AA}$ as a function of $N_{\text{part}}$ 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 $J/\psi R_{AA}$ as a function of $N_{\text{part}}$ for $6.5 < p_T < 30$ GeV/$c$ in different rapidity regions. (Middle) Double ratio $[N_{\psi(2S)/N_{J/\psi}}]_\text{PbPb}/[N_{\psi(2S)/N_{J/\psi}}]_\text{pp}$ as a function of $N_{\text{part}}$ 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 $J/\psi R_{FB}$ as a function of $p_T$ in different $y_{\text{CM}}$ regions.

Compared to the low $p_T$ measurements at the same energy [9], high $p_T$ $J/\psi$ 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 $[N_{\psi(2S)/N_{J/\psi}}]_\text{PbPb}/[N_{\psi(2S)/N_{J/\psi}}]_\text{pp}$ as a function $N_{\text{part}}$ for two different $p_T$ regions. The results indicate $\psi(2S)$ is less suppressed than $J/\psi$ 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 $J/\psi R_{FB} = \frac{\sigma(y_{\text{CM}} > 0)/dy_{\text{CM}}}{\sigma(y_{\text{CM}} < 0)/dy_{\text{CM}}}$ as a function of $p_T$ in 5.02 TeV $p$-Pb collisions, where positive $y_{\text{CM}}$ is defined as the proton-going direction. The prompt $J/\psi$ production in $y_{\text{CM}} > 0$ region is found to be less than that in $y_{\text{CM}} < 0$ region, presumably due to CNM effects. The $R_{FB}$ of prompt $J/\psi$ 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 $J/\psi$ 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 $N_{\text{part}}$ 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 $\frac{\Upsilon(nS)/\Upsilon(1S)}{\Upsilon(nS)/\Upsilon(1S)}_\text{PbPb}$ 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 $J/\psi$ 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 $\Upsilon$ and $J/\psi$ 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. $\frac{\Upsilon(nS)/\Upsilon(1S)}{\Upsilon(nS)/\Upsilon(1S)}$ in $p$-p and $p$-Pb collisions as a function of the charged tracks multiplicity in $|y| < 2.4$, where the $\Upsilon$ signals are selected in $|y_{\text{CM}}| < 1.93$ [14]. The $\frac{\Upsilon(nS)/\Upsilon(1S)}{\Upsilon(nS)/\Upsilon(1S)}$ is found to decrease toward higher multiplicity. Similar trend is observed at RHIC for $\psi(2S)$ and $J/\psi$ 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 Υ(1S) and Υ(2S) in Pb-Pb collisions. (Middle) $R_{AA}$ as a function of $p_T$ for Υ(1S) and Υ(2S) in Pb-Pb collisions. (Right) Double ratio $[Υ(nS)/Υ(1S)]_{pPb}/[Υ(nS)/Υ(1S)]_{pp}$ for Υ(2S) and Υ(3S) in p-Pb and Pb-Pb collisions.

Figure 3. (Left) Ratio $Υ(nS)/Υ(1S)$ as a function of $N_{\text{tracks}}$ in 2.76 TeV p-p and 5.02 TeV p-Pb collisions for Υ(2S) and Υ(3S) in $|y_{CM}|<1.93$. (Middle) Normalized $Υ(nS)$ cross section as a function of the normalized charged track multiplicity for Υ(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 Υ(2S).

d-Au collisions.

Since a $QQ$ 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 measurements of the frame-invariant parameter $\lambda$, 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 $\Upsilon$ states in $10 < p_T < 15$ GeV/$c$ and $15 < p_T < 35$ GeV/$c$ [16]. No significant variation of $\Upsilon$ 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 $\bar{\lambda}$ 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 $J/\psi$ from $B$-hadron decays is measured. The left panel of Figure 6 shows non-prompt $J/\psi$ $R_{AA}$ as a function of $p_T$ in 2.76 TeV Pb-Pb collisions in 0-100% centrality region for $6.5 < p_T < 30$ GeV/c [8]. For non-prompt $J/\psi$ 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 $J/\psi$ results. With large uncertainties, the comparison indicates larger non-prompt...
Figure 6. (Left) Non-prompt \(J/\psi\) \(R_{AA}\) 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 \(J/\psi\) \(R_{FB}\) as a function of \(p_T\) in three different \(y_{CM}\) regions in 5.02 TeV \(p-A\) collisions. (Right) \(B^+\) meson \(R_{P\Lambda}^{FONLL}\) in \(|y_{lab}| < 2.4\) as a function of \(p_T\) in 5.02 TeV \(p-Pb\) collisions.

\(J/\psi\) \(R_{AA}\) than that of \(D^0\) at \(p_T \sim 10\) GeV/c. Further information can be provided when the non-prompt \(J/\psi\) 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 \(B^+\) \(R_{P\Lambda}^{FONLL}\) 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 \(J/\psi\) in \(p-Pb\) shows that the production in the \(y_{CM} > 0\) region is less than that in the \(y_{CM} < 0\) region at \(p_T \sim 6\) GeV/c, as observed in the prompt \(J/\psi\) 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 \(R_{PYTHIA}^{P}\) 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 $J/\psi$ 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 $J/\psi$ 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 $J/\psi$ 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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