Chapter 9.

Summary and Outlook

The deconfinement transition and the properties of hot, strongly-interacting matter can be studied experimentally in heavy-ion collisions [38,132]. A significant part of the extensive experimental heavy-ion program is dedicated to measuring quarkonium yields, since Matsui and Satz suggested that quarkonium suppression could be a direct signal of deconfinement [2]. However, not all of the observed quarkonium suppression in nucleus-nucleus collisions relative to scaled proton-proton collisions is due to quark gluon plasma formation. In fact, quarkonium suppression was also observed in proton-nucleus collisions, so that part of the nucleus-nucleus suppression is due to cold nuclear matter effects. Therefore it is necessary to disentangle hot and cold medium effects.

In this thesis first we reviewed present status of experimental signals for quark gluon plasma formation in chapter 1. Status of quarkonia production and suppression in SPS, RHIC and LHC energies is discussed in chapter 2. The observation of anomalous suppression of $J/\psi$ was considered a signal of QGP formation at SPS, but later at RHIC similar amount of suppression is measured despite an order of magnitude increase in center of mass energy. Upsilonons are supposed to be a better probe of QGP. Because three closely placed $\Upsilon$ states can provide a self calibrated measurement of temperature achieved in heavy ion collisions. At RHIC it was not possible to resolve the three $\Upsilon$ states.

This thesis concentrate on production and suppression of $b\bar{b}$ bound states, namely $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ which are measured in pp, pPb and PbPb collisions at LHC. This is the first time we are able to measure all three $\Upsilon$ states separately with good statistics thanks to the large integrated luminosity and high-tech detectors available at LHC. The quarkonium states are identified through their dimuon decay. Muons are reconstructed by matching tracks in the muon detectors and silicon tracker. These...
measurements are explained in detail in chapter 4, 5 and 6. Here a summary of important results is presented.

Figure 9.1. (a) Illustration of the excited to ground states relative Υ suppression in PbPb compared to pp. The fit to the PbPb data, shown by the continuous line, is overlaid with the result of the pp fit, represented by the dashed line (shown on top of a common PbPb background shape, for comparison). (b) The nuclear modification factor, $R_{AA}$, for Υ mesons as a function of $N_{\text{part}}$. The red filled squares show our results for Υ(1S) and the green filled circles are for Υ(2S).

Figure 9.1 (a) shows the invariant-mass distribution of three Υ states measured in PbPb collisions. The fit to the PbPb data is overlaid with the fit to the pp data collected at same center of mass energy. This figure is a graphical representation of suppression of excited Υ states. The excited Υ states (Υ(2S) and Υ(3S)) are found to be strongly suppressed in PbPb collisions. Figure 9.1 (b) shows the absolute suppression of Υ(1S) and Υ(2S) in PbPb collisions. The variable shown in the figure is nuclear modification factor ($R_{AA}$) as a function of centrality of the collision ($N_{\text{part}}$). This is the first measurement of Υ(2S) $R_{AA}$. In studying the data as a function of centrality, we find that the Υ(1S) and Υ(2S) suppression increases with $N_{\text{part}}$. For all the centrality bins, we observe the suppression of the Υ(2S) state to be larger than the suppression of the Υ(1S). In the most peripheral bin, the Υ(1S) nuclear modification factor is consistent with unity, while that for the Υ(2S) remains low. However, it should be noted that this bin includes a wide impact parameter range (50-100% of the total cross section), and it is expected that most of the events where an Υ will be produced will be biased towards larger $N_{\text{coll}}$. 

and hence smaller impact parameter. With the 150 μb⁻¹ integrated luminosity recorded during second LHC PbPb run at √sNN = 2.76 TeV, we are able to split the Υ(1S) and Υ(2S) data into seven centrality bins. But the limited pp data sample does not allow measurements of Υ RAA in kinematic bins. The new pp data sample collected during Jan 2013 at √s = 2.76 TeV will allow measurements of the RAA of the states as a function of pT and rapidity.

The quarkonia yields in heavy ion collisions are also modified due to non-QGP effects such as shadowing, an effect due to the change of the parton distribution functions inside the nucleus, and dissociation due to hadronic or comover interactions [5]. To get a quantitative idea about these effects, measurements of Υ production in pPb collisions at √sNN = 5.02 TeV are performed. Figure 9.2 shows the cross-section ratios Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) as a function of (a) transverse energy and (b) charged-particle multiplicity for pp, pPb and PbPb collisions. The ratio seems to be constantly decreasing with increasing multiplicity while trend is not very clear for transverse energy. These measurements suggest the presence of final state effects in pPb collisions.
Table 9.1.: Heavy flavor and Drell-Yan cross sections at $\sqrt{s_{NN}} = 2.76$ TeV. The cross sections are given per nucleon while $N_{Q\bar{Q}}$ and $N_{l^+l^-}$ are the number of $Q\bar{Q}$ and lepton pairs per Pb+Pb event. The uncertainties in the heavy flavor cross section are based on the Pb+Pb central values with the mass and scale uncertainties added in quadrature.

<table>
<thead>
<tr>
<th></th>
<th>$c\bar{c}$</th>
<th>$b\bar{b}$</th>
<th>Drell-Yan</th>
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<tbody>
<tr>
<td>$\sigma_{PbPb}$</td>
<td>$1.76^{+2.32}_{-1.29}$ mb</td>
<td>$89.3^{+42.7}_{-27.2}$ $\mu$b</td>
<td>70.97 nb</td>
</tr>
<tr>
<td>$N_{Q\bar{Q}}$</td>
<td>$9.95^{+13.10}_{-7.30}$</td>
<td>$0.50^{+0.25}_{-0.15}$</td>
<td>-</td>
</tr>
<tr>
<td>$N_{l^+l^-}$</td>
<td>$0.106^{+0.238}_{-0.078}$</td>
<td>$0.0059^{+0.0029}_{-0.0017}$</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

compared to pp collisions affecting ground state and excited states differently. A global understanding of effects at play in pp, pPb and PbPb collisions calls for more activity related study of $\Upsilon$ yields in pp collisions. More PbPb data are needed to investigate the dependence in three systems and their possible relation.

This thesis consist of measurements as well as theoretical results. In the first calculation we calculate open charm and bottom production and determine their contributions to the dilepton continuum in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with and without heavy quark energy loss. These rates are then compared with Drell-Yan and thermal dilepton production. The contributions of all these sources are obtained in kinematic regions relevant for the LHC detectors. The production cross sections along with their uncertainties for heavy flavor and Drell-Yan dileptons at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Tab. 9.1. The number of $Q\bar{Q}$ pairs in a minimum bias PbPb event is obtained from the per nucleon cross section. Figure 9.3 shows the invariant mass distributions for these four contributions to the dilepton spectra. Figure 9.3 (a) shows the heavy flavor mass distributions without any final-state energy loss while energy loss is included in the heavy flavor distributions on Fig. 9.3 (b). Dileptons from $D\bar{D}$ decays dominate over the entire mass range due to the large $c\bar{c}$ production cross section. Bottom pair decays are the next largest contribution followed by Drell-Yan production. Thermal dilepton contribution is very small. It can be concluded that measurement of thermal dileptons will be very challenging for the kinematic range relevant to LHC detectors.

In the second calculation we estimate the modification of quarkonia yields due to different processes in the medium produced in PbPb collisions at LHC energy. The quarkonia and heavy flavor cross sections calculated upto NLO are used in the study and
Figure 9.3.: The invariant mass distributions for the four contributions to the dilepton spectra discussed here: semileptonic charm (red, short-dashed) and bottom (blue, dot-dot-dashed) decays, Drell-Yan (magenta, long-dashed) and thermal (black, dotted) dileptons along with the sum (black, solid) in Pb+Pb collisions per nucleon pair at $\sqrt{s_{NN}} = 2.76$ TeV. Left panel shows distributions without any final state energy loss, right panel is after including heavy quark energy loss in the medium.

Shadowing corrections are obtained by EPS09 parameterization [12]. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. Quarkonia dissociation cross section due to gluon collisions has been considered and the regeneration rate has been obtained using the principle of detailed balance. The modification in quarkonia yields due to collisions with hadronic comovers has been estimated assuming it to be caused by pion. The manifestations of these effects in different kinematic regions in the nuclear modification factors for both $J/\psi$ and $\Upsilon$ has been demonstrated for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in comparison with the measurements.

Figure 9.4 shows the calculated nuclear modification factor ($R_{AA}$) as a function of $J/\psi$ transverse momentum. Both the suppression and regeneration due to deconfined medium strongly affect low $p_T$ range Fig. 9.4 (a). The large observed suppression of $J/\psi$ at high $p_T$ far exceeds the estimates of suppression by deconfined medium Fig. 9.4 (b).
Figure 9.4.: (Color online) Calculated nuclear modification factor \( R_{AA} \) as a function of \( J/\psi \) transverse momentum. Calculations are compared with ALICE and CMS measurements.