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Overview of Quarkonia and Heavy Flavour Measurements by CMS

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This writeup summarizes the recent CMS results on quarkonia measurements in pp, pPb and PbPb collisions at LHC. The excellent muon detection capability of CMS allows measurement of charmonia states at high transverse momentum (p_T) while the Υ states can be reconstructed starting at zero p_T. The absolute and relative yields of different charmonia and bottomonia states modified in PbPb collisions (over pp collisions) are described. The vertexing capability of CMS enables measurement of B meson energy loss via its decay to J/ψ. An overview of these measurements is given. How these measurements compare with other experiments at RHIC and LHC and have improved the understanding of heavy ion collisions has been discussed.

Key Words : Quark-Gluon Plasma; Quarkonia; Heavy Flavour; Charmonia; Bottomonia; LHC

Introduction

Heavy ion collisions at ultra-relativistic energies are performed to create and characterize quark gluon plasma (QGP), a phase of strongly interacting matter at an energy density where quarks and gluons are no longer bound within hadrons. Quarkonia states (J/ψ and Υ) have been one of the most popular tools since their suppression was proposed as a signal of QGP (Matusi and Satz, 1986). Quarkonia are produced early in the heavy ion collisions and if they evolve through the deconfined medium their yields should be suppressed in comparison with those in pp. The first such measurement was the 'anomalous' J/ψ suppression discovered in PbPb collisions at $\sqrt{s_{NN}} = 17.3$ GeV at the SPS, which was considered as a hint of QGP formation. The RHIC measurements in AuAu at $\sqrt{s_{NN}} = 200$ GeV (Adare *et al*., 2011) showed almost the identical suppression at a much higher energy contrary to the expectation (Brambilla *et al*., 2011). Such an

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observation was consistent with the scenario that at higher collision energy the expected large suppression is compensated by regeneration of J/ψ due to the recombination of two independently produced charm quarks (Andronic *et al*., 2003).

After the LHC started PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, a wealth of results have become available on quarkonia production (Muller *et al*., 2012; Schukraf, 2013). The suppression of quarkonia in PbPb collisions can quantify the colour screening properties of strongly interacting matter (Matsui and Satz, 1986) or alternatively the thermal gluon dissociation cross section of quarkonia (Bhanot and Peskin, 1979; Xu *et al*., 1996). The statistical models (Andronic *et al*., 2003) offer estimates of the regeneration of quarkonia from charm quark pairs. The inverse of the gluon dissociation process is also used to estimate regeneration (Thews *et al*., 2001). There have been many recent calculations to explain the LHC results on quarkonia using a combination of above theoretical frameworks and models (Zhao and Rapp, 2011; Emerick *et al*., 2012).

The CMS experiment with its muon detection capabilities has enabled several measurements on quarkonia (both charmonia as well as bottomonia) via dimuon channel. The excellent mass resolution in dimuon channel allows precise measurement of the three Υ states and their relative yields in pp, pPb as well as PbPb systems. Detailed measurements of J/ψ and $\psi(2S)$ have been made in different kinematic ranges. We give the results of these measurements and compare them with the other experiments at LHC and RHIC. The excellent vertexing capability of CMS enables measurement of B mesons via its decay to J/ψ. The measurement of suppression of hadrons containing different quark flavours can constrain various energy loss mechanisms (Djordjevic and Gyulassy, 2004).

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 (Vogt, 2010). To get a quantitative idea about these effects, measurements in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are performed. Some of them are discussed in this writeup.

Charmonia Measurements

The CMS experiment carries out J/ψ measurements at high transverse momentum ($p_T > 6.5$ GeV/c) and in the rapidity range $|y| \leq 2.4$. Fig. 1 shows the nuclear modification factor ($R_{\rm AA}$) of J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of number of participants (centrality) measured by CMS (Chatrchyan *et al*., 2012a; Mironov *et al*., 2013). The $R_{\rm AA}$ of these high p_T prompt J/ψ decreases with increasing centrality showing moderate suppression even in the most peripheral collisions. On comparing with the STAR results (Tang *et al*., 2011) at RHIC, it follows that the suppression of (high p_T) J/ψ has increased with collision energy. The ALICE results on J/ψ correspond to a low p_T range which have little or no centrality dependence except for the most peripheral collisions (Abelev *et al*., 2012b).

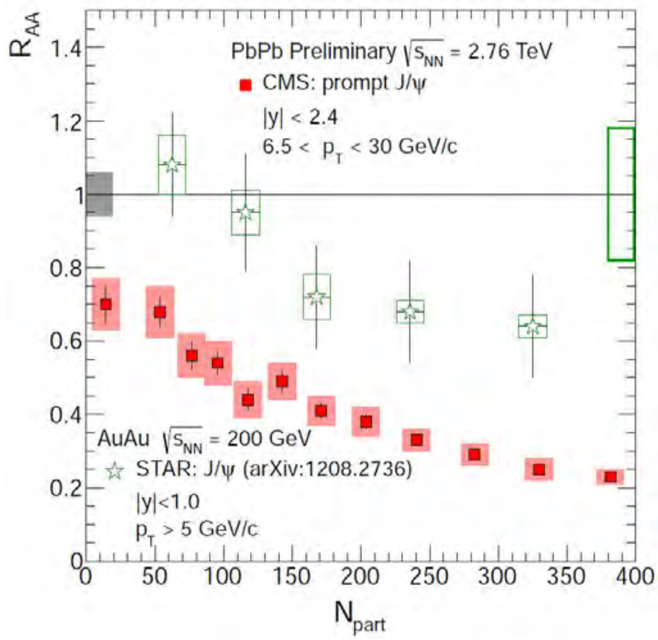

Fig. 1: The nuclear modification factor (R_{AA}) of J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of number of participants measured by CMS experiment (Chatrchyan *et al*., 2012a; Mironov *et al*., 2012). RHIC measurements are shown for comparison (Tang *et al*., 2011)

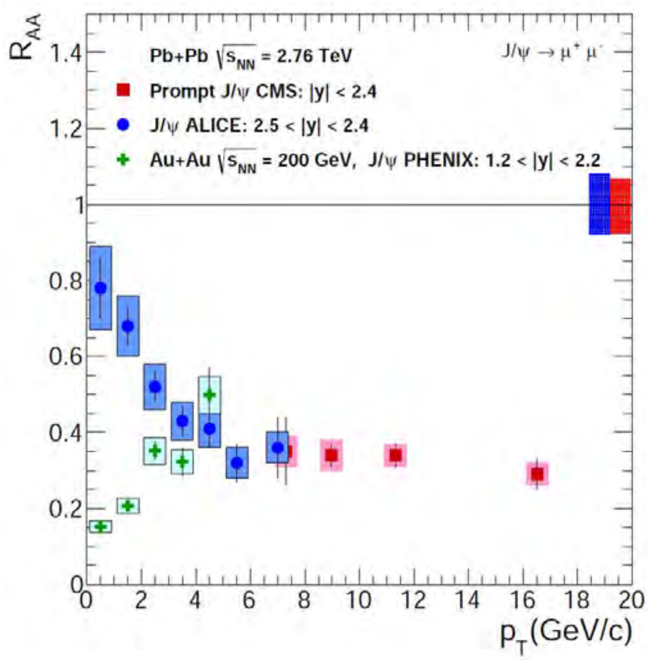

Fig. 2: Nuclear modification factor (R_{AA}) of J/ψ as a function of p_T measured by CMS (Chatrchyan *et al*., 2012a; Mironov *et al*., 2012), ALICE (Abelev *et al*., 2014) and PHENIX (Adare *et al*., 2011) experiments

Fig. 2 shows $R_{\rm AA}$ of J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of p_T measured by CMS, ALICE and PHENIX experiments. The $R_{\rm AA}$ is found to be nearly independent of p_T (above 6.5 GeV$/c$) showing that J/ψ remains suppressed even at very high p_T upto 16 GeV$/c$ (Chatrchyan *et al.*, 2012a; Mironov *et al.*, 2013). The ALICE J/ψ data (Abelev *et al.*, 2014) shows that $R_{\rm AA}$ increases with decreasing p_T below 4 GeV/c. On comparing with the PHENIX forward rapidity measurement (Adare *et al.*, 2011), it can be said that low p$_T$ J/ψ at LHC are enhanced in comparison to RHIC. These observations suggest regeneration of J/ψ at low p_T by recombination of independently produced charm pairs. Another hint of regeneration is given by CMS measurement of ratios of charmonia in PbPb and pp collisions.

Fig. 3 shows the double ratio of $\psi(2S)$ and J/ψ as a function of centrality measured by CMS in two kinematic regions (Khachtryan *et al.*, 2014). The (A) plot is for low p_T and forward rapidity region ($p_T > 3$ GeV/c and $1.6 < |y| < 2.4$) and the (B) is for high p_T and central rapidity region ($p_T > 6.5$ GeV/c and $|y| < 1.6$). Although there are large pp uncertainties, one can conclude that at low p_T, $\psi(2S)$ is less suppressed than J/ψ clearly for the most central collisions. Measurements with larger pp statistics will be able to confirm this conclusion.

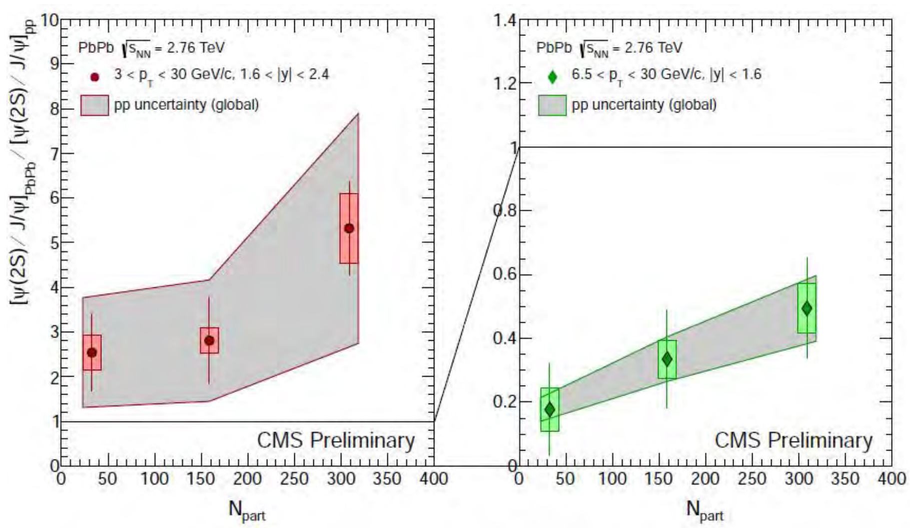

Fig. 3: Double ratio (ratio of ratios in PbPb to pp) of $\psi(2S)$ and J/ψ as a function of centrality measured by CMS in two kinematic regions (Khachtryan *et al*., 2014)

Bottomonia Measurements

CMS measurements reveal that the higher Υ states are more suppressed relative to the ground state (Chatrchyan *et al.*, 2011, Chatrchyan *et al.*, 2012b). This phenomenon is called sequential suppression where the bound states with smaller binding energies are more suppressed. Fig. 4 shows the $R_{\rm AA}$ of Υ(1S) and

Υ(2S) measured by CMS. The figure also shows STAR inclusive measurement of three Υ states (Adamczyk *et al*., 2014). The centrality integrated R_{AA} of Υ(1S) state by CMS is $0.56 \pm 0.08 \pm 0.07$ as compared to $0.71 \pm 0.06 \pm 0.09$ by STAR which allows us to conclude that Υ's are more suppressed at higher collision energy. The new pp measurements made in 2013 will allow the extraction of R_{AA} of the Υ states as a function of p_T and rapidity.

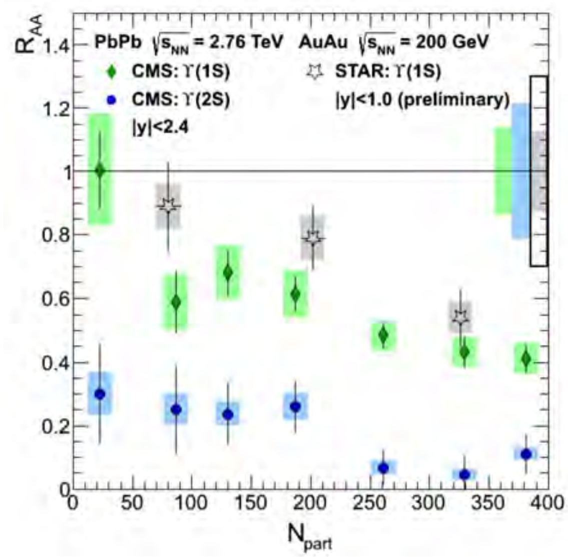

Fig. 4: Nuclear modification factor (R_{AA}) of Υ(1S) and Υ(1S) measured by CMS (Chatrchyan *et al*., 2012b). RHIC measurements are plotted for comparison (Adamczyk *et al*., 2014)

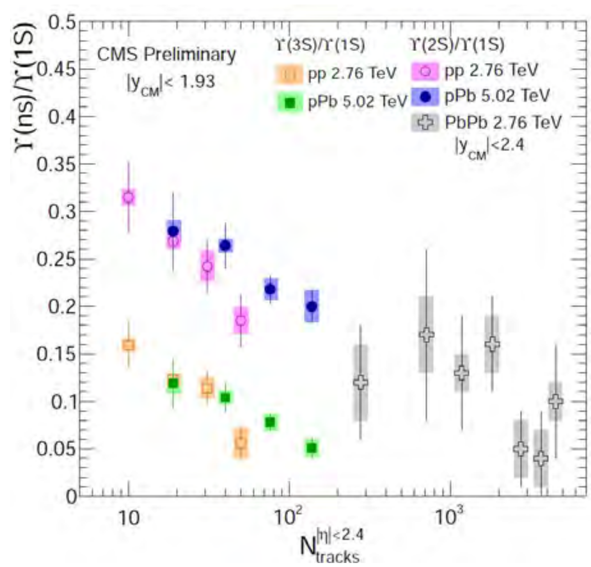

Fig. 5: The yield ratios Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) as a function of number of track in event for different collision systems (Chatrchyan *et al*., 2014)

To study the effect of system size on the modification of quarkonia, pPb collisions are performed at $\sqrt{s_{NN}} = 5.02$ TeV with an integrated luminosity 5.4 (pb)$^{-1}$ (Chatrchyan *et al.*, 2014). These measurements suggest the presence of final state effects in pPb collisions compared to pp collisions affecting ground state and excited states differently. Fig. 5 shows the yield ratios Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) as a function of number of tracks in the event for pp, pPb and PbPb collisions. The ratio seems to be constantly decreasing with increasing multiplicity. More PbPb data are needed to investigate the dependence in three systems and their possible relation.

Heavy Flavour Measurements

CMS offers B meson measurement via detecting secondary J/ψ coming from a displaced vertex. Fig. 6 shows the $R_{\rm AA}$ of B mesons via secondary J/ψ compared to $R_{\rm AA}$ of light hadrons (Chatrchyan *et al.*, 2012a; Mironov *et al.*, 2013). We can conclude that at high $p_T > 10$ GeV/c the suppression of B mesons and light hadrons are consistent, but at low p_T B meson $R_{\rm AA}$ is larger as compared to light hadrons. Combining this results with the ALICE measurements of D-meson (Abelev *et al.*, 2012a) containing c-quarks it follows that at low p_T there is mass hierarchy in the amount of suppression such that, $R_{\rm AA}$ (light hadrons) $< R_{\rm AA}$ (D meson) $< R_{\rm AA}$ (B meson).

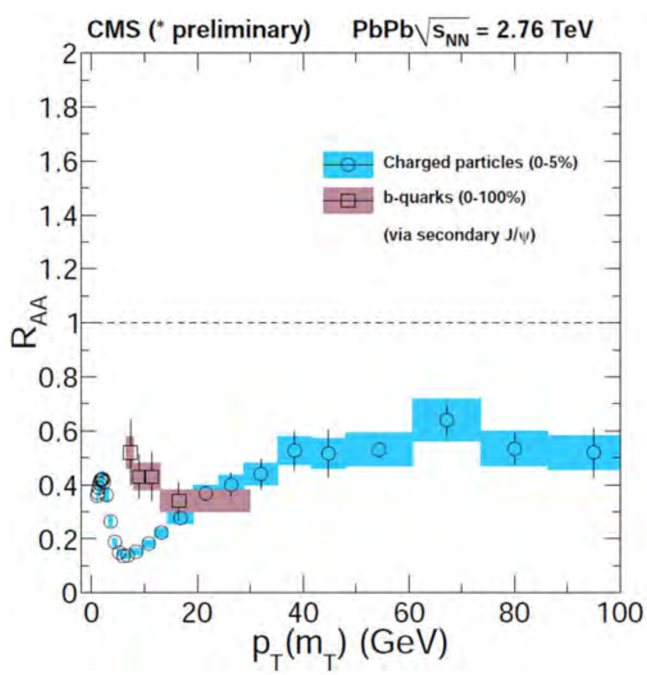

Fig. 6: Nuclear modification factor ($R_{\rm AA}$) of B mesons via secondary J/ψ compared to $R_{\rm AA}$ of light charged hadrons (Chatrchyan *et al.*, 2012a; Mironov *et al.*, 2013)

Summary

With the recent LHC measurements combined with RHIC measurements an overall understanding of quarkonia and heavy flavour production in heavy ion collisions is emerging. One of the the most noticeable results is sequential suppression of Υ states observed first time in heavy ion collisions. The Υ suppression at LHC is more than that at RHIC showing that the matter at LHC has stronger colour screening. The measurements of Υ states in pPb collisions suggest the presence of final effects in pPb collisions affecting ground state and excited states differently.

High p_T J/ψ is more suppressed at LHC as compared to RHIC. The enhancement of low p_T J/ψ as compared to RHIC hints that that there is substantial regeneration. The enhancement of ratio of yields of excited to ground state charmonia at low p_T also points in this direction. More statistics expected in PbPb collisions at 5 TeV, a better p_T and rapidity dependence of quarkonia will certainly quantify the effects of colour screening and regeneration.

The LHC hints mass hierarchy in suppression of hadrons below $p_T \sim 8$ GeV/c. For $p_T > 10$ GeV/c, the suppression of light hadrons, charm mesons and bottom mesons are consistent. Better precision and larger p_T reach will help quantifying the energy loss properties of the medium.

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