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Quarkonia results in heavy-ion collisions from CMS

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This writeup summarizes CMS results on quarkonia measurements in pp, pPb and PbPb collisions at LHC. CMS has excellent muon detection capabilities which has resulted in a wealth of results on quarkonia (both charmonia as well as bottomonia) measured in dimuon channel. The good mass resolution in dimuon channels allows precise measurement of all three Υ states and their relative yields in pp, pPb as well as PbPb systems, which have ability to quantify the properties of strongly interacting matter. In the charmonia sector, measurements of relative yields of J/ψ, ψ(2S) are equally useful. In addition excellent vertex capability of CMS enables measurement of B mesons via its decay to J/ψ which are useful tool to verify energy loss mechanisms of heavy quarks in medium. 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.

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1. Introduction

The goal of the SPS, RHIC, and LHC heavy-ion programmes is to validate the existence and study the properties of the quark-gluon plasma (QGP), a state of deconfined quarks and gluons. One of its most striking expected signatures is the suppression of quarkonium states [1], both of the charmonium (J/ψ, ψ(2S), χ_c, etc.) and the bottomonium (Υ(1S, 2S, 3S), χ_b, etc.) families. This is thought to be a direct effect of deconfinement, when the binding potential between the constituents of a quarkonium state, a heavy quark and its antiquark, is screened by the colour charges of the surrounding light quarks and gluons. The suppression is predicted to occur above the critical temperature of the medium (T_c) and depends on the $Q\overline{Q}$ binding energy alternatively the suppression can be understood in terms of quarkonium dissociation by collisions with gluons [2, 3].

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 [4] showed almost the same suppression at a much higher energy contrary to the expectation [5]. Such an observation was consistent with the scenario that at higher collision energy the expected greater suppression is compensated by regeneration of J/ψ by recombination of two independently produced charm quarks [6]. Since the LHC first performed Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, a wealth of quarkonia results have become available [7, 8]. Some of these results are presented in this writeup and their significance is discussed. The quarkonia yields in heavy-ion collisions can also be modified by non-QGP effects such as, modification of the parton distribution functions inside the nucleus, known as shadowing and dissociation due to hadronic or comover interaction [9, 10]. To get a quantitative idea about these effects, quarkonia measurements in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are performed. These measurements are also discussed in this writeup.

2. CMS detector at LHC

The central feature of CMS is a superconducting solenoid, of 6m internal diameter, providing a field of 3.8T Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The muons are measured in the pseudorapidity window $|\eta| \leq 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution better than 1.5% for p_T smaller than 100 GeV/c. A much more detailed description of CMS can be found in ref. [11]. Table 1 shows all the systems, center of mass energies and collected integrated luminosities for the measurements described in the writeup.

3. Measurements of charmonia states at CMS

The CMS experiment carries out J/ψ measurements at high transverse momentum ($p_T > 6.5$ GeV/c) and in the rapidity range $|y| \leq 2.4$. Figure 1 (left) shows 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

Table 1: LHC runs of heavy ion intrest.

year	system	$\sqrt{s_{\mathrm{NN}}}$(TeV)	L_{int}
2010	Pb−Pb	2.76	$\sim$10 μb^{-1}
2011	pp	2.76	$\sim$250 nb^{-1}
2011	Pb−Pb	2.76	$\sim$150 μb^{-1}
2013	p−Pb	5.02	$\sim$30 nb^{-1}
2013	pp	2.76	$\sim$ 5 pb^{-1}

(centrality) measured by CMS [12, 13]. The nuclear modification factor of these high p_T prompt J/ψ decreases with increasing centrality showing moderate suppression even in the most peripheral collisions. By comparing with the STAR results [14] at RHIC it follows that the suppression of high p_T J/ψ has increased with collision energy. The ALICE J/ψ results [15] cover low p_T range

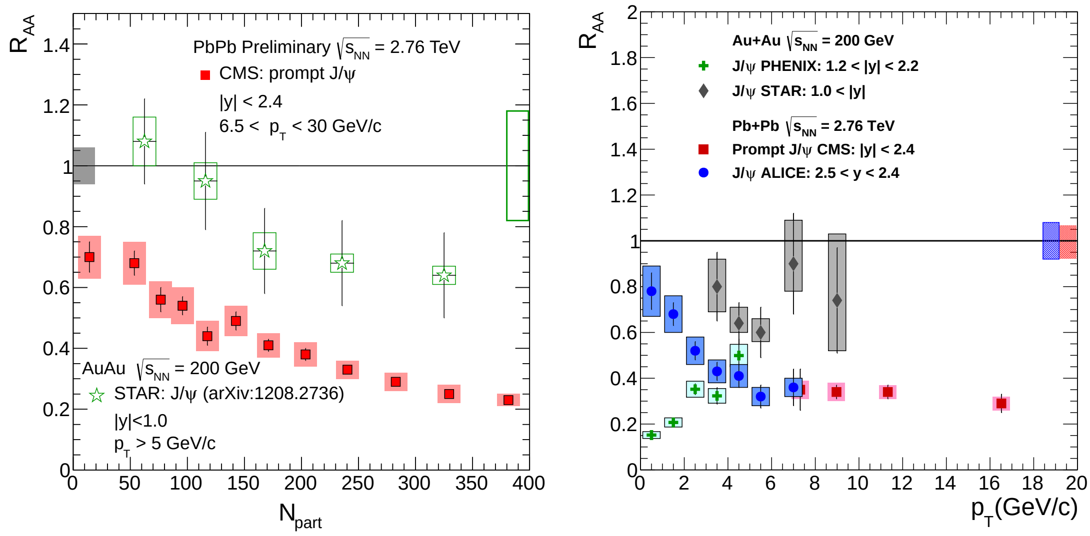

Figure 1: The nuclear modification factor (R_{AA}) of J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of number of participants (left) and p_T (right), measured by CMS experiment [12, 13]. Measurements from other detectors are also shown for comparison.

at forward rapidity. At low p_T the R_{AA} has little or no centrality dependence except very peripheral collisions.

Figure 1 (right) shows R_{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_{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, up to $\sim$ 16 GeV/c [12, 13]. By comparing with the STAR results [14] at RHIC it follows that the suppression of high p_T J/ψ has increased with collision energy. The ALICE J/ψ data [15] shows that R_{AA} increases with decreasing p_T below 4 GeV/c. On comparing with the PHENIX forward rapidity measurement [4], 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. Figure 2 (left) shows the double ratio of ψ(2S) and J/ψ as a function of centrality measured by CMS in two kinematic regions [16]. In the midrapidity bin, where all measured charmonia must have $p_T > 6.5$ Gev/c, the double ratio is less than unity in all three centrality bins, with a central-integrated value of 0.45 ± 0.13 (stat.) $\pm$ 0.07 (syst.), including the global pp uncertainties. In the forward rapidity bin, which includes charmonia with p_T extending down to 3 GeV/c, the double ratio increases with centrality, reaching the value 2.31 ± 0.53 (stat.) $\pm$ 0.38 (syst.) $\pm$ 0.15 (pp) in the most central collisions. It indicates that central PbPb collisions produce more ψ(2S) mesons than J/ψ mesons, with respect to the pp reference.

Additional insight into properties of the QGP can be obtained through study of the azimuthal anisotropy of quarkonia in lead-lead (PbPb) collisions. A non-zero elliptic anisotropy, for example, could provide evidence for recombination of thermalized charm quarks. Figure 2 (right) shows CMS measurement of prompt J/ψ v_2 [17] as a function of J/ψ transverse momentum in 10-60% centrality events. The results are compatible with a p_T independent, non zero anisotropy, whether measured at low-p_T ($3 < p_T < 6.5$ GeV/c) in the forward rapidity interval $1.6 < |y| < 2.4$, or at high-p_T ($6.5 < p_T < 30$ GeV/c) in rapidity interval $|y| < 2.4$.

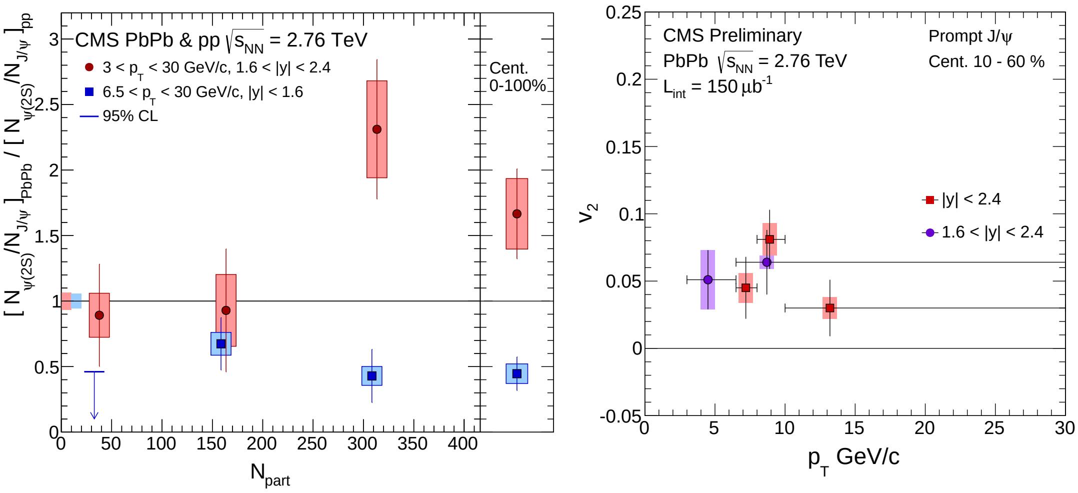

Figure 2: (left) Double ratio of prompt ψ(2S) and J/ψ as a function of centrality measured by CMS in two kinematic regions [16]. (right) Prompt J/ψ azimuthal anisotropy (v_2) as a function of J/ψ transverse momentum [17].

4. Measurements of bottomonia states at CMS

At LHC energies, the Υ states are produced with good statistics. The CMS measurements [18, 19] reveal that the higher Υ states, Υ(2S) and Υ(3S), are more suppressed relative to the ground state Υ(1S), a phenomenon known as sequential suppression. Figure 3(left) shows the R_{AA} of Υ(1S) and Υ(2S) measured by CMS. The figure also shows STAR measurement of Υ(1S) R_{AA} [20]. We can clearly see from the figure that Υ's are more suppressed at higher collision energy. Figure 3(right) shows the R_{AA} of Υ(1S) and Υ(2S) measured by CMS along with the ALICE measurements [21] at forward rapidity, $(2.5 \leq y^{\Upsilon} \leq 4.0)$. The figure indicate that at forward rapidity, Υ(1S) is slightly more suppressed than the CMS measurements at midrapidity, $|y^{\Upsilon}| \leq 2.4$.

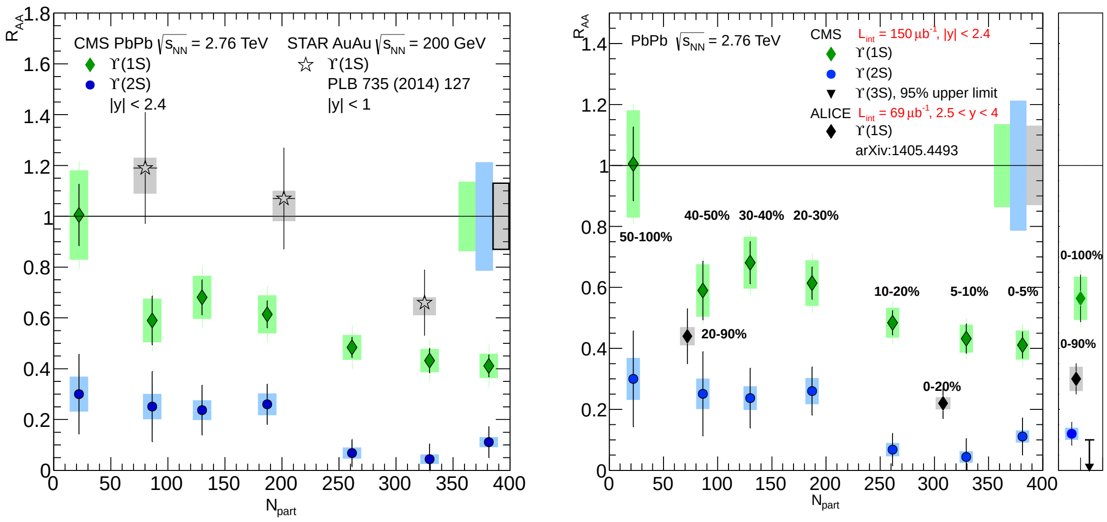

Figure 3: (left) Comparison of the Υ(1S) nuclear modification factor R_{AA} centrality dependence result to the Υ(1S) R_{AA} measurent by STAR [20]. The STAR Results are binned in classes of centrality 0-10%, 10-30% and 30-60%. (right) Comparison of the Υ(1S) and Υ(2S) nuclear modification factor R_{AA} centrality dependence results to the Υ(1S) R_{AA} measured in the forward rapidity range (2.5<y<4) by ALICE[21]

To understand different mechanism of suppression in hot and cold nuclear matter CMS utilizes proton-lead (pPb) collision data provided by LHC in the start of 2013. This data provides an essential reference to understand initial state effects and may also provide insight into cold nuclear effects that may be distinct from the suppression effects observed in PbPb collisions [18, 19]. Figure 4 (left) shows the ratios of the excited states, Υ(2S) and Υ(3S), to the ground state, Υ(1S) in pPb collisions at $\sqrt{s_{NN}}$=5.02 TeV with respect to pp collisions at $\sqrt{s}$=2.76 TeV. These ratios are compared to the corresponding ratios for PbPb (cross) collisions at $\sqrt{s_{NN}}$=2.76 TeV [19, 22]. Double ratios in pPb collision are larger than PbPb ratios but still are less than one. This suggest presence of final state effects in pPb and PbPb collisions, which affect more strongly excited states Υ(2S) and Υ(3S) than Υ(1S). The pp and pPb data are further analyzed separately as a function of event activity variables. Figure 4 (right) shows the excited to ground states cross section ratios, Υ(2S)/Υ(1S), as a function of number of charged particles in the rapidity range $|\eta|$ <2.4 for all three collision systems. These ratios, are found to decrease with increasing charged-particle multiplicity. This trend can be explained in two opposite ways. If, on the one hand, the Υ(1S) is systematically produced with more particles than the excited states, it would influence the underlying distribution of charged particles and create an artificial effect when selected in small multiplicity bins. This effect should be sensitive to the underlying multiplicity distribution, and would result in a larger correlation if one reduces the size of the multiplicity bins. On the other hand, if the Υ are interacting with the surrounding environment, the Υ(1S) is expected, as the most tightly bound state and the one of smallest size, to be less affected than Υ(2S) and Υ(3S), leading to a decrease of the Υ(nS)/Υ(1S) ratios with increasing multiplicity. In either case, the ratios will continuously decrease from the pp to pPb to PbPb systems, as a function of event multiplicity.

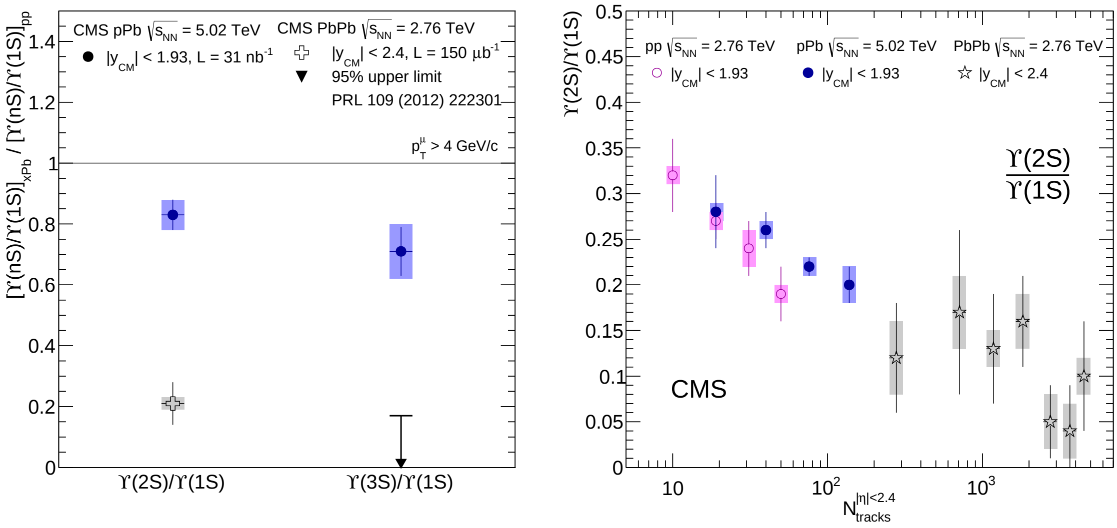

Figure 4: (left) Event activity integrated double ratios of the excited states, ϒ(2S) and ϒ(3S), to the ground state, ϒ(1S) in pPb collisions at $\sqrt{s_{NN}}$=5.02 TeV with respect to pp collisions at $\sqrt{s}$=2.76 TeV (circles), compared to the corresponding ratios for PbPb (cross) collisions at $\sqrt{s_{NN}}$= 2.76 TeV [19, 22]. (right) Single cross section ratios ϒ(2S)/ϒ(1S) for $|y_{\text{CM}}| < 1.93$ versus number of charged tracks measured in $|\eta| < 2.4$ for pp collisions at TeV $\sqrt{s}$ (open symbols), pPb collisions at $\sqrt{s_{NN}}$ 5.02 TeV(closed symbols) and PbPb collisions at $\sqrt{s_{NN}}$ 2.76 TeV (open stars).

5. Heavy flavour measurements

CMS offers B meson measurements via detecting secondary J/ψ coming from a displaced vertex. Figure 5 shows the R_{AA} of B mesons via secondary J/ψ compared to R_{AA} of light hadrons [12, 13]. 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_{AA} is larger as compared to light hadrons. Combining CMS B meson results with the ALICE measurements of D-meson [23] containing c-quarks it follows that at low p_T there is mass hierarchy in the amount of suppression such that, $R_{\text{AA}}^{\text{light hadrons}} < R_{AA}^{\text{D meson}} < R_{AA}^{\text{B meson}}$. Several theoretical models claims to get similar mass scaling if they include both collisional as well as radiative energy loss [24, 25].

6. 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.

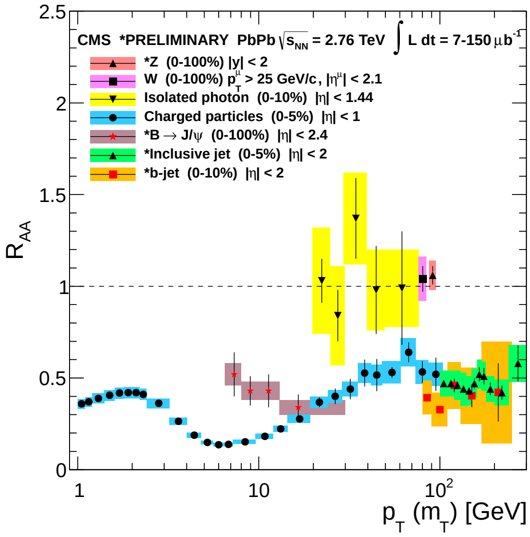

Figure 5: Nuclear modification factor (R) of B mesons via secondary J/ψ compared to R_{AA} of light charged hadrons [12, 13].

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.

References

[1] T. Matsui and H. Satz, "J/ψ Suppression by Quark-Gluon Plasma Formation," Phys. Lett. B **178**, 416 (1986).

[2] X. -M. Xu, D. Kharzeev, H. Satz and X. -N. Wang, "J/ψ suppression in an equilibrating parton plasma," Phys. Rev. C **53**, 3051 (1996).

[3] V. Kumar, P. Shukla and R. Vogt, "Quarkonia suppression in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV," Phys. Rev. C **92**, no. 2, 024908 (2015).

[4] A. Adare *et al.* [PHENIX Collaboration], "J/ψ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **84**, 054912 (2011).

[5] N. Brambilla, S. Eidelman, B. K. Heltsley, R. Vogt, G. T. Bodwin, E. Eichten, A. D. Frawley and A. B. Meyer *et al.*, "Heavy quarkonium: progress, puzzles, and opportunities," Eur. Phys. J. C **71**, 1534 (2011).

[6] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, "Statistical hadronization of charm in heavy ion collisions at SPS, RHIC and LHC," Phys. Lett. B **571**, 36 (2003).

[7] B. Muller, J. Schukraft and B. Wyslouch, "First Results from Pb+Pb collisions at the LHC," Ann. Rev. Nucl. Part. Sci. **62**, 361 (2012).

[8] P. Shukla [CMS Collaboration], "Overview of quarkonia and heavy flavour measurements by CMS," arXiv:1405.3810 [nucl-ex].

[9] R. Vogt, "Cold Nuclear Matter Effects on J/ψ and Υ Production at the LHC," Phys. Rev. C **81**, 044903 (2010).

[10] R. Vogt, "Shadowing Effects on J/ψ and Υ Production at the LHC," arXiv:1507.04418 [hep-ph].

[11] S. Chatrchyan *et al.* [CMS Collaboration], "The CMS experiment at the CERN LHC," JINST **3**, S08004 (2008).

[12] S. Chatrchyan *et al.* [CMS Collaboration], "Suppression of non-prompt J/ψ, prompt J/ψ, and Y(1S) in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," JHEP **1205**, 063 (2012).

[13] C. Mironov [CMS Collaboration], "Overview of results on heavy flavour and quarkonia from the CMS Collaboration," Nucl. Phys. A **904-905**, 194c (2013).

[14] Z. Tang [STAR Collaboration], "J/ψ production and correlation in p+p and Au+Au collisions at STAR," J. Phys. G **38**, 124107 (2011).

[15] B. B. Abelev *et al.* [ALICE Collaboration], "Centrality, rapidity and transverse momentum dependence of J/ψ suppression in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV," Phys. Lett. **743**, 314 (2014).

[16] V. Khachatryan *et al.* [CMS Collaboration], "Measurement of Prompt $\psi(2S) \to J/\psi$ Yield Ratios in Pb-Pb and $p-p$ Collisions at $\sqrt{s_{NN}} = 2.76$ TeV," Phys. Rev. Lett. **113**, no. 26, 262301 (2014).

[17] CMS Collaboration, CMS Physics Analysis Summary CMS-HIN-12-001 (2012)

[18] S. Chatrchyan *et al.* [CMS Collaboration], "Indications of suppression of excited Υ states in PbPb collisions at $\sqrt{S_{NN}} = 2.76$ TeV," Phys. Rev. Lett. **107**, 052302 (2011).

[19] S. Chatrchyan *et al.* [CMS Collaboration], "Observation of sequential Upsilon suppression in PbPb collisions," Phys. Rev. Lett. **109**, 222301 (2012).

[20] L. Adamczyk *et al.* [STAR Collaboration], "Suppression of Υ production in d+Au and Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV," Phys. Lett. B **735**, 127 (2014) [Phys. Lett. B **743**, 537 (2015)].

[21] B. B. Abelev *et al.* [ALICE Collaboration], "Suppression of Υ(1S) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV," Phys. Lett. B **738**, 361 (2014).

[22] S. Chatrchyan *et al.* [CMS Collaboration], "Event activity dependence of Υ(nS) production in $\sqrt{s_{NN}}$=5.02 TeV pPb and $\sqrt{s}$=2.76 TeV pp collisions," JHEP **1404**, 103 (2014).

[23] B. Abelev *et al.* [ALICE Collaboration], "Suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV," JHEP **1209**, 112 (2012).

[24] U. Jamil and D. K. Srivastava, "Nuclear suppression of heavy quark production at forward rapidities in relativistic heavy ion collisions," J. Phys. G **37**, 085106 (2010).

[25] K. Saraswat, P. Shukla and V. Singh, "Constraining heavy quark energy loss using B and D meson measurements in heavy ion collision at RHIC and LHC energies, arXiv:1507.06742 [nucl-th].

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