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Experimental overview: Quarkonium production in relativistic particle collisions

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Abstract. Quarkonium provides a golden probe of the formation of the Quark Gluon Plasma (QGP). Its production in heavy-ion collisions can be affected by an interplay of different phenomena such as medium-induced dissociation and heavy-quark (re)combination in the QGP, and cold nuclear matter effects due to the presence of the nucleus. The measurement of quarkonium states in different collision systems and beam energies allows to gain further insights on these effects and probe the properties of the QGP. In these proceedings, an overview of the main experimental quarkonium measurements in proton-proton, proton-nucleus and nucleus-nucleus collisions is presented, giving emphasis on the most recent results from the Large Hadron Collider and Relativistic Heavy Ion Collider experiments shown at the 2023 Quark Matter conference.

1 Introduction

Quarkonium ($Q\bar{Q}$) is a bound state of charm-anticharm ($c\bar{c}$, also called charmonium) or bottom-antibottom ($b\bar{b}$, bottomonium) quarks. It can be formed in a variety of states, such as the charmonium states J/ψ, ψ(2S) and χ_c, or bottomonium states Υ(1S), Υ(2S) and Υ(3S), which are characterised by different masses and binding energies, and there are still new quarkonium states being discovered (i.e. ψ_3(3842)) [1]. Due to its large mass, quarkonium is predominantly produced in the initial hard scattering of partons and experience the full evolution of the collision.

The measurement of quarkonia in heavy-ion (HI) collisions represents one of the most ideal probes to study the properties of the strongly interacting medium, the so-called quark-gluon plasma (QGP), formed in such interactions [2]. The original idea was proposed by T. Matsui and H. Satz [3], where the J/ψ yields in nucleus-nucleus (AA) collisions are expected to be significantly suppressed compared to the proton-proton (pp) yields scaled by the number of binary nucleon-nucleon collisions (N_{coll}), due to the color screening of the force binding the quarkonium state in the presence of a hot and deconfined medium. In this scenario, quarkonium states are sequentially melted into open charm or bottom mesons following the ordering of their binding energies for a given medium temperature [3]. In other words, strongly bound resonances such as J/ψ (Υ(1S)) should dissociate at higher temperatures compared to the more loosely bound ψ(2S) (Υ(2S) and Υ(3S)) states. However, theoretical studies based on lattice QCD and effective field theory calculations have shown that quarkonium states can also dissociate even before the medium has reached the dissociation temperature due to the broadening of the quarkonium width modeled as the imaginary

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part of the heavy-quark potential [4–6], which obscure the connection between the medium temperature and quarkonium suppression.

Experimentally, the study of the quarkonium in-medium dissociation faces several challenges. The first hurdle is that the fraction of directly produced quarkonia, as opposed to those created in feed-down decays of higher excited $Q\bar{Q}$ states, is currently not well know in pp and HI collisions, which complicates the understanding of the suppression pattern specially for J/ψ and Υ(1S).

Another important challenge is that the quarkonium production can also be modified by other phenomena competing with the in-medium suppression mechanism. As the collision energy is increased, more heavy quarks and antiquarks are produced in the collision which can lead to the formation of new quarkonia in the QGP from the (re)combination of these quarks either at the hadronization stage [7, 8] or throughout the evolution of the QGP [9, 10], enhancing the quarkonium yields. At the Large Hadron Collider (LHC) energies, given the higher number of $c\bar{c}$ than $b\bar{b}$ pairs produced, the (re)combination effect is mostly dominant for charmonia. In addition, the production of quarkonium is expected to be affected, even in the absence of a QGP medium, by the so-called cold-nuclear matter (CNM) effects due to the nuclear environment. The CNM effects are investigated in proton-nucleus (pA) collisions, where the formation of a large hot medium is not foreseen, and include the modifications of parton distributions in the nucleus (e.g. gluon shadowing) [11], interactions of the $Q\bar{Q}$ state with either nucleons of the target nuclei (e.g. nuclear absorption) [12] or co-moving particles produced in the collision [13] resulting in the break-up of the meson, and effects of parton energy loss [14].

The first evidence of a J/ψ anomalous suppression (i.e. beyond CNM effects) was observed in lead-lead (PbPb) collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}}$ = 17 GeV at the CERN Super Proton Synchrotron (SPS) [15]. Afterwards, the study of quarkonium production has been carried out at the Relativistic Heavy Ion Collider (RHIC) by colliding different beam species and varying the collision energy. The RHIC gold-gold (AuAu) data at $\sqrt{s_{\rm NN}}$ = 200 GeV showed a similar level of J/ψ suppression at mid-rapidity as seen at SPS, despite the higher energy densities at RHIC, suggesting an interplay of dissociation and (re)combination already at RHIC energies [16]. Since 2011, the charmonium measurements at the LHC performed in PbPb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV, have shown a larger contribution from J/ψ (re)combination at LHC than at RHIC [17]. In addition, the higher $\sqrt{s_{\rm NN}}$ (up to 5.02 TeV) at LHC has expanded the access to bottomonia, allowing to measure the Υ(1S) and Υ(2S) suppression in PbPb collisions, while only upper limits have been published so far for the Υ(3S) state [18]. Apart from AA collisions, the quarkonium production has also been extensively studied in pp and pA collisions, with the initial idea of providing a baseline for AA measurements and characterise the production mechanism in smaller systems.

An overview of some of the latest quarkonium experimental measurements presented at the 2023 Quark Matter conference will be discussed in the following sections, covering results from small and large collision systems at RHIC and LHC.

2 Quarkonia in small systems

New quarkonium results in pp collisions performed at LHC were presented covering a wide range of collision energies up to $\sqrt{s}$ = 13.6 TeV [19, 20]. The measured cross sections are well described by quarkonium production models [21, 22], significantly surpassing the theoretical uncertainties, which will help to further constrain the models. At high particle multiplicities, models including multi-particle interactions depict the relative charged-particle density dependence of the normalised J/ψ yields seen at RHIC.

In the case of pPb collisions, the LHC measurements show a sequential suppression of the nuclear modification factor (R_{pPb}) of quarkonium states, as seen in Fig. 1 for bottomonium (left) and charmonium (right). Moreover, the PHENIX results at RHIC [23], shown in Fig. 2 left, also displays a stronger ψ(2S) suppression than J/ψ towards pAu collisions with larger N_{coll} at $\sqrt{s_{NN}}$ = 200 GeV, consistent with LHC results in pPb at 8.16 TeV [24]. The R_{pPb} pattern observed in data is modeled considering final-state interactions with co-moving particles produced in the collision [13].

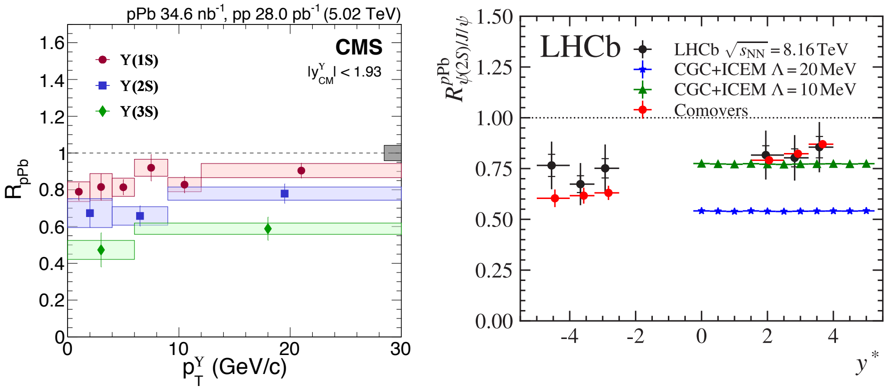

Figure 1. Left: R_{pPb} of Υ(1S) (red), Υ(2S) (blue) and Υ(3S) (green) as functions of p_T obtained by the CMS experiment at 5.02 TeV [25]. Right: Double ratio of prompt ψ(2S)-to-J/ψ yields versus rapidity, measured in pPb at 8.16 TeV by the LHCb experiment [26] (black) and compared to glun saturation [27] (blue and green) and comover [13] (red) models.

The measurement of the χ_c production in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV was derived, for the first time at LHC, by the LHCb Collaboration. The measured ratios of prompt χ_c-to-J/ψ in pPb and pp collisions are overall similar as displayed in Fig. 2 right, consistent with previous results at RHIC in pAu at 200 GeV [28] and HERA in pA at 41.6 GeV [29], although a slight upward deviation is seen at backward rapidity for $p_T < 3$ GeV. These results open new opportunities to study how χ_c states are affected by CNM effects at LHC energies, and further extract their feed-down fraction to J/ψ in HI collisions.

3 Quarkonia in AA collisions

The CMS Collaboration studied the centrality dependence of the bottomonium production in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The large PbPb luminosity recorded in 2018 and the use of multi-variate analysis techniques allowed to observe for the first time the Υ(3S) in AA collisions. The corresponding nuclear modification factor R_{AA}, as a function of the average number of participant nucleons (N_{part}), shows a clear suppression pattern of the Υ(1S), Υ(2S) and Υ(3S) states [32]. Furthermore, the CMS Υ(1S) R_{AA} is comparable to the new STAR results [33] extracted in AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV while the CMS Υ(2S) R_{AA} is smaller than at RHIC, as displayed in Fig. 3, implying that the direct Υ(1S) might not be significantly dissociated in the QGP at LHC. Thus further measurements of higher excited states in AA collisions, specially of χ_b, will be important to discern the impact of feed-down contributions for bottomonia.

The charmonium production in AA collisions has also been studied at LHC and RHIC. The J/ψ production measured in central PbPb collisions by the ALICE Collaboration [34, 35]

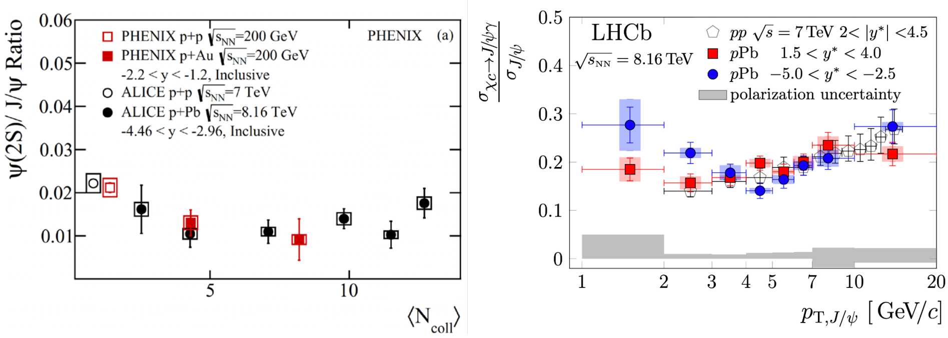

Figure 2. Left: Ratio of ψ(2S)-to-J/ψ yields as functions of N_{coll} at backward rapidity, measured by PHENIX in pAu at 200 GeV [23] (red) and ALICE in pPb at 8.16 TeV [24] (black). Right: LHCb ratio of prompt χ_c-to-J/ψ yields versus p_T at forward (red) and backward (blue) rapidities derived in pPb at 8.16 TeV [30] and compared to pp at 7 TeV [31] (open markers).

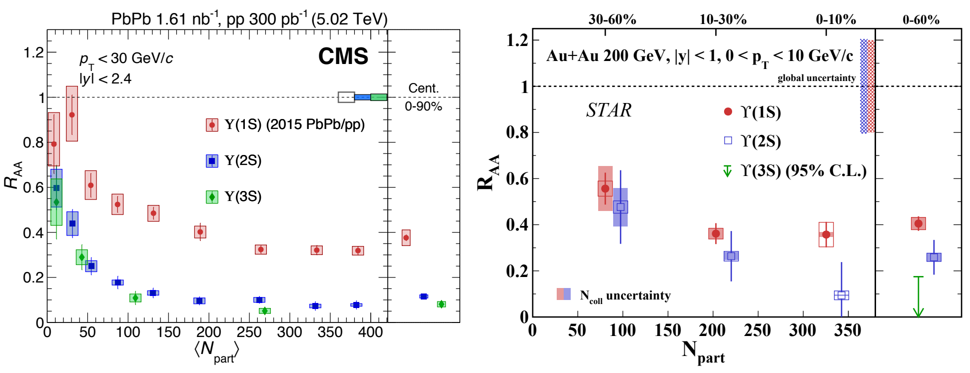

Figure 3. R_{AA} of Υ(1S) (red), Υ(2S) (blue) and Υ(3S) (green) as a function of N_{part} measured by CMS in PbPb at 5.02 TeV [32] (left) and STAR in AuAu at 200 GeV [33] (right).

is in accordance with models including dissociation and (re)combination effects [7–9]. Furthermore, as seen in Fig. 4, recent ALICE results [36] show a larger suppression of ψ(2S) than J/ψ over the full spectra but the ψ(2S) R_{AA} slightly increases towards lower p_T, compatible with transport models including ψ(2S) (re)combination [9]. The STAR Collaboration also reported new results on the study of the energy and system-size dependence of charmonium R_{AA}. No significant energy dependence of J/ψ R_{AA} for collision energies up to 200 GeV is observed and a stronger ψ(2S) suppression than J/ψ is seen in the most central isobar (RuRu and ZrZr) collisions at RHIC.

4 Summary

The 2023 Quark Matter conference showcased several new quarkonium measurements in a wide range of collision species and energies performed at RHIC and LHC. The latest quarkonium data in pp collisions have reached a level of precision that far surpasses the current theoretical uncertainties, improving our understanding of the production mechanism of quarkonium in vacuum. Moreover, the nuclear modification of quarkonia in pA collisions displays

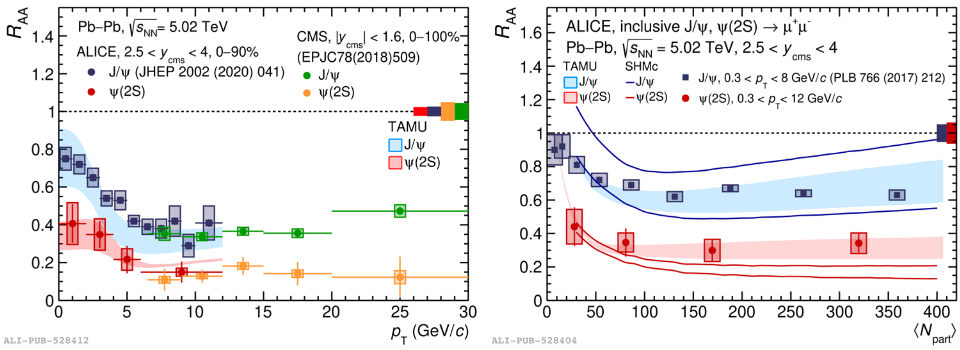

Figure 4. Inclusive ψ(2S) [36] (red) and J/ψ [37] (blue) R_{AA} as a function of p_T (left) and N_{part} (right), measured at forward rapidity by the ALICE Collaboration in PbPb at 5.02 TeV. The p_T-dependence of prompt ψ(2S) (orange) and J/ψ (green) R_{AA} from the CMS experiment [38] are also shown (left). The data is compared to transport [9] (shaded area) and statistical hadronization [7, 8] (lines) models.

a clear sequential suppression of states, where the higher excited states are more suppressed than the ground states at both LHC and RHIC, which was described by models relying on comover interactions and CNM effects. In addition, the χ_c-to-J/ψ ratio is measured by the LHCb Collaboration in pPb collisions for the first at LHC, showing no significant deviation from pp collisions. The production of quarkonia was also extensively studied in AA collisions. At the LHC, the CMS Collaboration reported the first observation of Υ(3S) and measured the sequential suppression of Υ(1S), Υ(2S) and Υ(3S). On the other hand, the ALICE Collaboration studied the charmonium suppression in more detail and found hints of ψ(2S) (re)combination at low p_T. These results are compatible with the dissociation and (re)combination picture of quarkonia in HI collisions. And at RHIC, the STAR Υ(1S) R_{AA} results are similar to the CMS measurements, despite the higher energy densities at LHC, questioning whether the directly produced Υ(1S) measured at RHIC and LHC is significantly dissociated in the QGP. The sPHENIX and STAR upgrade programs at RHIC and the LHC Run 3 data, are going to improve in the upcoming years the precision of the quarkonium measurements and will allow to reach a more comprehensive description of quarkonium production from small to large collision systems.

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