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Quarkonia – Experimental Summary

Hugo Pereira Da Costa*
Université Paris-Saclay
E-mail: hugo.pereira-da-costa@cea.fr

Quarkonia are mesons formed out of either a charm and anti-charm quark pair (charmonia, e.g. J/ψ and $\psi(2S)$) or a beauty and anti-beauty quark pair (bottomonia, e.g. $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$). Their hadronic production starting very early in a heavy-ion collision, via the hard scattering of two partons, they constitute a prominent tool to study the properties of the Quark-Gluon Plasma (QGP), formed in such collisions. Two competing effects are expected to modify the quarkonium production in presence of the QGP with respect to expectations based on production rates in proton-proton (pp) collisions: a suppression due to a Debye-like color screening mechanism and an enhancement due to the (re)combination of uncorrelated heavy quark pairs from the hot medium. In absence of the QGP, quarkonium production also carry information about so-called Cold Nuclear Matter (CNM) effects, such as the modifications of the parton distribution functions in the nucleus and parton energy loss. Those are studied by measuring quarkonium production in lighter collision systems, in which the QGP is not expected to be formed. Finally, pp collisions are used not only as a mandatory near-vacuum reference for the study of hot and cold effects on quarkonia, but also to study the still debated quarkonium production mechanism as well as the possible role of Multi-Parton Interactions (MPI). In these proceedings we will present a summary of the recent results on quarkonium production presented at the International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, and how these address the topics above.

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*Speaker.

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1. Introduction

The hadronic production of quarkonia, bound states of either a charm and anti-charm quark pair (charmonia, e.g. J/ψ and $\psi(2S)$) or a beauty and anti-beauty quark pair (bottomonia, e.g. $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$), starts very early in a heavy-ion collision, via the hard scattering of two partons. As such quarkonia constitute a prominent tool to study the properties of the Quark-Gluon Plasma (QGP), formed in such collisions. Two competing effects are expected to modify the quarkonium production in presence of the QGP with respect to expectations based on production rates in proton-proton (pp) collisions: a suppression due to a Debye-like color screening mechanism [1] and an enhancement due to the (re)combination of uncorrelated heavy quark pairs from the hot medium [2, 3, 4]. The magnitude of the suppression effect depends on the temperature of the plasma and the binding energy of the quarkonium. The magnitude of the enhancement depends mainly on the abundance of the heavy quarks and thus on both the collision energy and the heavy quark mass. In particular it is expected that the (re)combination effect would play a smaller role for bottomonium than for charmonium. In absence of the QGP, quarkonium production also carries information about so-called Cold Nuclear Matter (CNM) effects such as the modifications of the parton distribution functions in the nucleus and parton energy loss. Those are studied by measuring quarkonium production in lighter collision systems, in which the QGP is not expected to be formed. Parton distribution functions (specifically those of gluons) can also be studied in so-called ultra-peripheral heavy ion collisions, characterized by a distance between the two colliding nuclei being larger than the sum of their respective radius, and for which the dominant source of quarkonia is from photoproduction. Finally, pp collisions are used not only as a mandatory near-vacuum reference for the study of hot and cold effects on quarkonia, but also to study the still debated quarkonium production mechanism as well as the possible role of Multi-Parton Interactions (MPI).

These proceedings are organized as follow: Sec. 2 is dedicated to quarkonium production in pp collisions; Sec. 3 to proton-nucleus (pA) collisions and small systems; Sec. 4 to nucleus-nucleus (AA) collisions and Sec. 5 to quarkonium photoproduction.

2. Proton-proton collisions

Several models attempt at describing quarkonium production cross sections in pp collisions as a function of its transverse momentum p_T and rapidity y. They are: the (improved) Color Evaporation Model [5, 6], the Color Singlet Model [7] and Non-Relativistic QCD (NRQCD) [8]. The STAR, ALICE, and ATLAS collaborations have presented comparisons of J/ψ production cross sections as a function of p_T at collision energies $\sqrt{s} = 500$ GeV (STAR) and $\sqrt{s} = 5.02$ TeV (ALICE, ATLAS [9]) with colinear next-to-leading order NRQCD calculations at high p_T and at low p_T (< 5 GeV/c) with a model in which the NRQCD matrix elements are coupled to gluon distributions evaluated from the Color-Glass-Condensate (CGC) effective field theory [10]. A good description of the data is obtained at both energies and over the full transverse momentum range. A similar level of agreement has been obtained in the past at other collisions energies, for both J/ψ and $\psi(2S)$ as well as for the y dependence of the cross sections. Issues remain however, when trying to describe also the J/ψ polarisation, or the production of the η_c. It is also to be noted that there is no consensus yet on the set of Long Distance Matrix Elements to be used for the NRQCD calculations, and that large differences exist depending on the group producing the calculation, the data sets used for adjusting these coefficients and the minimum p_{T} at which these are both evaluated and applicable.

The role of Multi-Parton Interactions on quarkonium production as well as possible correlations between quarkonium production and the underlying event can be studied by measuring quarkonium yields as a function of the event activity, characterized for instance by the number of charged particles produced at mid-rapidity. ALICE observes an increase of the relative quarkonium yields (that is, normalized to the minimum-bias yield) for increasing relative charged particle multiplicity (Fig. 1 left). This increase is approximately linear for forward-rapidity quarkonia. It is independent of the collision energy (comparing $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV pp collisions) and of the quarkonium species (comparing J/ψ, Υ(1S) and Υ(2S)). On the other hand, it is faster than linear for quarkonia produced at mid-rapidity. This observed y dependence could be a consequence of additional correlation effects when the quarkonia and the event activity are measured in the same rapidity range. Correlations between the quarkonia and the surrounding hadrons can also be studied by measuring in-jet quarkonium production via fragmentation functions. CMS measured a J/ψ fragmentation function that peaks at values lower than that predicted by PYTHIA 8, indicating that J/ψ are less isolated in the data than in PYTHIA (Fig. 1 right).

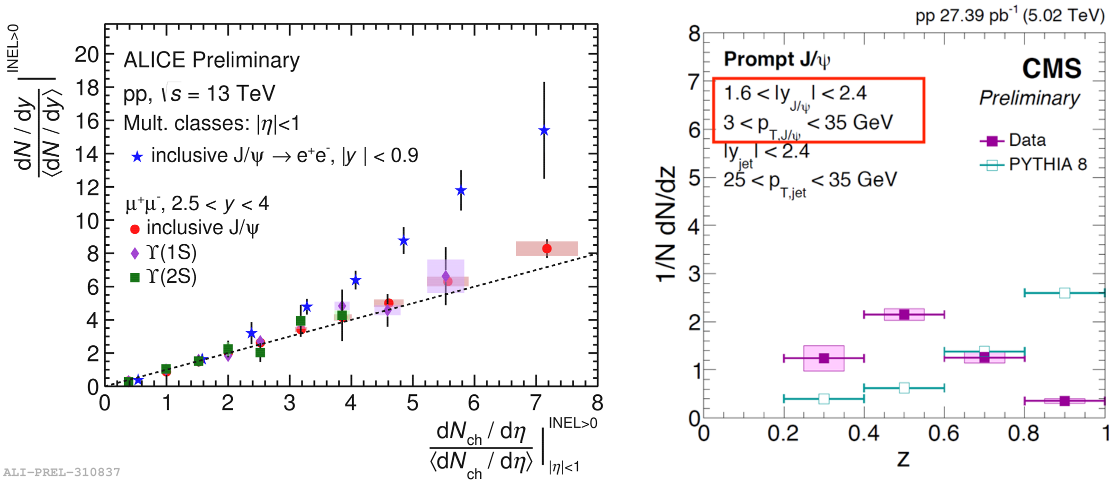

Figure 1: Relative J/ψ, Υ(1S) and Υ(2S) yields as a function of the relative charged particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV (left). J/ψ fragmentation function in pp collisions at $\sqrt{s} = 5.02$ TeV (right).

3. Proton-nucleus collisions and small systems

Turning to small collision systems and cold nuclear matter effects, PHENIX has presented results on the J/ψ nuclear modification factor R_{AB} in p–Al, p–Au, d–Au and ^{3}He–Au collisions at a center of mass energy per nucleon-nucleon collision $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (Fig. 2) and in two rapidity ranges. For the lighter p–Al collision system, R_{AB} is consistent with unity indicating that J/ψ production in such collisions is identical to that in pp. For the other systems on the other hand, a suppression is observed for J/ψ produced in the direction opposite to that of the Au nucleus, consistent with gluon shadowing and gluon saturation expectations. In the other direction, some amount of suppression is also observed, possibly due to the nuclear dissociation of the J/ψ pre-resonant state.

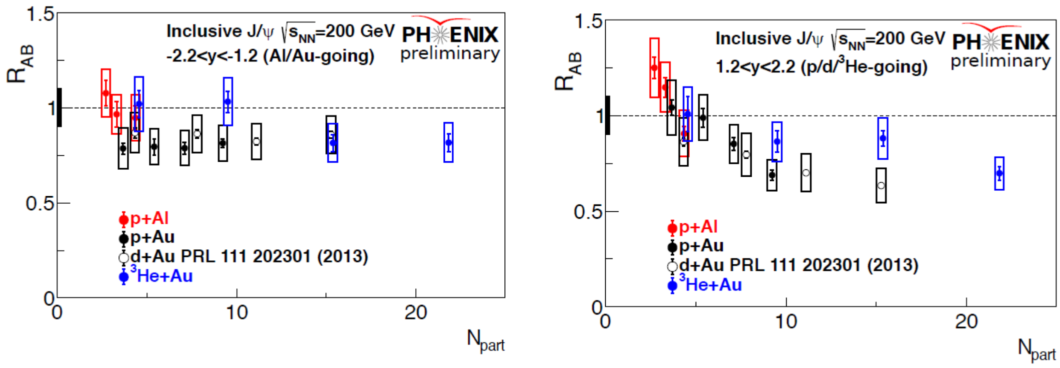

Figure 2: J/ψ nuclear modification factor $R_{\rm AB}$ in p–Al, p–Au, d–Au and ^{3}He–Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, at negative (left) and positive (right) rapidity.

The nuclear modification factor of J/ψ and Υ(1S) measured by ALICE [11] and LHCb [12] in centrality-integrated p–Pb collisions at $\sqrt{s_{\rm NN}} = 8$ TeV as a function of both $p_{\rm T}$ and y is qualitatively consistent with calculations that include nuclear modifications of the parton distribution functions and partonic energy loss. These show that the suppression is larger for quarkonia produced in the proton-going direction (corresponding to low-x gluons in the Pb nucleus) and is larger at low $p_{\rm T}$. Detailed measurements of the J/ψ centrality-dependent nuclear modification factor such as those presented by ALICE are expected to provide stringent constraints on models of the cold nuclear matter effects. It is found that such models can reproduce the trends of the measured $R_{\rm AB}$ in central collisions, but fail to reproduce their magnitude, in particular at low $p_{\rm T}$ and in the Pb going direction (large x).

The ψ(2S) $R_{\rm AB}$ is significantly smaller than that of the J/ψ at both RHIC energies ($\sqrt{s_{\rm NN}}$ = 200 GeV p–Au collisions), as measured by PHENIX [13], and LHC energies ($\sqrt{s_{\rm NN}} = 8.16$ TeV p–Pb collisions), as measured by ALICE. Similarly, the Υ(2S) and Υ(3S) are more suppressed (smaller $R_{\rm AB}$) than the Υ(1S) in $\sqrt{s_{\rm NN}} = 5.02$ [14, 9] and 8.16 TeV p–Pb collisions (Fig. 3 left). In contrast, a new measurement from STAR in p–Au at $\sqrt{s_{\rm NN}} = 200$ GeV shows a ψ(2S)-to-J/ψ $R_{\rm AB}$ ratio whose central value is larger than unity. However, the uncertainties on this measurement are rather large, and the measured ratio is consistent with the PHENIX mid-y measurement in d–Au within $\sim 1.5\sigma$.

Initial state cold nuclear matter effects, such as shadowing or energy loss cannot explain the differences observed for the nuclear modification factor of the excited states of a given flavor and the ground state, because those affect only the heavy quark pair and are independent of the final state's quantum numbers and binding energy. In order to explain the measured differences between ψ(2S) and J/ψ, or between Υ(2S), Υ(3S) and Υ(1S), final state effects must be included, such as the interaction of the quarkonium state with a comoving medium of either hadronic or partonic nature [16, 17]. Whether the presence of such comoving interactions constitutes a signature for the existence of QGP *droplets* in pA collisions is still debated.

Finally, a non-zero J/ψ elliptic flow v_2, corresponding to the second Fourier transform coefficient of the J/ψ azimuthal distribution has been measured in central p–Pb collisions at mid-rapidity

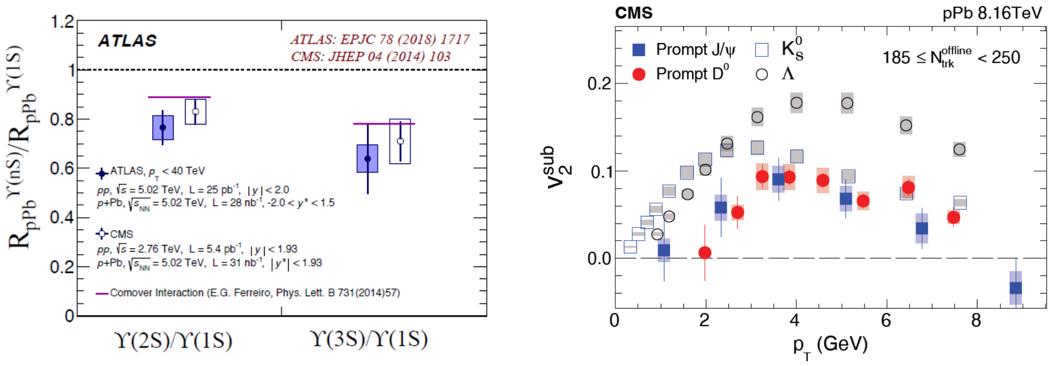

Figure 3: Υ(nS)-to-$\Upsilon(1S)$ nuclear modification ratios in $\sqrt{s_{\rm NN}} = 5$ TeV p–Pb collisions [14, 9] (left). prompt J/ψ and D^0 elliptic flow v_2 as a function of $p_{\rm T}$ in high-multiplicity $\sqrt{s_{\rm NN}} = 8.16$ TeV p–Pb collisions [15] (right).

and intermediate $p_{\rm T}$ by CMS [15] (Fig. 3 right) and at forward-rapidity by ALICE [18]. There can be two origins for a non-zero v_2: initial conditions (possible azimuthal asymmetries in the gluon distributions from the colliding nuclei) and final state effects in which the azimuthal asymmetry is a signature for collective behaviors in the created medium, resulting from some level of thermalization of its constituent, as it is expected to be the case in presence of a QGP. According to transport models capable of describing the J/ψ v_2 measured in Pb–Pb collisions, assuming the presence of QGP droplets in central p–Pb collisions is not enough to explain the magnitude of the observed effect [19]. On the other hand, calculations of the expected J/ψ elliptic flow based on initial conditions of the collisions are not available at this time, and the observed non-zero v_2 measurement remains a puzzle to date.

4. Nucleus-nucleus collisions

Nucleus-nucleus collisions are used to study the properties of the QGP and how it affects the production of quarkonia. One of the key observation for the J/ψ nuclear modification factor in Pb–Pb collisions at LHC energies is that it is larger (corresponding to a smaller suppression) than the one measured at RHIC, in $\sqrt{s_{\rm NN}} = 200$ GeV Au–Au collisions, and that the difference is concentrated at low $p_{\rm T}$ [20]. This difference is attributed to the onset of the contribution from (re)generated J/ψ out of uncorrelated c and $\bar{c}$ quarks from the hot medium, which on the other hand is only playing a marginal role at RHIC, due to the smaller $c\bar{c}$ pair abundance. With this respect, ALICE has presented new results on the inclusive mid-rapidity J/ψ $R_{\rm AA}$ in $\sqrt{s_{\rm NN}} = 5.02$ TeV Pb–Pb collisions. Both the $p_{\rm T}$-integrated mid-rapidity $R_{\rm AA}$ as a function of the collision centrality and the low-$p_{\rm T}$ mid-rapidity $R_{\rm AA}$ for central collisions are larger than that measured at forward-rapidity, which further confirms the (re)generation origin of the corresponding J/ψs.

Turning to high-$p_{\rm T}$ J/ψs, here the contribution from (re)combination is expected to be negligible and it is observed by ATLAS that the J/ψ $R_{\rm AA}$ decreases dramatically with increasing centrality, from unity in peripheral collisions down to about 0.2 for most central collisions [21]. These values are consistent with those measured at RHIC, for $p_{\rm T}$-integrated J/ψs [22]. As a function of transverse momentum, it is observed by ATLAS [21] and CMS [23] that for $p_{\rm T} > 10$ GeV/c, the

J/ψ R_{AA} starts to increase, with values that are similar to those measured for D^0 and $\overline{D^0}$ mesons, suggesting a common origin for both, namely in-medium energy loss of the c quarks, in contrast to the color-screening mechanism usually invoked to explain J/ψ suppression in the QGP.

Concerning higher mass excited states (ψ(2S), for charmonia, and Υ(2S), Υ(3S) for bottomonia), STAR, ATLAS [21] and CMS [23, 24] have consistently measured a larger suppression (smaller R_{AA}) than for the corresponding ground state (J/ψ and Υ(1S), respectively). For ψ(2S) there is some tension in the most central collisions between ATLAS and CMS. For Υs, it is observed on the one hand that the Υ(1S) suppression increases with centrality and is similar at RHIC energies, as measured by STAR and at LHC energies, as measured by CMS [24], and on the other hand that the Υ(2S)-to-Υ(1S) R_{AA} ratio at LHC is also similar to that measured at RHIC for Υ(2S)+Υ(3S)-to-Υ(1S) (Fig. 4). Additionally, it appears that the Υ(3S) is entirely suppressed at LHC energies [24]. This is consistent with expectations from a sequential melting picture, in which larger, looser bound excited states are suppressed at lower temperatures than the ground state. All these suppression patterns are reasonably well reproduced by transport models such as those from [25, 26].

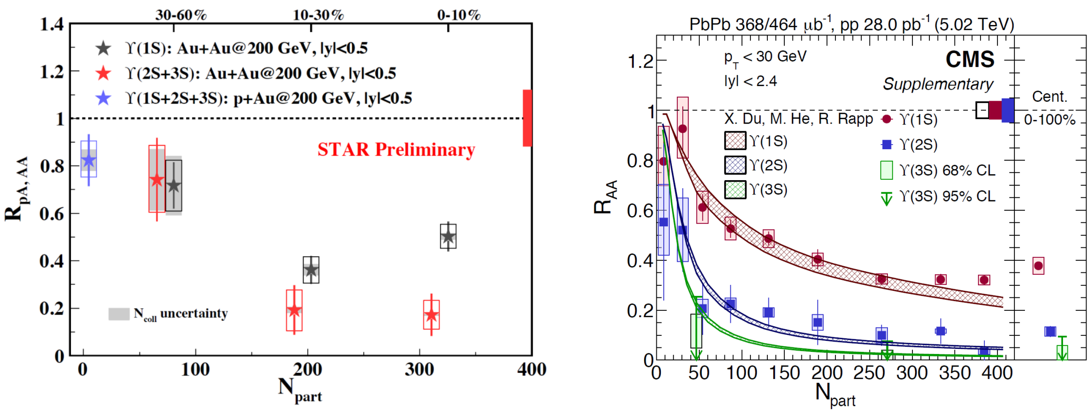

Figure 4: Υ(1S), Υ(2S) and Υ(3S) nuclear modification factor R_{AA} as a function of the collision centrality in $\sqrt{s_{NN}} = 200$ GeV Au–Au (left) and $\sqrt{s_{NN}} = 5.02$ TeV Pb–Pb (right) collisions [24].

A sizeable elliptic flow has been measured for both prompt and inclusive J/ψ in Pb–Pb semi-central collisions [27, 28] (Fig. 5 left). At low p_T ($p_T < 5$ GeV/c), the magnitude of the J/ψ v_2 is well reproduced by models [29, 30]. However, the observation of a non-zero v_2 for larger J/ψ p_T (up to 20 GeV/c) is not. Moreover the fact that the J/ψ v_2 for this p_T range is of similar magnitude to that observed in central, high-multiplicity p–Pb collisions, might point to a common origin, not included in the models. A first measurement of the J/ψ triangular flow v_3 was also presented by ALICE, in 0-50% centrality $\sqrt{s_{NN}} = 5.02$ TeV Pb–Pb collisions, with a significance of 3.7σ [31] (Fig. 5 right). This further confirms the presence of J/ψ from recombined charm quarks.

5. Quarkonium photoproduction

The last section of these proceedings is dedicated to quarkonium photoproduction in pp, pA and AA, for either ultra-peripheral collisions, defined as collisions for which the impact parameter is larger than the sum of the radius of the two colliding nuclei, or peripheral collisions. This

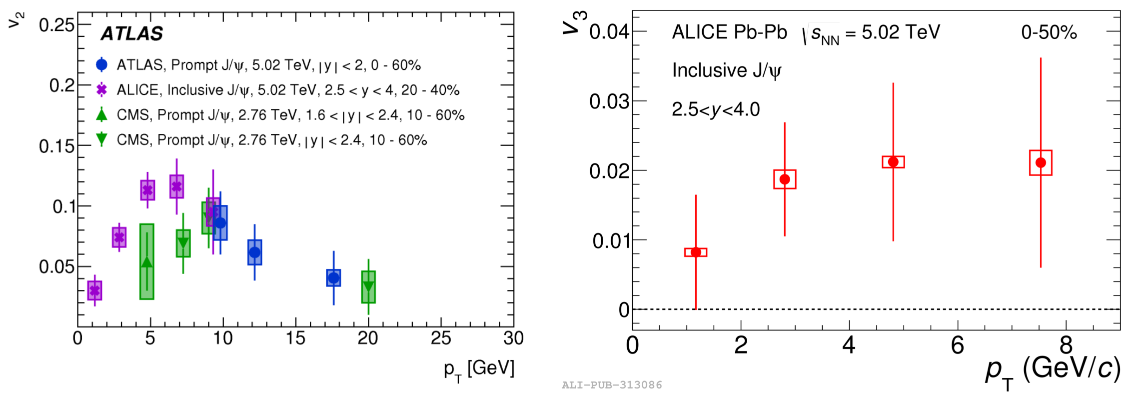

Figure 5: Prompt and inclusive J/ψ elliptic flow v_2 in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [27] (left). Inclusive forward-rapidity J/ψ triangular flow v_3 in 0-50% centrality $\sqrt{s_{NN}} = 5.02$ TeV Pb–Pb collisions [31] (right).

production mechanism involves a photon from the projectile and two gluons (a pomeron) from the target nucleus. In pp and pA collisions, this allows to probe the gluon distributions in the target proton, with the photon coming from the electromagnetic field of either the other proton or the projectile nucleus. Measuring the quarkonium photoproduction cross section as a function of W the center-of-mass energy of the γp system allows one to compare results obtained at different energies and quarkonium rapidity ranges. For J/ψ, a common trend is observed for measurements carried out by LHCb in pp collisions at $\sqrt{s} = 7$ and 13 TeV, ALICE, H1 and ZEUS as well as several other fixed-target experiments [32]. This trend is well reproduced by pQCD NLO calculations from the JMRT group [33]. The same is true for Υ(1S), in both pp collisions at $\sqrt{s} = 7$ and 8 TeV, as measured by LHCb at forward rapidity [34] and in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as measured by CMS at mid-rapidity [35] (Fig. 6 left).

In AA collisions, quarkonium photoproduction cross sections are sensitive to modifications of the gluon parton distribution functions in the nucleus. With respect to pp and pA collisions, there is the extra complication that photoproduction can be either coherent, meaning that the projectile photon interacts coherently with the entire target nucleus, or incoherent, in which the photon interacts only with one or several nucleons from the target. The later production is characterized by larger transverse momenta than the former. New results on forward-rapidity J/ψ photoproduction in ultra-peripheral Pb–Pb collisions have been presented by LHCb at $\sqrt{s_{NN}} = 5.02$ TeV (Fig. 6 right). They are compared to a collection of models that include different set of modifications of the gluon pdf. Unfortunately the discriminating power of these data for such models is rather limited, since they all tend to predict similar cross sections at forward-rapidity. This is in strong contrast with mid-rapidity measurements, for which the span of the predicted cross sections is much larger [36].

Quarkonium photoproduction is also expected to happen in AA peripheral collisions in parallel to hadroproduction. As for the ultra-peripheral case, this production source is characterized by a very low p_T ($p_T < 100$ MeV/c) and an excess is expected in this regime with respect to hadronic production, as estimated using N_{coll}-scaled pp production cross sections. Such an excess has been observed at RHIC, by STAR, and at LHC, by ALICE [37]. Quantifying this excess and subtracting both the hadronic and the incoherent photoproduction contributions allows one to measure cross

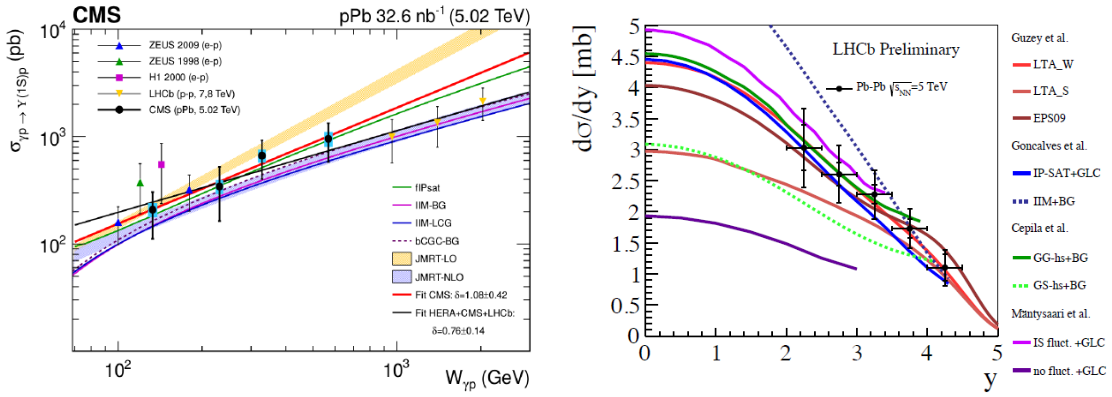

Figure 6: Υ(1S) photoproduction cross section in *e*–p, pp and p–Pb collisions as a function of the center-of-mass energy W of the γp system (left). J/ψ coherent photoproduction cross section as a function of the J/ψ rapidity in $\sqrt{s_{\rm NN}} = 5.02$ TeV ultra-peripheral Pb–Pb collisions (right).

sections and compare to models. This has been carried out by ALICE for inclusive J/ψ at both mid- and forward rapidity in $\sqrt{s_{\rm NN}} = 5.02$ TeV Pb–Pb collisions in the centrality ranges $70-90\%$ and $50-70\%$. For models, the additional challenge is to calculate the photon-flux from the projectile nucleus in configurations for which this nucleus breaks during the collision. Several assumptions can be made depending on whether one considers all the nucleons or only the spectators (i.e. the nucleons that do not participate to the collision). This impacts directly the centrality dependence of the predicted cross sections [38]. On the other hand, such measurements could provide a novel way of probing color screening in the QGP: the photoproduction of J/ψ taking place very early in the collision, the resulting J/ψ would pass through the QGP and be subject to color screening while at the same time an insignificant contribution from (re)generation is expected, due to their very low $p_{\rm T}$.

6. Outlook

The wealth of measurements discussed in these proceedings demonstrate that after about 30 years (the time at which J/ψ suppression was proposed as an unambiguous signature of the QGP), the study of quarkonium production in heavy-ion collisions is still very rich and active. Below is an arbitrary list of selected topics to follow up on: in pp collisions, the event activity dependence of quarkonium production and whether it is possible to go continuously from pp to pA to AA collisions; in pA collisions, the differences between ground and excited states, and the observation of non-zero azimuthal anisotropy, as a possible signature for collective phenomena in high-multiplicity collisions; in AA collisions, the study of quarkonium suppression at high $p_{\rm T}$ and the interplay between screening and energy loss, and understanding the measured non-zero J/ψ elliptic flow at intermediate to high $p_{\rm T}$.

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