1 Quarkonia

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1.1 Introduction

A key objective in high-energy heavy-ion physics is to determine the in-medium forces that give rise to the remarkable many-body features of the quark-gluon plasma (QGP). In the QCD vacuum, the unravelling of the fundamental force between two static color charges was made possible by the discovery of the charmonium and bottomonium states in the 1970's. Subsequent quantitative analyses of the bound-state spectra established a phenomenological potential of the Cornell type [1],

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r \ , \tag{1}$$

with a colour-Coulomb term due to gluon exchange dominant at short distances and a linear term with string tension $\sigma \simeq 0.9$ GeV/fm to account for confinement at large distance. This potential has also been quantitatively confirmed by lattice-QCD (lQCD) simulations [2], cf. also Ref. [3]. The corresponding effective field theory of QCD, potential non-relativistic QCD (pNRQCD), allows for the definition of the static potential in a $1/m_Q$ expansion for large heavy-quark mass, m_Q [4, 5]. The heavy-quark (HQ) potential thus provides a well calibrated starting point to probe the QCD medium, and the in-medium spectroscopy of quarkonia is the natural tool to carry this out in heavy-ion collisions, cf. [6–10] for recent reviews. The string term in the HQ potential, eq. (1), characterizes the long-range nonperturbative part of the force and is associated with the confining property of QCD. It is expected to play a critical role in the transition from hadronic to partonic degrees of freedom, and may well be responsible for the remarkable transport properties of the QGP, *i.e.*, its strongly coupled nature, up to temperatures of 2-3 times the pseudo-critical temperature, T_c [11].

Much like in vacuum, a systematic investigation of the in-medium force must involve the *spectroscopy* of different states, as they subsequently dissolve with increasing temperature. In this sense, quarkonia are not straightforwardly usable as a thermometer, which would imply that their dissociation pattern provides a known gauge. In the vacuum, only the 1S ground-state bottomonia ($\Upsilon(1S)$ and η_b) are small enough in size to be mostly bound by the colour-Coulomb force. All excited bottomonia and all charmonia are predominantly bound by the nonperturbative string term (and/or residual mesonic forces). Thus, charmonia and excited bottomonia are excellent probes of the in-medium confining force, as originally envisioned for the J/ψ [12]. However, in the cooling of the expanding fireball, quarkonia can also be "(re)generated" through recombination of individual heavy quarks and anti-quarks diffusing through the medium. It is important to emphasize that quarkonium formation occurs also from quarks and antiquarks from different initial pairs (hence the spelling "(re)generation"). This mechanism [13, 14] has turned out to be critical in understanding the J/ψ production systematics at the LHC where (re)generation constitutes the major part of the yield observed in central Pb-Pb collisions. The data is also compatible with production of J/ψ exclusively through statistical hadronisation at the crossover phase boundary [15]. A definite statement will become possible when the $c\bar{c}$ production cross section and the charm-quark diffusion coefficient will be measured with adequate precision in Run 3 and 4; these are key objectives discussed in the chapter **??** on open heavy-flavor production.

For bottomonia, the current understanding suggests that (re)generation is less important (although still significant) for $\Upsilon(1S)$, but possibly figures as a major component in the strongly suppressed yield of excited states, especially the $\Upsilon(2S)$. It is therefore of great importance to obtain additional information about the production "times" of the observed yields, in particular through p_T spectra and elliptic flow which contain information about the fireball's collectivity imprinted on the quarkonia by the time of their decoupling. A schematic illustration of the current knowledge extracted from "in-medium quarkonium spectroscopy", *i.e.*, their production systematics in heavy-ion collisions is shown in Fig. 1.

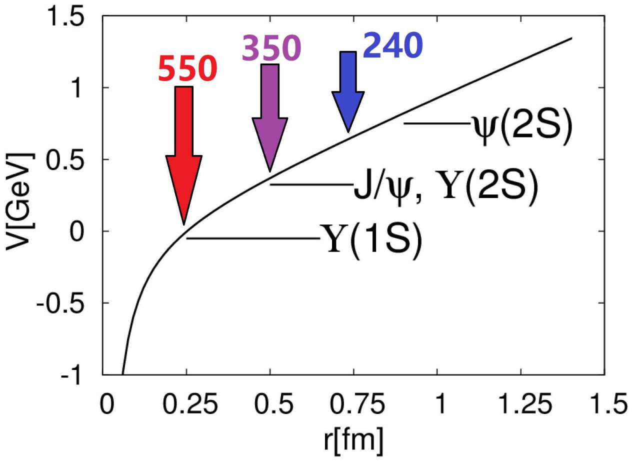

Fig. 1: The vacuum heavy-quark potential as a function of $Q\bar{Q}$ separation. The vertical lines indicate the approximate locations of the vacuum bound states while the horizontal arrows indicate the minimal screening distances of the media produced at the SPS, RHIC and LHC, as extracted from quarkonium production systematics in Pb-Pb and Au-Au collisions, along with approximate initial temperatures reached in these collisions. Figure taken from Ref. [16]

On the theoretical side, the basic objects are the quarkonium spectral functions which encode the information on the quarkonium binding energies, in-medium HQ masses and the (inelastic) reaction rates. Ample constraints on the determination of the quarkonium spectral functions are available from thermal lQCD, *e.g.*, in terms of the heavy-quark free energy, euclidean and spatial quarkonium correlation functions, and HQ susceptibilities, and are being implemented into potential model calculations [17–23]. In particular, the role of dissociation reactions has received increasing attention. Early calculations of gluo-dissociation [24,25] or inelastic parton scattering [26] have been revisited and reformulated, e.g., as a singlet-to-octet transition mechanism [20] or in terms of an imaginary part of a two-body potential [27], respectively. In particular, the latter accounts for interference effects which reduce the rate relative to "quasi-free" dissociation [26] in the limit of small binding; interference effects can also be calculated diagramatically [28]; they ensure that, in the limit of vanishing size, a color-neutral $Q\bar{Q}$ dipole becomes "invisible" to the color charges in the QGP.

The information from the spectral functions can then be utilized in heavy-ion phenomenology via transport models. The latter provide the connection between first-principles information from lQCD and experiment that greatly benefits the extraction of robust information on the in-medium QCD force and its emergent transport properties, most notably the (chemical) equilibration rates of quarkonia. Thus far most transport models are based on rate equations and/or semiclassical Boltzmann equations. In recent years quantum transport approaches have been developed using, e.g., a Schrödinger-Langevin [29–31] or density-matrix [32,33] formulation. These will enable to test the classical approximation underlying the Boltzmann and rate equation treatments and ultimately quantify the corrections. Quantum effects may be particular relevant at high p_{T} in connection with the in-medium formation times of quarkonia, augmented by the Lorentz time dilation in the moving frame; schematic treatments of this effect in semiclassical approaches suggest that varying formation times can leave observable differences for high-momentum charmonia and bottomonia [34–38]. Finally, the implementation of phase-space distributions of explicitly diffusing heavy quarks into quarkonium transport is being investigated by various groups (see, e.g., Ref. [39]), which, as mentioned above, will provide valuable constraints on the magnitude and $p_{\rm T}$ dependence of (re)generation processes.

The higher statistics of experimental data in Runs 3,4, combined with improved detector performance and measurement techniques, will allow to significantly improve over the current measurements, with extended kinematic coverage (in $p_{\rm T}$) and allowing to reach also currently-unmeasured quarkonium states, like $\psi(2S)$ and $\Upsilon(3S)$. The complementarity (and overlap) of all 4 LHC experiments is crucial in this endeavour and will call for a data combination strategy. We present below data projections and simulations for a selection of observables and compare to model predictions (which sometimes constitute the basis for the projections). The shown model uncertainties represent the current knowledge; we expect significant improvements both in what concerns the conceptual aspects discussed above as well for the input parameters, which will be constrained by data and theory (for instance in what concerns nuclear PDFs).

1.2 Charmonia in PbPb collisions

A remarkable discovery at the LHC was that the suppression of J/ψ is significantly reduced in comparison to lower energies [40] and that the nuclear modification factor R_{AA} is enhanced towards lower $p_{\rm T}$ [41, 42], confirming predictions of (re)generation at the (crossover) phase boundary of QCD [13] or throughout the deconfined phase [14, 43]. Recently, the measurement of a significant elliptic flow coefficient v_2 of J/ψ [44] brought further crucial support that charm quarks thermalize in QGP.

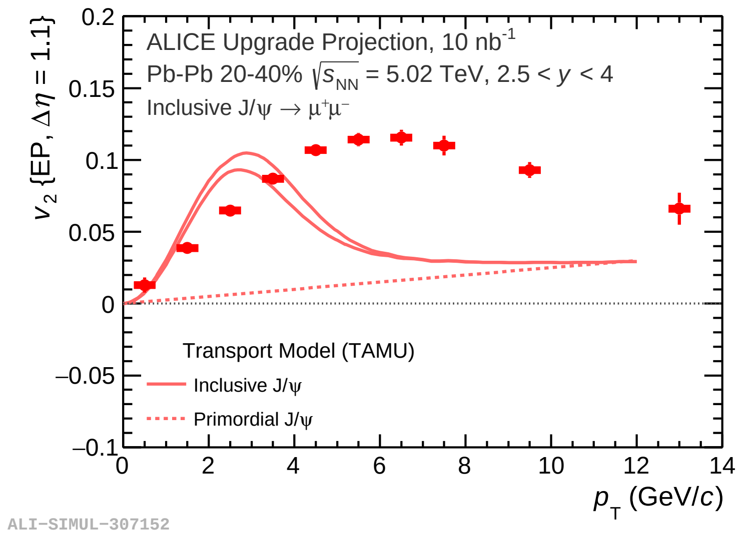

Fig. 2: Projected measurement of elliptic flow coefficient v_2 as a function of $p_{\rm T}$ for J/ψ mesons (measured in ALICE, for $2.5 < y < 4$), for the centrality class 20–40%, in comparison to model calculations [45].

The projected measurement of J/ψ v_2 as a function of $p_{\rm T}$ for the centrality class 20–40%, for $2.5 < y < 4$, in comparison to model calculations [45] is shown in Fig. 2. Currently, transport model calculations [45, 46] underestimate the data for $p_{\rm T} \gtrsim 6$ GeV/c [44]. Since the current data are for inclusive J/ψ production and the component from B meson decays is expected to be significant for high $p_{\rm T}$, only the data in Runs 3,4 will allow to conclude, aided by precision separation of the prompt and B-decay components. Measurements at midrapidity will become significant too and also a very good measurement of the v_3 coefficient is in reach; polarization will be measured too [47].

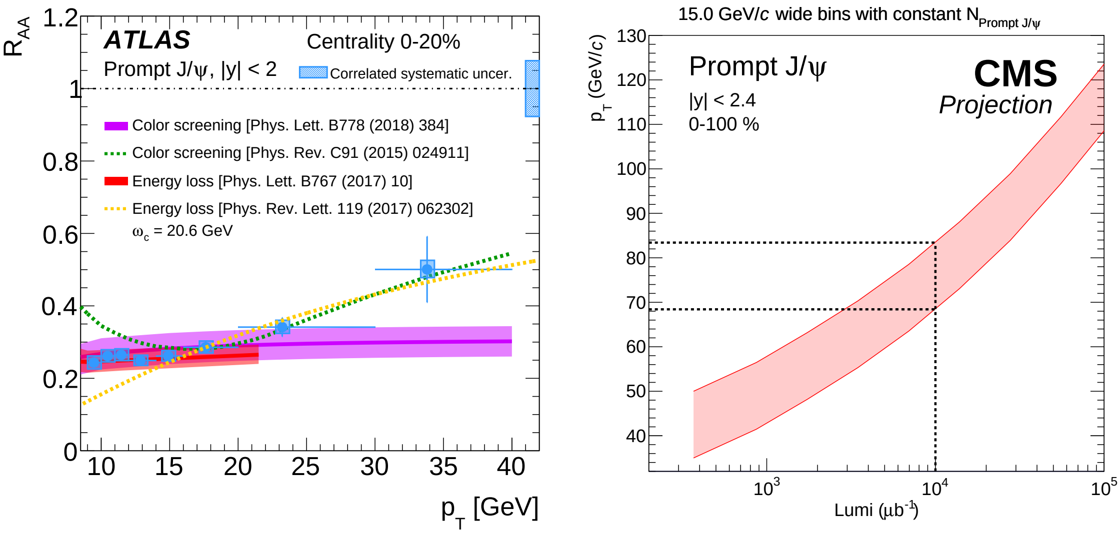

Fig. 3: Left: R_{AA} vs p_{T} for prompt J/ψ in central (0-20%) collisions (ATLAS, $|y| < 2$, [48]). Right: CMS projection for the reach in p_{T} for minimum bias (0-100%) collisions.

At high p_{T}, currently the production mechanisms cannot be resolved, given the statistical limitation in th edata, see Fig. 3 (left), but the Run3,4 data, as illustrated in ig. 3 (right) with a CMS projection for the p_{T} reach, will allow to conclude on the important question of J/ψ formation as determined by the Debye screening mechanism [37, 49] or by charm quark energy loss [50, 51].

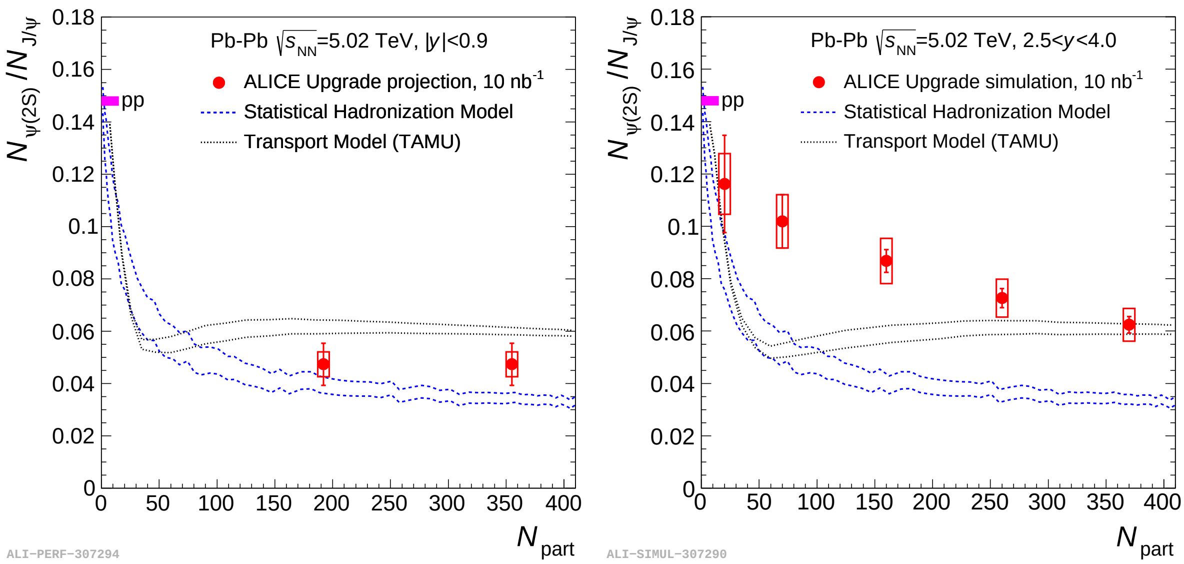

Fig. 4: Production ratio $\psi(2S)$/J/ψ vs. N_{part} for $|y| < 0.9$ (left) and $2.5 < y < 4$ (right) [47, 52]. Model predictions in the transport approach [45] and from statistical hadronization [15] are included.

The projections for the measurement of the $\psi(2S)$ state in ALICE are shown in Fig. 4 as a function of centrality and compared to model predictions in the transport approach [45] and from the statistical hadronization model [15]. This (p_{T}-integrated) measurement will significantly contribute to make a distinction between the two models that currently describe charmonium data. Other states, for instance χ_c, may be measured too, albeit the measurement down to p_{T} =0 will remain challenging.

1.3 Bottomonia in PbPb collisions

The study of bottomonia with Pb–Pb data from the Runs 3 and 4 of the LHC can bring further information on the various physics aspects described above, and more. Although their production is a priori subject to the same effects as charmonia, in practice the two quarkonium families feature some fundamental differences. Binding energies differ, which is reflected in the different dissociation temperatures: about twice the critical temperature T_C for $\Upsilon(1\mathrm{S})$, much high than the about $1.2T_C$ for J/ψ or $\Upsilon(2\mathrm{S})$, for instance. The feed-down pattern is also more complex: while the contribution of B meson decays is specific to charmonia, more states can contribute to the different S-wave bottomonia, owing to decays of $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$, as well as the many states of the χ_b family. In practice, up to $30-40\%$ of the measured $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ yields actually result from the feed-down from other states. At the same time, this important feature of bottomonium production means that a large portion of measured $\Upsilon(1\mathrm{S})$ suppression can be due to the stronger suppression of the feed-down states. In addition, the feed-down fractions, for the contribution of the different states to the measured bottomonium states, are constrained experimentally as a function of p_T but with limited precision, which is one source of uncertainty in the models. The impact of regeneration from uncorrelated $\mathrm{b\bar{b}}$ is also expected to be much smaller than for charmonia, because of the much smaller number of $\mathrm{b\bar{b}}$ pairs per Pb–Pb event compared to $\mathrm{c\bar{c}}$. The importance of regeneration for bottomonia is however still very model dependent, and no unambiguous experimental signal for it has been found yet. Possible ways of constraining this contribution will be discussed in this section.

Experimentally, the higher mass of bottomonia compared to charmonia implies higher p_T decay leptons, allowing the ATLAS and CMS experiments to measure the production down to 0 p_T, as is possible for ALICE for both charmonia and bottomonia. The proximity in mass between the different mass states, especially between the $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ states, also means that good muon (or electron) momentum resolution is essential to their measurement, especially for excited states.

It is useful to remind quickly the status in 2018, based on results from Run1 and early Run2 LHC data as well as RHIC data. Υ production is found to be suppressed in Pb–Pb compared to pp collisions, in all rapidity, p_T and centrality ranges measured. Suppression is stronger in central events, as expected from the hotter and longer-lived medium in such events. Another striking feature is that excited states are more suppressed than the ground state, the $\Upsilon(3\mathrm{S})$ being still unmeasured in AA collisions ($R_\mathrm{AA}(\Upsilon(3\mathrm{S})) < 0.094$ at 95% confidence level, for $\sqrt{s_\mathrm{NN}} = 5.02\,\mathrm{TeV}$ [53]). In addition, the large suppression found for $\Upsilon(1\mathrm{S})$ in central collisions does not seem compatible with unmodified direct $\Upsilon(1\mathrm{S})$ production, though uncertainties on non-QGP effects (initial state modifications and final state effects) do not allow for an undebatable statement regarding $\Upsilon(1\mathrm{S})$ melting in the medium. No significant dependence of the suppression of Υ states is found on collision energy or rapidity.

The main striking features of Υ suppression can be observed in Fig. 5 and in current data: first a strong dependence of the suppression with the collision centrality, with a stronger suppression in the most central collisions, and also a higher suppression of the excited states compared to the ground state. Good qualitative agreement is already found between models and data regarding this suppression, within current uncertainties. Figure 5 shows the the projected uncertainty on the R_AA of $\Upsilon(1)$ will be much smaller than the current model uncertainties.

Differences exist however in the treatment of the suppression of the bottomonia in the medium. For instance, the heavy quark potential, qualitatively a Debye screened potential above the deconfinement temperature, as proposed originally [12], is one important ingredient. Some models assume a real potential, using usually the free energy or the internal energy (as in Ref. [36]). More recently, developments from lattice lQCD have allowed to also study the imaginary part of the potential, which physics implications are under study but may be related to Landau damping and singlet-octet transitions. Through the use of such lQCD-vetted potential, it has been shown [38] that predictions are quite sensitive to this choice, as compared to a perturbative potential.

Models also differ in the treatment of the evolution of the quarkonia with the medium. Frame-

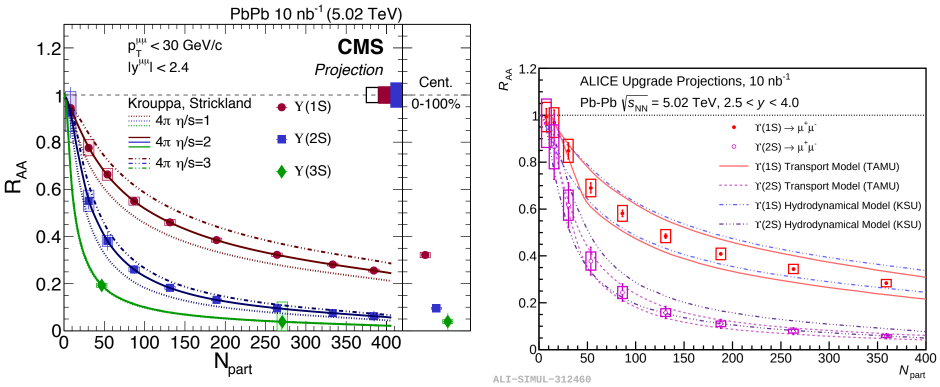

Fig. 5: Centrality dependence of $\Upsilon(1)$, $\Upsilon(2)$ and $\Upsilon(3)$ R_{AA}, as projected by the CMS [54, 55] (left) and ALICE (centre) experiments, and from a transport model [36]

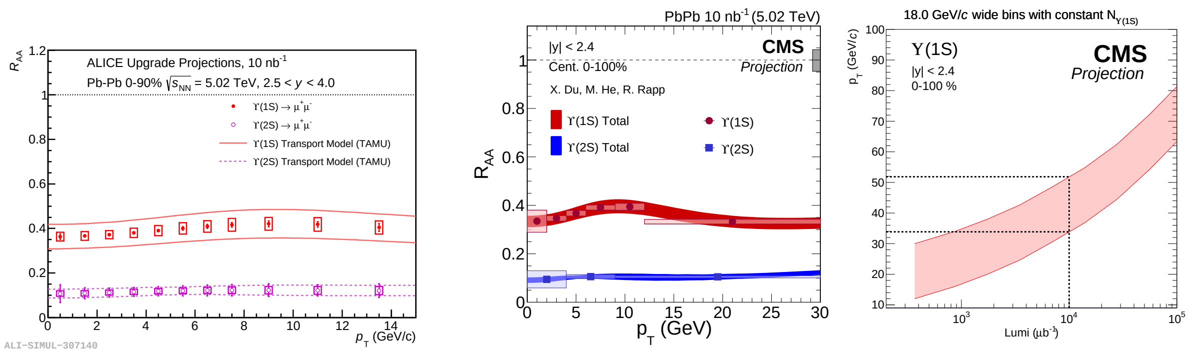

Fig. 6: Projected R_{AA} for $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ expected from the ALICE (left) and CMS (center) experiments, as a function of p_{T}, with $10\,\mathrm{nb}^{-1}$ of PbPb data. The expected p_{T} reach for $\Upsilon(1\mathrm{S})$, from the CMS experiment is also shown, as the position of the last p_{T} bin of the measurement, with constant number of observed $\Upsilon(1\mathrm{S})$, as a function of integrated luminosity.

works include a transport model with a kinetic-rate equation [36], anisotropic hydrodynamics [38], co-movers [56], effective field theory in the framework of open quantum systems with a Lindblad equation [57]. Precise predictions require many other ingredients. Some can be constrained using measurements in pp collisions, such as the feed-down fractions from other states, or in p–Pb collisions for cold nuclear matter and initial state effects (including nPDF). In other cases, bottomonia may bring information complementary to other probes, using the sensitivity of the suppression to the medium shear viscosity or to its initial temperature.

A precise measurement of the p_{T} dependence of the $\Upsilon(1\mathrm{S})$ R_{AA} will be possible using LHC data from Runs 3 and 4. At low and medium p_{T}, up to about 15 GeV, the measurement is sensitive to the possible regeneration component in Υ meson production. Some projections for the expected precision of Υ measurements from the ALICE and CMS detectors using $10\,\mathrm{nb}^{-1}$ of data after the Runs 3-4 are shown as a function of p_{T} in Fig. 6 and y in in Fig. 7, and compared to the expectations from two models [36, 38]. In the first model [38], all the measured Υ are from the primordial production and there is no regeneration, leading to a rather flat R_{AA} at low and medium p_{T}. Only at higher p_{T} is a small rise predicted, which will be discussed below. In the second model [36] however, a regeneration component is considered, and several assumptions are explored, especially on the degree of thermalisation of the bottom quarks. Indeed, because of the about three times higher mass of the bottom quark than that of

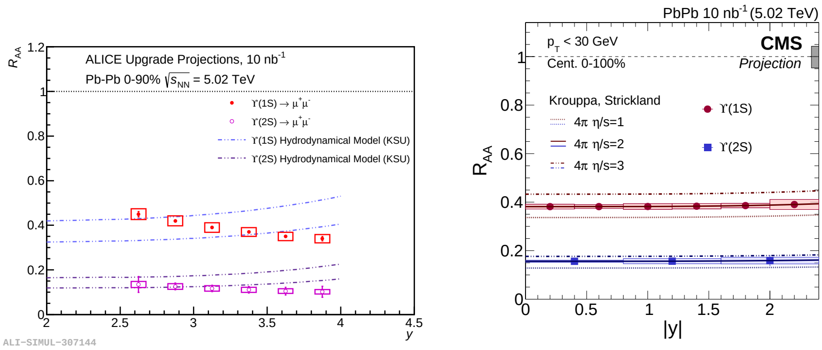

Fig. 7: Projected R_{AA} for $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ expected from the ALICE (left) and CMS (center) experiments, as a function of rapidity, with $10\,\mathrm{nb}^{-1}$ of PbPb data.

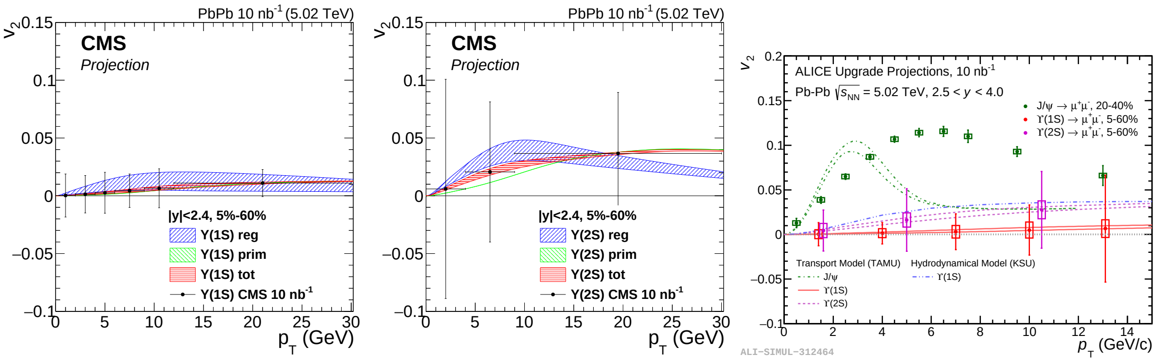

Fig. 8: v_2 projections for the CMS (left and centre) and ALICE (right) experiments for the $\Upsilon(1)$ and $\Upsilon(2)$ mesons, assuming the predictions from a transport model [36].

the charm quark, it cannot be assumed that regenerated bottomonia would have a thermal blast-wave expression, as is a good approximation for charmonia. In Fig. 6, the latter model uses an instantaneous coalescence model instead, providing more realistic nonequilibrium p_{T} spectra for the input b quarks. This leads to a maximum in the R_{AA} as a function of p_{T}, at around 10 GeVfor $\Upsilon(1\mathrm{S})$. The current data is not precise enough to confirm or disfavour this feature, but Run 3+4 data will allow to look for it.

Almost no rapidity dependence is expected at LHC for the nuclear modification factor of Υ mesons within the acceptance of ATLAS and CMS ($|\eta| \lesssim 2.5 - 3$), which can be better tested using Run 3+4 data. A modest increase is predicted in the acceptance of ALICE, as can be seen in Fig. 7, because of a cooler QGP. Again, this cannot be tested within the current experimental uncertainties, but can be looked for in future data.

Though not as sensitive as J/ψ to energy loss processes, because of their higher mass implying a lower boost at a given p_{T}, much can be learnt as well from the measurement of $\Upsilon(1)$ at high p_{T}. As can be seen in Fig. 6, it is expected that a measurement up to a p_{T} of about 50 GeVcan be performed with the ATLAS and CMS detectors with $10\,\mathrm{nb}^{-1}$ of data, where a small increase of the R_{AA} is predicted by current models, as can be seen in in Fig. 6.

If we come back to the matter of regeneration, much can be learnt about it by a measurement of the elliptic flow of $\Upsilon(1)$ mesons [58], unmeasured to date in any collision system. A parallel can be drawn with that of J/ψ, which is still not properly described by models. This observable requires a more detailed implementation of the dynamics of the interactions between the quarkonium and the medium: thermalisation of the heavy quarks, time dependence of regeneration, path length dependence of energy loss, as well as initial geometry fluctuations and elastic rescattering of the quarkonia in the medium. Thus, collective flow brings complementary information to the R_{AA}, and its measurement can help disentangle some effects. In the case of $\Upsilon(1)$ mesons, a small v_2 (order of 1–2%) is expected [36, 59, 60], as can be seen in Fig. 8, essentially because the ground state is formed early in the fireball evolution, at a time when anisotropies are limited. For the same reason, the elliptic flow of $\Upsilon(2)$ could be a factor 2 or more higher [36, 60], both from the regenerated and primordial components. For both states, projections show that experimental precision may not be enough for a significant v_2 measurement, assuming v_2 values as in Ref. [36]. For this reason, combining results between the different LHC experiments would be beneficial to reach a better sensitivity.

While we have focused on the R_{AA} and v_2 in this section, bottomonium production can be studied using other observables. For instance, fully corrected yields or cross sections in Pb–Pb can be studied, without making the ratio to a pp measurement in a R_{AA}. Such a measurement, already reported in some of the available experimental results [53], can directly be compared to a production model.

1.4 Quarkonia in p–Pb and pp collisions

1.4.1 p–Pb collisions

Quarkonium-production studies in high-energy p–Pb collisions are usually carried out to measure how much specific nuclear effects, those which do *not* result from the creation of a deconfined state of matter, can alter the quarkonium yields. They should indeed be accounted for in the interpretation of Pb–Pb results. They are also interesting on their own as they provide means to probe the modification of the gluon densities in the nuclei, the interaction between such pure heavy-quark bound states and light hadrons, or phenomena such as the coherent medium-induced energy loss of these quark-antiquark pairs. The measurements as a function of event activity (violence of the collision, quantified via the charged-particle multiplicity or any centrality-related selection) brought several surprises, hotly discussed presently.

Usually, a separation into initial-state and final-states effects is done (the energy loss effect can be seen as an interplay between the two effects). Yet, it is probably more instructive to separate out the effects which are believed to impact *all* the states of the charmonium or the bottomonium family with the *same* magnitude from those which are expected to affect much more the excited states. In principle, initial-state effects are of the first kind as the nature of the to-be produced quarkonium state is not yet fixed where the effects take place. On the contrary, final-state effects can be sensitive to the properties of the produced quarkonium state and can thus be of the second kind.

However, in p–Pb collisions at LHC energies, final-state interactions between the heavy-quark pair and the nuclear matter likely occur *before* the pair hadronises. This is due to the large boost between the nucleus and the pair – and thus the quarkonium. At rest, a $c\bar{c}$ or $b\bar{b}$ pair takes 0.3–0.4 fm to hadronise; seen from the nucleus, at, for instance $y^{\mathrm{lab}}_{\mathrm{pair}} - y_{\mathrm{beam}} \sim 7$, it takes $\gamma = \cosh(7) \simeq 500$ times longer. As such, final-state interactions with the nucleus likely do not discriminate ground and excited quarkonium states. Such an argument based on the existence of a large boost is nevertheless not applicable if one considers effects arising from the interactions between the pair and other particles *produced* by the p–Pb collisions, not those contained in the Pb nucleus. The former are indeed not moving at the Pb projectile rapidity. In fact, some of these particles can have similar rapidities as the quarkonium and can thus be considered as comoving with it.

The simultaneous study of open-heavy flavoured hadrons along with both ground and excited quarkonium states can shed light of all these phenomena. Along the lines exposed above, one expects forward-quarkonium production in p–Pb collisions (namely when the quarkonia flies in the direction of the proton) to be sensitive to low-x phenomena like the gluon shadowing or saturation in the lead ion or to the coherent energy loss. On the contrary, the backward production should be sensitive to the gluon antishadowing. Moreover, the scatterings of quarkonia with comoving particles occur more often backward than forward, due to the rapidity-asymmetric particle multiplicities, and more often as well with the larger and less tightly bound excited states.

With a wide rapidity coverage spanning from about -5 to 5, the LHC data from the 4 experiments are unique as they allow to probe much smaller x values than at RHIC and a with larger reach in p_{T}. The higher c.m.s. energy, the competitive luminosities and the resolution of the detectors also allow for more extensive studies of the bottomonium family. In fact, arguably the most striking observation, made already with Run 1 data, was that of a relative suppression in p–Pb collisions of the excited $\Upsilon(2\mathrm{S})$,$\Upsilon(3\mathrm{S})$ states compared to that of the $\Upsilon(1\mathrm{S})$ observed by CMS [61] as a function of the event activity (recently confirmed by ATLAS [62]). Not only was it unexpected, but it constitutes a challenge to the conventional interpretation of suppression observed in Pb–Pb collisions [63], which is of a significantly larger magnitude, but of a similar pattern. Such a relative suppression was also observed in the charmonium sector [64], where it is as well very remarkable.

As far as the suppression of the $\Upsilon(1\mathrm{S})$ and J/ψ is concerned, they seem to follow the expectations based on the RHIC results with a strong forward suppression compatible with a strong shadowing – of a compatible magnitude of that observed with HF data [65]. We should however note that the same observation can be explained by the coherent energy loss [66]. More data, including that on Υ and Drell-Yan production, are clearly needed to disentangle both effects. More precision for Υ and non-prompt J/ψ is in general critically needed as the typical experimental uncertainties are still on the order of the expected effects. As a case in point, backward y data are not yet precise enough to quantify the magnitude of the gluon antishadowing, see section 11 for the relevance of quarkonium p–Pb LHC data on nuclear PDF fits.

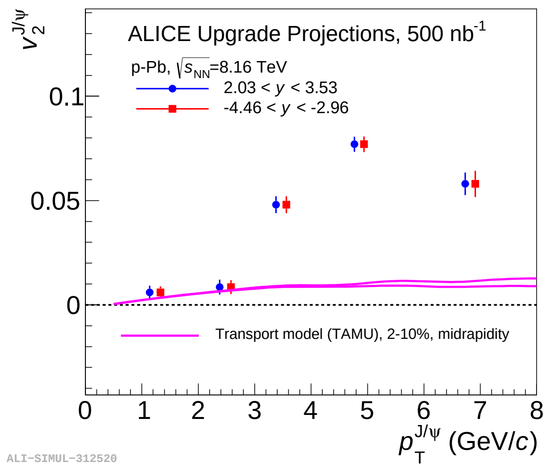

Fig. 9: The p_{T} dependence of the v_2 coefficient of J/ψ mesons in p–Pb collisions, for 500 nb^{-1} (ALICE). The projections are based on current ALICE data for 0–20% centrality [67] and are shown separately for negative and positive y_{CM}), assuming the same magnitude and are compared with transport model (TAMU) calculations [68] for midrapidity.

Recently, the measurement of v_2 of J/ψ in p–Pb collisions became available [67, 69], indicating a large – and completely unexpected – flow magnitude. Recent transport model calculations [68], which are successful in describing the features of the data, including the transverse momentum and centrality dependence of J/ψ and $\psi(2S)$ production, cannot reach the high value of the v_2 coefficient seen in data [67, 69] (see Fig. 9, where the current 1-σ reduction of the data implies a v_2 smaller by about 20% for $p_{\mathrm{T}} = 5$ GeV/c), suggesting that the ob served v_2 is in p–Pb collisions mostly an initial state effect. A precision measurement in Run 3, 4 for a broad rapidity range will clarify this. We illustrate the expected quality of the measurement with the projections for the p_{T} dependence of the v_2 coefficient of J/ψ mesons in p–Pb collisions in ALICE for 500 nb^{-1} (ALICE), shown in Fig. 9.

In addition to conventional LHC collider data, one should not overlook the discriminating power of data which can be collected in the fixed-target mode [70, 71]. Not only they correspond to completely different energy and (c.m.s.) rapidity ranges, but extremely competitive luminosities, up to fb^{-1}, are easily reachable. This is far beyond anything which can be reached in the collider mode during Run 3 & 4. The LHCb collaboration has paved the way for a full fixed-target program at the LHC with their SMOG luminosity monitor [72] used as an internal (He, Ne, Ar) gas target [73]. It is now clear that corresponding studies to those suggested above are possible [74] with the LHCb and ALICE detectors with light technical adjustments. They would drastically expand the scope of current proton-nucleus quarkonium studies.

1.4.2 High-multiplicity pp collisions

Systematic studies on quarkonium production in high-multiplicity pp events can play an important role in understanding hadronization. In particular, the correlation of quarkonium yields with the charged-particle multiplicity can provide insight into the production mechanism and into the interplay between hard and soft processes in particle production. Hidden and open heavy-flavour production measurements as a function of the event activity were initiated at the LHC during Run 1 [61, 75]. The striking feature of the data is that the production yields of quarkonia in high multiplicity events are significantly enhanced relative to minimum bias events, as is the case also for D mesons [76]. Specifically, the measurements of the self-normalized yields (the yield divided by the mean yield in minimum bias collisions) as a function of the self-normalized charged-particle multiplicity show an increase which is stronger than linear at the highest multiplicities. The similarity between D-meson and J/ψ results [75, 76] suggests that this behaviour is most likely related to the production processes, and that hadronisation may play a secondary role. When comparing J/ψ preliminary results at $\sqrt{s} = 13\,\mathrm{TeV}$ [77] to the ones previously obtained at $\sqrt{s} = 7\,\mathrm{TeV}$ [75], no significant energy dependence is observed, *i.e.* the relative J/ψ yields for events with identical relative multiplicities give similar results.

The data are described both by initial-state models as well as by a model assuming hydrodynamic evolution [78], considering that the energy density reached in pp collisions at LHC is high enough to apply such evolution. Initial-state (saturation) effects are considered within i) the Color-Glass-Condensate (CGC) framework [79]; ii) the percolation approach [80, 81]; iii) a model with higher Fock states [82], based on parameters derived from p–Pb collisions. The energy dependence of the cross sections is controlled by the saturation momentum $Q_s(x)$ in the case of the CGC or density of colour ropes $\rho_s(y, p_T)$ in the percolation model, which also governs the charged-hadron multiplicity; events at different energies with the same Q_s or ρ_s are therefore identical. For a given event multiplicity, they predict the relative yields to be almost energy independent. It seems that, in any case, multiple interactions at the partonic level need to be taken into account in order to reproduce the data [83–85].

Runs 3, 4 data at unprecedented high multiplicities and with data sample sizes to allow for differential studies in p_{T} will discriminate models. For instance, in the percolation model, where colour interactions produce a reduction of the charged-particle multiplicities, the deviation from the linear behaviour is expected to be steeper for high-p_{T} quarkonia (and D mesons). Moreover, measurements of J/ψ yields relative to those of D mesons with the same transverse mass could help to elucidate the relative contribution of hadronisation and initial-state effects.

Studies of double differential ratios of excited-to-ground quarkonium states versus relative multiplicity could help to clarify the presence of final-state effects, either QGP-like or the ones proposed by the comover model [56, 86]. Also, within the CGC+NRQCD framework [79], the relative contribution of each channel ($^{2S+1}L_J^{[c]}$, where c refers to a color singlet $c = 1$ or color octet $c = 8$ state) with increasing event activity has been calculated. The contribution of $^3S_1^{[8]}$ to J/ψ production has been found to increase significantly with the event multiplicity, suggesting the growing importance of hard gluon fragmentation in J/ψ hadronization. The growth in the contributions of the $^1S_0^{[8]}$ and $^3P_J^{[8]}$ channels are relatively much smaller, which suggests that the long distance matrix elements (LDMEs) of these channels could potentially be smaller. This may provide a way for reconciling the LDMEs extracted from hadroproduction with the ones from $\mathrm{e}^{+}\mathrm{e}^{-}$ data (the current apparent breaking of LDMEs universality does call into question NRQCD factorization).

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