Results on high transverse momentum quarkonium production and dissociation in heavy ion collisions

Ivan Vitev
Los Alamos National Laboratory, Theoretical Division, Los Alamos, NM 87545, USA
E-mail: ivitev@lanl.gov

Abstract. We calculate the yields of quarkonia in heavy ion collisions at RHIC and the LHC as a function of the transverse momentum. Based upon NRQCD, these results include both color-singlet and color-octet contributions and feed-down effects from excited states. In reactions with ultra-relativistic nuclei, we focus on the consistent implementation of dynamically calculated nuclear matter effects, such as coherent power corrections, cold nuclear matter energy loss and the Cronin effect, in the initial state and collisional dissociation of quarkonia in the final state, as they traverse through the QGP. Theoretical results are presented for $J/\psi$ and $\Upsilon$ and compared to experimental data where applicable. At RHIC, a good description of the high-$p_T$ $J/\psi$ modification observed in central Cu+Cu and Au+Au collisions can be achieved within the model uncertainties. We find that $J/\psi$ measurements in proton-nucleus reactions are needed to constrain the magnitude of cold nuclear matter effects. At the LHC, a good description of the experimental data can be achieved only in mid-central and peripheral Pb+Pb collisions.

1. Introduction

Melting of heavy quarkonium states, like the $J/\psi$ and the $\Upsilon$, due to color screening in a deconfined quark-gluon plasma (QGP) [1] has been proposed as one of the principal signatures for its formation. An expected experimental consequence of this melting in the thermal medium created in heavy ion collisions (HIC) is a suppression of the yields of heavy mesons, when compared to their yields in nucleon-nucleon (NN) collisions scaled with the number of binary interactions.

Description of quarkonia is provided by non-relativistic quantum chromodynamics (NRQCD) [2]. In this picture, the $Q\bar{Q}$ state in the color-singlet combination is the lowest order Fock space component of the full quarkonium wavefunction. Higher Fock components in the wavefunction have additional partons and are suppressed by positive powers of the small parameter $v = p/M$ (velocity). In our calculation we will take into account the Fock components that allow for both color-singlet and color-octet $Q\bar{Q}$ contributions. The NRQCD formalism has been used to calculate differential yields of heavy mesons as a function of the transverse momentum $p_T$ in p+p collisions. Our goal is to combine the NRQCD formalism with cold nuclear matter (CNM) effects and the effects of propagation of quarkonia through a hot QGP to calculate the final yields in HIC [3]. We place special emphasis on the application of the collisional meson dissociation mechanism [4, 5], which has provided good description of $D$ and
B meson suppression, to quarkonia. We present results for the nuclear modification ratio,

\[ R_{AB}(p_T) = \frac{d\sigma_{coll}^{Q\bar{Q}}/dydp_T}{N_{coll}^{AB}d\sigma_{pp}^{Q\bar{Q}}/dydp_T}, \]  

(1)

in reactions with heavy nuclei. We discuss Au+Au and Cu+Cu collisions at RHIC at \( \sqrt{s} = 0.2 \text{ TeV} \) per nucleon pair and Pb+Pb collisions at LHC at \( \sqrt{s} = 2.76 \text{ TeV} \) per nucleon pair.

2. Quarkonium production in p+p collisions

In this section we describe the production of quarkonia at high transverse momentum in p+p collisions. It provides a baseline for the calculation of the nuclear modification factor \( R_{AB}(p_T) \) defined above in Eq. 1. It also gives the initial unquenched spectrum of “proto-quarkonia” in the heavy ion collision, excluding CNM effects and effects of the propagation of the quarkonium states through the QGP medium.

The dominant processes in evaluating the differential yields of heavy mesons as a function of \( p_T \) are the 2 \( \rightarrow \) 2 processes of the kind \( g + q \rightarrow H + q, q + q \rightarrow H + g \) and \( q + g \rightarrow H + g \), where \( H \) refers to the heavy meson. We label the process generically as \( a + b \rightarrow c + d \), where \( a \) and \( b \) are light incident partons, \( c \) refers to \( H \) and \( d \) is a light final-state parton. Given the matrix element for the process, \( M_{ab \rightarrow cd} \), the cross section has the form

\[ \frac{d\sigma}{dp_Tdy} = \int dx_a\phi_a(x_a, \mu_f)\phi_b(x_b, \mu_f) \frac{2p_T}{x_a - m_H^2(x_a x_b)} \]  

(2)

where \( \phi_a (\phi_b) \) is the distribution function of parton \( a \) (\( b \)) in the incident hadron traveling in the +z (−z) direction. We denote by \( x_a (x_b) \) the large lightcone momentum fraction carried by the parton. In Eq. (2) \( \sqrt{S} \) is the center-of-mass energy of the incident hadrons and \( s, \hat{t} \) and \( \hat{u} \) are the parton level Mandelstam variables. Momentum-energy conservation fix

\[ x_b = \frac{1}{\sqrt{S}} x_a\sqrt{S} m_T e_−y - m_H^2. \]  

(3)

We take the factorization and renormalization scales \( \mu_f, \mu_R \) to be \( m_T = \sqrt{p_T^2 + m_H^2} \). The invariant cross section is given by

\[ \frac{d\sigma}{dt} = \frac{|M|^2}{16\pi s^2}. \]  

(4)

We use NRQCD [2] results to calculate the production of quarkonia in p+p collisions. NRQCD provides a systematic procedure to compute any quantity as an expansion in the relative velocity \( v \) of the heavy quarks in the meson. For example, the wavefunction of the \( J/\psi \) meson (analogous expressions hold for the \( \psi(2S), \Upsilon(2S) \) and \( \Upsilon(3S) \)) is written as

\[ |J/\psi\rangle = |Q\bar{Q}([^3S_1]_1)\rangle + O(v^2)|Q\bar{Q}([^1S_0]_s)\rangle + O(v^4)|Q\bar{Q}([^3S_1]_{gg})\rangle + O(v^6)|Q\bar{Q}([^3P_1]_{sg})\rangle + O(v^8)|Q\bar{Q}([^3P_2]_{sg})\rangle + \cdots \]  

(5)

The differential cross section for the prompt (as opposed to inclusive which includes contributions from B–hadron decay) and direct (as opposed to the indirect from the decay of heavier charmed mesons) production of \( J/\psi \) can also be calculated in NRQCD. It can be written as the sum of the contributions,

\[ d\sigma(J/\psi) = d\sigma(Q\bar{Q}([^3S_1]_1))\langle Q\bar{Q}([^3S_1]_1) | J/\psi \rangle + d\sigma(Q\bar{Q}([^1S_0]_s)\langle Q\bar{Q}([^1S_0]_s) | J/\psi \rangle + d\sigma(Q\bar{Q}([^3S_1]_{sg})\langle Q\bar{Q}([^3S_1]_{sg}) | J/\psi \rangle + d\sigma(Q\bar{Q}([^3P_1]_{sg})\langle Q\bar{Q}([^3P_1]_{sg}) | J/\psi \rangle + d\sigma(Q\bar{Q}([^3P_2]_{sg})\langle Q\bar{Q}([^3P_2]_{sg}) | J/\psi \rangle + \cdots \]  

(6)
where the quantity in the brackets \([\cdot]\) represents the angular momentum quantum numbers of the \(QQ\) pair in the Fock expansion. The subscript on \([\cdot]\) refers to the color structure of the \(QQ\) pair, \(1\) being the color-singlet and \(8\) being the color-octet. The dots represent terms which contribute at higher powers of \(v\). The short distance cross sections \(\sigma(QQ)\) correspond to the production of a \(QQ\) pair in a particular color and spin configuration, while the long distance matrix element \(\langle O(QQ) \rightarrow J/\psi \rangle\) corresponds to the probability of the \(QQ\) state to convert to the quarkonium wavefunction. This probability includes any necessary prompt emission of soft gluons to prepare a color neutral system that matches onto the corresponding Fock component of the quarkonium wavefunction. Expressions similar to the ones shown in Eqs. (5), (6) hold for other quarkonium states (such as \(\Upsilon, \chi_c, \chi_b, \cdots\)). The parton level cross sections and non-perturbative probabilities are available in the literature, see a list of references in [3].

An illustration of the lowest-order (LO) NRQCD calculation of quarkonium production is given in Fig. 1. The left panel shows the cocktail of contributions that give the baseline production yield for \(J/\psi\) at LHC at \(\sqrt{S} = 2.76\) GeV in the NRQCD formalism. For the direct production, there are four contributions: one color-singlet contribution (\(\vert [S1]\vert\)) three color-octet contributions (\(\vert [01]S0\vert\), \(\vert [03]S1\vert\), and \(\vert [30]P0\vert\)). For the prompt yield, we add the feed-down contributions from the \(\chi_{cJ}\). The contributions of the \(\chi_{cJ}\) are also shown in Fig. 1. To obtain the feed-down contributions, we multiply the corresponding yields by the corresponding branching fractions,

\[
BR(\chi_{c0} \rightarrow J/\psi) = 0.0116 ,
BR(\chi_{c1} \rightarrow J/\psi) = 0.344 ,
BR(\chi_{c2} \rightarrow J/\psi) = 0.21 .
\tag{7}
\]

This gives the p+p baseline contribution for the \(J/\psi\). We have included experimental data on prompt \(J/\psi\) production at \(\sqrt{S} = 2.76\) TeV [6]. Each of the species will undergo a different modification due to CNM and QGP effects. To obtain the p+A and A+A yields, we calculate the modified yields for each species and combine them again to obtain the net modification.

The right panel of Fig. 1 shows a calculation of the yields of \(b\bar{b}\) states. We obtain the results for \(\Upsilon(1S), \Upsilon(2S)\) and \(\Upsilon(3S)\) separately (but include the relevant \(\chi_b\) feed-down for each). If only the \(\Upsilon(1S)\) yields are measured, then we can obtain that by adding to these yields, the feed-down from \(\Upsilon(2S)\) (branching fraction 31%) and \(\Upsilon(3S)\) (branching fraction 16.4%). The
theoretical calculation gives a good description of the experimental data within the limitations of the LO NRQCD approach. Specifically, the calculated spectra are somewhat harder than the experimental measurements and cannot be pushed down to low $p_T$. Any difference in normalization cancels out in the calculation of $R_{AA}$.

3. Quarkonium production in A+A collisions

3.1. Cold Nuclear Matter effects

In heavy ion reactions, the production yields of energetic particles are always affected by cold nuclear matter (CNM) effects. These include nuclear shadowing, initial state energy loss and transverse momentum broadening (also interpreted as the origin of the Cronin effect). In our calculation, the CNM effects are evaluated from the elastic, inelastic and coherent scattering processes of partons in large nuclei, see Refs. [8, 9, 10]. For quarkonia, cold nuclear matter effects are still not well-understood. To our knowledge, Ref. [3] is the first attempt to calculate the Cronin effect for $Q\bar{Q}$ production. We do not try to constrain its magnitude phenomenologically and point out that data from p+A reactions is needed to constrain all CNM effects. We find that including transverse momentum broadening in the same way as is done for light final states reduces the suppression for $p_T$ between 3 and 10 GeV significantly and may actually lead to a small enhancement of the charmonium cross section. It is not clear, given the large error bars, whether the Au+Au and Cu+Cu data at RHIC are better described by the Cronin calculation. In contrast, it is evident that the Cronin effect is not consistent with Pb+Pb data at the LHC, which sees a large attenuation at $p_T \sim 8$ GeV. At present, at high $p_T$, initial-state energy loss and the Cronin provide an estimate for the uncertainty range of CNM effects.

3.2. Quark-Gluon Plasma effects

In this section we present the details of the dissociation model of quarkonium propagation through the QGP. The essence of the dissociation model for heavy mesons is that they have short formation times and can therefore form in the medium on a time scale $t_{\text{form}}$. Interaction with the thermal medium can dissociate the mesons on a time scale $t_{\text{diss}}$. The final yield is given by a rate equation which takes into account the formation and dissociation processes. In the next section we first discuss the rate equation abstractly, using $t_{\text{form}}$ and $t_{\text{diss}}$ as parameters. In the later sections we will estimate $t_{\text{form}}$ and calculate $t_{\text{diss}}$. For more details on the dissociation model and its application to the phenomenology of open heavy flavor, see [4].

The approach to estimating the formation time of quarkonium states differs considerably from the approach used for open heavy flavor [5, 4] or light particles [11] that come from the fragmentation of a hard parton. For quarkonia, the $Q\bar{Q}$ state is prepared instantly ($\sim 1/\sqrt{p_T^2 + M^2}$) in the hard collision and subsequently expands to the spatial extent determined by the size of the asymptotic wavefunction. In this case all spatial directions are important. The velocity of the heavy quarks in the meson and a typical upper limit of the meson formation time can be evaluated as follows:

$$\beta_Q = \sqrt{\frac{\kappa^2}{\kappa^2 + m_Q^2}}, \quad t_{\text{max rest frame}}^\text{form} = \frac{a}{\beta_Q}, \quad (8)$$

where the typical momenta $\kappa$ and sizes $a$ are obtained by solving the Schödinger equation for the corresponding quarkonium state. In this paper we are interested in high transverse momentum mesons, in which case there is a boost in the direction of propagation and, consequently, time dilation

$$t_{\text{max rest frame}}(p_T, \alpha) = \gamma t_{\text{max rest frame}}(\alpha) = \gamma \frac{a}{\beta_Q}, \quad \gamma = \gamma = \sqrt{\frac{p_T^2 + M^2}{M}}. \quad (9)$$
Here, $\gamma$ is the meson boost factor. Since the formation process is non-perturbative and can not be modeled accurately, the values of $t_{\text{form}}$ obtained from Eq. 9 should be considered as an estimate of the upper bound. Therefore, in addition to calculating the final yields for $t_{\text{form}} = t_{\text{max}} = \frac{\gamma a}{2\xi}$, we also calculate the yields for $t_{\text{form}} = t_{\text{min}} = \frac{\gamma a}{2\xi}$.

The propagation of a $Q\bar{Q}$ state in matter is accompanied by collisional interactions mediated at the partonic level, as long as the momentum exchanges can resolve the partonic structure of the meson. Two effects are related to these interactions: a) a broadening in the distribution of quarkonium states relative to the original direction; b) a modification of the quarkonium wavefunction. The latter effect leads to the dissociation of the meson state. Let us define:

$$\chi\mu^2\xi = \int_{t_0}^{t} dt' \frac{\mu^2}{\lambda_q} (x, t') \xi, \quad x(t) = x_0 + \beta(t - \tau_0).$$ \hspace{1cm} (10)

In Eq. (10) $\mu^2$ is the typical squared transverse momentum transfer given by the Debye screening scale, $\mu = gT$ for a gluon-dominated plasma. $\lambda_q$ is the mean scattering length of the quark and $\xi \sim \text{few}$ is an enhancement factor from the power law tail of the differential scattering cross section. Finally, $x_0$ is the position of the propagating $Q\bar{Q}$ and $\beta$ is the velocity of the heavy meson. By evaluation the overlap between the initial and final meson wavefunctions the meson survival probability $P_{\text{surv}}$. can be obtained. The dissociation rate is then given by

$$t_{\text{diss.}}(p_T, \alpha) = \frac{dP_{\text{diss.}}}{dt} = \frac{dP_{\text{surv}}}{dt}.$$ \hspace{1cm} (11)

The uncertainty in $t_{\text{diss.}}$ arises from the uncertainty in the coupling between the heavy quarks and the medium (described by the strong coupling constant $g$) and the enhancement that arises from the power law tails of the Moliere multiple scattering in the Gaussian approximation to transverse momentum diffusion [5] (described by $\xi$).

Let us denote by $N_{Q\bar{Q}}^{\text{hard}}(p_T, \alpha)$ the number of perturbatively produced point-like $Q\bar{Q}$ states at transverse momentum $p_T$. Up to an overall multiplicative Glauber scaling factor $T_{AB}$, these $p_T$ number distributions are directly proportional to the cross sections discussed in Section 2. The rate of formation of the corresponding hadronic state, with the appropriate quantum numbers $\{\alpha\}$, is given by the inverse formation time $1/t_{\text{form}}(p_T, \alpha)$. In the presence of a medium, the meson multiplicity, which we denote by $N_{Q\bar{Q}}^{\text{meson}}(p_T, \alpha)$, is reduced by collisional dissociation processes at a rate $1/t_{\text{diss.}}(p_T, \alpha)$. Finally, the number of dissociated $Q\bar{Q}$ pairs with a net transverse momentum $p_T$ is $N_{Q\bar{Q}}^{\text{diss.}}(p_T, \alpha)$.

The dynamics of such a system is governed by the following set of ordinary differential equations:

$$\frac{d N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha)}{dt} = -\frac{1}{t_{\text{form}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha),$$ \hspace{1cm} (12)

$$\frac{d N_{Q\bar{Q}}^{\text{meson}}(t; p_T, \alpha)}{dt} = \frac{1}{t_{\text{form}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha) - \frac{1}{t_{\text{diss.}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{meson}}(t; p_T, \alpha),$$ \hspace{1cm} (13)

$$\frac{d N_{Q\bar{Q}}^{\text{diss.}}(t; p_T, \alpha)}{dt} = \frac{1}{t_{\text{diss}}(t; p_T, \alpha)} N_{Q\bar{Q}}^{\text{meson}}(t; p_T, \alpha),$$ \hspace{1cm} (14)

subject to the constraint $N_{Q\bar{Q}}^{\text{hard}}(t; p_T, \alpha) + N_{Q\bar{Q}}^{\text{meson}}(t; p_T, \alpha) + N_{Q\bar{Q}}^{\text{diss.}}(t; p_T, \alpha) = N_{Q\bar{Q}}^{\text{hard}}(p_T, \alpha)$, and is uniquely determined by the initial conditions

$$N_{Q\bar{Q}}^{\text{hard}}(t = 0; p_T, \alpha) = N_{Q\bar{Q}}^{\text{hard}}(pQCD; p_T, \alpha),$$ \hspace{1cm} (15)

$$N_{Q\bar{Q}}^{\text{meson}}(t = 0; p_T, \alpha) = 0,$$ \hspace{1cm} (16)

$$N_{Q\bar{Q}}^{\text{diss.}}(t = 0; p_T, \alpha) = 0.$$ \hspace{1cm} (17)
Note that in Eqs. (14) the evolution of the dissociated $QQ$ pair into $D$- or $B$- mesons is not shown since it does not couple back to Eqs. (12), (13) (with an appreciable strength).

Realistic simulations include the velocity and $\{\alpha\}$ dependence of the formation rate of all quarkonium states and the time, position and $\{\alpha\}$ dependence of their dissociation rate.

4. Numerical results for the nuclear modification factors
In this section we neglect the Cronin effect but include initial-state cold nuclear matter energy loss and shadowing. Let us first consider the nuclear modification factor for $J/\psi$ mesons. From Fig. 2 we see that the measurement of $R_{AA}$ in RHIC Au+Au collisions [12] shows a suppression factor of about 0.8 at $p_T \sim 6$ GeV. Even including the uncertainty in our model parameters, we obtain a somewhat higher suppression (for $p_T \sim 6$ GeV, $R_{AA} \sim 0.35 - 0.45$ for Au+Au) than the one currently observed at RHIC. In Fig. 2, our results for the prompt yields of $J/\psi$ mesons are marked by upper and lower yellow bands corresponding to the upper ($t_{\text{form}}^{\text{max}}$) and lower ($t_{\text{form}}^{\text{min}} = t_{\text{form}}^{\text{max}}/2$) limits of our formation time estimate respectively. The bands themselves correspond to our estimate of the uncertainty in the sets of parameters that determine the coupling of the heavy quarks with the in-medium partons [$g = 1.85$, $\xi = 2$ (minimum considered coupling gives the upper limit of the yellow band) and $g = 2$, $\xi = 3$ (maximum considered coupling for the lower limit of the yellow band)]. The pronounced effect of the variation of the formation time can be intuitively seen as follows. From Eq. 14, we see that the dissociation mechanism is operative only when $N_{\text{meson}}^{\text{time}}$ is substantial, i.e. after $t_{\text{form}}$. Since the upper limit for formation time of quarkonia can be on the order of several fm/c, the density of the medium at $t_{\text{form}}^{\text{max}}$ is reduced considerably due to Bjorken expansion, giving weaker dissociation and smaller suppression.

In the right panel of Fig. 2 we show the $p_T$-averaged suppression,

$$R_{AA}(N_{\text{part}}) \text{ or } R_{CP}(N_{\text{part}}) = \frac{\int_{p_T^{\text{min}}}^{p_T^{\text{max}}} dp_T R_{AA}(p_T; N_{\text{part}}) \text{ or } R_{CP}(p_T; N_{\text{part}})}{\int_{p_T^{\text{min}}}^{p_T^{\text{max}}} dp_T \frac{d\sigma}{dp_T}} ,$$

of $J/\psi$ mesons versus centrality. We present a comparison to the ATLAS central-to-peripheral data [13]. Our theoretical predictions compare well to the measurement in mid-central and
Figure 3. Theoretical model predictions for $\Upsilon$ $R_{AA}$ in nucleus-nucleus collisions. Left panel: data from CMS is for $0-100\%$ centrality [6] compared to the theoretical prediction at the minimum bias $N_{\text{part}} \approx 110$. Theoretical model predictions for minimum-bias $R_{pA}(\Upsilon)$ and central 0-20\% $R_{AA}(\Upsilon)$. Right panel: RHIC p+Au and Au+Au collisions at $\sqrt{s} = 0.2$ TeV. Data is from STAR [14].

5. Conclusions

In summary, we carried out a detailed study of high transverse momentum quarkonium production and modification in heavy ion reactions at RHIC and at the LHC [3]. We used a NRQCD approach to calculate the baseline quarkonium cross sections. We found that for $J/\psi$ mesons the theoretically computed spectrum is slightly harder than the one observed in the experiment. For all $\Upsilon$ states (1S, 2S, 3S) the agreement is within a factor of two when we consider both the TeVatron and the LHC data. In reactions with heavy nuclei, we presented theoretical model predictions for the nuclear modification of quarkonium yields at high $p_T$ in minimum bias p(d)+A and 0-20\% central A+A collisions. We focused on the consistent inclusion of both

---

**Figure 3.** Theoretical model predictions for $\Upsilon$ $R_{AA}$ in nucleus-nucleus collisions. Left panel: data from CMS is for $0-100\%$ centrality [6] compared to the theoretical prediction at the minimum bias $N_{\text{part}} \approx 110$. Theoretical model predictions for minimum-bias $R_{pA}(\Upsilon)$ and central 0-20\% $R_{AA}(\Upsilon)$. Right panel: RHIC p+Au and Au+Au collisions at $\sqrt{s} = 0.2$ TeV. Data is from STAR [14].

Peripheral reactions. The deviation between data and theory is only for $N_{\text{part}} > 300$. (In the case of CMS data the deviation between data and theory is for $N_{\text{part}} > 200$.)

The CMS experiment at the LHC has also measured $R_{AA}$ for $\Upsilon(nS)$ states in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV per nucleon pair [6]. We cannot calculate the equivalent ratio of $R_{AA}$ for inclusive production because our formalism for the production and propagation of $\Upsilon$s is not applicable to $p_T(\Upsilon) \leq 6$ GeV. In our approach the meson should be boosted relative to the medium. Instead, in the left panel of 3 we show comparison to the minimum bias $p_T$-differential $\Upsilon(1S)$ CMS nuclear modification measurement. In this case, the theoretical calculation is performed for the average number of participants for minimum bias collisions. The combined results for $R_{AA}$ (0-20\% central) and $R_{pA}$ (minimum-bias) for bottomonia are given in the right panel of Fig. 3. The effect of transverse momentum broadening is much smaller for bottomonia when compared to the one for charmonia. This can be intuitively understood as follows. The mechanism for Cronin enhancement in this calculation is that initial state scattering increases the typical transverse momentum carried by the incident partons by a few GeV. For quarkonia, there is an additional scale $m_H$. For bottomonia the mass scale is considerably larger than the transverse momentum broadening scale and few additional GeV do not increase the yield significantly. Preliminary $\Upsilon$ suppression measurements are now available at RHIC [14]. More differential $p_T$ measurements will shed light on the similarities and differences in the CNM effects at RHIC and at the LHC.

5. Conclusions

In summary, we carried out a detailed study of high transverse momentum quarkonium production and modification in heavy ion reactions at RHIC and at the LHC [3]. We used a NRQCD approach to calculate the baseline quarkonium cross sections. We found that for $J/\psi$ mesons the theoretically computed spectrum is slightly harder than the one observed in the experiment. For all $\Upsilon$ states (1S, 2S, 3S) the agreement is within a factor of two when we consider both the TeVatron and the LHC data. In reactions with heavy nuclei, we presented theoretical model predictions for the nuclear modification of quarkonium yields at high $p_T$ in minimum bias p(d)+A and 0-20\% central A+A collisions. We focused on the consistent inclusion of both
cold (CNM) and hot (QGP) nuclear matter effects in different colliding systems at different center-of-mass energies. We compared our results to published and preliminary experimental data, where applicable.

We found that ignoring the Cronin effect leads to a small overestimate of the suppression of $J/\psi$ mesons in the $p_T$ region between 5 GeV and 10 GeV in central Cu+Cu and Au+Au collisions at $\sqrt{s} = 0.2$ TeV at RHIC. Including initial-state transverse momentum broadening leads to a somewhat better agreement between theory and the current experimental data only for the Cu+Cu reactions. A smaller Cronin enhancement will work better. We demonstrated that CNM effects can be easily constrained in d+A reactions at RHIC. For example, the d+Au calculation that includes power corrections and cold nuclear matter energy loss predicts 20% suppression of the $J/\psi$ cross section. Including transverse momentum broadening may lead to as much as 50% enhancement in the region of the Cronin peak. We also found that the Cronin-like modification of the $\Upsilon$ spectrum is much smaller. Current data on high-$p_T$ quarkonium production at RHIC does not indicate the presence of thermal effects at the level of the quarkonium wavefunction within our theoretical framework.

The conclusions from our theoretical model comparison to the $\sqrt{s} = 2.76$ TeV LHC data are not as clear cut. Our calculations underestimated the suppression for $J/\psi$ production reported by the ATLAS and CMS experiments in the most central Pb+Pb collisions. On the other hand, it works quite well in mid-central and peripheral reactions. We found that the Cronin enhancement at the LHC is smaller than the one at RHIC due to the harder spectra. However, any Cronin enhancement appears incompatible with the experimental results. For $\Upsilon$ mesons, $p_T$-differential data in A+A collisions is scarce. CMS measurements of minimum bias $\Upsilon(1S)$ indicate that the low $p_T$ suppression may decrease or disappear at high $p_T$. We plan to address the possibility of thermal effects at the level of the quarkonium wavefunction in a separate publication. We also plan to extend the meson dissociation mechanism to photon-tagged heavy flavor [15, 16] and heavy flavor-tagged jets [17].

References

[1] T. Matsui and H. Satz, Physics Letters B, 178, 416-422 (1986).
[2] G. T. Bodwin, E. Braaten and G. P. Lepage, Phys. Rev. D 51, 1125 (1995) [Erratum-ibid. D 55, 5853 (1997)] [arXiv:hep-ph/9407339].
[3] R. Sharma and I. Vitev, arXiv:1203.0329 [hep-ph].
[4] R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C 80, 054902 (2009) [arXiv:0904.0032 [hep-ph]].
[5] A. Adil and I. Vitev, Phys. Lett. B 649, 139 (2007) [hep-ph/0611109].
[6] S. Chatrchyan et al. [CMS Collaboration], [arXiv:1201.5009 [nucl-ex]].
[7] V. Khachatryan et al. [CMS Collaboration], Phys. Rev. D 83, 112004 (2011) [arXiv:1012.5545 [hep-ex]].
[8] J. -W. Qiu and I. Vitev, Phys. Lett. B 587, 52 (2004) [hep-ph/0401062].
[9] R. B. Neufeld, I. Vitev and B. -W. Zhang, Phys. Lett. B 704, 590 (2011) [arXiv:1010.3708 [hep-ph]].
[10] M. Gyulassy, P. Levai and I. Vitev, Phys. Rev. D 66, 014005 (2002) [nucl-th/0201078].
[11] C. Markert, R. Bellwied and I. Vitev, Phys. Lett. B 669, 92 (2008) [arXiv:0807.1509 [nucl-th]].
[12] Z. Tang [STAR Collaboration], J. Phys. G 38, 124107 (2011) [arXiv:1107.0532 [hep-ex]]; references therein.
[13] G. Aad et al. [Atlas Collaboration], Phys. Lett. B 697 (2011) 294 [arXiv:1012.5419 [hep-ex]].
[14] R. Reed [STAR Collaboration], J. Phys. Conf. Ser. 270, 012026 (2011) [Nucl. Phys. A 855, 440 (2011)]; Quark Matter 2011.
[15] Z. -B. Kang and I. Vitev, Phys. Rev. D 84, 014034 (2011) [arXiv:1106.1493 [hep-ph]].
[16] W. Dai, I. Vitev and B. -W. Zhang, arXiv:1207.5177 [hep-ph].
[17] Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713, 224 (2012) [arXiv:1105.2566 [hep-ph]].