Quarkonium production in pp and heavy-ion collisions

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Abstract. We describe quarkonium production in pp and heavy-ion collisions by using the Remler's formalism where quarkonium density operator is applied to all possible combination of heavy quark and heavy antiquark pairs. In pp collisions heavy (anti)quark momentum is provided by the PYTHIA event generator after rescaling p_T and rapidity to imitate the FONLL calculations. Then spatial separation between heavy quark and heavy antiquark is introduced based on the uncertainty principle. In heavy-ion collisions quarkonium wavefunction changes with temperature assuming heavy quark potential equals the free energy of heavy quark pair in heat bath. The density operator is updated whenever heavy quark or heavy antiquark scatters in quark-gluon plasma (QGP). Our results are consistent with the experimental data on bottomonia from ALICE and CMS Collaborations assuming that the interaction rate of bottom (anti)quark in bottomonium is suppressed to 10 % that of unbound bottom (anti)quark. We also find that off-diagonal recombination of bottomonium from two different initial pairs barely happens even in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

1 Introduction

Ultra-relativistic heavy-ion collisions produce an extremely hot and dense matter which is supposed to cross over the phase boundary between hadron gas and quark-gluon plasma. Quarkonium is a flavorless bound state of heavy quark pair, whose suppression in heavy-ion collisions was suggested as a signature for QGP formation, because the binding of heavy quark pair changes through the color screening and scattering with thermal partons [1]. However, it was discovered that J/ψ is less suppressed in mid-rapidity as well as in higher energy collisions at the top energies of RHIC and LHC, which indicates the regeneration of quarkonium from the uncorrelated heavy quark pairs [2]. So the complete description of quarkonium production in heavy-ion collisions requires suppression as well as regeneration.

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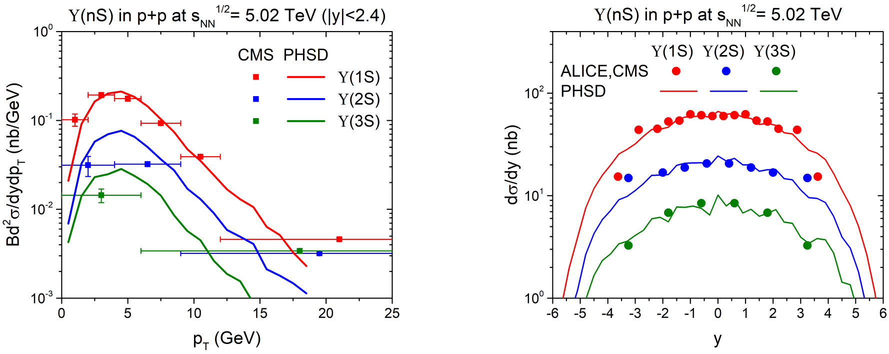

Figure 1. (Left) p_T spectra and (right) rapidity distributions of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ including the feed-out from excited states in pp collisions at $\sqrt{s}$ = 5.02 TeV, which are compared with experimental data from the CMS and ALICE Collaborations [6, 7].

Quarkonium production takes two steps. First, heavy quark pair is produced and then the produced heavy quark pair forms a bound state by emitting soft gluons to be a color singlet. The first step is a hard process which can be described by pQCD, while the second step is a soft process which requires a model. In heavy-ion collisions, the first step is modified by so-called cold nuclear matter effects such as shadowing effects and the second step by hot nuclear matter effects. In this study we try to describe quarkonium production not only in pp collisions but also in heavy-ion collisions by using the Remler's formalism.

2 Remler's formalism for quarkonium production

The probability that a quarkonium eigenstate i with momentum $\mathbf{P}$ is produced at $\mathbf{R}$ is given by [3, 4]

$$(2\pi)^3 \frac{dN_i}{d^3R\, d^3P} = \sum \int \frac{d^3r\, d^3p}{(2\pi)^3}\, \Phi_i^W(\mathbf{r},\mathbf{p}) \prod_{j>2} \int \frac{d^3r_j\, d^3p_j}{(2\pi)^{3(N-2)}}\, W^{(N)}(\mathbf{r_1},\mathbf{p_1},...,\mathbf{r_N},\mathbf{p_N}), \quad (1)$$

where $\mathbf{R} = (\mathbf{r_1}+\mathbf{r_2})/2$, $\mathbf{r} = \mathbf{r_1}-\mathbf{r_2}$, $\mathbf{P} = \mathbf{p_1}-\mathbf{p_2}$, $\mathbf{p} = (\mathbf{p_1}-\mathbf{p_2})/2$ with $\mathbf{r_k}$ and $\mathbf{p_k}$ being respectively the position and momentum of k'th (anti)heavy quark; $\Phi_i^W(\mathbf{r},\mathbf{p})$ is the Wigner density of quarkonium wavefunction which is nonvanishing only for flavorless and colorless combination; $W^{(N)}(\mathbf{r_1},\mathbf{p_1},\mathbf{r_2},\mathbf{p_2},...,\mathbf{r_N},\mathbf{p_N})$ is density matrix of the N (anti)heavy quarks produced in a proton-proton or a heavy-ion collision, which is simply taken for the classical phase space density distribution [4]. The summation in the right hand side implies that all possible combinations of heavy quark pairs are considered to form quarkonium state i.

In pp collisions the momentum of heavy quark and that of heavy antiquark are generated by the PYTHIA event generator followed by rescaling the transverse momentum and rapidity to imitate the FONLL calculations [5]. The cross section for charm production in pp collisions is parameterized from the experimental data [5]. The spatial separation between heavy quark and heavy antiquark is introduced based on the uncertainty principle [4].

Fig. 1 shows the p_T spectra and rapidity distributions of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ including the feed-out from excited states in pp collisions at $\sqrt{s}$ = 5.02 TeV. One can see that the results are consistent with the experimental data from CMS and ALICE Collaborations [6, 7].

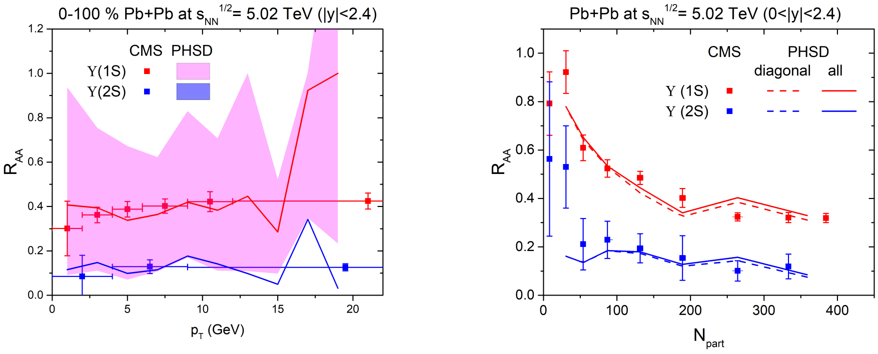

Figure 2. R_{AA} of $\Upsilon(1S)$ and $\Upsilon(2S)$ as a function of (left) transverse momentum and (right) number of participants in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in comparison with the experimental data from the CMS Collaboration [6].

A hot dense matter produced in relativistic heavy-ion collisions delays the formation of quarkonium, because quarkonium cannot be formed above its dissociation temperature. We assume that the free energy of heavy quark pair is equivalent to the heavy quark potential [8]. In this case the dissociation temperature of $\Upsilon(1S)$ is roughly 3 T_c, while those of excited states are near T_c [4]. The first Wigner projection of Eq. (1) is carried out when the local temperature of heavy quark pair becomes lower than the dissociation temperature of quarkonium state i. After that, whenever scattering happens to heavy quark or heavy antiquark, the Wigner production is updated [9], considering temperature-dependent quarkonium radius, which is obtained by solving Schrödinger equation with the heavy quark potential.

The left panel of Fig. 2 displays R_{AA} of $\Upsilon(1S)$ and $\Upsilon(2S)$ as a function of transverse momentum in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The upper limit of the magenta band indicates R_{AA} of $\Upsilon(1S)$ at the dissociation temperature of $\Upsilon(1S)$ and the lower limit of the band R_{AA} of $\Upsilon(1S)$ at T_c. One can see that Wigner density of $\Upsilon(1S)$ decreases with time, because bottom and antibottom quarks are more and more separated from each other. The red solid line indicates R_{AA} of $\Upsilon(1S)$ at T_c, assuming only 10 % of (anti)bottom quark scatterings update(change) the Wigner density of $\Upsilon(1S)$, which is consistent with the experimental data from the CMS Collaboration [6]. In this case the interaction rate of $\Upsilon(1S)$ is roughly estimated to be 40-100 MeV at T=0.2-0.4 GeV [4, 10]. This reduction is reasonable, because quarkonium is a color singlet and part of heavy quark interaction will be canceled with that of heavy antiquark interaction. We also note that the feed-down from excited state bottomonia to $\Upsilon(1S)$ in heavy-ion collisions is less than 10 %. As for $\Upsilon(2S)$ its dissociation temperature is close to T_c. That is why the blue band is so narrow that it looks like a line and the interaction rate of $\Upsilon(2S)$ cannot be constrained by R_{AA} of $\Upsilon(2S)$.

The right panel shows R_{AA} as a function of the number of participants. The solid lines include all contributions, while the dashed lines only diagonal contribution which originates from initial bottom quark pairs. One can see that the off-diagonal contribution which originate from two different initial bottom quark pairs is little even in central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, because the number of produced bottom quark pairs is not so large.

3 Conclusion

The description of quarkonium production in heavy-ion collisions is often separated from the quarkonium production in pp collisions, though the nuclear modification factor (R_{AA}) is defined as their ratio. In this study we have used an unified method, the Remler's formalism, for quarkonium production in pp as well as in heavy-ion collisions. Assuming that the interaction rate of bottom (anti)quark bound in quarkonium is 10 % that of unbound bottom (anti)quark, our results are consistent with the experimental data in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Furthemore, we have found that the off-diagonal contribution from two different initial pairs is little even at LHC.

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