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Bottomonium suppression at RHIC and LHC

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The strong suppression of heavy quarkonia is a good indicator that one has generated a quark-gluon plasma (QGP) in an ultrarelativistic heavy ion collision. Recent advancements in first principles calculations of the heavy quark potential provide additional insight into this suppression and can be used to further pin down the in-medium properties of the QGP. Realistic 3+1d dissipative hydrodynamical models can be used to simulate the QGP and, with bottomonium as a probe, one can make inferences for the initial temperature of the QGP and other phenomenological parameters such as the shear viscosity to entropy density ratio. However, progressing to LHC $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb collisions, one expects regeneration to have an increasingly important impact on the suppression observables. In this proceedings, we present a brief overview to set up the model and then provide model results for bottomonium suppression and regeneration, for ultrarelativistic heavy-ion collision experiments at RHIC and LHC.

Keywords:

Quark-gluon plasma, quarkonia

1. Introduction

The ultrarelativistic heavy-ion collision (URHIC) experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and the Large Hadron Collider (LHC) at CERN generate a hot medium of deconfined matter known as the quark-gluon plasma (QGP). Recent comparisons between theory and experiment suggest QGP formation with initial temperatures around $T_0 = 600 - 700$ MeV at $\tau_0 = 0.25$ fm/c for $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb collisions at the LHC. Studies also suggest the QGP formed in URHICs behaves like a nearly-perfect fluid with a shear viscosity to entropy density ratio η/s of $4\pi\eta/s \sim 1 - 3$. Bottomonium is of particular interest to study the QGP formed in URHICs due to several unique properties. With their relatively large vacuum binding energies ($\lesssim 1$ GeV), they can survive well into the phase of deconfined matter. Also, production yield ratios between the ground $\Upsilon(1S)$ and excited states reveal insight into properties of the QGP like the initial temperature and η/s .

The formation of bottomonium states before $\tau \sim 1$ fm/c mean bottomonia are sensitive to non-equilibrium early-time dynamics. Characterized by a breaking of symmetry of the $\mathcal{P}_L - \mathcal{P}_T$ plane, one can model to good approximation [1], a spheroidal form for the one-particle distribution function in the QGP which is due to anisotropies in momentum space. The initial geometry of a URHIC provides a system which is rapidly

expanding along the longitudinal direction. After a short amount of time, the finite speed of sound in the QGP catches up and the shockwave pushes expansion in the transverse plane. Moreover, bottomonia are sensitive to this momentum-space anisotropy in the heavy quark potential calculation [2, 3, 4, 5, 6].

With increasing collision energies, e.g. at the LHC, one expects a QGP which is hotter. With a larger inelastic cross section, the formation of $b\bar{b}$ pairs should become more common in URHICs. The increase in $b\bar{b}$ pairs provides a foundation for bottom quark and anti-bottom quark pairs to recombine following bottomonium state breakup, or combination after the pair forms from open bottom states. In this proceedings, we introduce a more comprehensive model for bottomonium suppression and regeneration at the RHIC and LHC experiments.

2. Model implementation and results

The model presented herein uses a 3+1d anisotropic hydrodynamics (aHydro) code that simulates the QGP and two different potentials [6, 7] which are used to describe the six bottomonium states' ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b(1P)$, $\chi_b(2P)$, $\chi_b(3P)$) binding energy as a function of energy density and momentum-space anisotropy. A non-relativistic QCD (pNRQCD)-based potential (Strickland-Bazow) is used along with a new potential derived in large part from first principle lattice QCD studies (Rothkopf) [7]. A regeneration model is used to compute the recombination of $b\bar{b}$ pairs which is based on models presented in Refs. [8, 9]. We assume all $b\bar{b}$ pairs are formed in initial hard scatterings and, throughout the evolution of the QGP, the pairs breakup and recombine depending on physical conditions found locally in the QGP. The initial number of $b\bar{b}$ pairs formed in each collision is determined via experimental measurements in proton-proton collisions and scaled up to heavy-ion collisions via the number of binary collisions N_{coll} as calculated via the smooth Glauber model, i.e.

$$N_{b\bar{b}} = \frac{\sigma_{b\bar{b}}}{\sigma_{\text{inel}}} N_{\text{coll}}. \quad (1)$$

The heavy quarkonium state breakup and regeneration is based on a first-order rate equation to compute the local particle density function,

$$\frac{dn(\tau, \mathbf{x})}{d\tau} = -\Gamma(T(\tau, \mathbf{x})) [n(\tau, \mathbf{x}) - n_{\text{eq}}(T(\tau, \mathbf{x}))], \quad (2)$$

where $n(\tau, \mathbf{x})$ is the bottomonium number density as a function of the spatiotemporal evolution of the QGP, $n_{\text{eq}}(\tau, \mathbf{x})$ is the equilibrium distribution of bottomonium, and $\Gamma(T(\tau, \mathbf{x}))$ is the temperature-dependent breakup rate which is primarily associated with the imaginary part of the bottomonium binding energy, i.e.

$$\Gamma(\tau, \mathbf{x}) = \begin{cases} 2\Im[E_{\text{bind}}(\tau, \mathbf{x}_{\perp}, \varsigma)] & \Re[E_{\text{bind}}(\tau, \mathbf{x}_{\perp}, \varsigma)] > 0 \\ \gamma_{\text{dis}} & \Re[E_{\text{bind}}(\tau, \mathbf{x}_{\perp}, \varsigma)] \leq 0, \end{cases} \quad (3)$$

where γ_{dis} is chosen to be 10 GeV to quickly breakup unbound bottomonia.

Input for the regeneration model includes bottomonium state cross sections from experiment [9, 10, 11, 12, 13, 14], and leads to modification of n_{eq} due to the bottom quark fugacity γ_b . We take n_{eq} from the following expression calculated in [15]

$$n_{\text{eq}}(m, T) = \gamma_b^2 4\pi \tilde{N} T^3 \hat{m}_{\text{eq}}^2 K_2(\hat{m}_{\text{eq}}^2), \quad (4)$$

where $\hat{m}_{\text{eq}} = m/T$, $\tilde{N} = 4\pi/(2\pi\hbar c)^3$, and K_2 is the modified Bessel function of the second kind.

Initial temperatures for QGP evolution using aHydro are fixed via particle-spectra fits performed in other studies [16, 17]. The number density is integrated in the particle freeze-out hypersurface for each run to self-consistently compute the initial temperature for each initial η/s and value of the momentum-space anisotropy, ξ . Initial temperatures for RHIC 200 GeV/nucleon collisions are $T_0 = \{0.442, 0.440, 0.439\}$ and for LHC 5.02 TeV collisions we have $T_0 = \{0.641, 0.632, 0.629\}$ for $4\pi\eta/s = \{1, 2, 3\}$, respectively. For LHC 5.02 TeV collisions, initial temperatures were derived via a prediction made in Ref. [18].

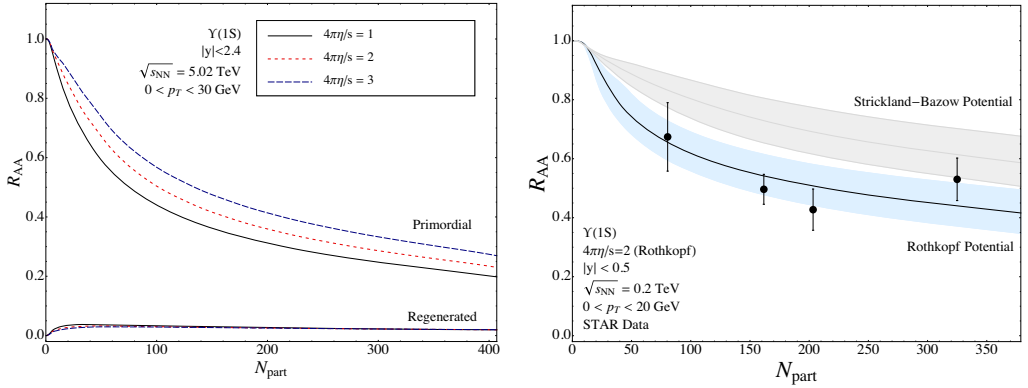


Fig. 1. (Left) The inclusive feed down suppression and regeneration results for the $\Upsilon(1S)$ bottomonium state as a function of N_{part} . (Right) A comparison between the Strickland-Bazow and Rothkopf potentials the inclusive feed down $\Upsilon(1S)$ at RHIC energies. Experimental $\Upsilon(1S)$ suppression data is taken from the STAR collaboration [19].

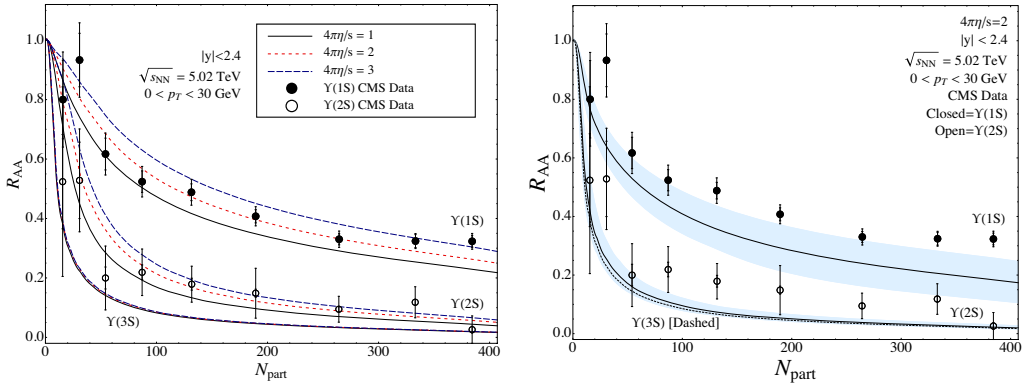


Fig. 2. (Left) The Strickland-Bazow bottomonium and (Right) Rothkopf potential calculation for the inclusive $\Upsilon(nS)$ suppression as a function of N_{part} . A comparison is made with the CMS experiment at the LHC. CMS data taken from [20].

3. Discussion and conclusions

The model presented herein provides a more comprehensive description of bottomonium suppression seen at RHIC and LHC. The pNRQCD-based Strickland-Bazow potential describes URHICs at the LHC well while underestimating the amount of suppression seen at RHIC 200 GeV/nucleon collisions. The lattice-vetted Rothkopf potential does a good job at reproducing suppression in 200 GeV/nucleon RHIC Au-Au collisions, however slightly overestimates suppression for 2.76 TeV/nucleon and 5.02 TeV/nucleon LHC Pb-Pb collisions. Future work on continuum-extrapolated potential extractions using lattice QCD may relieve some tension with the data. In addition, the momentum-space anisotropy of the QGP causes one to insert non-equilibrium effects by hand to the lattice-QCD-based Rothkopf potential. Further advancements in the aHydro framework have pushed our understanding of URHICs for a variety of other observables such as particle spectra, flow coefficients, and HBT radii at both RHIC for 200 GeV/nucleon collisions [16] and the LHC for 2.76 TeV/nucleon collisions [17]. It will be interesting to see if these new phenomenological fits for the soft-hadron spectra, etc. have an effect on the predicted bottomonium suppression.

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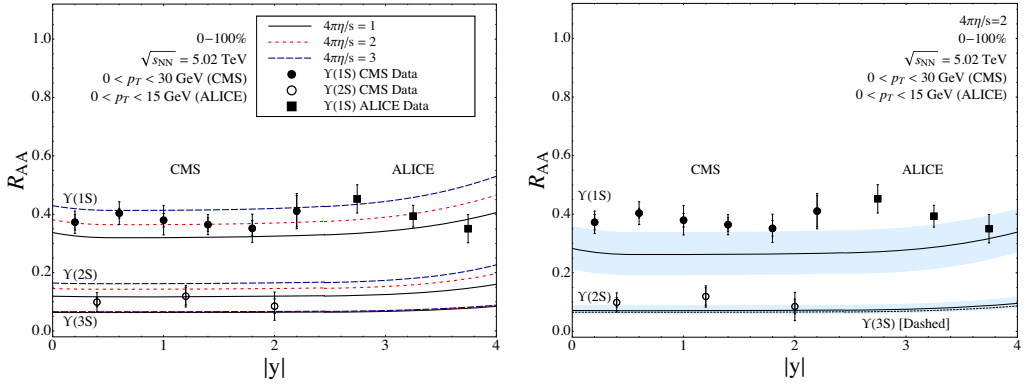


Fig. 3. (Left) The Strickland-Bazow potential and (Right) Rothkopf potential results for the inclusive $\Upsilon(nS)$ R_{AA} as a function of rapidity. A comparison is made with the CMS and ALICE experiments at the LHC. CMS data taken from [20] and ALICE data taken from [21].

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