Charmonium in strongly-coupled quark-gluon plasma

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Motivation: J/ψ suppression in heavy-ion collisions
Quarkonium dynamics in sQGP as a stochastic process
Heavy quark and quarkonium dynamics
Properties of the J/ψ in sQGP

Quarkonium as an open quantum system

The path integral approach to quantum Brownian motion
Imaginary-time correlators

Au+Au RHIC collisions

Langevin-with-interaction simulation of charmonium
Recombinant production
Cold nuclear matter effects
Anomalous J/ψ suppression for two values of T_c

Conclusions and future work

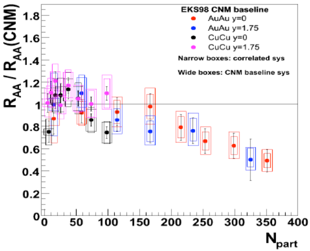
Part I: Modeling charmonia with Langevin equations

Motivation: J/ψ suppression in heavy-ion collisions

Matsui and Satz, 1986: Changes in the heavy quark-antiquark potential result in changes in the quarkonium spectrum: when $r_{bind} > r_{Debye}$, no bound states exist. This is the first prediction of *significant* J/ψ suppression.

2009: The latest analysis of "anomalous" R_{AA} in many heavy-io collision experiments

Slow decrease in the ratio at large N_{part} cannot be explained simply from examining changes in the charmonium spectrum



Quarkonium dynamics in sQGP as a stochastic process

When M_{HQ} is sufficiently larger than T, the dynamics of each heavy quark can be described by

$$\frac{dp_i}{dt} = -\eta p_i + \xi_i - \nabla_i U, \tag{1}$$

where

$$\langle \xi_i(t)\xi_j(0)\rangle = \kappa \delta_{ij}\delta(t). \tag{2}$$

Requiring thermalization to temperature T yields the Einstein relation between noise and dissipation:

$$\eta = \frac{\kappa}{2MT}. \tag{3}$$

Heavy quark and quarkonium dynamics

Heavy quark diffusion: $3\kappa = \int d^3q|\mathbf{q}|^2 \frac{d^3\Gamma}{dq^3}$

- HTL approximation at NLO (Caron-Huot and Moore)[1]:

$$\kappa = \frac{16\pi}{3}\alpha_s^2 T^3 \left(\log(1/g_s) + .07428 + 1.9026 g_s\right) \qquad (4)$$

- Drag force and diffusion from AdS/CFT (Gubser, Casalderrey-Solana and Teaney, Mia et al.) [2], [3], [4], [5]:

$$\kappa = \pi\sqrt{\lambda}T^3 \qquad (5)$$

- Phenomenology (van Hees and Rapp, Moore and Teaney) [6].

$Q\bar{Q}$ potential

- Lattice calculations of $Tr\left\langle W(\mathbf{x})W^{\dagger}(\mathbf{0})\right\rangle$ (Kaczmarek et al.) [7].
- Internal or Free Energy? (Shuryak and Zahed) [8].
- Potential models (Mocsy and Petreczky) [9].

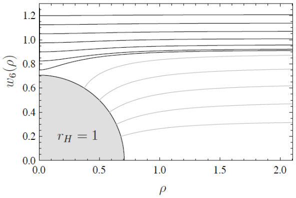
D_{HQ} vs. quarkonium diffusion

Quarkonium $\neq$ two heavy quarks!

First AdS/CFT calculations for quarkonium suggested *zero drag*, only influence of the thermal medium from a "hot wind"

Dusling et al.: Fluctuations on D7 in $AdS_5 \times S_5$ dual to effective theory for dipoles

Momentum diffusion suppressed by factor of $1/N_c^2$, smaller than perturbative $\mathcal{N} = 4$ prediction by a factor of 4. Exact opposite of heavy quark situation!



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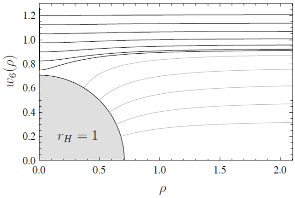


However, this treatment only valid when $E_B >> T$

Appropriate for Υ, inappropriate for J/ψ

J/ψ dynamics at RHIC somewhere between "photoelectric effect" and "Rayleigh scattering"

Ito integration

When a stochastic process satisfies a relaxed version of continuity, it can be integrated:

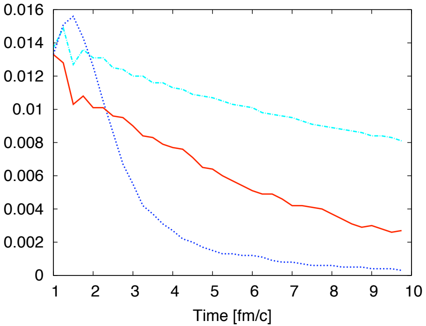
$$p^i_{n+1} = (1 - \eta \Delta t) p^i_n + \xi^i_n \Delta t, \tag{6}$$

where ξ^i_n is now selected from a Gaussian distribution with expectation value κ, thanks to the central limit theorem (the sum of a sufficiently large number of random variables will approach a Gaussian distribution).

Evolution of an ensemble of $Q\bar{Q}$ pairs in sQGP

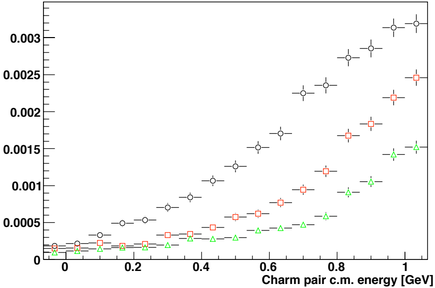
The probability for a $Q\bar{Q}$ pair to be bound as a function of time:

- **Green:** $2\pi TD_c = 1.5$
- **Red:** $2\pi TD_c = 3.0$
- **Blue:** $2\pi TD_c = 1.5$, no $Q\bar{Q}$ interaction



Quasi-equilibrium of $Q\bar{Q}$-pair ensemble

- **Black:** Ensemble after $\tau = 2$ fm/c
- **Red:** Ensemble after $\tau = 3$ fm/c
- **Green:** Ensemble after $\tau = 10$ fm/c



Only the normalization changes after the initial thermalization ~ 2 fm/c.

Summary of $Q\bar{Q}$ in sQGP

- Thermalization in momentum space relatively fast, spatial diffusion relatively slow.
- The $Q\bar{Q}$-potential can greatly enhance the survival probability.
- Quasi-equilibrium forms: relative abundances predicted by Boltzmann factors.

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An explanation for J/ψ survival at RHIC?

Part II: Quarkonium as an open quantum system

The reduced density matrix

Imagine a single degree of freedom minimally coupled to a bath:

$$\begin{aligned} L &= \frac{1}{2}M\dot{x}^2 - V(x) \\ &+ \frac{1}{2}\sum_i m_i\dot{R}_i^2 - \frac{1}{2}\sum_i m_i\omega_i^2 R_i^2 \\ &- \sum_i C_i x R_i. \end{aligned} \tag{7}$$

The *reduced* density matrix

$$\begin{aligned} \rho_{red}(x,x',\beta) &= \int dR_i \rho(x,R_i,x',R_i,\beta) \\ &= \int Dx \exp(-\int_0^\beta d\tau[\frac{1}{2}M\dot{x}^2 + V(x) \\ &- \sum_i \frac{C_i^2}{2m_i\omega_i \sinh(\omega_i\beta/2)} x(\tau)\int_0^\tau ds\, x(s)\cosh(\omega_i(\tau - s - \beta/2))]) \end{aligned} \tag{8}$$

Caldeira and Leggett, 1983

Intuitively, when the proper infinite limit is taken for the bath, the dynamics for the heavy particle may be dissipative. The density of states

$$C^2(\omega)\rho_D(\omega) = \begin{cases} \frac{2m\eta\omega^2}{\pi} & \text{if } \omega < \Omega \\ 0 & \text{if } \omega > \Omega \end{cases} \tag{9}$$

yields Langevin dynamics when $\Omega \to \infty$, with η the usual drag coefficient.

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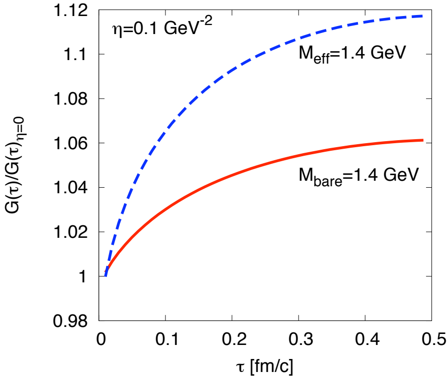
The reduced density matrix becomes, after integrating by parts and renormalizing...

The reduced density matrix for an open system

$$
\begin{aligned}
\rho_{red}(x_i, x_f, \beta) &= \int_{x(0)=x_i}^{x(\beta)=x_f} \mathcal{D}x \;\exp\Bigg\{ - S_S^E[x] \\
&- \frac{\eta}{2\pi}(x_i - x_f)^2 \left[\gamma_E + \ln\left(\frac{\eta\beta}{\pi M}\right)\right] \\
&+ \frac{\eta}{\pi}(x_i - x_f) \int_0^\beta d\tau\; \dot{x}(\tau)\, \mathrm{lnsin}\left(\frac{\pi\tau}{\beta}\right) \\
&+ \frac{\eta}{\pi} \int_0^\beta d\tau \int_0^\tau ds\; \dot{x}(\tau)\dot{x}(s)\, \mathrm{lnsin}\left(\frac{\pi(\tau - s)}{\beta}\right) \Bigg\}. \quad (10)
\end{aligned}
$$

The effect of dissipation on $G_{rec}(\tau)$

- $\eta = 0.1 \text{GeV}^{-1}$,
- $T = 1.2 T_c$.



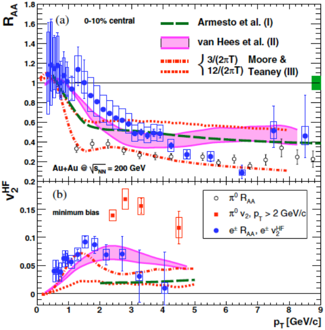
Part III: Langevin-with-interaction simulation of charmonium in Au+Au RHIC Collisions

Langevin-with-interaction simulation of charmonium

LO PYTHIA event generation

2+1-dimensional hydrodynamical simulation of the plasma phase

Langevin+interaction evolution of the $c\bar{c}$ pairs



Another consideration: recombinant production

- With many hard processes per collision, the possibility of recombinant production needs to be considered.
- May lead to less suppression or even an enhancement of J/ψ yields at the LHC

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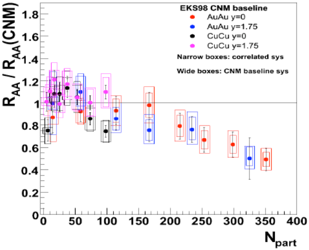
Facts about charm production at the RHIC:

- On average 18 pairs produced in the most central Au+Au collisions.
- Only 5.5% of charm quarks produced are "neighbors" (close enough to form a bound state) with a single anti-quark. Only an additional 0.2% have more than one neighbor.

J/ψ suppression and CNM effects

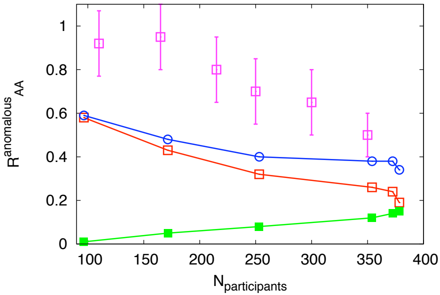
Our results compared with latest CNM effect analysis, where shadowing and breakup are treated separately

Successful in explaining greater supression at forward rapidity as a CNM effect

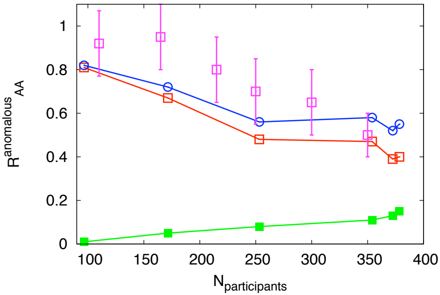


Anomalous J/ψ suppression for two values of T_c

For $T_c = 165$ MeV:



For $T_c = 190$ MeV:

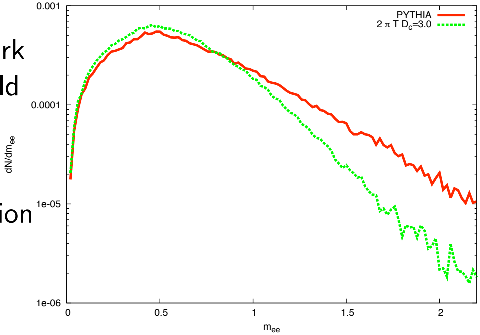


Similar to the results of Zhao and Rapp

Another important observable: differential dielectron yields due to charm pair semi-leptonic decays

Semi-leptonic decays of charm quark pairs dominates the differential yield in the $1 - 3\ \mathrm{GeV}$ invariant mass range.

Because of this, heavy quark diffusion can change dielectron yields.



Conclusions and future work

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Future work

Calculate surviving and recombinant yields at the LHC

Extract spectral functions for quarkonium correlators with the maximal entropy method

Other observables at the RHIC (invariant mass spectrum of dielectrons, bottomonium)?

What more can AdS/CFT tell us about quarkonium?

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Thanks!

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