Munich-KSU Contribution to Suppression and (Re)Generation of Quarkonium in Heavy-Ion Collisions at the LHC

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Munich-KSU Approach

- aim: describe the out-of-equilibrium, in-medium evolution of heavy quarkonium states
- tools: potential nonrelativistic QCD (pNRQCD) and the formalism of open quantum systems (OQS)
  - pNRQCD: an EFT of QCD describing the strong dynamics of small heavy-heavy bound states
  - OQS: formalism to treat the out-of-equilibrium evolution of a system (quarkonium) in the presence of an environment (QGP)
- method and results are fully quantum, non abelian, heavy quark number conserving; take into account dissociation and recombination; quantum field theoretically describe the nonequilibrium evolution; depend only on the transport coefficients taken from lattice data

Physical Setup

work with hierarchy of scales: $M \gg 1/a_0 \gg (\pi)T \gg E$

- heavy quark mass M is a scheme dependent quantity; we work in $1S$ scheme

$$M = m_b = m_{\Upsilon(1S)}/2 = 4.73\text{ GeV}$$

- Bohr radius calculated by solving its defining relation with the 1-loop, 3-flavor running of α_s with $\Lambda_{\overline{\text{MS}}}^{N_f=3} = 332\text{ MeV}$

$$a_0 = 2/C_f\alpha_s(1/a_0)m_b = 0.678\text{ GeV}^{-1}$$

- thermal scale related to temperature of the medium (up to factor(s) of π):

$$190 < T/\text{MeV} < 500$$

- binding energy is scheme dependent quantity; Coulombic binding energy sets the scale of the spacing of the energy levels

$$|E| = 1/\left(Ma_0^2\right) = 460\text{ MeV}$$

pNRQCD[1] for in-medium Bottomonium[2]

$$\mathcal{L}_{\text{pNRQCD}} = \text{Tr}\Big[S^\dagger(i\partial_0 - h_s)S + \tilde{O}^\dagger(i\partial_0 - h_o)\tilde{O} + \tilde{O}^\dagger \mathbf{r}\cdot g\,\tilde{\mathbf{E}}\,S$$
$$+S^\dagger \mathbf{r}\cdot g\,\tilde{\mathbf{E}}\,\tilde{O} + \frac{1}{2}\tilde{O}^\dagger\left\{\mathbf{r}\cdot g\,\tilde{\mathbf{E}}\,,\ \tilde{O}\right\}\Big]$$

- singlet and octet field S and O interacting via chromo-electric dipole vertices
- $h_{s,o} = \frac{\mathbf{p}^2}{M} + V_{s,o}$: singlet, octet Hamiltonian
  - $V_s = -\frac{C_f \alpha_s(1/a0)}{r}$: attractive singlet potential
  - $V_o = \frac{\alpha_s(1/a0)}{2N_c r}$: repulsive octet potential
- $\tilde{E}^{a,i}(s,\mathbf{0}) = \Omega^\dagger(s)E^{a,i}(s,\mathbf{0})\Omega(s)$ where $\Omega(s) = \exp\left[-ig\int_{-\infty}^{s} \mathrm{d}s' A_0(s',\mathbf{0})\right]$
- derive coupled evolution equations for singlet and octet density matrices $\rho_s(t)$ and $\rho_o(t)$

[1] Nucl.Phys.B 566 (2000) 275 (Brambilla, Pineda, Soto, Vairo)
[2] Phys. Rev. D 97 (2018) 7, 074009 (Brambilla, Escobedo, Soto, Vairo)

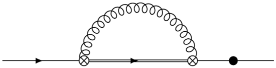
Diagrammatic Evolution

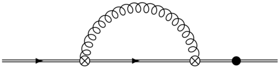
singlet evolution given by

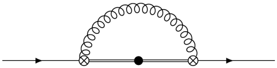
$$\frac{\mathrm{d}\rho_s(t)}{\mathrm{d}t} = -i\left[h_s, \rho_s(t)\right] - \Sigma_s\rho_s(t) - \rho_s(t)\Sigma_s^\dagger + \Xi_{so}(\rho_o(t))$$

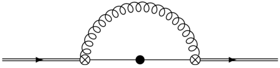
$$\frac{\mathrm{d}\rho_o(t)}{\mathrm{d}t} = -i\left[h_o, \rho_o(t)\right] - \Sigma_o\rho_o(t) - \rho_o(t)\Sigma_o^\dagger + \Xi_{os}(\rho_s(t)) + \Xi_{oo}(\rho_o(t))$$

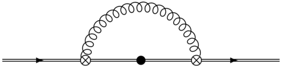
where

$\Sigma_s\rho_s(t) \sim$ 

$\Sigma_o\rho_o(t) \sim$ 

$\Xi_{so}(\rho_o(t)) \sim$ 

$\Xi_{os}(\rho_s(t)) \sim$ 

$\Xi_{oo}(\rho_o(t)) \sim$ 

Elements of Evolution Equations

- medium interactions encoded in
$$A_i^{uv} = \frac{g^2}{6N_c} \int_0^\infty \mathrm{d}s\, e^{-ih_u s} r^i e^{ih_v s} \langle \tilde{E}^{a,j}(0,\mathbf{0}) \tilde{E}^{a,j}(s,\mathbf{0}) \rangle$$
- for $(\pi)T \gg E$, exponentials may be expanded; up to linear order
$$A_i^{uv} = \frac{r_i}{2}(\kappa - i\gamma) + \kappa \left(-\frac{ip_i}{2MT} + \frac{\Delta V_{uv}}{4T} r_i \right)$$
- κ is the heavy quarkonium momentum diffusion coefficient; γ is its dispersive counterpart
- $\Sigma_s^{(\dagger)}$ encode the in-medium width and mass shift; state of the art results, $\Upsilon(1S)$ decay width given up to $(E/T)^2$ by
$$\langle 1S|\Gamma|1S\rangle = 3a_0^2\kappa \left\{ 1 - \frac{2N_c^2-1}{2(N_c^2-1)} \frac{E}{T} + \frac{(2N_c^2-1)^2}{12(N_c^2-1)^2} \left(\frac{E}{T} \right)^2 \right\}$$
and mass shift by
$$\langle 1S|\delta m|1S\rangle = \frac{3}{2} a_0^2 \gamma$$

Extraction of Transport Coefficients

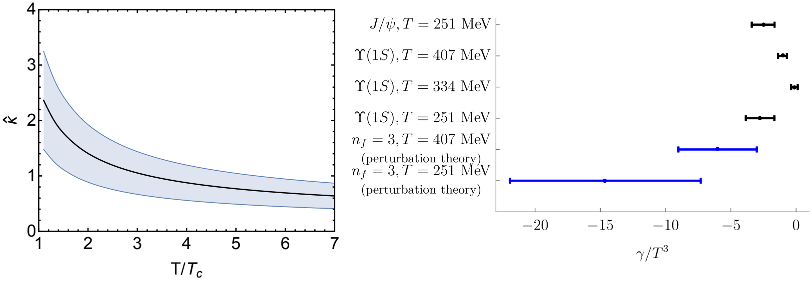


Figure: (Left) Direct, quenched lattice measurement of the heavy quark momentum diffusion coefficient.[3] (Right) Indirect extractions[4] of $\hat{\gamma} = \gamma/T^3$ from unquenched lattice measurements of $\delta M(1S)$.[5]

We solve the Lindlbad equation using the upper, central, and lower $\hat{\kappa}(T) = \kappa(T)/T^3$ curves and $\hat{\gamma} = \gamma/T^3 = \{-3.5, -2.6, 0\}$.

[3] Phys. Rev. D 102, 074503 (2020) (Brambilla, Leino, Petreczky, Vairo)
[4] Phys. Rev. D 100 (2019) 5, 054025 (Brambilla, Escobedo, Vairo, PVG)
[5] JHEP 11 (2018) 088 (Kim, Petreczky, Rothkopf); Phys.Rev.D 100 (2019) 7, 074506 (Larsen, Meinel, Mukherjee, Petreczky).

Evolution

- Gaussian-smeared delta initial state
$$\psi_\ell(t_0) \propto r^\ell e^{-r^2/(0.2a_0)^2}$$
- initialize wave function at $t = 0$; evolve in vacuum until initialization of coupling to medium at $t = 0.6$ fm; evolve in vacuum when local temperature falls below $T_f = 190$ MeV
- medium evolution implemented using a $3 + 1$D dissipative relativistic hydrodynamics code using a realistic equation of state fit to lattice QCD measurements
- approximately $7 - 9 \times 10^5$ physical trajectories
    - production point sampled in transverse plane using nuclear binary collision overlap profile $N_{AA}^{\text{bin}}(x, y, b)$, initial p_T from an E_T^{-4} spectrum, and ϕ uniformly in $[0, 2\pi)$

Homework 1: Reaction Rates

- in-medium width calculated in pNRQCD:

$$\langle 1S|\Gamma|1S\rangle = 3a_0^2\kappa\left\{1-\frac{2N_c^2-1}{2(N_c^2-1)}\frac{E}{T}+\frac{(2N_c^2-1)^2}{12(N_c^2-1)^2}\left(\frac{E}{T}\right)^2\right\}$$

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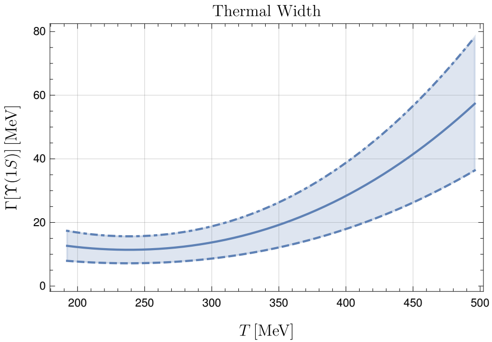

Figure: The in-medium width of the $\Upsilon(1S)$. Dashed, solid and dot-dashed curves represent the lower, central and upper determinations of $\hat{\kappa}(T) = \kappa/T^3$.

Homework 2.(a): in-medium Corrections

- the heavy quark mass M and the binding energy E are scheme dependent quantities
- M enters our formalism as an input parameter and receives no medium corrections
- we work in the $1S$ scheme in which M is half the ground state mass
- the Coulombic binding energy is calculated from M and a_0: $|E| = 1/(Ma_0^2)$
- the in-medium mass shift of the ground state is a non-scheme-dependent, observable quantity; from this, one can, in principle, extract an in-medium correction to M and to E

$$\langle 1S|\delta m|1S\rangle = \frac{3}{2}a_0^2\gamma$$

Ground State Mass Shift

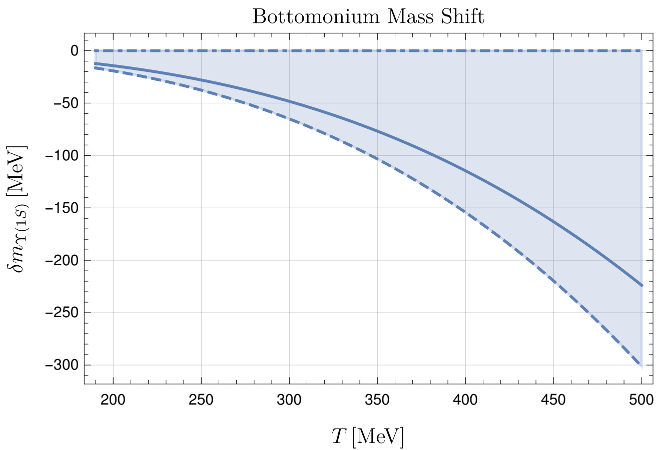

Figure: The in-medium mass shift of the $\Upsilon(1S)$. Dashed, solid, and dot-dashed curves represent $\hat{\gamma} = \gamma / T^3 = \{-3.5, -2.6, 0\}$, respectively.

Homework 2.(b): p-Dependence of Γ

- we are comoving with the medium, so Γ has no p-dependence
- can be added

Homework 3.(a, b): Suppression for Linear Γ

- solve for functional form of $\hat{\kappa}(T)$ producing specified linear $\Gamma(T)$
- suppression results:

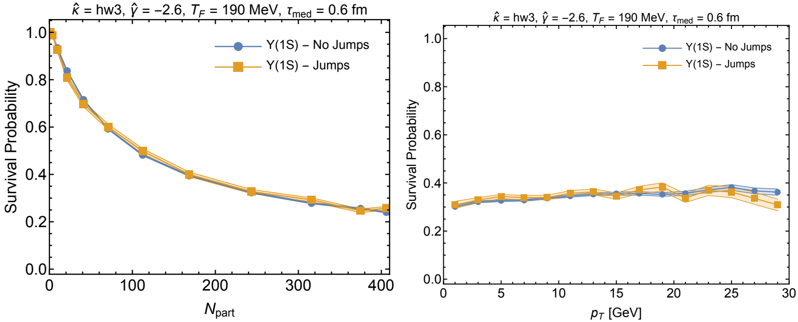

Figure: Survival probability of the $\Upsilon(1S)$ with linear $\Gamma(T)$. "No Jumps" represents suppression; "Jumps" represents suppression and regeneration.

Homework 4.(a, b): Ground State Suppression

- in-medium ground state calculated taking medium interactions as quantum mechanical perturbations
- suppression results:

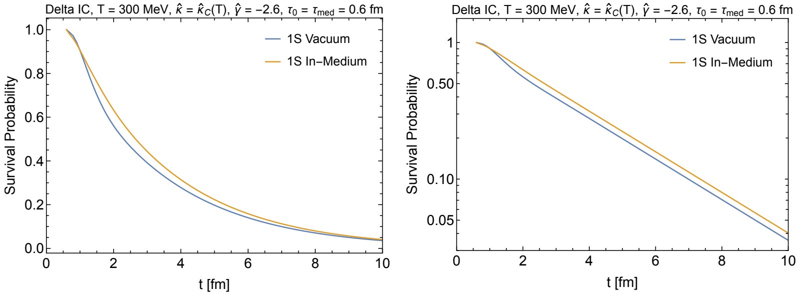

Figure: Survival probabilities of the vacuum and in-medium ground states in the bottom sector as a function of time t.

Thank you!