Quarkonia dynamics in the QGP with open quantum systems

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A virtual tribute to Quark Confinement and the Hadron Spectrum 2021

Collaborators:

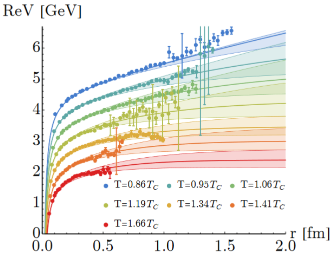
- Pol-Bernard Gossiaux (Ph.D supervisor)
- Thierry Gousset (Ph.D supervisor)
- Roland Katz (Post-doc)

Quarkonium in heavy-ion collisions

Static screening

T $\neq$ 0 $\rightarrow$ Suppression of color attraction

Melting of pairs at high T
$\Rightarrow$ Suppression

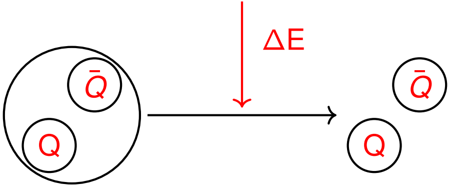


Lafferty, A. Rothkopf
Phys. Rev. D101, 056010 (2020)

Dynamical processes

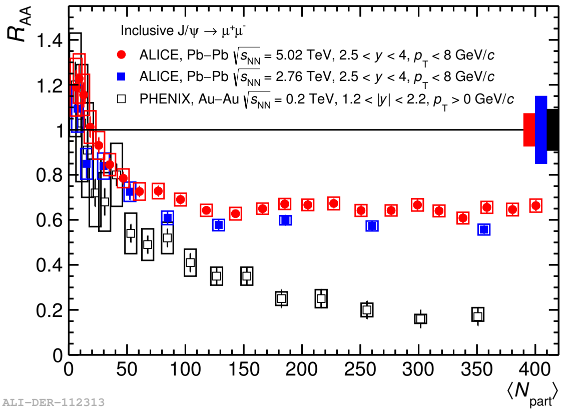
Collisions with medium partons
$\rightarrow$ Pair dissociation

$\Rightarrow$ Suppression



Often described by an imaginary potential

Quarkonium in heavy-ion collisions



Recombination

Initially uncorrelated heavy quarks form a quarkonium

Essential to have a formalism that can treat this effect

Need to treat in-medium real time quarkonium dynamics
⇒ Open quantum systems

Open quantum systems

System + environment

$$\rho(t=0) = \rho_{Q\bar{Q}} \otimes \rho_{QGP}$$

Unitary evolution

Evolution of the total system

$$\rho(t) = U(t,0)\left[\rho_{Q\bar{Q}} \otimes \rho_{QGP}\right] U(t,0)^\dagger$$

Trace out environment degrees of freedom

System ($Q\bar{Q}$ pair)

$$\rho_{Q\bar{Q}}(t=0)$$

Non-unitary evolution

Evolution of the system

$$\rho_{Q\bar{Q}}(t) = Tr_{QGP}\left[U(t,0)\rho(t=0)U(t,0)^\dagger\right]$$

3D Quantum Master Equation

singlet density operator

J.P. Blaizot, M.A. Escobedo, J. High Energy Phys. 06 (2018) 034.

$$\frac{d}{dt}\begin{pmatrix}\mathcal{D}_s\\ \mathcal{D}_o\end{pmatrix} = \mathcal{L}\begin{pmatrix}\mathcal{D}_s(\mathbf{s},\mathbf{s}',t)\\ \mathcal{D}_o(\mathbf{s},\mathbf{s}',t)\end{pmatrix}$$

octet density operator

$$\mathcal{L} = \begin{pmatrix}\mathcal{L}_{ss} & \mathcal{L}_{so}\\ \mathcal{L}_{os} & \mathcal{L}_{oo}\end{pmatrix}$$

singlet-octet transitions

- Weak coupling between heavy quarks and plasma particles
- Valid in the quantum brownian regime (high temperature)
- Resolved through a semi-classical approximation
- Pioneering work to be explored

3D Quantum Master Equation

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3$$

$\mathcal{L}_0$: Kinetic terms

$\mathcal{L}_1$: Static screening (V)

$\mathcal{L}_2$: Fluctuations (W)

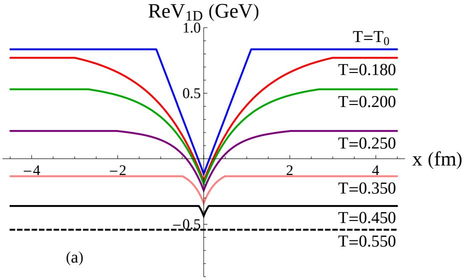
$\mathcal{L}_3$: Dissipation (W'/W")

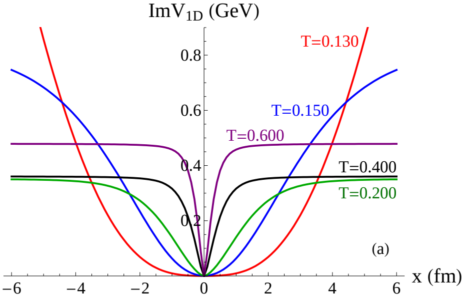
Transition between color states and dissipation effects

Our work:

- Extension of the equations to preserve positivity $\Rightarrow$ new $\mathcal{L}_3'$ and $\mathcal{L}_4$
- Direct resolution in 1D
- New potential better suited for 1D studies
  R. Katz, S. Delorme, P.B. Gossiaux (in preparation)
- For now: focus on charmonia

Optimized 1D potential





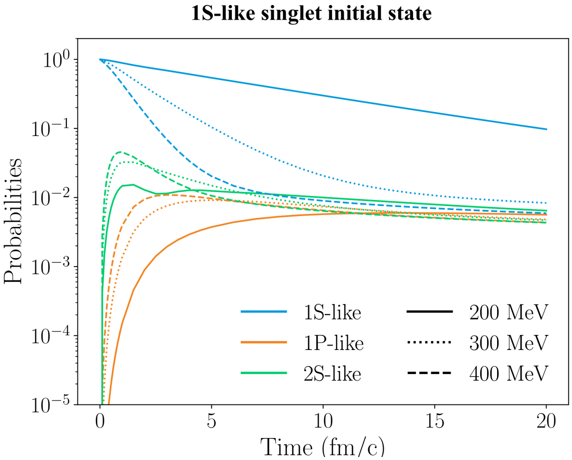
- Based on 3d lattice data

  D. Lafferty, A. Rothkopf

  Phys. Rev. D101, 056010 (2020)

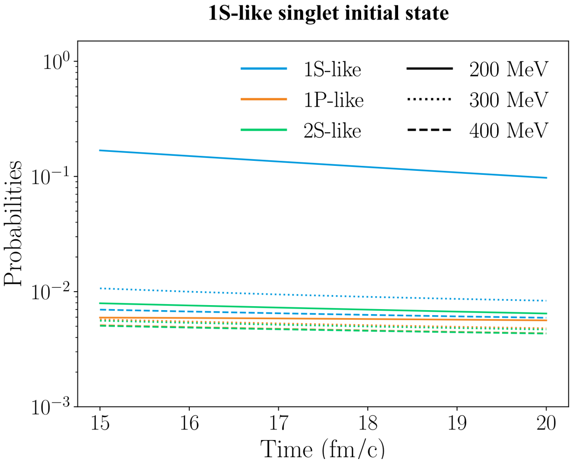
- 1d parametrization to reproduce 3d decay widths and temperature-dependant mass spectra
- Different parametrizations for charmonia and bottomonia

1D equations resolution: State probabilities



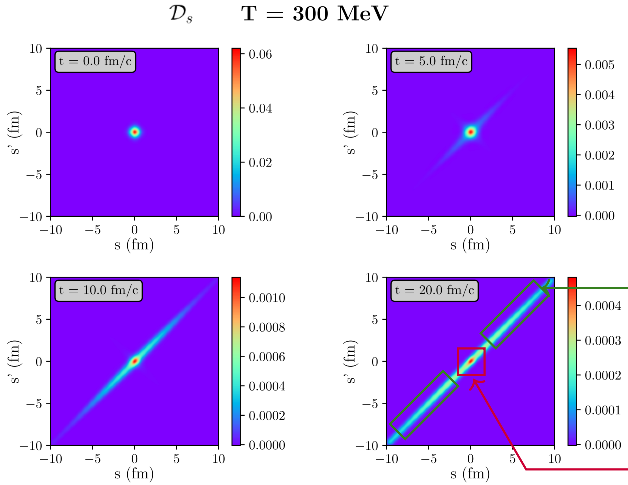
- Higher suppression at larger temperatures for S-like states
- Transient phase up to $\sim$ 5 fm/c: re-equilibration
- Same late-time evolution for S-like states at 300 and 400 MeV
- Interplay between binding, diffusion and transitions between states

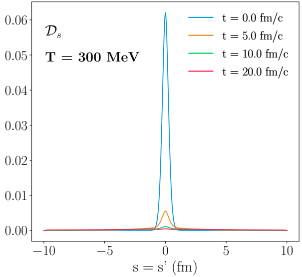
1D equations resolution: State probabilities



- 1S-like and 1P/2S-like states closer at larger temperature
- Statistical distribution (although not detailled balance)

1D equations resolution: Singlet density operator



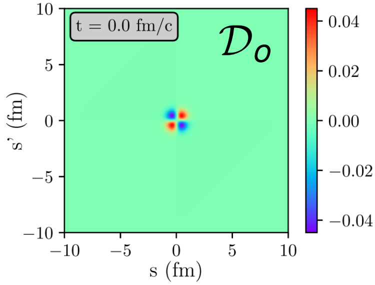


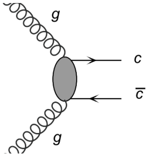
Dissociated component

Bound core to be studied
Quantum coherences?

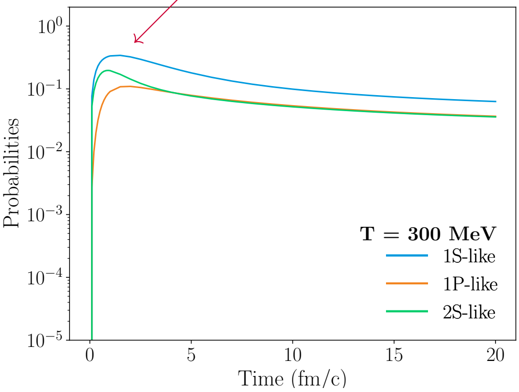
More realistic initial state

- P-like octet initial state



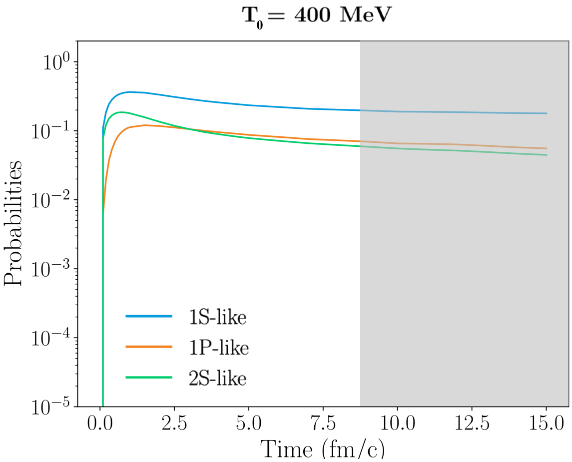


Singlet bound state intermediate formation



- Same late-time evolution as the 1S-like singlet initial state

Evolving medium



- Initial P-like octet state with initial temperature 400 MeV
- $T(t) = T_0 \left(\frac{1}{1+t}\right)^{1/3}$
- After $\approx$ 8 fm/c, temperature too low $\rightarrow$ Outside of potential validity range

Conclusion & Perspectives

- We have a fully functionnal tool to explore the 1D dynamics
- We developped a new potential based on 3d Lattice QCD, tailored for 1d studies
- Work on the feasability of a semi-classical treatment under way

- Further study the validity of semi-classical approximations
- Application of a semi-classical treatment if possible and comparison with full quantum dynamics
- Study the bottomonium system
- Go to more realistic background: 3d dynamics, hydro...