Open quantum systems description of quarkonia dynamics in the Quark-Gluon Plasma

Stéphane Delorme

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Collaborators:

- Pol-Bernard Gossiaux
- Thierry Gousset
- Jean-Paul Blaizot

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INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

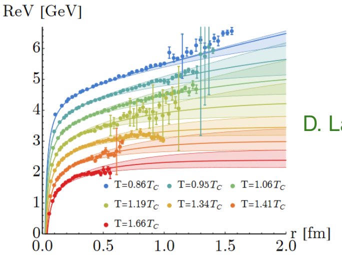
Subatech

Quarkonium in heavy-ion collisions

Static screening

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

Melting of pairs at high T
$\Rightarrow$ Suppression

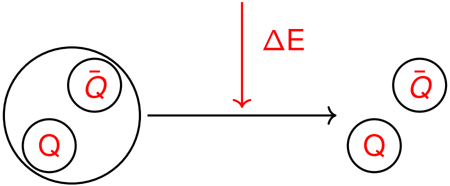


D. Lafferty, A. Rothkopf (2020)

Dynamical processes

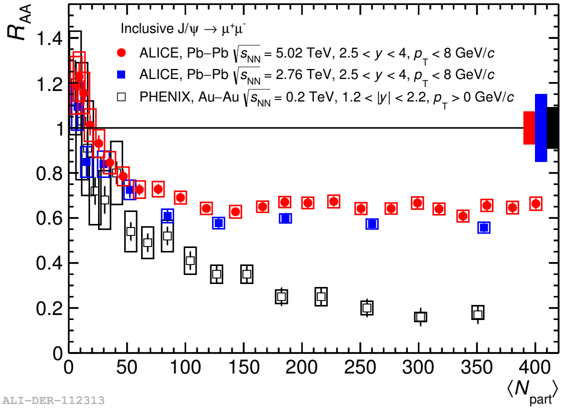
Collisions with medium partons
$\rightarrow$ Pair dissociation

$\Rightarrow$ Suppression



Often described by an imaginary potential

Quarkonium in heavy-ion collisions



Recombination

- Initially uncorrelated heavy quarks form a quarkonium
- Can happen below the dissociation temperature
- Essential to have a formalism that can treat this effect

Still a challenge for open quantum systems

Open quantum systems

$$\begin{tikzcd}
\begin{array}{c}\text{System + environment}\\ \rho(t) = \rho_{Q\bar{Q}} \otimes \rho_{QGP}\end{array} \arrow[r, "\frac{\mathrm{d}}{\mathrm{d}t}\rho = -i[H,\rho]"] \arrow[d] & \begin{array}{c}\text{Evolution of the total system}\\ \rho(t') = U(t',t)\left[\rho_{Q\bar{Q}} \otimes \rho_{QGP}\right] U(t',t)^\dagger\end{array} \arrow[d] \\
\begin{array}{c}\text{System } (Q\bar{Q} \text{ pair})\\ \rho_{Q\bar{Q}}(t)\end{array} \arrow[r, "\frac{\mathrm{d}}{\mathrm{d}t}\rho_{Q\bar{Q}} = \mathcal{L}\rho_{Q\bar{Q}}"'] & \begin{array}{c}\text{Evolution of the system}\\ \rho_{Q\bar{Q}}(t') = Tr_{QGP}\left[U(t',t)\rho(t)U(t',t)^\dagger\right]\end{array}
\end{tikzcd}$$

Trace out environment degrees of freedom

Quantum Master Equation (Quantum Brownian Regime)

singlet density operator

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

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

octet density operator

singlet-octet transitions

S.D, P-B. Gossiaux, T. Gousset, R. Katz, J-P. Blaizot (in preparation)

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3 + \boxed{\mathcal{L}_4}$$

Higher-order terms, expected to be subleading

$\mathcal{L}_0$: Kinetic terms

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

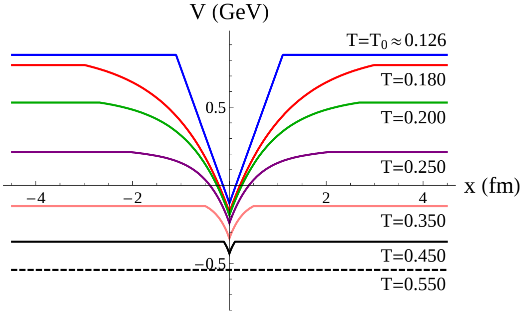
$\mathcal{L}_2$: Fluctuations (W)

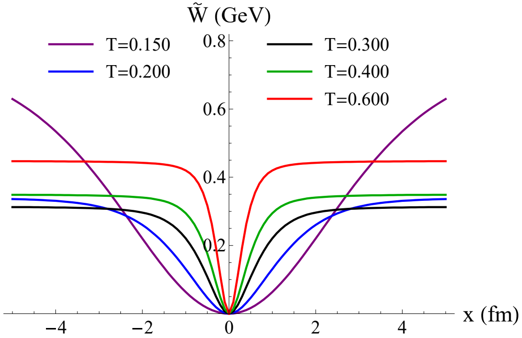
$\mathcal{L}_3/\mathcal{L}_4$: Dissipation (W'/W"/W"')

Dynamical processes

Transition between color states and dissipation effects

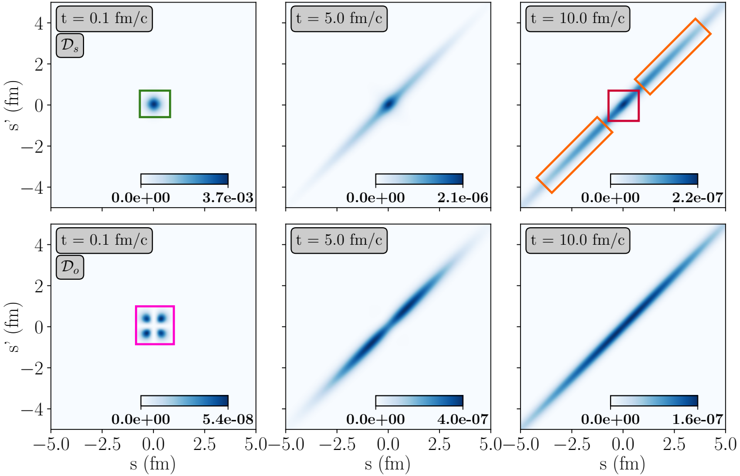
1D Potential





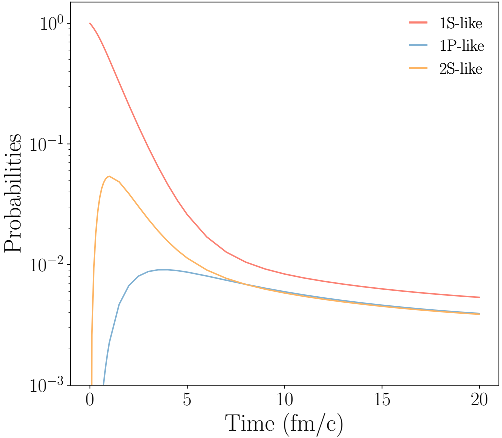
- Based on a 3D potential inspired from Lattice results D. Lafferty, A. Rothkopf (2020)
- Real part: parametrization to reproduce 3D mass spectra
- Imaginary part: separated in a coulombic and string part, aims at reproducing 3D decay widths R. Katz, S.D, P-B. Gossiaux (2022)

Charmonium dynamics at fixed temperature



- Initial 1S-like singlet state at T = 400 MeV
- Octet populated as a dipole
- Delocalization of initial state along $s = s'$ axis
- Remaining central correlation

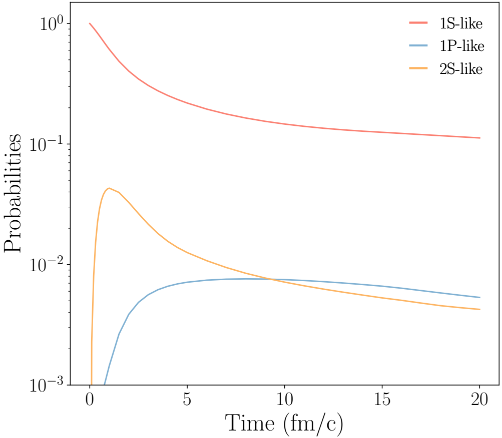
Charmonium dynamics at fixed temperature



- Instantaneous projections on vacuum eigenstates
- 2S-like state first populated from 1S-like then population of 1P-like (different types of transitions)
- Decay phase afterwards, with same decay rate for all states

What happens in a more realistic setting?

Charmonium dynamics in a dynamical medium



- Cooling medium following a Björken profile
- $T(t) = T_0 \left(\frac{1}{1+t}\right)^{1/3}, \quad T_0 = 400$ MeV
- 1S-like state less suppressed due to the cooling
- Inversion of 2S/1P populations
- Similar global evolution

What about bottomonia?

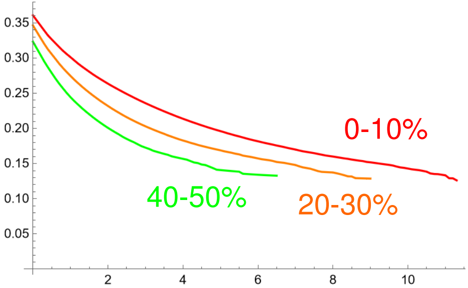
Bottomonium system

- 3 different initial states:
  - $\Upsilon(1S)$-like initial state
  - $\Upsilon(2S)$-like initial state
  - Mixture of S and P states:

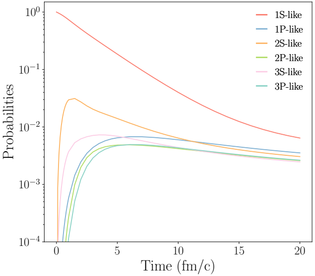
    $\Psi(x) \propto e^{-\frac{x^2}{2\sigma^2}} \left(1 + a_{\mathrm{odd}} \frac{x}{\sigma}\right)$
    $\sigma = 0.045\ \mathrm{fm} \quad a_{\mathrm{odd}} = 3.5$
    (see talk by P-B Gossiaux from HP2016)

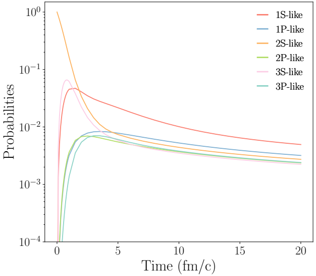
PRELIMINARY STUDY

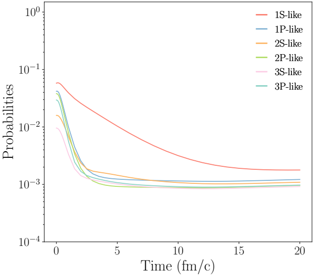
- 4 different medium settings
  - Fixed temperature T = 400 MeV
  - Average temperature profiles obtained from EPOS4 for three different centrality classes: 0-10%, 20-30% and 40-50% with $|y| < 2.4$ (CMS conditions)



Bottomonium dynamics at fixed temperature





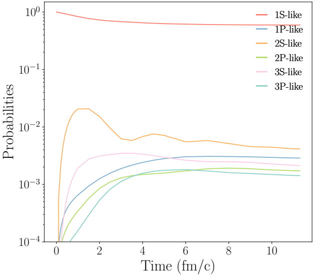


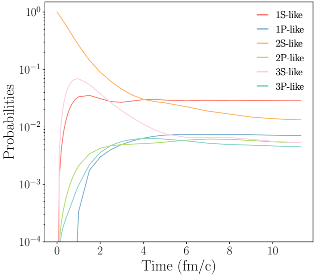
- Similar evolution to charmonium
- 1S-like reduced by a factor 100
- Factor 2 between 1S and 2S

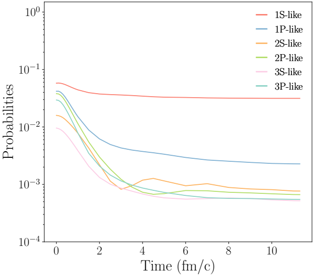
- Similar final state
- Similar 2S/1S ratio
- Inversion of populations

- Lower initial populations
- 1S (2S) evolution similar to the evolution with the 1S (2S) initial state

Bottomonium dynamics in a dynamical medium (0-10% profile)





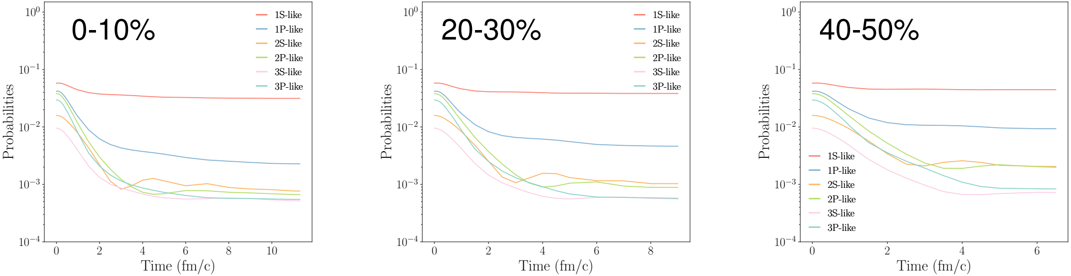


- Fast drop in temperature $\Rightarrow$ 1S $\rightarrow$ 2S feeding reduced
- Factor >100 between 1S and 2S

- Limited population inversion
- 1P not ordered $\Rightarrow$ far from statistical equilibrium

- Similar $P(t_f)/P(t_0)$ as with the other initial states

Bottomonium dynamics in a dynamical medium



- Reduction of suppression for more peripheral profiles
- "R_{AA}" of 1S seems too high, 2S too low
- Effect of the imaginary potential too strong
  $\Rightarrow$ Possible way to constrain potentials

Conclusions and perspectives

- Direct resolution of quantum master equations
- Progressive decoherence of the density operator
- Preliminary study of bottomonium dynamics with realistic temperature profiles from EPOS4
- Reduction of suppression for more peripheral collisions

- Study using multiple temperature profiles per centrality (not just averaged)
- Global effort of comparison between theoretical models (EMMI RRTF)

Back-up

Quantum Master Equation

$$\mathcal{L}_0\mathcal{D} = -i\,[H_Q, \mathcal{D}]$$

$$\mathcal{L}_1\mathcal{D} = -\frac{i}{2}\int_{xx'} V(x-x')\,[n_x^a n_{x'}^a, \mathcal{D}]$$

$$\mathcal{L}_2\mathcal{D} = \frac{1}{2}\int_{xx'} W(x-x')\,(\{n_x^a n_{x'}^a, \mathcal{D}\} - 2n_x^a \mathcal{D} n_{x'}^a)$$

$$\mathcal{L}_3\mathcal{D} = -\frac{i}{4T}\int_{xx'} W(x-x')\left(\dot{n}_x^a \mathcal{D} n_{x'}^a - n_x^a \mathcal{D} \dot{n}_{x'}^a + \frac{1}{2}\{\mathcal{D}, [\dot{n}_x^a, n_{x'}^a]\}\right)$$

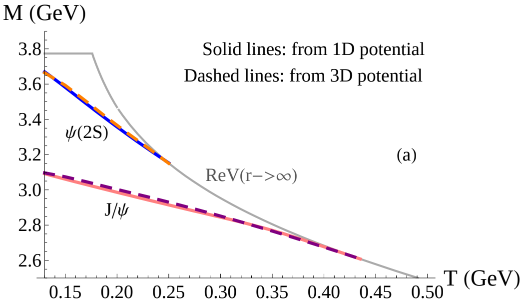
- n_x^a: color charge density
  $n_x^a = \delta(x-r)\,t^a \otimes \mathbb{I} - \mathbb{I} \otimes \delta(x-r)\,\tilde{t}^a$

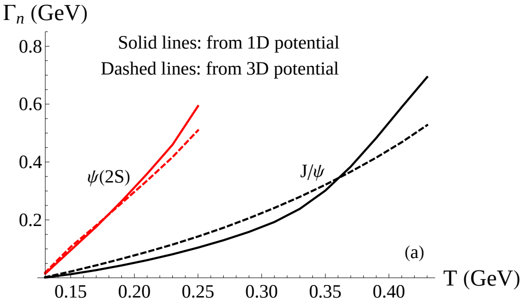
- Can recover $\mathcal{L}_3$ from $\mathcal{L}_2$ by performing:

$$(\{n_x^a n_{x'}^a, \mathcal{D}\} - 2n_x^a \mathcal{D} n_{x'}^a) \longrightarrow \left\{\left(n_x^a - \frac{i}{4T}\dot{n}_x^a\right)\left(n_{x'}^a + \frac{i}{4T}\dot{n}_{x'}^a\right), \mathcal{D}\right\} - 2\left(n_x^a + \frac{i}{4T}\dot{n}_x^a\right)\mathcal{D}\left(n_{x'}^a - \frac{i}{4T}\dot{n}_{x'}^a\right)$$

- Additionnal terms $\Rightarrow \mathcal{L}_4$

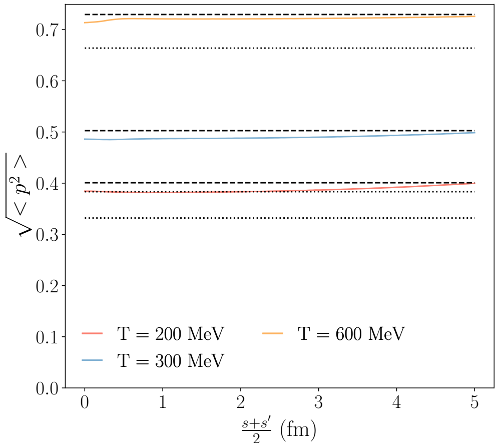
1D Potential





- Very good agreement for the mass spectra
- Good agreement for the decay widths, differences due to the large distance behaviour of the imaginary part

Asymptotic Wigner distribution



- $\sqrt{< p^2 >}$ does not scale as $\sqrt{\frac{MT}{2}}$ (dotted lines)
- Equilibrium limit modified by $\mathcal{L}_4$
- At large distances, scaling as $\sqrt{\frac{1}{1+\frac{\gamma}{2}}\frac{MT}{2}}$ with $\gamma = \frac{\tilde{W}^{(4)}(0)}{16MT\tilde{W}''(0)}$ (dashed lines)