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

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Polish Particle and Nuclear Theory Summit 2023

Collaborators:

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THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
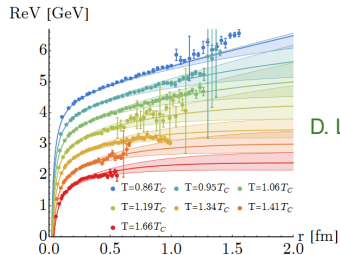**POLISH ACADEMY OF SCIENCES**

Subatech

Quarkonium in heavy-ion collisions

Static screening

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

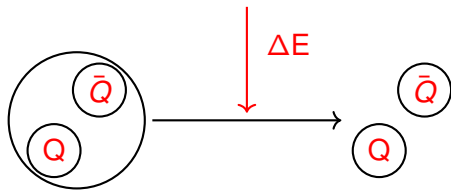Melting of pairs at high T
$\Rightarrow$ Suppression

ReV [GeV]

D. Lafferty, A. Rothkopf (2020)

T=0.86T_C T=0.95T_C T=1.06T_C
T=1.19T_C T=1.34T_C T=1.41T_C
T=1.66T_C

r [fm]

Dynamical processes

Collisions with medium partons
$\rightarrow$ Pair dissociation

$\Rightarrow$ Suppression

ΔE

$\bar{Q}$

Q

$\bar{Q}$

Q

Often described by an imaginary potential
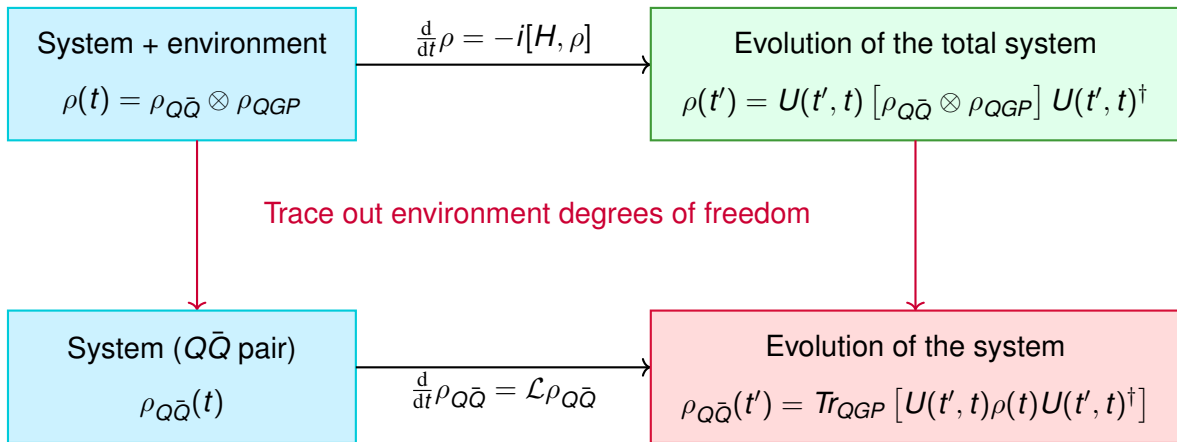
Quarkonium in heavy-ion collisions
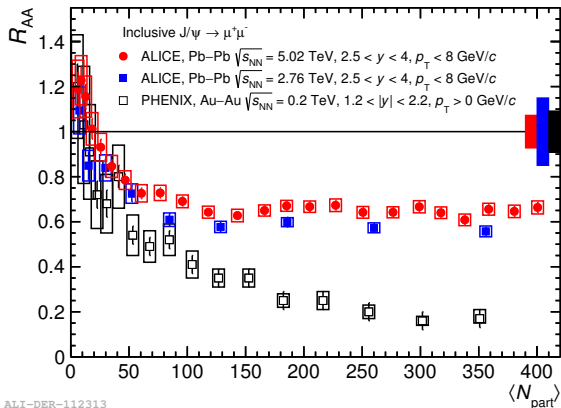
Recombination

- ▶ 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

Quantum Master Equation (Quantum Brownian Regime)

singlet density operator

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

octet density operator

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

singlet-octet transitions

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

$\mathcal{L}_0$: Kinetic terms

Higher-order terms, expected to be subleading

$\mathcal{L}_1$: 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

S.D, P-B. Gossiaux, T. Gousset,
R. Katz, J-P. Blaizot (in preparation)
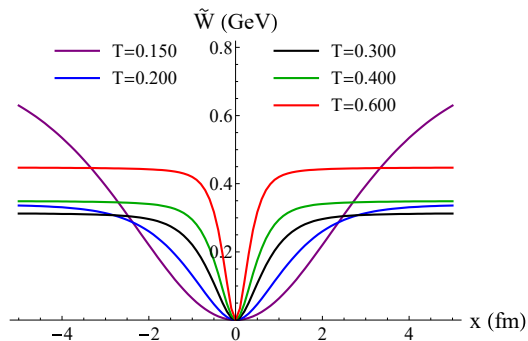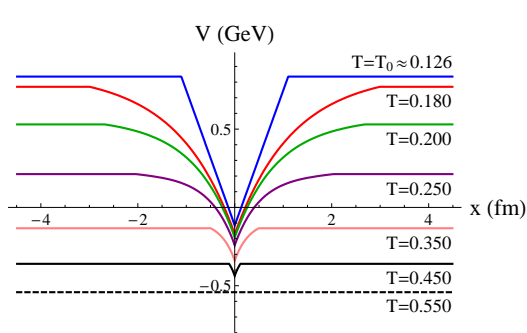
1D Potential



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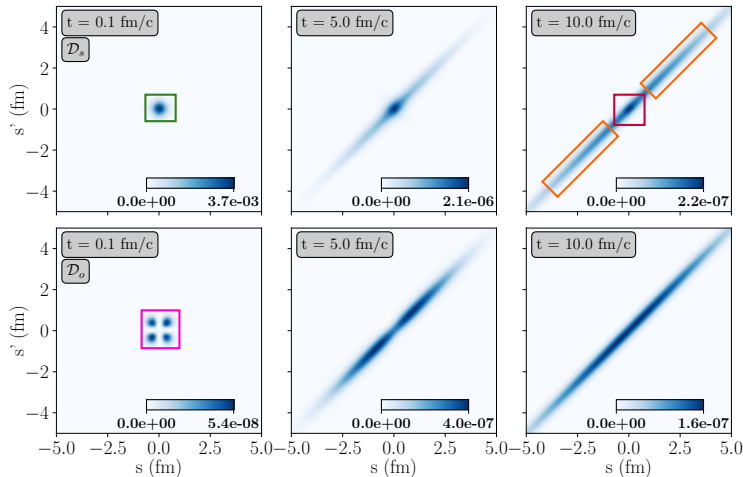
- ▶ Initial 1S-like singlet state at T = 400 MeV
- ▶ Octet populated as a dipole
- ▶ Delocalization of initial state along $s = s'$ axis
- ▶ Remaining central correlation

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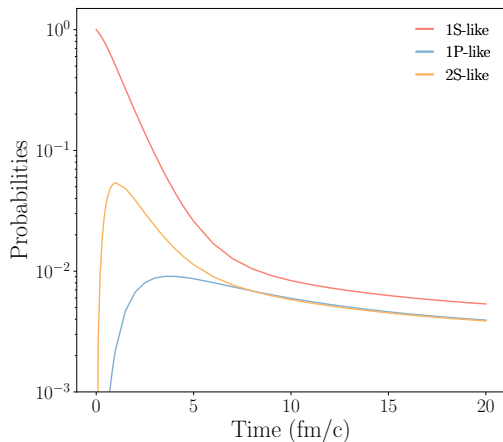
- ▶ Instantaneous projections on vacuum eigenstates
- ▶ 2S-like state first populated from 1S-like then population of 1P-like (different types of transitions)
- ▶ Decay phase afterwards, with same decay rate for all states

> What happens in a more realistic setting?

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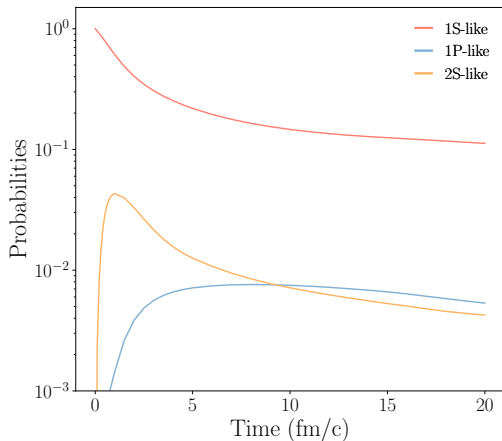
- ▶ Cooling medium following a Björken profile
- ▶ $T(t) = T_0 \left(\frac{1}{1+t} \right)^{1/3}, \quad T_0 = 400$ MeV
- ▶ 1S-like state less suppressed due to the cooling
- ▶ Inversion of 2S/1P populations
- ▶ Similar global evolution

What about bottomonia?

Bottomonium system

- ▶ 3 different initial states:
  - $\Upsilon(1S)$-like initial state
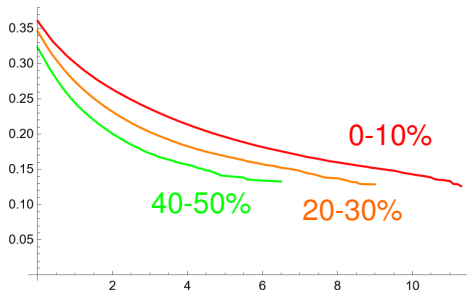 - $\Upsilon(2S)$-like initial state
  - Mixture of S and P states:
    $$\Psi(x) \propto e^{-\frac{x^2}{2\sigma^2}} \left(1 + a_{\text{odd}} \frac{x}{\sigma}\right)$$
    $\sigma = 0.045$ fm $a_{\text{odd}} = 3.5$
    (see talk by P-B Gossiaux from HP2016)
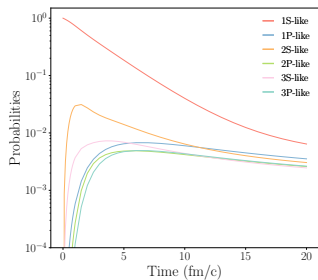
  PRELIMINARY STUDY

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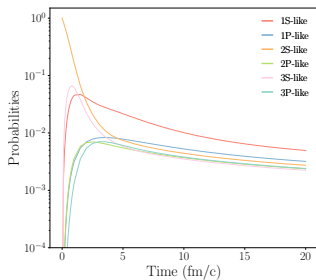 - Fixed temperature T = 400 MeV
  - Average temperature profiles obtained from EPOS4 for three different centrality classes: 0-10%, 20-30% and 40-50% with $|y| < 2.4$ (CMS conditions)
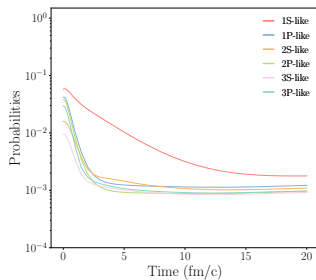
Bottomonium dynamics at fixed temperature

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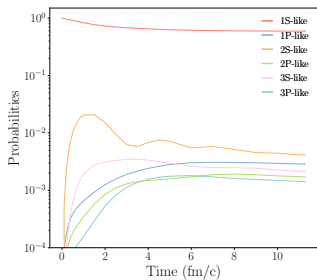- ▶ Factor 2 between 1S and 2S

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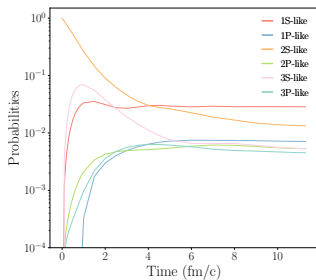- ▶ Similar 2S/1S ratio
- ▶ Inversion of populations

- ▶ Lower initial populations
- ▶ 1S (2S) evolution similar to the evolution with the 1S (2S) initial state
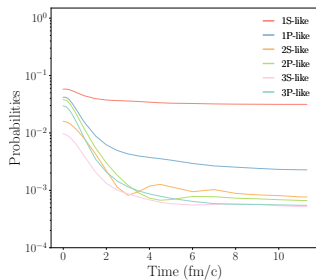
Bottomonium dynamics in a dynamical medium (0-10% profile)

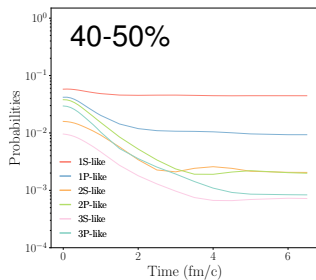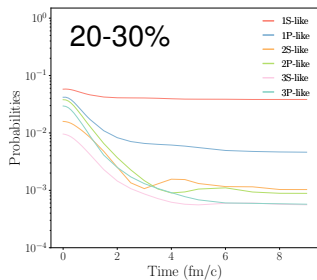- ▶ Fast drop in temperature ⇒ 1S → 2S feeding reduced
- ▶ Factor >100 between 1S and 2S
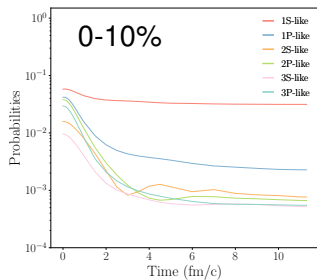
- ▶ Limited population inversion
- ▶ 1P not ordered ⇒ far from statistical equilibrium

- ▶ 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
  ⇒ 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

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

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

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

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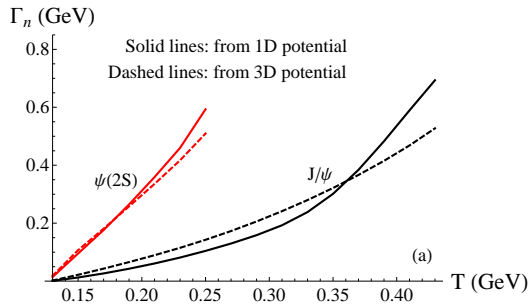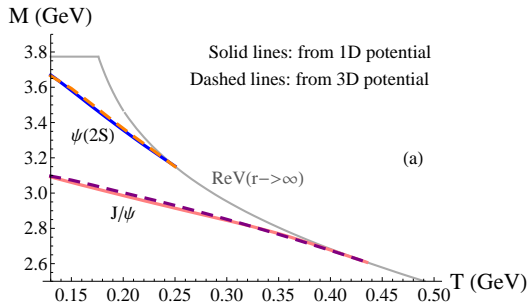
▶ n_x^a: color charge density

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

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

$$\left(\{ n_x^a n_{x'}^a, \mathcal{D} \} - 2 n_x^a \mathcal{D} n_{x'}^a \right) \;\longrightarrow\; \left\{ \left(n_x^a - \frac{i}{4T} \dot{n}_x^a \right) \left(n_{x'}^a + \frac{i}{4T} \dot{n}_{x'}^a \right), \mathcal{D} \right\} - 2 \left(n_x^a + \frac{i}{4T} \dot{n}_x^a \right) \mathcal{D} \left(n_{x'}^a - \frac{i}{4T} \dot{n}_{x'}^a \right)$$
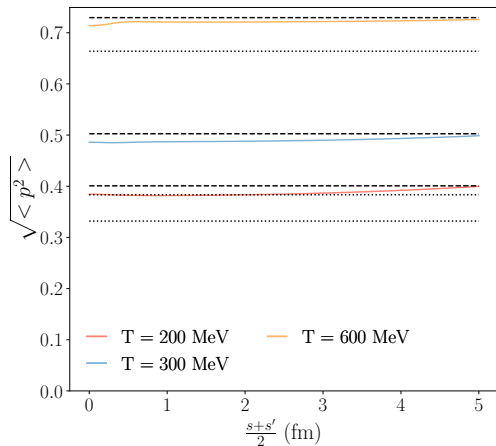
▶ Additionnal terms $\Rightarrow \mathcal{L}_4$

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)