The Nantes approach

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The model

- Work by Blaizot & Escobedo: SU(3): J-P. Blaizot, M. Escobedo (2018)
  - Heavy quarks-Plasma interaction described using NRQCD
  - Derivation of quantum master equations in the quantum brownian motion regime (high temperature) to describe the evolution of the density operator (not Lindblad equations)

- Our work:
  - Extension to preserve positivity $\Rightarrow$ Lindblad equations
  - Direct resolution in 1D and application to charmonium system
  - Study of the validity of a semi-classical treatment (not covered in this talk)
  - New potential developped specifically for 1D studies

    R. Katz, S.D., P-B. Gossiaux (2022)

Quantum Master Equation

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

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

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

Quantum Master Equation

$$\mathcal{L}_0\mathcal{D} = -i\,[H_Q, \mathcal{D}]$$
$$\mathcal{L}_1\mathcal{D} = -\frac{i}{2}\int_{xx'} V(x-x')\,[n_x^a n_{x'}^a, \mathcal{D}]$$
$$\mathcal{L}_2\mathcal{D} = \frac{1}{2}\int_{xx'} W(x-x')\,(\{n_x^a n_{x'}^a, \mathcal{D}\} - 2n_x^a\mathcal{D}n_{x'}^a)$$
$$\mathcal{L}_3\mathcal{D} = -\frac{i}{4T}\int_{xx'} W(x-x')\left(\dot{n}_x^a\mathcal{D}n_{x'}^a - n_x^a\mathcal{D}\dot{n}_{x'}^a + \frac{1}{2}\{\mathcal{D}, [\dot{n}_x^a, n_{x'}^a]\}\right)$$

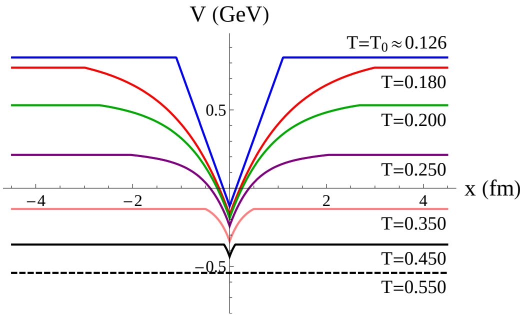
- n_x^a: color charge density
  $n_x^a = \delta(x-r)\,t^a \otimes \mathbb{I} - \mathbb{I} \otimes \delta(x-r)\,\tilde{t}^a$

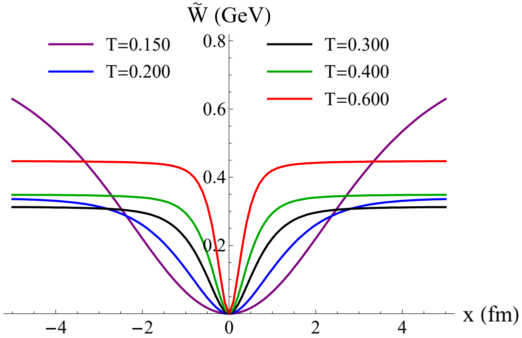
- Can recover $\mathcal{L}_3$ from $\mathcal{L}_2$ by performing:

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

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

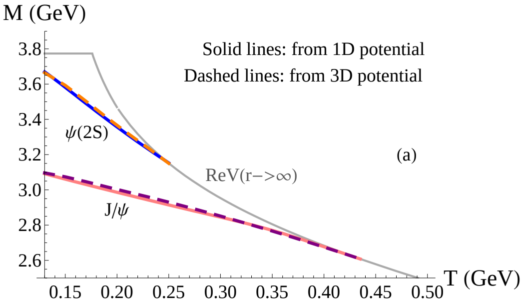
1D Potential

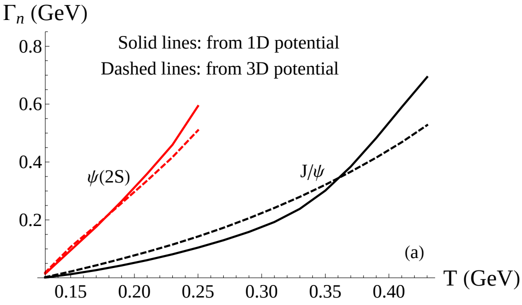




- Based on a 3D potential inspired from Lattice results D. Lafferty, A. Rothkopf (2020)
- Real part: parametrization to reproduce 3D mass spectra
- Imaginary part: separated in a coulombic and string part, aims at reproducing 3D decay widths

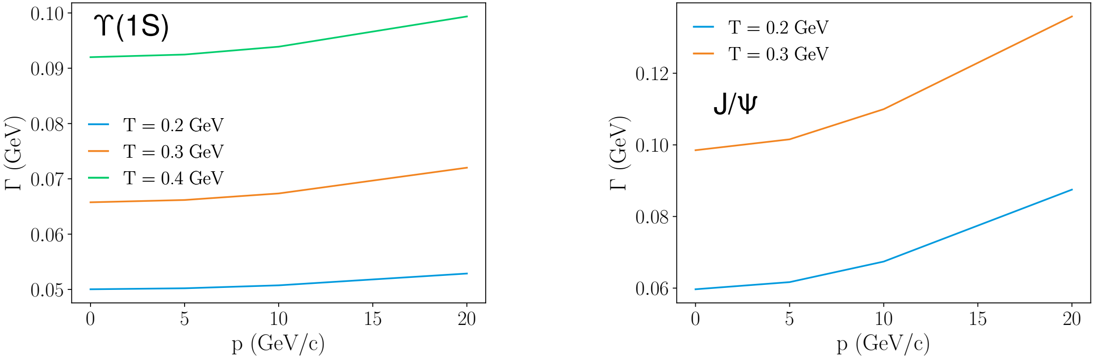
1D Potential





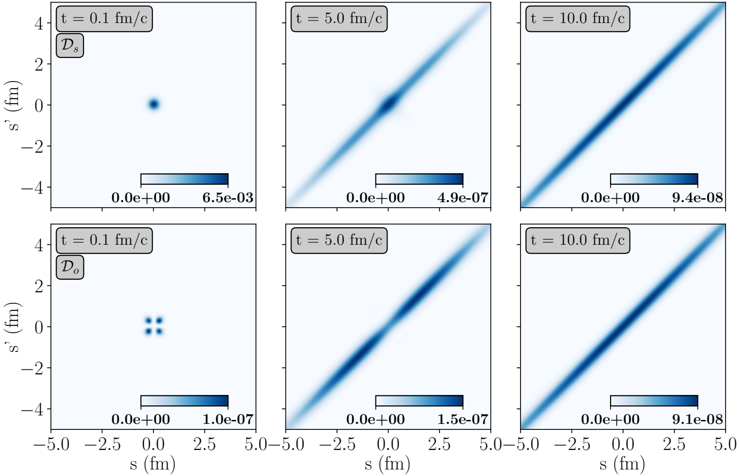
- Very good agreement for the mass spectra
- Good agreement for the decay widths, differences due to the large distance behaviour of the imaginary part

Reaction rates



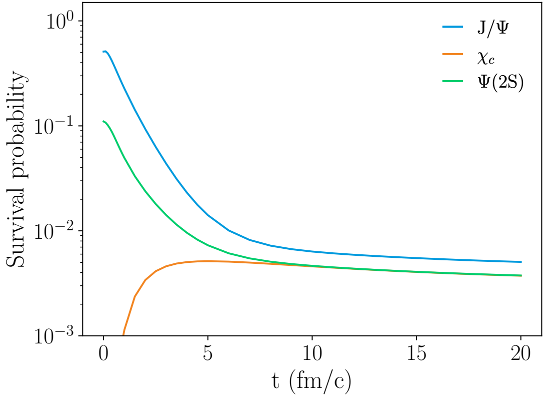
- Increase with temperature and momentum
- Stronger increase for J/Ψ

Charmonium gaussian singlet initial state T = 300 MeV



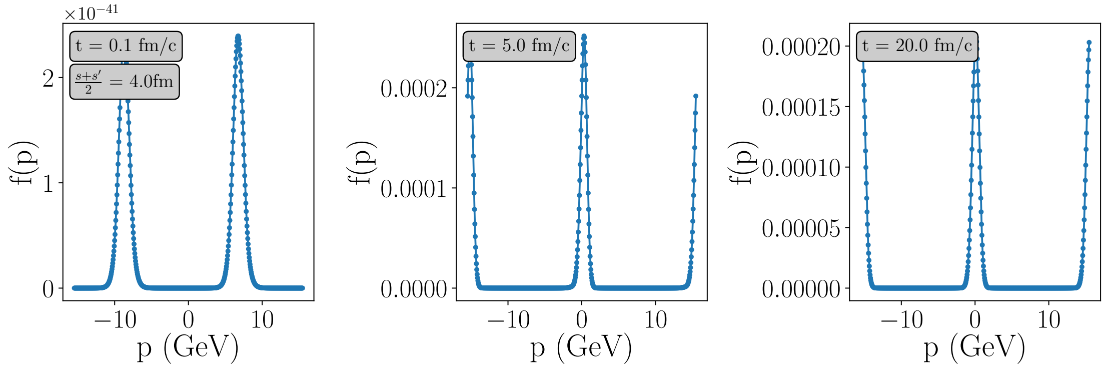
- Initial gaussian singlet state at T = 300 MeV ($\sigma = 0.1$ fm)
- Octet populated as a dipole
- Delocalization of initial state along $s = s'$ axis
- Remaining central correlation

Charmonium gaussian singlet initial state T = 300 MeV



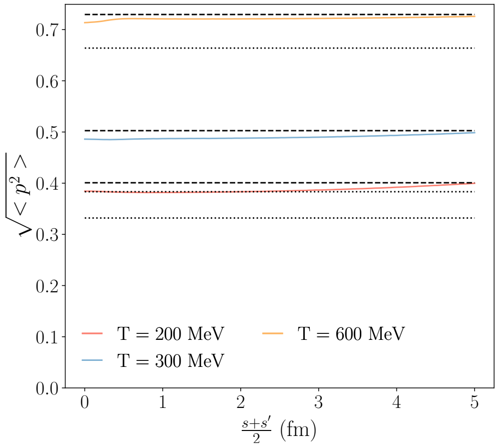
- Instantaneous projections on vacuum eigenstates defined as $P_\Phi(t) =< \Phi|\mathcal{D}_s(t)|\Phi >$
- Equilibration phase with transitions between states
- χ_c populated later due to different transitions
- Decay phase afterwards, with same decay rate for all states

Asymptotic Wigner distribution



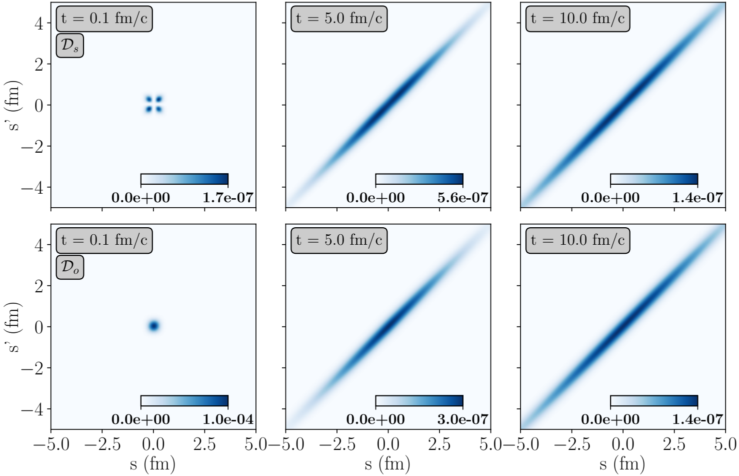
- Large distance
- Distribution progressively becomes Gaussian

Asymptotic Wigner distribution



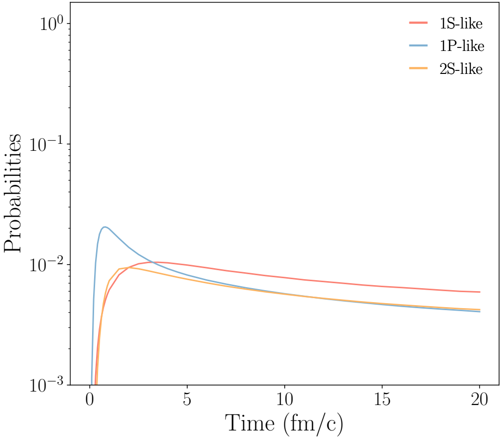
- $\sqrt{< p^2 >}$ does not scale as $\sqrt{\frac{MT}{2}}$ (dotted lines)
- Equilibrium limit modified by $\mathcal{L}_4$
- At large distances, scaling as $\sqrt{\frac{1}{1+\frac{\gamma}{2}}\frac{MT}{2}}$ with $\gamma = \frac{\tilde{W}^{(4)}(0)}{16MT\tilde{W}''(0)}$ (dashed lines)

Charmonium gaussian octet initial state in a cooling medium



- Cooling medium with gaussian octet initial state ($\sigma = 0.1$ fm)
- $T(t) = T_0\left(\frac{1}{1+t}\right)^{1/3}$
- $T_0 = 600$ MeV
- Delocalization of initial state along $s = s'$ axis
- Seems to reach same kind of limit

Charmonium gaussian octet initial state in a cooling medium



- Formation of bound states at early times
- Helped by the initial proximity of the two quarks
- Global evolution similar to the fixed temperature case