Medium evolution of quarkonium within the EFT framework

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Talk based on the following works

1. N. Brambilla, M. A. Escobedo, J. Soto and A. Vairo, Phys. Rev. D **96** (2017) no.3, 034021 [arXiv:1612.07248 [hep-ph]].
2. N. Brambilla, M. A. Escobedo, J. Soto and A. Vairo, Phys. Rev. D **97** (2018) no.7, 074009 [arXiv:1711.04515 [hep-ph]].
3. N. Brambilla, M. A. Escobedo, A. Vairo and P. Vander Griend, Phys. Rev. D **100** (2019) no.5, 054025 [arXiv:1903.08063 [hep-ph]].
4. N. Brambilla, M. A. Escobedo, M. Strickland, A. Vairo, P. Vander Griend and J. H. Weber, [arXiv:2012.01240 [hep-ph]].

Outline

Heavy quarkonium in heavy-ion collisions

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- Heavy quarks can only be created at the beginning of the collision. It is a hard process.
- However, the existence of a medium changes the probability that a bound state is formed and its lifetime.
- Measuring R_{AA}, the ratio of quarkonium states measured in heavy-ion collisions divided by the naive extrapolation of pp data, we can extract information about the medium.

The mechanisms of dissociation
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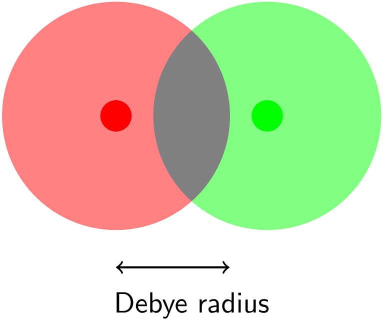
$$V(r) = -\alpha_s \frac{e^{-m_D r}}{r}$$

At finite temperature



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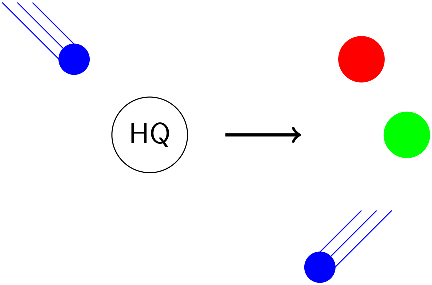
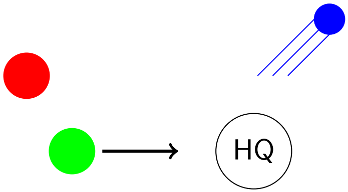


Recombination



Two heavy quarks coming from different origin may recombine to form a new quarkonium state.

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- In some cases, decays and recombination can be described with rate or Boltzmann equation in the semi-classical approximation. However, this is not always the case.
- When thermal effects are important, we need to describe all three effects taking into account quantum effects.
- The OQS framework has been discussed in the previous talk. In this talk, I focus on the EFT point of view. See also X. Yao's talk at the end of the session for EFT applications combined with Boltzmann equation.

Integrating out the heavy quark mass

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Classification of gluons

- Hard gluons, with energy and momentum of order m.
- Soft gluons, with energy and momentum of order mv.
- Potential gluons, with energy of order mv^2 and momentum of order mv.
- Ultrasoft gluons, with energy and momentum of order mv^2.

NRQCD

Caswell and Lepage (1986), Bodwin, Braaten and Lepage (1994)

$$\mathcal{L}_{NRQCD} = \mathcal{L}_g + \mathcal{L}_q + \mathcal{L}_\psi + \mathcal{L}_\chi + \mathcal{L}_{\psi\chi}$$

$$\mathcal{L}_g = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \frac{d_2}{m_Q^2}F^a_{\mu\nu}D^2F^{\mu\nu a} + d_g^3\frac{1}{m_Q^2}gf_{abc}F^a_{\mu\nu}F^{\mu b}_{\alpha}F^{\nu\alpha c}$$

$$\mathcal{L}_\psi = \psi^\dagger\left(iD_0 + c_2\frac{\mathbf{D}^2}{2m_Q} + c_4\frac{\mathbf{D}^4}{8m_Q^3} + c_F g\frac{\sigma\mathbf{B}}{2m_Q} + c_D g\frac{\mathbf{DE}-\mathbf{ED}}{8m_Q^2}\right.$$
$$\left. + ic_S g\frac{\sigma(\mathbf{D}\times\mathbf{E}-\mathbf{E}\times\mathbf{D})}{8m_Q^2}\right)\psi$$

$$\mathcal{L}_\chi = c.c \;of\; \mathcal{L}_\psi$$

$$\mathcal{L}_{\psi\chi} = \frac{f_1(^1S_0)}{m_Q^2}\psi^\dagger\chi\chi^\dagger\psi + \frac{f_1(^3S_1)}{m_Q^2}\psi^\dagger\sigma\chi\chi^\dagger\sigma\psi + \frac{f_8(^1S_0)}{m_Q^2}\psi^\dagger T^a\chi\chi^\dagger T^a\psi$$
$$+\frac{f_8(^3S_1)}{m_Q^2}\psi^\dagger T^a\sigma\chi\chi^\dagger T^a\sigma\psi$$

potential NRQCD Lagrangian at T=0

Brambilla, Pineda, Soto and Vairo, NPB566 (2000) 275

Starting from NRQCD and integrating out the scale $\frac{1}{r}$.

$$\mathcal{L}_{pNRQCD} = \int d^3\mathrm{r}\, Tr\left[S^\dagger\left(i\partial_0 - h_s\right)S\right.$$
$$\left.+O^\dagger\left(iD_0 - h_o\right)O\right] + V_A(r)\,Tr(O^\dagger \mathrm{r} g \mathrm{E} S + S^\dagger \mathrm{r} g \mathrm{E} O)$$
$$+\frac{V_B(r)}{2}\,Tr(O^\dagger \mathrm{r} g \mathrm{E} O + O^\dagger O \mathrm{r} g \mathrm{E}) + \mathcal{L}_g + \mathcal{L}_q$$

- Degrees of freedom are singlet and octets.
- Allows to obtain manifestly gauge-invariant results. Simplifies the connection with Lattice QCD.
- If $1/r \gg T$ we can use this Lagrangian as starting point. In other cases the matching between NRQCD and pNRQCD will be modified.

Plan

How to compute what we measure?

Experimentally, the most common way to detect quarkonium is thought its decay into leptons. What is the pNRQCD operator related with this observable?

$$Tr(J^{\mu}_{el}(t,0)J_{el,\mu}(t,0)\rho) \propto Tr(S^{\dagger}(t,0)S(t,0)\rho)$$

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Reinterpretation

We can understand $Tr(S^{\dagger}(t,\mathrm{x})S(t,\mathrm{x}')\rho)$ as the projection of the density matrix to the subspace in which we have a singlet. Quarkonium is an open quantum system interacting with a bath.

The $\frac{1}{r} \gg T, m_D \gg E$ regime

Brambilla, M.A.E., Soto and Vairo (2017-2018)

Because all the thermal scales are smaller than $\frac{1}{r}$ but bigger than E the evolution equation is of the Lindblad form. [1]

$$\partial_t \rho = -i[H(\gamma), \rho] + \sum_k (C_k(\kappa)\rho C_k^\dagger(\kappa) - \frac{1}{2}\{C_k^\dagger(\kappa)C_k(\kappa), \rho\})$$

$$\kappa = \frac{g^2}{6\,N_c} \mathrm{Re} \int_{-\infty}^{+\infty} ds \,\langle \mathrm{T}\, E^{a,i}(s,0) E^{a,i}(0,0)\rangle$$

$$\gamma = \frac{g^2}{6\,N_c} \mathrm{Im} \int_{-\infty}^{+\infty} ds \,\langle \mathrm{T}\, E^{a,i}(s,0) E^{a,i}(0,0)\rangle$$

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κ coincides with the heavy quark diffusion coefficient.

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From κ and γ to phenomenological predictions

We can take values of κ (in this case we use lattice QCD results of Francis, Kaczmarek, Laine, Neuhaus and Ohno (2015)) and γ (we use $\gamma = 0$).

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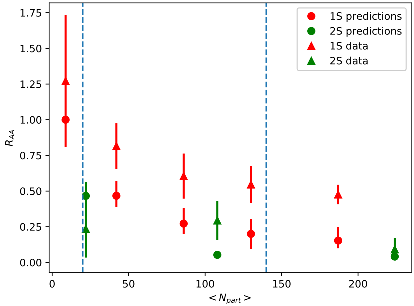

Comparison to CMS data at $\sqrt{s} = 2.76$ *TeV* (Phys.Lett. B770 (2017) 357-379), computation done in Brambilla, M.A.E., Soto and Vairo (2017-2018).

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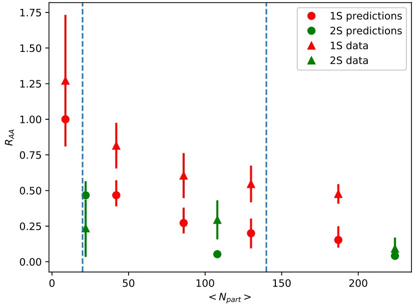

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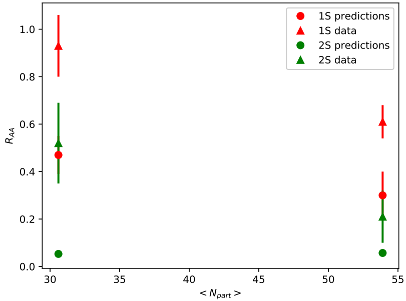

Comparison to CMS data at $\sqrt{s} = 5.02\ TeV$ (Phys. Lett. B 790, 270-293 (2019)), computation shown in Hard Probes 2018.

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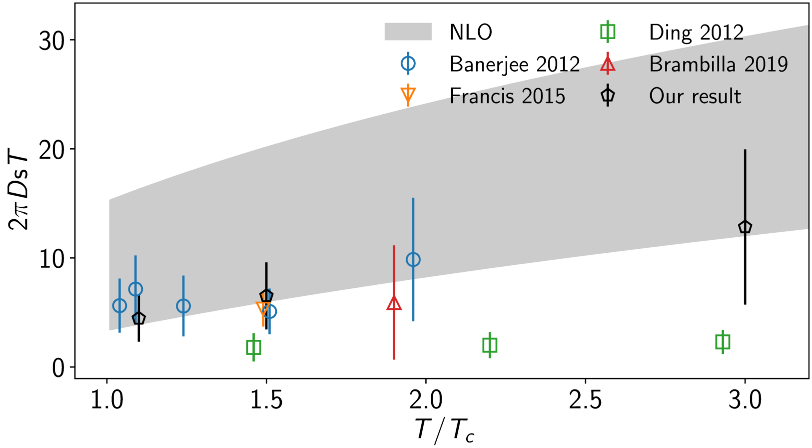
- γ can be obtained from Lattice QCD information on the thermal mass shift.
- To solve the Lindblad equation numerically is hard. In the past, we approximated medium evolution with a Bjorken expansion to reduce computational cost. I will discuss how we recently managed to reduce this cost.

New determination of κ. ($\kappa = 2\pi D_s T$)

Picture taken from N. Brambilla, V. Leino, P. Petreczky and A. Vairo, Phys. Rev. D **102** (2020) no.7, 074503 [arXiv:2007.10078 [hep-lat]].



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- In the case of κ, we have a determination which is based on an independent set of assumptions which can be compared with what is found studying heavy quark diffusion.
- In the case of γ, it is the first non-perturbative determination.
- The main assumption is that we are in the regime $\frac{1}{r} \gg T, m_D \gg E$ and that the bound states are Coulombic.

Determining κ and γ from quarkonium properties

Equations for κ and γ

$$\Gamma = \kappa\langle r^2\rangle \qquad \delta M = \frac{1}{2}\gamma\langle r^2\rangle$$

$\langle r^2\rangle$ is computed assuming that the wave function is well described with a Coulombic potential.

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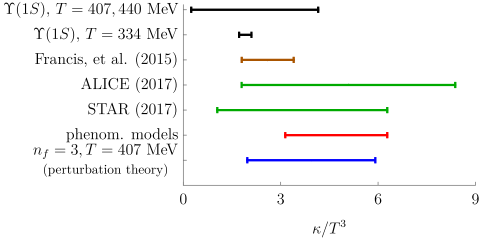
Lattice QCD data

- We use the results of Kim, Petreczky and Rothkopf (2018) for the thermal mass shift and as a lower bound for the decay width.
- We use the results of Aarts, Allton, Kim, Lombardo, Oktay, Ryan, Sinclair and Skullerud (2011) as upper bound for the decay width.
- Data at $T = 334\,MeV$, not used originally in our paper, is taken from Larsen, Meinel, Mukherjee and Petreczky (2019).

Determination of κ



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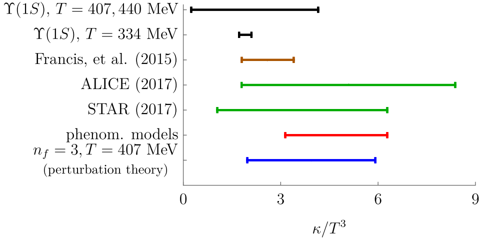

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- We took the value of Kim, Petreczky and Rothkopf (2018) at $T = 407\ MeV$ as a lower bound and the value of Aarts, Allton, Kim, Lombardo, Oktay, Ryan, Sinclair and Skullerud (2011) at the highest temperature available as an upper bound.

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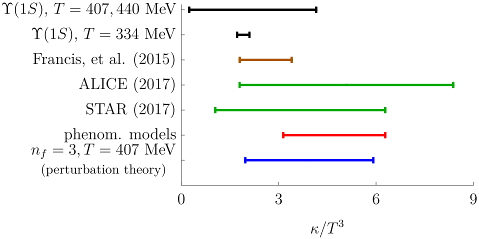

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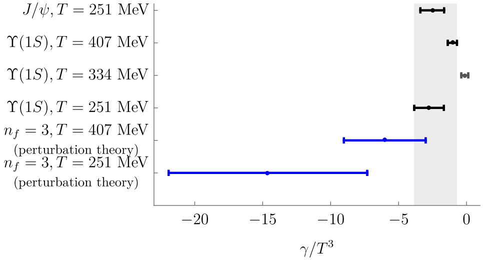
- Our result compares reasonably well to other determinations.

Determination of γ



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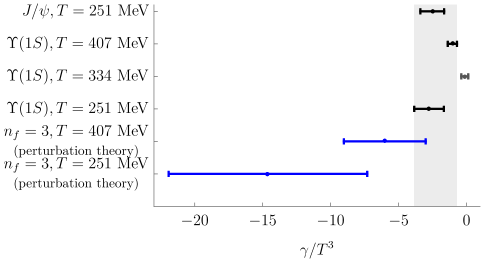

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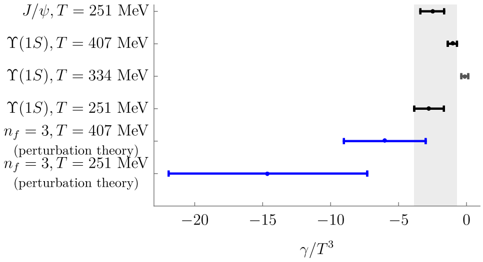

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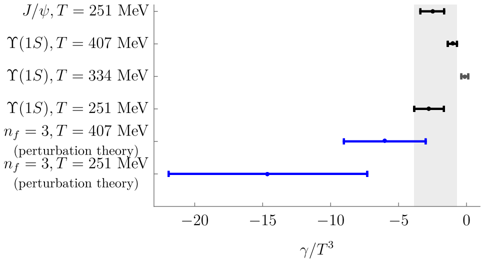

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- Results from different quarkonium state at the same temperature ($T = 251\, MeV$) are compatible with each other.
- Hint that $\frac{\gamma}{T^3}$ is not a constant.
- Lattice extracted results are much smaller than perturbative calculations.

The Monte-Carlo Wave Function method

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- In our previous papers, we used a N_r size lattice to discritize the radial component and we expand in angular momentum, with l_{max} the higher l taken into account. We had to compute the evolution of a $(2N_r \cdot l_{max}) \times (2N_r \cdot l_{max})$ matrix. Doubling the lattice size multiplies the computational cost by four and l_{max} can not be infinite.

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- Using MWFM, we need to simulate many times a stochastic evolution. However, the state of the system is represented by a vector of size N_r, a bit to store the color state and an integer to store the l quantum number. Doubling the lattice size only doubles the cost and l_{max} can be ∞.

The Monte-Carlo Wave Function method

Take the Lindblad equation

$$\partial_t \rho = -i[H(\gamma), \rho] + \sum_k \left(C_k(\kappa)\rho C_k^\dagger(\kappa) - \frac{1}{2}\{C_k^\dagger(\kappa) C_k(\kappa), \rho\} \right)$$

Let us define

$$\Gamma_n = C_n^\dagger C_n \qquad \Gamma = \sum_n \Gamma_n$$

and

$$H_{eff} = H - i\Gamma$$

$\rho(t) = \sum_n p_n |\Psi_n(t)\rangle\langle\Psi_n(t)|$. If we know how to evolve the case $\rho(t) = |\Psi(t)\rangle\langle\Psi(t)|$, it is straightforward to generalize.

The Monte-Carlo Wave Function method

The algorithm to evolve from t to $t + dt$

- With probability $1 - \langle\Psi(t)|\Gamma|\Psi(t)\rangle dt$.
  - Evolve the wave-function with $(1 - iH_{eff}\,dt)|\Psi(t)\rangle$. In our case, this implies solving a 1D Schrödinger equation because H_{eff} does not mix states with different color or angular momentum.
- With probability $\langle\Psi(t)|\Gamma_n|\Psi(t)\rangle dt$.
  - Take a quantum jump, $|\Psi(t)\rangle \to C_n|\Psi(t)\rangle$.
  - Only here transitions between different color and angular momentum are allowed.
- Normalize the resulting wave-function.

The average of this stochastic evolution of the wave-function is equivalent to the Lindblad equation for the density matrix.

Results

- Thanks to the reduction of the numerical cost, we can substitute the Bjorken by state-of-the-art hydrodynamical evolution (aHydroQP. Alqahtani, Nopoush and Strickland (2015)).

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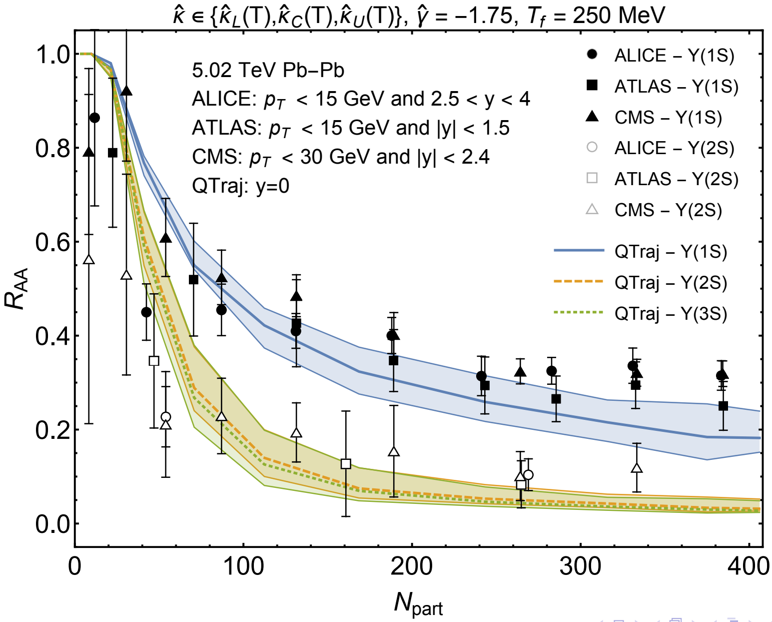
Results

- Thanks to the reduction of the numerical cost, we can substitute the Bjorken by state-of-the-art hydrodynamical evolution (aHydroQP. Alqahtani, Nopoush and Strickland (2015)).
- We know more about γ and the T dependence of κ.
- We observe that the effect of the quantum jumps is very small. Indeed, evolving with H_{eff} is a very good approximation.

Results



$\hat{\kappa} \in \{\hat{\kappa}_L(T), \hat{\kappa}_C(T), \hat{\kappa}_U(T)\}$, $\hat{\gamma} = -1.75$, $T_f = 250$ MeV
5.02 TeV Pb–Pb
ALICE: p_T < 15 GeV and 2.5 < y < 4
ATLAS: p_T < 15 GeV and |y| < 1.5
CMS: p_T < 30 GeV and |y| < 2.4
QTraj: y=0
ALICE – Υ(1S)
ATLAS – Υ(1S)
CMS – Υ(1S)
ALICE – Υ(2S)
ATLAS – Υ(2S)
CMS – Υ(2S)
QTraj – Υ(1S)
QTraj – Υ(2S)
QTraj – Υ(3S)
R_{AA}
N_{part}

Plan

Conclusions

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- κ is the heavy quark diffusion coefficient. The use of more precise Lattice data leads to a better agreement with experimental data.
- The use of the MCWF method reduces the computational cost. Thanks to this we can use a more realistic hydrodynamical description and obtain more realistic predictions.

Outlook

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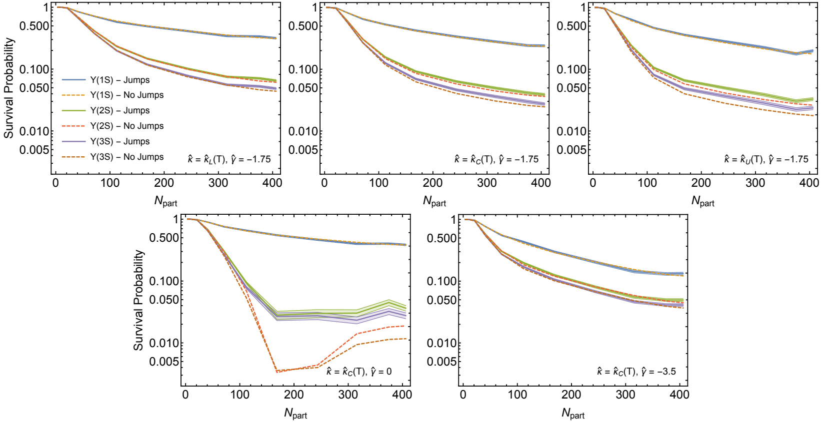
- We are looking at other observables, like v_2 of bottomonium and R_{AA} vs p_T.
- There are things that we can improve:
  - Extend the formalism to a wider range of temperature regimes. Master equations that are not of the Lindblad form.
  - Improve the initial conditions.

Thanks!

H_{eff} against full evolution



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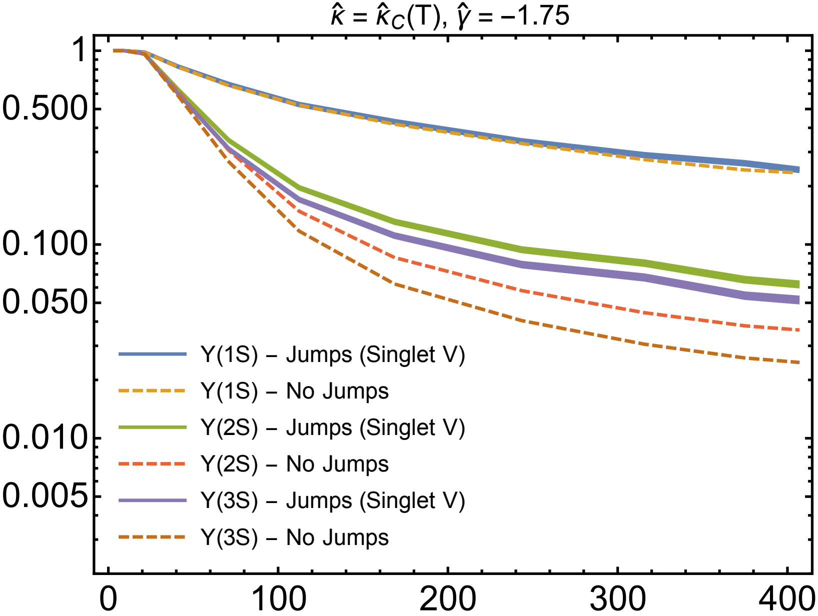
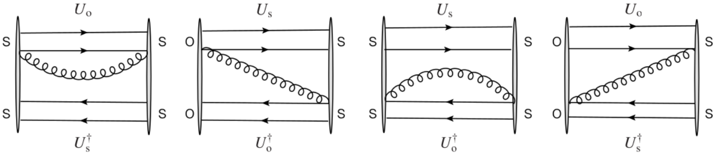
- Each jump changes the l quantum number by one unit. A s-wave state will always decay to p-wave. However, a p-wave only has $1/3$ probability to decay to s-wave.
- The octet has a repulsive potential. The quark and the antiquark separate and, if they do jump back to a singlet state, they are less likely to bound.

If the octet had an attractive potential...

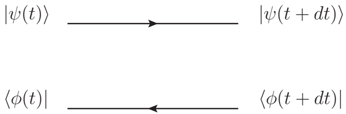


The evolution of the density matrix

4 diagrams that connect any state at time t with a singlet at time $t+dt$.



These diagrams represent the evolution of the density matrix



The evolution of the density matrix

8 diagrams that connect whatever state at time t with an octet at time $t + dt$.