Models for Onium production

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7th June, 2016

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1. Introduction
2. The very high temperature regime, $T \gg m_D \sim \frac{1}{r}$
3. The low temperature regime, $\frac{1}{r} \gg T$
4. Conclusions

The original idea of Matsui and Satz (1986)

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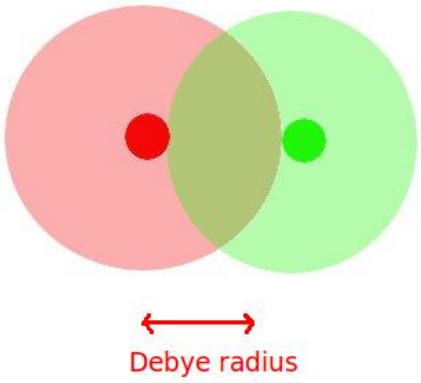
- Quarkonia is quite stable in the vacuum.
- Phenomena of colour screening, quantities measurable in Lattice QCD at finite temperature (static) support this. For example Polyakov loop.
- Dissociation of heavy quarkonium in heavy-ion collisions due to colour screening signals the creation of a quark-gluon plasma.

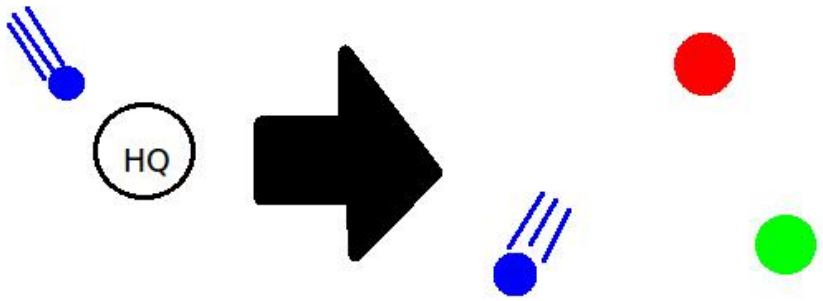
Colour screening

$$V(r) = -\alpha_s \frac{e^{-m_D r}}{r}$$

At finite temperature



Another mechanism, the decay width



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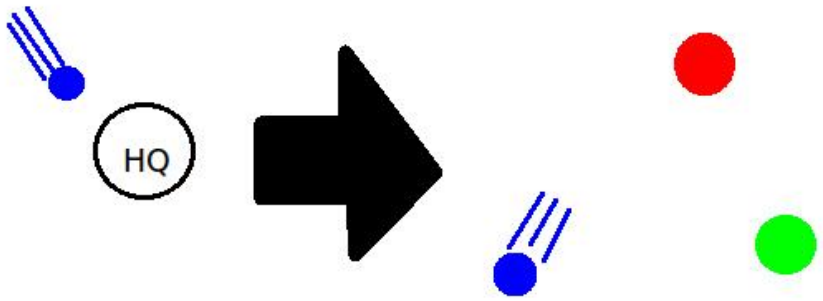

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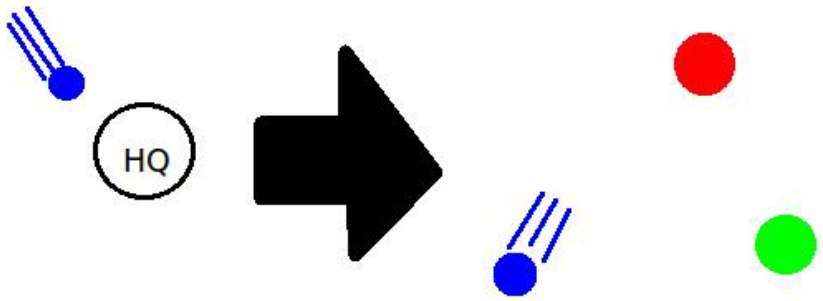

- A singlet state absorbing a gluon from the medium will turn into an octet.
- Interaction is attractive in a singlet state but repulsive in an octet state.
- Thermal decay width. Finite lifetime.

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- Quarkonium does not survive the end of the fireball.
- The probability to find a quarkonium state is low.

Question 2

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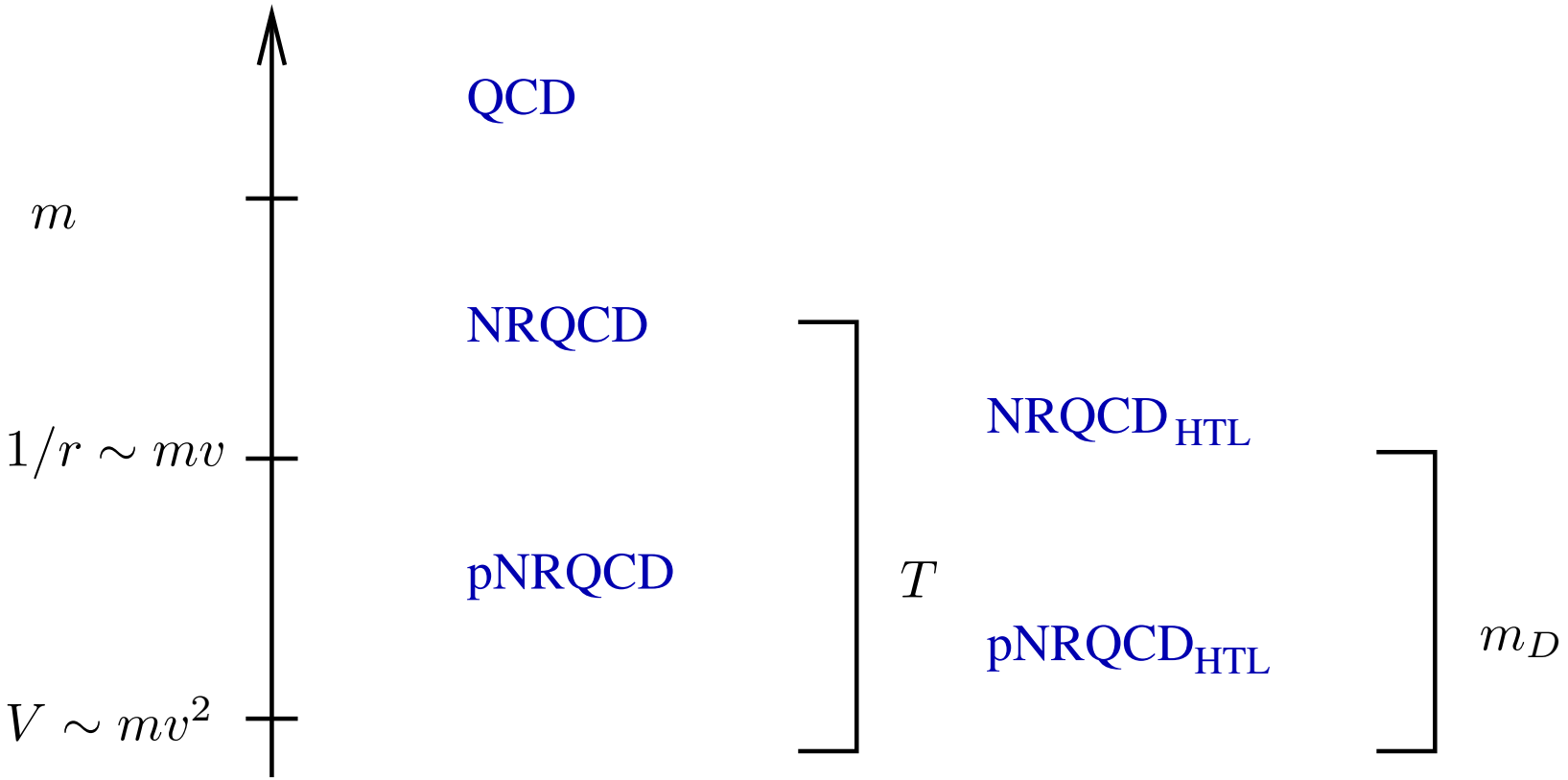
- Under which conditions a potential model is justified?
- What is the relevant potential? Internal energy, free energy...
- Which kind of behaviour do we expect when the potential model is not justified.

Effective field theories



Brambilla, Ghiglieri, Vairo and Petreczky (PRD78 (2008) 014017)
M. A. E and Soto (PRA78 (2008) 032520)

Some of the things that have been learnt by applying EFTs

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- A potential model is justified only if $T \gg E$.
- When this condition is meet the potential is a Wilson coefficient of pNRQCD.
- At any temperature such that $T \sim E$ or bigger quarkonium will have a decay width.
- The radius r of the heavy quark will determine how strong is the interaction with the medium.

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Laine et al. perturbative potential (2007)

$$V(r) = -\alpha_s C_F \left[m_D + \frac{e^{-m_D r}}{r} \right] - i\alpha_s T C_F \phi(m_D r)$$

with

$$\phi(x) = 2 \int_0^\infty \frac{dzz}{(z^2+1)^2} \left(1 - \frac{\sin(zx)}{zx} \right)$$

- This potential was obtained through the Wilson loop in Minkownski space at finite temperature.

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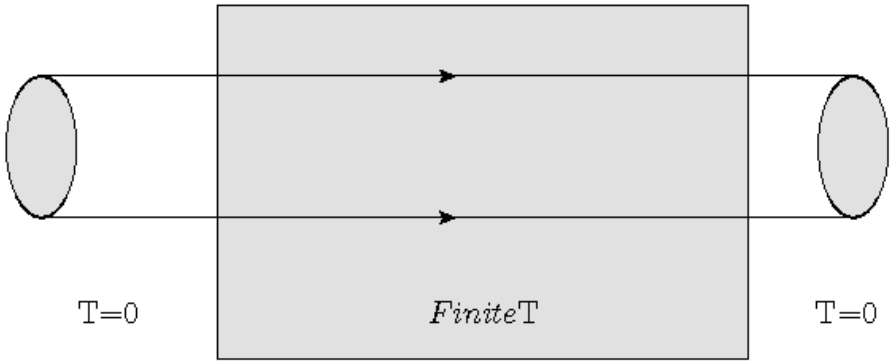
- This potential was obtained through the Wilson loop in Minkownski space at finite temperature.
- It has an imaginary part that has to be related with a decay width.
- This result is valid for $T \gg 1/r \sim m_D$. Other regimes have been explored using EFTs (Brambilla, Ghiglieri, Petreczky And Vairo, M. A. E and Soto).

Model for HQ passing through a QCD brick

$$\langle \phi_f | e^{-iH_M(t_f - t_i)} | \phi_i \rangle \ ,$$



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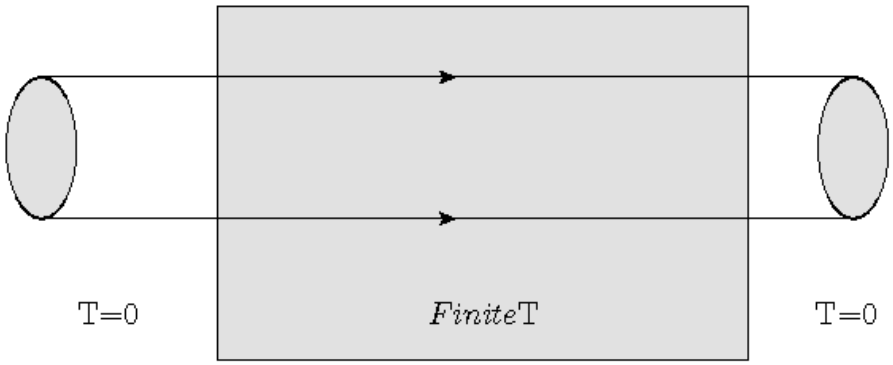

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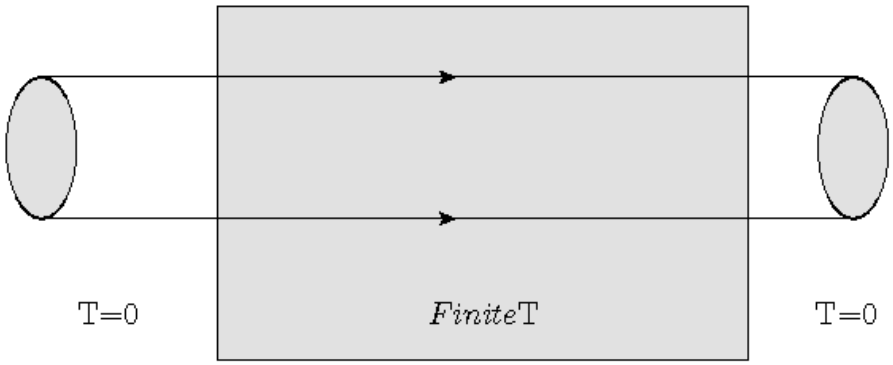
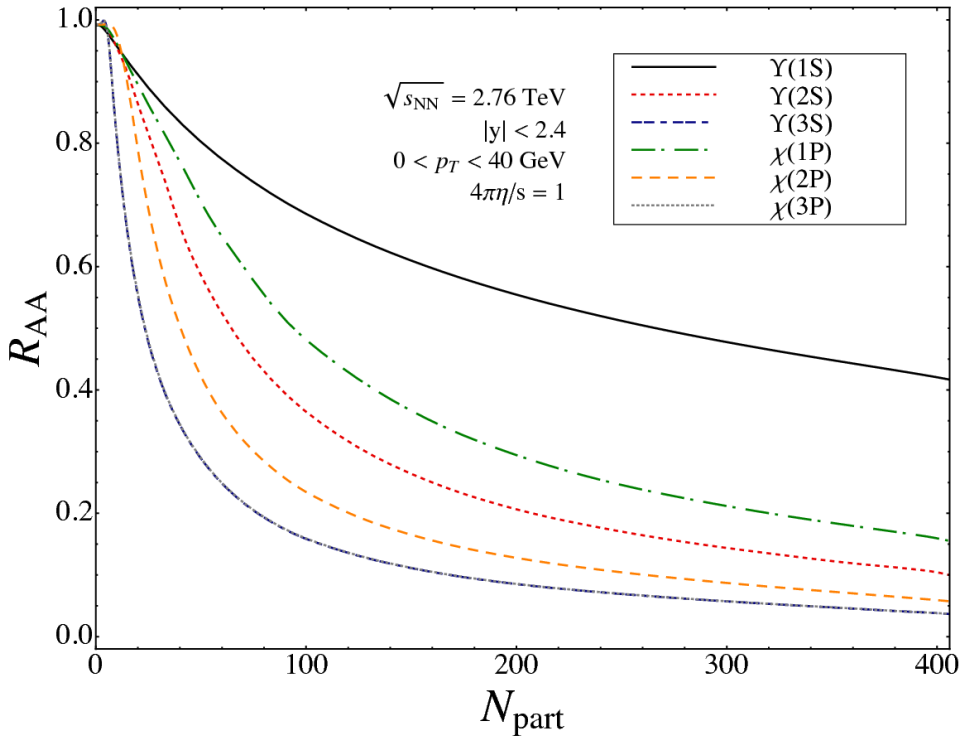


- If the potential is real dissociation is due to the fact that the eigenvectors in the vacuum do not coincide with the eigenvectors in the medium.
- If there is an imaginary part the norm of the wave function decreases. Related with the probability that the whole system remains in the same type of state (singlet+medium).

The imaginary part of the potential in phenomenology



Picture taken from B. Krouppa and M. Strickland (arXiv:1605.03561). Suppression without feed-down.

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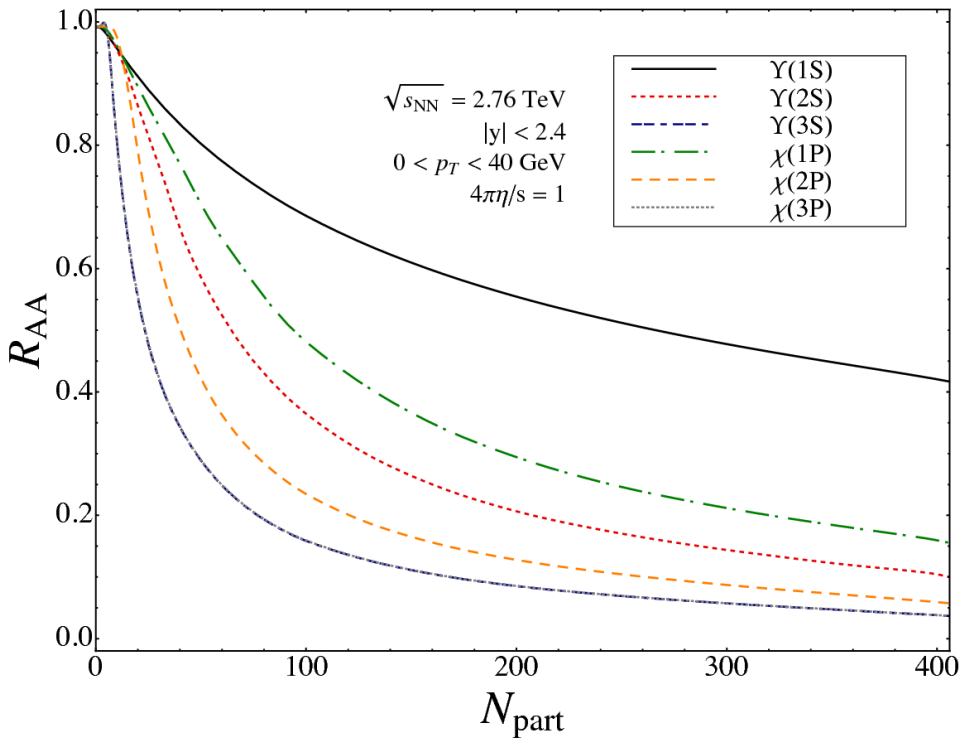

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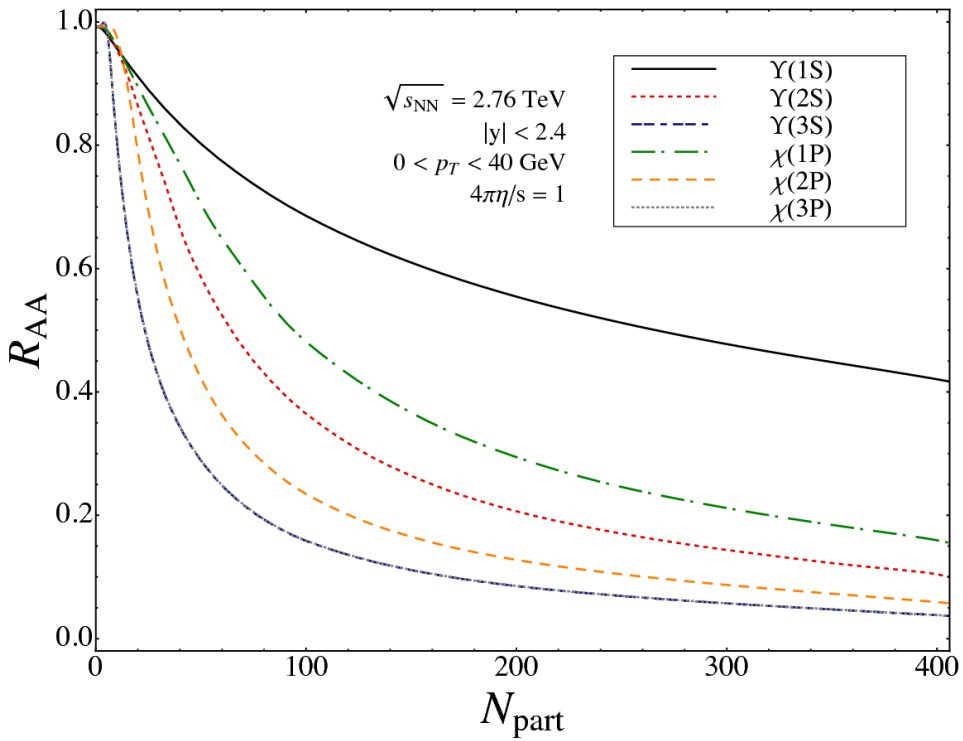

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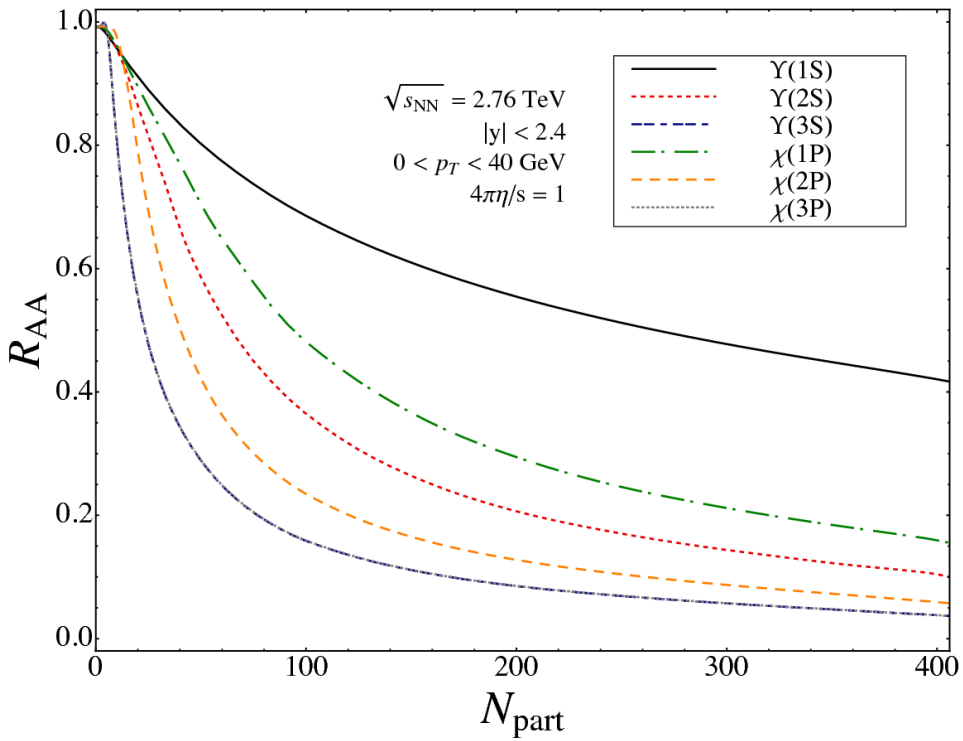

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- Many groups has studied suppression using potentials inspired by the computation of Laine and collaborators. (Strickland et al., Casalderrey-Solana, Wolschin et al.).
- Can reproduce experimental results combined with other ingredients (feed-down, viscosity...).
- In the $t \to \infty$ limit no bound states (regardless of the temperature!).

Open quantum systems

Introduced in the context of quarkonium by Akamatsu and Rothkopf.

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- $\mathcal{H} = \mathcal{H}_{System} \otimes \mathcal{H}_{Environment}$, the heavy particles are the system and the thermal bath is the environment.
- Wave-function $\rightarrow$ reduced density matrix. Trace over environment degrees of freedom.

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- $\mathcal{H} = \mathcal{H}_{System} \otimes \mathcal{H}_{Environment}$, the heavy particles are the system and the thermal bath is the environment.
- Wave-function $\rightarrow$ reduced density matrix. Trace over environment degrees of freedom.
- All the information of the system is not encoded in time-ordered correlators.

Open quantum systems

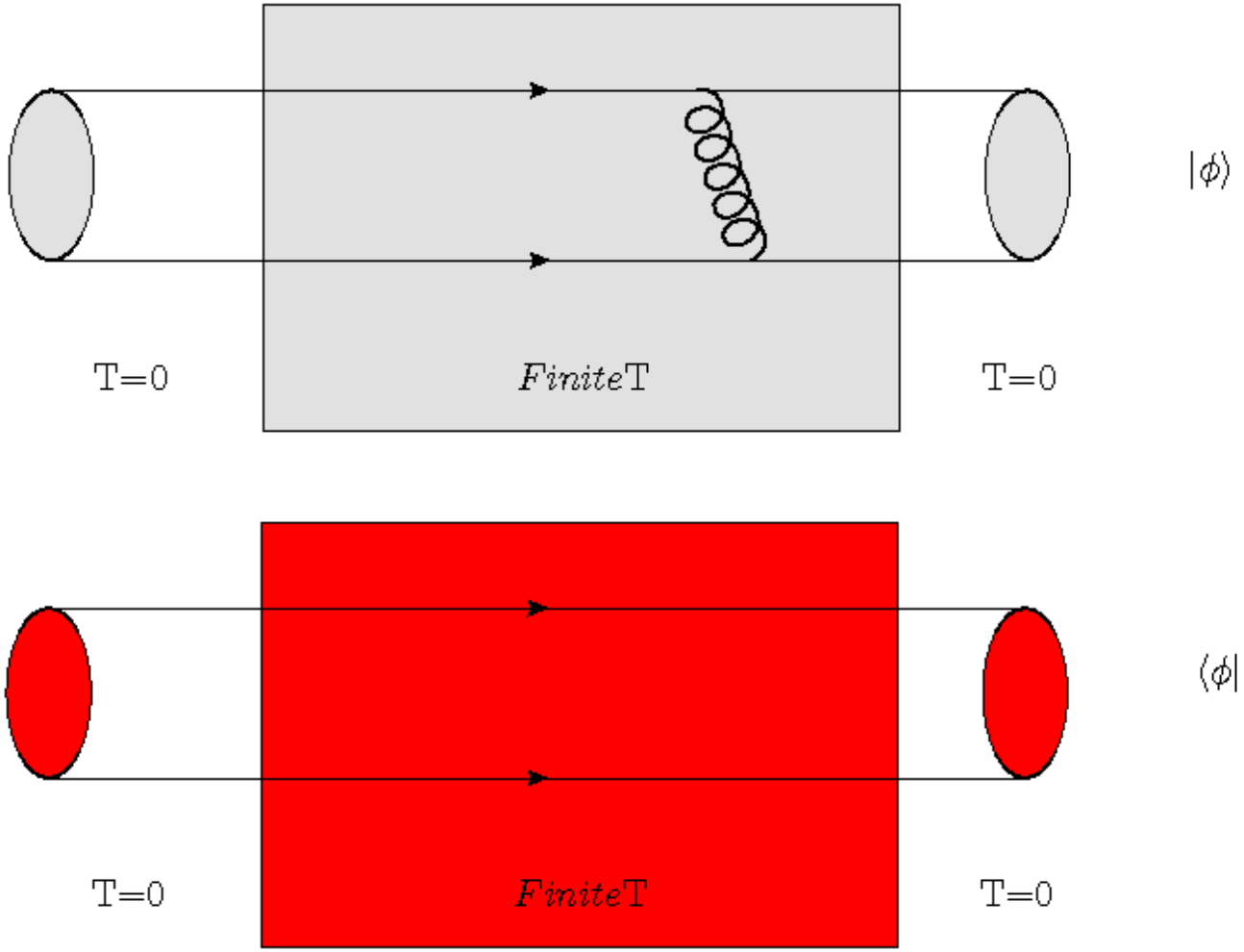
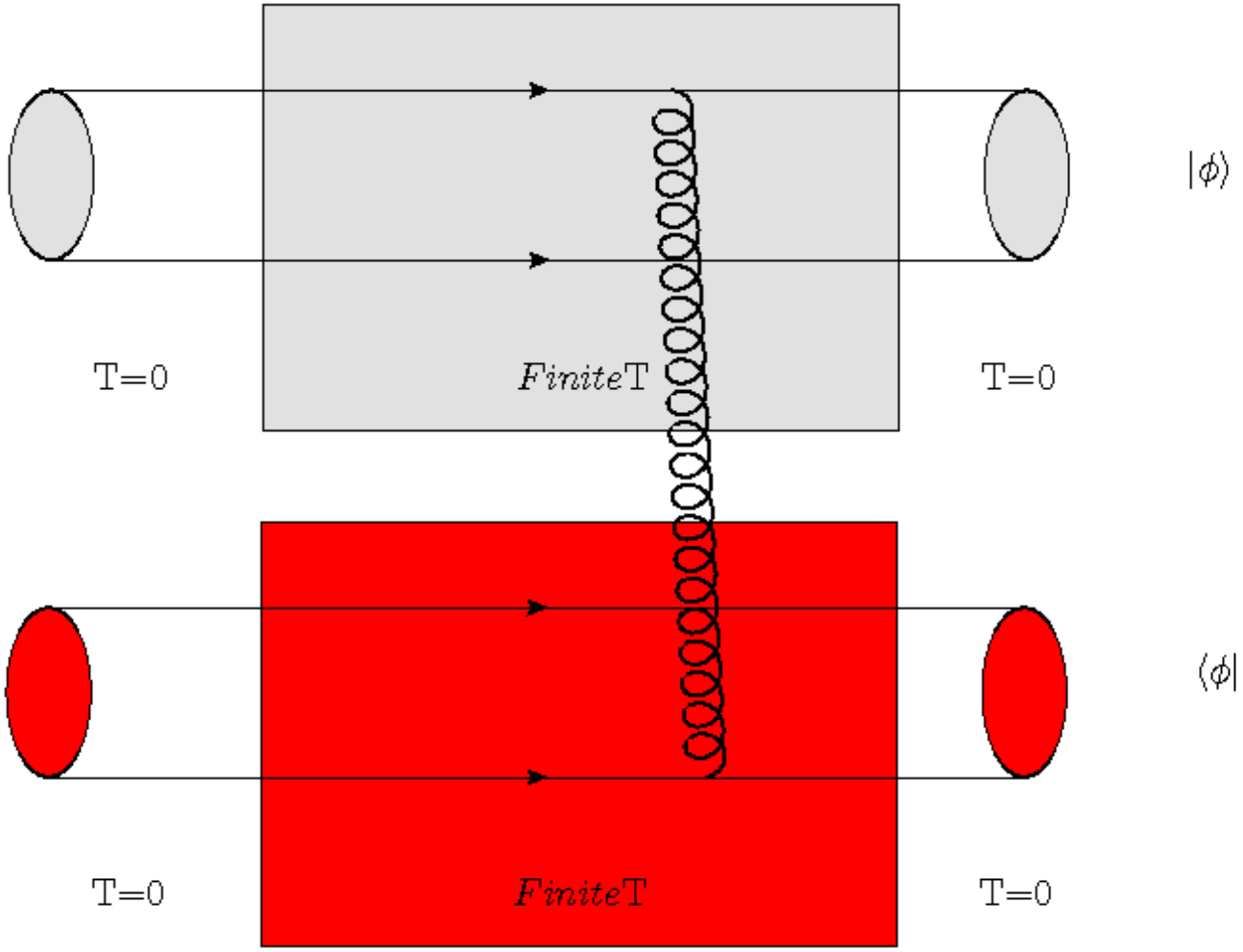


Diagram contributing to the potential. The initial and the final state are very similar.

Open quantum systems



Example:Initial state, singlet+plasma. Final state, octet+plasma+addition gluon. When I make the trace over the environment the effect is an increase on the number of octets.

Decoherence and quarkonium

Decoherence is a process that suffer all quantum systems interacting with a medium. The density matrix will tend to be diagonal in the so-called pointer basis $\rightarrow$ Classical behaviour.

- Decoherence can invalidate some assumptions made in deriving the quantum evolution.
- Justifies classical approximations that are easier to solve.

Decoherence in QED, the Langevin equation

Blaizot, De Boni, Faccioli and Garberoglio (NPA 946 (2016) 49-88)
Obtain a Langevin equation from the quantum evolution in the limit in which the density matrix is diagonal.

$$M\ddot{\mathbf{r}} = \mathbf{F}(\mathbf{r}) - \mathbf{F}_{drag}(\mathbf{r}) + \xi(\mathbf{r})$$

- Binding force. Gradient of the real part of the potential.
- Stochastic force. Hessian of the imaginary part of the potential at $r \to 0$.
- Drag force. Related with the stochastic force by the fluctuation-dissipation theorem.

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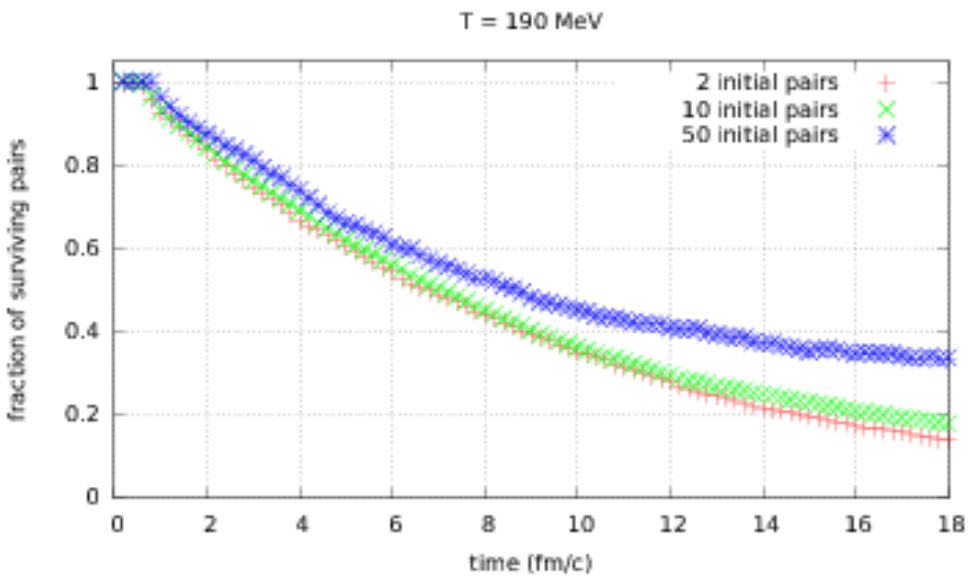


A lot of pairs can be simulated at the same time (recombination) without a prohibitive computational cost. Can we get something similar for QCD?

Langevin-like equations in QCD

On-going collaboration with Jean-Paul Blaizot.

$$\frac{d\rho_{HQ}}{dt} = -i\frac{\Re V}{2}[\rho_0^A\rho_0^A, \rho_{HQ}] + \frac{D}{2}(\{\rho_{HQ}, \rho_0^A\rho_0^A\} - 2\rho_0^A\rho_{HQ}\rho_0^A)$$
$$-\frac{iD}{8T}\left(\{\rho_{HQ}, \left(\frac{d\rho_0^A}{dt}\rho_0^A - \rho_0^A\frac{d\rho_0^A}{dt}\right)\} - 2\left(\rho_0^A\rho_{HQ}\frac{d\rho_0^A}{dt} - \frac{d\rho_0^A}{dt}\rho_{HQ}\rho_0^A\right)\right)$$

- Time-local interaction. Real and imaginary part of the potential.
- Drag force related terms. They are sub-leading if the density matrix is far from being diagonal but leading order if it is. Decoherence changes power counting.

What color state do we expect at large times?

Langevin equation obtained as a result of decoherence in position space $\rightarrow$ we expect also decoherence in color space $\rightarrow$ density matrix diagonal in color.
Nature doesn't have a favourite color.
The color of a heavy quark is independent of the color state of another heavy quark. Maximize entropy.

What color state do we expect at large times?

- The color state of each heavy quark is independent of the color state of the others.
- A heavy quark has equal probability to be in any color state.

This implies that whenever I have a heavy quark and a heavy antiquark pair

$$P_{singlet} = \frac{1}{N_c^2}$$

$$P_{octet} = \frac{N_c^2 - 1}{N_c^2}$$

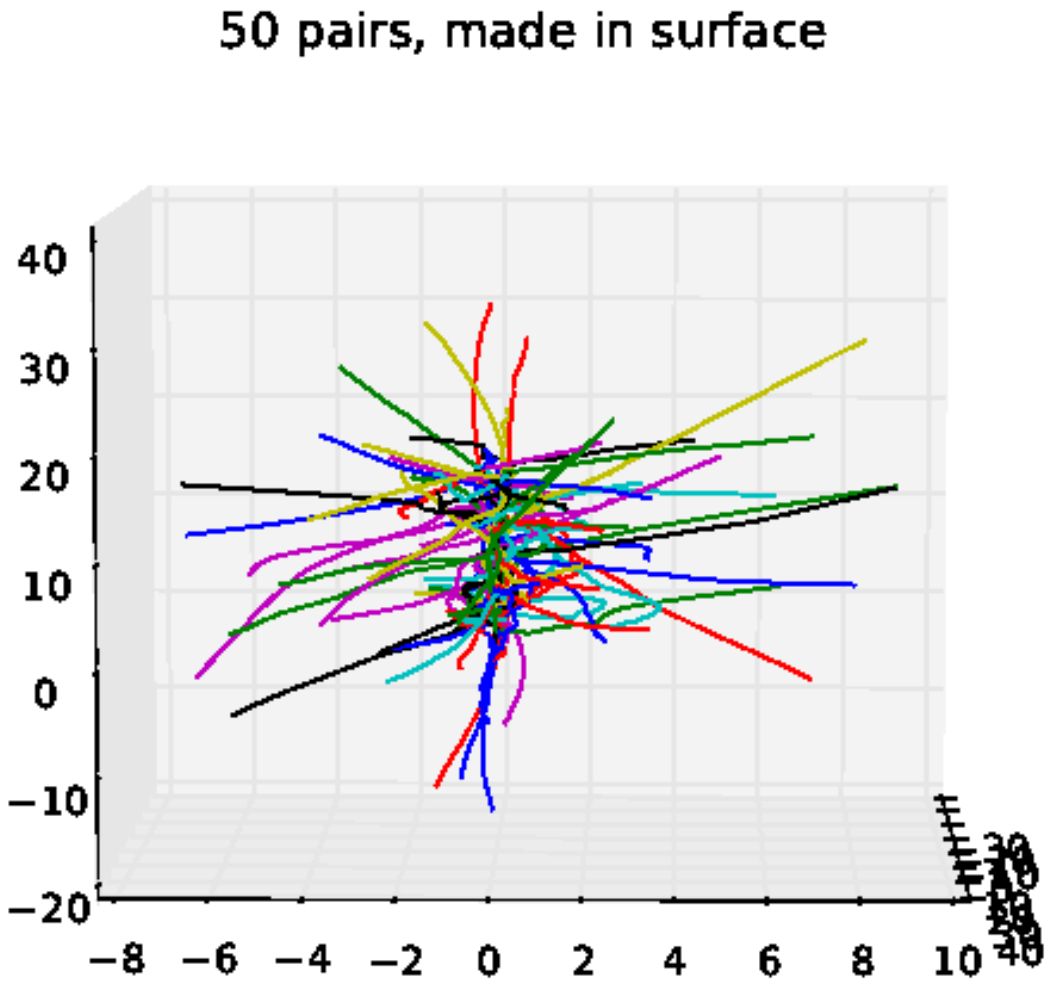
Force between two HQ's in a random color state

- Singlet. The force is attractive.
- Octet. The force is repulsive and $\frac{1}{N_c^2-1}$ weaker than that of the singlet.

$$F_{singlet}(\mathbf{r})P_{singlet} + F_{octet}(\mathbf{r})P_{octet} = 0$$

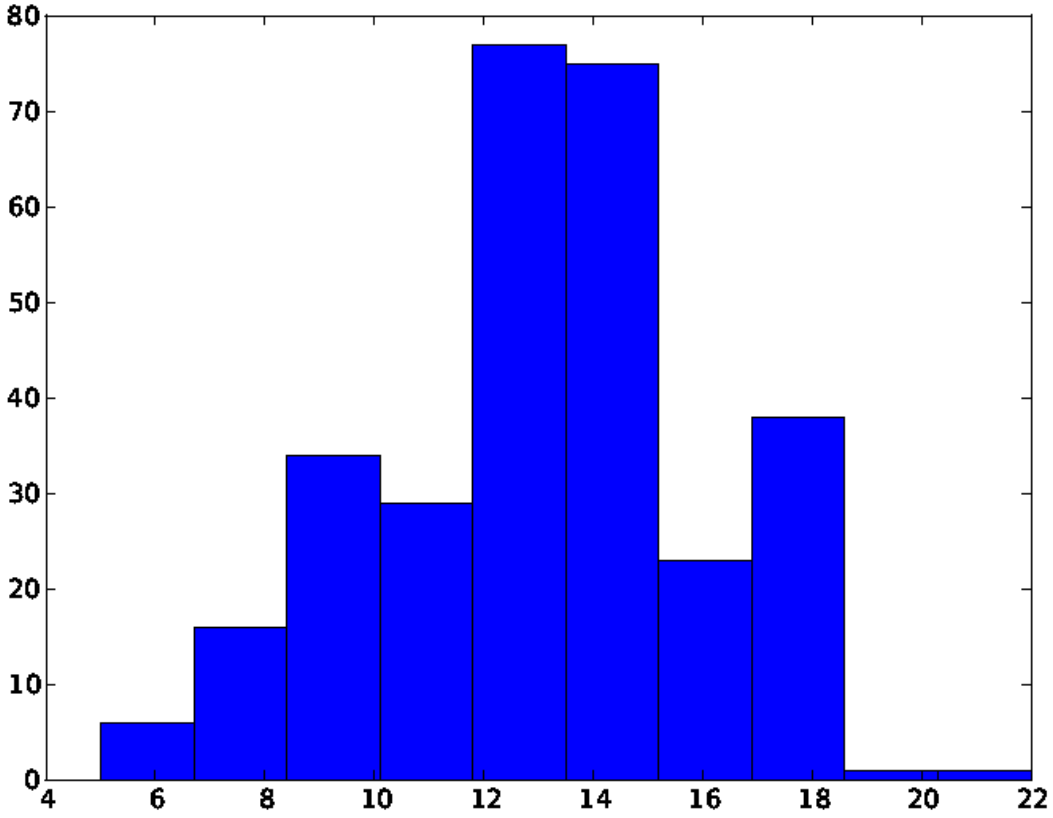
The mean value is 0 but we have fluctuations around this value $\rightarrow$ The force between heavy quarks is a stochastic force.

50 pairs created in a dirac delta distributed around a plane



50 pairs created in a dirac delta distributed around a plane

Histogram of bound states defined as pairs that stay at a distance smaller than $0.5fm$ during a time bigger than $0.1fm$.



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Compute the evolution of the density matrix in pNRQCD

On-going collaboration with Nora Brambilla, Joan Soto and Antonio Vairo.

- Because $\frac{1}{r} \gg T$ we can do the computation using pNRQCD (Brambilla, Pineda, Soto and Vairo, NPB566 (2000) 275).

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

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- Degrees of freedom are singlet and octets.
- Allows to obtain manifestly gauge-invariant results. Simplifies the connection with Lattice QCD.

Evolution of the number of singlets

$$f_s(x,y) = Tr(\rho S^\dagger(x) S(y))$$

We can use perturbation theory but expanding in r instead of α_s. In the interaction picture

$$i\partial_t S = [S, H_0]$$
$$i\partial_t \rho = [H_I, \rho]$$

Evolution of the number of singlets

$$\partial_t f_S = -i(H_{eff} f_s - f_s H_{eff}^\dagger) + \mathcal{F}(f_o)$$

- $H_{eff} = h_s + \Sigma$ where Σ corresponds with the self-energy that can be obtained in pNRQCD by computing the time-ordered correlator.
- $\mathcal{F}(f_o)$ is a new term that takes into account the process $O \to g + S$. In ensures that the total number of heavy quarks is conserved.
- $\mathcal{F}(f_o)$ is a complicated function of $Tr(\rho O^\dagger O)$ and $\langle E^i E^j \rangle$. The information about the medium enters only in the chromoelectric field correlator. It will not be a Markovian process for any correlator.

Evolution of the octet

Very similar reasoning.

$$f_o^{ab}(x,y) = Tr(\rho O^{\dagger,a}(x) O^b(y))$$

$$\partial_t f_o = -i[H_o, f_o] - \frac{1}{2}\{\Gamma, f_o\} + \mathcal{F}_1(f_s) + \mathcal{F}_2(f_o)$$

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

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

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

there is a transition singlet-octet

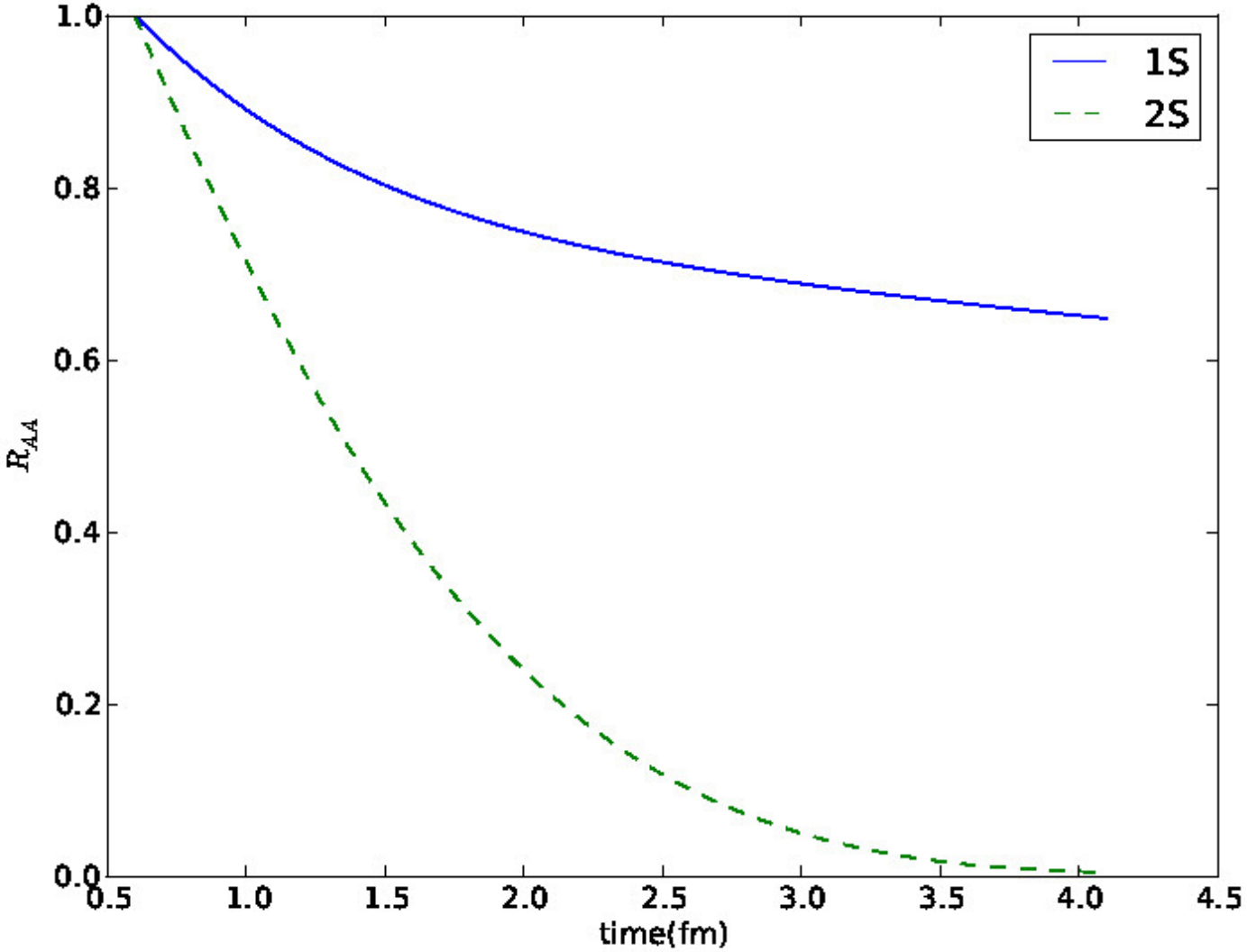
$$C_i^{so} = 2\sqrt{\frac{2T_F \kappa}{N_c(N_c^2-1)}} r \begin{pmatrix} 0 & \frac{1}{\sqrt{N_c^2-1}} \\ 1 & 0 \end{pmatrix}$$

and octet to octet

$$C_i^{oo} = \sqrt{\frac{2(N_c^2-4)\kappa}{N_c(N_c^2-1)}} r \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Toy model for $\frac{1}{r} \gg T_{eff} \gg m_D \gg E$

Preliminary study, $\kappa = \frac{C_F \alpha_s \log(2) m_D^2 T}{3}$ inspired by perturbation theory.



$\frac{1}{r} \gg T_{eff} \gg m_D \gg E$

Preliminary study, see which value of κ reproduces best the experimental results.

			$30-50\%$ centrality			$50-100\%$ centrality		
$\frac{\kappa}{T^3}$	γ	δ	$R_{AA}(1S)$	$\frac{R_{AA}(2S)}{R_{AA}(1S)}$	$\frac{R_{AA}(3S)}{R_{AA}(1S)}$	$R_{AA}(1S)$	$\frac{R_{AA}(2S)}{R_{AA}(1S)}$	$\frac{R_{AA}(3S)}{R_{AA}(1S)}$
2.5	0.144	1	0.138	0.216	0.188	0.722	0.512	0.458
25	0.144	1	0.0104	4.02	4.10	0.153	0.622	0.591
0.25	0.144	1	0.643	0.195	0.154	0.929	0.910	0.896
2.5	1.44	1	0.0191	0.542	0.485	0.528	0.657	0.609
2.5	0.0144	1	0.156	0.276	0.262	0.742	0.497	0.443
2.5	0.144	0.1	0.133	0.214	0.183	0.721	0.513	0.458
2.5	0.144	10	0.143	0.241	0.227	0.730	0.508	0.455

- γ is a constant that control the corrections to the real part of the potential.
- δ depend of the initial probabilities of having a singlet P_s or and octet P_o. $\delta = \frac{\alpha_s P_o}{P_s}$.

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- The existence of the imaginary part tells us that a more dynamical picture of quarkonium is needed.
- There is a complex interaction between the densities of octets and singlets.
- Decoherence is an important effect that needs to be taken into account and that simplifies the evolution equations.
- The low temperature regime is a very interesting one because the evolution is very constrained by the symmetries.