Quarkonium dissociation and regeneration

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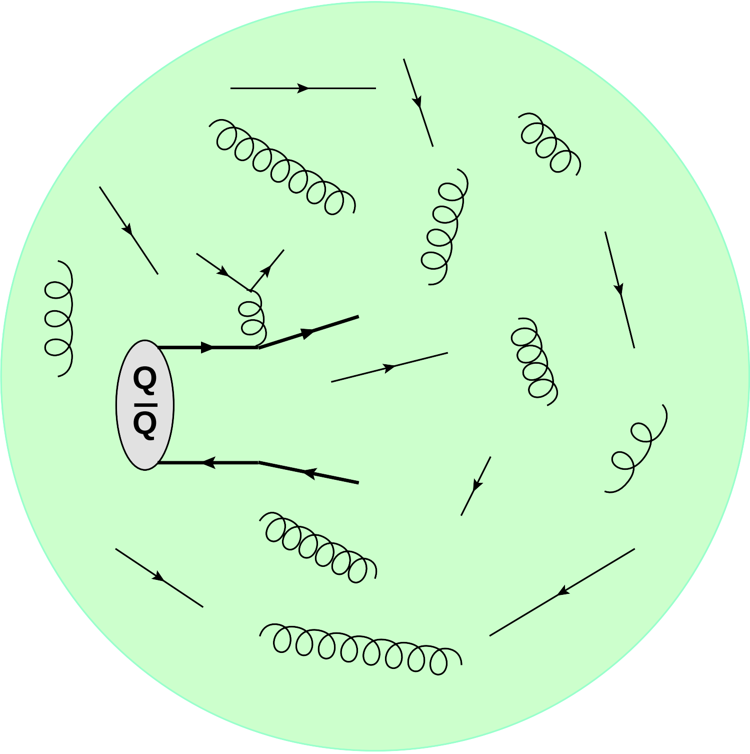
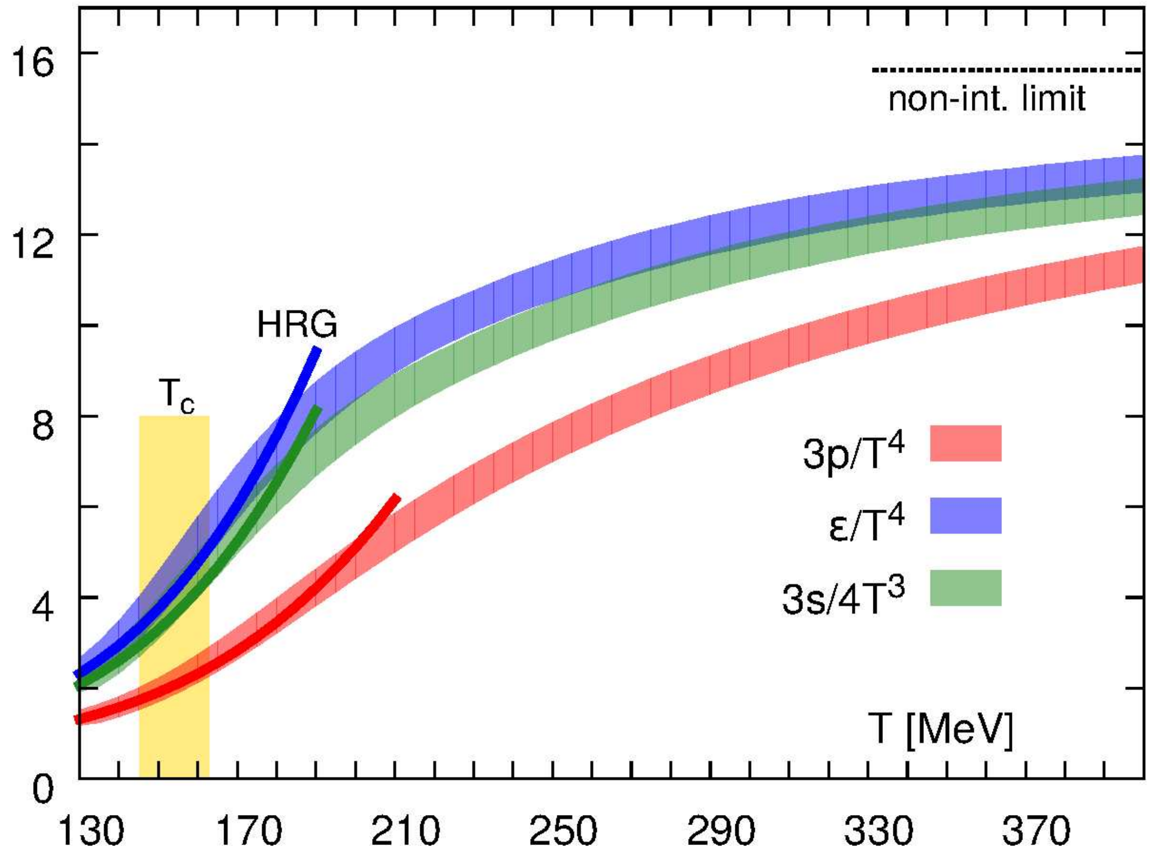
Quarkonium in a thermal bath



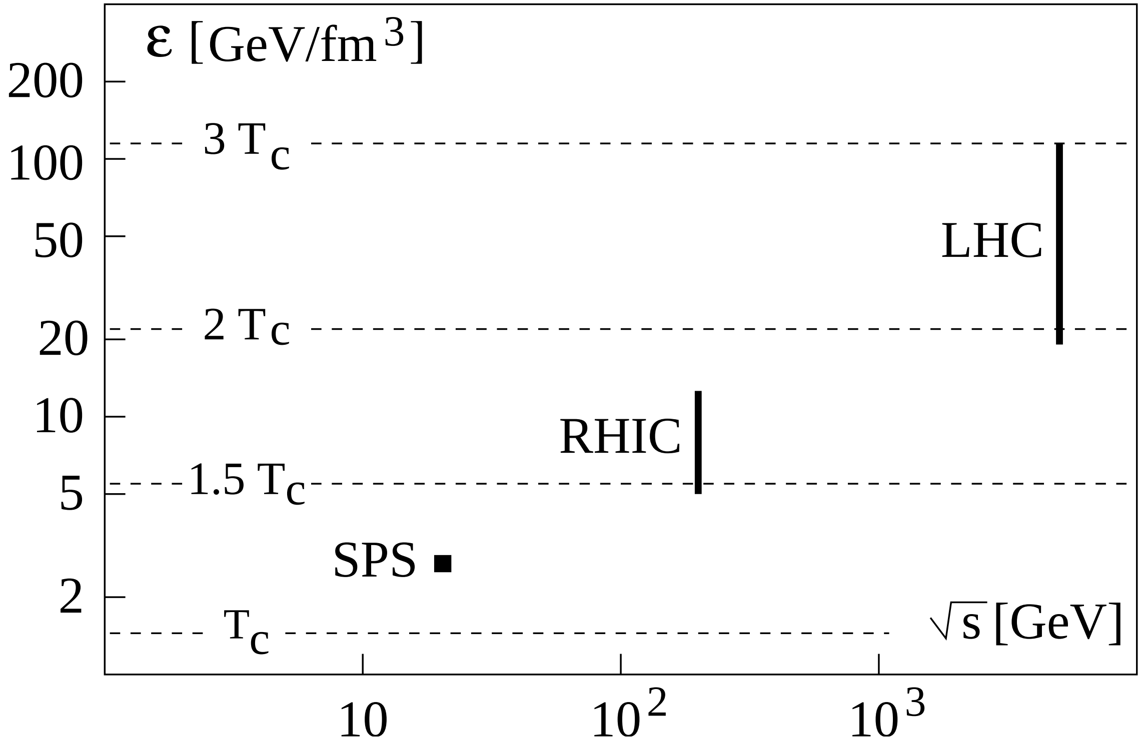
Colour deconfinement



Transition from hadronic matter to a plasma of deconfined quarks and gluons happening at some critical temperature $T_c = 154 \pm 9$ MeV as studied in finite temperature lattice QCD.

∘ Wuppertal-Budapest JHEP 1009 (2010) 073, HotQCD PRD 90 (2014) 094503

Heavy-ion experiments

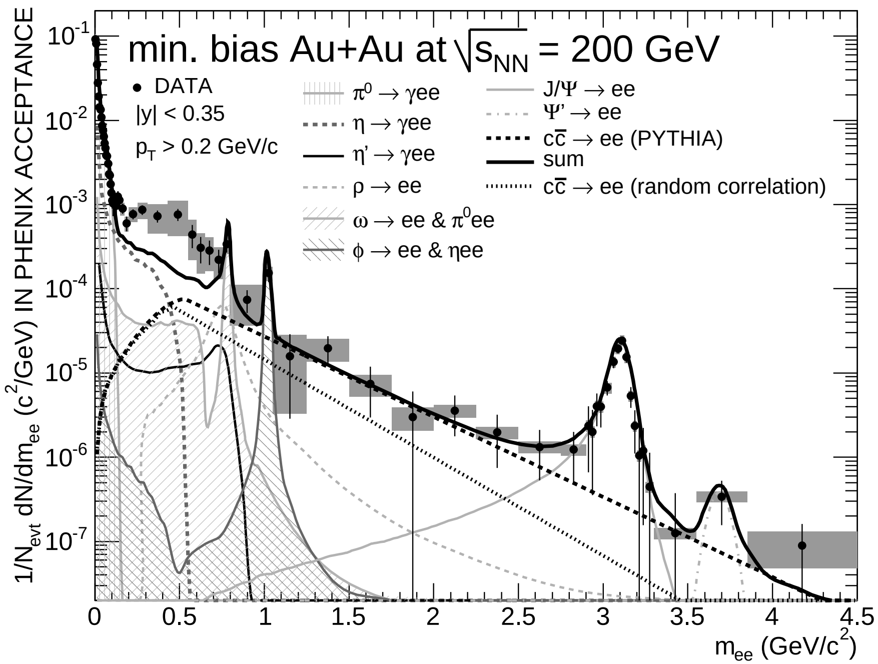


High energy densities and temperatures $> T_c$ as explored by the heavy-ion experiments at RHIC and LHC.

Quarkonium as a quark-gluon plasma probe

In 1986, Matsui and Satz suggested quarkonium as an ideal quark-gluon plasma probe.

- Heavy quarks are formed early in heavy-ion collisions: $1/M \sim 0.1$ fm < 0.6 fm.
- Heavy quarkonium formation will be sensitive to the medium.
- The dilepton signal makes the quarkonium a clean experimental probe.



Scales

Quarkonium being a composite system is characterized by several energy scales, these in turn may be sensitive to thermodynamical scales smaller than the temperature:

- the scales of a non-relativistic bound state
  (v is the relative heavy-quark velocity; $v \sim \alpha_{\rm s}$ for a Coulombic bound state):
  M (mass),
  Mv (momentum transfer, inverse distance),
  Mv^2 (kinetic energy, binding energy, potential V), ...

- the thermodynamical scales:
  πT (temperature),
  m_D (Debye mass, i.e. screening of the chromoelectric interactions), ...

The non-relativistic scales are hierarchically ordered: $M \gg Mv \gg Mv^2$
We assume this to be also the case for the thermodynamical scales: $\pi T \gg m_D$

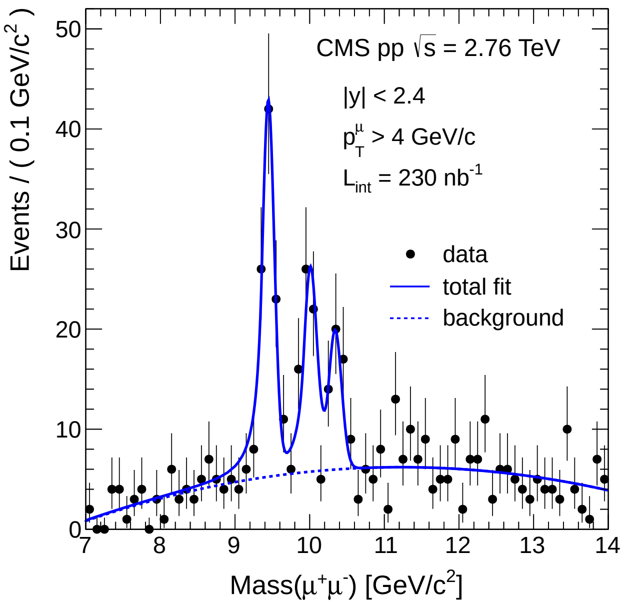
$\Upsilon(1S)$ scales

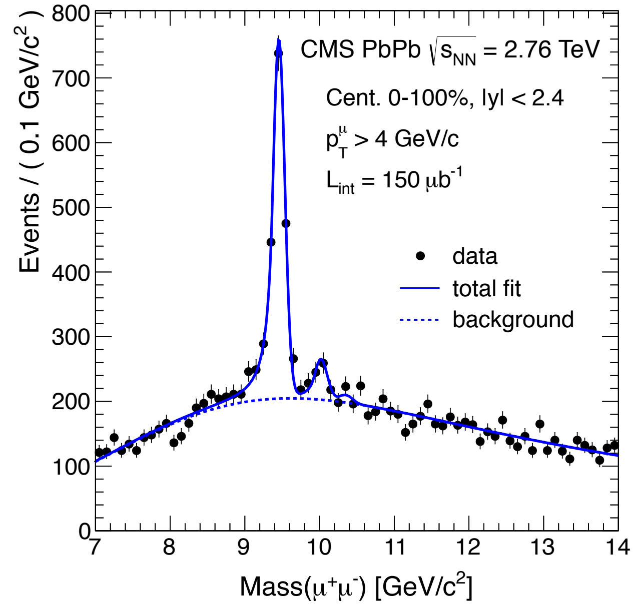
A weakly coupled quarkonium possibly produced in a weakly coupled plasma is the bottomonium ground state $\Upsilon(1S)$ produced in heavy-ion experiments at the LHC:

$$M_b \approx 5 \text{ GeV} > M_b\alpha_s \approx 1.5 \text{ GeV} > \pi T \approx 1 \text{ GeV} > M_b\alpha_s^2 \approx 0.5 \text{ GeV} \sim m_D \gtrsim \Lambda_{QCD}$$

◦ Brambilla Escobedo Ghiglieri Soto Vairo JHEP 1009 (2010) 038
Vairo AIP CP 1317 (2011) 241

Υ suppression at CMS

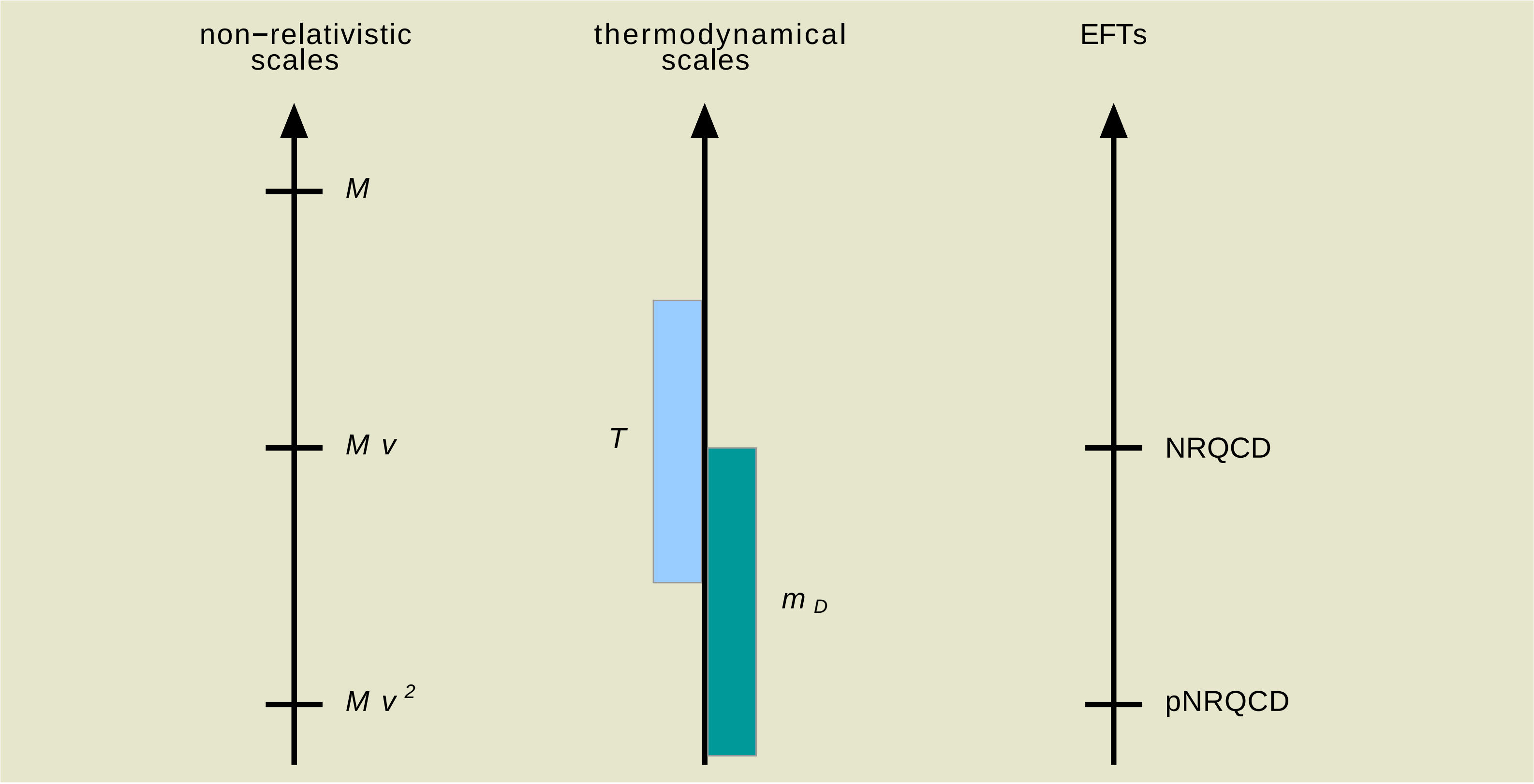




- CMS PRL 109 (2012) 222301

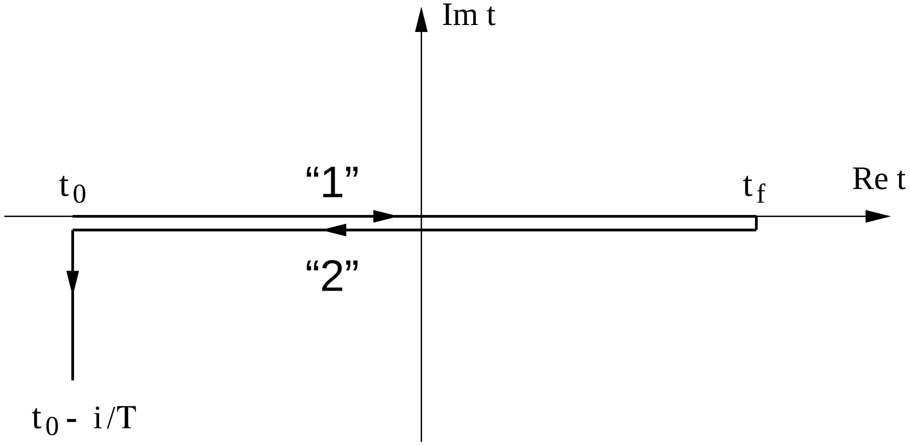
Non-relativistic EFTs of QCD

The existence of a hierarchy of energy scales calls for a description of the system (quarkonium at rest in a thermal bath) in terms of a hierarchy of EFTs.



Real-time formalism

Temperature is introduced via the partition function.
Sometimes it is useful to work in the real-time formalism.



In real time, the degrees of freedom double ("1" and "2"), however, the advantages are

- the framework becomes very close to the one for $T = 0$ EFTs;
- in the heavy-particle sector, the second degrees of freedom, labeled "2", decouple from the physical degrees of freedom, labeled "1".

This usually leads to a simpler treatment with respect to alternative calculations in imaginary time formalism.

Real-time gauge boson propagator

- Gauge boson propagator (in Coulomb gauge):

$$\mathbf{D}^{(0)}_{00}(\vec{k}) = \frac{i}{\vec{k}^2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{D}^{(0)}_{ij}(k) = \left(\delta_{ij} - \frac{k^i k^j}{\vec{k}^2}\right)\left\{\begin{pmatrix} \dfrac{i}{k^2 + i\epsilon} & \theta(-k^0)\, 2\pi\delta(k^2) \\ \theta(k^0)\, 2\pi\delta(k^2) & -\dfrac{i}{k^2 - i\epsilon} \end{pmatrix} + 2\pi\delta(k^2)\, n_{\mathrm{B}}(|k^0|) \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}\right\}$$

where

$$n_{\mathrm{B}}(k^0) = \frac{1}{e^{k^0/T} - 1}$$

Real-time heavy-particle propagator

- The free heavy-particle propagator is proportional to

$$\mathbf{S}^{(0)}(p) = \begin{pmatrix} \dfrac{i}{p^0 + i\epsilon} & 0 \\ 2\pi\delta(p^0) & \dfrac{-i}{p^0 - i\epsilon} \end{pmatrix}$$

Since $[\mathbf{S}^{(0)}(p)]_{12} = 0$, the static quark fields labeled "2" never enter in any physical amplitude, i.e. any amplitude that has the physical fields, labeled "1", as initial and final states.

These properties hold also for interacting heavy particle(s): interactions do not change the nature ("1" or "2") of the interacting fields.

◦ Brambilla Ghiglieri Vairo Petreczky PRD 78 (2008) 014017

Dissociation mechanisms at LO

A key quantity for describing the observed quarkonium dilepton signal suppression is the quarkonium thermal dissociation width.

Two distinct dissociation mechanisms may be identified at leading order:

- gluodissociation,
  which is the dominant mechanism for $Mv^2 \gg m_D$;
- dissociation by inelastic parton scattering,
  which is the dominant mechanism for $Mv^2 \ll m_D$.

Beyond leading order the two mechanisms are intertwined and distinguishing between them becomes unphysical, whereas the physical quantity is the total decay width.

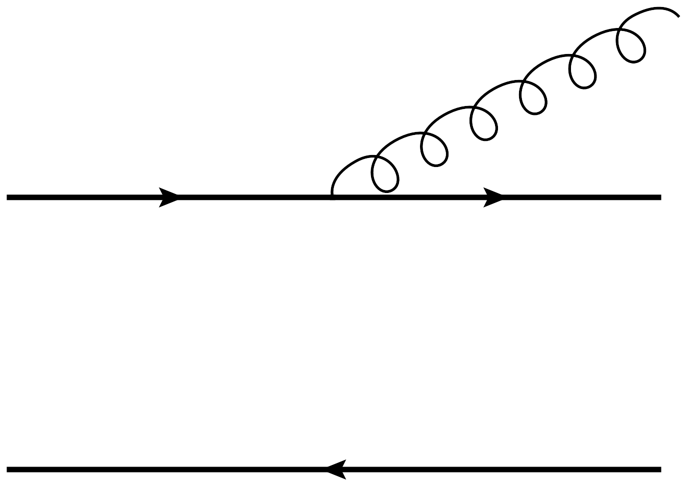
Gluodissociation

based on

- Brambilla Escobedo Ghiglieri Vairo JHEP 1112 (2011) 116

Gluodissociation

Gluodissociation is the dissociation of quarkonium by absorption of a gluon from the medium.

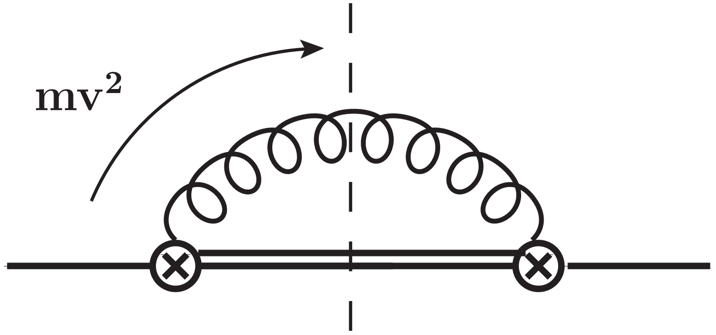


- The exchanged gluon is lightlike or timelike.
- The process happens when the gluon has an energy of order Mv^2.

○ Kharzeev Satz PLB 334 (1994) 155
Xu Kharzeev Satz Wang PRC 53 (1996) 3051

Gludissociation

From the optical theorem, the gludissociation width follows from cutting the gluon propagator in the following pNRQCD diagram



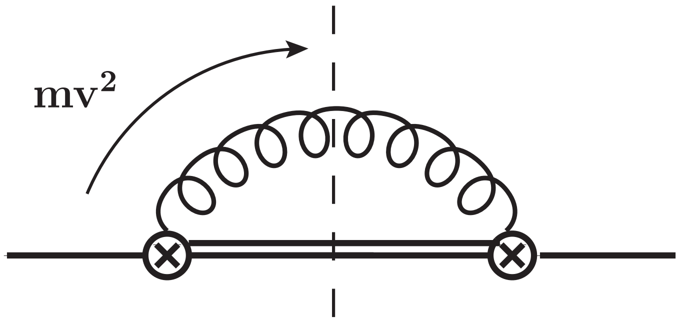
For a quarkonium at rest with respect to the medium, the width has the form

$$\Gamma_{nl} = \int_{q_{\min}} \frac{d^3q}{(2\pi)^3} \, n_{\rm B}(q) \, \sigma^{nl}_{\rm gluo}(q) \, .$$

- $\sigma^{nl}_{\rm gluo}$ is the in-vacuum cross section $(Q\overline{Q})_{nl} + g \to Q + \overline{Q}$.
- Gludissociation is also known as singlet-to-octet break up.

○ Brambilla Ghiglieri Vairo Petreczky PRD 78 (2008) 014017

$1S$ gluodissociation at LO



The LO gluodissociation cross section for $1S$ Coulombic states is

$$\sigma^{1S}_{\text{gluo LO}}(q) = \frac{\alpha_s C_F}{3} 2^{10}\pi^2 \rho(\rho+2)^2 \frac{E_1^4}{Mq^5}\left(t(q)^2+\rho^2\right) \frac{\exp\left(\frac{4\rho}{t(q)}\arctan\left(t(q)\right)\right)}{e^{\frac{2\pi\rho}{t(q)}}-1}$$

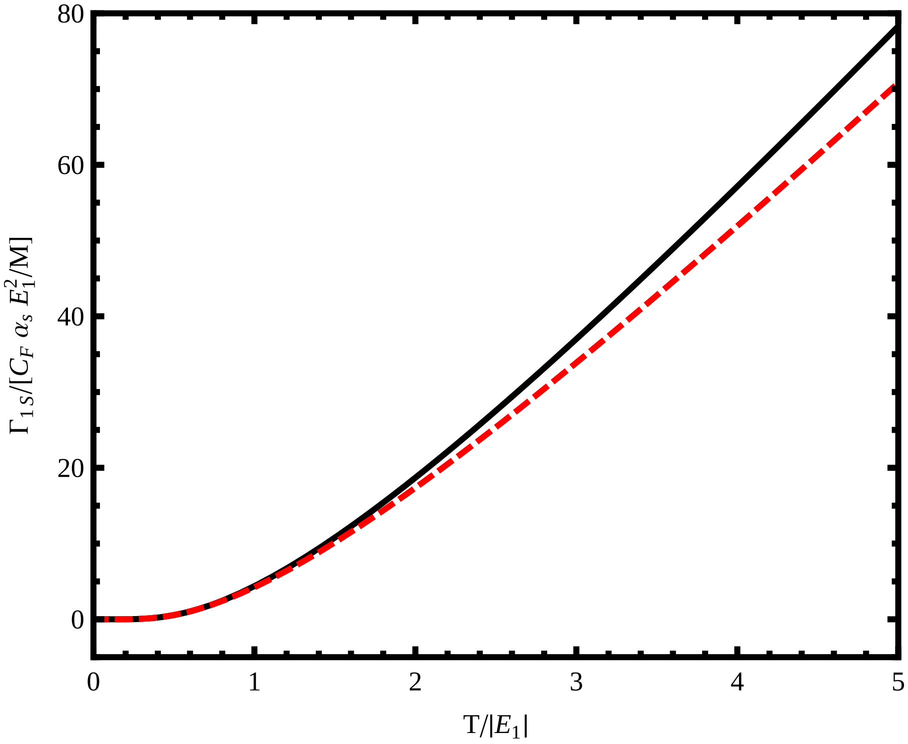
where $\rho \equiv 1/(N_c^2-1)$, $t(q) \equiv \sqrt{q/|E_1|-1}$ and $E_1 = -MC_F^2\alpha_s^2/4$.

- `Brambilla Escobedo Ghiglieri Vairo JHEP 1112 (2011) 116`
  `Brezinski Wolschin PLB 707 (2012) 534`

The Bhanot–Peskin approximation corresponds to the large N_c limit, i.e. to neglecting final state interactions (the rescattering of a $Q\overline{Q}$ pair in a color octet configuration).

- `Peskin NPB 156 (1979) 365, Bhanot Peskin NPB 156 (1979) 391`

Gluodissociation width vs Bhanot–Peskin width



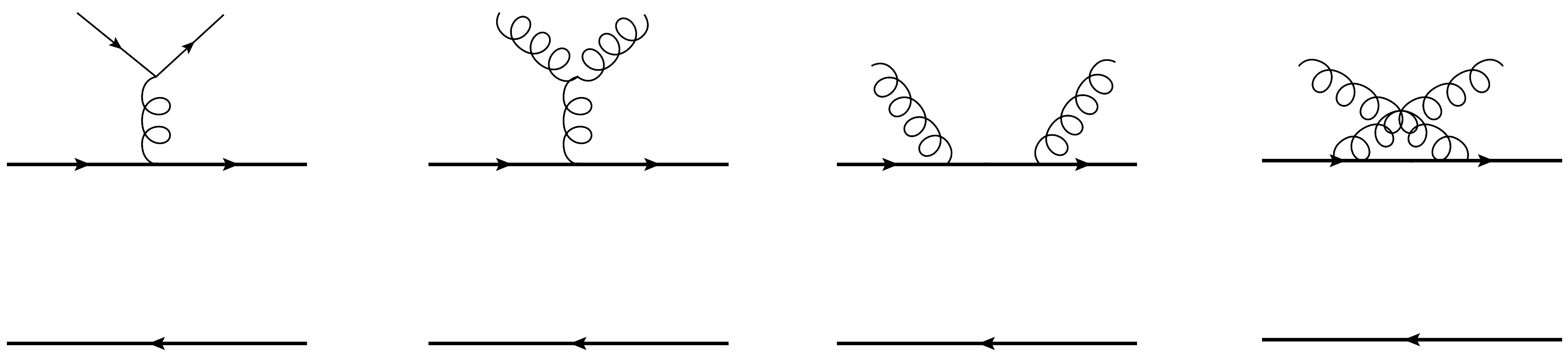
Dissociation by inelastic parton scattering

based on

- Brambilla Escobedo Ghiglieri Vairo JHEP 05 (2013) 130

Dissociation by inelastic parton scattering

Dissociation by inelastic parton scattering is the dissociation of quarkonium by scattering with gluons and light-quarks in the medium.



○ Grandchamp Rapp PLB 523 (2001) 60, NPA 709 (2002) 415

- The exchanged gluon is spacelike.
- External thermal gluons are transverse.
- In the NRQCD power counting, each external transverse gluon is suppressed by T/M.

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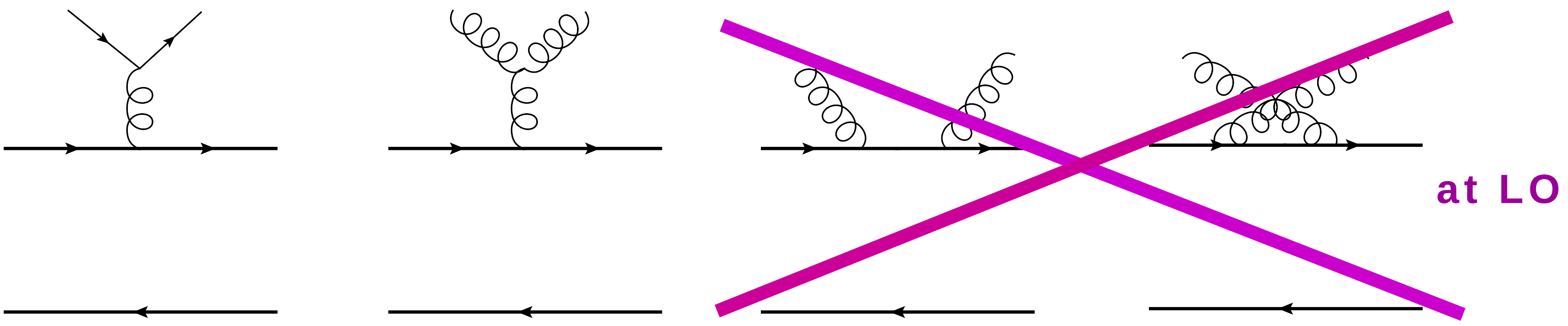

○ `Grandchamp Rapp PLB 523 (2001) 60, NPA 709 (2002) 415`

- The exchanged gluon is spacelike.
- External thermal gluons are transverse.
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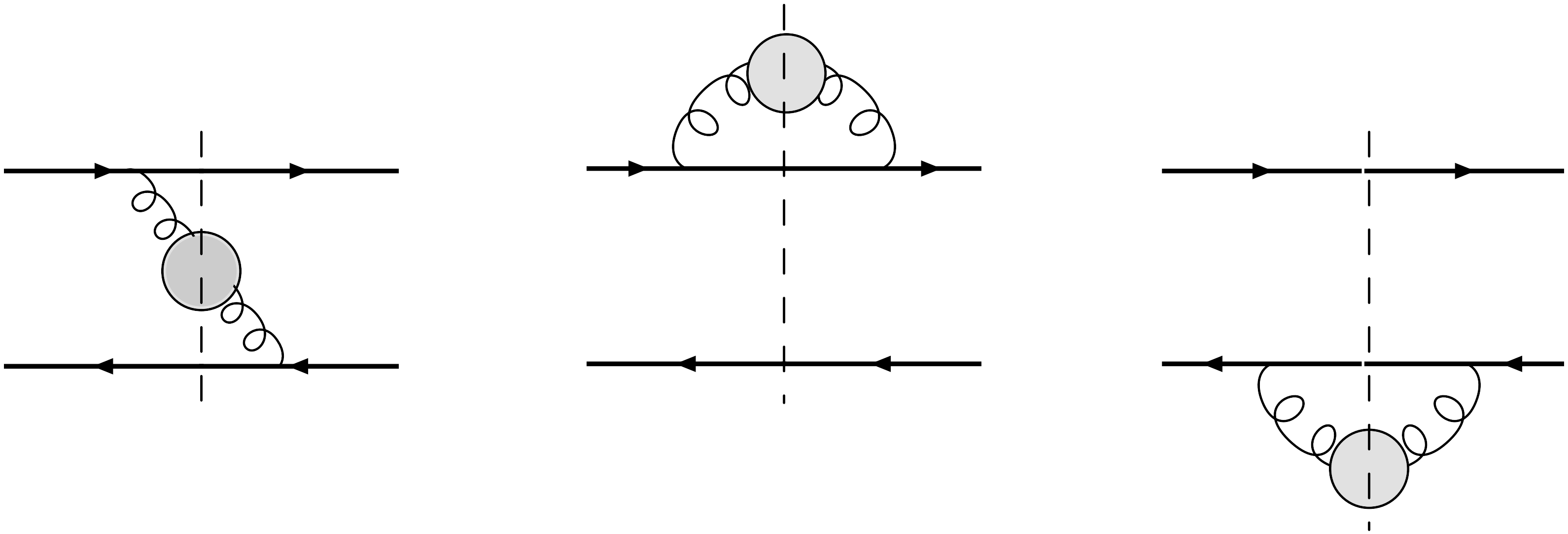
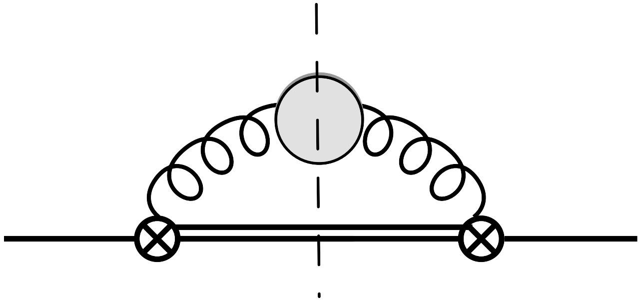
Dissociation by inelastic parton scattering

From the optical theorem, the thermal width follows from cutting the gluon self-energy in the following NRQCD diagrams (momentum of the gluon $\gtrsim Mv$)



and/or pNRQCD diagram (momentum of the gluon $\ll Mv$)



- Dissociation by inelastic parton scattering is also known as Landau damping.

Dissociation by inelastic parton scattering

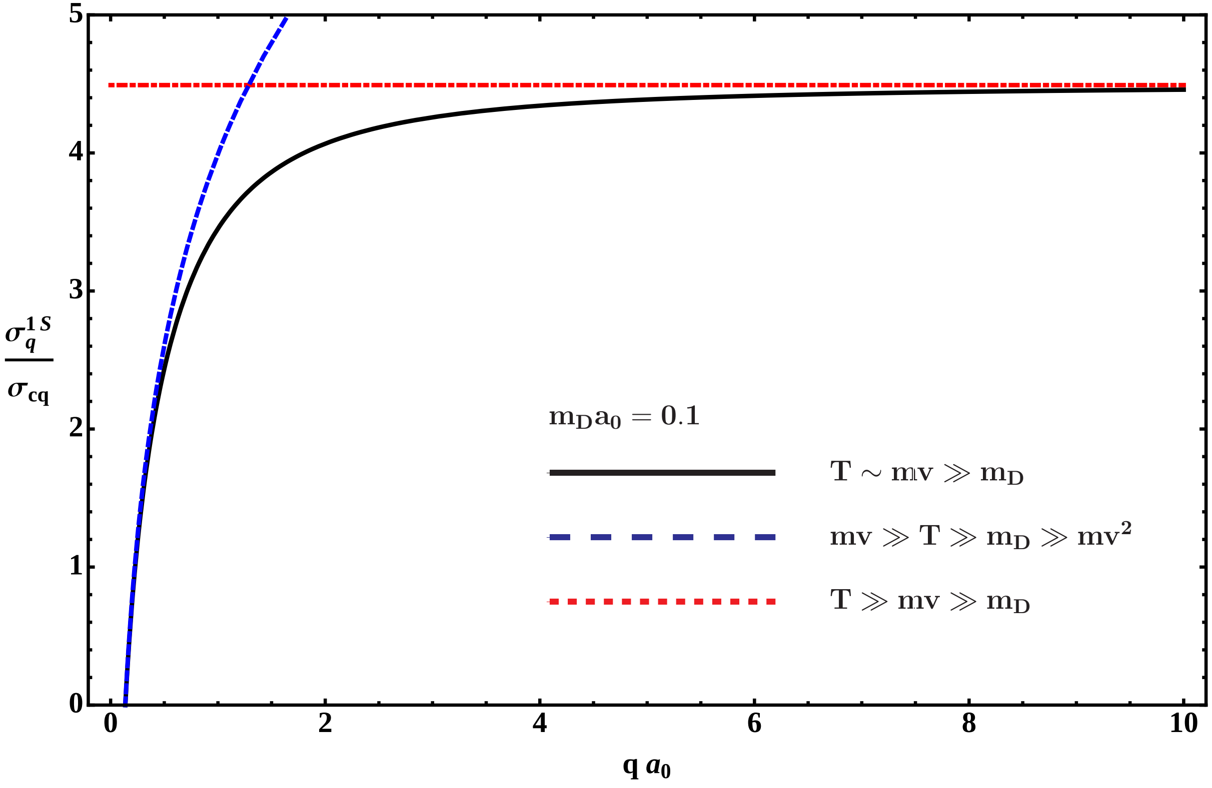
For a quarkonium at rest with respect to the medium, the thermal width has the form

$$\Gamma_{nl} = \sum_p \int_{q_{\min}} \frac{d^3q}{(2\pi)^3}\, f_p(q)\, [1 \pm f_p(q)]\, \sigma_p^{nl}(q)$$

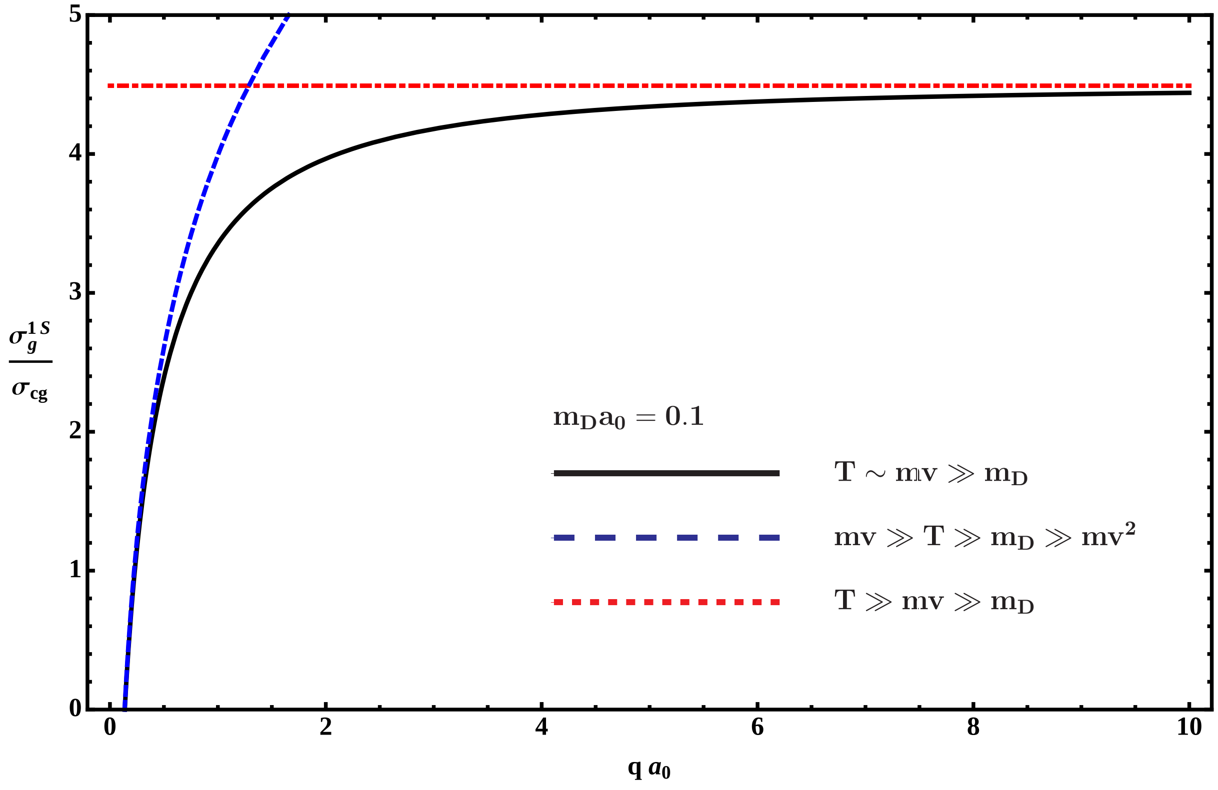
where the sum runs over the different incoming light partons and $f_g = n_{\rm B}$ or $f_q = n_{\rm F}$.

- σ_p^{nl} is the in-medium cross section $(Q\overline{Q})_{nl} + p \to Q + \overline{Q} + p$.
- The convolution formula correctly accounts for Pauli blocking in the fermionic case (minus sign).
- The formula differs from the gluodissociation formula.
- The formula differs from the one used for long in the literature, which has been inspired by the gluodissociation formula.
  - `Grandchamp Rapp PLB 523 (2001)`
    `Park Kim Song Lee Wong PRC 76 (2007) 044907, ...`

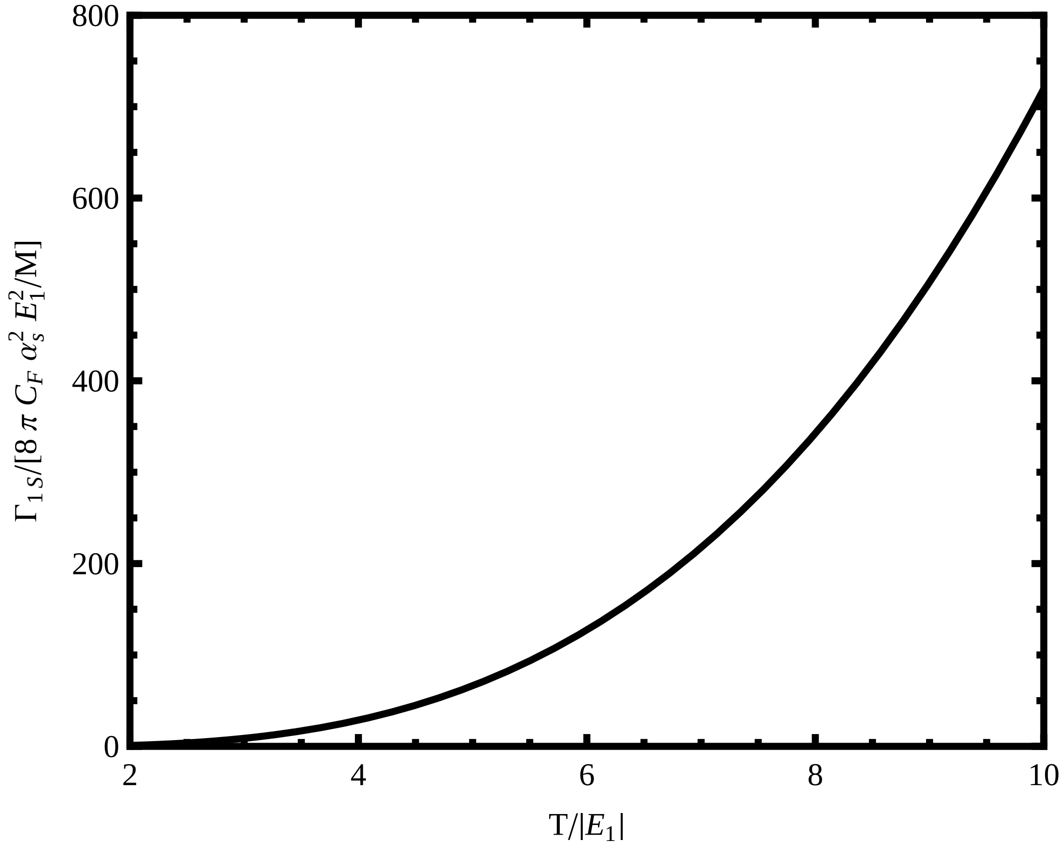
Dissociation by quark inelastic scattering



Dissociation by gluon inelastic scattering



Dissociation width



$m_D a_0 = 0.5$

$|E_1|/m_D = 0.5$

$n_f = 3$

- Vairo EPJ Web Conf 71 (2014) 00135

Quarkonium in a fireball

based on

- Brambilla Escobedo Soto Vairo, in preparation

Quarkonium in a fireball

- After the heavy-ion collisions, quarkonium propagates freely up to 0.6 fm.
- From 0.6 fm to the freeze-out time t it propagates in the medium.
- We assume the medium infinite, homogeneous, isotropic and in thermal equilibrium.
- The temperature T of the medium changes with time:

$$T = T_0 \left(\frac{t_0}{t}\right)^{v_s^2}, \quad t_0 = 0.6 \text{ fm}, \ v_s^2 = \frac{1}{3} \text{ (sound velocity)}$$

  ◦ Bjorken PRD 27 (1983) 140

  The initial temperature T_0 may account for different centralities

centrality (%)	$\langle b \rangle$ (fm)	T_0 (MeV) @ LHC
$0 - 10$	3.4	471
$10 - 20$	6.0	461
$20 - 30$	7.8	449
$30 - 50$	9.9	425
$50 - 100$	13.6	304

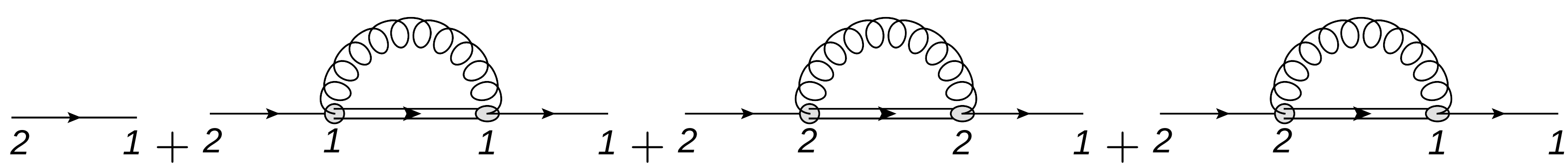
- We assume the heavy quarks comoving with the medium.

Quarkonium evolution equations

Quarkonium is not in equilibrium, as it can be created (in a color singlet state) or dissociated (in a color octet state) through emission of gluons. The singlet and octet density matrices can be defined in the close-time path formalism:

$$\rho_s(t_1, t_2) = \langle \mathcal{P} S_1(t_1) S_2^\dagger(t_2) \rangle \,, \quad \rho_o(t_1, t_2) = \langle \mathcal{P} O_1^a(t_1) O_2^{a\,\dagger}(t_2) \rangle$$

By resumming self-energy contributions,



they satisfy the evolution equations

$$\frac{d\rho_s(t;t)}{dt} = -ih_{s,eff}(t)\rho_s(t;t) + i\rho_s(t;t)h^\dagger_{s,eff}(t) + \mathcal{F}(\rho_o, t)$$
$$\frac{d\rho_o(t;t)}{dt} = -h_{o,eff}(t)\rho_o(t;t) + i\rho_o(t;t)h^\dagger_{o,eff}(t) + \mathcal{F}_1(\rho_s, t) + \mathcal{F}_2(\rho_o, t)$$

Lindblad equations

If $(1/T)\,dT/dt \ll E$ the evolution equations can be written in the Lindblad form

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_i (C_i \rho C_i^\dagger - \frac{1}{2}\{C_i^\dagger C_i, \rho\})$$

$$\rho = \begin{pmatrix} \rho_s & 0 \\ 0 & \rho_o \end{pmatrix}$$

$$C_i^0 = \sqrt{\frac{4T_F \alpha_s(\nu) T}{3N_c}} \left(\frac{2ip_i}{M_b} + \frac{N_c \alpha_s(1/a_o) r_i}{2N_c r}\right) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix},\ E \gg m_D$$

$$C_i^1 = \sqrt{\frac{4C_F \alpha_s(\nu) T}{3}} \left(-\frac{2ip_i}{M_b} + \frac{N_c \alpha_s(1/a_o) r_i}{2N_c r}\right) \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix},\ E \gg m_D$$

$$C_i^2 = \frac{2}{M_b} \sqrt{\frac{(N_c^2 - 4)\alpha_s(\nu) T}{N_c}}\, p_i \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix},\ E \gg m_D$$

H is an effective Hermitian Hamiltonian and C's are called collapse operators.

○ Akamatsu PRD 91 (2015) 056002

Initial conditions

The production of singlets is α_s suppressed compared to that of octets.

- Cho Leibovich PRD 53 (1996) 6203

Our choice at $t = 0$ is

$$\rho_s = A|\mathbf{0}\rangle\langle\mathbf{0}|, \qquad \rho_o = \frac{\delta}{\alpha_s(M_b)}\rho_s$$

A is fixed by $\mathrm{Tr}(\rho_s) + \mathrm{Tr}(\rho_o) = 1$

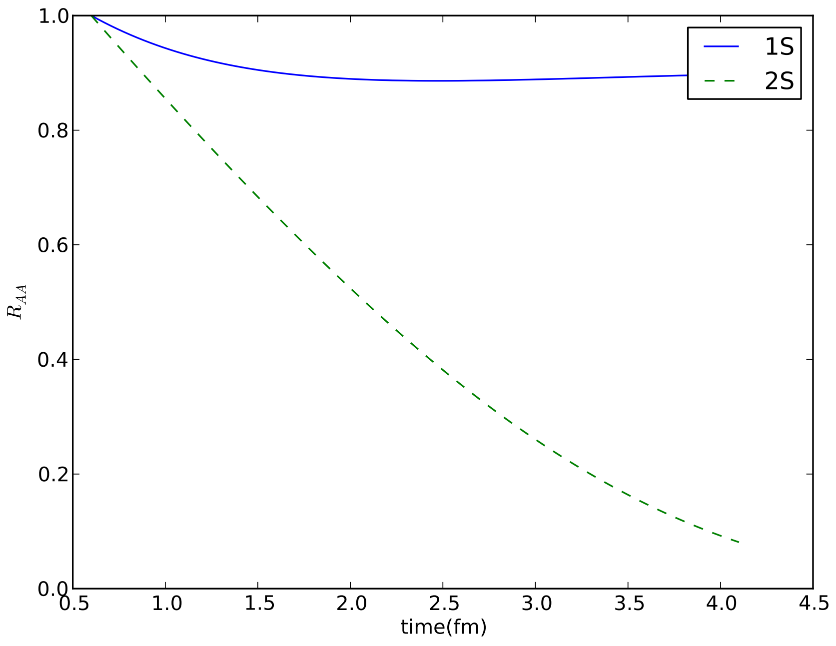
δ fixes the octet fraction with respect to the singlet: $\delta = 1, 0.1, 10$.

Dilepton suppression rate

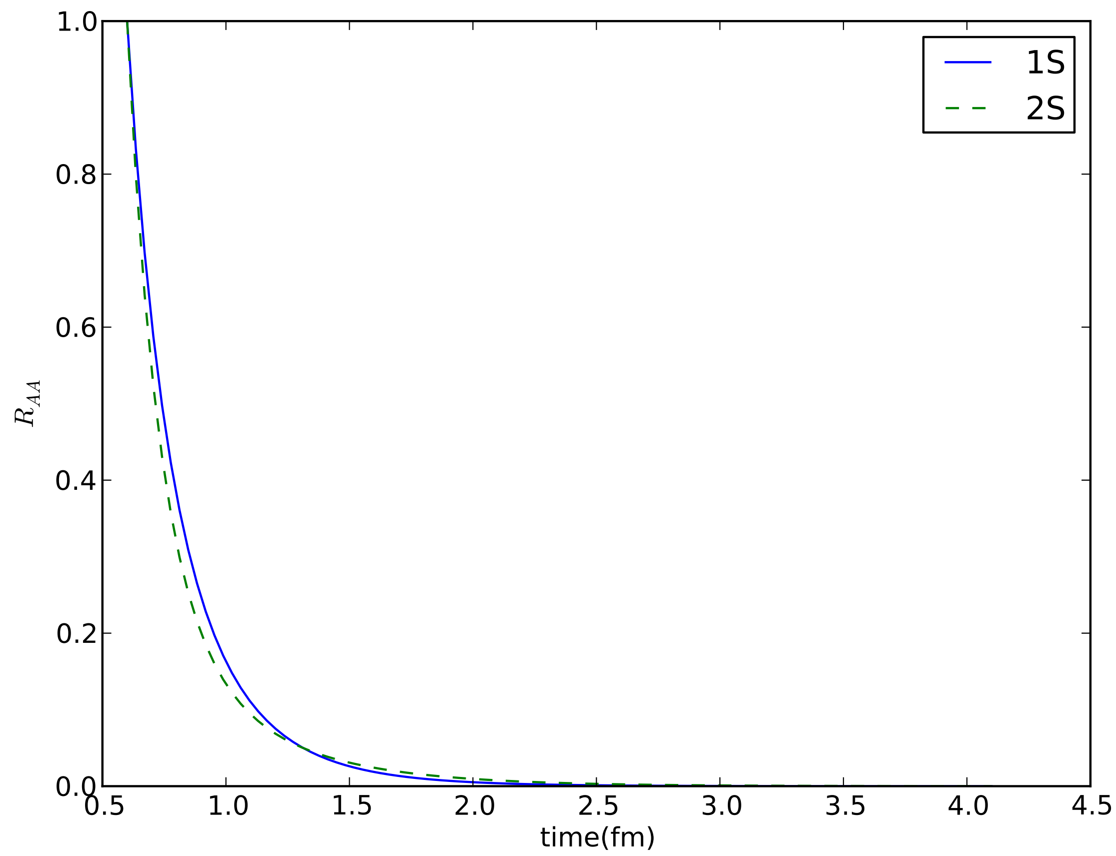
We compute the dilepton suppression rate R_{AA}:

$$R_{AA} \sim \frac{\rho_S|_{1S\,1S}^{AA}}{\rho_S|_{1S\,1S}^{pp}}$$

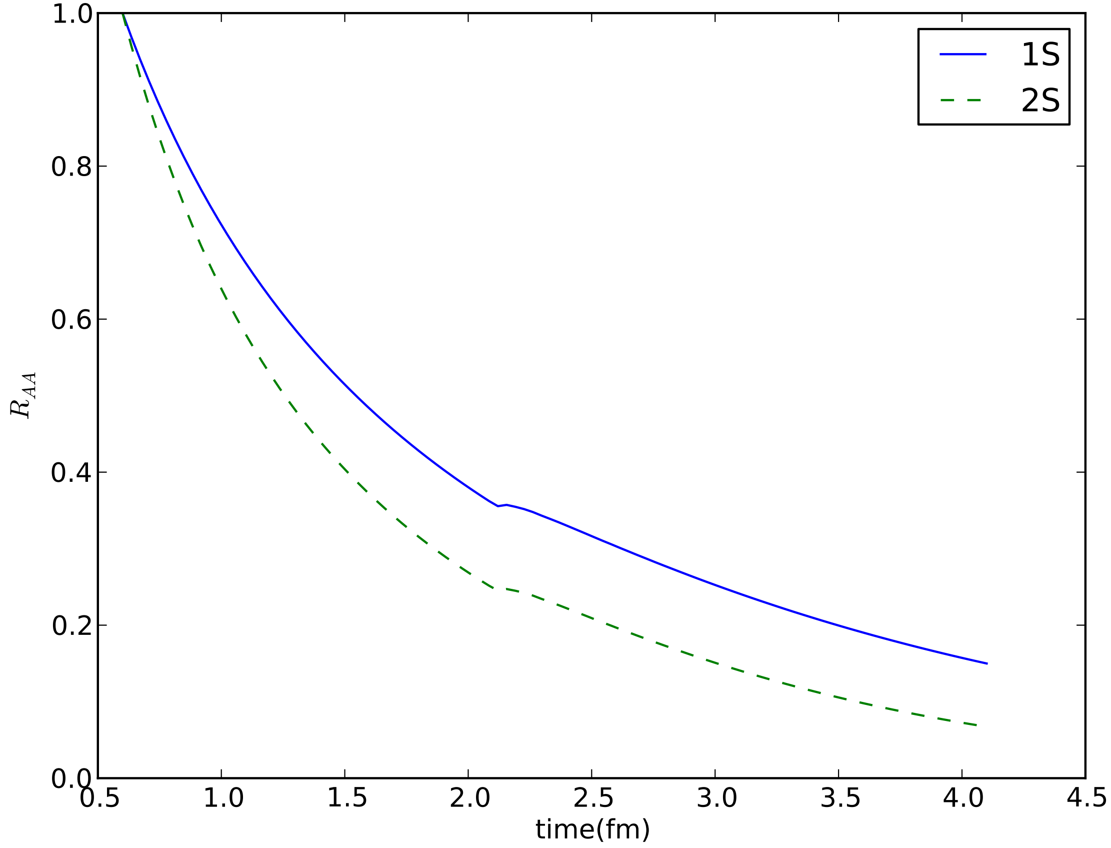
If R_{AA} is due only to screening for $M_b\alpha_s \gg T \gg m_D \gg E$, then



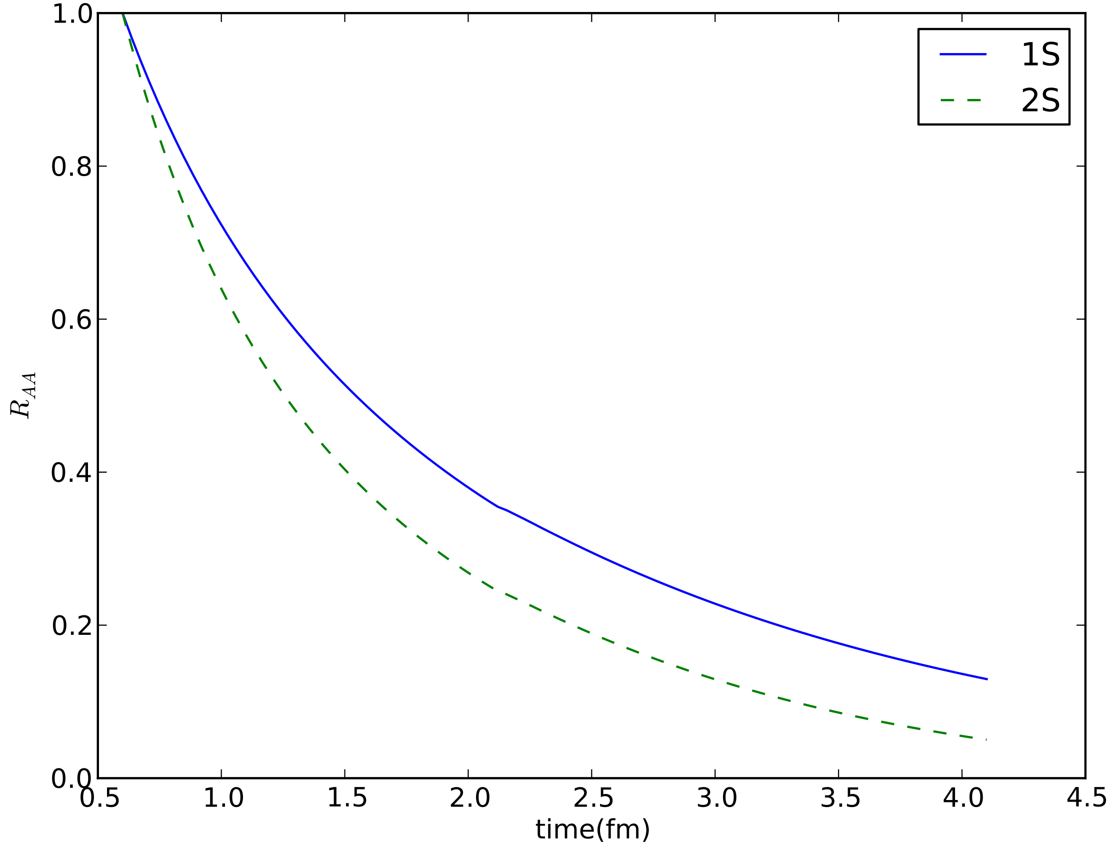
R_{AA} for $M_b\alpha_s \gg T \gg E \gg m_D$, $\delta = 1$ and $\nu = 372$ MeV



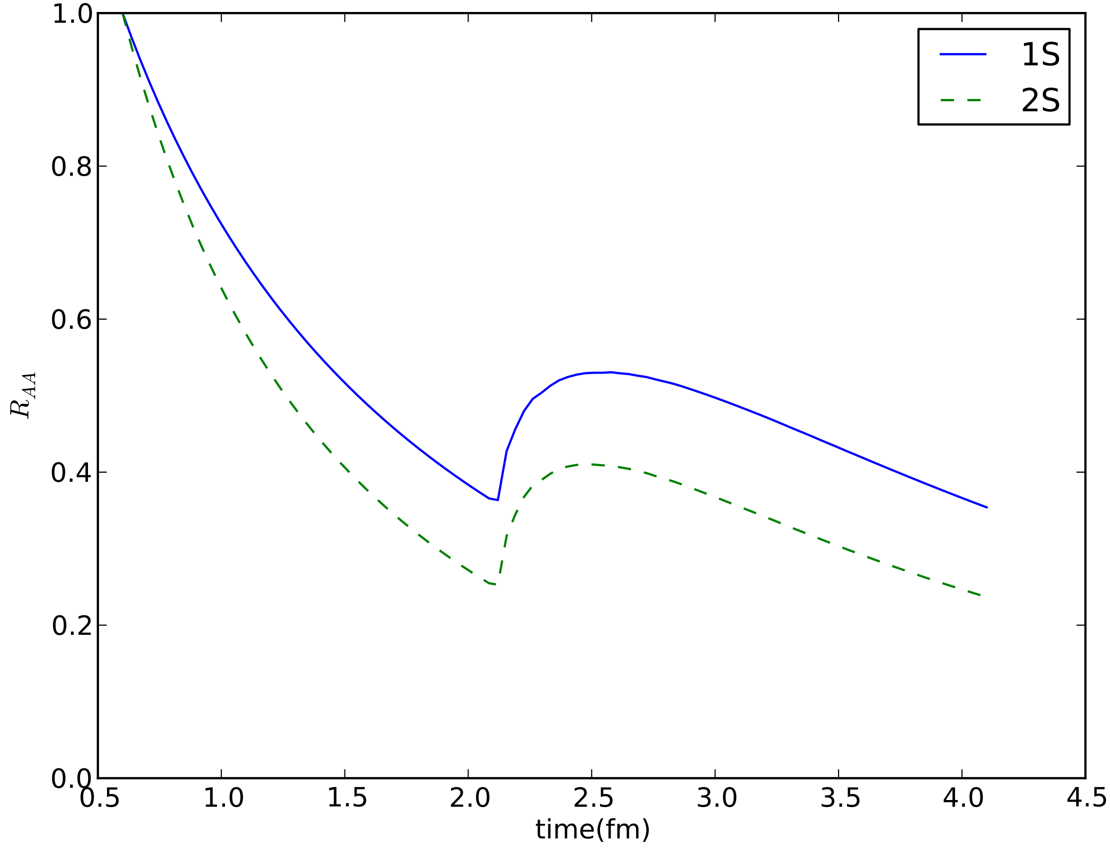
R_{AA} for $M_b\alpha_s \gg T \gg E \gg m_D$, $\delta = 1$ and $\nu = 2\pi T$



R_{AA} for $M_b\alpha_s \gg T \gg E \gg m_D$, $\delta = 0.1$ and $\nu = 2\pi T$



R_{AA} for $M_b\alpha_s \gg T \gg E \gg m_D$, $\delta = 10$ and $\nu = 2\pi T$



Conclusions

In a framework that makes close contact with modern effective field theories for non relativistic bound states at zero temperature, one can study the dissociation of a quarkonium in a thermal bath of gluons and light quarks.

In a weakly-coupled framework, the situation is the following.

- For $E > m_D$ quarkonium decays dominantly via gluodissociation (aka singlet-to-octet break up).
- For $m_D > E$ quarkonium decays dominantly via inelastic parton scattering (aka Landau damping).

In the same framework we have studied dissociation and ricombination of quarkonium out of thermal equilibrium.

- The results depends stronly on the initial conditions and on the renormalization scale.
- Under some reasonable choice of parameters it may come close to the experimental findings.