

Heavy quarks in a medium

Miguel A. Escobedo

Instituto Galego de Física de Altas Enerxías

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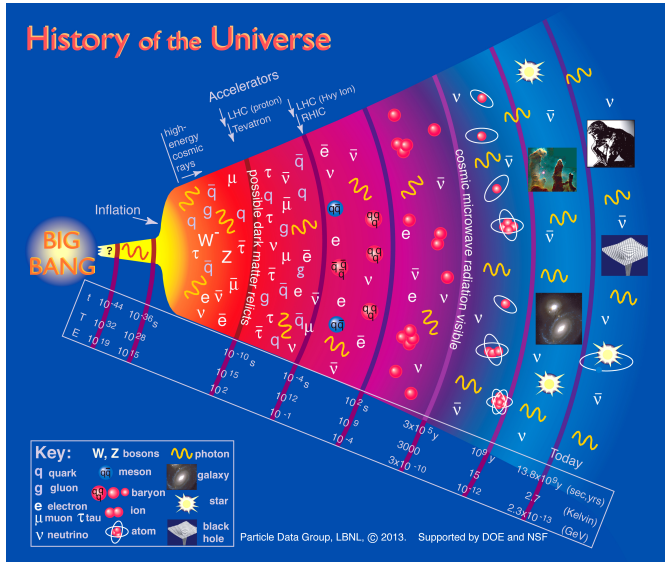


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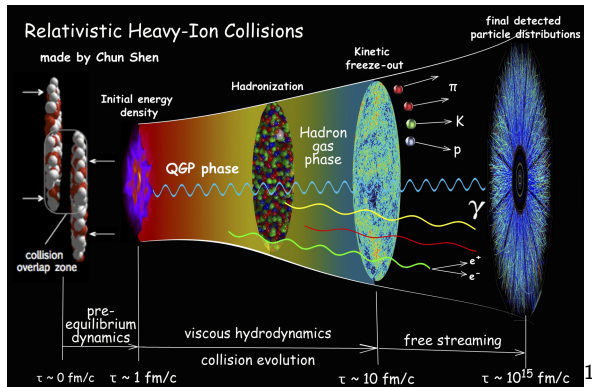
Plan

- 1 Introduction
- 2 Heavy quark diffusion
- 3 Quarkonium in thermal equilibrium
- 4 Open quantum system approach to quarkonium suppression
- 5 Conclusions

The big bang and the little bangs



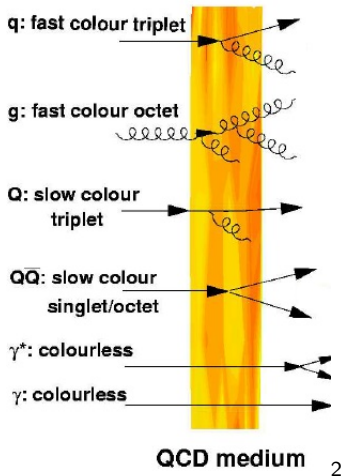
The big bang and the little bangs



- The quark-gluon plasma can be created in relativistic heavy-ion collisions.
- However, we do not directly measure the plasma. Instead we measure many particles.

¹Picture taken from Shen and Heinz (2015)

Hard probes



Probes that are created at the beginning of the collision (typically because its creation needs a high energy) that get modified in a substantial way and that are relatively easy to detect. In this talk we focus in the ones related with heavy quarks

- Heavy quark diffusion.
- Quarkonium suppression.

²Picture taken from d'Enterria (2007)

Probing the medium with heavy quarks

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- In the case of quarkonium, other energy scales appear. The inverse of the typical radius $\frac{1}{r}$ and the binding energy E .
- Using heavy quarks we can test the properties of the medium at different energy scales.

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Several theoretical approaches are used to describe these phenomena. For example, Langevin eq., Boltzmann eq., Fokker-Planck... A recent review can be found in Cao et al. (2018).

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- Phenomena of colour screening, quantities measurable in Lattice QCD at finite temperature (static) show this behaviour. For example Polyakov loop.

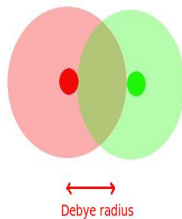
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- Quarkonium is quite stable in the vacuum.
- Phenomena of colour screening, quantities measurable in Lattice QCD at finite temperature (static) show this behaviour. For example Polyakov loop.
- Dissociation of heavy quarkonium in heavy-ion collisions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

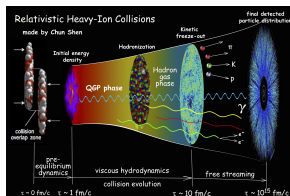
Colour screening

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

At finite temperature

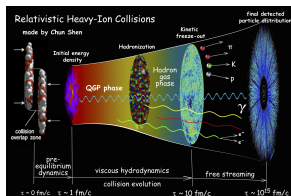


Colour screening in heavy-ion collisions



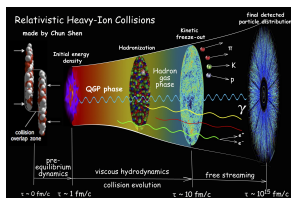
- A quark-antiquark pair is created at collision time $t = 0$. From the point of view of the scales $\frac{1}{r}$ and E it looks like as its was created in a point.

Colour screening in heavy-ion collisions



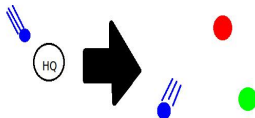
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Colour screening in heavy-ion collisions



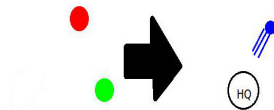
- A quark-antiquark pair is created at collision time $t = 0$. From the point of view of the scales $\frac{1}{r}$ and E it looks like as its was created in a point.
- A medium in which hydrodynamics can be applied around $t = 0.5 fm$.
- When the pair enters the medium, if, due to colour screening, there are no bound state solutions of the Schrödinger equation then the heavy quarks will get away from each other and they can not form a bound state.

Another mechanism, collisions



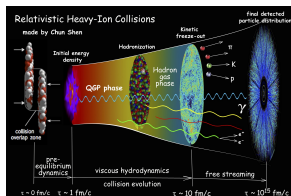
A singlet can decay into an octet. Interaction with the medium changes the color state. **Dissociation without screening**. This is the mechanism behind the imaginary part of the potential (First found by Laine et al. (2007)). This is related to singlet to octet transitions, Brambilla et al. (2008).

Recombination



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

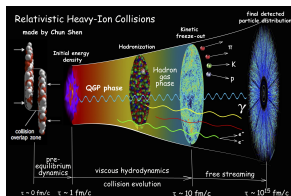
Heavy quarkonium in a heavy-ion collision



A heavy quark pair in a singlet state enters the medium.

- It can happen that a bound state can not be form simply because there are no bound state solutions of the Schrödinger equation.

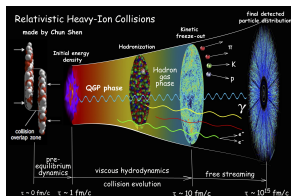
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- It can happen that a bound state can not be form simply because there are no bound state solutions of the Schrödinger equation.
- It can also happen that a bound state can be form. However, it has a chance of decaying into an octet, that can not form a bound state.
- After they have melted, one heavy quark can recombine with an antiquark to form a new bound state. This antiquark can originally come from another pair. Important effect for charmonium.

The use of Effective Field Theories to study heavy quarks

Reminder

- The mass of a heavy quark m is much bigger than Λ_{QCD} . The production or annihilation of heavy quarks is a perturbative process.
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Effective Field Theories

The appearance of different and very separated energy scales in a system can be a problem.

- Breaking of naive perturbation theory.
- All the relevant scales need to fit in the lattice. Large lattices, small lattice step.

This can be solved using EFTs.

Integrating out the heavy quark mass

- Integrating out the scale m can be useful both to study heavy quark diffusion and quarkonium suppression.
- This step can always be done perturbatively and is not affected by the presence of the medium. $m \gg \Lambda_{QCD}, T$.

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Remark

An EFT is not only determined by its Lagrangian. The power counting is also crucial. There are EFTs that are considered to be different but have the same Lagrangian.

- Non-relativistic QCD (NRQCD)^a. Suitable to study quarkonium.
 $p \sim \frac{1}{r}$.
- Heavy quark effective theory (HQET)^b. Suitable to study heavy-light mesons. $p \sim \Lambda_{QCD}$

^aCaswell and Lepage (1986), Bodwin, Braaten and Lepage (1994)

^bEichten and Hill (1990)

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

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

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

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

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

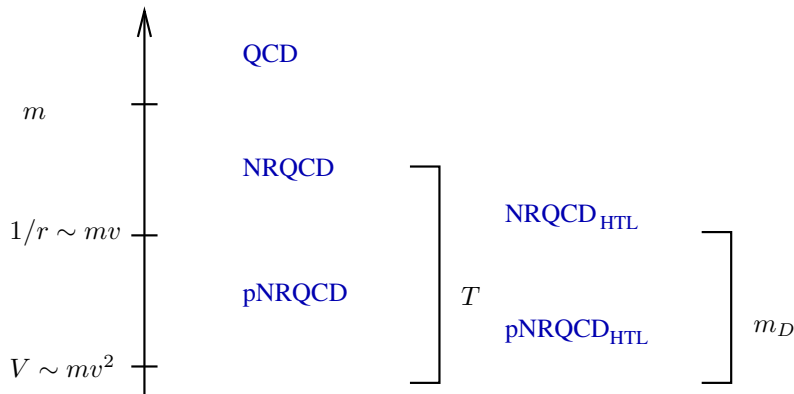
potential NRQCD Lagrangian at $T=0$

pNRQCD (Brambilla, Pineda, Soto and Vairo, NPB566 (2000) 275).
Starting from NRQCD and integrating out the scale $\frac{1}{r}$.

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

- 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.

EFTs to study quarkonium in a medium



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

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Heavy quark diffusion

Heavy quarks will diffuse in space in the presence of a medium. This can be quantified by the parameter D_s

$$\langle x^2(t) \rangle = 6D_s t$$

This can be related with the transport coefficient related with diffusion in momentum space

$$\kappa = \frac{2T^2}{D_s}.$$

³Picture taken from X. Dong talk in CIPANP 2018

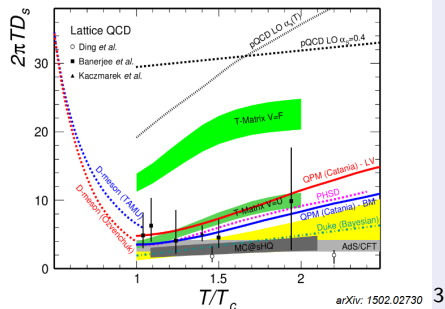
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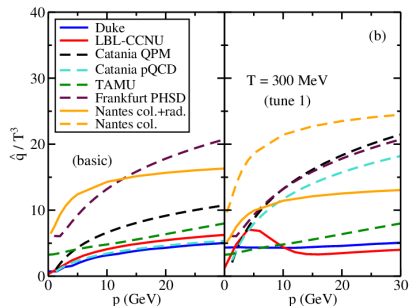


³Picture taken from X. Dong talk in CIPANP 2018

Heavy quark diffusion in different models

In Cao et al. (2018) a comparison of the transport coefficient \hat{q} ($\hat{q} = 2\kappa$) obtained using different models to fit experimental data is reported.

Very different theoretical descriptions are used (Boltzmann, Langevin, Fokker-Planck...) but the underlying physical mechanism is similar.



Heavy quark diffusion. Non-perturbatively

Langevin equation

$$\frac{dp_i}{dt} = -\eta_D p_i + \xi_i(t)$$

where $\eta_D = \frac{\kappa}{2mT}$ and $\langle \xi_i(t) \xi_j(t') \rangle = \kappa \delta_{ij} \delta(t - t')$.

It can be shown that κ fulfils

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

Can be computed on the lattice

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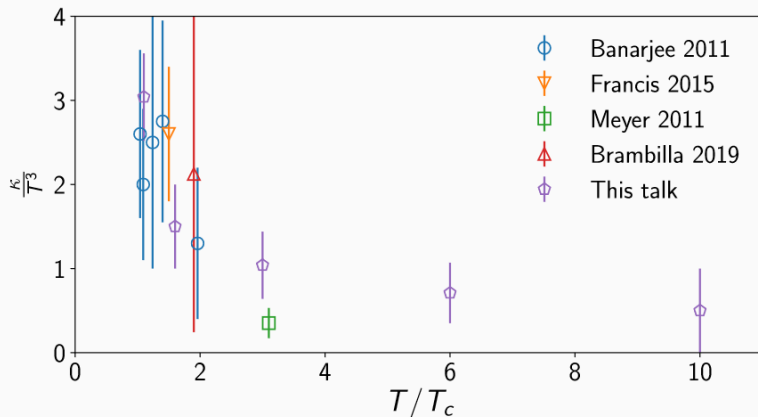
$$\kappa = \frac{g^2}{6 N_c} \text{Re} \int_{-\infty}^{+\infty} ds \langle \text{Tr} E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

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Status

- Most recent published result (quenched) is $\kappa = (1.8 - 3.4) T^3$. (Francis et al. (2015)).
- A new evaluation by the TUM group is in progress (also quenched).

Heavy quark diffusion. Non-perturbatively



- Picture taken from Viljami talk in QWG 2019.
- Preliminary result.
- Indication that $\frac{\kappa}{T^3}$ is not a constant and decreases with the temperature.

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$$\langle TS(t, \mathbf{r}, \mathbf{R}) S^\dagger(0, \mathbf{0}, \mathbf{0}) \rangle$$

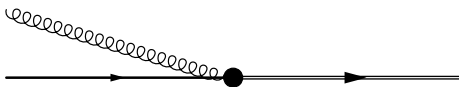
- Tells us about the in-medium dispersion relation. We can obtain binding energy and decay width modifications.
- It can be used to obtain the spectral function. Comparison with Lattice QCD.
- At $T = 0$ it fulfills a Schrödinger equation. At finite temperature this will also be the case in some situations.
- Question: Are there bound states in the medium? \rightarrow Does the time-ordered singlet propagator have bound state poles?
- It does not contain information about the number of bound states in the medium.

What can be learned from the time-ordered correlator?

- Leading order thermal effects can be encoded in a redefinition of the potential if $T, m_D \gg E$.
- In all cases this potential has both a correction in the real part and an imaginary part.
- In the case $T \gg 1/r \sim m_D$ we recover Laine et al. potential.

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

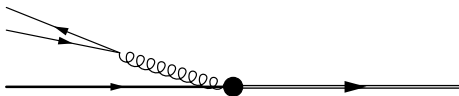
N. Brambilla, M. A. E., J. Ghiglieri, J. Soto and A. Vairo, JHEP 1009 (2010) 038



- Thermal effects are proportional to r^2 because the medium sees the singlet as a small color dipole.
- The process called gluon-dissociation dominates the decay width.
- Both the binding energy and the decay width contain terms that can not be encoded in a potential model.

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

N. Brambilla, M. A. E, J. Ghiglieri and A. Vairo, JHEP 1305 (2013) 130



Inelastic parton scattering, parton + singlet \rightarrow parton + octet.

- Thermal effects are proportional to r^2 because the medium sees the singlet as a small color dipole.
- Inelastic parton scattering dominates the decay width.
- All terms can be encoded in a potential model.

The case $T \gtrsim \frac{1}{r}$

The case $T \sim \frac{1}{r}$

- Potential with both a real and an imaginary part.
- The medium no longer sees the singlet as a color dipole. The potential is not a polynomial of rT .
- In perturbation theory thermal effects are suppressed by an additional α_s .

Case studied in M. A. E and Soto (2010)

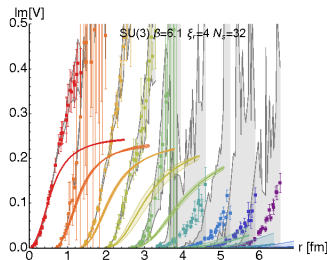
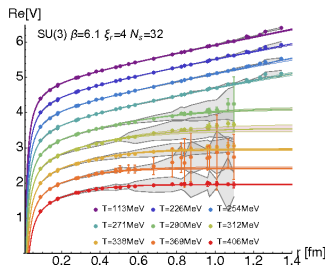
The case $T \gg m_D \sim \frac{1}{r}$

- EFT potential coincides with the one first studied by Laine et al.
- Thermal corrections give a leading order contribution.

Case studied in M. A. E and Soto (2008) and Brambilla, Ghiglieri, Vairo and Petreczky (2008)

The potential and lattice QCD

- In pNRQCD the potential is defined as a Wilson coefficient appearing in the Lagrangian.
- It can be deduced by computing a time-ordered Wilson loop in NRQCD. It can be computed non-perturbatively in lattice QCD.⁴



⁴Plots taken from Burnier and Rothkopf (2016).

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How to compute what we measure?

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

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

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Conclusion

We need to compute the time evolution of $\text{Tr}(S^\dagger(t, \mathbf{x}) S(t, \mathbf{x}') \rho)$ given an initial condition at $t = t_0$.

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Reinterpretation

We can understand $\text{Tr}(S^\dagger(t, \mathbf{x}) S(t, \mathbf{x}') \rho)$ 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.

How to describe quarkonium in a medium?

Potential model approach

$$i\partial_t\Psi = \left(\frac{p^2}{M} + V(r, T)\right)\Psi$$

Only screening:

- Compute whether, at a given temperature, the potential is compatible with the existence of a given bound states.
- Sequential meeting picture.

Including the effect of inelastic collisions:

- Encoded in an imaginary part of the potential.
- Identify the norm of the wave-function with survival probability. Zero at large times?

How to describe quarkonium in a medium?

Transport equation approach

$$\partial_t p^{1S} = f(p^{free}) - \Gamma p^{1S} \sim \Gamma(p_{eq}^{1S} - p^{1S})$$

- At large times it arrives to an equilibrium state.
- All quantum coherence information is lost. Can not fully include screening effects in this way. Quantum mechanics is needed to solve the bound state problem.

How to describe quarkonium in a medium?

Open quantum system approach

$$\partial_t \rho = -i[H, \rho] + \mathcal{D}(\rho)$$

- Quantum version of a transport equation.
- The state is represented by a density matrix.
- Can include in the same equation screening and dissociation by collisions.

Example: The Lindblad equation

Gorini, Kossakowski and Sudarshan (1976), Lindblad (1976)

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

Equation fulfilled by any evolution which:

- Is Markovian (no memory).
- Conserves the trace (sum of all probabilities is equal to 1).
- Is a completely positive map (no negative probabilities).

Setting of the problem

- We study, using pNRQCD, the evolution of a pair of heavy quarks in a colour singlet or colour octet configuration assuming that $\frac{1}{r} \gg T \gg E$. T means here all thermally induced energy scales.

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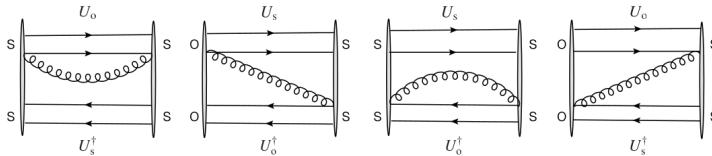
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- The temperature of the medium evolves following Bjorken evolution. Hydrodynamics in the limit of a medium infinite and homogeneous in the transverse direction.

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- The temperature of the medium evolves following Bjorken evolution. Hydrodynamics in the limit of a medium infinite and homogeneous in the transverse direction.
- A heavy quark-antiquark pair is created at the beginning of the collision in a Dirac delta configuration (high energy production process). After that it evolves in the vacuum until a medium is formed at $t_0 = 0.6 fm$.

The evolution of the density matrix

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

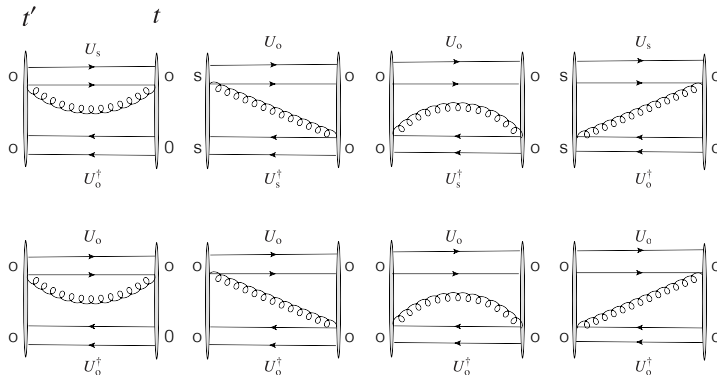


These diagrams represent the evolution of the density matrix

$$\begin{array}{ccc}
 |\psi(t)\rangle & \longrightarrow & |\psi(t+dt)\rangle \\
 \langle\phi(t)| & \longleftarrow & \langle\phi(t+dt)|
 \end{array}$$

The evolution of the density matrix

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



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.

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

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

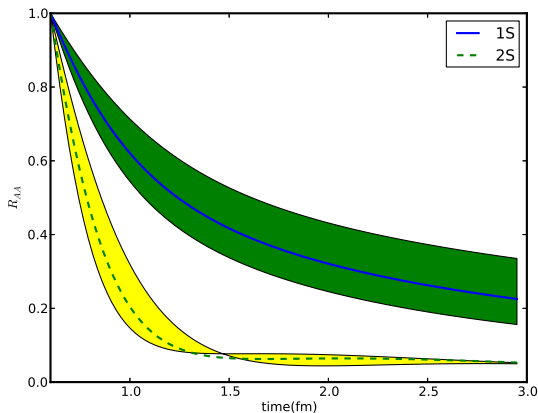
$$\gamma = \frac{g^2}{6 N_c} \text{Im} \int_{-\infty}^{+\infty} ds \langle T E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

No lattice QCD information on γ but we observe that we reproduce data better if it is small. For comparison, in pQCD

$$\gamma = -2\zeta(3) C_F \left(\frac{4}{3} N_c + n_f \right) \alpha_s^2(\mu_T) T^3 \approx -6.3 T^3$$

Results. 30 – 50% centrality. $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

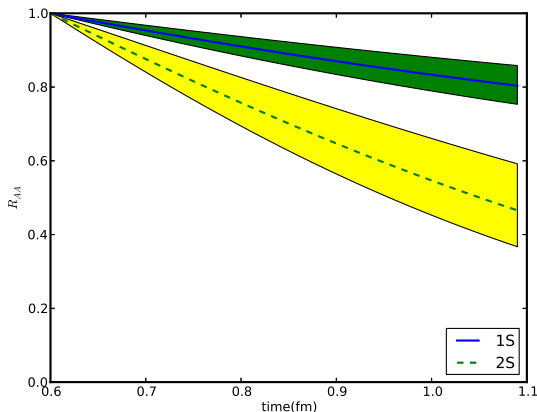
Brambilla, M.A.E., Soto and Vairo. PRD97 (2018) no. 7, 074009



Error bars only take into account uncertainty in the determination of κ . γ is set to zero.

Results. 50 – 100% centrality. $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

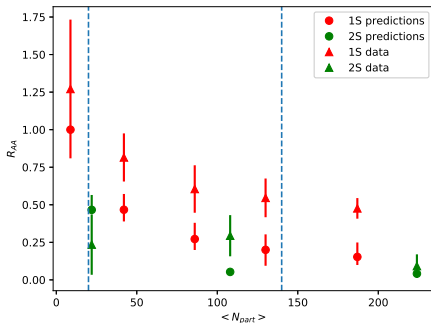
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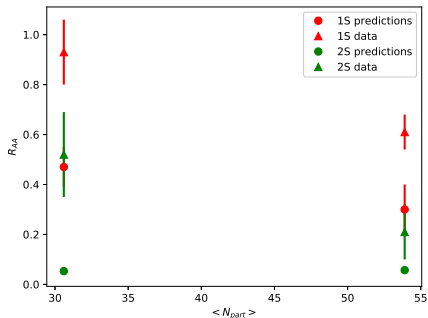
Brambilla, M.A.E., Soto and Vairo (2017-2018)



Comparison between the CMS data⁵ and our computation.

⁵Phys.Lett. B770 (2017) 357-379

Results. $\sqrt{s_{NN}} = 5.02 \text{ TeV}$



6

⁶Data taken from CMS paper (Phys. Lett. B 790, 270-293 (2019))

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Use of lattice data to constraint κ

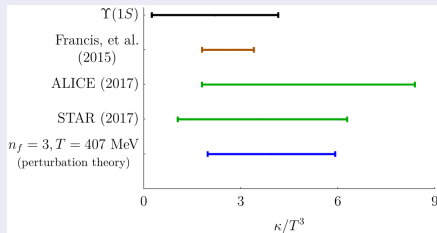
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Picture taken from Brambilla, M.A.E, Vairo and Vander Griend (2019)

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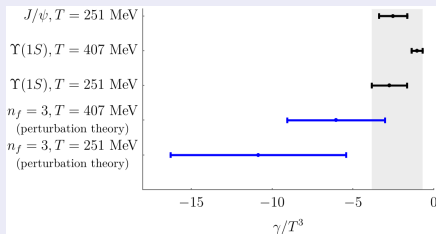
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- Study of the production of entropy and free energy. Blaizot and M.A.E (2018).

Plan

- 1 Introduction
- 2 Heavy quark diffusion
- 3 Quarkonium in thermal equilibrium
- 4 Open quantum system approach to quarkonium suppression
- 5 Conclusions**

- Heavy quarks are a crucial tool to obtain information about the medium created in heavy-ion collisions.
- The combination of EFTs and lattice QCD computations is very useful to study both heavy quark diffusion and quarkonium suppression.
- The transport parameter κ provides a link between heavy quark diffusion and quarkonium suppression.
- The work of several groups using the QQS framework to study quarkonium suppression is providing a more dynamical picture of quarkonium in a medium.