Effective field theory calculations in open charm and charmonium production in media

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Work in collaboration with N. Brambilla, J. Soto and A. Vairo. PRD 96 034021 and PRD 97 074009

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Plan

1. Introduction
2. Binding energies and decay widths corrections from EFTs
3. Open quantum systems combined with effective field theories. The $\frac{1}{r} \gg T$ case
4. Conclusions

The original idea of Matsui and Satz (1986)

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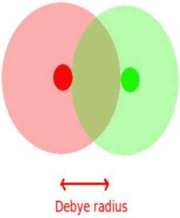
- Quarkonium is quite stable in the vacuum.
- Phenomena of colour screening, quantities measurable in Lattice QCD at finite temperature (static) support this. For example Polyakov loop.
- Dissociation of heavy quarkonium in heavy-ion collisions due to colour screening signals the creation of a quark-gluon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

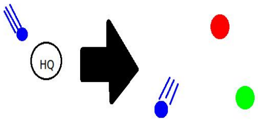
Colour screening

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

At finite temperature



Another mechanism, collisions



A singlet can decay into an octet. Interaction with the medium changes the color state. Dissociation without screening.

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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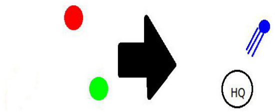
- It has an imaginary part that has to be related with a decay width.

Recombination



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

Questions

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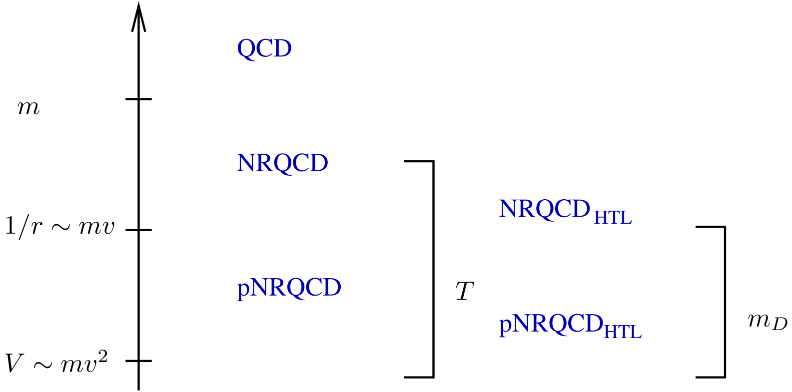
- Is the potential model picture valid? If not, what kind of picture is expected.
- Predict the dissociation pattern.

Plan

Effective Field Theories



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

pNRQCD Lagrangian at T=0

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

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

- 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.

Information contained in the time-ordered correlator

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

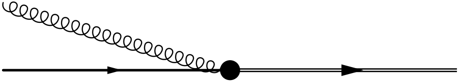
- Tells us about the in-medium dispersion relation. We can obtain binding energy and decay width modifications.
- It can be used to obtain the spectral function. Comparison with Lattice QCD.
- At $T = 0$ it fulfills a Schrödinger equation. At finite temperature this will also be the case in some situations.
- 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 $\frac{1}{r} \gg T \gg E \gg m_D$

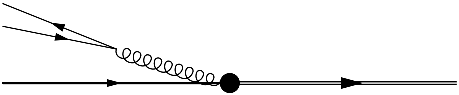
N. Brambilla, M. A. E., J. Ghiglieri, J. Soto and A. Vairo, JHEP 1009 (2010) 038



- Thermal effects are proportional to r^2 because the medium sees the singlet as a small color dipole.
- The process called gluo-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)

Towards a computation of R_{AA} in EFT

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- Both the decay width and the binding energy can be found in the EFT by studying the pole of the singlet time-ordered propagator.
- To compute R_{AA} we need to know how the state of the heavy quarks in the medium changes with time.
- The natural way to formulate this problem is in terms of density matrices $\rightarrow$ open quantum system.

Plan

Why the $\frac{1}{r} \gg T$ case?

- Multipole expansion ensures that thermal corrections are small even if the medium is strongly-coupled.
- The initial temperature depends on the impact parameter.
- At the most central collisions of LHC the higher temperature is around 450 MeV, therefore $\frac{1}{a_0} \sim \pi T$ where a_0 is the Bohr radius of Upsilon 1S.
- As time passes the system cools down.
- The $\frac{1}{r} \gg T$ case is realized in heavy-ion collisions for most collisions during some time.

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.

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

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

and octet to octet

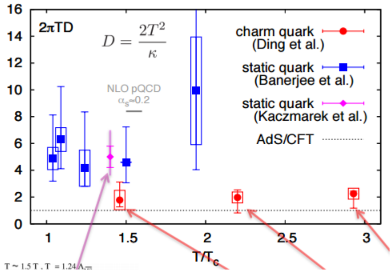
$$C_i^{oo} = \sqrt{\frac{(N_c^2 - 4)\kappa}{2(N_c^2 - 1)}} r_i \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

The parameter κ

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

quantity also appearing in heavy particle diffusion, recent lattice QCD evaluation in Francis, Kaczmarek, Laine, Neuhaus and Ohno (2015)

$$1.8 \lesssim \frac{\kappa}{T^3} \lesssim 3.4$$



Picture taken from O. Kaczmarek talk in "30 years in J/Ψ suppression".

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 (around 500 MeV for $\Upsilon(1S)$) the evolution equation is of the Lindblad form.

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

$$H = \begin{pmatrix} h_s & 0 \\ 0 & h_o \end{pmatrix} + \frac{r^2}{2}\gamma(t) \begin{pmatrix} 1 & 0 \\ 0 & \frac{N_c^2-2}{2(N_c^2-1)} \end{pmatrix}$$

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

No lattice QCD information on this but we observe that we reproduce data better if γ is small. In pQCD

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

Initial conditions and hydrodynamics

In order to understand well the underlying mechanism we worked in the simplest possible conditions. However it is possible and straightforward to couple our theory to the full hydro evolution and we will do it in the future

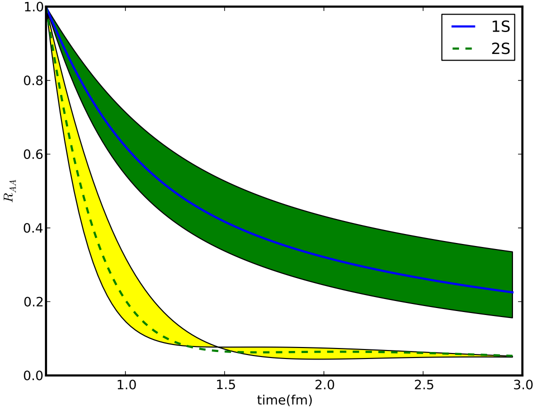
Initial conditions

- To create a pair of heavy particles is a high energy process $\rightarrow$ pair initially created in a Dirac delta state in the relative coordinate.
- Naively (without taking into account P_T dependence) it is α_s suppresses to create a spin 1 singlet compared to an octet.

Hydrodynamics

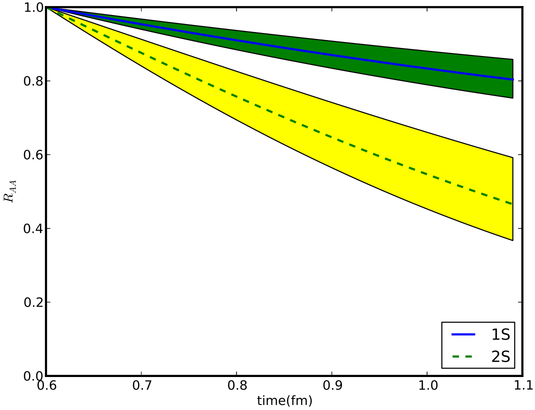
- Bjorken expansion.
- Optical Glauber model to compute dependence of initial temperature with centrality.
- Quarkonium propagates in the vacuum from $t = 0$ to $t_0 = 0.6\,fm$, then the plasma is created.

Results. $30 - 50\%$ centrality



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

Results. $50 - 100\%$ centrality



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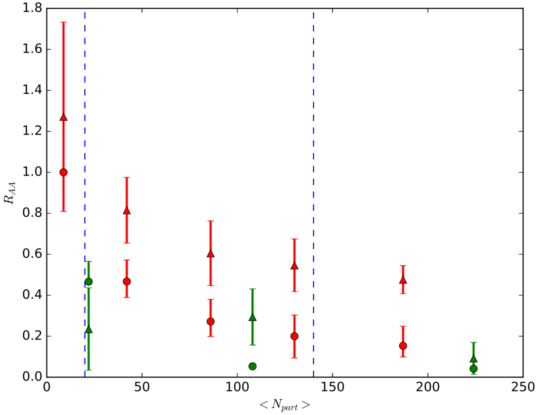

Comparison between the CMS data of 2016 (triangles) and our computation (circles). Upper (red) entries refer to the $\Upsilon(1S)$, lower (green) entries to the $\Upsilon(2S)$.

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Things to do

- Extend the formalism to other temperature regimes (like for example $T \gg 1/r$, we did study the case $T \gg E \gg m_D$ that was not discussed here). This will allow to study a wider range of bound states, collision energies and centralities.
- Reduce the computational cost. This will allow to use state-of-the-art hydrodynamics simulation (event-by-event initial conditions...).
- Model more accurately the initial distribution of quarkonium.

Conclusions

- Using NRQCD and pNRQCD power counting it can be understood in which temperature regimes potential models are applicable (for the time-ordered correlator) and what is the dominant mechanism behind the thermal modifications.
- Corrections to the binding energy and decay widths can be predicted at different temperature regimes.
- R_{AA} can be related with the $S^\dagger S$ operator in pNRQCD (S is the singlet field).
- In the temperature regime $1/r \gg T, m_D \gg E$ all the information needed from the medium can be encoded in two non-perturbative parameters κ and γ. κ is a well-known parameter in open heavy flavour physics and lattice determinations are available.
- In the mid-centrality region of LHC we can qualitatively reproduce upsilon results by using the measured lattice value of κ and setting γ to zero.

Plan

Backup slides

Bjorken expansion

$$T = T_0 \left(\frac{t_0}{t}\right)^{v_s^2}$$

- We assume the medium to be infinite and the temperature equal at all points.
- In a high temperature deconfined plasma $v_s^2 = \frac{1}{3}$.
- We take $t_0 = 0.6\, fm$.
- T_0 is a function of collision centrality computed by using the average impact factor of each centrality window.

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

To be sure that $\frac{1}{r} \gg T$ is fulfilled during all the evolution we take the two more peripheral windows of centrality.
We stop the computation of thermal effects when $T = 250\, MeV$ as we need to be sure that $T \gg T_c$.

Reducing the degrees of freedom of the density matrix

- The density matrix contains much more information than a wave-function $\rightarrow$ it requires a lot of memory to be simulated.
- By using pNRQCD Lagrangian we know that a s-wave state can only decay to a p-wave, a p-wave either to s-wave, p-wave or d-wave and so on.
- We can make an expansion in spherical harmonics. If we are interested in s-wave states a good approximation is to consider in the simulation only s-wave and p-wave.