From quarkonium potentials to quarkonium phenomenology

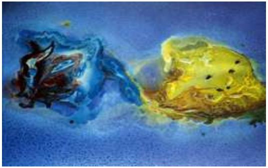
Simone Biondini

in collaboration with N. Brambilla, M. Escobedo and A. Vairo

T30f - Technische Universität München

Quarkonium 2014
CERN, November 13th

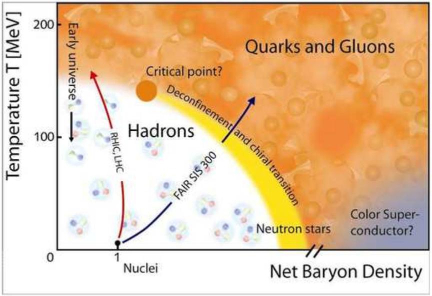
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



Outline

QCD phase diagram

- QCD phase diagram is explored in present day colliders and experiments

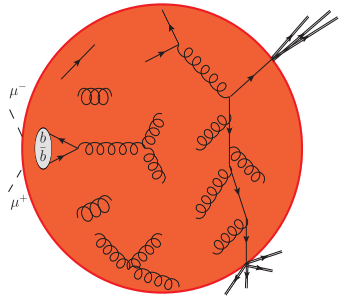


How can we study the properties of quark gluon plasma (QGP)?

- effective hydrodynamics description (bulk properties)
- hard probes, highly energetic particles not in equilibrium with QGP

Heavy Quarkonium and QGP

Heavy $Q\bar{Q}$ in medium



- Medium effect can dissociate the $Q\bar{Q}$
  T. Matsui and H. Satz (1986)

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

- At some T_d the bound state ceases to exist *due to Debye screening*

$\Rightarrow$ Suppressed yield of dilepton decay channel

$$R_{AA}(Q\bar{Q})$$

Potential models naturally follow *F. Karsch, M. T. Mehr and H. Satz (1988)*

- Medium effect entirely encoded in a T-depended potential
- Solve the Schrödinger equation $\rightarrow$ rather good agreement
  A. Bazavov, P. Petreczky and A. Velytsky (2009)
- Still lacking a first principle derivation from QCD

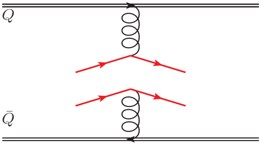
Towards a QCD derived potential

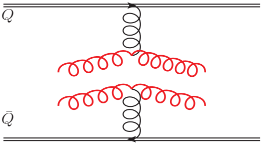
Perturbative computation of real-time potential

M. Laine, O. Philipsen, P. Romatschke and M. Tassler (2007)

- in the case $\pi T \gg 1/r \sim m_D \Rightarrow$ Im(V) $\gg$ Re(V) and $\Gamma = -2\langle \mathrm{Im}(V)\rangle$

$$V_{\mathrm{HTL}} = -\alpha_s C_F \frac{e^{-m_D r}}{r} + 2i\frac{\alpha_s C_F T}{m_D r} f(m_D r)$$





- Different dissociation mechanism: Landau damping

What is the temperature at LHC today?

- Many studies suggest $T_{max} \simeq 450$ MeV *M. Habich, J. L. Nagle and P. Romatschke (2014)*
- $\Upsilon(1S)$: $1/r \sim 1500\,\mathrm{MeV} \geq \pi T \sim 1200$ MeV, $1/r > m_D \sim 800$ MeV

Can we address different hierarchies?

EFTs for heavy quarkonium

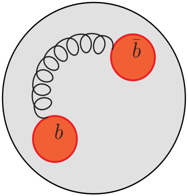
Many energy scales are there: (*perturbative regime and weak coupling*)

1) Non-relativistic scales (bound state):

$$m \gg mv \ (1/r) \gg mv^2 \ (E)$$

2) Thermodynamic scales:

$$\pi T \gg m_D$$



- The potential $\rightarrow$ matching coefficient of EFT
  - $T \neq 0$: pNRQCD$_{\mathrm{HTL}}$

    N. Brambilla, J. Ghiglieri, A. Vairo and P. Petreczky (2008)

    N. Brambilla, M. A. Escobedo, J. Ghiglieri, J. Soto and A. Vairo (2010)

$$\frac{1}{r} \gg \pi T \gg m_D \gg E \,, \quad \frac{1}{r} \gg \pi T \gg E \gg m_D$$

- Thermal corrections to Coulomb potential

$$\mathrm{Re}\, V_s = -C_F \alpha_s / r + \delta V(r, T)$$

- Thermal width (Landau damping and singlet-octet break up)

Nuclear modification factor and potentials

Towards phenomenology of quarkonia suppression

- Interesting studies for $\Upsilon(\mathrm{nS})$ with $\pi T \gg 1/r \sim m_D$

$$V_{\mathrm{HTL}} = -\alpha_s C_F \frac{e^{-m_D r}}{r} + 2i\frac{\alpha_s C_F T}{m_D r} f(m_D r) + \text{non-perturbative ansatz}$$

- Solve the Schrödinger equation numerically and plug the Γ_T in

$$R_{AA}(\Upsilon(\mathrm{nS})) \propto e^{-\int d\tau \Gamma_T(\tau)}$$

M. Strickland (2012), F. Nendzig and G. Wolschin (2013) and (2014)

- Address the same problem with EFT potentials

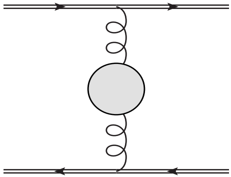
Different hierarchies

- $1/r \gg \pi T \gg E \gg m_D$: real and imaginary part of $V_s(r)$
- $1/r \sim \pi T \gg m_D \gg E$: imaginary part of $V_s(r)$, missing the real part

Real part: $V_s(r)$ for $1/r \sim \pi T \gg m_D \gg E$

Strategy of the calculation *M. A. Escobedo and J. Soto* (2010)

- We start with NRCQD at $T = 0$
- the $1/r$ and πT are integrated out at once $\rightarrow$ match with pNRQCD$_{\mathrm{HTL}}$



$$V_s(r) = C_F g^2 \mu^{4-D} \int \frac{d^{D-1}p}{(2\pi)^{D-1}} \left(e^{i\mathbf{p}\cdot\mathbf{r}} - 1\right) \Delta_{11}(p)$$

$$\Delta_{11} = \frac{1}{2}\left(\Delta_R + \Delta_A + \Delta_S\right), \; \Delta_R = \Delta_R^0 + \Delta_R^0 \Pi_R \Delta_R$$

Retarded gluon self energy in $p_0 \ll p \sim \pi T$

$$\mathrm{Re}\left[\Pi_{00}^R(p)\right] = \frac{g^2 T_F N_f}{\pi^2} \int_0^\infty dk_0 \, k_0 \, n_F(k_0) \left[2 + \left(\frac{p}{2k_0} - 2\frac{k_0}{p}\right) \ln\left|\frac{p-2k_0}{p+2k_0}\right|\right] \rightarrow \text{light-quarks}$$

$$+ \frac{g^2 N_c}{\pi^2} \int_0^\infty dk_0 \, k_0 \, n_B(k_0) \left[1 - \frac{p^2}{2k_0^2} + \left(-\frac{k_0}{p} + \frac{p}{2k_0} - \frac{p^3}{8k_0^3}\right) \ln\left|\frac{p-2k_0}{p+2k_0}\right|\right] \rightarrow \text{gluons}$$

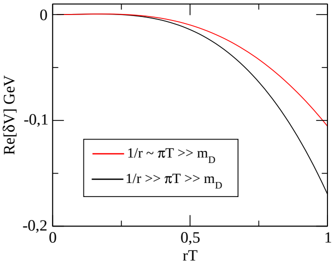
Result and check

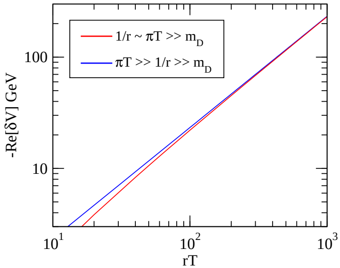
Light quarks contribution: $m_{D,q}^2 = T_F N_f g^2 T^2/3$

$$\mathrm{Re}\,[\delta V^q] = -\frac{C_F}{4}\,\alpha_s\, r\, m_{D,q}^2 - C_F \frac{3}{2\pi}\,\alpha_s\, r^2\, T\, m_{D,q}^2\,\zeta(3) + C_F \frac{\alpha_s\, m_{D,q}^2}{4\,\pi^2 r T^2}\, F_q(rT)$$

Gluon contribution $m_{D,g}^2 = N_c g^2 T^2/3$

$$\mathrm{Re}\,[\delta V^g] = -\frac{C_F}{4}\alpha_s\, r\, m_{D,g}^2 - C_F \frac{\alpha_s\, r^2\, T\, m_{D,g}^2}{\pi}\,\zeta(3) + C_F \frac{\alpha_s\, m_{D,g}^2}{8\,\pi^2 r T^2}\, F_g(rT)$$





Anisotropy in QGP

QGP is a rather complicated system...

- Longitudinal (beam axis) expansion is bigger than the radial expansion

1) Different temperatures
2) Anisotropic parton momenta

$\boxed{\text{Local momentum anisotropy : } \xi}$

- The anisotropy effects on the $Q\bar{Q}$ spectrum studied for $\pi T \gg 1/r \sim m_D$

Y. Burnier, M.Laine and M. Vepsalainen (2009), A. Dimitru, Y. Gou, and M. Strickland (2009)

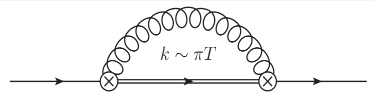
- We can address within EFTs the case $1/r \gg \pi T \gg E \gg m_D$

Modelling the anisotropy

$$f(\mathbf{k}) = f_{iso}\left(\sqrt{\mathbf{k}^2 + \xi(\mathbf{k}\cdot\mathbf{n})^2}\right) = \left(e^{\frac{\sqrt{\mathbf{k}^2+\xi(\mathbf{k}\cdot\mathbf{n})^2}}{T}} - 1\right)^{-1}$$

We start with pNRQCD: $1/r \gg \pi T \gg E \gg m_D$

$$\mathcal{L}_{\mathrm{pNRQCD}} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \sum_i \bar{q}_i i \not{D} q_i + \int d^3\mathbf{r}\, Tr\left\{S^\dagger\left(i\partial_0 - h_s\right)S + O^\dagger\left(iD_0 - h_o\right)O \right.$$
$$\left. + V_A\left(O^\dagger \mathbf{r}\cdot g\mathbf{E}S \; + h.c.\right) + \frac{V_B}{2}O^\dagger\left\{\mathbf{r}\cdot g\mathbf{E}, O\right\} + \cdots \right\}$$



- Match pNRQCD onto pNRQCD$_{\mathrm{HTL}}$
- T encoded in a redefined potential

$$\delta\Sigma(E) = -ig^2 C_F \frac{r^i}{D-1}\mu^{4-D}\int \frac{d^D k}{(2\pi)^D}\frac{i}{E-h_o-k_0+i\eta}\, k_0^2 D_{ii}(k_0,k) r^i$$

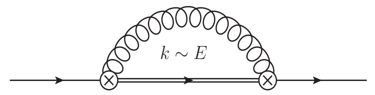
- Momentum region $k_0 \sim \pi T$ and $k \sim \pi T$. Since $\pi T \gg (E - h_0)$

$$\frac{i}{E-h_o-k_0+i\eta} = \frac{i}{-k_0+i\eta} - i\frac{E-k_0}{(-k_0+i\eta)^2} + \cdots$$

- At leading order in α_s we obtain

$$\delta V_s(r,T,\xi) = \frac{\pi\alpha_s C_F T^2}{3}\left(\frac{2}{m} + \frac{N_c\alpha_s r}{4} + \frac{N_c\alpha_s(\mathbf{r}\cdot\mathbf{n})^2}{4r}\right)\frac{\arctan\xi}{\xi}$$
$$+\frac{\pi N_c C_F \alpha_s^2 T^2}{12\xi r}\left(1 - \frac{\arctan\sqrt{\xi}}{\sqrt{\xi}}\right)\left(r^2 - 3(\mathbf{r}\cdot\mathbf{n})^2\right)$$

Strategy of the calculation: $1/r \gg \pi T \gg E \gg m_D$



- Effect of the scale E within pNRQCD$_{\rm HTL}$
- Octet unexpanded,
- $f(\mathbf{k}) \simeq \frac{T}{k\sqrt{1+\xi\cos^2\theta}} + \ldots$

- Thermal width from the scale E: $\Gamma = -2\,\langle n,l|\mathrm{Im}\delta\Sigma(E)|n,l\rangle$

$$\Gamma(T,\xi) = \left(\frac{1}{3}N_c^2 C_F\alpha_s^3 T + \frac{4}{3}\frac{C_F^2\alpha_s^3}{n^2}T(C_F+N_c)\right)\frac{\sinh^{-1}(\sqrt{\xi})}{\sqrt{\xi}}$$

$$+\left(\frac{1}{4}N_c^2 C_F\alpha_s^3 T + \frac{C_F^2\alpha_s^3}{n^2}T\left(C_F-\frac{N_c}{2}\right)\right)\frac{(1+\frac{2}{3}\xi)\sinh^{-1}(\sqrt{\xi})-\sqrt{\xi(1+\xi)}}{\sqrt{\xi^3}}\langle 2\,\ell\,0\,0|\ell\,0\rangle\langle 2\,\ell\,0\,m|\ell\,m\rangle$$

- Check with $\xi \to 0$, we recover the known result

  N. Brambilla, M. A. Escobedo, J. Ghiglieri, J. Soto and A. Vairo (2010)

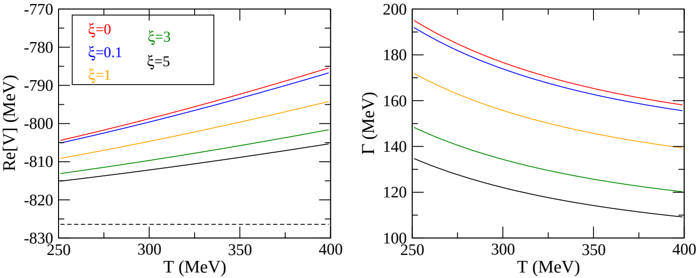
Check with known limits

Real part of the potential (for $\Upsilon(1S)$)

$$V_s(r, T, \xi) \to -c_F \frac{\alpha_s}{r} + \frac{\pi}{9} N_c C_F \alpha_s^2 T^2 r + \frac{2\pi}{3m_b} C_F \alpha_s T^2 + \mathcal{O}(\xi)$$

Thermal width

$$\Gamma(T, \xi) \to \frac{1}{3} N_c^2 C_F \alpha_s^3 T + \frac{4}{3} C_F^2 \alpha_s^3 T (C_F + N_c) + \mathcal{O}(\xi)$$



Conclusions and Outlook

- $Q\bar{Q}$ potential in medium is important to address $R(Q\bar{Q})_{AA}$
- EFTs allow to explore several hierarchies patterns, for example
$$1/r \geq \pi T \gg m_D \gg E, \quad 1/r \gg \pi T \gg E \gg m_D$$
- EFT potentials may be useful as input to Schrödinger equation and quarkonia suppression at LCH
- Address further relaxation of the hierarchies

- Anisotropy may play a role in quarkonia suppression
- Anisotropy of QGP can be treated within EFTs
- We can derive the spectrum (E, Γ) for $Q\bar{Q}$ at LO within
$$1/r \gg \pi T \gg E \gg m_D$$
- To improve the calculation $\rightarrow$ Gluon polarization at finite T in anisotropic plasma with no HTL approximation