Heavy Quark interactions in the QGP

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Heavy Quarkonium Production in Heavy-Ion Collisions
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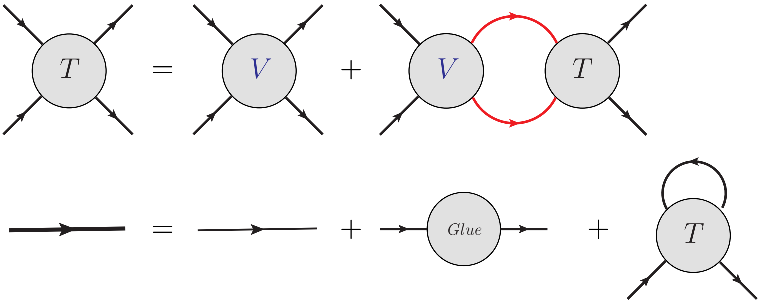
Outline

- T-matrix calculations
  - Formalism
  - Relativistic corrections
- In-medium Potentials
  (definition / value at infinity / string breaking)
- Calculations in different potentials
- Charm quark relaxation
- Conclusions / Outlook

Motivation

- Charmonium / bottomonium are a probe for the QGP
  - Strongly influenced by the plasma
  - Need good control of the in medium behaviour
- Make connection with lQCD potential (U or F?)
- Describe open and hidden charm / bottom in common approach
- Unified description of transport properties and bound states

T-Matrix formalism



- Start with the Bethe-Salpeter equation:

$$M = V + VG_{full}M \quad \Longrightarrow \quad \begin{aligned} M &= W + WG_{red.}M \\ W &= V + V(G_{full} - G_{red.})W \end{aligned}$$

- One and two particle properties in a comprehensive approach

3D reduction

- Assume instantaneous interaction $4D \longrightarrow 3D$

$$T(E, \vec{q}, \vec{k}) = V(\vec{q}, \vec{k}) + \int \frac{d^3\vec{p}}{(2\pi)^3} V(\vec{q}, \vec{p}) G(E, \vec{p}) T(E, \vec{p}, \vec{k})$$

- Total $\vec{P} = 0$
- Different 3D reductions:
  - Blankenbecler-Sugar

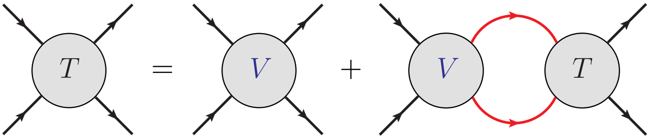
$$G(E, \vec{p}) = \frac{\omega_p}{E^2/4 - \omega_p^2 - 2\omega_p \Sigma(\omega_p, \vec{p})}$$

  - Thompson

$$G(E, \vec{p}) = \frac{1}{E/2 - \omega_p - \Sigma(\omega_p, \vec{p})}$$

- Calculations with both schemes agree quite well.

T-Matrix formalism



- Expand into partial waves
- No coupling between the different colour channels
- Poles in $T \Rightarrow$ bound states
- Potential

$$\mathcal{V}_{l,a} = \frac{1}{8\pi} F_{kin} F_{Breit} \int dx_{q'q} P_l(x_{q'q}) \int d^3r \, \mathcal{V}_a(r) e^{i(\vec{q}-\vec{q}\,')\vec{r}}$$

$\rightarrow$ Includes off-shell extension

Breit correction

Relativistic corrections: Current Current interaction leads to (magnetic interaction / Brown [52] / equal masses)

$$V \longrightarrow V(1 - \alpha_1 \cdot \alpha_2)$$

$$F_{Breit}(|\vec{q}\,'|, |\vec{q}\,|) = \left[1 + \frac{|\vec{q}\,|^2}{\omega_q^2}\right]^{\frac{1}{2}} \left[1 + \frac{|\vec{q}\,'|^2}{\omega_{q'}^2}\right]^{\frac{1}{2}}$$

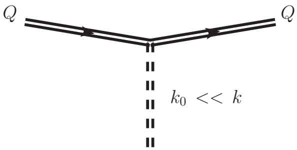
- Also other off shell extension

$$F_{Breit}(|\vec{q}\,'|, |\vec{q}\,|) = \left[1 + \frac{|\vec{q}\,||\vec{q}\,'|}{\omega_q\,\omega_{q'}}\right]$$

possible.

Main Features of the approach

- Non-perturbative method: Partial resummation
  - Large coupling
  - Bound states
- Comprehensive treatment of scattering and bound states
- BbS scheme uses relativistic kinematics
- Can treat hidden and open charm (bottom) on the same footing.

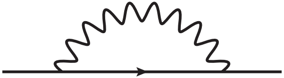


$\longrightarrow$ One heavy quark determines kinematics

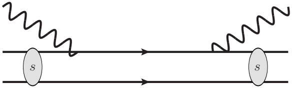
- Connect charmonium with transport properties (Coefficients in a Fokker-Planck equation)

Main Features of the approach

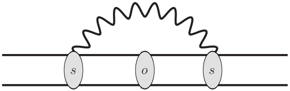
- Medium effects in the T-Matrix
  - Pauli-Blocking
  - Quark propagator



$\Leftrightarrow$



Coupled channel $\Leftrightarrow$

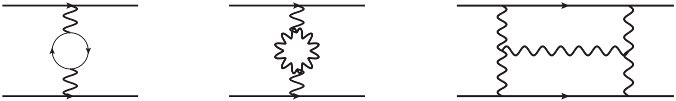


  - Interpret $V(r = \infty)$ as Tadpole self-energy

$$\Sigma_{Tad.} = \frac{1}{2} V(r = \infty)$$

Future Work

- Imaginary parts of the potential
  (Laine [07], Beraudo [07], Brambilla [08])



- Singlet - octet transitions and interactions with gluons
  $\Rightarrow$ coupled channel approach

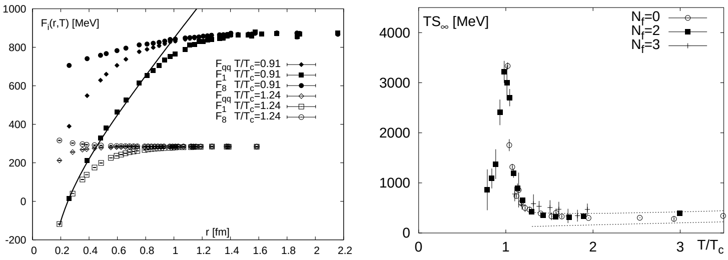
Potential

- Want to include medium effects (screening) in the potential
- Non-perturbative effects (string terms) important
- Use results from lQCD
    - Which potential to use? $F_{Q\bar{Q}}$ or $U_{Q\bar{Q}}$?
    - Unsolved problem ....
- For the moment try both ...

Time scales

- Basic idea (Shuryak[04]):
  - F is considered to be the thermodynamic ground state
  - Use of U or F depends on timescales
  - If $\tau_{sys} \sim r/\dot{r} >> \tau_{heat} \Rightarrow$ system adiabatic $\Rightarrow$ use U
  - If $\tau_{sys} << \tau_{heat} \Rightarrow$ system relaxes to groundstate $\Rightarrow$ use F
  - Suggested Landau Zener like interpolation
    $V = P\,U + (1 - P)\,F$ with $P = Exp\left[-\frac{2\pi\,|H_{12}|}{v|\sigma_1 - \sigma_2|}\right]$
  - Estimate interaction strength from transport properties.

Potential at infinity



- At large distances independent of colour state $\rightarrow$ supports mass interpretation
- What happens at T_c?
  $\rightarrow$ mass correction or long range correlation?

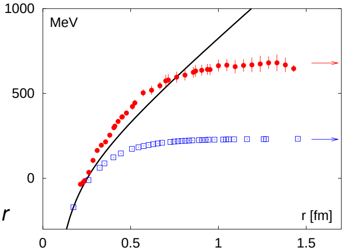
Kaczmarek [05]

In perturbation theory

$$F_1(r,T) = -\frac{4}{3}\frac{\alpha_s}{r}e^{-m_D r} - \frac{4}{3}\alpha_s m_D$$

$$S_1(r,T) = \frac{4}{3}\frac{\alpha_s m_D}{T}\left(1 - e^{-m_D r}\right)$$

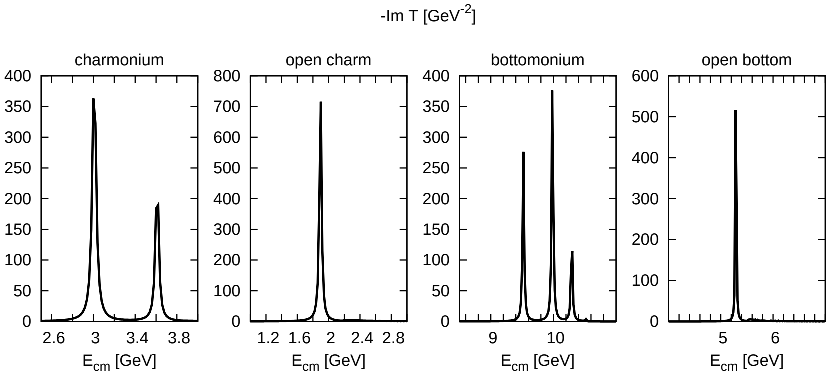
$$U_1(r,T) = -\frac{4}{3}\frac{\alpha_s}{r}e^{-m_D r} - \frac{4}{3}\alpha_s m_D e^{-m_D r}$$



Kaczmarek [05]

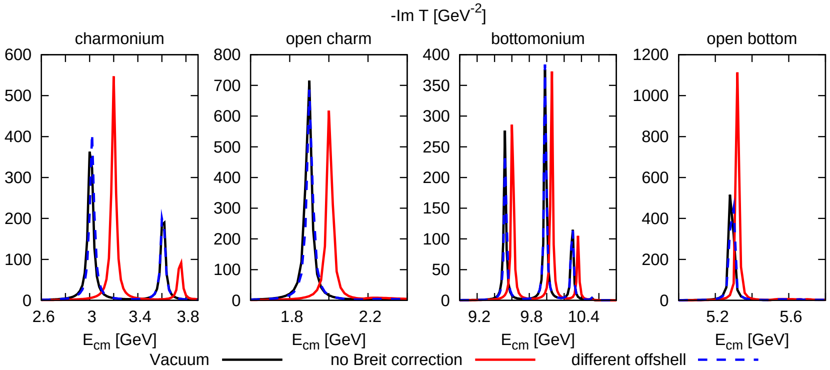
- Perturbative (and thermodynamicly consistent) result quite different from lattice.
- Only in higher orders $U(\infty) \sim Tg^5$
- Perturbative mass correction $\Delta m = \frac{2}{3}\alpha_s m_D$

Vacuum calculations



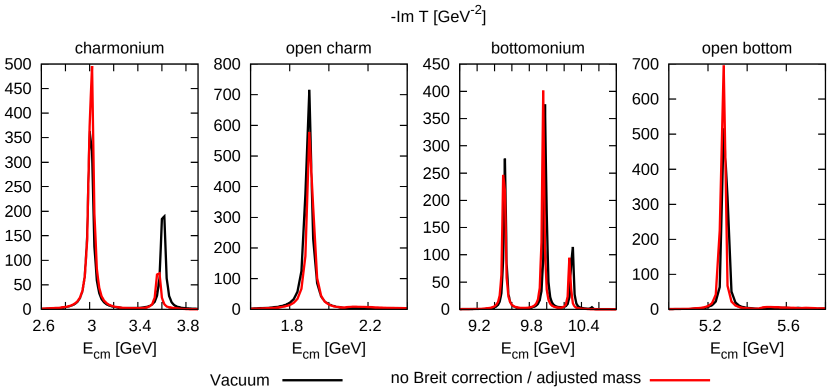
- 3 Parameters $m_q = 0.3$ GeV, $m_c = 1.425$ GeV and $m_b = 4.75$ GeV
- 3 trivial states / 4 non trivial states
- Works quite well
  $\longrightarrow$ uncertainties from relativistic and kinematic factors

Breit correction



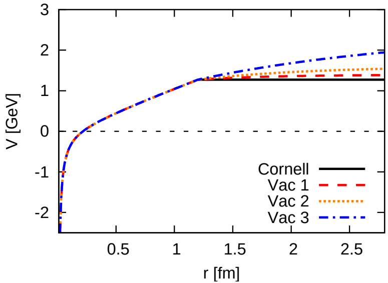
- No large influence of the off-shell prescription
- Effect of about 200 MeV (100 MeV) in the charm (bottom) sector

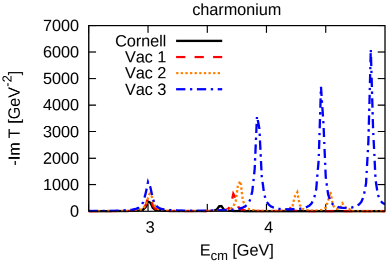
Breit correction / masses adjusted



- Readjustment of bare masses allows for equally good description
- Possible differences in the higher states

Vacuum calculations

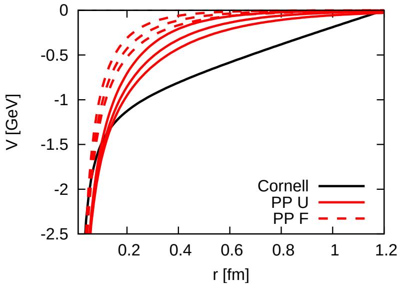




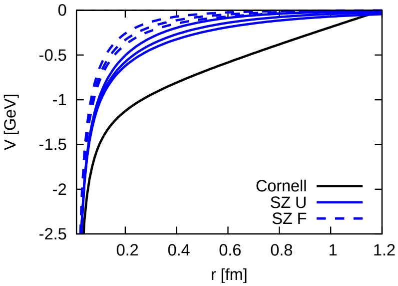
- Try different smooth introductions of string breaking
- Leads to too many bound states
- Seems to favour quite sudden string breaking

Medium Potentials ($T = 1.2, 1.5$ and $2.0\ T_c$)

Petreczky [04] ($N_f = 3$)

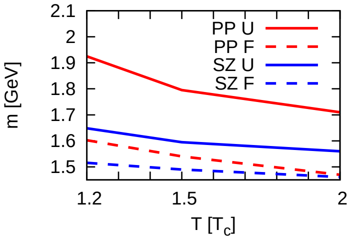


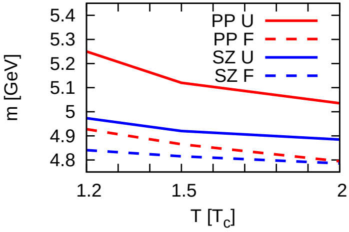
Kaczmarek [04] / Shuryak [04] ($N_f = 2$)



- Calculate U according to $U = F - T\frac{\partial F}{\partial T}$
- Potentials (and Parameterisations!) do not violate Entropy constraints
- Quantitative differences in the potentials

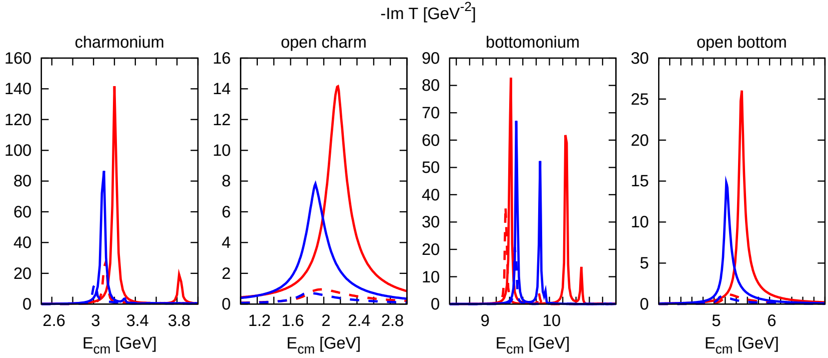
Masses





- $m = m_0 + \frac{1}{2}V(\infty)$
- Changes thresholds
- Common general trend ... but quantitative differences
- Include additional imaginary parts
  - about 100 MeV for the heavy light systems
  - about 10 MeV for the heavy heavy systems

1.2 T_c



-Im T [GeV^-2]
charmonium
open charm
bottomonium
open bottom
160
140
120
100
80
60
40
20
0
2.6
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3.4
3.8
16
14
12
10
8
6
4
2
0
1.2
1.6
2
2.4
2.8
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70
60
50
40
30
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9
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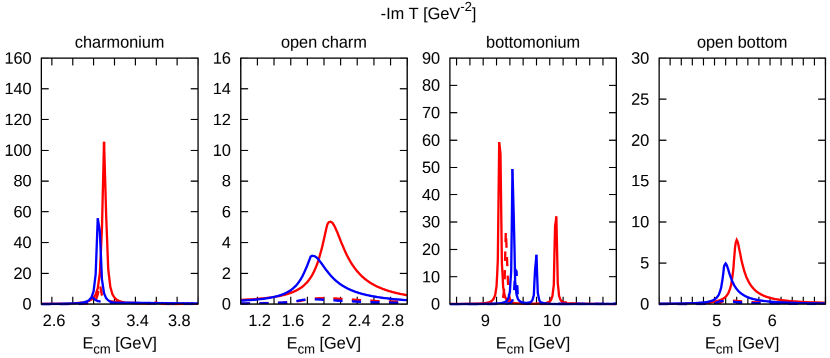
30
25
20
15
10
5
0
5
6
E_cm [GeV]

1.5 T_c



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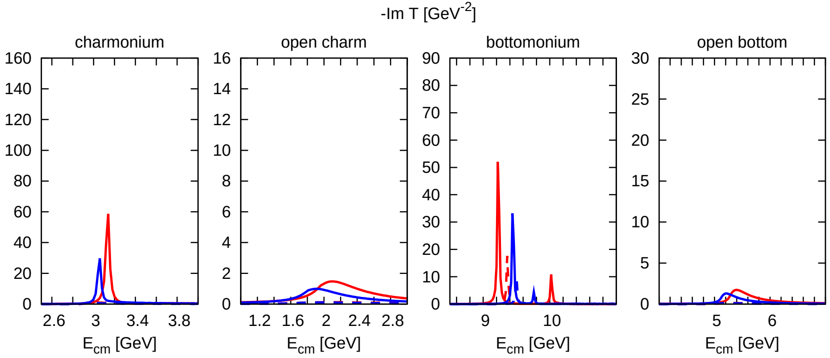
E_cm [GeV]

$2\ T_c$



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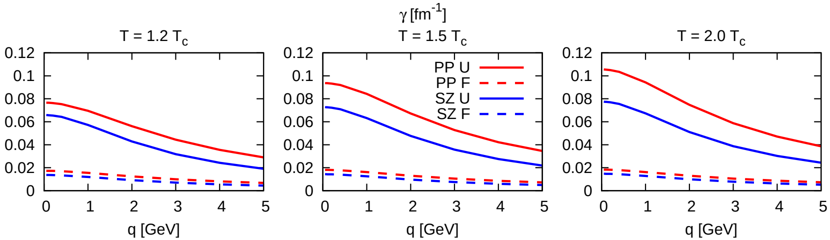
E_cm [GeV]

Charm quark relaxation

Consider Fokker-Planck equation:

$$\frac{\partial f_Q}{\partial t} = \frac{\partial}{\partial p_i}(p_i \gamma f_Q) + \frac{\partial^2}{\partial p_i \partial p_j}(B_{ij} f_Q)$$

$$\gamma(\vec{p}\,) = \frac{1}{2\,E_p} \int \frac{d^3\vec{q}}{(2\pi)^3 2\,E_q} \int \frac{d^3\vec{q}\,'}{(2\pi)^3 2\,E_{q'}} \int \frac{d^3\vec{p}\,'}{(2\pi)^3 2\,E_{p'}}$$
$$\times \frac{1}{\gamma_c}\, f_{kin.} \sum |T|^2\, (2\pi)^4\, \delta(q + p - q' - p') f_B(\vec{q}\,)$$



Conclusions / Outlook

- Conclusions
  - T-matrix is a consistent thermodynamic approach for scattering and bound states
  - Open and hidden charm / bottom can be described in one approach
  - T-Matrix includes specific medium effects (quark self-energies / in-medium potential)
  - Can make link to transport properties

- Outlook
  - Euclidian correlators → make contact with lQCD
  - Coupled channel calculations
  - Include imaginary parts of the potential