Transport coefficients of charmed and bottomed mesons in a hot meson gas

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Outline

1. Introduction
2. Modelling heavy-meson (D, B) interactions in a hadron gas
3. Heavy-meson transport coefficients
4. Summary and outlook

Based on:


**Introduction and motivation**

The QCD phase diagram

- **Motivation**: setup for strong interactions at extreme conditions
- Understand (de-)confinement
- Asymptotic freedom
- Phenomenological variety: also cold QGP, cold nuclear matter phases...
Introduction and motivation

Thermodynamics of QCD

Trace anomaly (e-3p)

M. Panero, PRL 103, 232001 (2009)

AIM: understand phase transition within phenomenological approaches

Fate of heavy quarkonia and open-heavy flavor

Pure gauge sector: existence of glueballs in the sQGP
**Introduction**

Heavy-flavor mesons in hadronic medium

- Keep memory of collision history (unlike light mesons: p, K)
- Still, blurred by interactions with hadron gas after crossover from sQGP
- Need be understood for reliable transport and bulk hydro simulations
- Advantage: In hadronic phase $\rightarrow$ effective theories of QCD

**Program:**

- State-of-the-art calculation of p-”Q” interaction: HQET + ChPT
- Transport coefficients: drag force ($F$) and momentum-space diffusion ($G_0$, $G_1$)

**IMPORTANT QUESTION:** Relevant degrees of freedom?
Modelling heavy-meson interactions in a hadron gas
Modelling heavy-meson interactions in a hadron gas

**D- and B-meson spectra**

- $D$, $D^*$ and $B$, $B^*$ mesons as (stable) degrees of freedom
- Coherently with HQ limit: 4 degenerate heavy-quark modes
- Constraints on low-energy effective Lagrangian
Modelling heavy-meson interactions in a hadron gas

NLO Chiral Lagrangian for spin-0,1 D (B) interactions with p

Final amplitude for scattering off a heavy quark* in a light meson gas, at \textit{NLO in chiral expansion} and \textit{LO in HQ expansion} (* in \(D/D^*\) (B/B*) meson state)

\[ V \simeq \frac{C_0}{2F^2}(s - u) + \frac{2C_1}{F^2}h_1 + \frac{2C_2}{F^2}h_3(p_2 \cdot p_4) + \frac{2C_3}{F^2}h_5 \left[ (p_1 \cdot p_2)(p_3 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3) \right] \]

- **LECs:** \( h_i, \ h_i, \ i = 0, \ldots, 5 \)
- Reduced to 3 from Large \( N_c \) and heavy quark symmetry

Constrained by \( D \) (B) mass difference and \( D^- \) (B-) resonance data \((M, G)\)
Modelling heavy-meson interactions in a hadron gas

Role of unitarization of NLO scattering amplitudes

- ChPT amplitudes valid at low energies
- Resonances: more efficient diffusion in hot meson gas
- Reach high temperatures (up to 150 MeV)
- Unitarization is required!

Relativistic Bethe-Salpeter equation in partial waves (S-wave)
Modelling heavy-meson interactions in a hadron gas

A word on determination of free parameters (LECs)

- **LO**: fixed by Chiral Symmetry breaking

<table>
<thead>
<tr>
<th>C_i</th>
<th>( B\pi(\frac{1}{2}) )</th>
<th>( B\pi(\frac{3}{2}) )</th>
<th>( BK(0) )</th>
<th>( BK(1) )</th>
<th>( B\bar{K}(0) )</th>
<th>( B\bar{K}(1) )</th>
<th>( B\eta(\frac{1}{2}) )</th>
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<tbody>
<tr>
<td>C_0</td>
<td>-2</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_1</td>
<td>-m^2_\pi</td>
<td>-m^2_\pi</td>
<td>m^2_K</td>
<td>-m^2_K</td>
<td>-2m^2_K</td>
<td>0</td>
<td>-m^2_3</td>
</tr>
<tr>
<td>C_2</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1/3</td>
</tr>
<tr>
<td>C_3</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1/3</td>
</tr>
</tbody>
</table>

- **NLO**: \( h_1, h_3, h_5 \) → fit to experimental data on \( D \) (\( B \)) resonances

<table>
<thead>
<tr>
<th>Heavy Spin, ( J^\pi )</th>
<th>D (quark model)</th>
<th>D (experimental)</th>
<th>(( M, \Gamma )) MeV</th>
<th>B (quark model)</th>
<th>B (experimental)</th>
<th>(( M, \Gamma )) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2, 0^+</td>
<td>( D_0 )</td>
<td>( D_0^*(2400) )</td>
<td>2318,267</td>
<td>( B_0 )</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>1/2, 1^+</td>
<td>( D_1 )</td>
<td>( D_1(2430) )</td>
<td>2427,384</td>
<td>( B_1 )</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>3/2, 1^+</td>
<td>( D_1 )</td>
<td>( D_1(2420)^0 )</td>
<td>2421,27</td>
<td>( B_1 )</td>
<td>( B_1(5721) )</td>
<td>5723,?</td>
</tr>
<tr>
<td>3/2, 2^+</td>
<td>( D_2 )</td>
<td>( D_2^*(2460) )</td>
<td>2466,49</td>
<td>( B_2 )</td>
<td>( B_2^*(5747) )</td>
<td>5743,23</td>
</tr>
</tbody>
</table>

- **Resonance parameters**

Guo et al, PLB 641, 27 (2006)
Flynn and Nieves, PRD 75 (2007) 074024
Heavy-meson transport coefficients in a hadron gas
Heavy-meson transport coefficients in a hadron gas

Fokker-Plank equation approach:

Momentum distribution function

\[ \frac{\partial f_c(t, \mathbf{p})}{\partial t} = \frac{\partial}{\partial p_i} \left( F_i(\mathbf{p}) f_c(t, \mathbf{p}) + \frac{\partial}{\partial p_j} \left[ T_{ij}(\mathbf{p}) f_c(t, \mathbf{p}) \right] \right) \]

Friction term

Diffusion term

Collision rate:

\[ w(\mathbf{p}, \mathbf{k}) = g_\pi \int \frac{d\mathbf{q}}{(2\pi)^9} f_\pi(\mathbf{q}) \left[ 1 + f_\pi(\mathbf{q} + \mathbf{k}) \right] \frac{1}{2E_\mathbf{q}} \frac{1}{2E_\mathbf{p}} \frac{1}{2E_{\mathbf{q} + k}} \frac{1}{2E_{\mathbf{p} - k}} \times (2\pi)^4 \delta(E^c_\mathbf{p} + E^\pi_\mathbf{q} - E^c_{\mathbf{p} - k} - E^\pi_{\mathbf{q} + k}) \sum |\mathcal{M}_{\pi c}(s, t, \chi)|^2 \]

(And similarly for bottomed mesons and other species in the gas)

Isospin-averaged D/D* \( p \) amplitude
Heavy-meson transport coefficients in a hadron gas

Fokker-Plank equation approach:

\[ \frac{\partial f_c(t,p)}{\partial t} = \frac{\partial}{\partial p_i} \left\{ F_i(p) f_c(t,p) + \frac{\partial}{\partial p_j} [\Gamma_{ij}(p)f_c(t,p)] \right\} \]

- \( F \) is the "drag force"
- \( G_0, G_1 \) are the diffusion coefficients

With time evolution...

- Initial momentum is "dragged" to zero
- Shape **broadens** towards Boltzmann distribution
Heavy-meson transport coefficients in a hadron gas

Drag and Diffusion coefficients: charmed mesons

Drag and diffusion strengthened in hotter stages

Resonant interaction!

Sizable momentum dependence of $G_1$ vs $G_0$

Sensitivity of anisotropic observables (elliptic flow)

$T = 150$ MeV
Heavy-meson transport coefficients in a hadron gas

Heavy-quark relaxation lengths and energy loss in p gas

\[ l = \frac{1}{F} \quad \text{and} \quad \frac{dE}{dx} = F \cdot p \]

"Thus, if the pion gas is in existence for, say, 4 fm, a D meson measured in the final state with a momentum of 800 MeV will have been emitted from the quark–gluon plasma phase with 1 GeV"
Heavy-meson transport coefficients in a hadron gas

More results and consistency tests of calculation

- Effect of $K$ and $h$ in the *hot meson gas*

- Transport coefficients at $p \to 0$: *Einstein relation*
  \[ F = \frac{G}{MT} \]

- Scaling of coefficients with *heavy-quark mass*
  \[ F \simeq \frac{1}{3} \sigma P \sqrt{\frac{m_\pi}{T}} \frac{1}{m_B} \]
  \[ \Gamma_0, \Gamma_1 \simeq \frac{1}{3} \sigma P \sqrt{m_\pi T} \]

- Unitarity!
Summary

- **Heavy quarks** stand as unique probes for testing strong interactions at extreme conditions, both below and beyond $T_c$, as long as we understand their dynamics.

- Effective theory of charm and bottom interactions in the hadron gas: ChPT, HQ symmetry + unitarization of scattering amplitudes + extension to SU(3).

- *Transport coefficients*: $F$ and $G_0$ soft momentum dependence, $G_1$ indicates sensitivity to elliptic flow observables.

- Heavy quarks will not relax completely during the lifetime of the hadron gas.

- Heavy-meson spectra have to be interpreted in the light of considerable energy loss due to resonant $D / D^* p$ and $B / B^* p$ scattering.

<table>
<thead>
<tr>
<th>Authors</th>
<th>$F$ (fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laine</td>
<td>0.05</td>
</tr>
<tr>
<td>He, Fries, Rapp</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Ghosh et al.</td>
<td>0.11</td>
</tr>
<tr>
<td>This work</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Backup slides
Potential model approach for heavy quarkonia

Heavy quarkonia: bound states of heavy (c or b) quark and anti-quark

- Strongly bound systems: $E_B(J/\psi) \approx 600$ MeV, $E_B(U) \approx 1.1$ GeV
- Typical hadron scale: $L \approx 0.2$ GeV
- Non-relativistic dynamics: pNRQCD

String breaking: $y \rightarrow DD$, $E_{th} \approx 3.8$ GeV, $V_{sb} \approx 1.1$ GeV

Figure by H. Satz, hep-ph/0602245

Kaczmarek, Zantow, PRD71, 114510 (2005)
Potential model approach for heavy quarkonia

Schrödinger Eq. [bound states] + uncorrelated (non-interacting) continuum

\[
\left[ -\frac{\nabla^2}{\bar{m}} + V_1(r, T) \right] \psi_E(r, T) = \varepsilon(T) \psi_E(r, T)
\]

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\chi_b$</th>
<th>$\Upsilon'$</th>
<th>$\chi'_b$</th>
<th>$\Upsilon''$</th>
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<tbody>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
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<tr>
<td>$\Delta M$ [GeV]</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.07</td>
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<tr>
<td>$r_0$ [fm]</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
<td>0.28</td>
<td>0.44</td>
<td>0.56</td>
<td>0.68</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Charmonium

Bottomonium
Potential model approach for heavy quarkonia

Heavy quarkonia at finite temperature (in the QGP)

- Strong interaction screened in the plasma (e.g. EM plasma)
- Assymptotic freedom at very high $T$ (free gas of quarks and gluons)
- Hope that may survive close to $T=T_c$
- Dissociation temperatures: signature of production of QGP

- Heavy quarkonia [Matsui-Satz ‘86]: spectroscopic probes of QCD matter in HIC’s
- *Mesonic spectral functions* from Lattice QCD: heavy quarkonia survive well beyond $T_c$
  

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**Strongly interacting QGP ($s$QGP)?**

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[Graphs and data plots showing spectral functions and dissociation signatures at various temperatures.]
Potential model approach for heavy quarkonia

Heavy quarkonia at finite temperature (in the QGP)

- Assume potential model approach still valid at finite $T$
- $V(r) \rightarrow V(r, T)$:
  - Model calculation (pQCD, screening theory)
  - Thermal Lattice QCD potentials + appropriate parameterization

Typically the highest uncertainty of calculation
- $F_1$ vs. $U_1$ discussion
- Different parameterizations – different potentials

Kaczmarek, Santow, 2005

Shuryak et al ’04; Wong ’05; Alberico et al ’05; Mocsy, Petreczky ’05
Mocsy et al ’06; Laine ’07; Wong et al ’07; Alberico et al ’07
Potential model approach for heavy quarkonia

Heavy quarkonia at finite temperature (in the QGP)

- A simple exercise (even for students…)

\[ \text{bb S-wave (U, h_b) @ } T = 1.1 \, T_c \]

- Numerov algorithm for central potential: reduced radial wave function
- Outgoing wave function “flapping” (nodes) signaling bound states
**T-matrix approach for heavy quarkonia in the QGP**

- Schematic model for spectral function: [bound states] + uncorrelated continuum
  
  $$\sigma(\omega, T) = \sum_i 2M_iP_i^2 \delta(\omega^2 - M_i^2) + \frac{3}{8\pi}\omega^2 f(\omega, E_{th}) \Theta(\omega - E_{th}).$$

- Lipmann-Schwinger Eq: $\bar{Q}Q$ T-matrix
  - 3D-reduction Bethe Salpeter Eq. (static interaction)
  - Partial-wave expansion
  - S- and P-wave scattering

  $T_{i}(E; q', q) = V_{i}(q', q) + \frac{2}{\pi} \int_{0}^{\infty} dk \, k^{2} \, V_{i}(q', k) \, G_{QQ}(E; k) \, T_{i}(E; k, q) \, [1 - 2f(\omega_{k})]$
T-matrix approach for heavy quarkonia in the QGP

- Two-(quasi)particle propagator
  - $S \rightarrow$ quark selfenergy

\[
G_{QQ}(E; k) = \frac{m^2}{\omega_k} \frac{1}{E^2/4 - \omega_k^2 - 2i \omega_k \text{Im} \Sigma(\omega_k, k)}
\]

\[
\omega_k = \sqrt{m^2 + k^2} + \text{Re} \Sigma(\omega_k, k)
\]

relativistic dispersion relations!

Q, $\bar{Q}$ many-body props. can be implemented!

- Matrix inversion algorithm: Haftel-Tabakin '70

\[
T = V + VGT \rightarrow \sum_{k=1}^{N} \mathcal{F}(E)_{ik} T(E)_{kj} = V_{ij}
\]

Bound states:

\[
\text{det} \mathcal{F}(E) = 0 \quad , \quad E < E_{th}
\]
**T-matrix approach for heavy quarkonia in the QGP**

In-medium quasi-particle properties

- Potential at large distances: *mass correction or long-distance correlation*?
- Independence of color state: thermal mass correction $m(T) = m_0 + d(T)$

\[
V_1(r, T) = U_1(r, T) - U_1^\infty(T)
\]
\[
m_Q^*(T) = m_Q + \frac{U_1^\infty(T)}{2}
\]
\[
E_Y \approx 2 m_Q^* - E_B
\]

2-LQCD Free and Internal Energy at large distances [Kaczmarek, Zantow '05]

Baseline results: $T$-matrix for $\bar{Q}Q$ scattering

Fix $m_c=1.7\text{GeV}$, $m_b=5.1\text{GeV}$ ($\text{Re}S=0$); $G_\gamma$ small ($\text{Im}S=-10\text{MeV}$)

No spin-spin interactions $\rightarrow (J/y, h_c), (U, h_b)$ degenerate

<table>
<thead>
<tr>
<th>c$\bar{c}$ S-wave $(J/y, h_c)$</th>
<th>b$\bar{b}$ S-wave $(U, h_b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
</tr>
</tbody>
</table>

- Binding energy decreases, $T$-matrix looses strength
- $J/y$ survives up to $T \approx 2.5-2.8 \ T_c$, then dissolves
- $U$ survives beyond $T > 3.5 \ T_c$

Smaller binding energies with other definitions of $V_1$:

$V_1 = F_1$, $V_1 = (1-\alpha) \ U_1 + \alpha \ F_1$

DC, Rapp, PRD76 (2007) 14506

$T = (1.1-3.5) \ T_c$

Wong, PRC72 (2005) 034906
Baseline results: correlations above threshold

- Full amplitude vs. Born approximation ($V$)
- $Q\bar{Q}$ system highly correlated above $E_{\text{th}}$: resonance-like structures

( $T = 1.1 \, T_c$ )

Non-perturbative strength in the continuum:

Important role for providing shorter thermalization times (both $Q, q$)

van Hees, Greco, Mannarelli, Rapp ‘08
Spectral function and Euclidean correlator from T-matrix

\[ \Gamma_M = 1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5 \rightarrow S, PS, V, AV \]

\[ G(\tau, T) = \int_0^\infty d\omega \sigma(\omega, T) \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh(\omega \beta/2)} \]

- Euclidean-time correlation function: \((t, p^+)\)

**In our T-matrix approach:**

- \[ G(E) = \int G_{QQ} + \int G_{\bar{Q}Q} T G_{\bar{Q}Q} \]
- \[ \sigma(E) \propto \text{Im} G(E) \]

- Normalization of the correlation function:

\[ G_r(\tau, T) = \int_0^\infty d\omega \sigma(\omega, T = 0) \frac{\cosh[\omega(\tau - \beta/2)]}{\sinh(\omega \beta/2)} \]

\[ R_G(\tau, T) \equiv \frac{G(\tau, T)}{G_r(\tau, T)} \]

Deviation from unity indicates medium effects in \(s(E)\)
Euclidean correlators: effect of normalization

Fix $m_c = 1.7$ GeV ($\text{Re}S=0$); $G_\gamma$ small

Normalization: $G_r = \text{vac. d-bound state} + \text{pert. cont.}$ VS $G_r = \text{vac. } T\text{-matrix} (V_{\text{Cornell}} + SB)$

$\bar{c}c$ **S-wave** ($J/\psi, h_c$)

$\bar{c}c$ **P-wave** ($c_0, c_{1,1}$)

[S-wave state (1.1$T_c$) overbound (40% variation of correlator)]

[P-wave state, missing strength, room for $m_c^*(T)$ + Zero modes!]

Kaczmarek, Zantow '05
In-medium single-particle properties: effective $m_c^*(T)$

**Eff. mass:** $m_c^*(T) = m_c + U_1^{\infty}(T) / 2$  
[from internal energy subtraction]

$E_{\text{th}} \approx 2 M_D$  

$m_c(T=0) = m_c + V_{sb} / 2$  

$[m_c = 1.35 \text{ GeV}, V_{sb} \approx 1.1 \text{ GeV} \rightarrow E_{\text{th}} \approx 2 M_D ]$  

- **upward shift** (low $T$)
- **$E_Y$ rather stable, $T>T_c$**
- **$J/Y$**
- **$c_0(1P)$**
- **vac. spectrum**

**Shift to higher energy** ($1.1T_c$)

**induces strong depletion**

$P$-wave: improved $T$ dependence, still missing strength
In-medium single-particle properties: effective $m_c^*(T)$

- $U_1^\infty(T)$ not likely to account for $\Delta m_c^*(T)$
- Leave some freedom to stabilize PS correlator:
  - ‘optimal’ eff. charm mass dependence

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In agreement with lQCD calculation of charmonium mass change in medium
H. Iida et al. PRD 74 (06) 074502
**In-medium effects: Zero modes**

\[
\sigma_{\text{zero-mode}}(\omega) = \omega \delta(\omega) \alpha_M \chi(T)
\]

\[
\chi(T') = -2 N_c \frac{1}{\pi^2} \int dk \frac{k^2 m_Q^2}{\omega_k^2} \frac{\partial n_F}{\partial \omega_k}
\]

---

Zero modes: diffusive contributions to 2-point correlation functions

- *accounted for* in spectral fncts. from LQCD
- interacting theory: related to HQ diffusion constant
- PS channel protected, all others (S, V, AV) sensitive
- Break degeneracy (PS, V) and (S, AV)
- Provide missing strength in \(P\)-waves

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T. Umeda, PRD 75 (2007) 094502
G. Aarts, J.M. Martinez-Resco, NPB 726 (2005) 93
A. Beraudo et al., PRD 77 (2008) 017502
In-medium effects: effective $m_c^*(T) +$ Zero modes

Pseudoscalar ($\eta_c$) and Vector ($J/\psi$) correlators

- 'Optimal' charm mass
- Degeneracy broken by zero modes


Fair agreement Also: Jakovac et al., PRD75 (2007) 014506
In-medium effects: effective $m_c^*(T) + Zero modes$

Scalar $(\chi_{c0})$ and Axial-Vector $(\chi_{c1})$ correlators

- ’Optimal’ charm mass
- Degeneracy broken by zero modes


Fair agreement Also: Jakovac et al., PRD75 (2007) 014506
### Spectral functions and correlators: some comments

<table>
<thead>
<tr>
<th></th>
<th>Potential</th>
<th>Rescattering</th>
<th>Thres. Effects</th>
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<tbody>
<tr>
<td>MP</td>
<td>Fenom.</td>
<td>Green’s fnct.</td>
<td>Yes</td>
</tr>
<tr>
<td>Ber</td>
<td>$(1-\alpha) U_1 + \alpha F_1$</td>
<td>Wave fnct.</td>
<td>Yes</td>
</tr>
<tr>
<td>Wo</td>
<td>$(1-\alpha) U_1 + \alpha F_1$</td>
<td>Res. states in cont.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Reasonable agreement with LQCD correlators within uncertainties (potential, matching with pQCD cont., etc.)

Can we sort out the form of $V$ at the level of accuracy of LQCD data (few per-cent level)?
More (bound) quasi-particle systems: Open Heavy flavor

- Microscopic calculation of HQ selfenergies in a $T$-matrix approach
- Potential: lattice-QCD based $U_1$ (survey to estimate uncertainties)
- $Q\bar{q}$ channels: 1 (meson), 8 (color octet)
- $Qq$ channels: 3 (diquark), 6 (diquark)
- Partial waves included: $S$, $P$
- Coupled Lippmann-Schwinger and Dyson eqs.
- HQ diffusion in QGP with Fokker-Plank eq.

**Casimir scaling:** (supported by lQCD $F_1$)

$V_8 = -V_1 / 8$; $V_3 = V_1 / 2$; $V_6 = -V_1 / 4$

van Hees, Mannarelli, Greco, Rapp PRL100 (2008) 192301

- S-wave $c\bar{q}$, $cq$
- On-shell $S_Q(p,T)$
- $c$ friction coeff. $(g)$
More (bound) quasi-particle systems: Open Heavy flavor

- Microscopic calculation of HQ selfenergies in a T-matrix approach
- Potential: lattice-QCD based $U_1$ (survey to estimate uncertainties)
- $Qq\bar{q}$ channels: $[1 \text{ (meson)}, 8 \text{ (color octet)}]$
- $Qq$ channels: $[3 \text{ (diquark)}, 6 \text{ (diquark)}]$  
  
  **Casimir scaling:** (supported by IQCD $F_1$)
  
  $$ V_8 = -V_1 / 8 \; ; \; V_3 = V_1 / 2 \; ; \; V_6 = -V_1 / 4 $$

- Partial waves included: $S, P$
- Coupled Lippmann-Schwinger and Dyson eqs.
- HQ diffusion in QGP with Fokker-Plank eq.

Langevin simulation $c, b$ quarks:

$T$-matrix + LO pQCD scattering off gluons

Fragmentation + coalescence model [Greco, Ko, Rapp '04]

+ $D, B$ decays

e$^\pm$ data (PHENIX, STAR) **fair agreement!**

van Hees, Mannarelli, Greco, Rapp PRL100 (2008) 192301

Greco, Ko, Rapp PRL98 (2007) 192301

Conclusions (I): beyond $T_c$

- **Heavy quarks** offer a unique lab for **testing strong interactions** at extreme conditions, particularly beyond the phase transition temperature.

- **Phenomenological models**: important to get a glimpse of the mechanisms leading to **survival and dissociation** of heavy quarkonia in sQGP as well as **heavy quark diffusion**.

- **T-matrix approach** with input from LQCD potentials:
  - $y$ and $U$ bound states gradually lose binding and dissolve into continuum
  - $Qq$ scattering in resonant channels: efficient heavy-quark diffusion

- **Connection to LQCD spectrum** possible if in-medium properties are properly accounted for.

- **T-matrix**: **appropriate scheme** to study **correlations in other interaction channels** ($gg$ sector, glueball bound states)