Heavy-Quark Transport in the QGP

Hendrik van Hees

Goethe University Frankfurt

March 09, 2012
1 Heavy-quark interactions in the sQGP
   - Heavy quarks in heavy-ion collisions
   - Heavy-quark diffusion: The Langevin Equation

2 Non-perturbative HQ interactions
   - Resonance model for HQ-q Scattering
   - Static heavy-quark potentials from lattice QCD
   - T-matrix approach

3 Non-photonic electrons

4 Summary and Outlook
Motivation

- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) ⇒ sQGP
- Heavy quarks as calibrated probe of QGP properties
  - produced in early hard collisions: well-defined initial conditions
  - not fully equilibrated due to large masses
  - heavy-quark diffusion ⇒ probes for QGP-transport properties
- Langevin simulation
- drag and diffusion coefficients
  - $T$-matrix approach with static lattice-QCD heavy-quark potentials
  - resonance formation close to $T_c$
  - mechanism for non-perturbative strong interactions
Heavy Quarks in Heavy-Ion collisions

hard production of HQs described by PDF’s + pQCD (PYTHIA)

c, b quark

HQ rescattering in QGP: Langevin simulation
drag and diffusion coefficients from microscopic model for HQ interactions in the sQGP

Hadronization to $D, B$ mesons via quark coalescence + fragmentation

semileptonic decay $\Rightarrow$

"non-photonic" electron observables

$R_{AA}^{e^+ e^-}(p_T), v_2^{e^+ e^-}(p_T)$
**Relativistic Langevin process**

- **Langevin process**: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

\[
\frac{d\vec{x}}{dt} = \frac{\vec{p}}{E_p} dt,
\]

\[
\frac{d\vec{p}}{dt} = -A \vec{p} dt + \sqrt{2} dt [\sqrt{B_0} P_\perp + \sqrt{B_1} P_\parallel] \vec{w}
\]

- \(\vec{w}\): normal-distributed random variable
- \(A\): friction (drag) coefficient
- \(B_{0,1}\): diffusion coefficients
- Einstein dissipation-fluctuation relation \(B_1 = E_p T A\).
- flow via Lorentz boosts between “heat-bath frame” and “lab frame”
- \(A\) and \(B_0\) from microscopic models for \(qQ, gQ\) scattering
Non-perturbative interactions: Resonance Scattering

- General idea: Survival of $D$- and $B$-meson like resonances above $T_c$
- model based on chiral symmetry (light quarks) HQ-effective theory
- elastic heavy-light-(anti-)quark scattering

$D, D', D_s$  \hspace{1cm} $D, D', D_s$

$D$- and $B$-meson like resonances in sQGP

parameters

- $m_D = 2 \text{ GeV}, \Gamma_D = 0.4 \ldots 0.75 \text{ GeV}$
- $m_B = 5 \text{ GeV}, \Gamma_B = 0.4 \ldots 0.75 \text{ GeV}$
total pQCD and resonance cross sections: comparable in size

BUT pQCD forward peaked ↔ resonance isotropic

resonance scattering more effective for friction and diffusion
Transport coefficients: pQCD vs. resonance scattering

- three-momentum dependence

\[ T=200 \text{ MeV} \]

\[ \gamma \text{[1/fm]} \]

\[ p\text{[GeV]} \]

\[ \Gamma = 0.3 \text{ GeV} \]

\[ \Gamma = 0.4 \text{ GeV} \]

\[ \Gamma = 0.5 \text{ GeV} \]

\[ \alpha_s = 0.3 \]

\[ \alpha_s = 0.4 \]

\[ \alpha_s = 0.5 \]

- resonance contributions factor \( \sim 2 \ldots 3 \) higher than pQCD!
Transport coefficients: pQCD vs. resonance scattering

- Temperature dependence

\begin{itemize}
  \item resonances: $\Gamma = 0.4$ GeV
  \item pQCD: $\alpha_s = 0.4$
  \item total
\end{itemize}
Spectra and elliptic flow for heavy quarks

- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances $\Rightarrow$ $c$-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro
color-singlet free energy from lattice $\rightarrow$ internal energy

$$U_1(r, T) = F_1(r, T) - T \frac{\partial F_1(r, T)}{\partial T},$$

$$V_1(r, T) = U_1(r, T) - U_1(r \rightarrow \infty, T)$$

Casimir scaling of Coulomb part for other color channels; confining part color blind [F. Riek, R. Rapp, Phys. Rev. C 82, 035201 (2010)].

$$V_3 = \frac{1}{2} V_1, \quad V_6 = -\frac{1}{4} V_1, \quad V_8 = -\frac{1}{8} V_1$$
T-matrix

- Brueckner many-body approach for elastic $Qq, Q\bar{q}$ scattering

\[ T = \sum_c V_T, \bar{q} + \sum_{glu} + T \Sigma \]

- Reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger
- $S$- and $P$ waves
- Relation to invariant matrix elements

\[ \sum_q \left| M(s) \right|^2 \propto \sum_q d_a \left( |T_{a,l=0}(s)|^2 + 3 |T_{a,l=1}(s)|^2 \cos \theta_{cm} \right) \]
**T-matrix results**

- **resonance formation** at lower temperatures $T \simeq T_c$
- melting of resonances at higher $T$
- model-independent assessment of elastic $Qq$, $Q\bar{q}$ scattering!
from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7 \text{ fm}/c) \simeq 4A_{\text{pQCD}}$

results for free-energy potential, $F$ considerably smaller
Bulk evolution and initial conditions

- bulk evolution as elliptic thermal fireball
- isentropic expansion with QGP Equation of State
- initial $p_T$-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming $\delta$-function fragmentation
  - exp. non-photonic single-$e^\pm$ spectra: Fix bottom/charm ratio

\[ \frac{1}{2\pi p_T} dN/dp_T \text{ [a.u.]} \]

**STAR D**

**STAR prelim. D** $^*$ $(\times 2.5)$

- c-quark (mod. PYTHIA)
- c-quark (CompHEP)

**d+Au $\sqrt{s_{NN}}=200$ GeV**

\[ \sigma_{bb}/\sigma_{cc} = 4.9 \times 10^{-3} \]

**Hendrik van Hees (GU Frankfurt)**

Heavy-Quark Transport

March 09, 2012 15 / 22
Spectra and elliptic flow for $c$-quarks

$R_{AA}$ and $v_2$ as a function of $p_T$ for Au-Au collisions at $\sqrt{s}=200$ GeV, with different transport models.

- $F_{Kac} + pQCD$ gluons
- $U_{Kac} + pQCD$ gluons
- $F_{Pet} + pQCD$ gluons
- $U_{Pet} + pQCD$ gluons

Hendrik van Hees (GU Frankfurt)
Spectra and elliptic flow for $b$-quarks

Au-Au $\sqrt{s}=200$ GeV (b=7 fm), $b$-quarks

**Left panel:**
- $R_{AA}$ vs. $p_T$ (GeV)
- $F_{Kac} + pQCD$ gluons
- $U_{Kac} + pQCD$ gluons
- $F_{Pet} + pQCD$ gluons
- $U_{Pet} + pQCD$ gluons

**Right panel:**
- $v_2$ (%) vs. $p_T$ (GeV)
- $F_{Kac} + pQCD$ gluons
- $U_{Kac} + pQCD$ gluons
- $F_{Pet} + pQCD$ gluons
- $U_{Pet} + pQCD$ gluons
Implementation in hybrid UrQMD

- Langevin simulation easily implemented into any “bulk background”
- UrQMD $\Rightarrow 1+3$ dim Hydro (Shasta) $\Rightarrow$ UrQMD
  - more realistic fireball evolution
  - possibility to study effects of fluctuations

[T. Lang, J. Steinheimer, HvH, work in progress]
Non-photonic electrons at RHIC (fireball)

- quark coalescence + fragmentation $\rightarrow D/B \rightarrow e + X$

- coalescence improves description of data
- increases both, $R_{AA}$ and $v_2$ $\Leftrightarrow$ “momentum kick” from light quarks!
- “resonance formation” towards $T_c \Rightarrow$ coalescence natural

Non-photonic electrons at RHIC (UrQMD)

- so far only quark fragmentation $\rightarrow D/B \rightarrow e + X$
so far only quark fragmentation $\rightarrow D/B \rightarrow e + X$
Summary and Outlook

- Heavy quarks in the sQGP
- non-perturbative interactions
  - mechanism for strong coupling: resonance formation at $T \gtrsim T_c$
  - lattice-QCD potentials parameter free
  - resonances melt at higher temperatures
    $\Leftrightarrow$ consistency betw. $R_{AA}$ and $v_2$!
- also provides “natural” mechanism for quark coalescence
- potential approach at finite $T$: $F$, $V$ or combination?
- Outlook
  - implementation of hadronic cross sections for D/B-meson diffusion
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - implement resonance-recombination model for hadronization
  - other heavy-quark observables like charmonium suppression/regeneration