Heavy-Quark Energy Loss in the QGP
and non-photonic Single-Electron Observables

Hendrik van Hees
Texas A&M University
October 25, 2006
Outline

Heavy quarks in the QGP
  Radiative energy loss
  Collisional energy loss

Dissipation and fluctuation: Fokker-Planck approach

Non-perturbative Effects
Motivation

- Measured $p_T$ spectra and $v_2$ of non-photonic single electrons
- Coalescence model describes data under assumption of $c$ quarks flowing with the bulk medium [Greco, Ko, Rapp 04]
Motivation

- Measured $p_T$ spectra and $v_2$ of non-photonic single electrons
- Coalescence model describes data under assumption of c quarks flowing with the bulk medium [Greco, Ko, Rapp 04]
- What is the underlying microscopic mechanism for thermalization?
  - Radiative energy loss
  - +pQCD collisional energy loss
  - Elastic three-body pQCD processes
- Additional problem: consistency between $R_{AA}$ and $v_2$
  - Importance of thermal fluctuations
  - Fokker-Planck approach to HQ rescattering $\Leftrightarrow$ thermalization
  - Langevin simulation to include (anisotropic) flow of sQGP
- Non-perturbative processes $\Leftrightarrow$ resonances in sQGP
Heavy quarks in the QGP

Hard production
Described by PDF’s + pQCD

$\bullet$ c, b quark

HQ rescattering in QGP
radiative/collisional energy loss
non-perturbative effects (sQGP)

Hadronization to D, B mesons
Fragmentation
Coalescence

$\bullet$ $K$

$e^\pm$ Semileptonic decay
$\Rightarrow$ “non-photonic” electron observables

$\nu_e$
Radiative energy loss

- medium modelled by static scattering centers [GW 94] ⇒ radiative energy loss only!
- $\Delta E \simeq \hat{q} L^2$ [BDMPS 96]
- generalized to “thin plasmas” in [GLV 00] and heavy-quark jets

![Diagram of radiative energy loss](image)
Radiative energy loss

- Calculation: [Armesto et al 06]
  (static medium + geometry + BDMPS rad energy loss)
- need to tune up $\hat{q} \rightarrow 14 \text{ GeV}^2$/fm (pQCD prediction: $\sim 1 \ldots 3 \text{ GeV}^2$/fm)
- $R_{AA}$ near to data but $v_2$ not described!
Collisional vs. radiative energy loss

- for heavy quarks: elastic pQCD scattering as important as radiative [Mustafa 05]

\[ \mu_D^2 = g^2 T^2(1 + N_f/6), \alpha_s = 0.3, N_f = 2.5 \]
\[ \frac{dN_g}{dy} = 1000 \]

- collisional energy loss important for light and heavy quarks!
Collisional vs. radiative energy loss

[Graph showing data points and curves for collisional and radiative energy loss]

[Wicks et al 05]
Three-body effects

- high densities (initially $\gtrsim 10/\text{fm}^3$)
- three-body elastic scattering possibly relevant [Liu, Ko 06]
Thermalization: Dissipation ↔ Fluctuation

- theoretical models discussed so far take into account only dissipation
- thermalization processes need also fluctuations
Thermalization: Dissipation $\leftrightarrow$ Fluctuation

- theoretical models discussed so far take into account only dissipation
- thermalization processes need also fluctuations
- principle of detailed balance

$\Rightarrow$ Use Fokker-Planck equation [Svetitsky 87; Mustafa, Thoma 98; HvH, Rapp 04; Moore, Teaney 04,...] $\leftrightarrow$ Langevin simulations
theoretical models discussed so far take into account only dissipation
thermalization processes need also fluctuations
principle of detailed balance

⇒ Use Fokker-Planck equation [Svetitsky 87; Mustafa, Thoma 98; HvH, Rapp 04; Moore, Teaney 04,...] ⇔ Langevin simulations
can we understand heavy-quark flow properties better?
consistency of $e^\pm - R_{AA}$ with $e^\pm - v_2$?
The Fokker-Planck Equation

- heavy particle (c, b quarks) in a heat bath of light particles (QGP)

\[
\frac{\partial f(t, \vec{p})}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(t, p) + \frac{\partial}{\partial p_j} B_{ij}(t, \vec{p}) \right] f(t, \vec{p})
\]

- Assumption: Relevant scattering processes are soft
The Fokker-Planck Equation

- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

\[
\frac{\partial f(t, \vec{p})}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(t, \vec{p}) + \frac{\partial}{\partial p_j} B_{ij}(t, \vec{p}) \right] f(t, \vec{p})
\]

- Assumption: Relevant scattering processes are soft

- \( A \) and \( B_{ij} \) ⇔ heavy-quark scattering processes

- \( A(t, \vec{p}) \) friction (drag) coefficient = \( 1/\tau_{eq} \)

\[
\langle p_i - p_i' \rangle = p_i A(t, \vec{p})
\]
The Fokker-Planck Equation

- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

\[
\frac{\partial f(t, \vec{p})}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(t, \vec{p}) + \frac{\partial}{\partial p_j} B_{ij}(t, \vec{p}) \right] f(t, \vec{p})
\]

- Assumption: Relevant scattering processes are soft

- $A$ and $B_{ij} \leftrightarrow$ heavy-quark scattering processes

- $A(t, \vec{p})$ friction (drag) coefficient $= 1/\tau_{eq}$

\[
\langle p_i - p'_i \rangle = p_i A(t, \vec{p})
\]

- $B_{ij}$: time scale for momentum fluctuations

\[
B_{ij}(t, \vec{p}) = \frac{1}{2} \langle (p_i - p'_i)(p_j - p'_j) \rangle
\]
The Fokker-Planck Equation

- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

\[
\frac{\partial f(t, \vec{p})}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(t, p) + \frac{\partial}{\partial p_j} B_{ij}(t, \vec{p}) \right] f(t, \vec{p})
\]

- Assumption: Relevant scattering processes are soft

- \(A\) and \(B_{ij}\) \(\leftrightarrow\) heavy-quark scattering processes

- \(A(t, \vec{p})\) friction (drag) coefficient = \(1/\tau_{eq}\)

\[
\langle p_i - p_i' \rangle = p_i A(t, \vec{p})
\]

- \(B_{ij}\): time scale for momentum fluctuations

\[
B_{ij}(t, \vec{p}) = \frac{1}{2} \langle (p_i - p_i')(p_j - p_j') \rangle
\]

- to ensure correct equilibrium limit: \(B_{\|}(t, p) = T(t) E_p A(t, p)\) (Einstein dissipation-fluctuation relation)
Langevin Study with pQCD elastic scattering

- pQCD elastic cross sections for charm-quark scattering in QGP [Moore, Teaney 04]

- hydro dynamics for bulk medium
- Langevin simulation for charm quarks
- have to increase $\alpha_s$ in cross sections (but set $\mu_D = 1.5T = \text{const!}$)
Non-perturbative Effects

- pQCD interactions of heavy quarks within QGP $\Rightarrow$ need to artificially scale up cross sections to understand $e^\pm$ data
- possible non-perturbative effects?
Non-perturbative Effects

- pQCD interactions of heavy quarks within QGP ⇒ need to artificially scale up cross sections to understand $e^\pm$ data
- possible non-perturbative effects?
- from Lattice QCD: survival of mesonic bound states/resonances above $T_c$ [Karsch, Laermann 03], [Asakawa, Hatsuda 03]
- also from IQCD based potential models [Shuryak, Zahed 04], [Wong 05], [Mannarelli, Rapp 05]
Non-perturbative Effects

- pQCD interactions of heavy quarks within QGP ⇒ need to artificially scale up cross sections to understand $e^\pm$ data
- possible non-perturbative effects?
- from Lattice QCD: survival of mesonic bound states/resonances above $T_c$ [Karsch, Laermann 03], [Asakawa, Hatsuda 03]
- also from IQCD based potential models [Shuryak, Zahed 04], [Wong 05], [Mannarelli, Rapp 05]

⇒ assumption:
  survival of $D$- and $B$-like resonance states up to $T \lesssim 2T_c$
- here: use “quasi-particle” model based on chiral symmetry and heavy-quark effective theory
- states included: $D, D^*$+chiral partners, $D_s$ (analogous for $B$) [HvH, Ralf Rapp, Phys. Rev. C 71, 034907 (2005)]
Resonance Scattering

- **elastic heavy-light-(anti-)quark scattering**

- **$D$- and $B$-meson like resonances in $s$QGP**

- **parameters**
  - $m_c = 1.5$ GeV, $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_b = 4.5$ GeV, $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV
  - Bethe-Salpeter calculations in NJL model [Blaschke et al 03]
Contributions from pQCD

- Lowest-order matrix elements [Combridge 79]

\[ \mu_g = gT, \ \alpha_s = 0.4 \]

- In-medium Debye-screening mass for \( t \)-channel gluon exchange:
Cross sections

- total pQCD and resonance cross sections: comparable in size
- BUT pQCD forward peaked $\leftrightarrow$ resonance isotropic
- resonance scattering more effective for friction and diffusion
The Coefficients: pQCD vs. resonance scattering

- Temperature dependence of thermalization rate
- charm-quark diffusion coefficient
- microscopic properties of sQGP $\leftrightarrow e^\pm$ observables

![Graph showing temperature dependence and charm-quark diffusion in QGP with pQCD and resonance contributions.]
Initial conditions

- **Langevin simulation:**
  - need initial $p_T$-spectra of charm and bottom quarks
    - fit D-meson spectra from pp and dAu@RHIC
    - exp. non-photonic single-$e^\pm$ spectra: Fix bottom/charm ratio

\[ \frac{1}{2\pi p_T} \frac{d^2N}{dp_T^2} \text{[a.u.]} \]

\[ d+Au \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \sigma_{bb}/\sigma_{cc} = 4.9 \times 10^{-3} \]
Spectra and elliptic flow for heavy quarks

- use Langevin simulation to solve Fokker-Planck equation
- expanding-fireball model to describe the sQGP medium

\[ \mu_D = gT, \quad \alpha_s = \frac{g^2}{4\pi} = 0.4 \]

- resonances \( \Rightarrow \) HQ thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- **Hadronization:** Coalescence with light quarks + fragmentation
  $\leftrightarrow c\bar{c}, b\bar{b}$ conserved

- single electrons from decay of $D$- and $B$-mesons

Without further adjustments: data quite well described
[HvH, V. Greco, R. Rapp, Phys. Rev. C 73, 034913 (2006)]
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- Hadronization: Fragmentation only
- single electrons from decay of $D$- and $B$-mesons

![Graph showing $R_{AA}$ and $v_2$ as functions of $p_T$]
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- Central Collisions
- single electrons from decay of $D$- and $B$-mesons

Coalescence+Fragmentation

Fragmentation only
How to check resonance assumption?

- scattering mechanism via *resonances* at $T > T_c$?
- dominant channel: quark-anti-$c$-quark $s$ channel

![Diagram showing scattering of quark, anti-$c$-quark, and mesons $D$, $D'$, $D_s$.]

- energy scan@RHIC: quark dominated $\Rightarrow$ $\bar{c}$ quarks most affected
- thermalization effects more pronounced for $\bar{D}$ ($D^-$) than for $D$ ($D^+$) mesons!
Implementation of radiative energy loss

- including **gluon radiation**
- work in progress [Vitev, HvH, Rapp 06]
Conclusions and Outlook

- non-photonic $e^\pm$ observables $\Leftrightarrow$ HQ interactions in sQGP
- HQ energy loss from pQCD
  - radiative energy loss $\Leftrightarrow$ upscaling of energy loss $\hat{q} \rightarrow 14$ or gluon density to explain strong effects in $e^\pm$-$R_{AA}$
  - collisional (elastic) energy loss
  - high density of plasma $\Leftrightarrow$ elastic 3-body collisions
- proper implementation of thermalization (Fokker-Planck Eq.)
  - need thermal fluctuations to describe thermalization
  - explains consistency between small $R_{AA}$ and large $v_2$
- non-perturbative interactions
  - survival of $D$- and $B$-meson like resonances above $T_c$
  - isotropic elastic-scattering cross sections $\Rightarrow$ efficient for thermalization

Further investigations (work in progress)

- microscopic models for HQ scattering [Mannarelli, HvH, Rapp 06]
- implementation of gluon-radiation processes [Vitev, HvH, Rapp 06]
- consequences for heavy quarkonia
Conclusions and Outlook

- non-photonic $e^\pm$ observables $\Leftrightarrow$ HQ interactions in sQGP
- HQ energy loss from pQCD
  - radiative energy loss $\Leftrightarrow$ upscaling of energy loss $\hat{q} \rightarrow 14$ or gluon density to explain strong effects in $e^\pm$-$R_{AA}$
  - collisional (elastic) energy loss
  - high density of plasma $\Leftrightarrow$ elastic 3-body collisions
- proper implementation of thermalization (Fokker-Planck Eq.)
  - need thermal fluctuations to describe thermalization
  - explains consistency between small $R_{AA}$ and large $v_2$
- non-perturbative interactions
  - survival of $D$- and $B$-meson like resonances above $T_c$
  - isotropic elastic-scattering cross sections $\Rightarrow$ efficient for thermalization
- Further investigations (work in progress)
  - microscopic models for HQ scattering [Mannarelli, HvH, Rapp 06]
  - implementation of gluon-radiation processes [Vitev, HvH, Rapp 06]
  - consequences for heavy quarkonia
Thermalization rate (p dependence)

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

- \( \text{resonances } \Gamma = 0.3 \text{ GeV} \)
- \( \text{resonances } \Gamma = 0.4 \text{ GeV} \)
- \( \text{resonances } \Gamma = 0.5 \text{ GeV} \)
- \( \text{pQCD: } \alpha_s = 0.3 \)
- \( \text{pQCD: } \alpha_s = 0.4 \)
- \( \text{pQCD: } \alpha_s = 0.5 \)
Spectra and elliptic flow for heavy quarks

With form-factor vertices instead of point vertices ($\Lambda = 1$ GeV)