Resonance Recombination model for Quarks in the Quark-Gluon Plasma

Hendrik van Hees
Justus-Liebig Universität Gießen

November 5, 2009
Outline

1 Motivation

2 Heavy-quark diffusion in the QGP
   • Resonance model for elastic quark scattering
   • Fokker-Planck equation and Langevin simulations
   • Nonphotonic electrons at RHIC

3 Transport approach to quark coalescence
   • Constituent-quark number and $KE_T$ scaling
   • Meson spectra

4 Conclusions
Motivation

- Strongly interacting medium in relativistic heavy-ion collisions (HICs)
  - (ideal) hydrodynamics describes low-$p_T$ spectra of hadrons
  - collective radial and elliptic flow
  - medium close to local thermal equilibrium
  - very small viscosity $\Rightarrow$ strongly coupled Quark-Gluon Plasma (sQGP)

- Possible explanation for strong interactions in QGP close to $T_c$:
  - formation of hadron-like resonances

- successful description of non-photonic $e^\pm$ data at RHIC
  - heavy-quark diffusion in QGP $\Leftrightarrow$ Fokker-Planck (FP) equation
  - non-perturbative elastic collisions close to $T_c$
  - facilitated by resonance formation
  - coalescence + fragmentation to $D$ and $B$-mesons
  - simultaneous description of $e^\pm$-$R_{AA}$ und $v_2$

[HvH, V. Greco, R. Rapp, Phys. Rev. C 73, 034913 (2006)]
[HvH, M. Mannarelli, V. Greco, Phys. Rev. Lett. 100, 192301 (2008)]
Motivation

- **Success of quark-coalescence models**
  - recombination of quarks to hadrons at the QGP phase transition
  - describes observed constituent-quark number scaling of elliptic flow:
    \[ v_{2 \text{hadrons}}(p_T) \simeq n_q v_{2 \text{quarks}}(p_T/n_q) \]
  - ⇒ recombination of comoving quarks to hadrons
  - describes large baryon/meson ratio in HICs compared to pp collisions

- **Shortcomings**
  - violates energy conservation
  - violates 2nd Law of Thermodynamics
  - CQNS better with \( KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m \) than with \( p_T \)

- **Resonance-recombination model**
  - based on kinetic theory: \( q\bar{q} \leftrightarrow R \)
  - detailed balance
  - fulfills energy-momentum conservation
  - obeys 2nd law of thermodynamics

Motivation

- **Constituent-Quark Number Scaling:** $v_2(p_T)$ vs. $v_2(KE_T)$

  - $v_2^{\text{(had)}}(p_T) = n_q v_2^{\text{(quark)}}(p_T/n_q)$
  - VS. $v_2^{\text{(had)}}(KE_T) = n_q v_2^{\text{(quark)}}(KE_T/n_q)$

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 $K^\pm e^\pm \nu_e \Rightarrow$ “non-photonic” electron observables $R_{AA}^{e^+e^-}(p_T), v_2^{e^+e^-}(p_T)$
Elastic pQCD processes

- Lowest-order matrix elements [Combridge 79]
- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on “non-photonic” electrons
Non-perturbative interactions: Resonance Scattering

- General idea: Survival of $D$- and $B$-meson like resonances above $T_c$
- elastic heavy-light-(anti-)quark scattering

$D$, $D'$, $D_s$- and $B$-meson like resonances in sQGP

- parameters
  - $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV
- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher $T! \Rightarrow s\text{QGP}$
- $P$ wave smaller
- resonances near $T_c$: natural connection to quark coalescence

[Ravagli, Rapp 07; Ravagli, HvH, Rapp 08]

- model-independent assessment of elastic $Qq, Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from lQCD in-medium potential $V$ vs. $F$?
Relativistic Langevin process

- FP equation equivalent to stochastic Langevin process
- Langevin process: friction force + Gaussian random force
- From models for heavy-light-quark scattering:
  - $A$: friction (drag) coefficient
  - $B_{0,1}$: diffusion coefficients
  - to implement flow of the medium:
    - use Lorentz boost to change into local “heat-bath frame”
    - use update rule in heat-bath frame
    - boost back into “lab frame”
Time evolution of the fire ball

- **Elliptic fire-ball parameterization**
  fitted to hydrodynamical flow pattern [Kolb ’00]

**Isentropic expansion:** $S = \text{const}$ (fixed from $N_{\text{ch}}$)

**QGP Equation of state:**
for semicentral collisions ($b = 7$ fm): $T_0 = 340$ MeV, 
QGP + mixed phase lifetime $\simeq 5$ fm/c.

**flow field** $\vec{v}_\perp(\vec{r}_\perp) \propto r_\perp$; $\perp$ isobars (confocal ellipses)
Initial conditions

- need 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

![Graph showing $1/(2\pi p_T) dN/dp_T$ vs. $p_T$ for STAR D$^0$, STAR prelim. D$^*$ ($\times 2.5$), c-quark (mod. PYTHIA), and c-quark (CompHEP) for d+Au $\sqrt{s_{NN}}=200$ GeV.]

![Graph showing $1/(2\pi p_T) dN/dp_T$ vs. $p_T$ for STAR (prel, pp), STAR (prel, d+Au/7.5), and STAR (pp), with $\sigma_{bb}/\sigma_{cc} = 4.9 \times 10^{-3}$.]

Hendrik van Hees (JLU Gießen)  
Resonance recombination in the QGP  
November 5, 2009  
12 / 22
- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances $\Rightarrow$ $c$-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro
Nonphotonic electrons at RHIC

\[ R_{AA} = \frac{dN_{\text{electrons}}}{d^3p} \text{Au+Au} @ S_{NN} = 200 \text{ GeV} \]

(a) 

\[ 0-10\% \text{ central} \]

van Hees et al. (II)

van Hees et al. (II)

Moore &

Teaney (III)

PHENIX Collaboration

PRL 98 172301 (2007)

(b)

minimum bias

\[ \pi^0, p_T > 4 \text{ GeV/c} \]

\[ e^\pm, v_2^{HF} \]

Comparison to resonance-scattering model for charm and bottom

Hendrik van Hees (JLU Gießen)

Resonance recombination in the QGP

November 5, 2009 14 / 22
Non-photonic electrons at RHIC

- **T-matrix model for charm and bottom**
- **quark coalescence + fragmentation** → $D/B \rightarrow e + X$

- coalescence crucial for description of data
- increases both, $R_{AA}$ and $v_2$ ⇔ “momentum kick” from light quarks!
- “resonance formation” towards $T_c$ ⇒ coalescence natural [Ravagli, Rapp 07]

Hendrik van Hees (JLU Gießen)  Resonance recombination in the QGP  November 5, 2009 15 / 22
Resonance-Recombination Model

- transport approach for hadronization by $q + \bar{q} \leftrightarrow \text{meson resonance}$

$$\frac{\partial}{\partial t} f_M(t, p) = -\frac{\Gamma}{\gamma_p} f_M(t, p) + g(p) \Rightarrow f_M^{(\text{eq})}(p) = \frac{\gamma_p}{\Gamma} g(p)$$

$$g(p) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} \int d^3x f_q(x, p_1) f_{\bar{q}}(x, p_2) \sigma(s) v_{\text{rel}} \delta^{(3)}(p - p_1 - p_2)$$

$$\sigma(s) = g\sigma \frac{4\pi}{k_{\text{cm}}^2} \frac{(\Gamma_m)^2}{(s - m^2)^2 + (\Gamma_m)^2}$$

Constituent-quark number scaling ($p_T$)

Scaling relations

(a) $v_{2,M}(p_T) \simeq v_{2,q1} \left( \frac{p_T}{2} \right) + v_{2,q2} \left( \frac{p_T}{2} \right)$

(b) $v_{2,M}(p_T) \simeq v_{2,q1} \left( \frac{m_{q1} p_T}{m_{q1} + m_{q2}} \right) + v_{2,q2} \left( \frac{m_{q2} p_T}{m_{q1} + m_{q2}} \right)$

Hendrik van Hees (JLU Gießen)
Resonance recombination in the QGP
November 5, 2009
$K_{ET}$ scaling of quarks

- usual coalescence models: **factorization ansatz**

$$f_q(p, x, \varphi) = f_q(p, x)[1 + 2v_2^q(p_T) \cos(2\varphi)]$$

- CQNS usually not robust with more realistic parametrizations of $v_2$

- here: $q$ input from relativistic Fokker-Planck-Langevin simulation

![Graph showing $v_2$ vs. $K_{ET}$ for charm, strange, and light quarks](image)
Constituent-quark number scaling ($KE_T$)

- usual coalescence models: factorization ansatz

$$f_q(p, x, \varphi) = f_q(p, x)[1 + 2v_2^q(p_T) \cos(2\varphi)]$$

- CQNS usually not robust with more realistic parametrizations of $v_2$

- here: $q$ input from relativistic Fokker-Planck-Langevin simulation
Meson spectra

- \( q-\bar{q} \) input: Fokker-Planck-Langevin
- meson output: resonance-recombination model

Data from [A. Adare et al. (PHENIX) PRL 98, 232301 (2007); S. S. Adler et al. (PHENIX) PRC 72, 014903 (2005); J. Adams et al. (STAR) PLB 612, 181 (2005) B. I. Abelev et al. (STAR) PRL 99, 112301 (2007)]
Conclusions

- **Heavy-quark diffusion in the QGP**
  - strongly interacting QGP ⇔ “hadron”-resonance formation close to $T_c$
  - resonance-scattering model
    (confirmed with T-matrix approach with lQCD potentials)
  - Fokker-Planck (FP) simulation of heavy quarks
  - coalescence + fragmentation ⇒ good description of non-photonic electron flow data

- **Kinetic Resonance-Recombination model**
  - quark recombination into meson-resonance states in the QGP at $T_c$
    (consistent with resonance-scattering approach in HQ diffusion!)
  - based on Boltzmann transport approach
  - energy-momentum conservation
  - detailed balance
  - 2nd Law of Thermodynamics
  - realistic space-momentum correlations ($v_2$) from FP simulation
  - results in CQNS and KET scaling of meson spectra
Problems and Outlook

- include inelastic (gluo-radiative) processes in heavy-quark interaction
- T-matrix approach: which potential is the correct one?
- FP approach for light (and strange?) quarks problematic (self-consistency problem between “bulk medium” in FP simulation and quark distributions used in recombination)
- Resonance recombination should be combined with fragmentation (particularly at higher $p_T$)
- analogous treatment of baryons (quark-diquark recombination!?)