

# Kinetics of Charm in Medium

Hendrik van Hees

Texas A&M University

July 25, 2006



Alexander von Humboldt



Stiftung / Foundation



# Outline

Heavy-quark rescattering in QGP

Non-photonic  $e^\pm$  Observables:  $v_2$  and  $R_{AA}$

Conclusions and Outlook

# Motivation

- ▶ Measured  $p_T$  spectra and  $v_2$  of non-photonic single electrons
- ▶ coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium

# Motivation

- ▶ Measured  $p_T$  spectra and  $v_2$  of non-photonic single electrons
- ▶ coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium
- ▶ What is the underlying microscopic mechanism for thermalization?
  - ▶ pQCD elastic HQ scattering: need unrealistically large  $\alpha_s$  [Moore, Teaney '04]
  - ▶ Gluon-radiative energy loss: need to enhance transport coefficient  $\hat{q}$  by large factor [Armesto et al '05] or enhanced gluon density [Djordjevic, Gyulassi et al '05]
  - ▶ including pQCD elastic scattering: still not enough equilibration of heavy quarks [Wicks et al '05]

# Motivation

- ▶ Measured  $p_T$  spectra and  $v_2$  of non-photonic single electrons
- ▶ coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium
- ▶ What is the underlying microscopic mechanism for thermalization?
  - ▶ pQCD elastic HQ scattering: need unrealistically large  $\alpha_s$  [Moore, Teaney '04]
  - ▶ Gluon-radiative energy loss: need to enhance transport coefficient  $\hat{q}$  by large factor [Armesto et al '05] or enhanced gluon density [Djordjevic, Gyulassi et al '05]
  - ▶ including pQCD elastic scattering: still not enough equilibration of heavy quarks [Wicks et al '05]
- ▶ Assumption: survival of  $D$ - and  $B$ -meson resonances in the sQGP
- ▶ facilitates elastic heavy-quark rescattering

# Free Lagrangian: Particle Content

- ▶ **Chiral symmetry**  $SU_V(2) \otimes SU_A(2)$  in light-quark sector of **QCD**

$$\mathcal{L}_D^{(0)} = \sum_{i=1}^2 [(\partial_\mu \Phi_i^\dagger)(\partial^\mu \Phi_i) - m_D^2 \Phi_i^\dagger \Phi_i] + \text{massive (pseudo-)vectors } D^*$$

- ▶  $\Phi_i$ : two doublets: **pseudo-scalar**  $\sim \begin{pmatrix} D^0 \\ D^- \end{pmatrix}$  and **scalar**
- ▶  $\Phi_i^*$ : two doublets: **vector**  $\sim \begin{pmatrix} D^{0*} \\ D^{-*} \end{pmatrix}$  and **pseudo-vector**

$$\mathcal{L}_{qc}^{(0)} = \bar{q} i \not{\partial} q + \bar{c} (i \not{\partial} - m_c) c$$

- ▶  $q$ : light-quark doublet  $\sim \begin{pmatrix} u \\ d \end{pmatrix}$
- ▶  $c$ : singlet

# Interactions

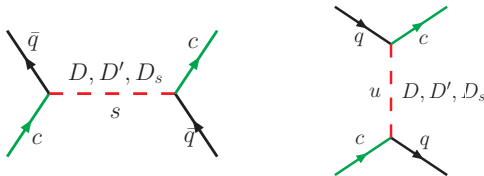
- ▶ Interactions determined by **chiral** symmetry
- ▶ For transversality of vector mesons:  
**heavy-quark effective theory vertices**

$$\begin{aligned} \mathcal{L}_{\text{int}} = & -G_S \left( \bar{q} \frac{1 + \not{v}}{2} \Phi_1 c_v + \bar{q} \frac{1 + \not{v}}{2} i\gamma^5 \Phi_2 c_v + h.c. \right) \\ & -G_V \left( \bar{q} \frac{1 + \not{v}}{2} \gamma^\mu \Phi_{1\mu}^* c_v + \bar{q} \frac{1 + \not{v}}{2} i\gamma^\mu \gamma^5 \Phi_{2\mu}^* c_v + h.c. \right) \end{aligned}$$

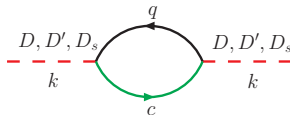
- ▶  $v$ : four velocity of heavy quark
- ▶ in **HQET**: spin symmetry  $\Rightarrow G_S = G_V$

# Resonance Scattering

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



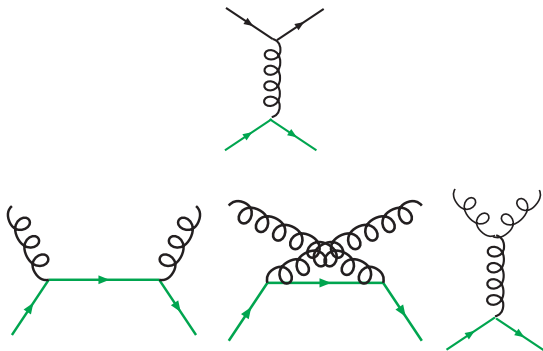
- ▶  $D$ - and  $B$ -meson like resonances in sQGP



- ▶ parameters
  - ▶  $m_D = 2 \text{ GeV}$ ,  $\Gamma_D = 0.4 \dots 0.75 \text{ GeV}$
  - ▶  $m_B = 5 \text{ GeV}$ ,  $\Gamma_B = 0.4 \dots 0.75 \text{ GeV}$

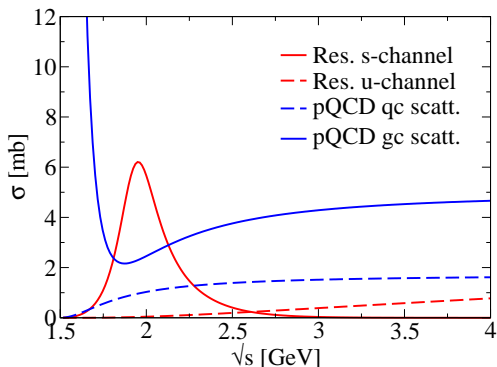
# Contributions from pQCD

- ▶ Lowest-order matrix elements (Cambridge '79)



- ▶ In-medium **Debye-screening mass** for  $t$ -channel gluon exchange:  
 $\mu_g = gT$ ,  $\alpha_s = 0.4$

# 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 Fokker-Planck Equation

- ▶ Neglect **flow** of the medium (only for the moment!)
- ▶ 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

- ▶ Neglect **flow** of the medium (only for the moment!)
- ▶ 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  $B_{ij}$  given by **averages** with matrix elements (cross sections) from **resonance model**

$$\langle X(\vec{p}') \rangle = \frac{1}{\gamma_c} \frac{1}{2E_p} \int \frac{d^3\vec{q}}{(2\pi)^3 2E_q} \int \frac{d^3\vec{q}'}{(2\pi)^3 2E_{q'}} \int \frac{d^3\vec{p}''}{(2\pi)^3 2E_{p''}} \sum |\mathcal{M}|^2 (2\pi)^4 \delta^{(4)}(p + q - p' - q') \hat{f}(\vec{q}) X(\vec{p}'')$$

# The Fokker-Planck Equation

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

- ▶  $A(t, \vec{p})$  friction (drag) coefficient =  $1/\tau_{\text{eq}}$   
 $\langle p_i - p_i' \rangle = p_i A(t, \vec{p})$

# The Fokker-Planck Equation

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

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

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

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

$$\begin{aligned} B_{ij}(t, \vec{p}) &= \frac{1}{2} \langle (p_i - p'_i)(p_j - p'_j) \rangle \\ &= B_0(t, p) \left( \delta_{ij} - \frac{p_i p_j}{p^2} \right) + B_1(t, p) \frac{p_i p_j}{p^2} \end{aligned}$$

# The Fokker-Planck Equation

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

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

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

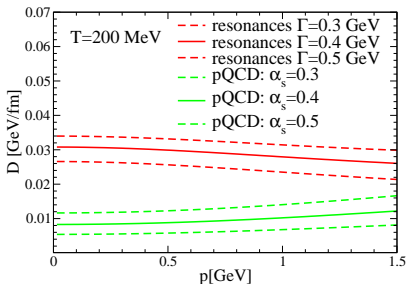
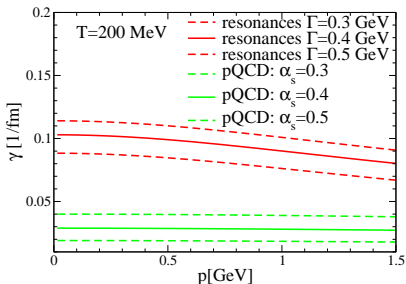
- ▶  $B_{ij}$ : time scale for momentum fluctuations

$$\begin{aligned} B_{ij}(t, \vec{p}) &= \frac{1}{2} \langle (p_i - p'_i)(p_j - p'_j) \rangle \\ &= B_0(t, p) \left( \delta_{ij} - \frac{p_i p_j}{p^2} \right) + B_1(t, p) \frac{p_i p_j}{p^2} \end{aligned}$$

- ▶ to ensure correct equilibrium limit:  $B_1(t, p) = T(t) E_p A(t, p)$   
(Einstein dissipation-fluctuation relation)

# Drag and Diffusion: pQCD vs. resonance scattering

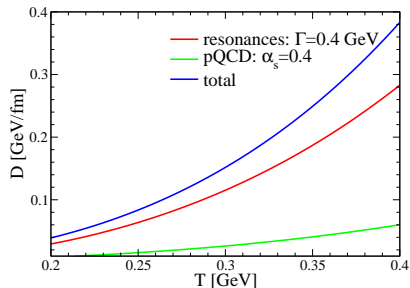
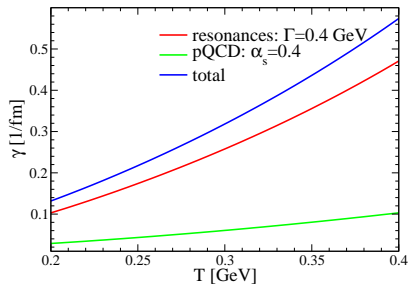
- ▶ three-momentum dependence



- ▶ resonance contributions factor  $\sim 2 \dots 3$  higher than pQCD!

# The Coefficients: pQCD vs. resonance scattering

## ► Temperature dependence



# Time evolution of the fire ball

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

$$V(t) = \pi(z_0 + v_z t)a(t)b(t), \quad a, b: \text{half-axes of ellipse,}$$
$$v_{a,b} = v_\infty[1 - \exp(-\alpha t)] \mp \Delta v[1 - \exp(-\beta t)]$$

## Time evolution of the fire ball

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

$$V(t) = \pi(z_0 + v_z t)a(t)b(t), \quad a, b: \text{half-axes of ellipse,}$$

$$v_{a,b} = v_\infty[1 - \exp(-\alpha t)] \mp \Delta v[1 - \exp(-\beta t)]$$

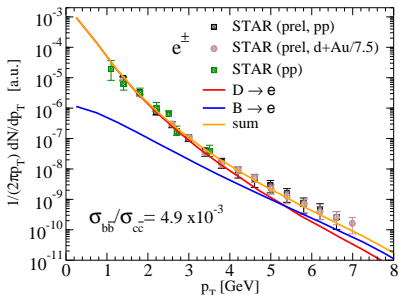
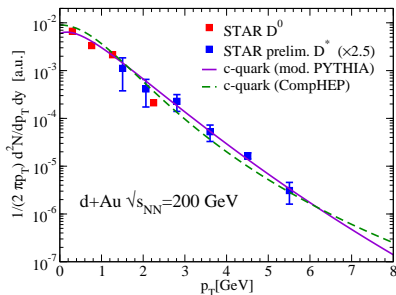
- ▶ **Isentropic expansion**:  $S = \text{const}$  (fixed from  $N_{\text{ch}}$ )
- ▶ **QGP Equation of state**:

$$s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5n_f^*), \quad n_f^* = 2.5$$

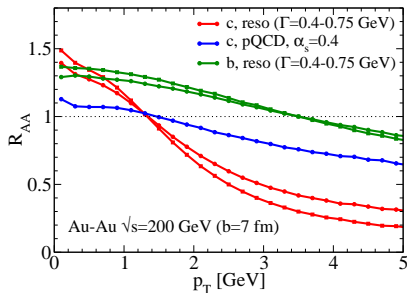
- ▶ obtain  $T(t) \Rightarrow A(t, p)$ ,  $B_0(t, p)$  and  $B_1 = TEA$
- ▶ for semicentral collisions ( $b = 7$  fm):  $T_0 = 340$  MeV,  
QGP lifetime  $\simeq 5$  fm/ $c$ .
- ▶ simulate FP equation as **relativistic Langevin process**

# Initial conditions

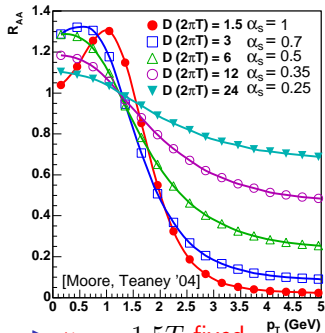
- ▶ need initial  $p_T$ -spectra of **charm** and **bottom** quarks
  - ▶ (modified) PYTHIA to describe exp. **D** meson spectra, assuming  **$\delta$ -function fragmentation**
  - ▶ exp. **non-photonic single- $e^\pm$  spectra**: Fix bottom/charm ratio



# Spectra and elliptic flow for heavy quarks

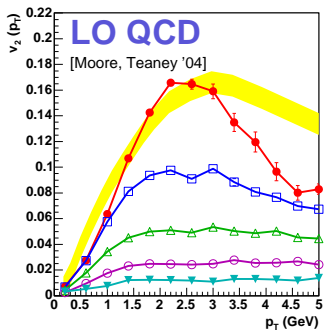
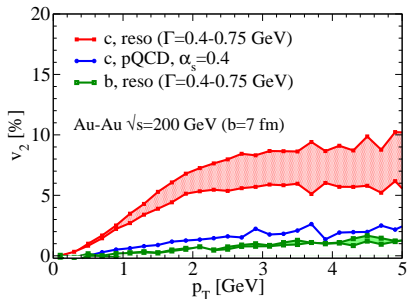


- ▶  $\mu_D = gT$ ,  $\alpha_s = g^2/(4\pi) = 0.4$
- ▶ resonances  $\Rightarrow$   $c$ -quark thermalization **without upscaling of cross sections**
- ▶ Fireball parametrization consistent with hydro



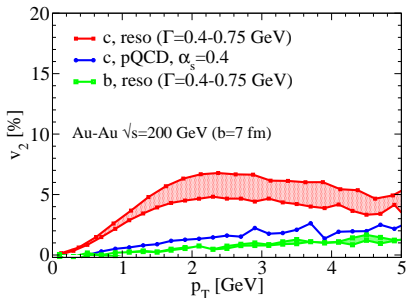
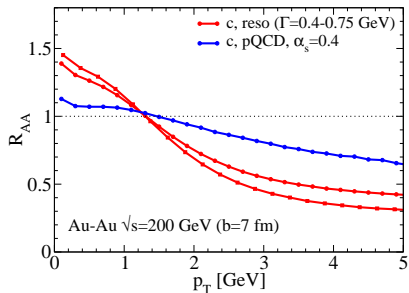
- ▶  $\mu_D = 1.5T$  fixed
- ▶  $2\pi TD \simeq \frac{3}{2\alpha_s^2}$

# Spectra and elliptic flow for heavy quarks



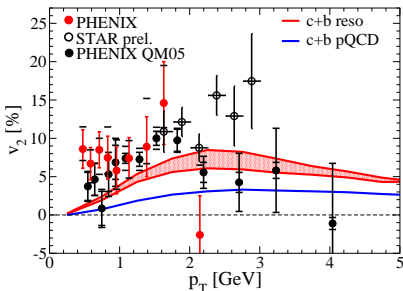
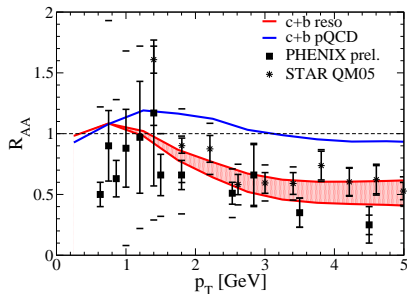
# Spectra and elliptic flow for heavy quarks

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



# Observables: $p_T$ -spectra ( $R_{AA}$ ), $v_2$

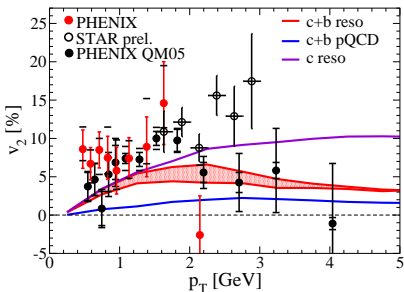
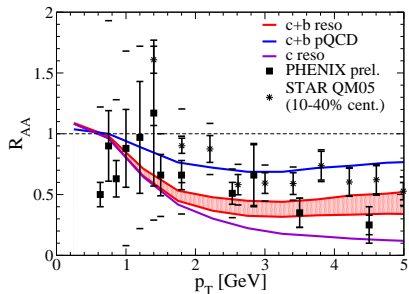
- ▶ **Hadronization: Coalescence** with light quarks (fixed before [Greco et al 03]) + **fragmentation** ( $c\bar{c}$ ,  $b\bar{b}$  conserved)
- ▶ single electrons from decay of  $D$ - and  $B$ -mesons



- ▶ Without further adjustments: data quite well described

# Observables: $p_T$ -spectra ( $R_{AA}$ ), $v_2$

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

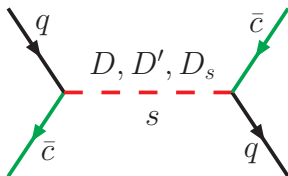


## How to check resonance assumption?

- ▶ scattering mechanism via **resonances** at  $T > T_c$ ?

## How to check resonance assumption?

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



- ▶ **CBM@FAIR**: quark dominated  $\Rightarrow$   $\bar{c}$  quarks most affected
- ▶ thermalization effects more pronounced for  $\bar{D}$  ( $D^-$ ) than for  $D$  ( $D^+$ ) mesons!

# Conclusions and Outlook

- ▶ Assumption: survival of **resonances** in the (s)QGP
- ▶ **nonperturbative re-interactions** of heavy quarks in QGP
- ▶ **Observables** via Langevin approach and coalescence+fragmentation
  - ▶ **Elastic resonance scattering**  $\Rightarrow R_{AA}^{(c)} \simeq 0.2, v_2^{(c)} \simeq 0.1$   
**without upscaling of cross sections**
  - ▶ small effects on **bottom quarks**
  - ▶ **Heavy-light quark coalescence** enhances  $v_2^{(e)}$  and  $R_{AA}$  for  
 $p_T \simeq 2$  GeV
  - ▶ **bottom** dominates for  $p_T > 3.5$  GeV  $\Rightarrow$  reduced suppression,  $v_2^{(e)}$

# Conclusions and Outlook

- ▶ Assumption: survival of **resonances** in the (s)QGP
- ▶ **nonperturbative re-interactions** of heavy quarks in QGP
- ▶ **Observables** via Langevin approach and coalescence+fragmentation
  - ▶ **Elastic resonance scattering**  $\Rightarrow R_{AA}^{(c)} \simeq 0.2, v_2^{(c)} \simeq 0.1$   
**without upscaling of cross sections**
  - ▶ small effects on **bottom quarks**
  - ▶ **Heavy-light quark coalescence** enhances  $v_2^{(e)}$  and  $R_{AA}$  for  
 $p_T \simeq 2$  GeV
  - ▶ **bottom** dominates for  $p_T > 3.5$  GeV  $\Rightarrow$  reduced suppression,  $v_2^{(e)}$
- ▶ Further investigations
  - ▶ improved (softer) fragmentation
  - ▶ implementation of gluon-radiation processes
  - ▶ quantitative consequences for quarkonia