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

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Outline

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]

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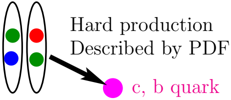
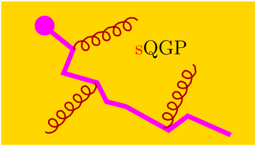
- Measured p_T spectra and v_2 of non-photonic single electrons
- coalescence model describes data under assumption of c quarks flowing with the bulk medium [Greco, Ko, Rapp 04]
- What is the underlying microscopic mechanism for thermalization?
  - Radiative energy loss
  - $+$pQCD collisional energy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

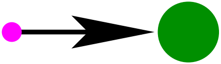
Heavy quarks in the QGP



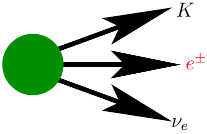
Hard production
Described by PDF's + pQCD



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



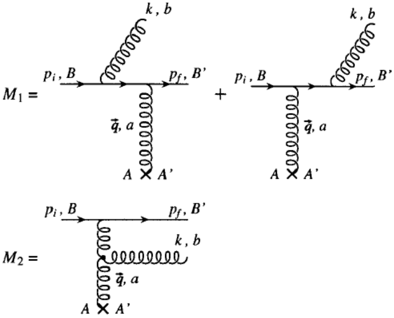
Hadronization to D, B mesons
Fragmentation
Coalescence



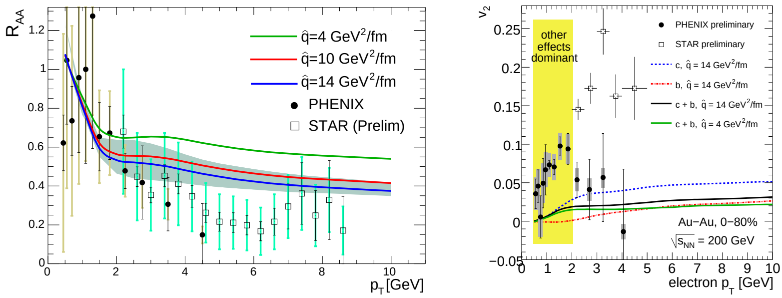
Semileptonic decay
⇒ “non-photonic” electron observables

Radiative energy loss

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



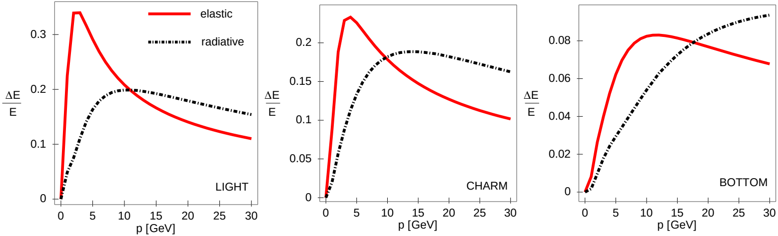
Radiative energy loss



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

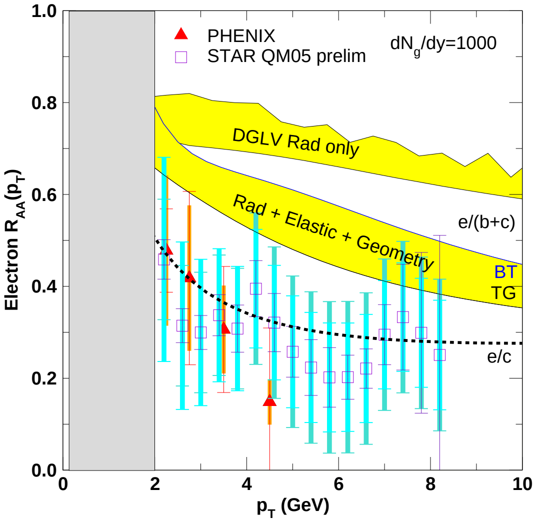
Collisional vs. radiative energy loss

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



- calculation [Djordjevic '06]: t-channel gluon exchange
  dressed gluon propagator
  $\mu_D^2 = g^2 T^2 (1 + N_f/6)$, $\alpha_s = 0.3$, $N_f = 2.5$
  $\mathrm{d}N_g/\mathrm{d}y = 1000$
- collisional energy loss important for light and heavy quarks!

Collisional vs. radiative energy loss

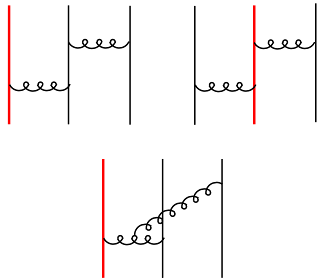


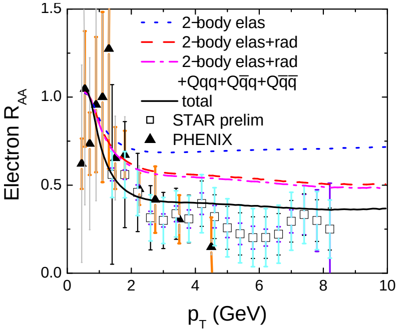
[Wicks et al 05]

Three-body effects

- high densities (initially $\gtrsim 10/\text{fm}^3$)

$\Rightarrow$ three-body elastic scattering possibly relevant [Liu, Ko 06]





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- thermalization processes need also fluctuations

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$\Rightarrow$ Use Fokker-Planck equation [Svetitsky 87; Mustafa, Thoma 98; HvH, Rapp 04; Moore, Teaney 04,...] $\Leftrightarrow$ Langevin simulations

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- 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

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- Assumption: Relevant scattering processes are soft
- A and B_{ij} $\Leftrightarrow$ heavy-quark scattering processes
- $A(t,\vec{p})$ friction (drag) coefficient $= 1/\tau_{\text{eq}}$

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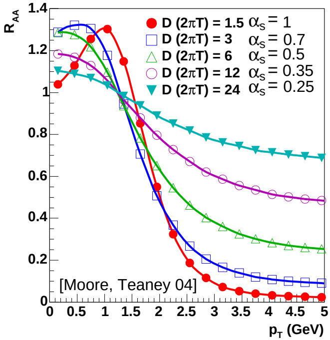
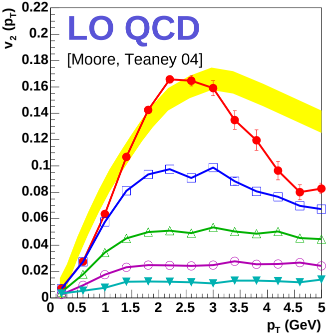
- to ensure correct equilibrium limit: $B_{\|}(t,p) = T(t) E_p A(t,p)$ (Einstein dissipation-fluctuation relation)

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 α_s in cross sections (but set $\mu_D = 1.5\,T =$ const!)

Non-perturbative Effects

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

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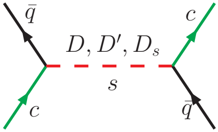
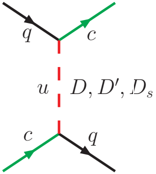
$\Rightarrow$ assumption:
survival of D- and B-like resonance states up to $T \lesssim 2T_c$

- 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)]

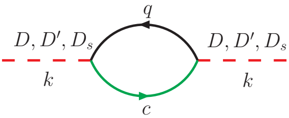
Resonance Scattering

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





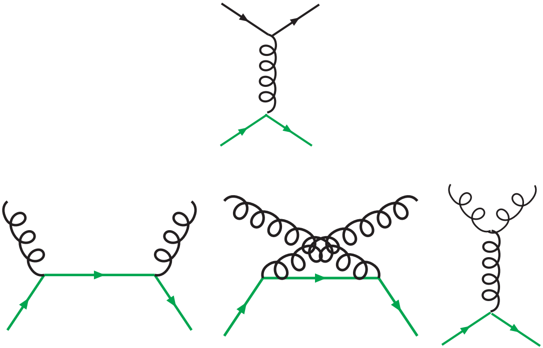
- D- and B-meson like resonances in sQGP



- 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]

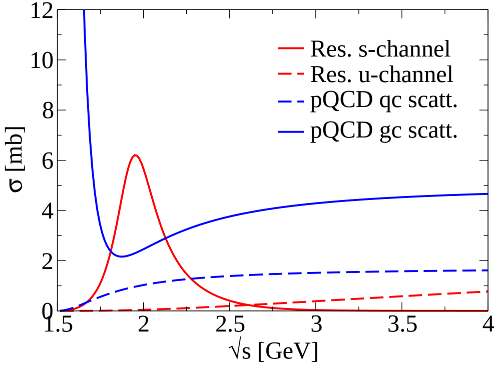
Contributions from pQCD

- Lowest-order matrix elements [Combridge 79]



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

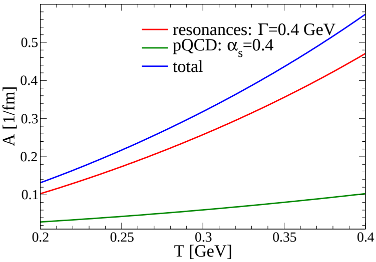
Cross sections



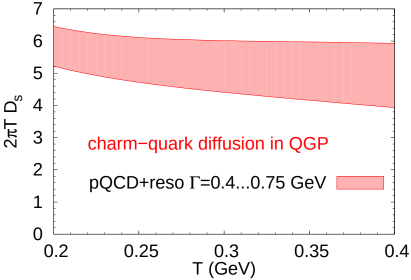
- total pQCD and resonance cross sections: comparable in size
- BUT pQCD forward peaked ↔ resonance isotropic
- resonance scattering more effective for friction and diffusion

The Coefficients: pQCD vs. resonance scattering

- Temperature dependence of thermalization rate

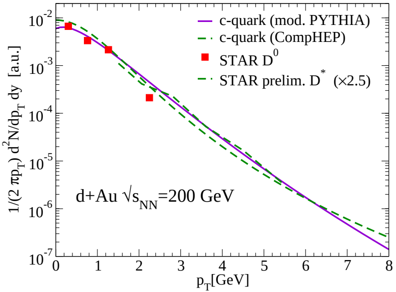


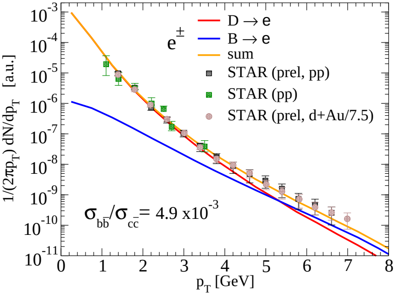
- charm-quark diffusion coefficient
- microscopic properties of sQGP $\Leftrightarrow$ $e^{\pm}$ observables



Initial conditions

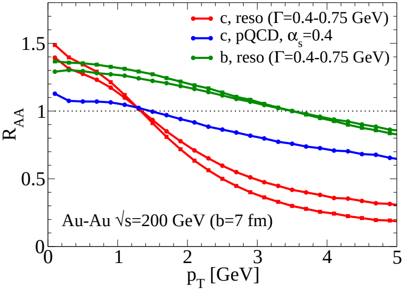
- Langevin simulation:
  need initial p_T-spectra of charm and bottom quarks
  - fit D-meson spectra from pp and dAu@RHIC
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio

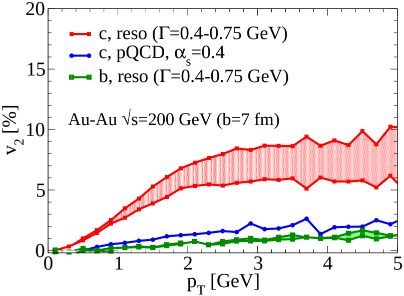




Spectra and elliptic flow for heavy quarks

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

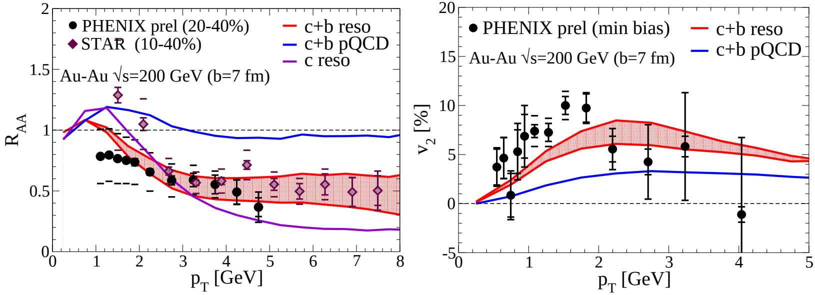




- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances ⇒ HQ thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

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

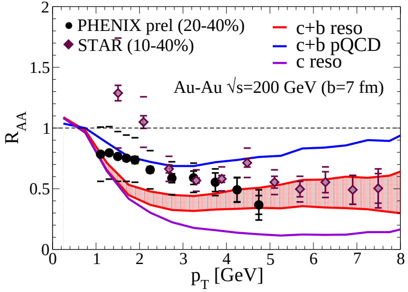
- Hadronization: Coalescence with light quarks + fragmentation
  $\Leftrightarrow$ $c\bar{c}$, $b\bar{b}$ conserved
- single electrons from decay of D- and B-mesons

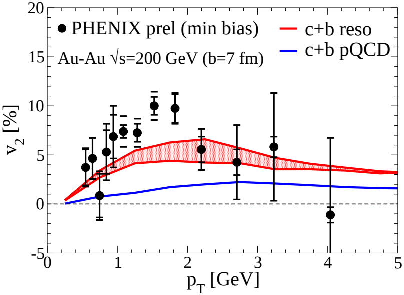


- Without further adjustments: data quite well described
  [HvH, V. Greco, R. Rapp, Phys. Rev. C **73**, 034913 (2006)]

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

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

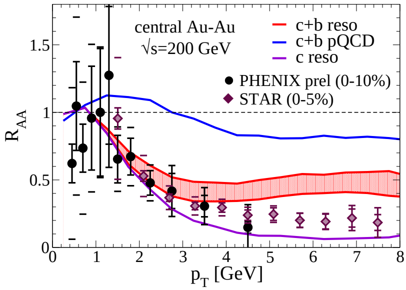




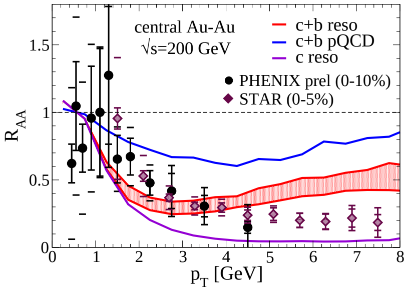
Observables: p_T-spectra (R_{AA}), v_2

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

Coalescence+Fragmentation

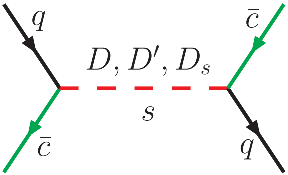


Fragmentation only



How to check resonance assumption?

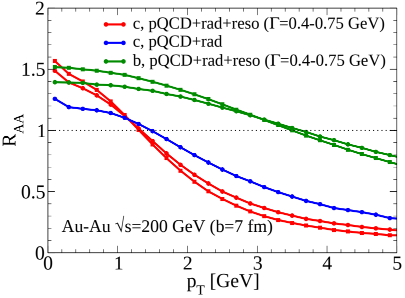
- scattering mechanism via resonances at $T > T_c$?
- dominant channel: quark-anti-c-quark s channel

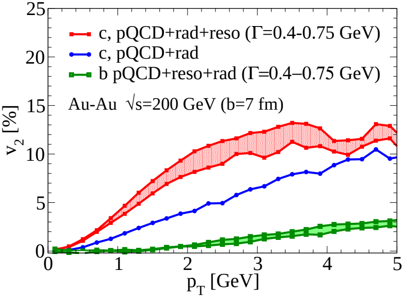


- energy scan@RHIC: quark dominated $\Rightarrow$ $\bar{c}$ quarks most affected
- thermalization effects more pronounced for $\bar{D}$ (D^-) than for D (D^+) mesons!

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 $\hat{q} \to 14$ 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

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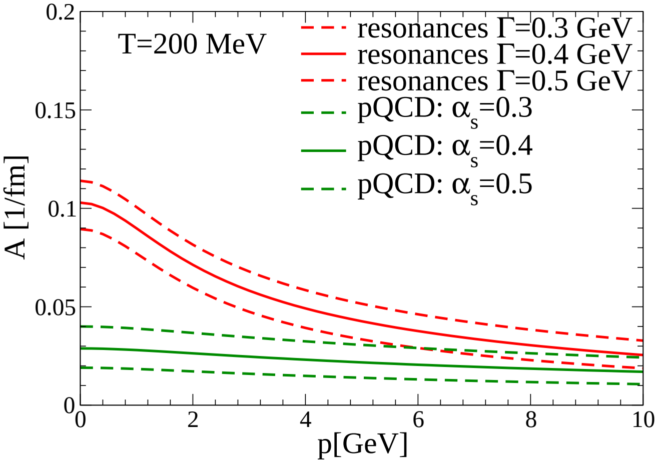
- Further investigations (work in progress)
  - microscopic models for HQ scattering [Mannarelli, HvH, Rapp 06]
  - implementation of gluon-radiation processes [Vitev, HvH, Rapp 06]
  - consequences for heavy quarkonia

Thermalization rate (p dependence)



Spectra and elliptic flow for heavy quarks

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