Heavy-Quark Kinetics in the Quark-Gluon Plasma

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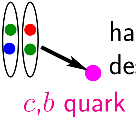
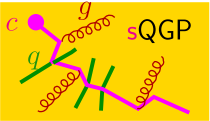
Outline

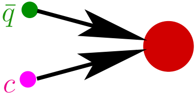
Heavy Quarks in Heavy-Ion collisions



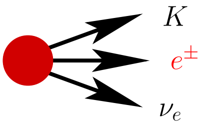
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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
V. Greco, C. M. Ko, R. Rapp, PLB **595**, 202 (2004)



semileptonic decay $\Rightarrow$
"non-photonic" electron observables
$R_{AA}^{\mathrm{e}^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$

Relativistic Langevin process

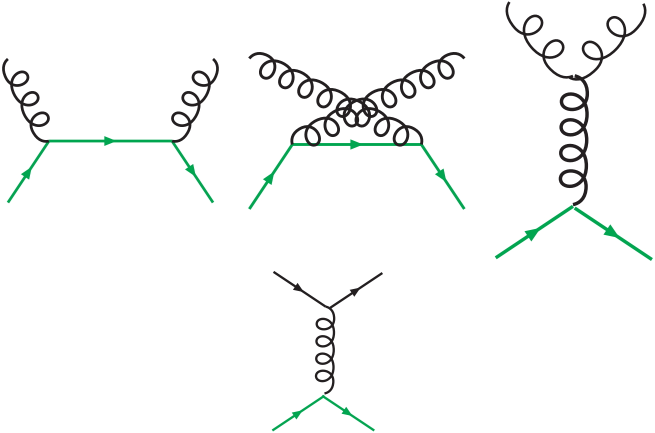
- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\parallel]\vec{w}$$

- $\vec{w}$: normal-distributed random variable
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- dependent on realization of stochastic process
- to guarantee correct equilibrium limit: Use Hänggi-Klimontovich calculus, i.e., use $B_{0/1}(t,\vec{p}+\mathrm{d}\vec{p})$
- Einstein dissipation-fluctuation relation $B_0 = B_1 = E_p T A$.
- 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"

Elastic pQCD processes

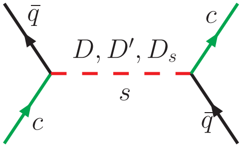
- Lowest-order matrix elements [Combridge 79]

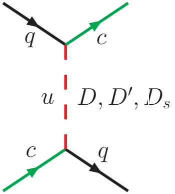


- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on "non-photonic" electrons

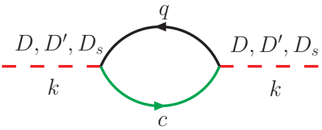
Non-perturbative interactions: Resonance Scattering

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



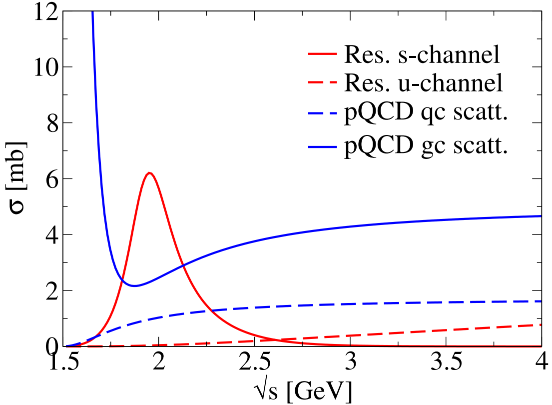


- D- and B-meson like resonances in sQGP



- 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

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

Time evolution of the fire ball

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

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

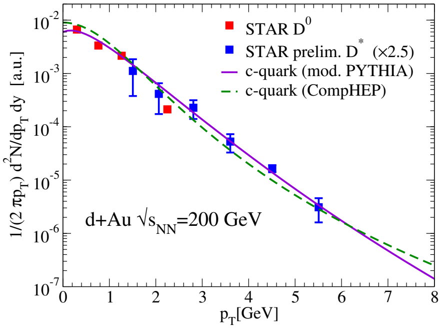
- Isentropic expansion: $S = \text{const}$ (fixed from N_{ch})
- QGP Equation of state:

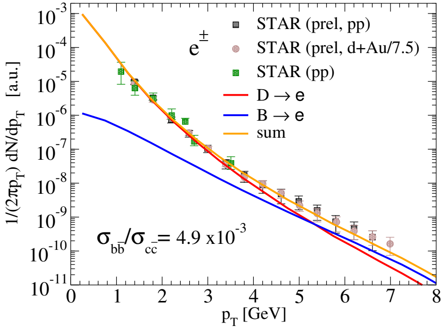
$$s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5 n_f^*), \quad n_f^* = 2.5$$

- 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

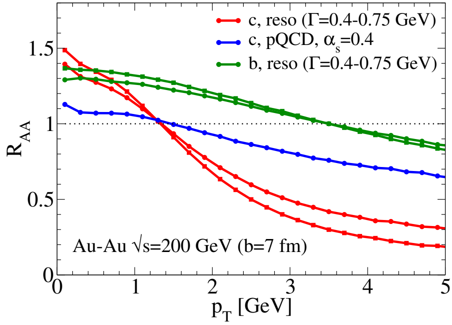
Initial conditions

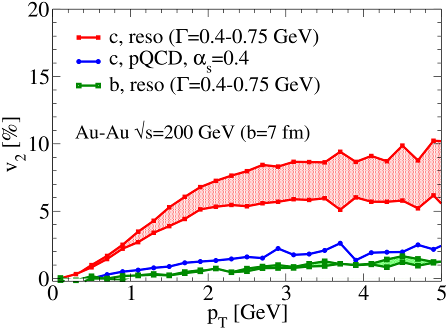
- need initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio





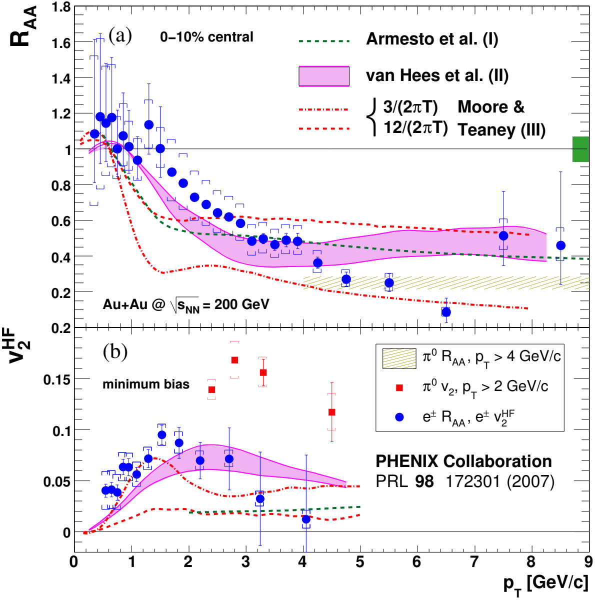
Spectra and elliptic flow for heavy quarks



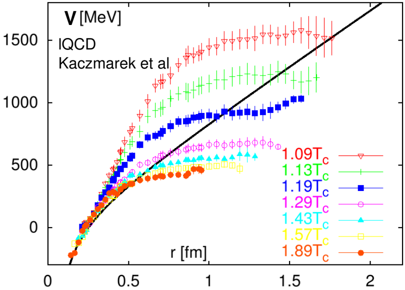


- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances ⇒ c-quark thermalization
  without upscaling of cross sections
- Fireball parametrization consistent with hydro

Comparison to single-electron spectra @ RHIC



Microscopic model: Static potentials from lattice QCD



- color-singlet free energy from lattice
- use internal energy

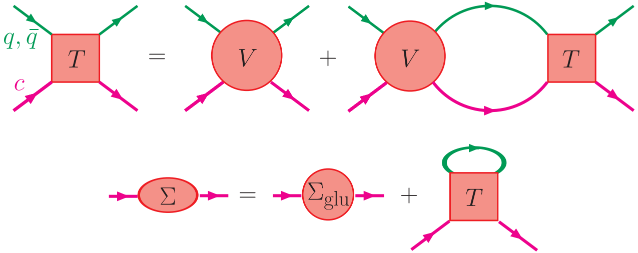
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

- Casimir scaling for other color channels [Nakamura et al 05; Döring et al 07]

$$V_{\bar{3}} = \frac{1}{2}V_1, \quad V_6 = -\frac{1}{4}V_1, \quad V_8 = -\frac{1}{8}V_1$$

T-matrix

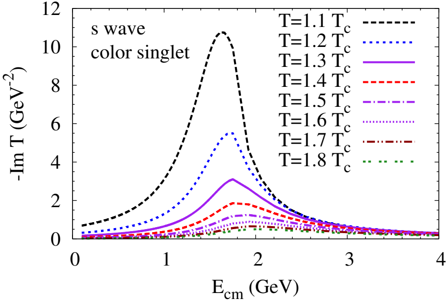
- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering

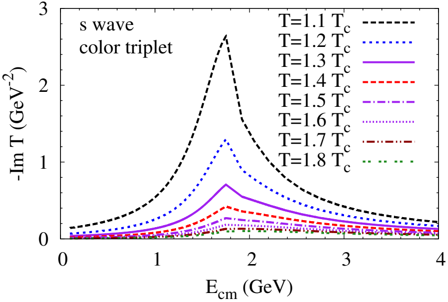


- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- same scheme for light quarks (self consistent!)
- Relation to invariant matrix elements

$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}}\right)$$

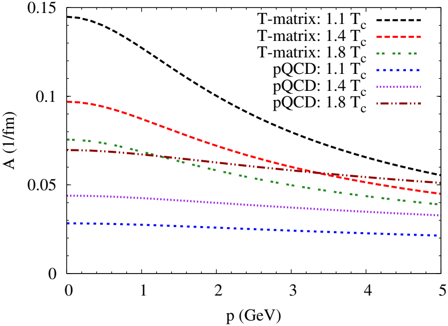
Microscopic justification for resonances: T-matrix calculation

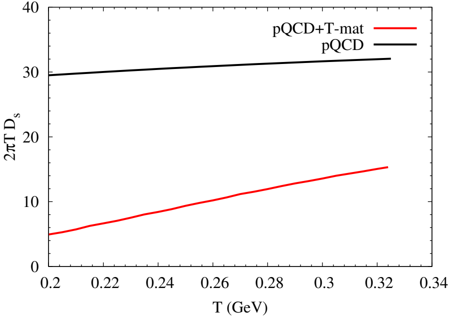




- use static heavy-quark potentials from lQCD
- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T! $\Rightarrow$ sQGP
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from lQCD in-medium potential V vs. F?

Transport coefficients





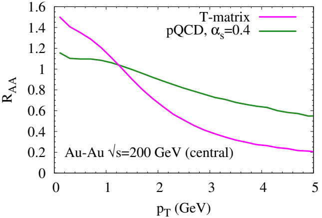
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7 \text{ fm}/c) \simeq 4 A_{\text{pQCD}}$
- A decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

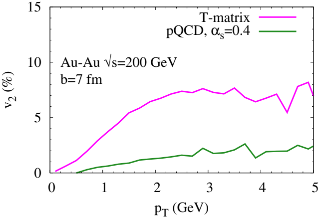
$$D_s = \frac{T}{mA}$$

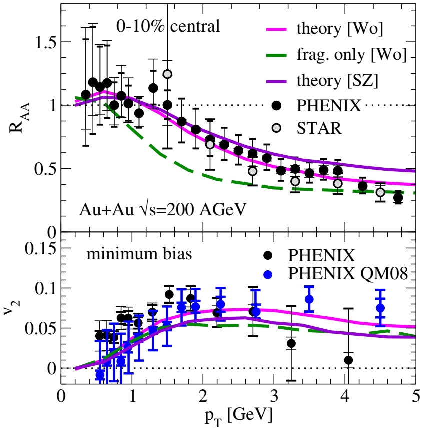
increases with temperature

Non-photonic electrons at RHIC

- same model for bottom
- quark coalescence+fragmentation $\rightarrow D/B \rightarrow e + X$





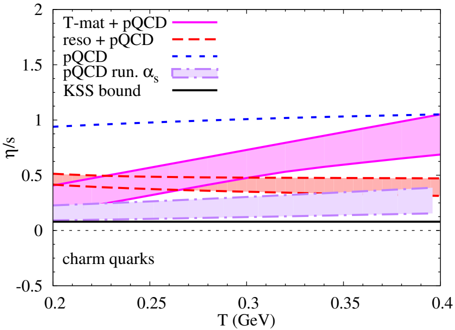


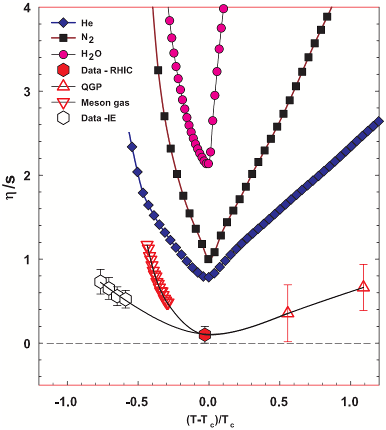
- coalescence crucial for description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards $T_c \Rightarrow$ coalescence natural [Ravagli, Rapp 07]

Transport properties of the sQGP

- spatial diffusion coefficient: Fokker-Planck $\Rightarrow D_s = \frac{T}{mA} = \frac{T^2}{D}$
- measure for coupling strength in plasma: η/s

$$\frac{\eta}{s} \simeq \frac{1}{2} T D_s \qquad \text{(AdS/CFT)}, \qquad \frac{\eta}{s} \simeq \frac{1}{5} T D_s \qquad \text{(wQGP)}$$





[Lacey, Taranenko (2006)]

Summary and Outlook

- Summary
  - Heavy quarks in the sQGP
  - non-perturbative interactions
    - mechanism for strong coupling: resonance formation at $T \gtrsim T_c$
    - lQCD potentials parameter free
    - res. melt at higher temperatures $\Leftrightarrow$ consistency betw. R_{AA} and v_2!
  - also provides "natural" mechanism for quark coalescence
  - resonance-recombination model [L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]
  - problems
    - potential approach at finite T: F, V or combination?
- Outlook
  - use more realistic bulk-medium description (real hydro)
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - take into account D/B-meson rescattering in the hadronic phase
  - other heavy-quark observables like charmonium suppression/regeneration