Heavy-Quark Transport in the QGP

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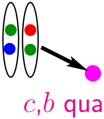
Outline

1. Heavy-quark interactions in the sQGP
   - Heavy quarks in heavy-ion collisions
   - Heavy-quark diffusion: The Langevin Equation
2. Non-perturbative HQ interactions
   - Resonance model for HQ-q Scattering
   - Static heavy-quark potentials from lattice QCD
   - T-matrix approach
3. Non-photonic electrons
4. Summary and Outlook

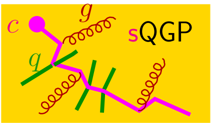
Motivation

- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) $\Rightarrow$ sQGP
- Heavy quarks as calibrated probe of QGP properties
  - produced in early hard collisions: well-defined initial conditions
  - not fully equilibrated due to large masses
  - heavy-quark diffusion $\Rightarrow$ probes for QGP-transport properties
- Langevin simulation
- drag and diffusion coefficients
  - T-matrix approach with static lattice-QCD heavy-quark potentials
  - resonance formation close to T_c
  - mechanism for non-perturbative strong interactions

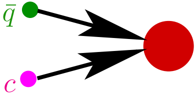
Heavy Quarks in Heavy-Ion collisions



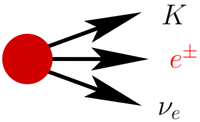
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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



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

Relativistic Langevin process

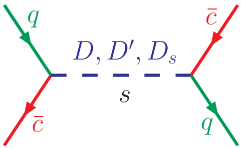
- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

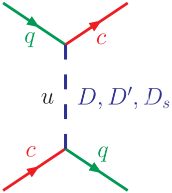
$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\parallel]\vec{w}$$

- $\vec{w}$: normal-distributed random variable
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- Einstein dissipation-fluctuation relation $B_1 = E_p T A$.
- flow via Lorentz boosts between "heat-bath frame" and "lab frame"
- A and B_0 from microscopic models for qQ, gQ scattering

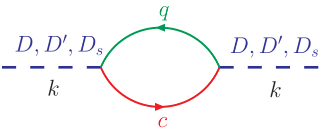
Non-perturbative interactions: Resonance Scattering

- General idea: Survival of D- and B-meson like resonances above T_c
- model based on chiral symmetry (light quarks) HQ-effective theory
- elastic heavy-light-(anti-)quark scattering



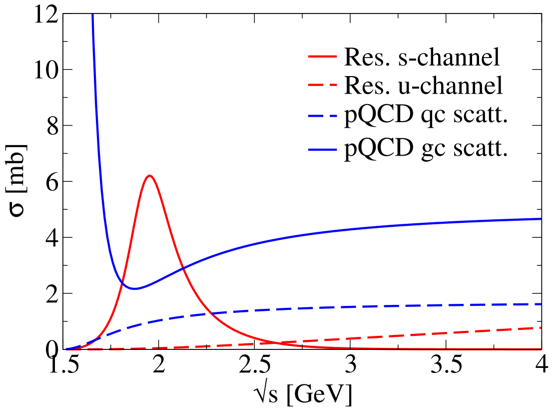


- D- and B-meson like resonances in sQGP



- 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

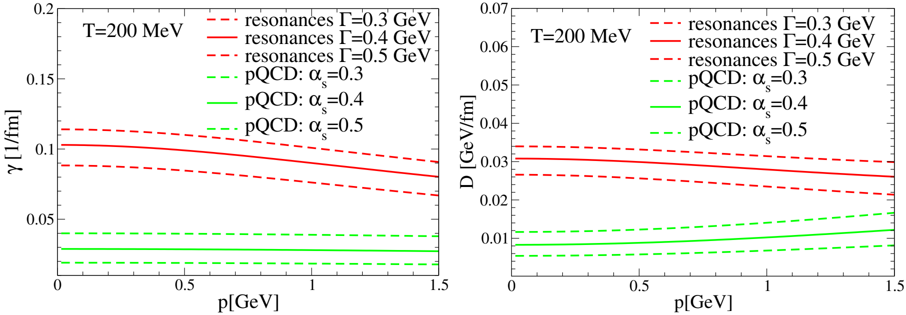
Cross sections



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

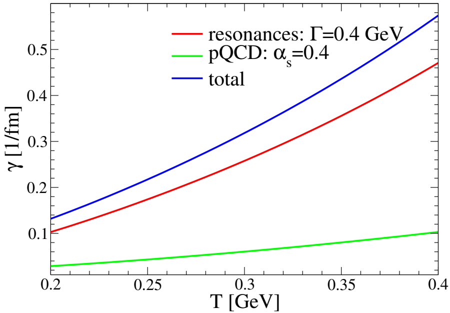
Transport coefficients: pQCD vs. resonance scattering

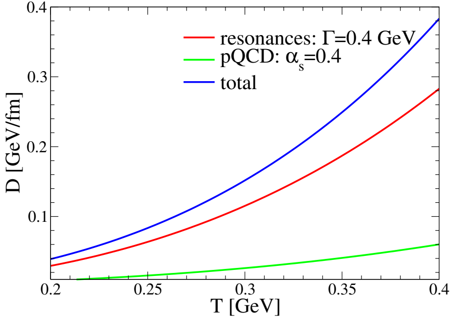
- three-momentum dependence



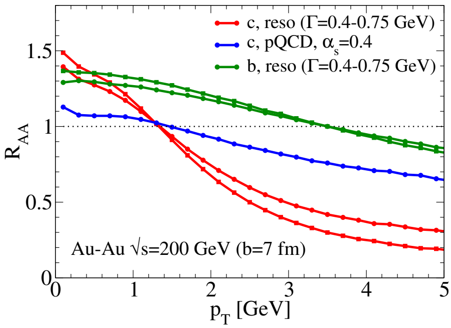
- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

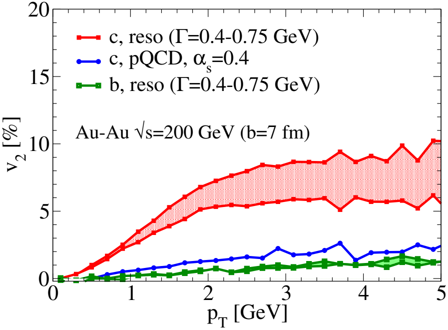
- Temperature dependence





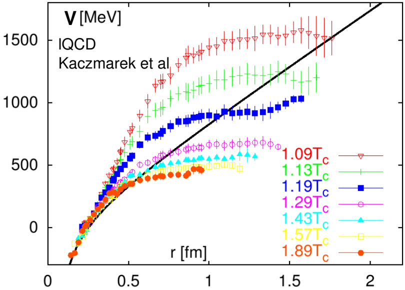
Spectra and elliptic flow for heavy quarks





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

Static heavy-quark potentials from lattice QCD



- color-singlet free energy from lattice → internal energy

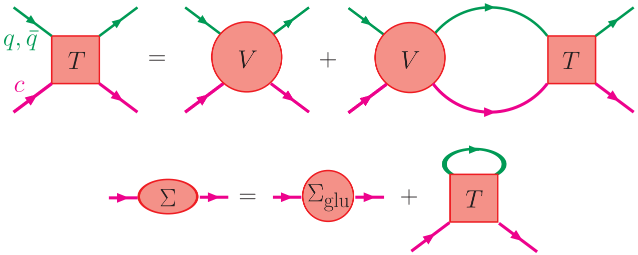
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

- Casimir scaling of Coulomb part for other color channels; confining part color blind [F. Riek, R. Rapp, Phys. Rev. C **82**, 035201 (2010)].

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

T-matrix

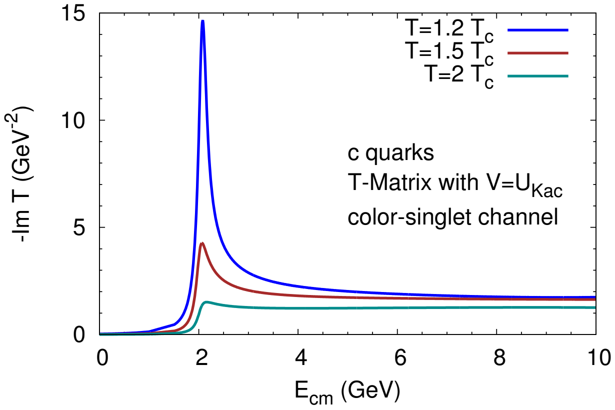
- Bruckner many-body approach for elastic Qq, $Q\bar{q}$ scattering



- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- Relation to invariant matrix elements

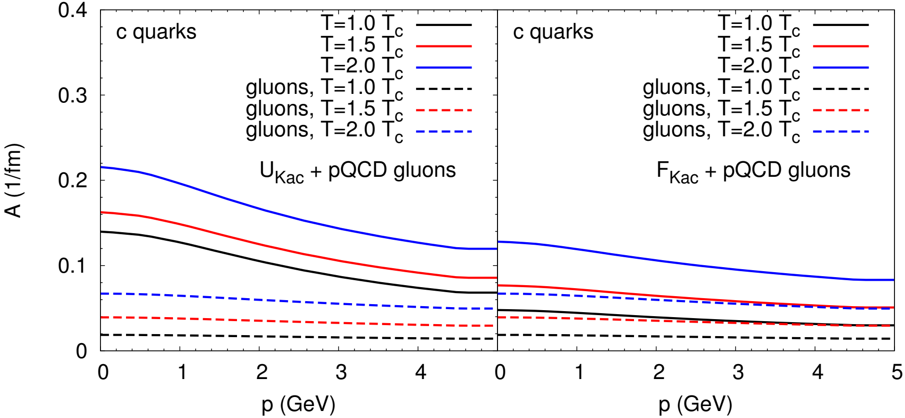
$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}} \right)$$

T-matrix results



- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering!

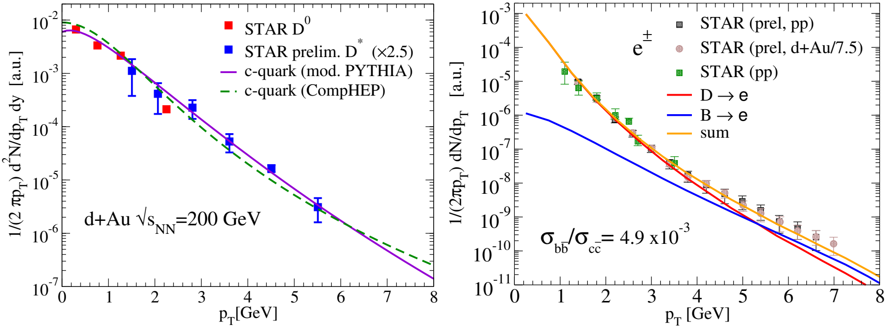
Transport coefficients



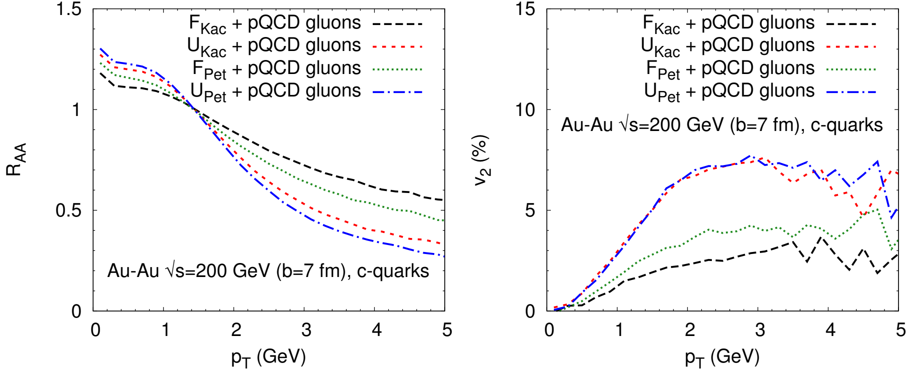
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\ \text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- results for free-energy potential, F considerably smaller

Bulk evolution and initial conditions

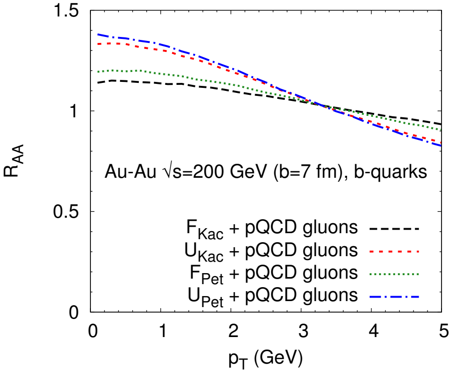
- bulk evolution as elliptic thermal fireball
- isentropic expansion with QGP Equation of State
- initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio

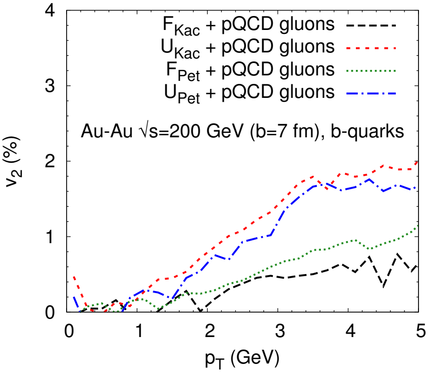


Spectra and elliptic flow for c-quarks



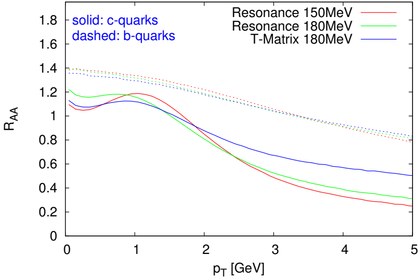
Spectra and elliptic flow for *b*-quarks

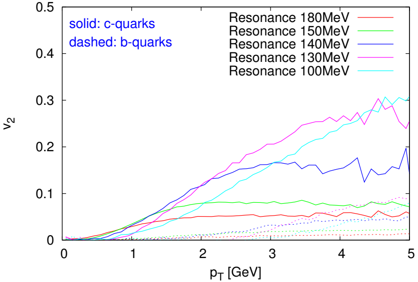




Implementation in hybrid UrQMD

- Langevin simulation easily implemented into any “bulk background”
- UrQMD ⇒ 1+3 dim Hydro (Shasta) ⇒ UrQMD
  - more realistic fireball evolution
  - possibility to study effects of fluctuations

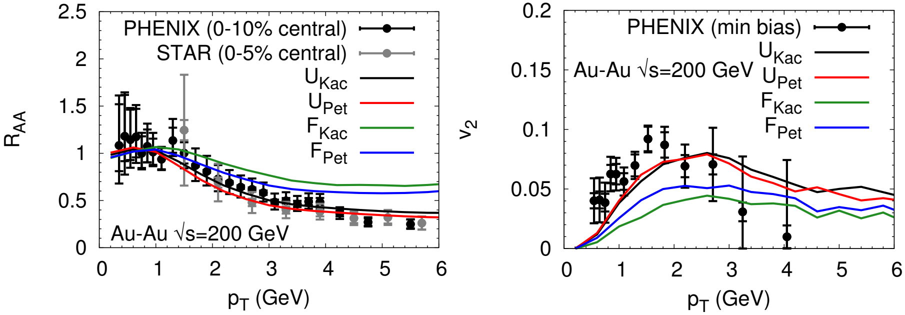




[T. Lang, J. Steinheimer, HvH, work in progress]

Non-photonic electrons at RHIC (fireball)

- quark coalescence+fragmentation $\rightarrow D/B \rightarrow e + X$

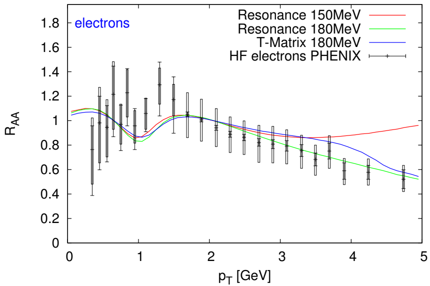


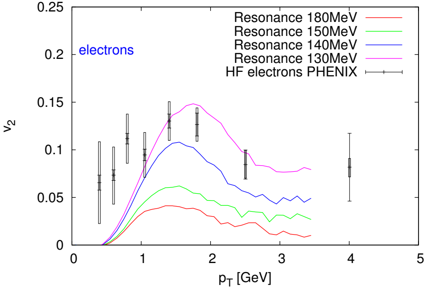
- coalescence improves description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards $T_c \Rightarrow$ coalescence natural

[L. Ravagli, R. Rapp, Phys. Lett. B **655**, 126, (2007); L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]

Non-photonic electrons at RHIC (UrQMD)

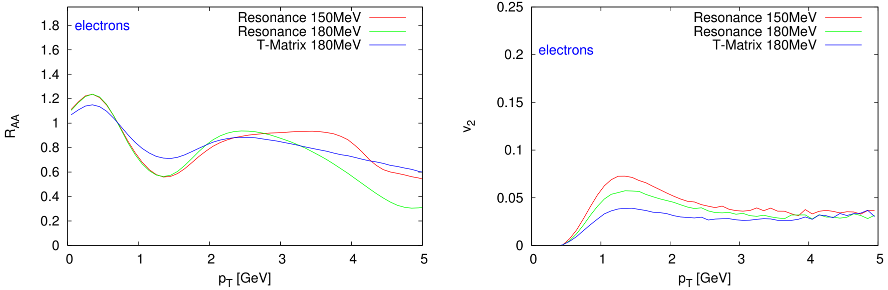
- so far only quark fragmentation $\to D/B \to e + X$





Non-photonic electrons at LHC (UrQMD)

- so far only quark fragmentation $\rightarrow D/B \rightarrow e + X$



Summary and Outlook

- Heavy quarks in the sQGP
- non-perturbative interactions
  - mechanism for strong coupling: resonance formation at $T \gtrsim T_c$
  - lattice-QCD potentials parameter free
  - resonances melt at higher temperatures
    $\Leftrightarrow$ consistency betw. R_{AA} and v_2!
- also provides "natural" mechanism for quark coalescence
- potential approach at finite T: F, V or combination?
- Outlook
  - implementation of hadronic cross sections for D/B-meson diffusion
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - implement resonance-recombination model for hadronization
  - other heavy-quark observables like charmonium suppression/regeneration