Heavy-Quark Transport in the QGP

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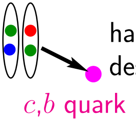
Outline

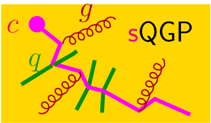
Motivation

- 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 only 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

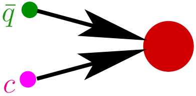
Heavy Quarks in Heavy-Ion collisions



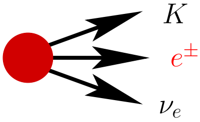
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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
$R_{AA}^{\mathrm{e}^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$

The Fokker-Planck Equation

- Fokker-Planck equation

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

- transition rates

$$w(\vec{p},\vec{k}) = \gamma_q \int \frac{\mathrm{d}^3 \vec{q}}{(2\pi)^3} f_q(\vec{q}) v_{\text{rel}}(\vec{p},\vec{q} \rightarrow \vec{p}-\vec{k}, \vec{q}+\vec{k}) \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

- with drag and diffusion coefficients

$$A_i(\vec{p}) = \int \mathrm{d}^3\vec{k}\; k_i w(\vec{p},\vec{k}), \quad B_{ij}(\vec{p}) = \frac{1}{2} \int \mathrm{d}^3\vec{k}\; k_i k_j w(\vec{p},\vec{k})$$

- equilibrated light quarks and gluons: coefficients in heat-bath frame
- matter homogeneous and isotropic

$$A_i(\vec{p}) = A(p) p_i, \quad B_{ij}(\vec{p}) = B_0(p) P_{ij}^{\perp} + B_1(p) P_{ij}^{\parallel}$$

$$\text{with} \quad P_{ij}^{\parallel}(\vec{p}) = \frac{p_i p_j}{\vec{p}^2}, \quad P_{ij}^{\perp}(\vec{p}) = \delta_{ij} - \frac{p_i p_j}{\vec{p}^2}$$

Relativistic Langevin process

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

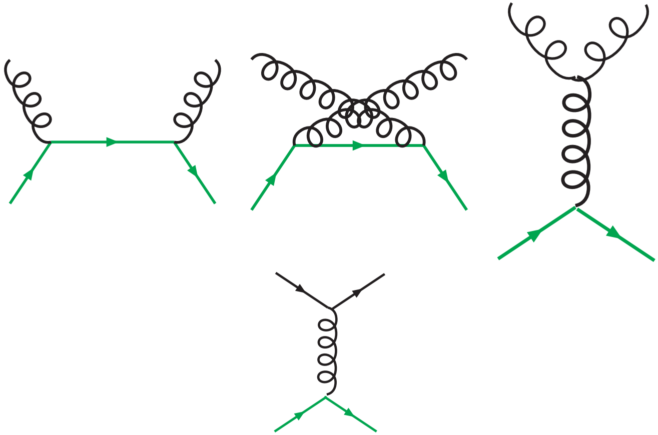
$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\|]\vec{w}$$

- $\vec{w}$: 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: Lorentz boost between heat-bath and lab frame
- still ambiguities in "freeze-out description"

[P. B. Gossiaux, S. Vogel, HvH, J. Aichelin, R. Rapp, M. He, M. Bluhm, arXiv: 1102.1114 [hep-ph]]

Elastic pQCD processes

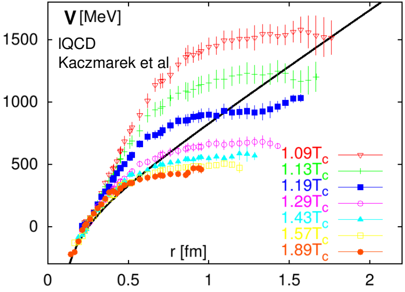
- Lowest-order matrix elements [Combridge 79]

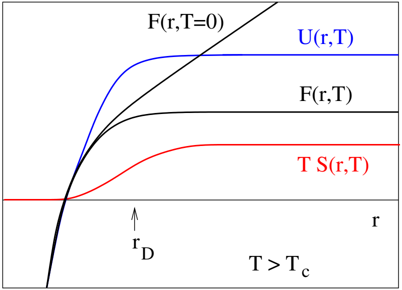


- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on "non-photonic" electrons

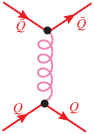
Static heavy-quark potentials from lattice QCD

- lattice QCD at finite temperature: calculate free energy $F = U - TS$
- calculate difference between $F_{\bar{Q}Q}$ with Q and $\bar{Q}$ at distance, r and F
- average Hamiltonian for static $\bar{Q}Q$: $\langle H \rangle_T = U = -T^2 \partial(F/T)/\partial T$
- long-distance limit: $2M_D(T) \simeq 2m_c + U(\infty, T)$
- can be reinterpreted as medium-modified heavy-quark mass
- short-distance: enhancement of U over $T = 0$ Cornell potential
- "right" potential $V = xU + (1-x)F$?





The potential fit to lattice data



- non-perturbative static gluon propagator

$$D_{00}(\vec{k}) = 1/(\vec{k}^2 + \mu_D^2) + m_G^2/(\vec{k}^2 + \tilde{m}_D^2)^2$$

- finite-T HQ color-singlet-free energy from Polyakov loops

$$\exp[-F_1(r,T)/T] = \left\langle \mathrm{Tr}[\Omega(x)\Omega^\dagger(y)]/N_c \right\rangle$$

$$= \exp\left[\frac{g^2}{2N_c T^2}\left\langle A_{0,\alpha}(x)A_{0,\alpha}(y) - A_{0,\alpha}^2(x)\right\rangle\right] + \mathcal{O}(g^6)$$

- identify $\langle A_{0,\alpha}(x)A_{0,\alpha}(y)\rangle = D_{00}(x-y)$
- color-singlet free energy

$$F_1(r,T) = -\frac{4}{3}\alpha_s\left\{\frac{\exp(-m_D r)}{r} + \frac{m_G^2}{2\tilde{m}_D}[\exp(-\tilde{m}_D r) - 1] + m_D\right\}$$

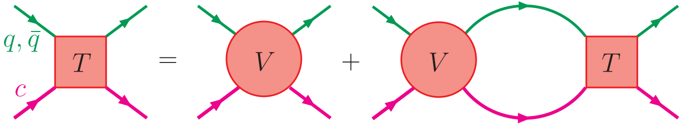
- in vacuo $m_D, \tilde{m}_D \to 0$

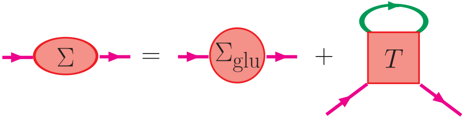
$$F_1(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r, \quad \sigma = \frac{2\alpha_s m_G^2}{3}$$

[F. Riek, R. Rapp, PRC **82**, 035201 (2010)]

T-matrix approach for qQ scattering

- T-matrix Brückner approach for heavy quarkonia as for HQ diffusion
- consistency between HQ diffusion and $\bar{Q}Q$ suppression!



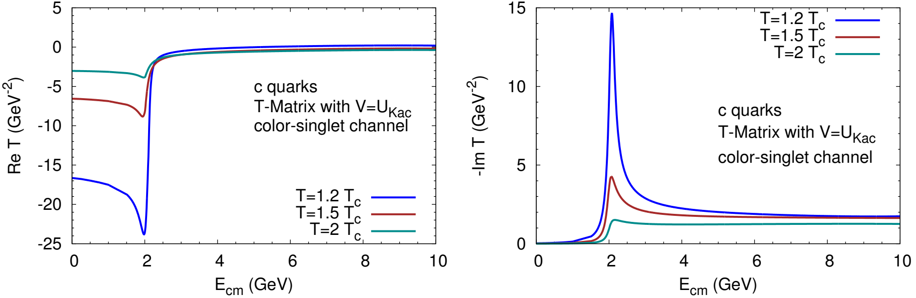


- 4D Bethe-Salpeter equation $\rightarrow$ 3D Lippmann-Schwinger equation
- relativistic interaction $\rightarrow$ static heavy-quark potential (lQCD)

$$T_\alpha(E; q', q) = V_\alpha(q', q) + \frac{2}{\pi} \int_0^\infty \mathrm{d}k\, k^2 V_\alpha(q', k) G_{Q\bar{Q}}(E; k) T_\alpha(E; k, q) \times \{1 - n_F[\omega_1(k)] - n_F[\omega_2(k)]\}$$

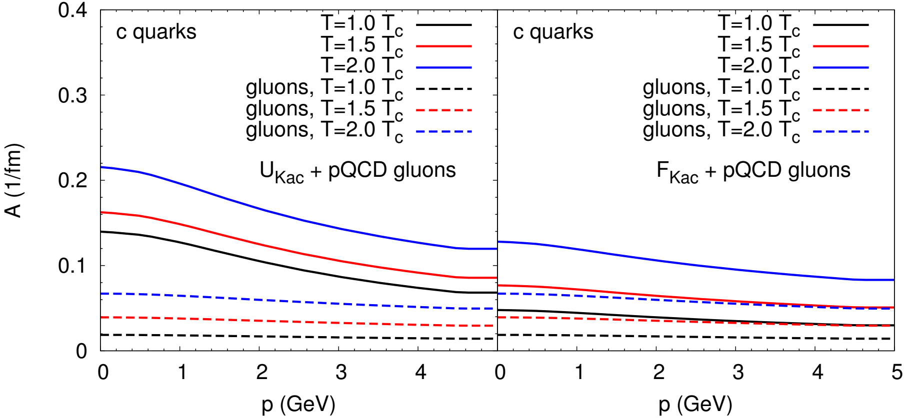
- q, q', k relative 3-momentum of initial, final, interm. qQ or $\bar{q}Q$ state
  [F. Riek, R. Rapp, PRC **82**, 035201 (2010)]

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!

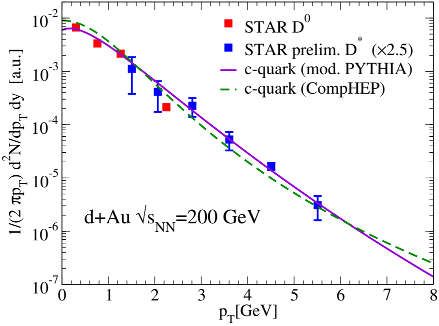
Transport coefficients

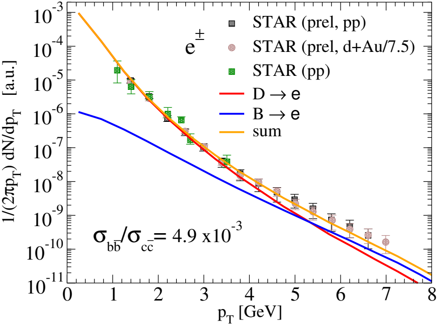


- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\ \text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- results for free-energy potential, F considerably smaller

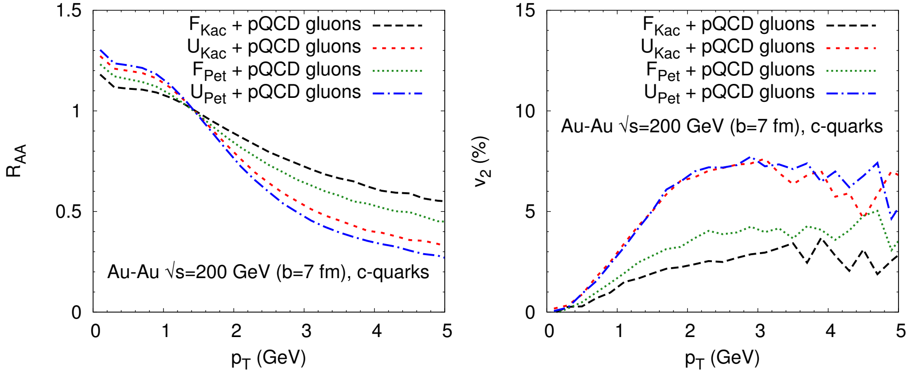
Bulk evolution and initial conditions

- 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

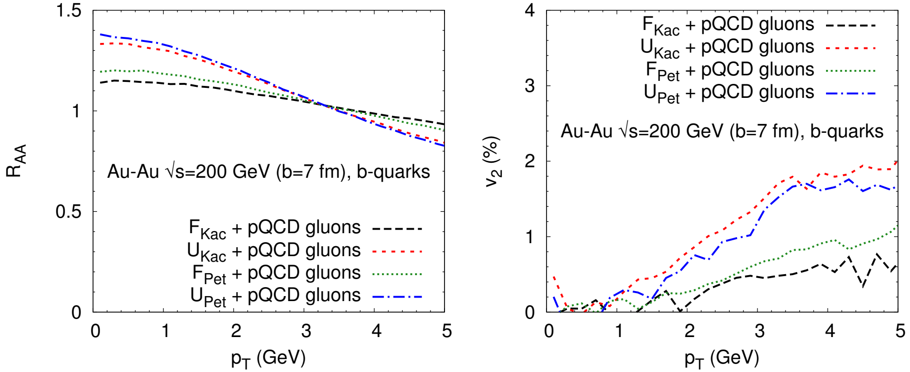




Spectra and elliptic flow for c-quarks

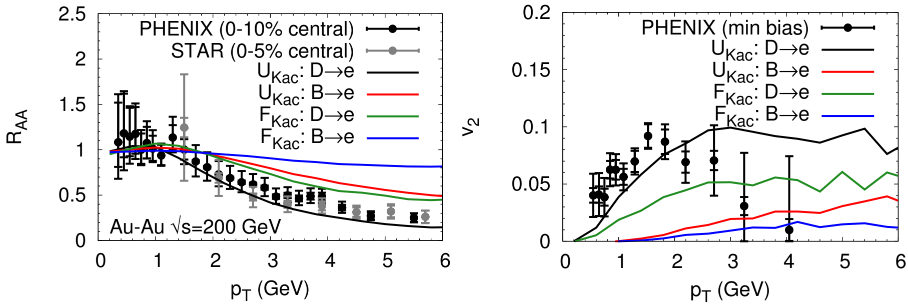


Spectra and elliptic flow for *b*-quarks



Non-photonic electrons at RHIC

- 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

[L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]

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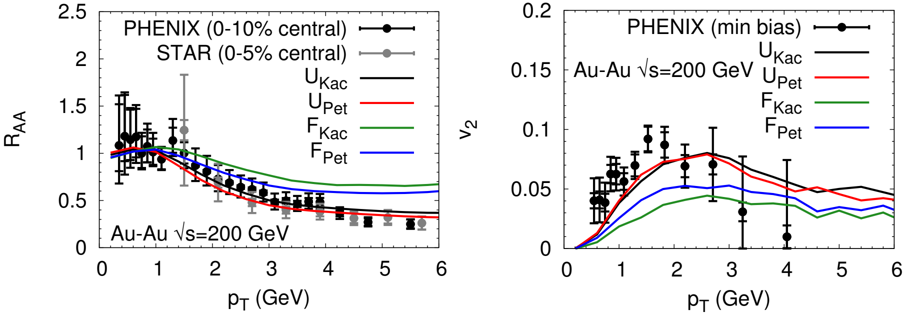

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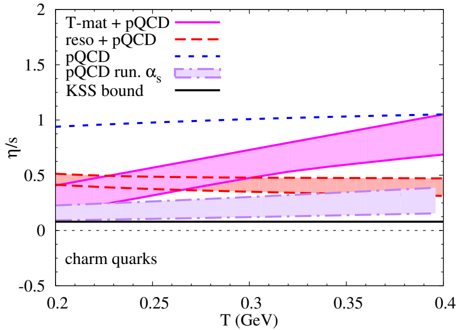
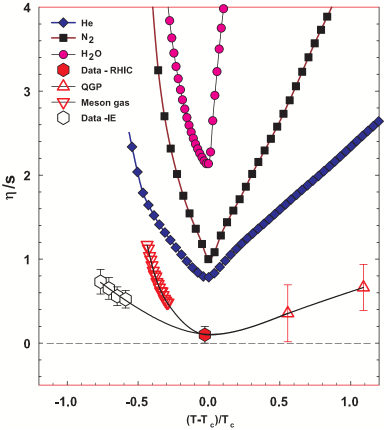
Transport properties of the sQGP

- 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

- 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
- resonance-recombination model [L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]
- potential approach at finite T: F, V or combination?
- Non-photonic electron observables
  - described by model independent lQCD-based potentials
  - resonance formation provides strong coupling of HQs to plasma
  - $\Rightarrow$ transport properties of sQGP (small η/s)
- Outlook
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - other heavy-quark observables like charmonium suppression/regeneration