Heavy-Quark Transport in the QGP

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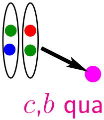
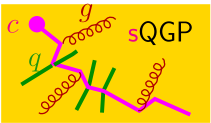
Motivation

- 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

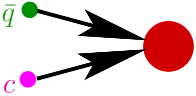
Heavy Quarks in Heavy-Ion collisions



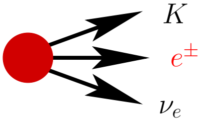
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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

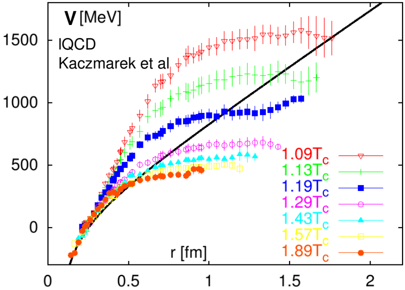
Relativistic Langevin process

- 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

Microscopic model: Static potentials from lattice QCD



- color-singlet free energy from lattice → internal energy

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

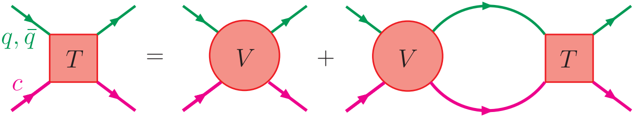
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

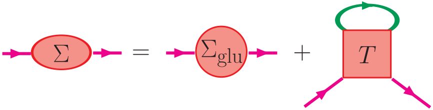
- Casimir scaling of Coulomb part for other color channels; confining part color blind [F. Riek, R. Rapp, Phys. Rev. C **82**, 035201 (2010)].

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

T-matrix

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

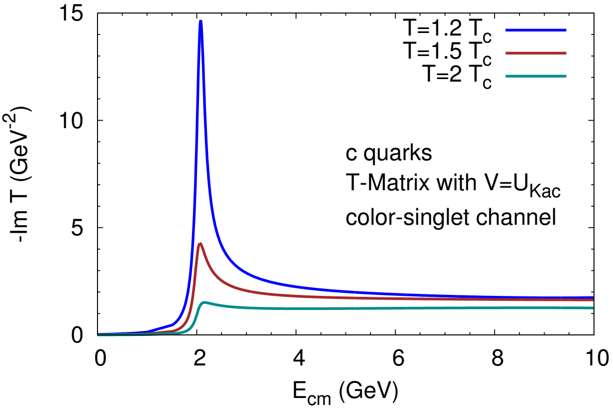




- reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger
- S- and P waves
- Relation to invariant matrix elements

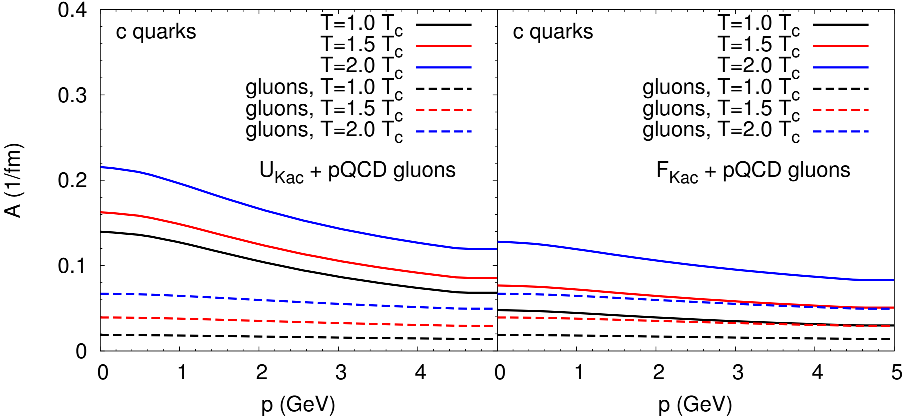
$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}} \right)$$

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!

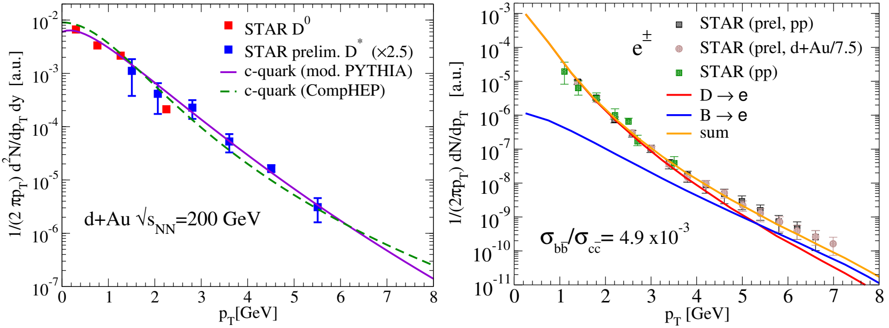
Transport coefficients



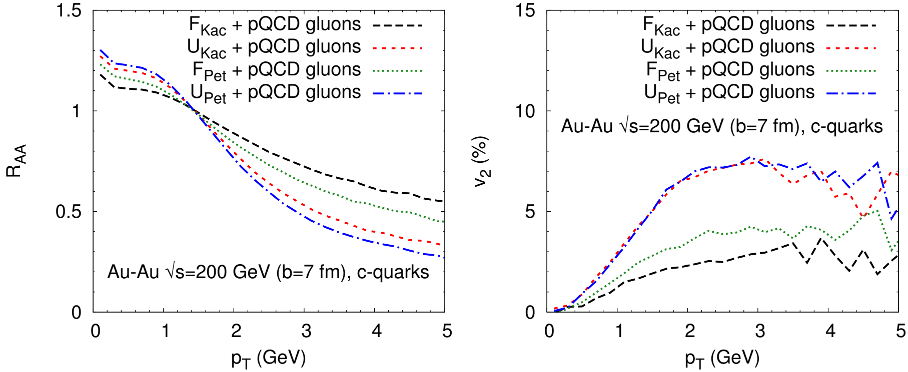
- from non-pert. interactions reach $A_{\mathrm{non-pert}} \simeq 1/(7\ \mathrm{fm}/c) \simeq 4 A_{\mathrm{pQCD}}$
- results for free-energy potential, F considerably smaller

Bulk evolution and initial conditions

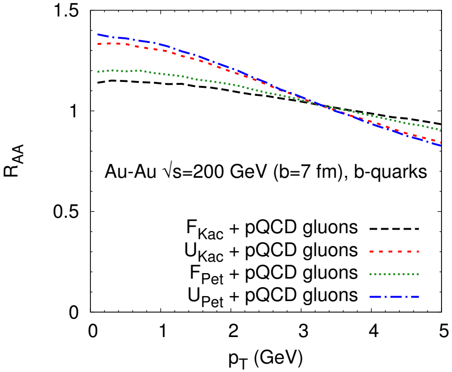
- bulk evolution as elliptic thermal fireball
- isentropic expansion with QGP Equation of State
- initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio

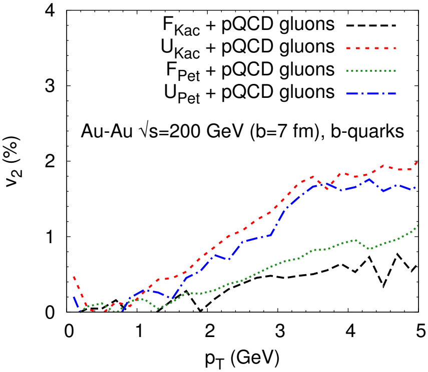


Spectra and elliptic flow for c-quarks



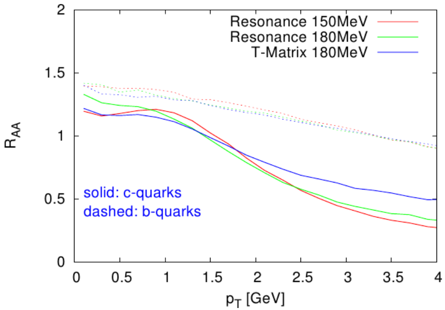
Spectra and elliptic flow for *b*-quarks

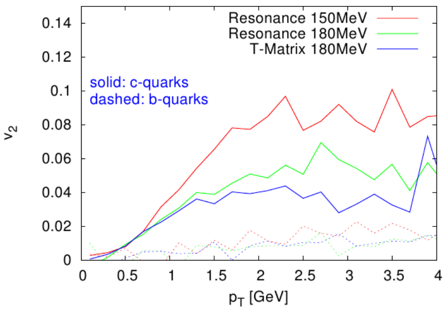




Implementation in UrQMD

- Langevin simulation easily implemented into any "bulk background"
- UrQMD (hybrid cascade/hydro mode)
  - more realistic fireball evolution
  - possibility to study effects of fluctuations

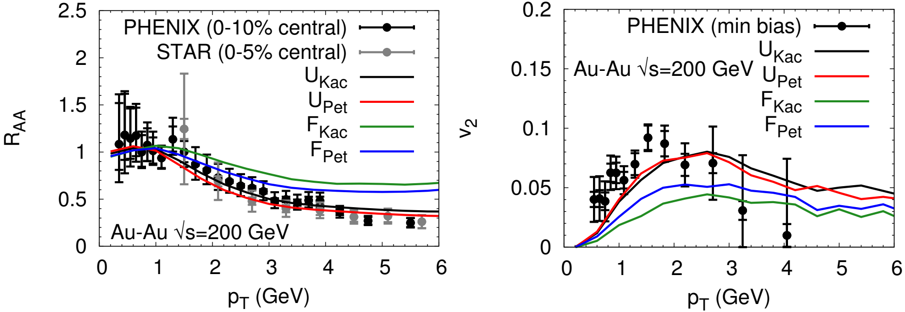




[T. Lang, J. Steinheimer, HvH, work in progress]

Non-photonic electrons at RHIC

- here: fireball model!
- 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, R. Rapp, Phys. Lett. B **655**, 126, (2007); L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]

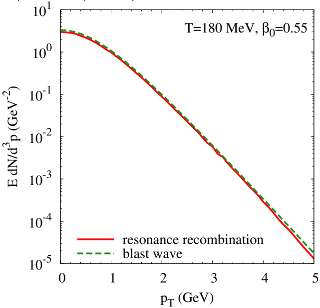
Resonance-Recombination Model

- transport approach for hadronization by $q + \bar{q} \leftrightarrows$ meson resonance

$$\frac{\partial}{\partial t} f_M(t,p) = -\frac{\Gamma}{\gamma_p} f_M(t,p) + g(p) \Rightarrow f_M^{(\text{eq})}(p) = \frac{\gamma_p}{\Gamma} g(p)$$

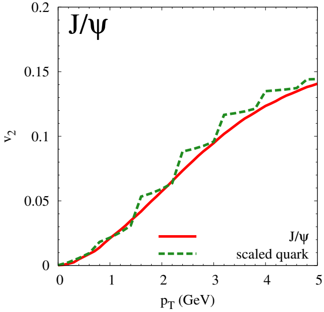
$$g(p) = \int \frac{\mathrm{d}^3 p_1 \mathrm{d}^3 p_2}{(2\pi)^6} \int \mathrm{d}^3 x f_q(x,p_1) f_{\bar{q}}(x,p_2) \sigma(s) v_{\text{rel}} \delta^{(3)}(p - p_1 - p_2)$$

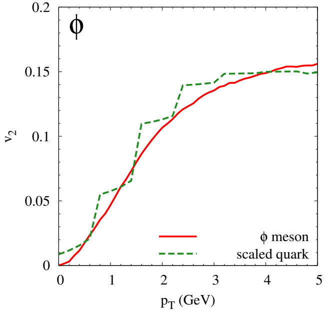
$$\sigma(s) = g_\sigma \frac{4\pi}{k_{\text{cm}}^2} \frac{(\Gamma m)^2}{(s-m^2)^2 + (\Gamma m)^2}$$

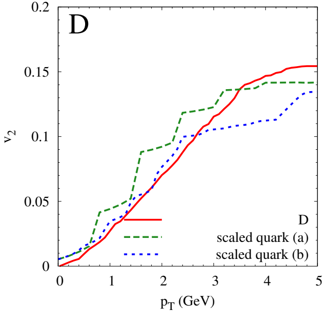


[L. Ravagli, R. Rapp, Phys. Lett. B **655**, 126, (2007); L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]

Constituent-quark number scaling (p_T)







Scaling relations

(a) $$v_{2,M}(p_T) \simeq v_{2,q_1}\left(\frac{p_T}{2}\right) + v_{2,q_2}\left(\frac{p_T}{2}\right)$$

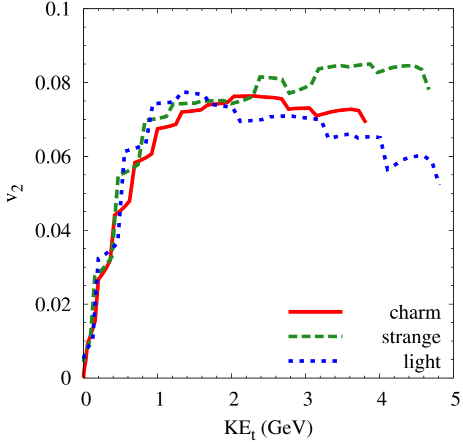
(b) $$v_{2,M}(p_T) \simeq v_{2,q_1}\left(\frac{m_{q_1} p_T}{m_{q_1}+m_{q_2}}\right) + v_{2,q_2}\left(\frac{m_{q_2} p_T}{m_{q_1}+m_{q_2}}\right)$$

KE_T scaling of quarks

- usual coalescence models: factorization ansatz

$$f_q(p,x,\varphi) = f_q(p,x)[1 + 2v_2^q(p_T)\cos(2\varphi)]$$

- CQNS usually not robust with more realistic parametrizations of v_2
- here: q input from relativistic Fokker-Planck-Langevin simulation



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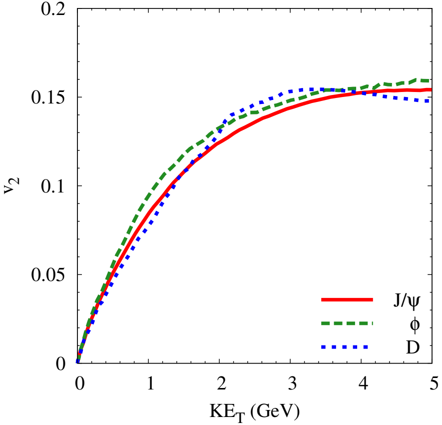
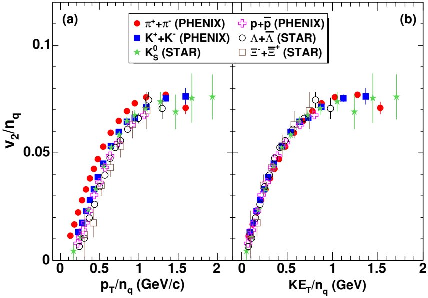
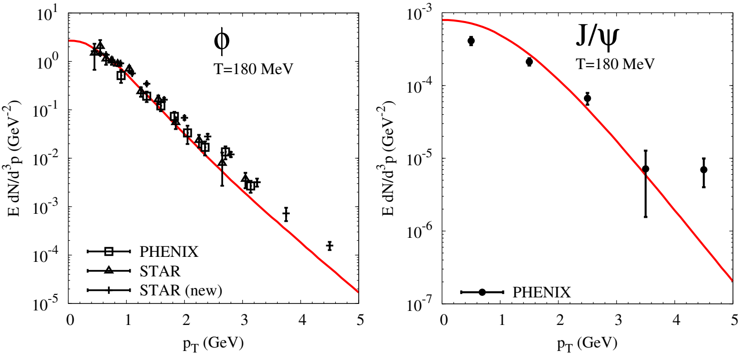




Meson spectra

- q-$\bar{q}$ input: Fokker-Planck-Langevin
- meson output: resonance-recombination model



Data from [A. Adare et al. (PHENIX) PRL **98**, 232301 (2007); S. S. Adler et al. (PHENIX) PRC **72**, 014903 (2005); J. Adams et al. (STAR) PLB **612**, 181 (2005) B. I. Abelev et al. (STAR) PRL **99**, 112301 (2007)]

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
- potential approach at finite T: F, V or combination?
- Outlook
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - other heavy-quark observables like charmonium suppression/regeneration
  - implementation of RRM in transport models (BAMPS) as a consistent hadronization model
  - study QCD phase transition(s)
  - fluctuations; finite μ_B; cross-over $\leftrightarrow$ 1st order; CEP(!?!)