Heavy-Quark Diffusion in the Quark-Gluon Plasma

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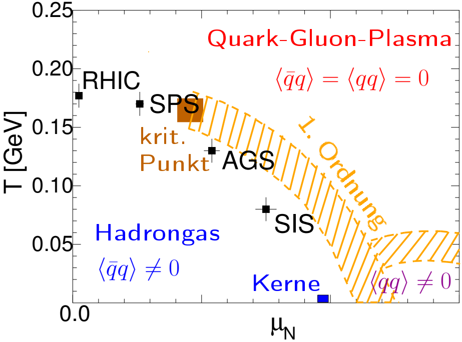
Outline

1. Heavy-ion phenomenology
   - The phase diagram of strongly interacting matter
   - Hydrodynamical collective flow
   - Contituent-quark-number scaling of v_2
2. Heavy-quark interactions in the sQGP
   - Heavy quarks in heavy-ion collisions
   - Heavy-quark diffusion: The Langevin Equation
   - Elastic pQCD heavy-quark scattering
   - Non-perturbative interactions: effective resonance model
   - Comparison to RHIC data: "non-photonic electrons"
3. Microscopic model for non-perturbative HQ interactions
   - Static heavy-quark potentials from lattice QCD
   - T-matrix approach
   - Estimate on transport properties of the sQGP
4. Summary and Outlook

The phase diagram of strongly interacting matter

- hot and dense matter: Quarks and Gluons close to each other
- relativistic collisions ⇒ Deconfinement
- Quarks and gluons relevant degrees of freedom ⇒ Quark-Gluon-Plasma
- still strongly interacting: fast thermalization!

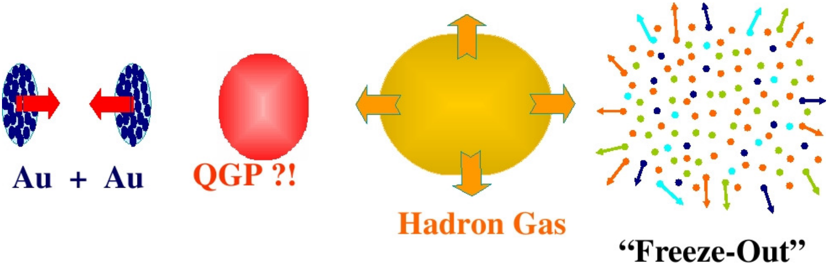


NB: 100 MeV $\simeq 1.16 \cdot 10^{12}$ K

$T_{\text{center of sun}} \simeq 1.57 \cdot 10^{7}$ K $\simeq 1.3 \cdot 10^{-3}$ MeV

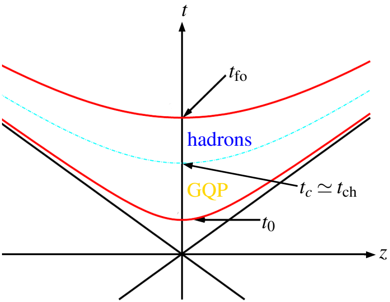
Heavy-ion collisions

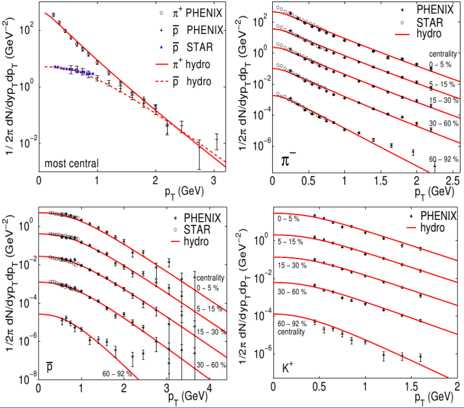
- collisions of relativistic (heavy) nuclei
- many collisions of partons inside nucleons
- creation of many particles ⇒ hot and dense fireball
- formation of (thermalized) QGP?
- how to learn about properties of QGP?



Hydrodynamical radial flow of the bulk

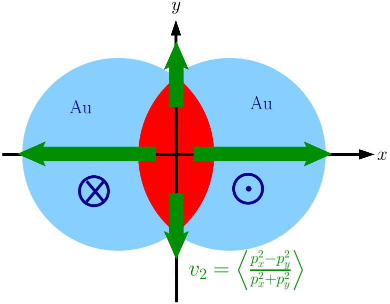
- ideal fluid in local thermal equilibrium ⇒ low viscosity/(entropy density), η/s
- needs strong interactions
- hydrodynamical model for ultra-relativistic heavy-ion collisions
  - after short formation time ($t_0 \lesssim 1$ fm/c)
  - QGP in local thermal equilibrium → hadronization at $T_c \simeq 160 - 190$ MeV
  - chemical freeze-out: (inelastic collisions cease) $T_{\text{ch}} \simeq 160 - 175$ MeV
  - thermal freeze-out: (also elastic scatterings cease)

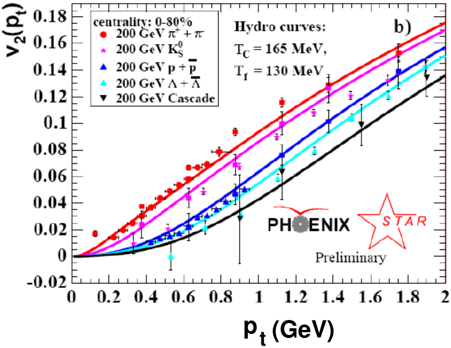




Hydrodynamical elliptic flow of the bulk

- particle spectra compatible with
  collective flow of a (nearly) ideal fluid $\Rightarrow$ small η/s
- medium in local thermal equilibrium



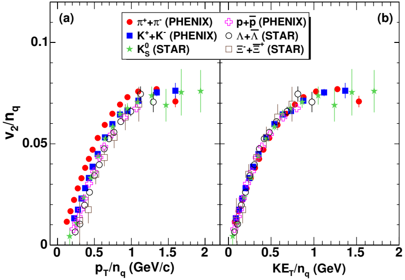


Constituent-quark-number scaling of v_2

- elliptic flow, v_2 scales with number of constituent quarks

$$v_2^{(\mathrm{had})}(p_T^{(\mathrm{had})}) = n_q v_2^{(q)}(p_T^{(\mathrm{had})}/n_q)$$

- suggests coalescence of quarks at T_c

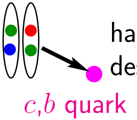


- possible microscopic mechanism hadron-resonance formation at $T_c \Rightarrow$ resonance-recombination model [Ravagli, HvH, Rapp, PRC **79**, 064902 (2009)]
- other hint to quark coalescence:
  enhanced baryon/meson ratio compared to pp collisions

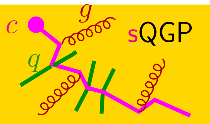
Heavy quarks in heavy-ion collisions: motivation

- 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

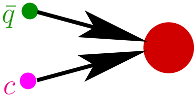
Heavy Quarks in Heavy-Ion collisions



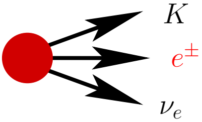
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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

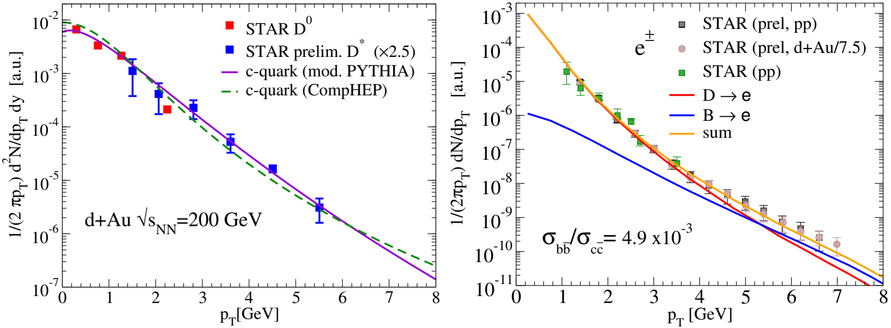
- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

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

- $\vec{w}$: 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

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



Meaning of the Coefficients

- solution for nonrelativistic case: Gaussian with

$$\langle \vec{p}(t) \rangle = \vec{p}_0 \exp(-At), \quad \Delta \vec{p}^2(t) = \left\langle \vec{p}^2 \right\rangle - \langle \vec{p} \rangle^2 = \frac{3B}{A}[1 - \exp(-2At)].$$

  - A: friction/drag coefficient $\Rightarrow$ dissipation
  - $1/A$: relaxation time to reach equilibrium
  - B: momentum-diffusion coefficient
  - measures size of momentum fluctuations
    (result of random uncorrelated collisions of heavy quarks with medim)
  - $\Rightarrow$ effective description of collisions: white-noise-random force
- equilibrium limit $(t \rightarrow \infty)$

$$F_Q(t, \vec{p}) \underset{t \rightarrow \infty}{\cong} \left(\frac{2\pi B}{A} \right)^{3/2} \exp\left(-\frac{A\vec{p}^2}{2B} \right)$$

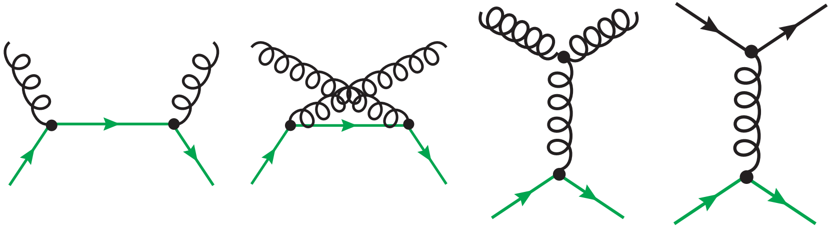
- has to be Maxwell-Boltzmann distribution $\Rightarrow$

$$B = m_Q A T$$

  - T: given temperature of the QGP
  - Einstein's dissipation-flucutation relation (1905)

Elastic pQCD processes

- Lowest-order matrix elements [Combridge 79]

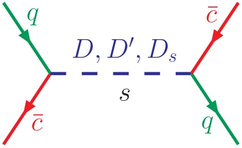


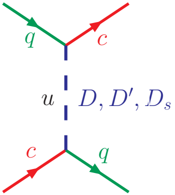
- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on "non-photonic" electrons

[Moore, Teaney PRC **71**, volume 71, 064904 (2005)]

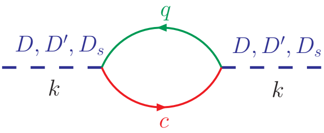
Non-perturbative interactions: Resonance Scattering

- 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



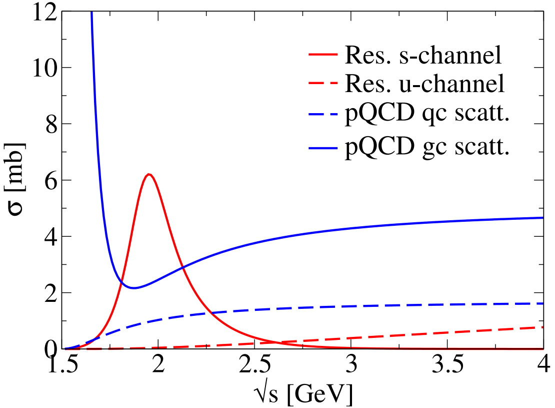


- D- and B-meson like resonances in sQGP



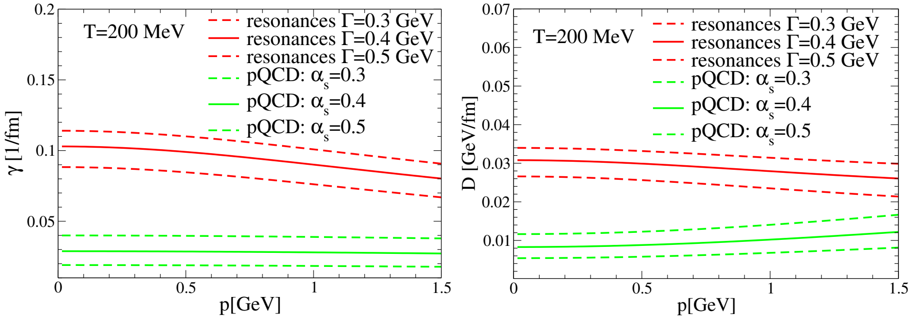
- parameters
  - $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV

Cross sections



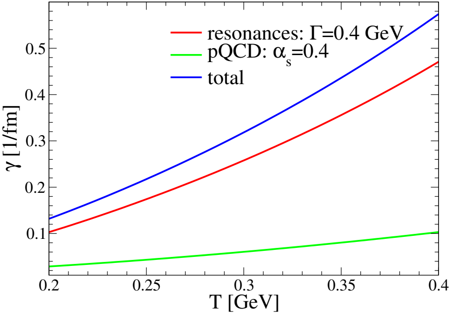
- total pQCD and resonance cross sections: comparable in size
- BUT pQCD forward peaked ↔ resonance isotropic
- resonance scattering more effective for friction and diffusion

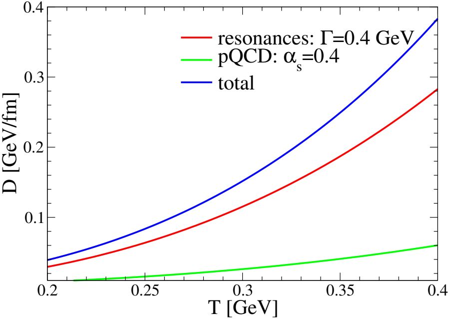
- three-momentum dependence



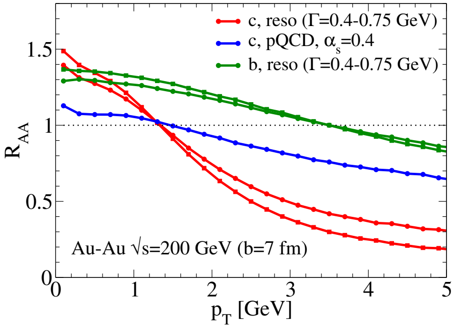
- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

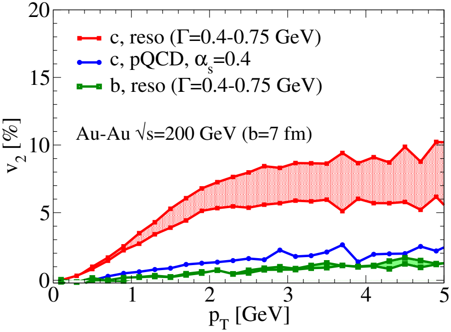
- Temperature dependence





Spectra and elliptic flow for heavy quarks

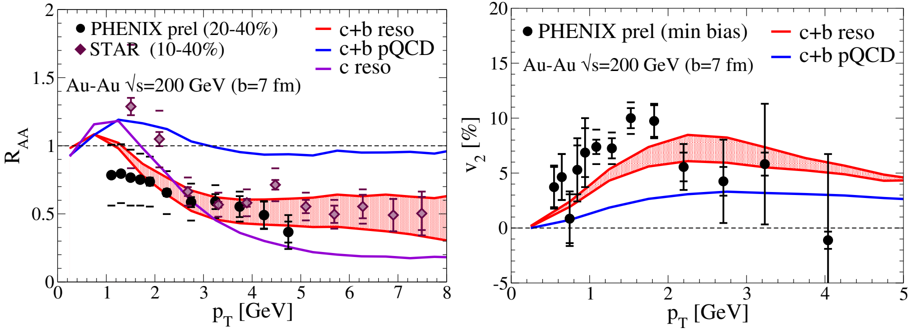




- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances $\Rightarrow$ c-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

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

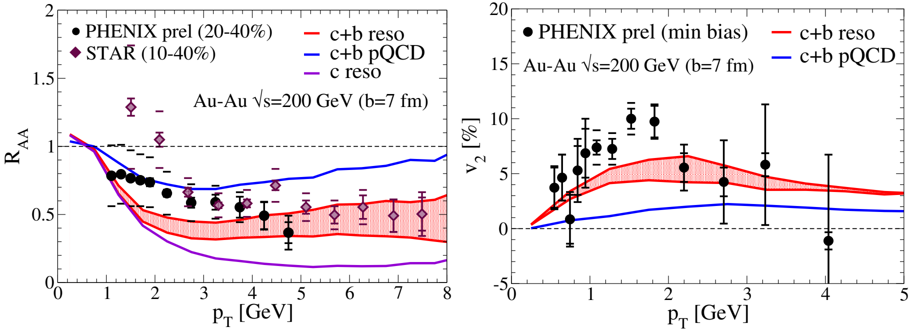


- Without further adjustments: data quite well described

[HvH, V. Greco, R. Rapp, Phys. Rev. C **73**, 034913 (2006)]

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

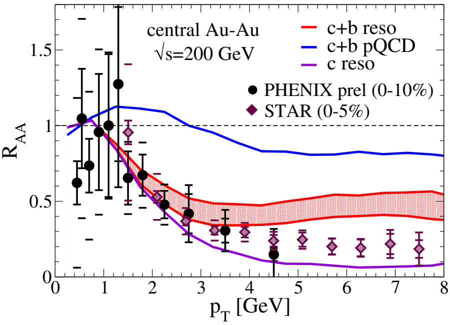
- Hadronization: Fragmentation only
- single electrons from decay of D- and B-mesons



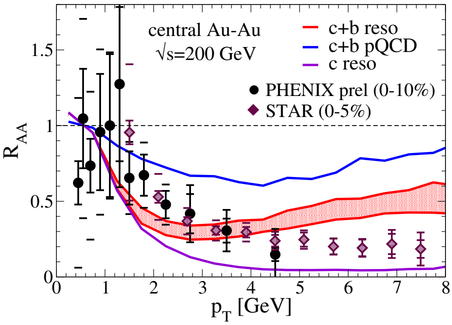
- coalescence brings up both, R_{AA} and v_2
- due to additional momentum kick from light quarks

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

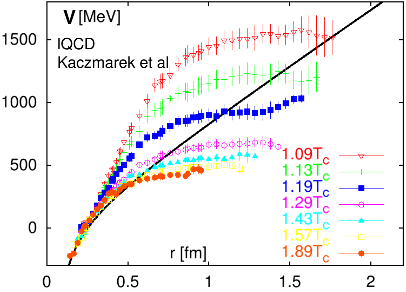
Coalescence+Fragmentation



Fragmentation only



Microscopic model: Static potentials from lattice QCD



- color-singlet free energy from lattice → internal energy

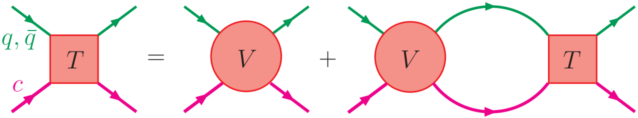
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

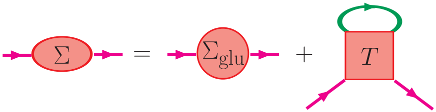
- Casimir scaling of Coulomb part for other color channels; confining part color blind [F. Riek, R. Rapp, Phys. Rev. C **82**, 035201 (2010)].

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

T-matrix

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

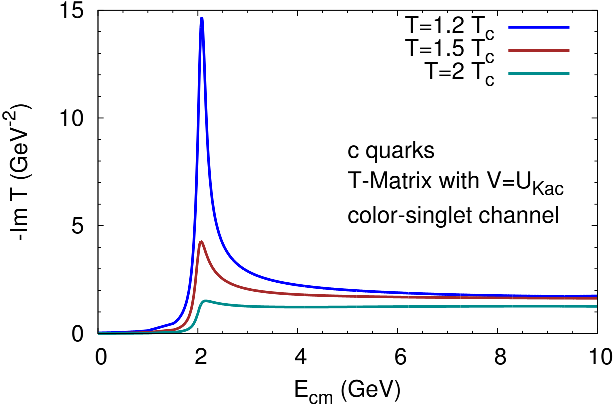




- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- Relation to invariant matrix elements

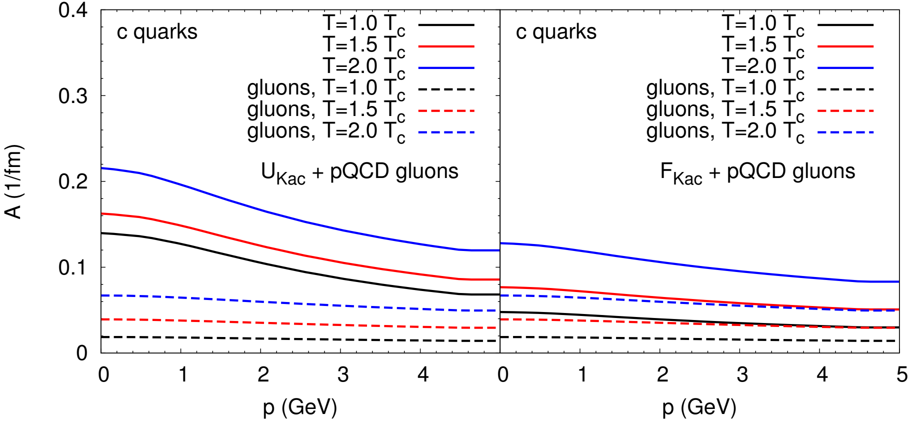
$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}}\right)$$

T-matrix results



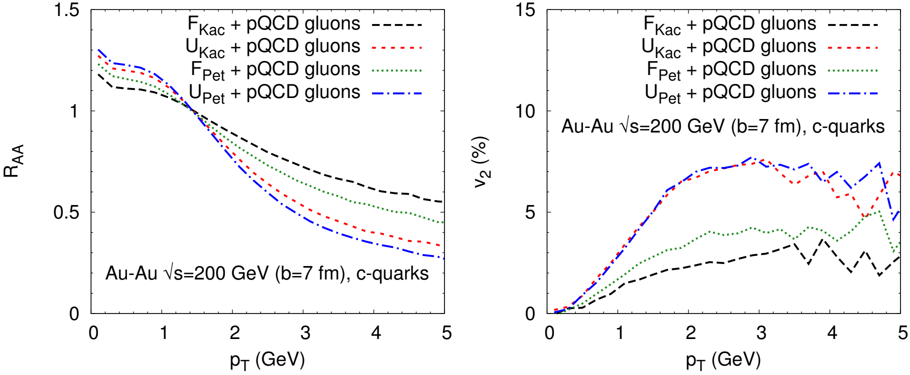
- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering!

Transport coefficients

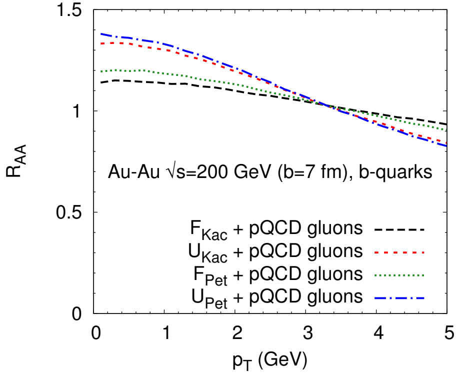


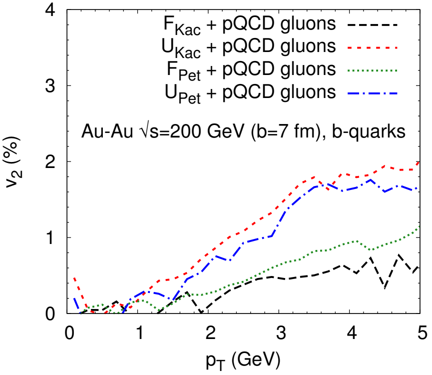
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7 \text{ fm}/c) \simeq 4 A_{\text{pQCD}}$
- results for free-energy potential, F considerably smaller

Spectra and elliptic flow for c-quarks



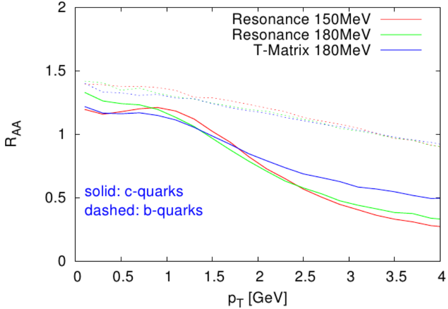
Spectra and elliptic flow for *b*-quarks

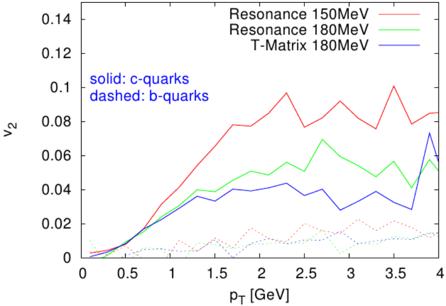




Implementation in UrQMD

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

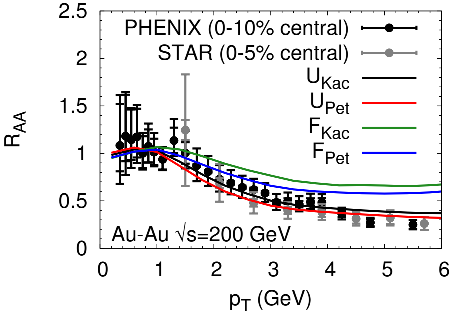


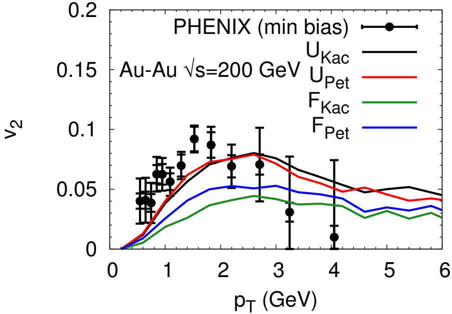


[T. Lang, J. Steinheimer, HvH, work in progress]

Non-photonic electrons at RHIC

- here: fireball model!
- quark coalescence+fragmentation $\rightarrow D/B \rightarrow e + X$



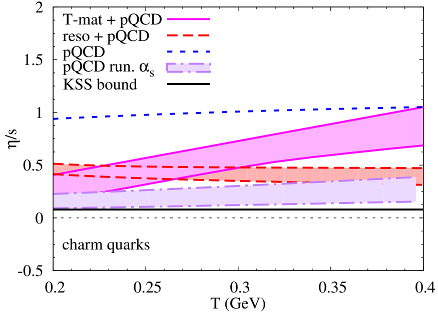


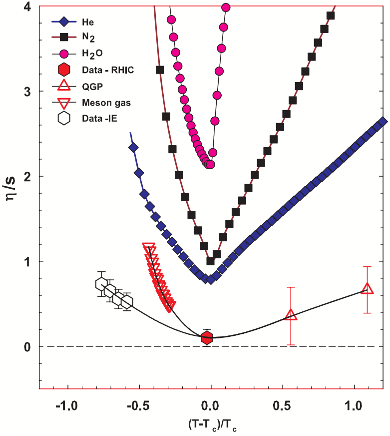
- coalescence crucial for description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards $T_c \Rightarrow$ coalescence natural

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

- spatial diffusion coefficient: Fokker-Planck $\Rightarrow D_s = \frac{T}{mA} = \frac{T^2}{D}$
- coupling strength in plasma: viscosity/entropy density, 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, FRNC2006, **021** (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
- 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(!?!)