Heavy Quarks in the QGP

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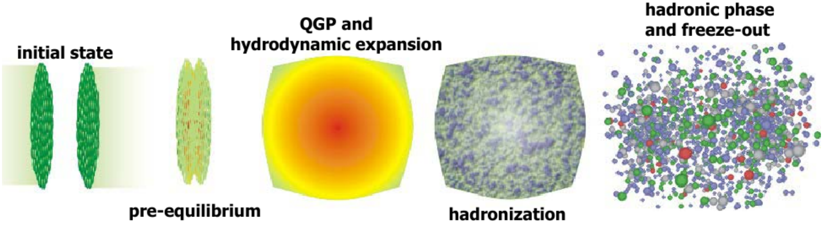
Outline

1. Heavy-quark interactions in the sQGP
   - Heavy-quark observables in heavy-ion collisions
   - Heavy-quark diffusion: The Langevin Equation
   - Elastic pQCD heavy-quark scattering
   - Non-perturbative interactions: effective resonance model
2. Non-photonic electrons at RHIC
3. Microscopic model for non-perturbative HQ interactions
   - Static heavy-quark potentials from lattice QCD
   - T-matrix approach
4. Alternative Approaches
   - pQCD with running coupling
   - Radiative energy loss
   - Collisional dissociation/fragmentation in the QGP
5. Summary and Outlook

Heavy-Ion collisions in a Nutshell

- Theory of strong interactions: Quantum Chromo Dynamics, QCD
- At high enough densities/temperatures: hadrons dissolve into a Quark-Gluon Plasma (QGP)
- hope to create QGP in Heavy-Ion Collisions at RHIC (and LHC)
- RHIC: collide gold nuclei with energy of $200\ \mathrm{GeV}$ per nucleon:

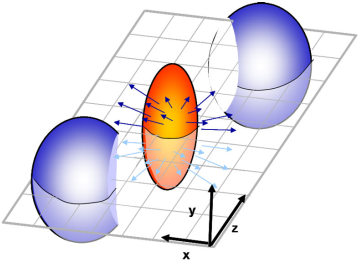


Evidence for QGP from heavy-ion observables

- particle p_T spectra show hydrodynamical behavior
- collective flow of matter in local thermal equilibrium
- nuclear modification factor $\Rightarrow$ degree of thermalization

$$R_{AA}(p_T) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_T}{N_{\mathrm{coll}}\mathrm{d}N_{pp}/\mathrm{d}p_T}$$

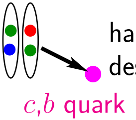
- no QGP $\Rightarrow R_{AA} = 1$; observed: $R_{AA} < 1$ (suppression) at high p_T
- in non-central collisions: anisotropic collective flow



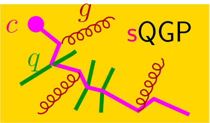
- initially reaction zone of elliptic shape
- pressure gradients: $\langle |p_x| \rangle > \langle |p_y| \rangle$
- measure of flow anisotropy:

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos(2\phi_p) \rangle$$

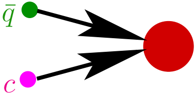
Heavy Quarks in Heavy-Ion collisions



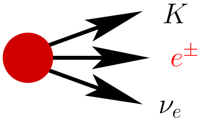
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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 ⇒
"non-photonic" electron observables

Relativistic Langevin process

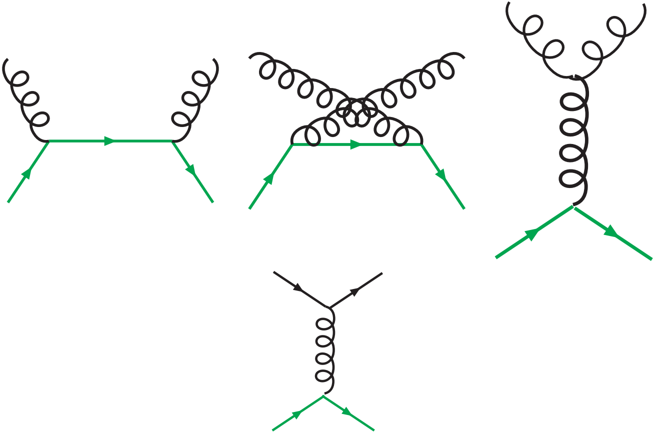
- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

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

- $\vec{w}$: 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

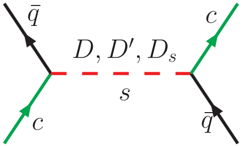
- Lowest-order matrix elements [Combridge 79]

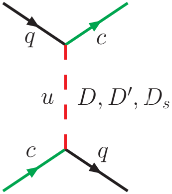


- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on "non-photonic" electrons

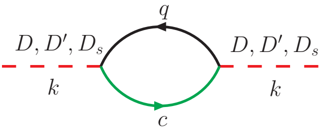
Non-perturbative interactions: Resonance Scattering

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



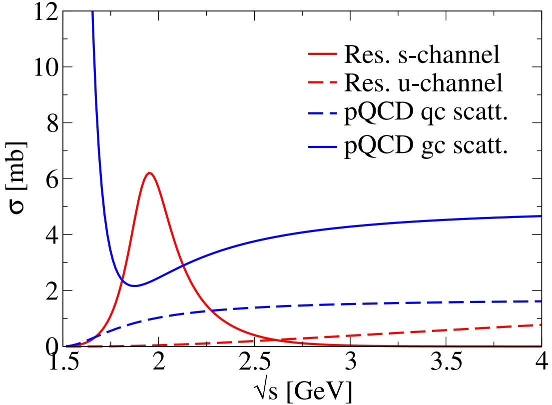


- D- and B-meson like resonances in sQGP



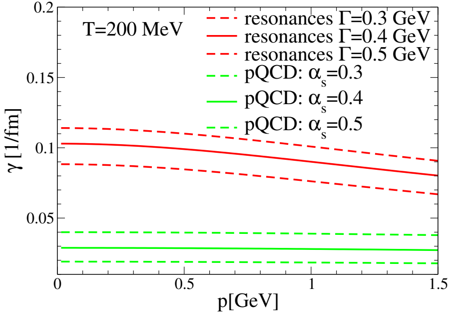
- parameters
  - $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV

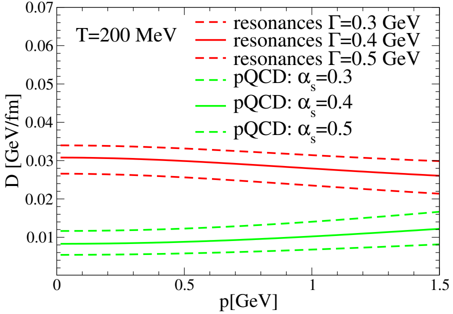
Cross sections



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

- three-momentum dependence

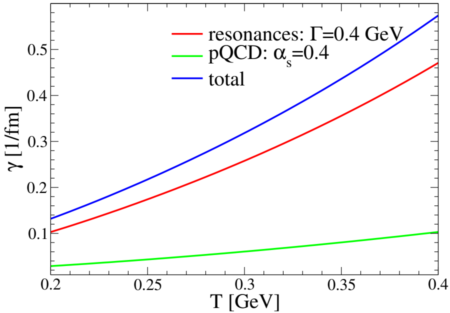


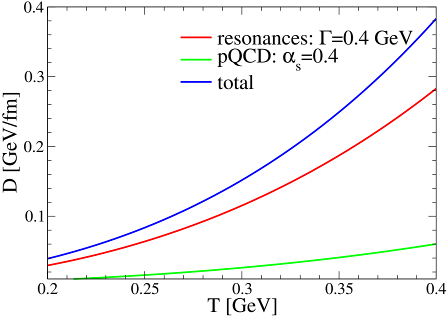


- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

Transport coefficients: pQCD vs. resonance scattering

- Temperature dependence





Time evolution of the fire ball

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

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

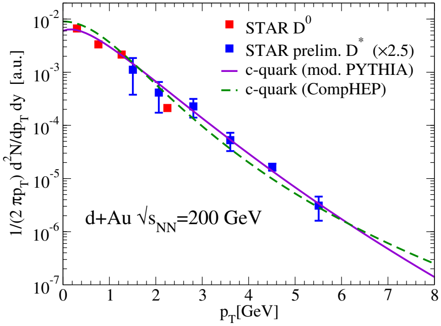
- Isentropic expansion: $S = \text{const}$ (fixed from N_{ch})
- QGP Equation of state:

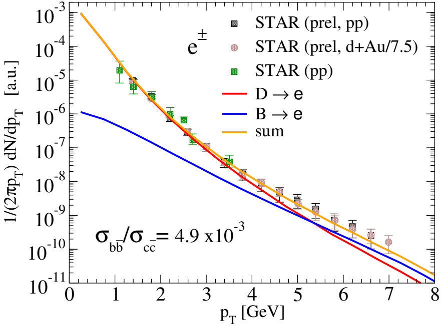
$$s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5 n_f^*), \quad n_f^* = 2.5$$

- 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

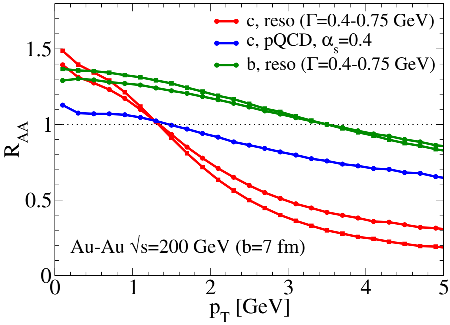
Initial conditions

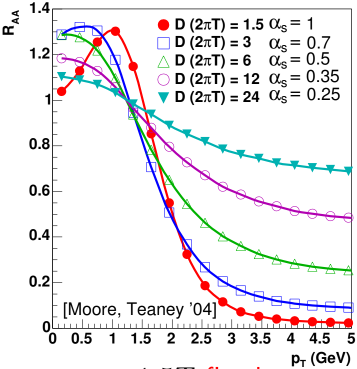
- need initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio





Spectra and elliptic flow for heavy quarks

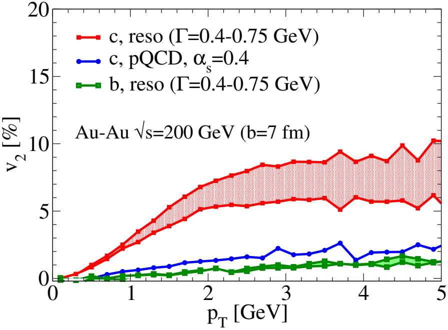


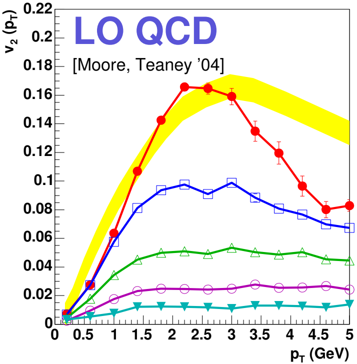


- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances $\Rightarrow$ c-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

- $\mu_D = 1.5T$ fixed
- spatial diff. coefficient: $D = D_s = \frac{T}{mA}$
- $2\pi T D \simeq \frac{3}{2\alpha_s^2}$

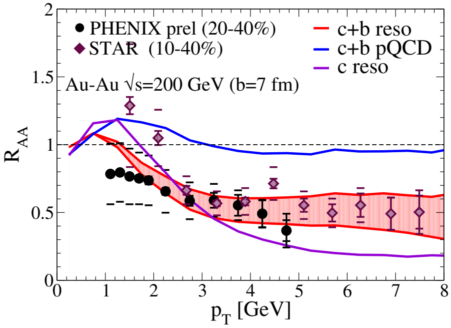
Spectra and elliptic flow for heavy quarks

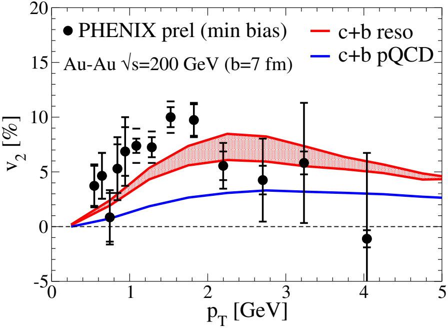




Observables: p_T-spectra (R_{AA}), v_2

- Hadronization: Coalescence with light quarks + fragmentation
  $\Leftrightarrow c\bar{c}$, $b\bar{b}$ conserved
- single electrons from decay of D- and B-mesons

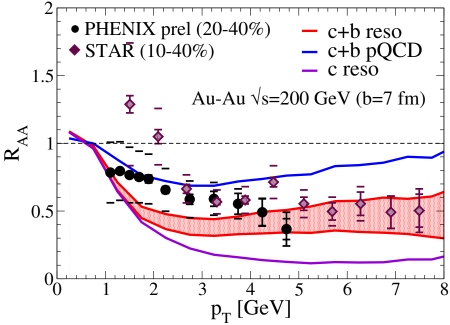


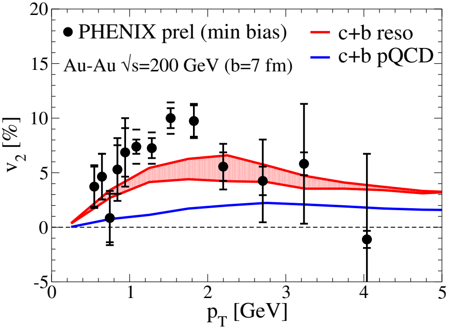


- Without further adjustments: data quite well described
  [HvH, V. Greco, R. Rapp, Phys. Rev. C **73**, 034913 (2006)]

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

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

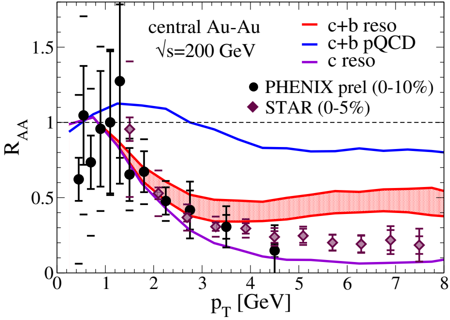




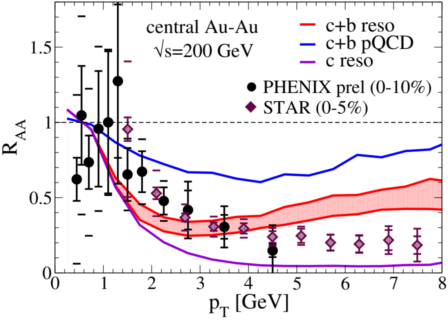
Observables: p_T-spectra (R_{AA}), v_2

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

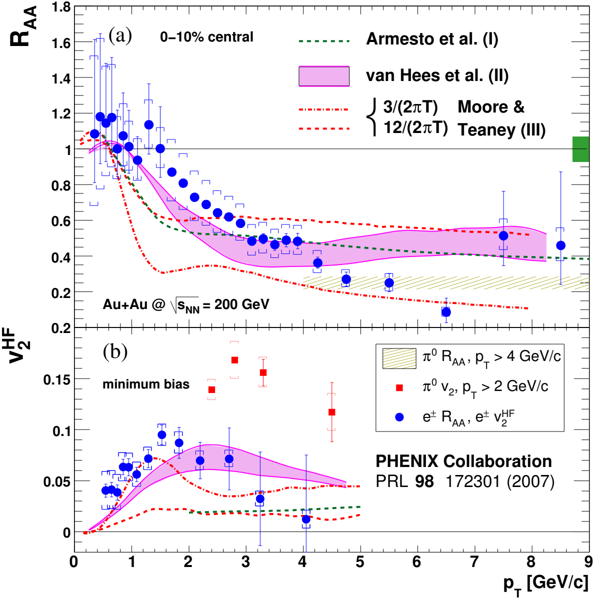
Coalescence+Fragmentation



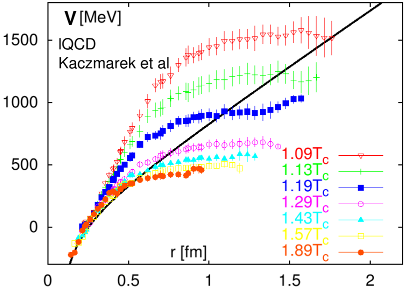
Fragmentation only



Comparison to newer data



Microscopic model: Static potentials from lattice QCD



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

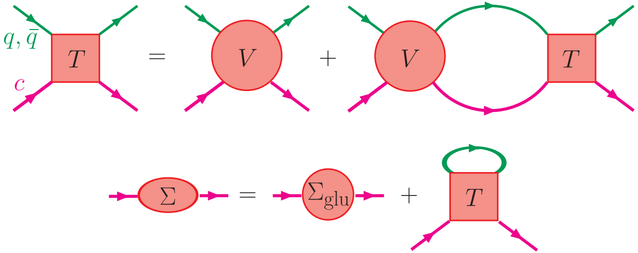
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

- 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

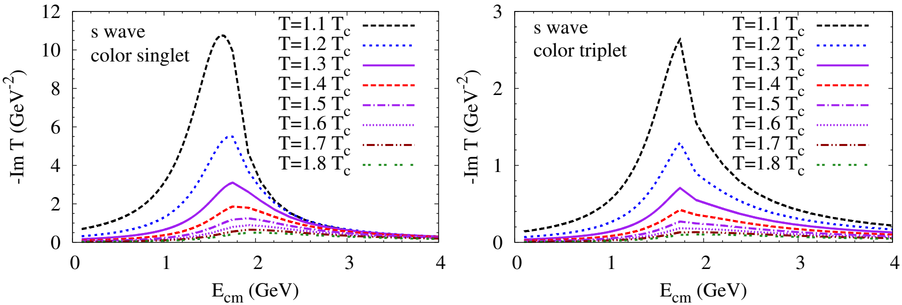
- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering



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

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

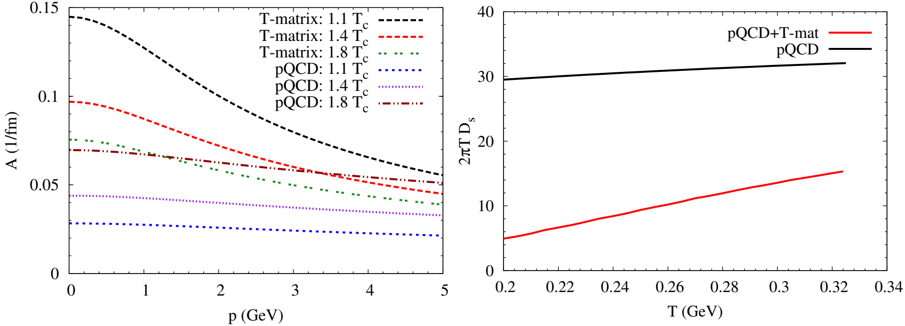
T-matrix



- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T! $\Rightarrow$ sQGP
- P wave smaller
- resonances near T_c: natural connection to quark coalescence

  [Ravagli, Rapp 07; Ravagli, HvH, Rapp 08]
- 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

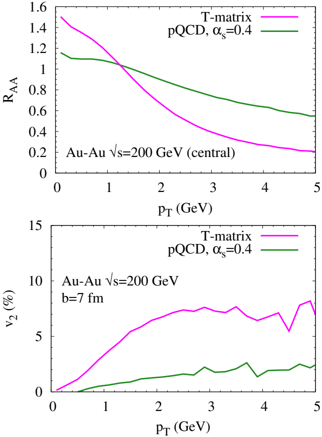


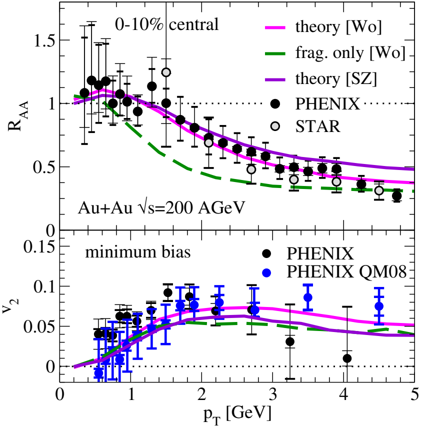
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\ \text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- A decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

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

increases with temperature

- 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]

pQCD with running coupling

- Ansatz for screen gluon propagator

$$G_g(t) \propto \frac{1}{t - \kappa \mu_D^2}$$

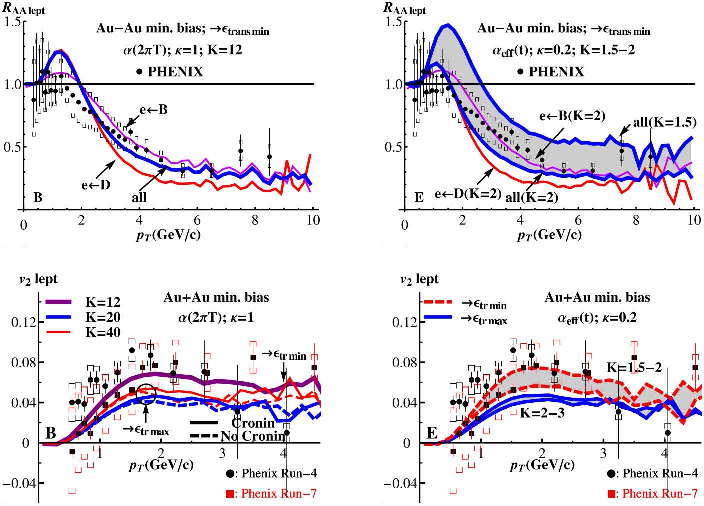
- requiring $\mathrm{d}E/\mathrm{d}x$ to match calculation with HTL-gluon propagator for $|t| < |t^*|$ and pert. gluon propagator for $|t| > |t^*|$, where $|t^*| \in (g^2 T^2, T^2)$
- in QED result independent of $|t^*|$, in QCD IR regulator in hard part $\Rightarrow \kappa \simeq 0.15\text{-}0.2$
- Running coupling

$$\frac{\alpha}{t} \rightarrow \frac{\alpha_{\text{eff}}(t)}{t - \lambda \tilde{\mu}_D{}^2}, \quad \tilde{\mu}_D^2 = \frac{N_c}{3}\left(1 + \frac{N_f}{6}\right) 4\pi\alpha(-\tilde{\mu}_D^2) T^2$$

- IR regulator mass λ: similar strategy as for κ

[Peigné, Peshier 2008, Gossiaux, Aichelin 2008]

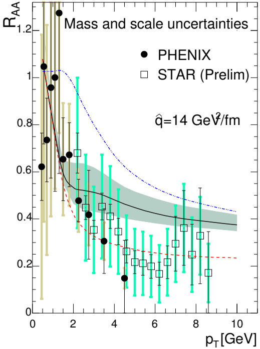
Boltzmann-transport model with fixed and running-coupling model

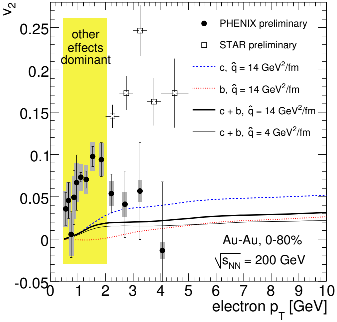


[Gossiaux, Aichelin 2008]

Radiative energy loss

- Gluo-bremsstrahlung energy-loss calculations
  - medium modelled by static scattering centers
  - energy loss through gluo bremsstrahlung: $\Delta E = \frac{\alpha_s}{2} \hat{q} L^2$
  - perturbative estimate for RHIC conditions: $\hat{q} \simeq 1 \; \mathrm{GeV}^2/\mathrm{fm}$



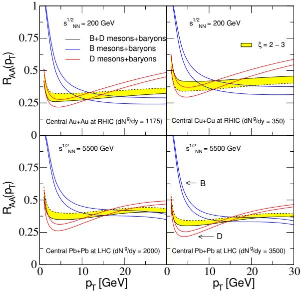


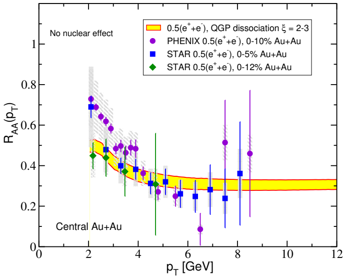
[Armesto, Cacciari et al. (2006)]

  - Need $\hat{q} = 14 \; \mathrm{GeV}^2/\mathrm{fm}$; v_2: only through almond-shape geometry
  - without drag $\Rightarrow$ no heavy-quark collective flow:
    no consistent description of R_{AA} and v_2!

Collisional dissociation/fragmentation in the QGP

- in-medium dissociation of D/B mesons $\leftrightarrow$ in-medium fragmentation of c/b quarks
  - medium modification of quark-wave functions in QGP
  - dissociation by collision with QGP particles
  - in-medium fragmentation $c/b \rightarrow D/B$





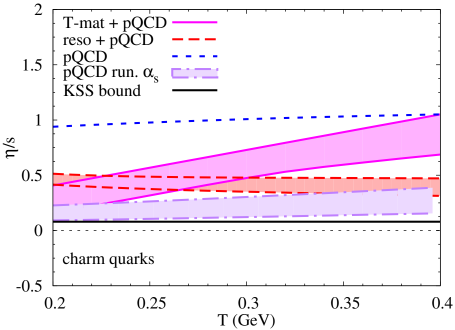
[Adil, Vitev (2007)]

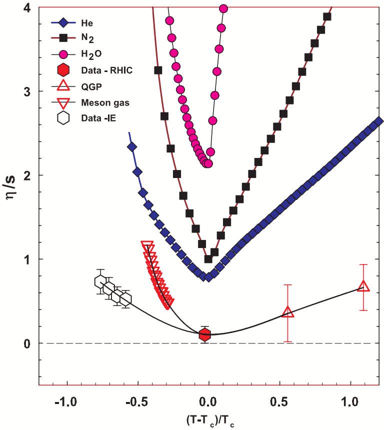
  - B mesons stronger bound than D mesons
  - smaller B formation times $\Leftrightarrow$ stronger suppression for B than for D!
  - could be distinguished from HQ elastic-scattering processes by separate measurement of D and B only!

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

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





[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
  - problems
    - extraction of V from lattice data
    - 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