Kinetics of Charm in Medium

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Outline

Motivation

- Measured p_T spectra and v_2 of non-photonic single electrons
- coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium

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- What is the underlying microscopic mechanism for thermalization?
  - pQCD elastic HQ scattering: need unrealistically large α_s [Moore, Teaney '04]
  - Gluon-radiative energy loss: need to enhance transport coefficient $\hat{q}$ by large factor [Armesto et al '05] or enhanced gluon density [Djordjevic, Gyulassi et al '05]
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  - including pQCD elastic scattering: still not enough equilibration of heavy quarks [Wicks et al '05]
- Assumption: survival of D- and B-meson resonances in the sQGP
- facilitates elastic heavy-quark rescattering

Free Lagrangian: Particle Content

- Chiral symmetry $\mathrm{SU}_V(2) \otimes \mathrm{SU}_A(2)$ in light-quark sector of QCD

$$\mathscr{L}_D^{(0)} = \sum_{i=1}^{2} [(\partial_\mu \Phi_i^\dagger)(\partial^\mu \Phi_i) - m_D^2 \Phi_i^\dagger \Phi_i] + \text{massive (pseudo-)vectors } D^*$$

- Φ_i: two doublets: pseudo-scalar $\sim \binom{\overline{D^0}}{D^-}$ and scalar
- Φ_i^*: two doublets: vector $\sim \binom{\overline{D^{0*}}}{D^{-*}}$ and pseudo-vector

$$\mathscr{L}_{qc}^{(0)} = \bar{q} \mathrm{i} \partial\!\!\!/ q + \bar{c}(\mathrm{i}\partial\!\!\!/ - m_c)c$$

- q: light-quark doublet $\sim \binom{u}{d}$
- c: singlet

Interactions

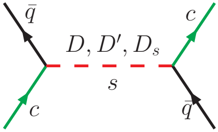
- Interactions determined by chiral symmetry
- For transversality of vector mesons:
  heavy-quark effective theory vertices

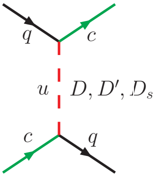
$$\begin{aligned}\mathscr{L}_{\text{int}} = &- G_S \left(\bar{q} \frac{1+\not{v}}{2} \Phi_1 c_v + \bar{q} \frac{1+\not{v}}{2} \mathrm{i}\gamma^5 \Phi_2 c_v + h.c. \right) \\ &- G_V \left(\bar{q} \frac{1+\not{v}}{2} \gamma^\mu \Phi_{1\mu}^* c_v + \bar{q} \frac{1+\not{v}}{2} \mathrm{i}\gamma^\mu \gamma^5 \Phi_{2\mu}^* c_v + h.c. \right)\end{aligned}$$

- v: four velocity of heavy quark
- in HQET: spin symmetry $\Rightarrow G_S = G_V$

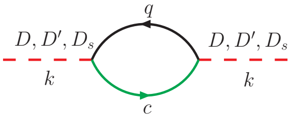
Resonance Scattering

- elastic heavy-light-(anti-)quark scattering





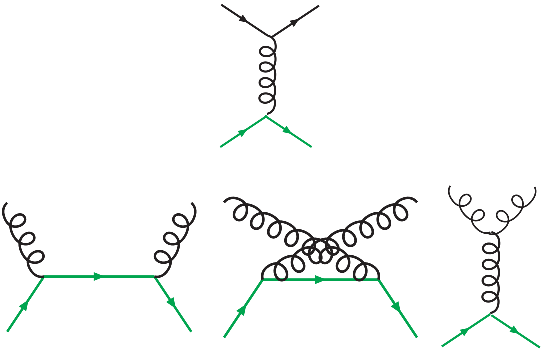
- D- and B-meson like resonances in sQGP



- 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

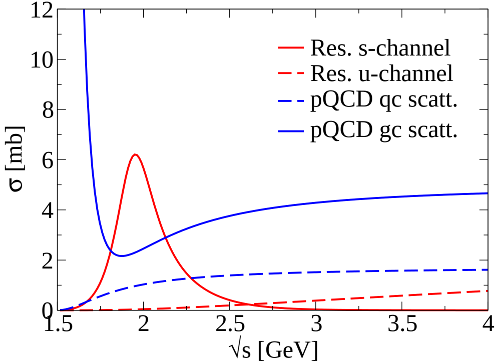
Contributions from pQCD

- Lowest-order matrix elements (Combridge '79)



- In-medium Debye-screening mass for t-channel gluon exchange: $\mu_g = gT$, $\alpha_s = 0.4$

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

The Fokker-Planck Equation

- Neglect flow of the medium (only for the moment!)
- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

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

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- A and B_{ij} given by averages with matrix elements (cross sections) from resonance model

$$\langle X(\vec{p}')\rangle = \frac{1}{\gamma_c}\frac{1}{2E_p}\int \frac{\mathrm{d}^3\vec{q}}{(2\pi)^3 2E_q}\int \frac{\mathrm{d}^3\vec{q}'}{(2\pi)^3 2E_{q'}}\int \frac{\mathrm{d}^3\vec{p}'}{(2\pi)^3 2E_{p'}} \sum |\mathcal{M}|^2 (2\pi)^4 \delta^{(4)}(p+q-p'-q')\hat{f}(\vec{q}) X(\vec{p}')$$

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$$\begin{aligned} B_{ij}(t,\vec{p}) &= \frac{1}{2}\left\langle (p_i - p_i')(p_j - p_j') \right\rangle \\ &= B_0(t,p)\left(\delta_{ij} - \frac{p_i p_j}{p^2}\right) + B_1(t,p)\frac{p_i p_j}{p^2} \end{aligned}$$

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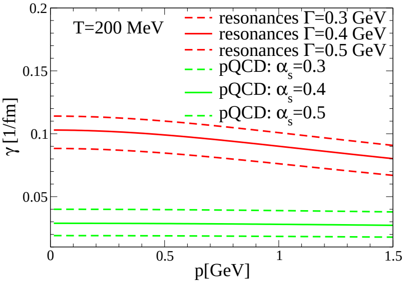
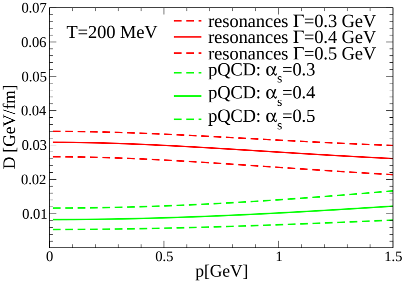
- to ensure correct equilibrium limit: $B_1(t,p) = T(t) E_p A(t,p)$ (Einstein dissipation-fluctuation relation)

Drag and Diffusion: pQCD vs. resonance scattering

- three-momentum dependence

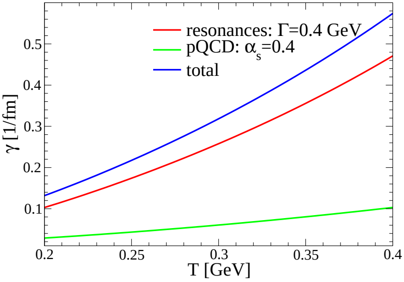


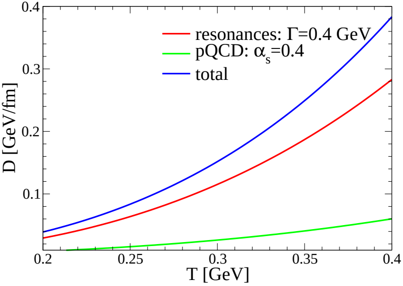


- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

The Coefficients: pQCD vs. resonance scattering

- Temperature dependence





Time evolution of the fire ball

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

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

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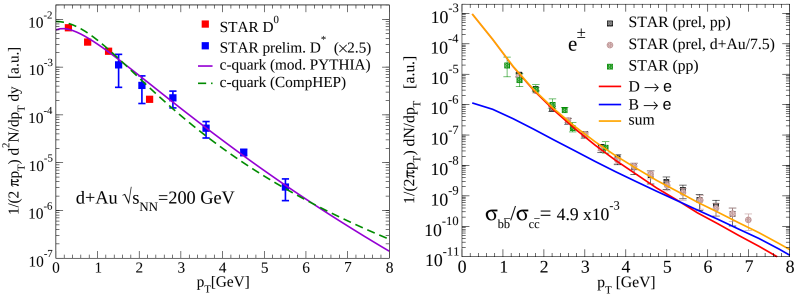
- Isentropic expansion: $S =$ const (fixed from N_{ch})
- QGP Equation of state:

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

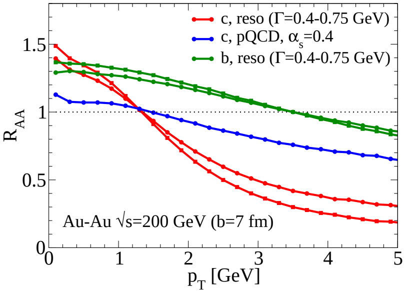
- obtain $T(t) \Rightarrow A(t,p)$, $B_0(t,p)$ and $B_1 = TEA$
- for semicentral collisions ($b = 7$ fm): $T_0 = 340$ MeV,
  QGP lifetime $\simeq 5$ fm$/c$.
- simulate FP equation as relativistic Langevin process

Initial conditions

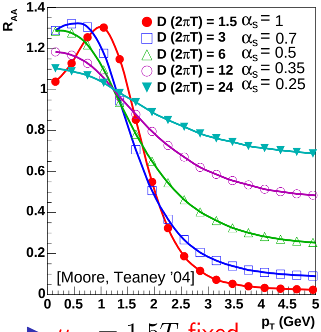
- need initial p_T-spectra of charm and bottom quarks
  - (modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation
  - exp. non-photonic single-$e^{\pm}$ spectra: Fix bottom/charm ratio



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
- $2\pi T D \simeq \frac{3}{2\alpha_s^2}$

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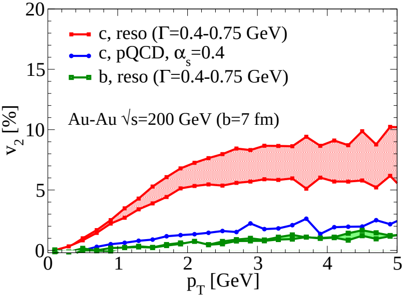
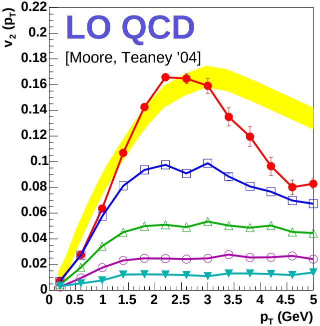
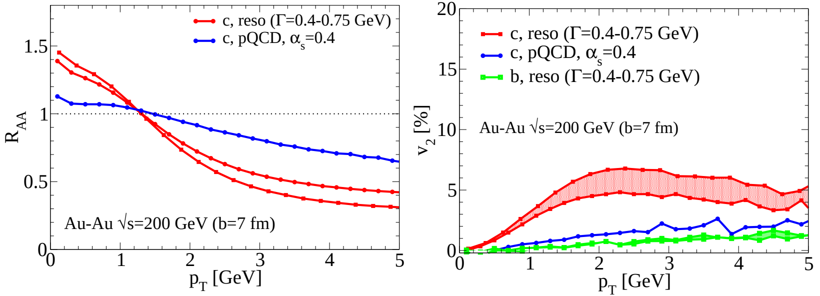




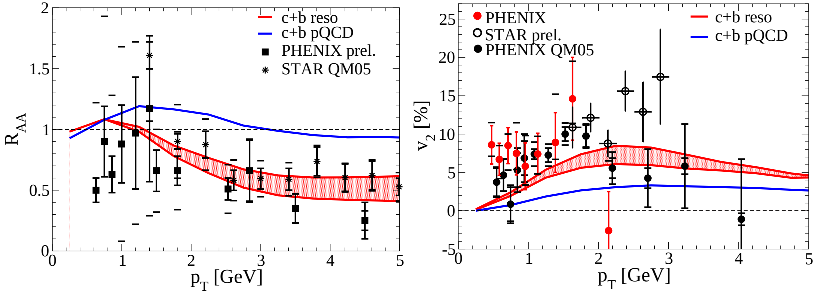
Spectra and elliptic flow for heavy quarks

With form-factor vertices instead of point vertices ($\Lambda = 1$ GeV)



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

- Hadronization: Coalescence with light quarks (fixed before [Greco et al 03]) + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)
- single electrons from decay of D- and B-mesons



- Without further adjustments: data quite well described

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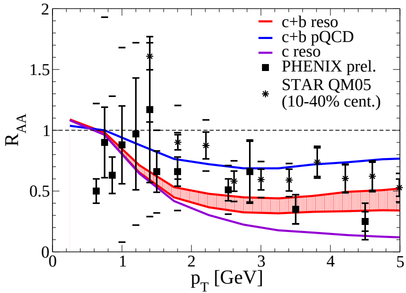

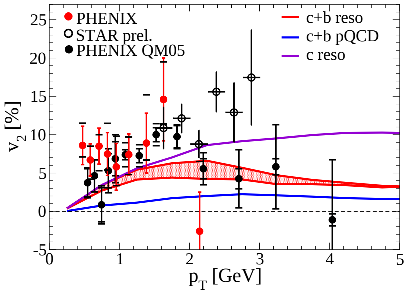

How to check resonance assumption?

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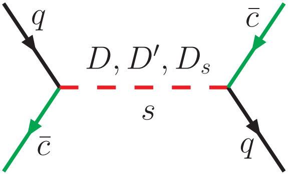
- dominant channel: quark-anti-c-quark s channel



- CBM@FAIR: quark dominated $\Rightarrow$ $\bar{c}$ quarks most affected
- thermalization effects more pronounced for $\bar{D}$ (D^-) than for D (D^+) mesons!

Conclusions and Outlook

- Assumption: survival of resonances in the (s)QGP
- nonperturbative re-interactions of heavy quarks in QGP
- Observables via Langevin approach and coalescence+fragmentation
  - Elastic resonance scattering $\Rightarrow R_{AA}^{(c)} \simeq 0.2$, $v_2^{(c)} \simeq 0.1$ without upscaling of cross sections
  - small effects on bottom quarks
  - Heavy-light quark coalescence enhances $v_2^{(e)}$ and R_{AA} for $p_T \simeq 2$ GeV
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- Further investigations
  - improved (softer) fragmentation
  - implementation of gluon-radiation processes
  - quantitative consequences for quarkonia