Charm and beauty production in AA collisions in a Fokker-Planck approach

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Outline

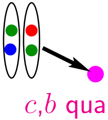
1. Heavy-quark interactions in the sQGP
   - Heavy quarks in heavy-ion collisions
   - Heavy-quark diffusion: The Langevin Equation
2. Non-perturbative HQ interactions
   - Resonance model for HQ-q Scattering
   - T-matrix approach with lQCD potentials
3. Comparison with data
   - Nonphotonic electrons at RHIC
   - D mesons at LHC
   - Predictions for D mesons at FAIR
   - Dileptons from correlated D $\overline{\text{D}}$ decays
4. Summary and Outlook

Motivation

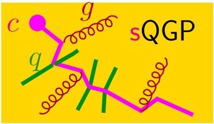
- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) $\Rightarrow$ sQGP
- Heavy quarks as calibrated probe of QGP properties
  - produced in early hard collisions: well-defined initial conditions
  - not fully equilibrated due to large masses
  - heavy-quark diffusion $\Rightarrow$ probes for QGP-transport properties
- Langevin simulation within UrQMD-hydro hybrid model
- sensitivity to medium evolution

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

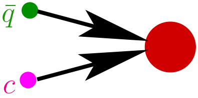
Heavy Quarks in Heavy-Ion collisions



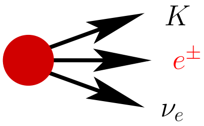
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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 $\Rightarrow$
"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

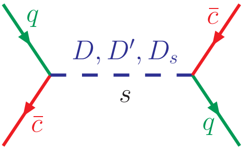
$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\parallel]\vec{w}$$

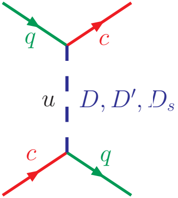
- $\vec{w}$: normal-distributed random variable
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- Einstein dissipation-fluctuation relation $B_1 = E_p T A$.
- flow via Lorentz boosts between "heat-bath frame" and "lab frame"
- A and B_0 from microscopic models for qQ, gQ scattering
- background medium: UrQMD → hydro → UrQMD

[R. Rapp, HvH, R. C. Hwa and X. N. Wang (eds.), Quark-Gluon Plasma Vol. IV, World Sientific (2010), arXiv: 0903.1096 [hep-ph]; M. He, HvH, P. B. Gossiaux, R. J. Fries, R. Rapp, Phys. Rev. E **88**, 032138 (2013)]

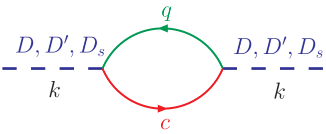
Non-perturbative interactions: Resonance Scattering

- 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





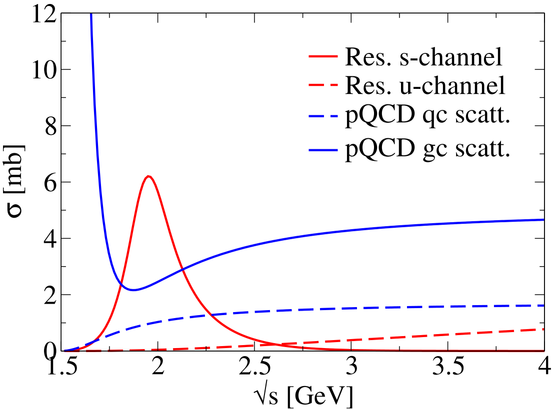
- D- and B-meson like resonances in sQGP



- 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

[HvH, R. Rapp, Phys. Rev. C **71**, 034907 (2005); HvH, V. Greco, R. Rapp, Phys. Rev. C 73, 034913 (2006)]

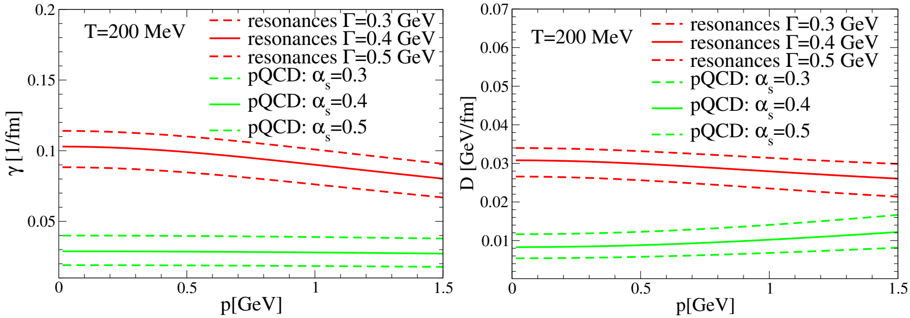
Cross sections



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

Transport coefficients: pQCD vs. resonance scattering

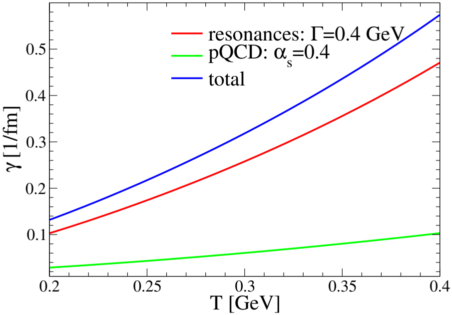
- three-momentum dependence

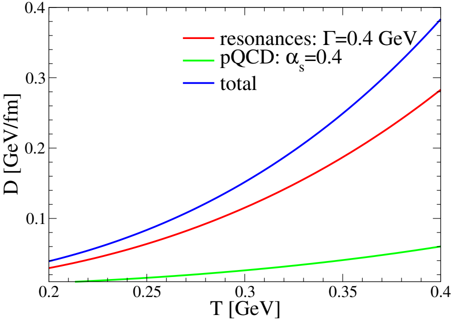


- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

Transport coefficients: pQCD vs. resonance scattering

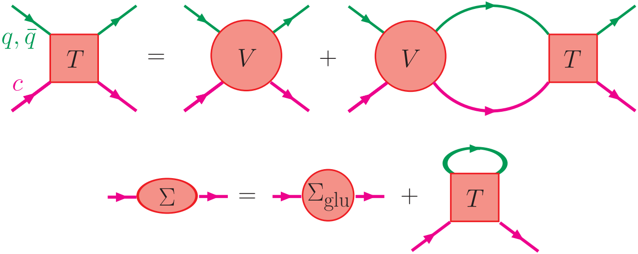
- Temperature dependence





T-matrix

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

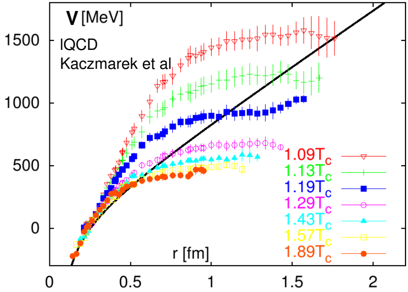


- V: static $q\bar{q}$ potential from lattice QCD (F and U)
- reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger
- S- and P waves
- Relation to invariant matrix elements

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

[HvH, M. Mannarelli, V. Greco, R. Rapp, Phys. Rev. Lett. **100**, 192301 (2008)]

Static heavy-quark potentials from lattice QCD



- color-singlet free energy from lattice → internal energy

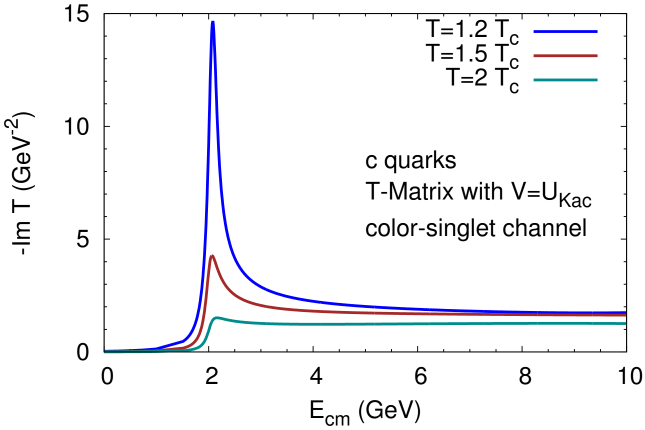
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$

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

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

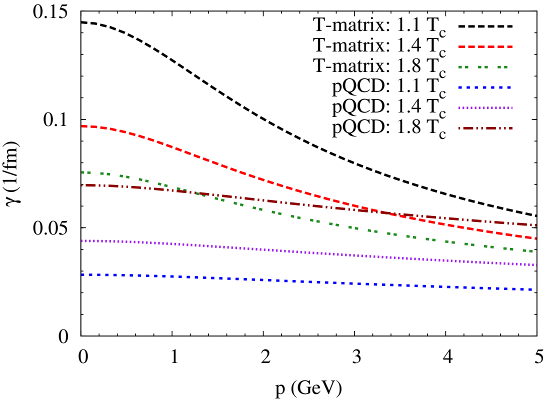
$$V_{\bar{3}} = \frac{1}{2}V_1, \quad V_6 = -\frac{1}{4}V_1, \quad V_8 = -\frac{1}{8}V_1$$

T-matrix 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!

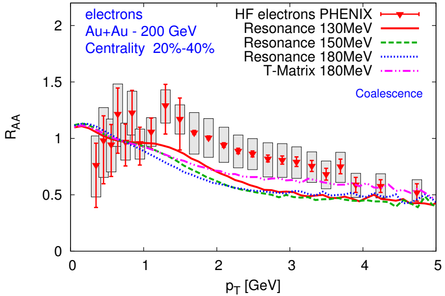
Transport coefficients

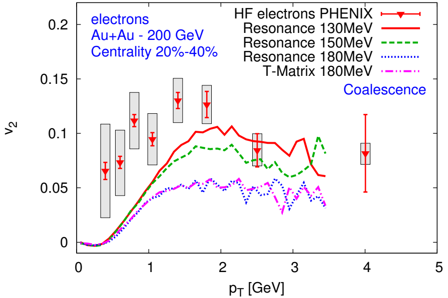


- T-matrix resonance-scattering coefficients: decrease with T
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\text{ fm}/c) \simeq 4 A_{\text{pQCD}}$
- results for free-energy potential, F considerably smaller

Nonphotonic electrons at RHIC

- form D and B mesons via quark-antiquark coalescence
- use PYTHIA for semi-leptonic decays
- comparison to single-electron data from PHENIX (200 AGeV Au-Au collisions)

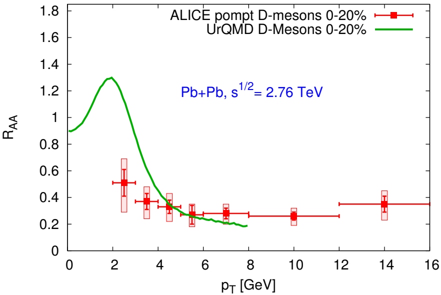


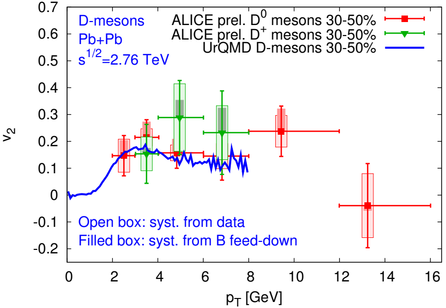


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]

D mesons at LHC

- form D via quark-antiquark coalescence
- comparison to D-meson data from ALICE (2.76 *A*TeV Pb-Pb collisions)

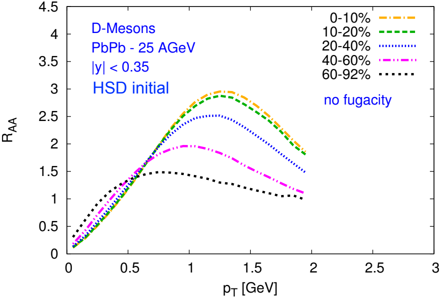


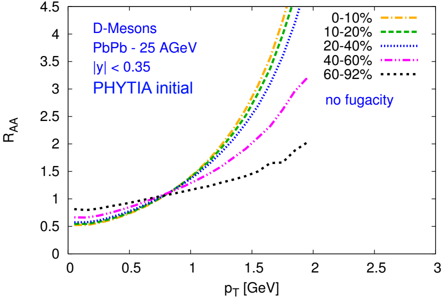


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]

D mesons at FAIR

- form D via quark-antiquark coalescence
- large sensitivity to initial HQ distributions (use estimates from HSD and PYTHIA)





[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

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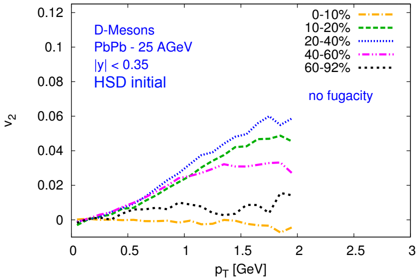
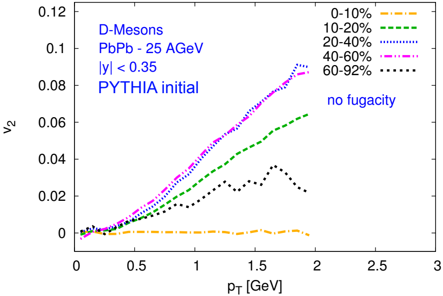
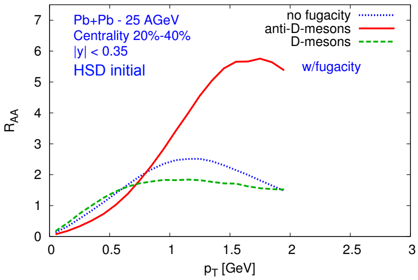


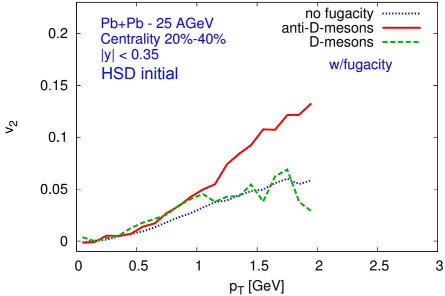


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

D mesons at FAIR

- form D via quark-antiquark coalescence
- large sensitivity to initial HQ distributions (use estimates from HSD and PYTHIA)
- large μ_B in resonance model: $\bar{c}$ more dragged than c

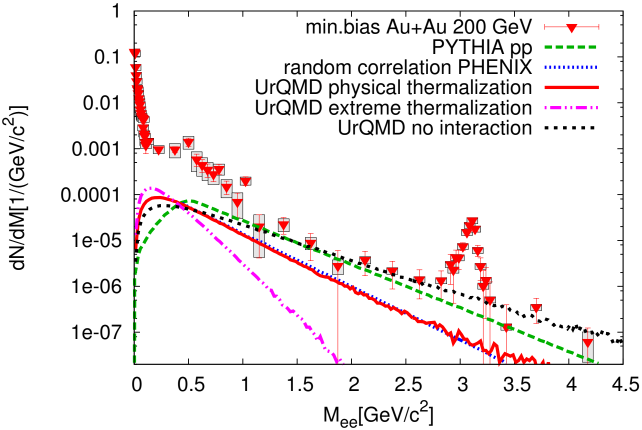




[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

Dileptons from correlated D $\overline{\text{D}}$ decays

- for $m_\phi \lesssim M_{\ell^+\ell^-} \lesssim m_{J/\psi}$:
  dilepton emission from thermal QGP and from correlated D $\overline{\text{D}}$ decays
- medium modifications of D and $\overline{\text{D}}$ destroy correlations



[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.7377 [hep-ph]]

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
  - also provides "natural" mechanism for quark coalescence

    [R. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]
- Comparison to data and predictions for FAIR
  - R_{AA} and v_2 of non-photonic electrons at RHIC
  - R_{AA} and v_2 for D mesons at LHC
  - R_{AA} and v_2 for D mesons at FAIR (pp baseline mandatory!)
  - impact of medium modifications on correlated D $\overline{\text{D}}$ decays to dileptons
- Outlook
  - implementation of hadronic cross sections for D/B-meson diffusion
  - include inelastic heavy-quark processes (gluo-radiative processes)
  - implement resonance-recombination model for hadronization
  - charmonium/bottomonium suppression/regeneration