

Heavy flavor at RHIC, LHC, and FAIR

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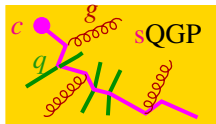
- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) \Rightarrow sQGP
- Heavy quarks as calibrated probe of QGP properties
 - produced in early hard collisions: well-defined initial conditions
 - not fully equilibrated due to large masses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

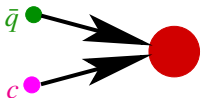


hard production of HQs
described by PDF's + pQCD (**PYTHIA**)

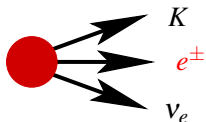
c, b quark



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

$$d\vec{x} = \frac{\vec{p}}{E_p} dt,$$

$$d\vec{p} = -A\vec{p} dt + \sqrt{2dt}[\sqrt{B_0}P_{\perp} + \sqrt{B_1}P_{\parallel}]\vec{w}$$

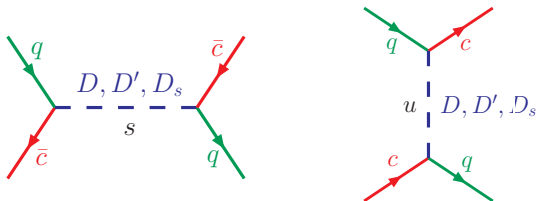
- \vec{w} : normal-distributed random variables
- A : friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- Einstein dissipation-fluctuation relation $B_1 = E_p T A$.
- flow via Lorentz boosts between “heat-bath frame” and “lab frame”
- A and B_0 from microscopic models for qQ , gQ scattering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

[R. Rapp, HvH, R. C. Hwa and X. N. Wang (eds.), Quark-Gluon Plasma Vol. IV, World Scientific (2010), arXiv: 0903.1096 [hep-ph]; M. He, HvH, P. B. Gossiaux, R. J.

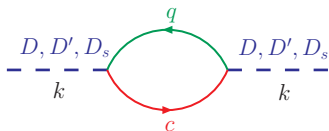
Fries, R. Rapp, Phys. Rev. E **88**, 032138 (2013)]

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 **s**QGP

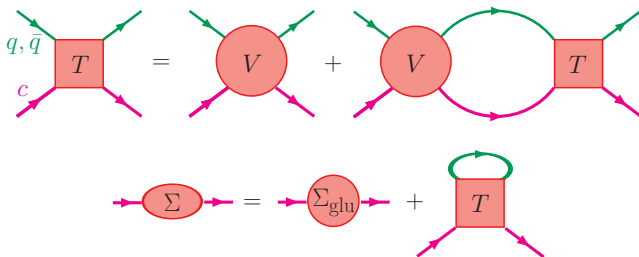


- parameters

- $m_D = 2 \text{ GeV}$, $\Gamma_D = 0.4 \dots 0.75 \text{ GeV}$
- $m_B = 5 \text{ GeV}$, $\Gamma_B = 0.4 \dots 0.75 \text{ GeV}$

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

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

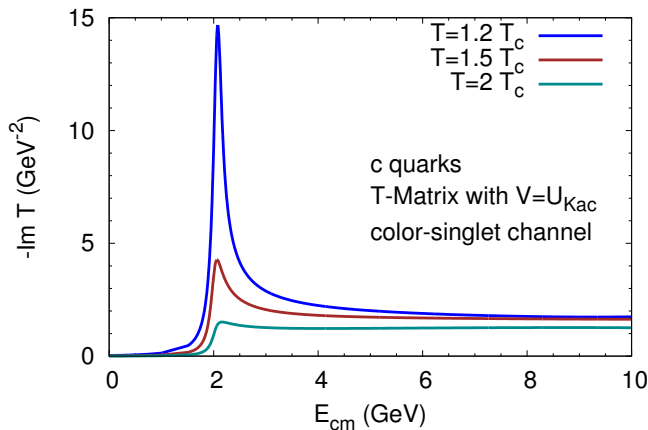


- V : static $q\bar{q}$ potential from lattice QCD (F and U)
- reduction scheme: 4D Bethe-Salpeter \rightarrow 3D Lipmann-Schwinger
- S - and P waves
- Relation to invariant **matrix elements**

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

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

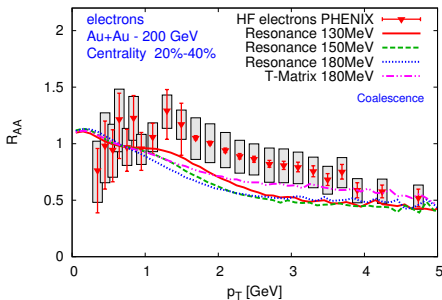
T-matrix results



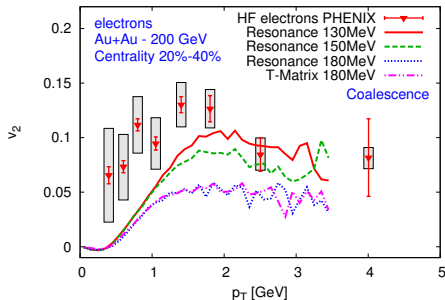
- **resonance formation** at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic $Qq, Q\bar{q}$ scattering!

Nonphotonic electrons at RHIC

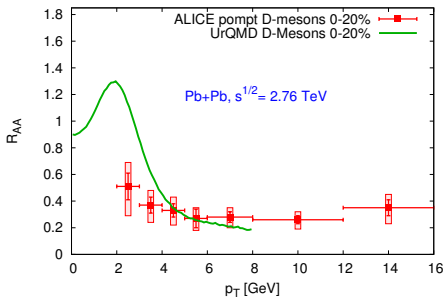
- UrQMD-hydro hybrid model for bulk evolution
- Langevin simulation for heavy quarks
- form D and B mesons via **quark-antiquark coalescence**
- use PYTHIA for semi-leptonic decays
- comparison to non-photonic electron data from PHENIX
(200 AGeV Au-Au collisions)



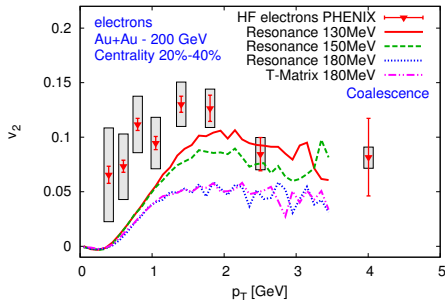
[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]



- UrQMD-hydro hybrid model for bulk evolution
- Langevin simulation for heavy quarks
- form D via **quark-antiquark coalescence**
- comparison to D-meson data from ALICE (2.76 ATeV Pb-Pb collisions)

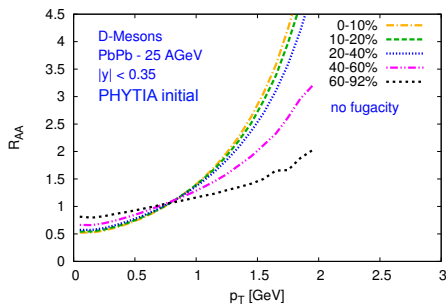
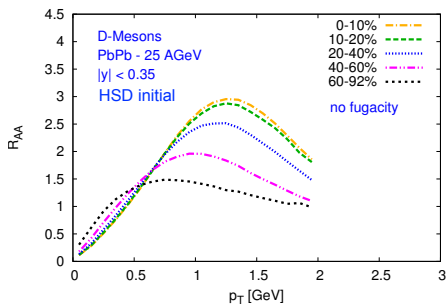


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]



D mesons at FAIR (Pb Pb at 25 AGeV)

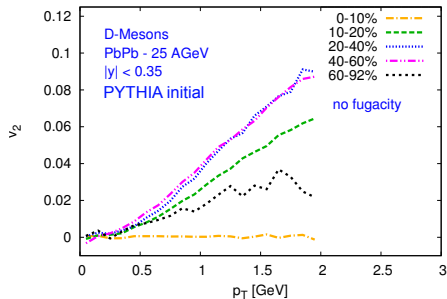
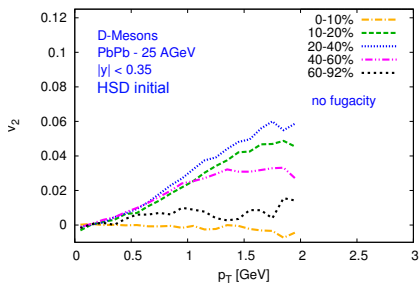
- UrQMD-hydro hybrid model for bulk evolution
- Langevin simulation for heavy quarks
- form D via **quark-antiquark coalescence**
- large sensitivity to initial HQ distributions (use estimates from HSD and PYTHIA)
- no pp data at this energy \Rightarrow **mandatory to get pp (and pA?) baseline from CBM!**



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

D mesons at FAIR (Pb Pb at 25 A GeV)

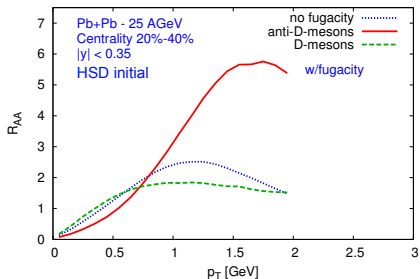
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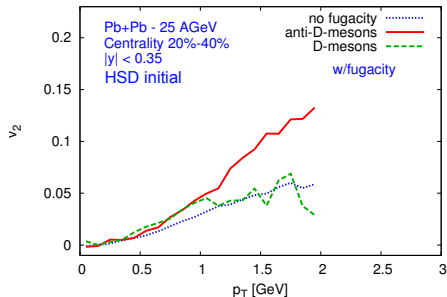
[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

D mesons at FAIR (Pb Pb at 25A GeV)

- 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

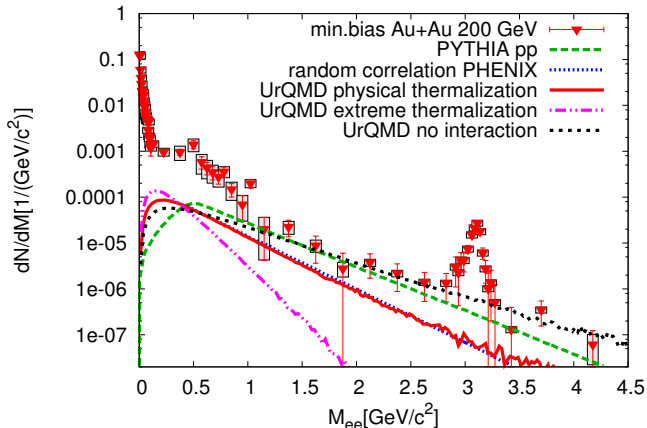


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]



Dileptons from correlated $D\bar{D}$ decays

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