Heavy flavor with CBM@FAIR

Hendrik van Hees

Goethe University Frankfurt and FIAS

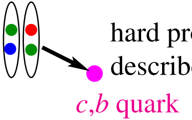
April 21, 2015

Outline

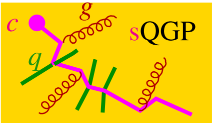
Motivation

- Open heavy-flavor mesons
  - Fast equilibration of hot and dense matter in heavy-ion collisions
  - 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 $\Rightarrow$ QGP- and hadron-transport properties
    - drag and diffusion coefficients
  - Questions at FAIR
    - importance of D and $\overline{\text{D}}$ reactions in hadronic medium?
    - influence of high net-baryon density?
    - pp/pA baseline mandatory for theory!
- Charmonia
  - Matsui and Satz (1986): Melting of quarkonia in QGP
    - suppression $\longleftrightarrow$ regeneration in QGP
    - binding $\longleftrightarrow$ color screening, dissociation through collisions
    - importance of hadronic processes?
  - Questions at FAIR
    - charmonia in medium at low energies?
    - again pp/pA baseline needed!

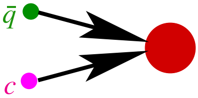
Open-heavy-flavor transport in Heavy-Ion collisions



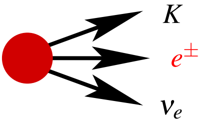
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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
$R_{AA}^{\mathrm{e}^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$

Relativistic Langevin process

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

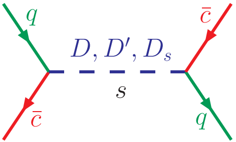
$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$

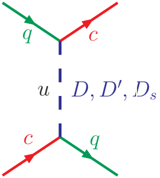
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}\left[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\parallel\right]\vec{w}$$

- $\vec{w}$: normal-distributed random variables
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients

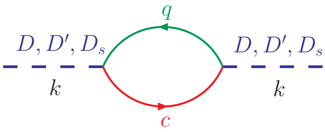
Non-perturbative interactions: Resonance Scattering

- 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





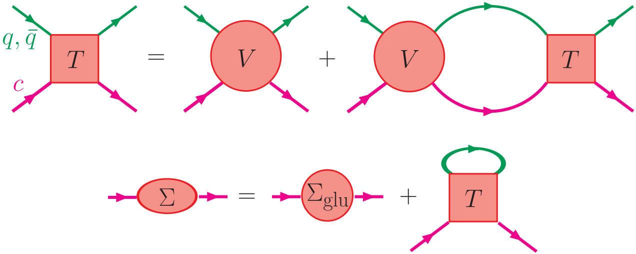
- D- and B-meson like resonances in sQGP



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

T-matrix

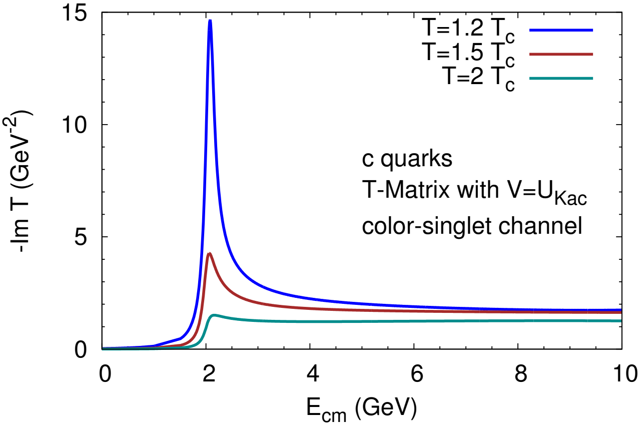
- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering



- 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

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

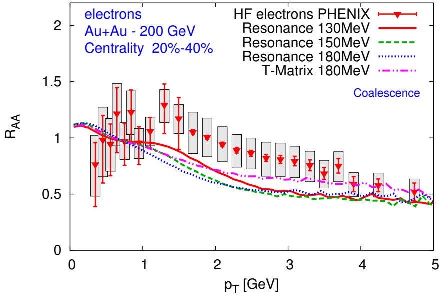
T-matrix results

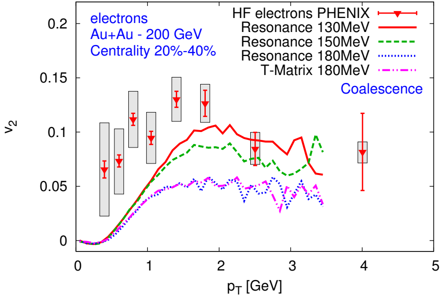


- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering!

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 *A*GeV Au-Au collisions)

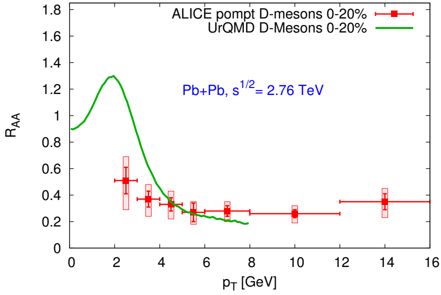


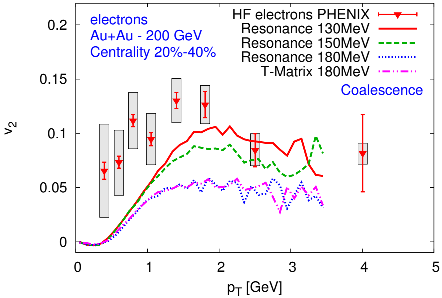


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]

D mesons at LHC

- 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 *A*TeV Pb-Pb collisions)

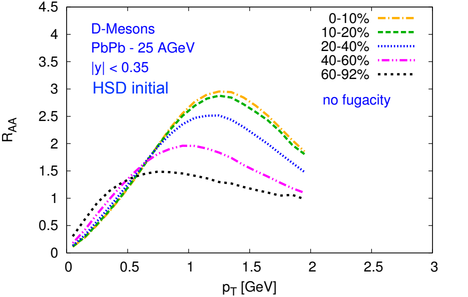


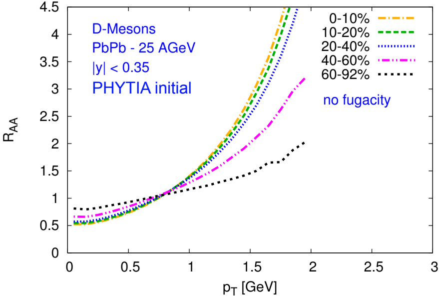


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1211.6912 [hep-ph]]

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

- 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)
- mandatory to get pp (and pA?) baseline from CBM!

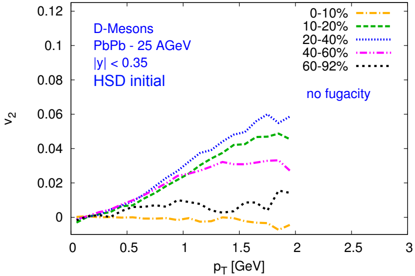


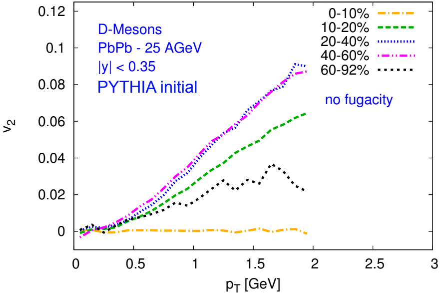


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

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

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

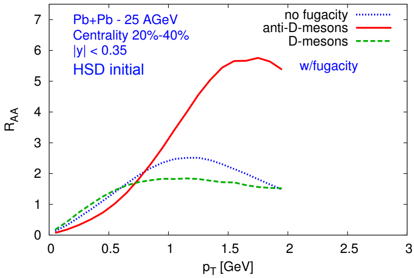


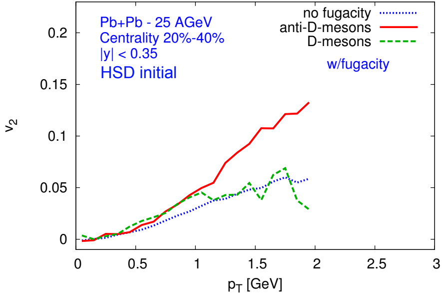


[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

D mesons at FAIR (Pb Pb at 25AGeV)

- 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

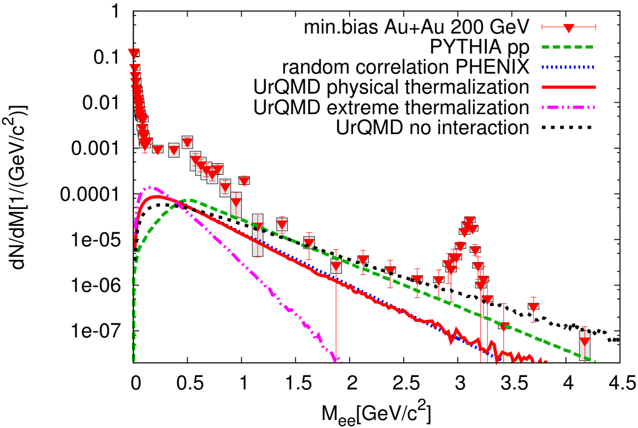




[T. Lang, HvH, J. Steinheimer, M. Bleicher, arXiv: 1305.1797 [hep-ph]]

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

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



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

Charmonia in AA collisions

- $c\bar{c}$ bound states: non-relativistic Schrödinger eq.

$$\left[2m_c - \frac{\Delta}{m_c} + V(r)\right]\psi(\vec{r}) = m_\psi \psi(\vec{r})$$

- in vacuum: Cornell potential

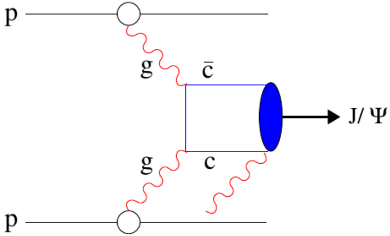
$$V(r) = \sigma r - \frac{\alpha}{r}$$

- in the vacuum: good charmonia (bottomonia) spectroscopy
- potential in medium?
  - expect some (partial) screening
  - Matsui, Satz (1986): melting of charmonia in medium
  - newer developments: NRQCD methods in medium [N. Brambilla et al] ; thermal T-matrix approach with lQCD potentials

    [S. Y. F. Liu, R. Rapp, arXiv:1501.07892 [hep-ph]]
- at low energies: hadronic interactions?

Production of charmonia: pp

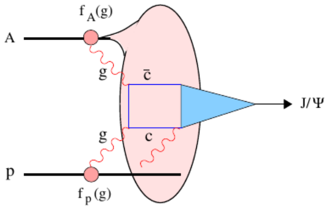
- production dominated by gluon fusion



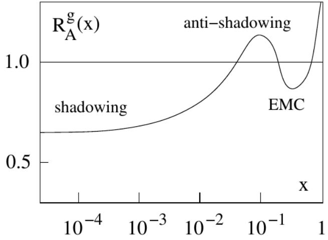
[L. Kluberg, H. Satz, Landolt-Börnstein, arXiv:0901.3831 [hep-ph]]

Production of charmonia: pA

- in pA: cold nuclear-matter effects



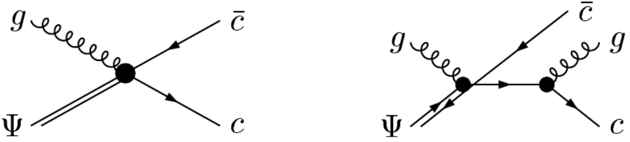
- shadowing/anti-shadowing: nuclear modification of f_g:



[L. Kluberg, H. Satz, Landolt-Börnstein, arXiv:0901.3831 [hep-ph]]

Charmonia in AA: suppression $\longleftrightarrow$ regeneration

- at high energies: QGP formation
- suppression and regeneration of charmonia
- relative to formation in pp + CNM effects!
- gluon absorption; Bhanot + Peskin: strongly bound states; $g + J/\psi \rightarrow c + \overline{c}$
- suppressed for weak binding (higher temperatures!): quasifree dissociation; $g + J/\psi \rightarrow c + \overline{c} + g$

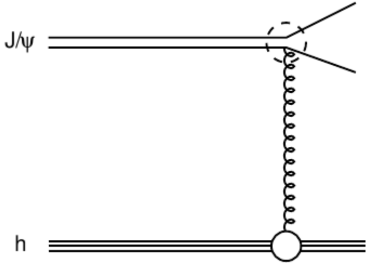


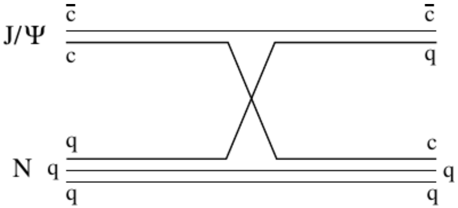
[R. Rapp, HvH, in HwaQuark Gluon Plasma IV, arXiv: 0903.1096 [hep-ph]]

- and inverse reaction (detailed balance!): regeneration

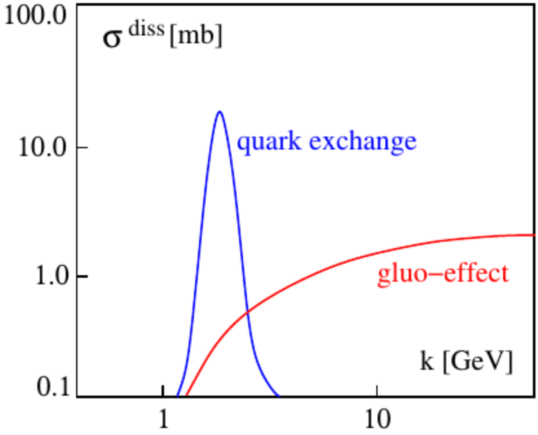
Charmonia in AA: suppression $\longleftrightarrow$ regeneration

- at low energies: reactions in hot/dense hadronic matter:
  $J/\psi + h \longleftrightarrow D\overline{D}$
- gluo effect [Bhanot, Peskin 1979; Kharzeev, Satz 1995]
- comover quark exchange [Brodsky, Müller 1988; Martins, Blaschke, Quack 1994; Matinyan, Müller 1998]





Charmonia in AA: suppression $\longleftrightarrow$ regeneration



[H. Satz, talk at H4F Heavy-Quark Workshop 2014]

Challenges for CBM experiment

- want to learn about charmonia in dense/hot hadronic medium
- need to understand total charm-production cross sections at low energies for pp, pA, and AA
- need all this for both open and hidden charm
- if possible at same $\sqrt{s}$

Summary

- Open heavy flavor
  - 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)]
  - heavy-quark diffusion in hot/dense medium
    - model calibrated by comparison to R_{AA} and v_2 of non-photonic electrons at RHIC, D mesons at LHC
    - R_{AA} and v_2 for D mesons at FAIR (pp baseline mandatory!)
    - impact of medium modifications on correlated $D\overline{D}$ decays to dileptons
- Charmonia
  - Charmonium production in pp and pA (CNM effects)
  - in partonic medium: gluo dissociation, quasi-free scattering
  - in hadronic medium: gluon effect, comover quark exchange
- FAIR has a chance to shed light on “terra incognita” of charmonia
  - production processes for open and hidden charm at low energies
  - hadron-charmonium processes in baryon rich matter