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 $\bar{D}$ decays

4. Summary and Outlook
Motivation

- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) ⇒ 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 ⇒ probes for QGP-transport properties
- Langevin simulation within UrQMD-hydro hybrid model
- sensitivity to medium evolution
- 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

$R_{AA}^{e^+e^-}(p_T), \nu_2^{e^+e^-}(p_T)$
Relativistic Langevin process

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

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

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

- \(\vec{w}\): normal-distributed random variable
- \(A\): friction (drag) coefficient
- \(B_{0,1}\): diffusion coefficients
- Einstein dissipation-fluctuation relation \(B_1 = E_p TA\).
- 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

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

\[ m_D = 2 \text{ GeV}, \Gamma_D = 0.4 \ldots 0.75 \text{ GeV} \]
\[ m_B = 5 \text{ GeV}, \Gamma_B = 0.4 \ldots 0.75 \text{ GeV} \]

**Cross sections**

- total $pQCD$ and resonance cross sections: comparable in size
- **BUT** $pQCD$ forward peaked $\leftrightarrow$ 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

\[ \gamma \text{[1/fm]} \quad \text{resonances: } \Gamma = 0.4 \text{ GeV} \]
\[ \text{pQCD: } \alpha_s = 0.4 \]
\[ \text{total} \]

\[ D \text{[GeV/fm]} \quad \text{resonances: } \Gamma = 0.4 \text{ GeV} \]
\[ \text{pQCD: } \alpha_s = 0.4 \]
\[ \text{total} \]
T-matrix

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

\[ T = V + V T \]

- $V$: 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

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

[HvH, M. Mannarelli, V. Greco, R. Rapp, Phys. Rev. Lett. 100, 192301 (2008)]
color-singlet free energy from lattice $\rightarrow$ internal energy

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

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

Casimir scaling of Coulomb part for other color channels; confining part color blind \cite{F. Riek, R. Rapp, Phys. Rev. C 82, 035201 (2010)}.

$$V_3 = \frac{1}{2} V_1, \quad V_6 = -\frac{1}{4} V_1, \quad V_8 = -\frac{1}{8} V_1$$
T-matrix results

- Im $T$ (GeV$^{-2}$) vs $E_{cm}$ (GeV)

- Resonance formation at lower temperatures $T \sim T_c$

- Melting of resonances at higher $T$

- Model-independent assessment of elastic $Qq, Q\bar{q}$ scattering!
$T$-matrix resonance-scattering coefficients: decrease with $T$

from non-pert. interactions reach $A_{\text{non-pert}} \approx 1/(7 \text{ fm}/c) \approx 4A_{\text{pQCD}}$

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)

D mesons at LHC

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

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D mesons at FAIR

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

![Graph showing R_AA vs p_T for D-meson production in PbPb collisions at 25 AGeV with |y| < 0.35, comparing HSD and PHYTIA initial conditions for different collision centrality bins.](image)

D mesons at FAIR

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

[Graphs showing $v_2$ vs. $p_T$ for D-Mesons in PbPb collisions with $|y| < 0.35$, comparing HSD initial and PYTHIA initial with different centrality bins.]

D mesons at FAIR

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

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

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


- 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