Heavy Quark Dynamics in a Hot & Dense QCD Medium

Steffen A. Bass
Duke University
About this Talk

• Heavy Quarks in QGP Matter have become a vast research area
• entire conferences are held on the subject matter
• need to be selective & focus only on a few aspects/developments
  • no Quarkonia
  • no discussion of HQ production
• focus on open charm dynamics in a QGP
• only highlight a few developments & point out some major challenges

• apologies to all colleagues whose work & contributions are not mentioned!

recommended recent comprehensive review:
Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions
A. Andronic et al. (56 authors), arXiv:1506.03981
How do we learn about Heavy Quarks in a QGP Medium?
HQ Interactions with the QCD Medium

- Djordjevic & Gyulassy
- Buzatti & Gyulassy
- Sharma & Vitev
- Armesto, Cacciari, Dainese, Salgado & Wiedemann
- Nahrgang, Gossiaux & Aichelin
- Cao & Bass
- Maumder, Bhattacharyya, Alam & Das
- Uphoff, Fochler, Xu & Greiner
- Huang, Kang & Vitev
- ...

- Teaney & Moore
- Gossiaux & Aichelin
- Uphoff, Fochler, Xu & Greiner
- Meistrenko, Uphoff, Greiner & Peshier
- Young, Schenke & Gale
- ...

- Abir, Jamil, Mustafa & Srivastava
- ...

- v. Hees, Greco & Rapp
- He, Fries & Rapp
- Lang, v. Hees & Bleicher
- ...

- Horowitz & Gyulassy
- Chesler, Lekaveckas & Rajagopal
- ...

visualization adapted from talks by C. Greiner & J. Uphoff
• Lippmann-Schwinger equation: 

\[ T_\alpha(E;q,q') = V_\alpha(q,q') + \int k^2 dk \, V_\alpha(q,k) \, G_{QQ}^0(E,k) \, T_\alpha(E;k,q') \]

- thermal 2-particle propagator: 
  \[ G_{QQ}^0(E,k;T) = T \sum_\nu D_Q(z_\nu,\vec{k})D_{\bar{Q}}(E-z_\nu,-\vec{k}) \]

- selfenergy: 
  \[ \Sigma_Q(\omega,k) = \sum_{p=q,g} \int T_{Qp}(\omega + \omega_p) \, f^p(\omega_p) \]

- in-medium potential \( V \) extracted from analysis of Lattice data on free energy

van Hees, Mannarelli, Greco & Rapp: PRL 100 (2008) 192301
Riek & Rapp: PRC 82 (2010) 035201

• approach allows for consistent calculation of drag and diffusion coefficients from Lattice data
• \( T \)-matrix interactions lead to resonance formation close to \( T_C \):
  • strong interactions near \( T_C \)
  • provides basis for coalescence processes (i.e. diffusion and hadronization based on same interaction)
Extraction of HQ and QGP Properties from Data

**Data:**

- Extracted HQ & QGP properties: $\eta/s$, $D$, $\kappa$...

**Model:**

- Initial conditions, $\tau_0$, $\eta/s$, $D$, $\kappa$....

---

**Graphs and Plots:**

- Pb-Pb, $|\eta| = 2.76$ TeV
  - Average $D^0$, $D^+$, $D^{*+}$, $|y|<0.5$, 0-7.5%
  - With pp $p_T$-extrapolated reference
  - Charged particles, $|y|<0.8$, 0-10%
  - Charged pions, $|y|<0.8$, 0-10%

- ALICE: $|\eta| = 2.76$ TeV
  - Centrality 30-50%

- STAR D0: 0-10%
  - D(s)T=6, no hadronic interaction
  - D(s)T=0, with UQMD

- ALICE: $D_0$, $D_+$, $D^{*+}$
  - D(s)T=6, no hadronic interaction
  - D(s)T=0, with UQMD

**Extracted HQ & QGP properties: $\eta/s$, $D$, $\kappa$...**
**Energy Scales: Tomography vs. Transport**

**Tomographic Regime:**
- at sufficiently high energies, heavy quarks will behave like light quarks
- hadronization and mass effects become negligible
- initial medium composition & properties outweighs dynamical evolution

**Transport Regime:**
- for low and intermediate transverse momenta ($p_T < 10$ GeV), heavy quarks exhibit behavior similar to bulk matter
- QGP evolution and hadronization play important role
- note that HQ collective flow does not prove thermalization per se!
partons propagating through a QGP medium loose energy via two mechanisms:

- **collisional energy-loss**: heavy quarks at low momenta
- **radiative energy loss**: light quarks, gluons & heavy quarks at high momenta

Dominant mechanism depends on parton mass and energy:
- **collisional energy-loss**: heavy quarks at low momenta
- **radiative energy loss**: light quarks, gluons & heavy quarks at high momenta
- **two-particle correlation observables as discriminators?**
Dynamics of Heavy Quarks in a QGP Medium
**Transport Models for HQ in Medium**

**Choice of transport approach allows for study of HQ-medium interactions:**
- **Langevin+vRFD:** sQGP + strong (non-perturbative) HQ-medium interaction
- **linearized Boltzmann+vRFD:** sQGP + pQCD driven HQ-medium interaction

**(viscous) relativistic fluid dynamics:**
- transport of macroscopic degrees of freedom
- based on conservation laws:

\[
\partial_\mu T^{\mu\nu} = 0
\]

\[
T_{ik} = \varepsilon u_i u_k + P (\delta_{ik} + u_i u_k)
- \eta \left( \nabla_i u_k + \nabla_k u_i - \frac{2}{3} \delta_{ik} \nabla \cdot u \right)
+ \xi \delta_{ik} \nabla \cdot u
\]

(plus an additional 9 eqns. for dissipative flows)

**Diffusive transport models** based on the **Langevin Equation:**
- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

\[
\overline{p}(t + \Delta t) = \overline{p}(t) - \frac{\kappa}{2T} \overline{v} \cdot \Delta t + \overline{\xi}(t) \Delta t
\]

**Microscopic transport models** based on the **Boltzmann Equation:**
- transport of a system of microscopic particles
- all interactions are based on binary scattering

\[
\begin{bmatrix}
\frac{\partial}{\partial t} + \frac{\overline{p}}{E} \times \frac{\partial}{\partial \vec{r}}
\end{bmatrix} f_1(\overline{p}, \vec{r}, t) = \sum_{\text{processes}} C(\overline{p}, \vec{r}, t)
\]

**Hybrid transport models:**
- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling
modify Langevin Eqn. with force term due to gluon radiation:

\[
\frac{d\vec{p}}{dt} = -\eta_D(p) \vec{p} + \xi + \vec{f}_g
\]

\[
\{ \text{radiation force defined through rate of radiated gluon momenta:} \quad \vec{f}_g = \frac{d\vec{p}}{dt} \}
\]

- same noise correlator and fluctuation-dissipation relation still hold:

\[
\eta_D(p) = \frac{\kappa}{2TE} \quad \text{and} \quad \langle \xi^i(t) \, \xi^j(t') \rangle = \kappa \, \delta^{ij} \, \delta(t - t')
\]

- gluon radiation calculated in Higher Twist formalism:

\[
\frac{dN_g}{dx \, dk_{\perp}^2 \, dt} = 2\alpha_s(k_{\perp}) \frac{P(x)}{\pi} \frac{\hat{q}}{k_{\perp}^4} \sin^2 \left( \frac{t - t_i}{2\tau_f} \right) \left( \frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2} \right)^4
\]

- relevant transport coefficients are now:

\[
D = \frac{t}{M \eta_D(0)} = \frac{2T^2}{\kappa} \quad \text{and} \quad \hat{q} = 2 \kappa \frac{C_A}{C_F}
\]

Guo & Wang: PRL 85, 3591
Majumder: PRD 85, 014023
Zhang, Wang & Wang: PRL 93, 072301
Thermalization in Langevin+Radiation

**radiative term in Langevin Equation violates detailed balance:**
- radiation should be suppressed for thermal momentum scale
  - introduce low momentum cut-off for gluon radiation: $p_{\text{cut}} = \alpha 3T$
- vary parameter $\alpha$ to ensure proper HQ thermalization

redo thermalization analysis in Langevin+Radiation approach:
- system shows proper thermalization dynamics for $\alpha \approx 2$
- note that $\tau_{\text{therm}}$ may depend on initial HQ momentum distribution
- for this particular set of parameters thermalization time: $\tau_{\text{therm}}$ is reduced from $\approx 35$ fm/c to $\approx 25$ fm/c
Recombination+Fragmentation Model

basic assumptions:

• at low $p_t$, the parton spectrum is thermal and HQs recombine with light quarks into hadrons locally “at an instant”:

$$\frac{dN_M}{d^3 P} = C_M \frac{V}{(2\pi)^3} \int \frac{d^3 q}{(2\pi)^3} w\left(\frac{1}{2} P - q\right) w\left(\frac{1}{2} P + q\right) |\hat{\phi}_M(q)|^2$$

• at high $p_t$, the parton spectrum is given by a pQCD power law, HQs suffer radiative energy loss and hadrons are formed via fragmentation of HQs:

$$E \frac{dN_h}{d^3 P} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \int_0^1 \frac{dz}{z^2} \sum_\alpha w_\alpha(R, \frac{1}{z} P) D_{\alpha \rightarrow h}(z)$$

• shape of spectrum determines if reco or fragmentation is more effective:
  • for thermal distribution recombination yield dominates fragmentation yield
  • vice versa for pQCD power law distribution
Hadronic Rescattering for HQs

soft hadrons from QGP
heavy mesons from heavy quarks

scattering cross sections for heavy mesons:

• Ziwei Lin, T.G. Di & C.M. Ko: Nucl. Phys. A689 (2001), 965
• consider scattering of D and D* with $\pi$ and $\rho$ mesons
• $\Lambda$: cutoff parameter in hadron form factors

future plans:

• resonant scattering via D* formation (see e.g. He, Fries & Rapp: PLB701 (2011), 445
Summary of HF Dynamics Setup

- **Bulk Matter**: Glb/KLN initial condition, (2+1)D viscous hydro (OSU), Cooper-Frye (OSU iSS)
  - UrQMD

- **Heavy Flavor**: Glauber for $x$, LOpQCD+CTEQ, improved Langevin, hybrid model of frag.+coal.
  - EPS09 for $p$

• setup allows for consistent event-by-event treatment of hard probes and underlying soft medium
• necessary for calculating two particle correlation functions involving heavy/light flavor combinations
Comparison to Data
Langevin w/ Microscopic Interaction

Current State-of-the-Art:
• Langevin for HQ + coalescence & fragmentation for hadronization + heavy meson diffusion in a hadron gas

From RHIC to LHC:
• Heavy Quarks now (partially) ultra-relativistic:
  ‣ radiative energy-loss
  ‣ fragmentation as dominant hadronization mechanism

He, Fries, Rapp, Phys. Rev C86: 014903, arXiv:1208.0256, and private communication with He
LHC - radiative Langevin: $R_{AA}$ and Elliptic Flow

- Collisional energy loss dominates at low $p_T$, radiative at high $p_T$
- Recombination important at low momenta
- Combination of recombination and fragmentation provides a good description of data

$v_2$ significantly underpredicted:
- Most data in $p_T$ domain already dominated by fragmentation as hadronization mechanism
- Even pure recombination underpredicts data - check for initial conditions and EbE effects
**HQ Elliptic Flow Puzzle**

- HQ transport calculations can all reproduce $R_{AA}$ (albeit with different values of $D$)
- however, they yield very different outcomes for $v_2$

![Graph showing elliptic flow results](image1.png)

- range of $v_2$ values for good description of $R_{AA}$ varies by factor of 3 depending on approach!

**Current Status:**
- Boltzmann dynamics w/ recombination works best
- validation with $c\bar{c}$ correlation functions?

![Graph showing correlation functions](image2.png)

*Cao, Qin & Bass: PRC 88 (2013) 012035*
*Nahrgang, Aichelin, Bass, Gossiaux & Werner: NPA 931 (2014) 575*

Initial State Effects

- shadowing improves agreement with $R_{AA}$ data
- however, it also provides a degree of uncertainty
• good description of $N_{\text{part}}$ dependence of the $D$ meson $R_{AA}$
• with the same transport coefficient for $c$ and $b$ quarks, reasonable description of the non-prompt $J/\psi$ $R_{AA}$
• mass hierarchy of heavy quark energy loss: $\Delta E_c > \Delta E_b$
HQ Correlations
Angular HQ Correlations

assume back-to-back production of initial Q & Qbar with the same magnitude of momentum

angular correlation of the final state QQbar is sensitive to:
• momentum broadening of heavy quark
• degree of thermalization of heavy quarks
• coupling strength between heavy quarks and the QGP
• each energy loss mechanism alone can fit $R_{AA}$ with certain accuracy and choice of diffusion coefficient, yet they display very different behavior in the angular correlation function
• experimental observation may discriminate between the energy loss mechanisms of heavy quarks inside the QGP
Heavy-Light Hadron Correlations

(e from c, b) - h correlation
(talk by Pereira at HP2013)

• peaks are seen around 0 and π, strongly affected by medium flow
• differences between various energy loss mechanisms depend on y and $p_T$ cut (to be investigated further)
Current Status of HQ Transport

Multiple different transport frameworks:
- Langevin
- Langevin with Radiation
- Boltzmann (full microscopic treatment)
- Linearized Boltzmann (Hydro w/ microscopic HQ collision term)
- ...

Multiple different physics ingredients:
- pQCD cross sections (w/ & w/o radiation)
- Drag/Diffusion coefficients from pQCD or a variety of effective nonperturbative approaches
- Different implementations of the LPM effect
- Treatment of initial state and shadowing

Open Questions & Future Direction:
- diversity of approaches: how to isolate relevant physics and verify/falsify underlying concepts and assumptions?
- guidance from Lattice QCD calculations? (what are the uncertainties and caveats?)
- Consistency of QGP medium: require agreement with light hadron data?
- How important is the treatment of EbE fluctuations?
- Is there a minimum feature set that we should require from all HQ calculations (e.g. in terms of observables predicted or physics ingredients)?
The next 5-10 years of the RHIC & LHC heavy-ion program will deliver a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium, as well as Quarkonia measurements that will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.

- new and improved heavy flavor measurements will provide a rich tapestry of observables that will allow us to study the interactions of heavy quarks in medium in great detail

- different collision energies, system sizes and p+A will be essential to pin down all the details
The End
HQ Correlations
Angular correlation of the final state QQ\bar{q} is sensitive to:

- momentum broadening of heavy quark
- degree of thermalization of heavy quarks
- coupling strength between heavy quarks and the QGP

assume back-to-back production of initial Q & Q\bar{q} with the same magnitude of momentum
Correlations: Elastic vs. Radiative Processes

- each energy loss mechanism alone can fit $R_{AA}$ with certain accuracy and choice of diffusion coefficient, yet they display very different behavior in the angular correlation function
- experimental observation may discriminate between the energy loss mechanisms of heavy quarks inside the QGP
Correlations II: D Mesons

- Initial HQ production: MCNLO + Herwig
- Calculate angular correlation of final state ccbar pairs

Within each event, correlate each D with all Dbar’s
- Similar shape as direct ccbar correlation, but on top of a large background

Viable signal with good sensitivity to HQ energy loss mechanism if experiments could measure D Dbar angular correlation functions!
Radial Flow and $p_T$ Dependence

- Angular correlation functions of D-Dbar pair in pp collisions generated by PYTHIA 8
- Flat for no $p_T$ cut; forward and backward peaked for higher $p_T$ cut

- D-Dbar correlation without $p_T$ cut
- Forward peaked for pure collisional energy loss
- The above peak disappears when the QGP flow is shut off
D-Dbar in Au-Au with $p_T^D > 2$ GeV

with increasing $p_T$ cut:
- forward peak becomes smaller and backward peak becomes larger
- differences between various energy loss mechanism tend to become smaller

D-Dbar correlation
PYTHIA initialization

D-Dbar in Au-Au with $p_T^D > 4$ GeV

p$_T$ > 4 GeV for D

Au-Au @ 200 GeV 0-10%
Heavy-Light Hadron Correlations

(e from c, b) - h correlation
(talk by Pereira at HP2013)

- Peaks are seen around 0 and π, strongly affected by medium flow.
- Differences between various energy loss mechanisms depend on y and $p_T$ cut (to be investigated further).