Theory aspects of open heavy flavor production and suppression in cold and hot nuclear matter

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What do we want to study?

- Properties of strongly interacting many-body systems.
- Phases of hot and dense nuclear matter.
- Tool: (ultra)relativistic heavy-ion collisions.
- LHC: PbPb at $\sqrt{s_{NN}} = 2.76$, 5 TeV
  RHIC: AuAu at $\sqrt{s_{NN}} = 200 – 7.7$ GeV

How to probe the properties of the quark-gluon plasma?
Probes

- Probes should not thermalize with the medium, e.g. dileptons, high-pT jets, ...
- The mass of heavy quarks (HQ) sets another scale: $m_c, m_b$
  (top is too heavy to be produced abundantly and decays quickly)
- HQ vacuum shower terminates much earlier: $E / Q_H^2$
  with $Q_H = \sqrt{Q_0^2 + m_Q^2}$.
- The HQ mass reduces the radiation phase space: dead cone effect.
- Number of thermally excited HQ is negligibly small.
- HQ as leading parton is always tagged (hard radiations change energy but not identity).
Quark-gluon plasma and its properties

Expectation in heavy-ion collisions:

Formation of QGP, which evolves fluid dynamically as a nearly perfect fluid.

collective flow

jet quenching

observable: Fourier coefficients of

\[
\frac{d^2 N}{dp_T dy} \propto \sum_n v_n \cos(n \phi)
\]

sensitive to viscosity \( \eta / s \)

observable: nuclear modification factor

\[
R_{AA}(p_T) = \frac{1}{N_{\text{coll}}} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}
\]

sensitive to jet quenching parameter \( \hat{q} \)
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B. Schenke et al. PLB702 (2011)

Jet Collab. PRC90 (2014)
Modeling of heavy-quark dynamics in the QGP

production interaction with the medium hadronization

- LO pQCD $\rightarrow$ including resummation of logs: FONLL $\rightarrow$ inclusive spectra $\Rightarrow$ back-to-back initialization, no information about the azimuthal $Q\bar{Q}$ correlations
  
  M. Cacciari et al. PRL95 (2005), JHEP 1210 (2012)

- NLO pQCD matrix elements plus parton shower, e.g. POWHEG or MC@NLO $\Rightarrow$ exclusive spectra, like $Q\bar{Q}$ correlations
  

- Cold nuclear matter effects, i.e. shadowing, $p_T$ broadening aka Cronin effect, etc.
  
Modeling of heavy-quark dynamics in the QGP

- Collisional (elastic) cross sections ⇒ $\Delta E \sim \log(E)L$
- Incoherent radiation (GB regime) ⇒ $\Delta E \sim EL/l_{mfp}$
- Coherent radiation (BDMPS-Z regime) ⇒ $\Delta E \sim \sqrt{E}L$
- Dead cone effect reduces radiative energy loss for heavy quarks.
- For very energetic partons and thin media ⇒ $\Delta E \sim L^2$
- Further radiative effects: finite gluon mass and width

Modeling of heavy-quark dynamics in the QGP

production interaction with the medium hadronization

- Coalescence/Recombination – predominantly at small $p_T$.

- Fragmentation – predominantly at large $p_T$.

S. Cao et al. arxiv:1505.01413

Gossiaux et al. PRC 78 (2008)
What to expect from heavy-quark observables?

at low $p_T \sim m_Q$

- Very different from light partons.
- Nonperturbative!
- Partial thermalization with the light partons in the QGP?
- Diffusion $D$ mainly via collisional processes?
- Hadronization via coalescence/recombination?
- Initial shadowing and cold nuclear matter effects?

at high $p_T \gg m_Q$

- Similar to light partons.
- Perturbative regime...
- Rare processes, probe the opacity of the matter.
- Energy loss $dE/dx$ via collisional and radiative processes?
- Coherent energy loss $\to$ jet-quenched parameter $\hat{q}$?
- Hadronization via (medium-modified) fragmentation?
Boltzmann equation for HQ phase-space distribution

\[ \frac{df_Q}{dt}(t, \mathbf{x}, \mathbf{p}) = C[f_Q] \quad \text{with} \quad C[f_Q] = \int d\mathbf{k} \left[ w(\mathbf{p} + \mathbf{k}, \mathbf{p}) f_Q(\mathbf{p} + \mathbf{k}) - w(\mathbf{p}, \mathbf{k}) f_Q(\mathbf{p}) \right] \]

expanding \( C \) for small momentum transfer \( k \ll p \) (in the medium \( k \sim \mathcal{O}(gT) \)) and keeping lowest 2 terms \( \Rightarrow \) Fokker-Planck equation

\[ \frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \sum_i \left( A^i(\mathbf{p}) f_Q(t, \mathbf{p}) + \sum_j B^{ij}(\mathbf{p}) f_Q(t, \mathbf{p}) \right) \]

friction (drag) \quad momentum diffusion

Recast to Langevin equation (probably good for bottom, but for charm?)

\[ \frac{d}{dt} \mathbf{\bar{p}} = -\eta_D(\mathbf{p}) \mathbf{\bar{p}} + \xi \quad \text{with} \quad \langle \xi^i(t) \xi^j(t') \rangle = \kappa \delta^{ij} \delta(t - t') \]

Transport coefficients connected by fluctuation-dissipation theorem (Einstein relation):

\[ \eta_D = \frac{\kappa}{2m_Q T}, \quad D_s = \frac{T}{m_Q \eta_D} \]  

spatial diffusion
Diffusion coefficient from lattice QCD

Lattice QCD at finite $T$ is performed in Euclidean space ⇒ notoriously difficult to calculate dynamical quantities.

Transport coefficients calculated from correlation function of conserved currents via slope of spectral function $\rho_E$ at $\omega = 0$ (Kubo formula)

momentum diffusion:

$$\frac{\kappa}{T^3} = \lim_{\omega \to 0} \frac{2T\rho_E(\omega)}{\omega}$$

⇒ No reliable input from lattice QCD calculations yet...
Collisional (elastic) energy loss

LO Feynmann diagrams for perturbative heavy quark scattering off a light parton

- Dominant contribution from the $t$-channel
- Well-known IR singularity, regulated by the Debye screening mass $m_D$
- Gluon propagator: $G(t) = \frac{\alpha_s}{t} \rightarrow \frac{\alpha_s}{t - m_D^2}$ with $m_D \sim O(gT)$
- Use the Hard-Thermal Loop (HTL) resummed gluon propagator for small $|t| \ll t^*$ and the bare gluon propagator $|t| \gg t^*$ to calculate energy loss.
- For well-separated scales $g^2 T^2 \ll T^2$ results are independent of the intermediate scale $t^*$. 
Nantes model

- Relevant separation of scales $g^2 T^2 \ll T^2$ probably not fulfilled in RHIC and LHC experiments.
- Idea: introduce a reduced IR regulator $\lambda m_D^2$ in the hard part: HTL+semi hard $\Rightarrow$ by tuning $\lambda$ achieve independence from $t^\ast$.
- Calibrate pQCD Born matrix elements with $G(t) = \frac{\alpha_s}{t-\lambda m_D^2}$ to HTL+semi hard energy loss.
- Use a running coupling at the scale of the specific process $\alpha_{\text{eff}}(t)$.
- Self-consistently determine the Debye-mass from $m_D^2 = (1 + 6n_f)4\pi\alpha_s(m_D^2)T^2$.

Non-perturbative resonance scattering

- Basic assumption: two-body interactions $\rightarrow$ potential $V(t)$ with $t \simeq -\vec{q}^2$ ($c$, $b$ quarks; $T \lesssim 3T_c$)

- $T$-matrix follows from Lippmann-Schwinger equation: $T = V + \int d^3k V G_2 T \rightarrow$ HQ transport coefficients, e.g. $A_Q(\vec{p}) \sim |T|^2$

- Medium-modified HQ potential from lQCD free/internal energy:
  - Stronger interaction from internal energy based $V$
  - Enhanced $\Delta E_{\text{loss}}$ than in pQCD due to resonant HQ-meson and di-quark states in scattering channels

- Spatial diffusion coefficient $D_s = 2\pi T^2 / m_Q A_Q$:
  - comparable to quenched lQCD
  - smooth transition to hadronic medium with minimum close to $T_c$

Radiative energy loss

- LO pQCD matrix element for $2 \rightarrow 3$ process Kunszt et al. PRD21 (1980)
- Gunion-Bertsch approximation derived in the high-energy limit, where the radiated gluon $k_\perp$ and the momentum transfer $q_\perp$ are soft $\ll \sqrt{s}$.
- Incoherent radiation off a massless parton, mid-rapidity
- Extention beyond mid-rapidity and to finite mass $m_Q$ (heavy quarks!)
  $\Rightarrow$ distribution of induced gluon radiation:

$$P_g(x, \vec{k}_\perp, \vec{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2} \frac{1 - x}{x} \left( \frac{\vec{k}_\perp}{\vec{k}_\perp^2 + x^2 m_Q^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2 m_Q^2} \right)^2$$

$\Rightarrow E^{\text{loss}}_{\text{rad}} \propto E L$

J. Gunion, PRD25 (1982); O. Fochler et al. PRD88 (2013); J. Aichelin et al. PRD89 (2014)
Coherent emission - LPM

- coherent emission if $\tau_{\text{form}} = \sqrt{\frac{\omega}{\hat{q}}} > l_{\text{mfp}}$
- QCD analogon to the Landau-Pomeranchuk-Migdal (LPM) effect
- Important in QCD: rescattering of the forming gluon with medium partons $\Rightarrow$ less suppression than in QED
- At large energies in BDMPS-Z: $\Rightarrow$ $E_{\text{loss}}^{\text{rad}} \propto \sqrt{E} L$
- For very energetic partons $\tau_{\text{form}} > L$, then $E_{\text{loss}}^{\text{rad}} \propto L^2$, estimate for the LHC ($L \sim 2 \text{ fm}$, $\hat{q} \sim 2 \text{ GeV/fm} \Rightarrow \omega_c \sim 20 \text{ GeV}$)


Baier et al. PLB 345 (1995); NPB 483 (1997); ibid. 484 (1997); B. G. Zakharov, JETP Lett. 63 (1996) 952
Dead cone effect

suppression of high-energetic (small angle) gluon emission by the heavy quark mass:

\[ \frac{d\sigma_{\text{rad}}}{\theta d\theta} \propto \frac{\theta^2}{(\theta^2 + M_Q^2/E_Q^2)} \]

Dokshitzer et al., PLB 519 (2001)

- Suppresses gluon emission in the dead cone \( \theta_D = M_Q/E_Q \)
- Introduces a mass hierarchy in the radiative energy loss.
- But: assumes hard scatterings!

When the hard scattering assumption is relaxed, emission at low \( k_\perp \) is significantly less suppressed:

\[ \frac{P_g(x,k_\perp;M)}{P_g(x,k_\perp;0)} \]

hard-scattering approximation
all scatterings

J. Aichelin et al. PRD89 (2014)
From theoretical input to dynamical modeling

- No reliable input for the HQ diffusion coefficient from lattice QCD calculations.
- pQCD and pQCD inspired models of collisional and radiative processes.
- In a fully dynamical system processes on many scales involved, simple approximations are prone to fail at intermediate $p_T$.
- Due to uncertainties all models when compared to data contain (implicit or explicit) parameter tuning.
- Proper modeling of the QGP evolution is important! Should be well tested in the light hadron sector!

And finally some results...
pQCD at high momenta

- Collisional and radiative pQCD energy loss implemented, only applicable at high $p_T$.
- Good simultaneous description of D mesons, light hadrons and J/psi.
- While D meson suppression = charm quark suppression, the fragmentation into light hadron distorts the picture ⇒ light hadron suppression dominated by light quark suppression.
- No dynamical QGP description, only parametrized temperatures.

M. Djordjevic, PLB734 (2014)
• Langevin models have problems describing both the $R_{AA}$ and the $v_2$.

Alberico et al. EPJC73 (2013); Cao et al. arxiv:1505.01413
Recombination needs to be included in order to describe the $R_{AA}$ at lower $p_T$.

Cao et al. arxiv:1505.01413
Nonperturbative diffusion at the LHC

- Transport coefficients from $T$-matrix approach, Langevin dynamics and $2 + 1d$ ideal fluid dynamical QGP evolution.

- Rather good description of $R_{AA}$ but $\nu_2$ underestimated.

- Strangeness enhancement as signal of the QGP (thermal production) $\Rightarrow$ enhancement of $D_s$ compared to $D$ mesons.

H. Min et al. PLB735 (2014)
**pQCD Boltzmann transport**

- pQCD-inspired Boltzmann transport in $3 + 1d$ ideal fluid dynamics (EPOS) or in partonic transport (BAMPS).

**MN et al. (Nantes) - MC@sHQ+EPOS2**

- Rather good description of the $R_{AA}$ and the $v_2$.
- Slight preference for purely collisional energy loss in MC@sHQ+EPOS2.

**Uphoff et al. (BAMPS)**

- $\kappa = 1.0, X_{LPM} = 1.0$
- $\kappa = 0.2, X_{LPM} = 0.2$
- only $2 \rightarrow 2, \kappa = 0.2, K = 3.5$
- $0-7.5\%$ (ALICE)

- $\kappa = 1.0, X_{LPM} = 1.0$
- $\kappa = 0.2, X_{LPM} = 0.2$
- only $2 \rightarrow 2, \kappa = 0.2, K = 3.5$
- $30-50\%$ (ALICE)

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How much of the observed suppression really comes from the hot QGP? Look at reference systems, like p+Pb collisions.

- The parton distribution function (pdf) is different for a proton in a nucleus than for a free proton: shadowing (ie. a depletion) at small $x$ and possibly antishadowing (ie. enhancement) at intermediate $x$. $\rightarrow$ effect is parametrized in sets of npdf

- Parton saturation at small $x$: large parton densities in the nucleus. E.g. Color Glass Condensate formalism (JIMWLK non-linear evolution equations).

- multiple scattering of partons in the cold nucleus before & after the hard scattering $\Rightarrow$ transverse momentum broadening, Cronin effect

- If high-multiplicity pA collisions produce a QGP hot medium effects will also contribute (work in progress by groups in Duke, Nantes,...)

For much more, see talk by R. Vogt this afternoon!
Beyond traditional observables...

Conclusion: too many models can (more or less) well describe the available data.

⇒ Need new observables with high discriminating power between purely collisional and collisional+radiative approaches: eg. azimuthal correlations of $Q\bar{Q}$ pairs.

$p_\perp$ from MC@sHQ+EPOS2:

$c\bar{c}$ correlation plot from Duke model

- Advantages: sensitive to the interaction mechanism: purely coll or coll+rad
- Difficulties: already the $c\bar{c}$ proton-proton baseline is not well understood theoretically, contributions from final hadronic interactions, experimental feasibility...

MN et al. PRC90 (2014)
Cao et al., arxiv:1505.01869
Beyond traditional observables...

- What can we learn from comparison to data from flow measurements?
- Most models give a $\tau_{\text{relax}}$ for charm quarks much longer than the evolution of the QGP, but HF $v_2$ is very similar to light hadron $v_2$.
- Further contributions from coalescence and energy loss.
- What about higher-order Fourier coefficients?

- Expectation: $v_3$ and higher-order coefficients show the incomplete coupling of HQ to the medium.

MN et al. PRC91 (2015)
Summary

- HQ probe partial thermalization at low $p_T$ and energy loss at high $p_T$ in the QGP.
- Mass ordering is seen in collisional and radiative interaction mechanisms from light hadrons $\rightarrow$ charm $\rightarrow$ bottom.
- Many effects important at intermediate $p_T$: onset of coherent gluon emission, gluon thermal mass, finite path length, nonperturbative scatterings,...
- Transport coefficients/scattering cross sections in Langevin or Boltzmann transport.
- In order to compare to experiment theory of energy loss needs to be coupled to a dynamical evolution of the QGP (better to use a model which is well tested in the light hadron sector!)
- $R_{AA}$ and $v_2$ are described well by (too?) many models.
- Need for further observables, like $Q\bar{Q}$ correlations and higher-order flow coefficients, for veri/falsi-fication of models!
backup
Modeling of heavy-quark dynamics in the QGP

- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!

smooth initial conditions

fluctuating initial conditions

production interaction with the medium hadronization

medium description coupling medium - HF sector

- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Use a fluid dynamical description which describes well the bulk observables!
“Partonic wind” effect


- Due to the radial flow of the matter low-\(p_T\) \(c\bar{c}\)-pairs are pushed into the same direction.
- Initial correlations at \(\Delta \phi \sim \pi\) are washed out but additional correlations at small opening angles appear.
- This happens only in the purely collisional interaction mechanism!
- No “partonic wind” effect observed in collisional+radiative(+LPM) interaction mechanism!
QGP: initial state and bulk flow (1)

- Bulk flow is driven by the initial elliptic or triangular eccentricity $\epsilon_2$ and $\epsilon_3$

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}$$

- In the light hadron sector the final $v_2 \propto \epsilon_2$ and $v_3 \propto \epsilon_3$ for not too large centralities.
  
  G.-Y. Qin et al., PRC 82 (2010); H. Niemi et al., PRC 87(2013)

- Proportionality depends on viscosity and higher-order flow is more sensitive!

$$\frac{v_n}{\epsilon_n} = \left( \frac{v_n}{\epsilon_n} \right)_{\text{ideal}} (1 - O(n^mK)) \quad m \sim 1 - 2$$

B. H. Alver et al., PRC 82, (2010); P. Staig and E. Shuryak, PRC 84 (2011); Y. Hatta et al., arXiv:1407.5952

- Dependence on centrality already in the ideal case: FO dynamics, core-corona separation, etc.
QGP: initial state and bulk flow (2)

average temperature and overlap area

centrality dependence:
+ increase of initial eccentricities
+ decrease of interaction rate and medium size

⇒ expectation: heavy-flavor flow shows a weaker dependence on centrality, especially for $v_3$
At small $p_T$: relative enhancement of flow in purely collisional scenario over collisional+radiative(+LPM) larger for $v_3$ than for $v_2$
Charm flow: hadronization and energy loss

collisional+radiative(+LPM), $K = 0.8$

- Contribution to the flow from hadronization.
- For low $p_T$ the charm flow is predominantly due to the flow of the bulk.
Flow of B mesons reflects well the bottom quark flow.

Flow of B mesons for $p_T \lesssim 6$ GeV entirely due to bulk flow.
Diffusion coefficient in MC@$sHQ$

\[
\begin{align*}
\text{El. (K=1)} & \quad \text{El. + radiat LPM (K=1)} \\
\text{El. (K=1.5)} & \quad \text{El. + radiat LPM (K=0.8)}
\end{align*}
\]

\[2\pi T D_s \]

$T/T_c$ vs $T/T_c$

$\text{MC}@_{s\text{HQ V508}}$

Banerjee et al., PRD 85 (2012)  
Ding et al., PRD 86 (2012)
Radiative energy loss

- Incoherent radiation: Gunion-Bertsch spectrum extended to finite quark mass.
  
  J. Aichelin et al., PRD 89 (2014), arXiv:1307.5270

- Inclusion of an effective suppression of the spectra in the coherent radiation regime (LPM effect)

- Influence of gluon damping (not in this talk)
  