Elastic and radiative heavy quark energy loss within a transport model

Jan Uphoff
with O. Fochler, Z. Xu and C. Greiner

Heavy quark energy loss mechanism

- Perturbative QCD
- Elastic scatterings
- Radiative processes
- Resonance scattering
- AdS/CFT
Heavy quark energy loss mechanism

- Djordjevic, Gyulassy
- Buzatti, Gyulassy
- Sharma, Vitev
- Armesto, Cacciari, Dainese, Salgado, Wiedemann
- Nahrgang, Gossiaux, Aichelin
- Cao, Bass
- Mazumder, Bhattacharyya, Alam, Das
- **JU, Fochler, Xu, Greiner**

- Moore, Teaney
- Gossiaux, Aichelin
- Alberico, Beraudo, et al.
- **JU, Fochler, Xu, Greiner**
- Meistrenko, JU, 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

- Perturbative QCD
- Elastic scatterings
- Radiative processes
- Resonance scattering
- AdS/CFT
BAMPS: Boltzmann Approach to MultiParton Scatterings

- 3+1 dimensional, fully dynamic parton transport model
- Solves the Boltzmann equations for on-shell partons with pQCD interactions

\[
\left( \frac{\partial}{\partial t} + \frac{p_i}{E_i} \frac{\partial}{\partial r} \right) f_i(r, p_i, t) = C^{2\rightarrow2}_i + C^{2\leftrightarrow3}_i + \ldots
\]

- Divide collision zone into cells

- Using stochastic method

\[
P_{2\rightarrow2} = \nu_{\text{rel}} \frac{\sigma_{2\rightarrow2}}{N_{\text{test}}} \frac{\Delta t}{\Delta^3 x}
\]

Interactions in BAMPS with $N_{\text{flavor}} = 3+2$

Light flavors

$g \ g \rightarrow g \ g$
$g \ g \rightarrow q \ q\bar{q}$
$q \ q\bar{q} \rightarrow g \ g$ \quad \text{and} \quad q \ q\bar{q} \rightarrow q' \ q'\bar{q}'$
$q \ g \rightarrow q \ g$ \quad \text{and} \quad \bar{q} \ g \rightarrow \bar{q} \ g$
$q \ q\bar{q} \rightarrow q \ q\bar{q}$
$q \ q \rightarrow q \ q$ \quad \text{and} \quad \bar{q} \ q\bar{q} \rightarrow \bar{q} \ q\bar{q}$
$q \ q' \rightarrow q \ q'$ \quad \text{and} \quad q \ q' \rightarrow q \ q'$

Heavy flavors

Binary

$g + g \rightarrow Q + \bar{Q}$
$Q + \bar{Q} \rightarrow g + g$
$q + \bar{q} \rightarrow Q + \bar{Q}$
$Q + \bar{Q} \rightarrow q + \bar{q}$
$g + Q \rightarrow g + Q$
$q + Q \rightarrow q + Q$
$g + J/\psi \rightarrow c + \bar{c}$
$c + \bar{c} \rightarrow g + J/\psi$

Inelastic

$g + Q \rightarrow g + Q + g$
$q + Q \rightarrow q + Q + g$
Sketch of heavy flavor in HIC

Initial hard parton scatterings
Sketch of heavy flavor in HIC

Initial hard parton scatterings
Sketch of heavy flavor in HIC
Sketch of heavy flavor in HIC

Charm production

Initial hard parton scatterings

Energy loss

QGP
Sketch of heavy flavor in HIC

Charm production

Initial hard parton scatterings

Energy loss

J/ψ regeneration

J/ψ dissociation

QGP

J/ψ
Sketch of heavy flavor in HIC

Initial hard parton scatterings

Energy loss

J/ψ regeneration

J/ψ dissociation

Charm production

QGP

Hadronic phase
No interactions taken into account
Sketch of heavy flavor in HIC

- Initial hard parton scatterings
- Energy loss
- J/ψ regeneration
- J/ψ dissociation
- Charm production

Hadronic phase
No interactions taken into account
Heavy quark scattering

Leading order perturbative QCD:

\[ g + Q \rightarrow g + Q \]
\[ q + Q \rightarrow q + Q \]

Improved Debye screening by comparing to HTL

\[ \frac{1}{t} \rightarrow \frac{1}{t - \kappa m_D^2} \]
\[ \kappa = \frac{1}{2e} \approx 0.2 \]


Running coupling

Heavy quark $v_2$ and $R_{AA}$ at RHIC

only elastic heavy quark processes

$\sigma_{gQ\rightarrow gQ} \rightarrow K \sigma_{gQ\rightarrow gQ}$

JU, Fochler, Xu, Greiner

PHENIX data,
D meson $R_{AA}$ and electron $v_2$ at LHC

Only elastic heavy quark processes

JU, Fochler, Xu, Greiner

ALICE data, QM12
D meson $R_{AA}$ and electron $v_2$ at LHC

Only elastic heavy quark processes

\[ \sigma_{gQ \rightarrow gQ} \rightarrow K \sigma_{gQ \rightarrow gQ} \]

JU, Fochler, Xu, Greiner

ALICE data, QM12
Radiative processes: Improved Gunion-Bertsch matrix element

Can radiative processes account for $K \sim 3.5$?

\[
g + Q \rightarrow g + Q + g \\
q + Q \rightarrow q + Q + g
\]

Improved Gunion-Bertsch matrix element generalized to heavy quarks:

\[
\left| \overline{M}_{qQ\rightarrow qQg} \right|^2 = 12g^2(1 - \bar{x})^2 \left| \overline{M}_{0}^{qQ} \right|^2 \left[ \frac{k_\perp}{k_\perp^2 + x^2M^2} + \frac{q_\perp - k_\perp}{(q_\perp - k_\perp)^2 + x^2M^2} \right]^2
\]


In accordance to scalar QCD result at mid- and forward rapidity from Gossiaux, Aichelin, Gousset, Guiho, J.Phys.G37 (2010)
Radiative pQCD processes

Exact matrix element

$$|\mathcal{M}|^2 = -16 \sum_{i,j=1}^{5} C_{ij} \frac{N_{ij}}{D_{ij}}$$

\[
\begin{align*}
P &= \left[ n_1, n_2, n_3, n_4, n_5 \right]^T, \\
D &= \left[ d_1, d_2, d_3, d_4, d_5 \right]^T.
\end{align*}
\]

Gunion Bertsch (GB) approximation

$$|\mathcal{M}_{qQ \rightarrow qQg}|^2 = 12g^2(1-\bar{x})^2 \left| \mathcal{M}^q_{0} \right|^2 \left[ \frac{k_\perp}{k_\perp + x^2 M^2} + \frac{q_\perp - k_\perp}{(q_\perp - k_\perp)^2 + x^2 M^2} \right]^2$$
Dead cone effect can be seen in BAMPS

**Heavy quark suppression factor**

\[
D = \frac{1}{\left(1 + \frac{M^2}{\theta^2 E^2}\right)^2} = \frac{1}{\left(1 + \frac{\theta_D^2}{\theta^2}\right)^2}
\]


\[\theta_D = \frac{M}{E}\]

---

**More accurate: valid for all order of mass M and also for large angles**

\[
D = \frac{1}{1 + \frac{M^2}{s \tan^2(\frac{\theta}{2})}}
\]

Abir, Greiner, Martinez, Mustafa, JU, Phys.Rev. D85 (2012)
LPM cut-off

Mean free path \( \lambda > X \tau \)

Formation time

2 \to 3 \text{ process only allowed if mean free path of jet larger than formation time of radiated gluon}

\[ X = 0 \quad \text{No LPM effect} \]

\[ X = 1 \quad \text{Only completely independent scatterings (forbids too many interactions)} \]

\[ 0 < X < 1 \quad \text{Allows effectively some interference effects} \]
D meson $R_{AA}$ and $v_2$ at LHC

Pb+Pb, $\sqrt{s} = 2.76$ TeV

$b = 3.6$ fm, $|y| < 0.5$

LHC

ALICE data, QM12
Energy loss and transport cross section

Energy loss in static medium

Transport cross section in static medium

\[
\frac{dE}{dx} \text{ [GeV/fm]} \\
\langle \sigma \sin^2 \theta \rangle \text{ [mb]}
\]

- \(2 \rightarrow 2 \) & \(2 \rightarrow 3\), running \( \alpha_s, \kappa = 0.2, X_{\text{PM}} = 0.2 \)
- only \(2 \rightarrow 2\), running \( \alpha_s, \kappa = 0.2, K = 3.5 \)

\( T = 400 \text{ MeV} \)
Heavy flavor and charged hadron $R_{AA}$ at LHC

for more BAMPS results on light particles
see talk by Florian Senzel, Monday 5:30 pm, europium
Heavy flavor and charged hadron $R_{AA}$ at LHC

charged hadrons, $\kappa=1$, $X_{LPM}=0.3$
D mesons, $\kappa=1$, $X_{LPM}=0.3$
charged hadrons 0-5\% (ALICE)
D mesons 0-7.5\% (ALICE)

$b = 3.6$ fm, running $\alpha_s$
Pb+Pb, $\sqrt{s} = 2.76$ TeV

for more BAMPS results on light particles
see talk by Florian Senzel, Monday 5:30 pm, europium
Heavy flavor and charged hadron $R_{AA}$ at LHC

charged hadrons, $\kappa=1$, $X_{LPM}=0.3$
D mesons, $\kappa=1$, $X_{LPM}=0.3$
non-prompt J/psi, $\kappa=1$, $X_{LPM}=0.3$

charged hadrons 0-5% (ALICE)
D mesons 0-7.5% (ALICE)
non-prompt J/psi 0-20% (CMS)

$b = 3.6$ fm, running $\alpha_s$

Pb+Pb, $\sqrt{s} = 2.76$ TeV

for more BAMPS results on light particles
see talk by Florian Senzel, Monday 5:30 pm, europium
Conclusions & outlook

**Full space-time evolution of QGP with charm and bottom quarks**

- **Only binary collisions:**
  
  With running coupling and improved Debye screening, $v_2$ and $R_{AA}$ agreement only with $K=3.5$

- **Radiative and binary collisions:**
  
  - Sensitivity on LPM implementation
  - $R_{AA}$ and $v_2$ simultaneously seems difficult
  - $R_{AA}$ of light and heavy hadrons can be described


**Future tasks:**

- Improvement of LPM effect
Thank you for your attention.
Radiative energy loss

\[
\left. \frac{dE}{dx} \right|_{\text{light quark}} > \left. \frac{dE}{dx} \right|_{\text{charm}} > \left. \frac{dE}{dx} \right|_{\text{bottom}}
\]

\[
\alpha_s = 0.3, \ k = 1
\]

\[
\frac{dE}{dx} \text{ [GeV/fm]}
\]

\[
E \text{ [GeV]}
\]

\[
\alpha_s = 0.3
\]
Radiative energy loss

\[ \frac{dE}{dx} \bigg|_{\text{light quark}} > \frac{dE}{dx} \bigg|_{\text{charm}} > \frac{dE}{dx} \bigg|_{\text{bottom}} \]

\(\alpha_s = 0.3, \kappa = 1\)

\(\alpha_s = 0.3\)
Angle distribution in lab frame

With LPM

Dead cone due to mass is overlayed by second dead cone from LPM cut-off

Without LPM

Dead cone due to mass is visible
LPM: X dependence

\[ \frac{dE}{dx} \text{ [GeV/fm]} \]

- \(2 \rightarrow 3, \text{ light quark} \)
- \(2 \rightarrow 3, \text{ charm} \)
- \(2 \rightarrow 3, \text{ bottom} \)

\[ \alpha_s = 0.3, \kappa = 1 \]

\[ E = 10 \text{ GeV} \]
Heavy quark $R_{AA}$ at RHIC

\[ \alpha_s = 0.3, \ \kappa = 1 \]
\[ \text{running } \alpha_s, \ \kappa = 0.2 \]
\[ \text{running } \alpha_s, \ \kappa = 0.2, \ X = 0.2 \]
\[ \text{running } \alpha_s, \ \kappa = 0.2, \text{ only } 2 \rightarrow 2, \ K = 3.5 \]
\[ \text{20-40}\% \ (\text{PHENIX}) \]

RHIC

\[ \sqrt{s} = 200 \text{ GeV} \]

b = 8.2 fm

Heavy quark $v_2$ at RHIC

$\alpha_s=0.3$, $\kappa=1$
running $\alpha_s$, $\kappa=1$
running $\alpha_s$, $\kappa=0.2$
running $\alpha_s$, $\kappa=0.2$, $X=0.2$
running $\alpha_s$, $\kappa=0.2$, only $2\to2$, $K=3.5$
20-40% (PHENIX)

Non-prompt J/psi $R_{AA}$ at LHC

Running $\alpha_s$, $\kappa=1$, $X=1$

Running $\alpha_s$, $\kappa=0.2$, $X=0.2$

Running $\alpha_s$, $\kappa=0.2$, only $2\to2$, $K=3.5$

0-20% (CMS)

$Pb+Pb$, $\sqrt{s} = 2.76$ TeV

$|y| < 2.4$  
$b = 5.0$ fm

LHC

CMS data,  
arXiv:1201.5069
Initial heavy flavor spectrum

From MC@NLO

JU, Fochler, Xu, Greiner

JU, Fochler, Xu, Greiner
Total charm production


Sizeable charm production in QGP at LHC

STAR, QM12

Jan Uphoff
Elastic and radiative heavy quark energy loss
D meson $R_{AA}$ from STAR

**He:** arXiv:1204.4442
Focker-Planck
Resonance recombination

**Gossiaux:**
arXiv:1207.5445
Boltzmann
pQCD with running coupling

STAR data, QM 2012
Fragmentation and Decay

- Peterson fragmentation

\[ D_{H/Q}(z) = \frac{N}{z \left( 1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z} \right)^2} \]

- Decay to electrons with PYTHIA


\[ z = \frac{|\vec{p}_H|}{|\vec{p}_Q|} \]

\[ \epsilon_c = 0.05 \]

\[ \epsilon_b = 0.005 \]

Impact of hadronization and decay small
Heavy quark scattering cross section

\[ \alpha_s = 0.3, \kappa = 1 \]
\[ \alpha_s = 0.3, \kappa = 0.2 \]
running coupling, \( \kappa = 1 \)
running coupling, \( \kappa = 0.2 \)

\[ M = 1.5 \text{ GeV} \]
LPM effect vs. dead cone effect

\[ \lambda > \tau \]

2 → 3 process only allowed if mean free path of jet larger than formation time of radiated gluon

Independent scatterings
D meson angle correlations

\[ P(\Delta \phi) \]

\[ \Delta \phi \]

\[ \text{w/o QGP} \]
\[ \text{only } 2 \rightarrow 2, K=3.5, \text{ with QGP} \]
\[ 2 \rightarrow 2, 2 \rightarrow 3, X=0.3, \text{ with QGP} \]

\[ \text{Pb+Pb, } \sqrt{s} = 2.76 \text{ TeV} \]
\[ p_T^D > 0 \text{ GeV} \]
D meson angle correlations

\[ P(\Delta \phi) \]

- w/o QGP
- only $2 \to 2$, $K=3.5$, with QGP
- $2 \to 2$, $2 \to 3$, $X=0.3$, with QGP

**Pb+Pb, \( \sqrt{s} = 2.76 \) TeV**

\[ p_T^D > 5 \text{ GeV} \]
Momentum imbalance $A_D$

D meson momentum imbalance

$$A_D = \frac{p^{D}_{T;1} - p^{D}_{T;2}}{p^{D}_{T;1} + p^{D}_{T;2}}$$

Analogous to

$$A_J = \frac{p^{J}_{T;1} - p^{J}_{T;2}}{p^{J}_{T;1} + p^{J}_{T;2}}$$

No jet reconstruction necessary
Momentum imbalance $A_D$ for low triggers

PYTHIA IC

$P(A_D)$ vs. $A_D$

- w/o QGP
- with QGP

Pb+Pb, $\sqrt{s} = 2.76$ TeV

$p_T^{D, \text{leading}} > 10$ GeV

$p_T^{D, \text{subleading}} > 4$ GeV

$\Delta \phi > 2\pi/3$
$A_D$ for high triggers – PYTHIA

$P(A_D)$

PYTHIA IC, w/o QGP
PYTHIA IC, with QGP

$Pb+Pb$, $\sqrt{s} = 2.76$ TeV

$p_T^{D,\text{leading}} > 25$ GeV

$p_T^{D,\text{subleading}} > 15$ GeV

$\Delta \phi > 2\pi/3$
$A_D$ for high triggers – Mini-jets

Mini-jets IC, w/o QGP
Mini-jets IC, with QGP

Pb+Pb, $\sqrt{s} = 2.76$ TeV

$p_T^{D,\text{leading}} > 25$ GeV
$p_T^{D,\text{subleading}} > 15$ GeV
$\Delta \phi > 2\pi/3$
Length imbalance

PYTHIA IC, with QGP
Mini-jets IC, with QGP

$D_{leading} > 25$ GeV
$D_{subleading} > 15$ GeV
$\Delta \phi > 2\pi/3$

$\text{Pb+Pb}, \sqrt{s} = 2.76$ TeV