Azimuthal correlations and hadronic rescattering of heavy quarks in AA collisions

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in collaboration with

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Why heavy quarks are interesting?

Interaction of heavy quarks with the plasma
- different approaches
- our model (elastic and inelastic collisions, LPM)

- is there more than $R_{AA}$ and $v_2$
- correlations between quarks and antiquarks
- hadronic rescattering
What makes heavy quarks (mesons) so interesting?

- produced in hard collisions (initial distribution: FONLL confirmed by STAR/Phenix)

- high $p_T$: no equilibrium with plasma particles (information about the early state of the plasma)

- not very sensitive to the hadronisation process

Ideal probe to study properties of the QGP during its expansion

Caveat: two major ingredients: expansion of the plasma and elementary cross section $(c(b)+q(g) \rightarrow c(b)+q(g))$ difficult to separate (arXiv:1102.1114)
Complexity of heavy quark physics in a nutshell:

- Hadronic interactions (hadron physics)
- Hadronisation of light quarks: Cross over or phase transition (statistical physics, nonpert. QCD)
- D/B formation at the boundary of QGP fragmentation or coalescence (pQCD)
- (hard) production of heavy quarks in initial NN collisions (generalized parton distribution fcts, pQCD, FONLL)
- Interaction of heavy quarks with plasma constituents, LPM pQCD, transport theory
- Evolution of the QGP (transport theory lattice gauge theory)
- Quarkonia formation in QGP through c+c→Ψ+g fusion process (finite temp QCD, pQCD)
Presently the discussion is centered around two heavy quark observables:

I)

\[ R_{AA} = \frac{d\sigma_{AA}/dp_t}{N_{bin}d\sigma_{pp}/dp_t} \]

Low \( p_t \) partial thermalization
High \( p_t \) energy loss due to elastic and radiative collisions
Energy loss tests the initial phase of the expansion

II) Elliptic flow \( v_2 \) tests the late stage of the expansion

Many models on the market which describe these observables reasonably well
Mostly based on Fokker Planck approaches

\[ \frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i}[A_i(p)f(p,t) + \frac{\partial}{\partial p_j}(B_{ij}(p)f(p,t))] \]

which need only a drag \( A_i \) and a diffusion \( B_{ij} \) coefficients
Both related by Einstein correlation (or not)

At most qualitative predictions possible (LPM, elementary cross sections..)
Our approach:

- We assume that pQCD provides the tools to study the processes.

We want to:
- model the reaction with a minimum of approximations:
  - Exact Boltzmann collisions kernel, no Fokker Planck approx.
- take into account all the known physics with:
- no approximations of scattering processes (coll+ radiative).
- make connection to the light quark sector ($v_2$ jets particle spectra) by embedding the heavy quarks into EPOS.

- This serves then as a benchmark:
  - deviation from data points towards new physics.
Key ingredients: pQCD cross section like $qQ \rightarrow qQ$

pQCD cross section in a medium has 2 problems:

a) Running coupling constant

$$\frac{d\sigma_F}{dt} = \frac{g^4}{\pi(s-M^2)^2} \left[ \frac{(s-M^2)^2}{(t-\kappa m_D^2)^2} + \frac{s}{t-\kappa m_D^2} + \frac{1}{2} \right]$$

b) Infrared regulator

$$V(r) \sim \exp(-m_D r)$$

$m_D$ regulates the long range behaviour of the interaction

Neither $g^2 = 4\pi \alpha(t)$ nor $\kappa m_D^2$ are well determined standard: $\alpha(t) =$ is taken as constant or as $\alpha(2\pi T)$

$\kappa = 1$ and $\alpha = 0.3$: large K-factors ($\approx 10$) are necessary to describe data
A) Running coupling constant

“Universality constraint” (Dokshitzer 02) helps reducing uncertainties:

IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss. Large values for intermediate momentum-transfer.

\[
\frac{1}{Q_u} \int_{|Q^2| \leq Q_u^2} dQ \alpha_s(Q^2) \approx 0.5
\]

$\alpha_{qq}(r) \equiv \frac{3}{4} \frac{r^2}{dV(r)}$
If $t$ is small ($<<T$): Born has to be replaced by a hard thermal loop (HTL) approach. For $t>T$ Born approximation is (almost) ok.

(Braaten and Thoma PRD44 (91) 1298,2625) for QED: Energy loss indep. of the artificial scale $t^*$ which separates the regimes.

We do the same for QCD (a bit more complicated) Phys.Rev.C78:014904

Result: $\kappa \approx 0.2$

much lower than the standard value
C) Inelastic Collisions

Low mass quarks: radiation dominantes energy loss
Charm and bottom: radiation of the same order as collisional

4 QED type diagrams

Commutator of the color SU(3) operators

\[ T^b T^a = T^a T^b - i f_{abc} T^c \]

M1-M5: 3 gauge invariant subgroups

\[ M_{QED}^1 = T^a T^b (M_1 + M_2) \quad M_{QED}^2 = T^a T^b (M_3 + M_4) \]

\[ M_{QCD} = i f_{abc} T^c (M_1 + M_3 + M_5) \]

\( M_{QCD} \) dominates the radiation
In the limit \( \sqrt{s} \to \infty \) the radiation matrix elements factorize in leading order: no emission

\[
M_{tot}^2 = M_{elast}^2 \cdot P_{rad}
\]

\( k_t, \omega = \) transv mom/ energy of gluon  \( E = \) energy of the heavy quark

\[
P_{rad} = C_A \left( \frac{k_t^2}{k_t^2 + (\omega/E)^2 m^2} - \frac{k_t^2 - q_t^2}{(q_t - k_t)^2 + (\omega/E)^2 m^2} \right)^2
\]

leading order: no emission from light q heals colinear divergences

\[
\frac{\omega d^4 \sigma^{rad}}{dx d^2 k_t d\text{\scriptsize q}_t^2} = \frac{N_c \alpha_s}{\pi^2} (1 - x) \cdot \frac{d\sigma^{el}}{dq_t^2} \cdot P_{rad}
\]

\( x = \gamma/E \)

\[
M_{QCD} = M_{SQCD} \left( 1 - \frac{(\omega/E)^2}{(1 - \omega/E)^2} \right)
\]
Landau Pomeranschuk Migdal Effekt (LPM)

reduces energy loss by gluon radiation

Heavy quark radiates gluons
gluon needs time to be formed

Collisions during the formation time
do not lead to emission of a second gluon

emission of one gluon
(not N as Bethe Heitler)

Multiple scatt. QCD: \( N_{\text{coll}} \approx \frac{<k_t^2>=t_f}{\hat{q}} \)

dominates \( x<1 \)

dominates \( x\approx 1 \)
dominates \( x<<1 \)

(hep-ph/0204343)
At intermediate gluon energies formation time is determined by multiple scattering.
For $x < x_{cr} = m_g / M$, basically no mass effect in gluon radiation.

For $x > x_{cr} = m_g / M$, gluons radiated from heavy quarks are resolved in less time than those from light quarks and gluons => radiation process less affected by coherence effects.

Most of the collisions $\frac{d\sigma}{dx}$

Dominant region for average E loss $x \frac{d\sigma}{dx}$

LPM important for intermediate $x$ where formation time is long.
Consequences of LPM on the energy loss

Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass
.. and if the medium is absorptive (PRL 107, 265004)

\[- \frac{d^2 W}{dz d\omega} \approx -\frac{2\alpha}{3\pi} \frac{q}{E^2} \int_0^\infty dt \omega \cos(\omega t) \sin \left( \omega |n_r| \beta t \left( 1 - \frac{\hat{q} t}{6E^2} \right) \right) F(t)\]

\[F(t) = \exp[-\omega |n_i| \beta t (1 - \hat{q} t/(6E^2))]\]

with

\[n^2(\omega) = 1 - m^2/\omega^2 + 2i\Gamma/\omega \quad t_f\]

New timescale \(1/\Gamma\)

\(\text{damping dominates radiation spectrum}\)

\(\text{single} \quad \text{multipl}\)

\(x = \omega/E\)
Influence of LPM and damping on the radiation spectra

\[
\frac{dI}{dI_{GB}} \approx \frac{\tilde{t}_f}{t_{GB}} \quad \tilde{t} = \min\{t^{\text{single}}, t^{\text{multiple}}, t^{\text{damping}}\}
\]

LPM, damping, mass:
Strong reduction of gluon yield at large \(\omega\)

LPM:
Increase with energy \(\sim \omega^{-1/2}\)
Decrease with mass \(\sim \omega^{-2}\)

Weak damping

Strong damping
Heavy-quark propagation in the QGP

Production:
- FONLL
  ⇒ inclusive spectra, no information about correlations → equivalent to a back-to-back initialization of $Q\bar{Q}$-pairs.
- Next-to-leading order QCD matrix elements plus parton shower evolution, e.g. POWHEG or MC@NLO
  ⇒ exclusive spectra, like $Q\bar{Q}$ correlations

Interaction with the medium
- Energy loss at high transverse momentum.
- Thermalization at low transverse momentum.
- Different interaction mechanisms: purely collisional or collisional+radiative (+LPM).
- Longitudinal vs. transverse dynamics.

Hadronization:
- Coalescence – predominantly at small $p_T$.
- Fragmentation – predominantly at large $p_T$.

X. Zhu et al., PLB 647 (2007); P. B. Gossiaux et al., JPG 32 (2006); X. Zhu et al, PRL 100 (2008); Y. Akamatsu et al, PRC 80 (2009)
1. Coll: too little quenching (but very sensitive to freeze out) -> K=2

2. Radiative Eloss indeed as important as the collisional one

3. Flat experimental shape is well reproduced

4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC) separated contributions e from D and e from B.
1. Collisional + radiative energy loss + dynamical medium: *compatible* with data

2. To our knowledge, one of the first model using radiative Eloss that reproduces $v_2$

For the hydro code of Kolb and Heinz:

- $K = 1$ compatible with data
- $K = 0.7$ best description – remember influence of expansion
RHIC IV: D mesons

Elastic

0-10%

Elastic + radiative LPM

0-80%

No form difference between coll and coll + rad
Hydro Kolb Heinz a bit outdated, to make progress:

Marriage of two large simulation programs MC@sHQ and EPOS

MC@sHQ:
- Evolution by the Boltzmann transport equation.
- Cross sections from the QCD Born approximation with HTL+semi-hard propagators.
- Including a running coupling $\Rightarrow$ selfconsistently determined Debye mass.
- Radiative corrections from scalar QCD.

EPOS:
- Initial conditions from a flux tube approach to multiple scattering events.
- $3 + 1$ d ideal fluid dynamics.
- Including a parametrization of the equation of state from lattice QCD.
- Finite initial radial velocity.
- Event-by-event fluctuating initial conditions.

For calibration a global rescaling of the cross sections by a $K$-factor is required!

P. B. Gossiaux and J. Alchelin, PRC 78 (2008);
Expanding plasma: EPOS event generator

Three options:
- Collisions only $K$ factor = 1.5
- Collision and radiation $K$ = 0.8
- Radiation only $K$ = 1.8

$R_{AA}$ and $v_2$ for coll and coll + radiative about the same
Are there other observables which are sensitive on the interaction mechanism?

Possible candidate: **heavy flavor correlations**

They may be sensitive to

- Properties of the energy loss model: path length dependence?
  Parton mass dependence?
- Properties of the interaction inside a medium: drag coefficient, jet quenching parameter?

**WHY?**

**Single scattering:**

<table>
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<th>Scenario</th>
<th>coll, $K = 1.5$, $T = 400$ MeV</th>
<th>coll+rad, $K = 0.8$, $T = 400$ MeV</th>
<th>coll, $K = 1.5$, $T = 180$ MeV</th>
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**Scattering rate:**

(a) | coll+rad, $K = 0.8$, $T = 400$ MeV | coll, $K = 1.5$, $T = 400$ MeV | coll+rad, $K = 0.8$, $T = 180$ MeV | coll, $K = 1.5$, $T = 180$ MeV |
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- $p_T$-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Scattering rate is larger for **coll ($K = 1.5$)**!
The purely **collisional** scatterings lead to a larger average $\langle p_\perp^2 \rangle$ than the **radiative** corrections.

The final $p_\perp$ also depends indirectly on the drag coefficients.

The drag coefficients increases faster for the **collisional+radiative** interaction scenario $\Rightarrow$ A quick loss in longitudinal momentum leads to less perpendicular momentum broadening.

Expectation: Initial correlations will be broadened more effectively in a purely **collisional** interaction mechanism.
Heavy-quark azimuthal correlations

central collisions, back-to-back initialization, no background from uncorrelated pairs

class quarks

coll, $K = 1.5$

coll+rad, $K = 0.8$

[1-4] GeV

[4-10] GeV

[10-20] GeV

\( c\bar{c}, 0 - 20\% \)

(\( a \))

bottom quarks

coll, $K = 1.5$

coll+rad, $K = 0.8$

[1-4] GeV

[4-10] GeV

[10-20] GeV

\( b\bar{b}, 0 - 20\% \)

(\( b \))

- Stronger broadening in a purely collisional than in a collisional+radiative interaction mechanism
- Variances in the intermediate $p_T$-range: 
  0.18 vs. 0.094 (charm) and 0.28 vs. 0.12 (bottom)
- At low $p_T$ initial correlations are almost washed out: small residual correlations 
  remain for the collisional+radiative mechanism, “partonic wind” effect for a purely collisional scenario.
- Initial correlations survive the propagation in the medium at higher $p_T$. 

Realistic initial $b\bar{b}$ distributions - MC@NLO

Next-to-leading order QCD matrix elements coupled to parton shower (HERWIG) evolution: MC@NLO.


- Gluon splitting processes lead to an initial enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate $p_T$: increase of the variances from 0.43 (initial NLO) to 0.51 ($\sim 20\%$) for the purely collisional mechanisms and to 0.47 ($\sim 10\%$) for the interaction including radiative corrections.
- Correlations at large $p_T$ seem to be dominated by the initial correlations.
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!
Azimuthal correlations and flow

- DD correlations, 30-50% central.
- Flow harmonics from 2-particle correlation functions
  \[ \propto \frac{N}{2\pi} (1 + 2 \sum V_n \cos(n\Delta\phi)). \]

Collisional, \( K = 1.5 \)

- Similar \( V_n \) for both interaction mechanisms at low \( p_T \).
- Nonvanishing higher flow coefficients.
Azimuthal correlations and flow

as an example collisional, $K = 1.5$

- Compare $DD$ correlations to $D\bar{D}$ correlations to learn about the flow contribution and the degree of isotropization of $D\bar{D}$ pairs.

- Similar $V_2$ for $DD$ and $D\bar{D}$ at low $p_T$.

- Dominant initial back-to-back correlation in $D\bar{D}$-correlations at higher $p_T$. 
Conclusions I

All experimental midrapidity data are compatible with the assumption that pQCD describes energy loss and elliptic flow $v_2$ of heavy quarks.

RHIC and LHC described by same program (hydro ini is diff)

Special features running coupling constant
adjusted Debye mass
Landau Pomeranschuk Migdal

Description of the expansion of the medium (freeze out, initial cond.) can influence the results by at least a factor of 2 \(1102.1114\).
Conclusions II

The present heavy quark data are do not allow discriminate between radiative and collisional energy loss

Correlations of c and cbar offer more possibilities:

They show that low pt heavy quarks equilibrate with the plasma (isotropic azimuthal distribution) high pt heavy quarks do not equilibrate. Widening in pt depends on the reaction mechanism.

There is hope that this can be measured.

Hadronic rescattering has little influence on $R_{AA}$ and $v_2$. 

Hadronic rescattering
Most advanced cross section of D mesons with hadrons based on next to leading order chiral Lagrangian

We obtain drag coefficients
Chemical freeze out at $\epsilon = 0.5$ GeV/fm$^3$
kinetic freeze out at $T = 100$ MeV

Modeled by effective chemical potentials (Rapp PRC66 017901)
Hadronic rescattering in the Fokker Planck approach

Little effect for $R_{AA}$ and $v_2$

If the transition between partons and hadrons takes place at $\epsilon = 0.5$ GeV/fm$^3$
All experimental data are compatible with the assumption that QCD describes energy loss and elliptic flow $v_2$ of heavy quarks.

RHIC and LHC described by same program (hydro ini is diff)

Special features: running coupling constant, adjusted Debye mass, Landau Pomeranschuk Migdal

Description of the expansion of the medium (freeze out, initial cond.) can influence the results by at least a factor of 2 (1102.1114)
Conclusions:

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Background subtraction

Experimentally impossible to distinguish initially correlated/uncorrelated pairs... ⇒ background!

Naive subtraction via something like ZYAM:

- Initially correlated pairs, which isotropized in the medium...

Background consists of:

- Initially uncorrelated pairs - uninteresting! Can be removed by mixed-event or like-sign, $DD$ correlations?

- Initially correlated pairs, which isotropized in the medium...
“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 interaction mechanism!