Tomography of the QGP at RHIC and LHC by heavy mesons

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in collaboration with

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Why heavy quarks are interesting?

Interaction of heavy quarks with the plasma
- collisional
- radiative
- Landau Pomeranschuk Migdal (LPM) effect
- and if gluons get absorbed...

Results for RHIC and LHC
What makes heavy quarks (mesons) so interesting?

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

- 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 \((c(b)+q(g) \to c(b)+q(g))\) difficult to separate (arXiv:1102.1114)
different processes

E.Scomparin
Nantes approach: Elastic heavy quark – q(g) collisions

Key ingredients: pQCD cross section like qQ -> 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

$$V(r) \sim \frac{\exp(-m_D r)}{r}$$

$m_D$ 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 $\alpha =.3$: large K-factors ($\approx 10$) are necessary to describe data
“Universality constraint” (Dokshitzer 02) helps reducing uncertainties:

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

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

Comp w lattice results PRD71,114510
Collisional Energy Loss

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

PRC78 014904, 0901.0946

hep-ph/0607275
Collisional Energy Loss

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

Consequences for cross sections

- Large enhancement of cross sections at small \( t \)
- Little change at large \( t \)
- Largest energy transfer from u-channel gluons

\[
\frac{d\sigma_{cq\rightarrow cg}}{dt} \text{ (arb. units)}
\]

\[
E_c=10\text{GeV} \quad T=0.4\text{GeV}
\]

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\[
E_c=10\text{GeV} \quad T=0.4\text{GeV}
\]
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

\[
\begin{align*}
M^1_{QED} &= T^a T^b (M_1 + M_2) \\
M^2_{QED} &= T^a T^b (M_3 + M_4)
\end{align*}
\]

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

**M_{QCD} dominates the radiation**
In the limit \( \sqrt{s} \to \infty \) the radiation matrix elements factorize in

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

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

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

Emission from heavy q

Emission from g

\( m=0 \rightarrow \text{Gunion Bertsch} \)

Energy loss:

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

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

reduces energy loss by gluon radiation

Heavy quark radiates gluons

Glueon 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 <k_t^2> = t_f \hat{q}

dominates $x<1$

dominates $x=1$
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 $\Rightarrow$ radiation process less affected by coherence effects.

Most of the collisions $rac{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)

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

Damping Ter-Mikaelian

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

with

\[
n^2(\omega) = 1 - \frac{m^2}{\omega^2} + 2i\Gamma/\omega
\]

New timescale $1/\Gamma$

damping dominates radiation spectrum

\[x = \frac{\omega}{E}\]
Influence of LPM and damping on the radiation spectra

\[
\frac{dI}{dI_{GB}} \approx \frac{\tilde{t}_f}{t_{GB}} \\
\tilde{t} = \min\{t^{\text{single}}, t^{\text{multiple}}, t^{\text{damping}}\} \\
t_{GB} \approx 2\omega/m_g^2 = 2xE/m_g^2
\]

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

LPM: increase with energy, decrease with mass
. c,b-quark transverse-space distribution according to Glauber

- c,b-quark transverse momentum distribution as in d-Au (STAR)... very similar to p-p (FONLL) Cronin effect included.


- QGP evolution: 4D / Need local quantities such as $T(x,t)$ taken from hydro dynamical evolution (Heinz & Kolb)

- D meson produced via coalescence mechanism. (at the transition temperature we pick a u/d quark with the a thermal distribution) but other scenarios possible.

- No damping yet
1. Too large quenching (but very sensitive to freeze out)

2. Radiative $E_{\text{loss}}$ indeed dominates 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 $e^D$ and $e^B$. 
Results RHIC II

ArXiv 1005.1627 (PHENIX)

$v_2$ of heavy mesons depends on where fragmentation/coalescence takes place

$R_{AA}$ centrality dependence (PHENIX) well reproduced

$v_2$ of heavy mesons depends on where fragmentation/coalescence takes place

end of mixed phase

beginning of mixed phase
Results RHIC III

1. Collisional + radiative energy loss + dynamical medium: compatible with data

2. To our knowledge, one of the first model using radiative $E_{\text{loss}}$ that reproduces $v_2$

For the hydro code of Kolb and Heinz:

$K = 1$ compatible with data
$K = 0.7$ best description
Results RHIC IV: D mesons

No form difference between coll and coll + rad
Results LHC I

\( v_2 \) very similar at RHIC and LHC

B and b flow identical

D and c 20% difference (hadronization)

Difference between B and D can validate the model

(only difference is the mass)
Results LHC II

Same calculations as at RHIC
only difference:
initial condition
dN/dy (central) = 1600

Elastic

High pt: coll+rad give more suppression
Absorptive medium influences the spectra at high $p_T$

RHIC « reference »: no effect seen for $\Gamma=0.75T$

Possible crossing at intermediate $p_T$?
Results LHC III

Ratio charm/bottom (Horowitz et al.)

Charm/bottom ratio will show whether pQCD or AdS/CFT is the right theory to describe HI reactions

Wicks et al NPA743,493

LHC 5.5 ATeV

Is AdS/CFT still valid?
Conclusions

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)

Refinements still necessary: Running coupling constant for gluon emission vertex gluon absorption and LPM effect improvement Expansion scenario (fluctuating initial conditions :EPOS)
Energy loss per unit length:

\[
\frac{dE}{dz} = \int d^3k \, \rho_k \int \Delta E \frac{d\sigma}{dx} \, dx = \int d^3k \, \rho_k \, E \int x \frac{d\sigma}{dx} \, dx
\]

For large quark masses:
Collisional and radiative energy loss of the same order

Small q masses:
radiative dominant
Rad: \( \Delta E \propto E \)
Coll: \( \Delta E \propto \ln E \)

\( E_q = 20 \text{ GeV}, \, T=300 \text{ MeV} \)
\( m_g=300\text{MeV} \) radiative

Collisional
(Peigne & Smilga) arXiv:0810.5702
Landau Pomeranschuk Migdal (LPM) Effect:

A second gluon can only be emitted after the first is formed.

In leading order no gluon emission from light quarks.

Formation time for a single collision:

\[ t_f \approx \frac{2(1 - x)\omega}{(k_\perp - q_\perp)^2 + x^2M^2 + (1 - x)m_g^2} \]

\[ x = \omega/E \]

At \( q_t = k_t = 0 \):

\[ l_{f,sing} \approx \frac{2x(1 - x)E}{m_g^2 + x^2M^2} \]
For \( x > x_{cr} = \frac{m_g}{M} \), gluons radiated from heavy quarks are resolved in less time than those from light quarks and gluons \( \Rightarrow \) 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 \( x \)
Presumably at RHIC and LHC a plasma (QGP) is formed which is, however, not directly visible. One has to conclude on its existence from decay products.

**This is all but easy:**
- The multiplicity of almost all particles coincides with the expectation of a statistical model for given $\mu \approx 0$ and $T \approx 160$ MeV = $T_c$
  Consequence: loss of memory of the history of the QGP may measure simply freeze out condition
- Spectra distorted by final state hadronic interactions

- most of single particle obs. do not elucidate the enigma
  - collective variables
  - Jets
  - heavy mesons (containing a c or b quark and which do not come to equilibrium)
D mesons at LHC (more differential observables)

“in plane” – “out of plane” analysis

Some systematic trends: el. + rad. LPM shows more coupling… sensitive to larger x in the radiation spectra

Late build up of the flow Possible contribution from the hadronic phase (neglected in our approach) at intermediate $p_T$?
Energy loss in elast. and radiat. collisions is different

Probability $P$ of energy loss $\omega$ per unit length ($T, M, \ldots$):

$$|\omega| \frac{dP(\omega)}{dz} \quad [\text{fm}^{-1}]$$

Radiative energy loss stronger than collisional