Heavy-light correlations in heavy ion collisions

2nd Workshop on jets and heavy flavor

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P.B. Gossiaux
SUBATECH, UMR 6457
Université de Nantes, IMT Atlantique, IN2P3/CNRS

with

J. Aichelin, Th. Gousset, M. Nahrgang,
K. Werner, M. Rohrmoser
Motivation and context: jet vs HF

- Most of the *interesting* HF observables so far: located at *intermediate* $p_T$ ($\approx$ 3 GeV-50 GeV)

- Interest of HF in jets? At least some conserved quark directly from initial production? Really helpful? Really true? *HF flavor production in jet splitting*

- Interest of jets for HF? During many years, most of the HF community could live ignoring the implications of jets... but things are starting to evolve... If focus on intermediate $p_T$: which implications for jets?
Part I: HF production in AA collisions
Motivation and context: intermediate $p_T$

- Most of the *interesting* HF observables so far: located at *intermediate* $p_T$
  $(\approx 3 \text{ GeV}-50 \text{ GeV})$

- Intermediate $p_T$: hope that pQCD (or pQCD inspired models) apply (as compared to low $p_T$)

- Intermediate $p_T$: mass effect still present and thus hope to learn something more as compared to large $p_T$

Low (Energy conservation under control)

- Braaten-Thoma + Gunion-Bertsch
  $\cong$ Bethe-Bloch + Bethe-Heitler

Intermediate

- Coherence effects

High (coherence under control)

- Finite E + finite mass corrections

BDMPS-Z, GLV, ASW, ...
  $\cong$ LPM

Approach pursued in our **models**... Unfortunately too many of them

$\Rightarrow$ Need for falsification (more observables; lQCD): *Azimuthal correlations* ?
Insufficient control on energy loss theory in QCD

Basic ingredient in the derivation of QED collisional Eloss; transverse force

In QCD: non perturbative « corrections » even at large HQ energy

In most models:

Lattice QCD:

\[ V(q) \propto \frac{\alpha_s}{q^2 - \mu^2} \]

Static scattering center

Significant r-tail in the transverse force acting on the high E HQ
Our basic ingredients for HQ energy loss

**Elastic**

Motivation: Even a fast parton with the largest momentum $P$ will undergo collisions with moderate $q$ exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant is often “forgotten/neglected” in some approaches.

**Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)**

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

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

\[m_{D_{self}}^2(T) = (1+n_f/6) 4\pi \alpha_{eff}(m_{D_{self}}^2) T^2\]

\[\text{prop } \propto \frac{1}{q^2 - \kappa m_{D_{self}}^2(T)}\]

+ $u$ and $s$ channels

One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of $dE/dx$ in Braaten-Thomas scheme.

IR safe. $Q^2$ close to 0 does not contribute to $E_{loss}$

Large values for intermediate momentum-transfer $\Rightarrow$ larger cross section
Insufficient control on energy loss theory

Non perturbative « corrections » even at large HQ energy

In most models:

Lattice QCD:

\[ V(q) \propto \frac{\alpha_s}{q^2 - \mu^2} \]

Our force is close to the one extracted from the free energy as a potential

\[ \alpha_{qq}(r) \equiv \frac{3}{4} r^2 \frac{dV(r)}{dr} \]

O. Kaczmarek & F. Zantow (KZ) (nf=2 QCD), P.R.D71 (2005) 114510

T=0

KZ P.R. D71 (2005) V=F


T\approx 1.1 \ T_c

\[ \frac{dV}{dr} \text{[GeV/fm]} \]

\[ T = 0 \]

optimal \( \mu \), running \( \alpha_{\text{eff}} \)

=> Allow for some global rescaling of the rates: “K” fixed on experiment
The Monte Carlo @ Heavy Quark Generator

No force on HQ before thermalization of QGP (0.6 fm/c)

Evolution according to Bjorken time

(hard) production of heavy quarks in initial NN collisions (NLO or FONLL or any pp generator + k_T broad. (0.2 GeV^2/coll)

Quarkonia formation in QGP through c+c→Ψ+g fusion process
Bulk Evolution: non-viscous hydro (Heinz & Kolb) \( \rightarrow \) \( T(M) \) & \( v(M) \)

Evolution of HQ in bulk: Fokker-Planck or reaction rate + Boltzmann (no hadronic phase)

Recently: coupling to EPOS 2/3 instead of KH
The Monte Carlo @ Heavy Quark Generator

D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) or fragmentation (high p_T)

Bulk Evolution: non-viscous hydro (Heinz & Kolb) → T(M) & v(M)

Evolution of HQ in bulk: Fokker-Planck or reaction rate + Boltzmann (no hadronic phase)

Nothing spectacular at freeze-out (quarkonia are white objects already)
Elastic D mesons @ RHIC

=> Allow for some global rescaling of the rates: “K” fixed on experiment

\[ R_{AA}(D) \]

**Au–Au @ 200 GeV/c; 0–10%**

- **col, K=2**

**MC@HQ V507**

\[ p_T \text{ (GeV/c)} \]
We “explain” it all provided we allow for a multiplication of our pQCD (inspired) cross section by a factor 2…
Induced Energy Loss

Generalized Gunion-Bertsch (NO COHERENCE) for finite HQ mass, dynamical light partons

Eikonal limit (large E, moderate q)

With

\[
\frac{J^2_{QCD}}{\omega^2} = \left( \frac{\vec{k}_\perp}{k^2 + x^2M^2 + (1-x)m_q^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2M^2 + (1-x)m_q^2} \right)^2
\]

Gluon thermal mass \(\sim 2T\) (phenomenological; not in BDMPS)

Quark mass

Both cures the collinear divergences and influence the radiation spectra (dead cone effect)

Gluon thermal mass \(\sim 2T\) (phenomenological; not in BDMPS)
Incoherent Induced Energy Loss

... & finite energy!

Finite energy lead to strong reduction of the radiative energy loss at intermediate $p_T$

Incoherent Induced Energy Loss

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

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

HUGE differences expected

Caveat: no detailed balance implemented yet
$R_{AA}(D)$

Au–Au @ 200 GeV/c; 0–10%

- col, $K=2$
- col+rad GB, $K=1.3$

K coming closer to unity if radiation included
Good agreement for NPSE as well
The role of coherence for HF at intermediate $p_T$

Coherent Induced Radiative

Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$

Model: all $N_{coh}$ scatterers act as a single effective one with probability $p_{Ncoh}(Q_\perp)$ obtained by convoluting individual probability of kicks

$$\frac{d^2 I_{eff}}{dz \, d\omega} \sim \frac{\alpha_s}{N_{coh} \lambda} \ln \left( 1 + \frac{N_{coh} \mu^2}{3 \left( m_g^2 + x^2 M^2 + \sqrt{\omega q} \right)} \right)$$

arXiv:1209.0844
\{\text{Radiative} + \text{Elastic}\} \text{ vs Elastic for D mesons @ RHIC}

\rightarrow \text{Allow for some global rescaling of the rates: “K” fixed on experiment}

\begin{align*}
R_{AA}(D) &
\end{align*}

\text{Au–Au @ 200 GeV/c; 0–10%}

col, K=2

\begin{align*}
\text{col+rad GB, K=1.3} & \\
\text{col+rad LPM, K=1.3} & \\
\text{rad LPM, K=3} &
\end{align*}

MC@HQ V507

\begin{align*}
p_T (\text{GeV/c}) &
\end{align*}
“Early” Conclusions from RHIC

- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) \( \Rightarrow \) Not sensitive to the large-\( \omega \) tail of the Energy-loss probability (thanks to initial HQ \( p_T \)-distribution)

- Good consistency between NPSE and D mesons (10% difference in K values)...

- … within a model with mass hierarchy

- \( \Delta E \) radiative \(<\) \( \Delta E \) elastic

- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) \( \Rightarrow \) Not sensitive to the large-\( \omega \) tail of the Energy-loss probability (thanks to initial HQ \( p_T \)-distribution)
QGP properties from HQ probe at RHIC (why do we care ?)

Gathering all *rescaled models* (*coll. and radiative*) compatible with RHIC $R_{AA}$:

- The drag coefficient reflects the average momentum loss (per unit time) $\Rightarrow$ large weight on $x \sim 1$

- Present RHIC experiments cannot resolve between those various trends

- **Hope that LHC can do !!!**

**Main message**

It is possible to reveal some fundamental property of QGP using HQ probes

- Similar diffusion coefficient at low $p$
- We extract it from data (starting from SQM 2008)
- We compare with recent lattice results
Bright future of RHIC

=> Discriminating power of B mesons

Larger mass hierarchy for radiative Eloss
Going LHC: EPOS as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density @ RHIC (central Au-Au)

Kolb Heinz (used previously) 

More realistic hydro and initial conditions => original HQ studies such as:

1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)
2) correlations between HF and light hadrons

Beware: ≠ color scales
Going LHC: EPOS2 as a background for MC@sHQ

Same microscopic ingredients as for RHIC ($\Delta E \propto L$);

N.B.: K values: slightly smaller than what obtained from RHIC

Data at large $p_T$ seems to favor « Collisional only »-like average momentum loss
Further comparison with model calculations at LHC

Sapore Gravis report (arxiv 1506.03981)

Elastic

(Elastic +) Radiative

Other

With SHADOWING
Refined observables

Central question (to better understand the probe):
How to distinguish between

Typical - Collisional

Large cross-section, moderate E-loss per collision
large angular deflection
Mass comes as a scale in a log

Typical - Radiative

Small cross-section, large E-loss per collision
small angular deflection
Mass regularizes collinear divergence
=> stronger mass-influence
Distinguishing between the models: angular correlations...

Large cross-section, moderate E-loss per collision
large angular deflection,

Small cross-section, large E-loss per collision
small angular deflection,

Transverse plane

Transverse broadening ./ Initial direction

Initial correlation ; back to back at leading order

Effect of hadronization on angular correlation ?

Heavy quarks azimuthal correlations: Back-to-back

Pb-Pb at LHC, HQ initialized back-to-back, no background from uncorrelated pairs, eff.deg=1; decoupling at T=155 MeV

- Stronger broadening in a purely collisional than in a collisional+radiative interaction mechanism
- At low pT, initial correlations are almost washed out. Some collectivity seen in the purely collisional scenario
- Variances in the intermediate pT range (4 GeV-10 GeV): 0.18 vs 0.094 (charm) and 0.28 vs 0.12 (bottom)
- At higher pT, initial correlations survive the propagation in the medium

… and with Realistic initial 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 ($\approx 20\%$) for the purely collisional mechanisms and to 0.47 ($\approx 10\%$) for the interaction including radiative corrections (no additivity with initial width).

- At larger $p_T$, the deviations from back to back correlations are mostly due to initial NLO corrections.

- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!

Consequences on the observables: $p_T(c)-p_T(cbar)$ correlations

Toy study: back to back c-cbar (LO). Pb-Pb @ 2.76 TeV; 40-60%.

Long. fluctuations ./.
Initial direction

Residual correlation after evolution through QGP
(similar path length for most of HQ produced in the core of the reaction)
Variety of approaches

Sapore Gravis report (arxiv 1506.03981)

Elastic

(Elastic +) Radiative

Other

With SHADOWING

With SHADOWING

With SHADOWING
Variety of approaches

Some of the model « explaining » the data include pure radiative Eloss, radiative + colisional Eloss… and even pure colisional Eloss?
Part II: HF and IF through jet evolution in QGP
Heavy – light correlations in the near side

Maybe the best direct way to probe the HQ – GQP interactions...

Remnants of induced radiation (small relative angles)

Medium recoil (large relative angles)
Heavy – light correlations in the near side

... However, the « initial state » radiation has to be taken into account has well

Remnants of induced radiation (small relative angles)

Medium recoil (large relative angles)
Heavy – light correlations in the near side

Our motivation to join HQ - jet physics:

Origin of the associated light hadron? Initial DGLAP gluon which has propagated/fragmented → QGP boundary or « late » induced gluon (nearly on shell)

Hybrid scheme:
1. First, modified DGLAP (à la YAJEM)
2. then (when $Q^2 \approx m_{HQ}^2$) Gunion Bertsch – BDMPS radiation (see part I)
Heavy – Quark jet

Time in DGLAP?

At the best in the semi-classical sense:

$$\Delta t \sim \frac{E}{Q^2 - m^2}$$

If finite parton mass

Other prescriptions tested in JEWEL, with limited consequences on the observables
Heavy – quark jet

Hybrid scheme:
1. First, modified DGLAP (à la YAJEM)
2. then (when $Q^2 \approx m_{HQ}^2$) Gunion Bertsch – BDMPS radiation

For intermediate c-jet energies c-quark in $\approx$ on-shell in less than 1 fm/c $\Rightarrow$
substantiate the hybrid model
We follow YAJEM phenomenological prescription to increase the virtuality of the off shell parton according to

\[ \frac{dQ^2}{dt} = \hat{q}(x) \quad \text{(No momentum change)} \]

Raises a lot of questions, but, at least:

- is compliant with induced energy loss (larger $Q^2$ at final vertex -> more radiation)
- Is easy to implement in time-dependent background

Modified DGLAP (referred to as model A)


During a small time step $\Delta t$:

\[ Q \rightarrow \sqrt{Q^2 + \hat{q}\Delta t} \]
\[ \vec{p} \rightarrow \vec{p} \, , \]
\[ E \rightarrow \sqrt{E^2 + \hat{q}\Delta t} \]

Absolue energy gain (but compensated by additional radiative energy loss); 3-momenta in shower only changed due to additional radiation!
Some YaJEM benchmark

[Th. Renk: PRC 88, 014905 (2013)]

YaJEM-DE

\[ Q_i \]

\[ Q_0 = \sqrt{E/L} \]

Vacuum

\[ Q_h = 1 \text{ GeV} \]

\[ R_{AA} \]

\[ P_T \text{ [GeV]} \]

\[ \Delta t \sim \frac{E}{Q^2} \]

\[ \hat{q} \rightarrow 0 \text{ at QGP boundary} \]

Renk: Details of the evolution are found in the scales!

For \( L = 2 \text{ fm} \), \( Q_0 > Q_h \) for \( E > 10 \text{ GeV} \) => explains the hierarchy
Some YaJEM benchmark

Jet $R_{AA}$

Th. Renk: high pT workshw, Nantes (2014)
Modified DGLAP (Elastic interaction; model B)

Rescattering according to Langevin dynamics

\[ \vec{p} = (\vec{0}, p) \mapsto \vec{p}' = (\vec{p}_\perp, p_\parallel), \]

\[ p_\perp = \sqrt{\hat{q} \Delta t}, \quad p_\parallel = p - A \Delta t. \]

transverse momentum transfer \hspace{1cm} (longitudinal) drag force

\[ A = \frac{\hat{q}}{\kappa T} \]  

[H. Berrehrah et al. PRC 90, 064906 (2014)]

No increase of the virtuality => no induced radiation. However, Eloss -> reduction of the vacuum radiation
Modified DGLAP (Elastic interaction; model B)

Rescattering according to Langevin dynamics

\[ \bar{p} = (\bar{0}, p) \mapsto \bar{p}' = (\bar{p}_\perp, p_\parallel), \]

\[ p_\perp = \sqrt{\hat{q}\Delta t}, \quad p_\parallel = p - A\Delta t. \]

Transverse momentum transfer (longitudinal) drag force

\[ E(t) \to E(t + \Delta t) - \frac{||\bar{p}||}{E(t)} A(t) \Delta t + \frac{\hat{q}(t)}{2E(t)} \Delta t + O(\Delta t^2) \]

Dominant for \( E > T \) Energy transferred to the medium
Modified DGLAP ("full"; model D)

« Full » : we combine ingredients from model A and model B:

Both induced radiation, rescattering of partons in the jet and energy loss -> medium

| model                                      | $Q$ | $\vec{p}_{||}$ | $\vec{p}_\perp$ | $E$ |
|--------------------------------------------|-----|----------------|------------------|-----|
| A (radiative/YaJEM-like)                   | ↑   | =             | =                | ↑   |
| B (collisional)                            | =   | ↓             | ↑                | ↓↑  |
| C (hybrid/no transverse force)             | ↑   | ↓             | =                | ↓↑  |
| D (hybrid/transverse force)                | ↑   | ↓             | ↑                | ↓↑  |

Most « realistic »

Most questionable

Motivation: Looking at various observables for these models may help us to better understand the role of induced energy loss

Medium evolution: For the time, we use a toy-model parametrization of the transport coefficient:

D & C vs A: role of the Energy transfer -> medium & medium response
Further model ingredients

1. Medium evolution: For the time, we use a toy-model parametrization of the transport coefficient:

\[ \hat{q}(t) = \frac{a}{(t + b)^c} \]

With \( b = 1.5 \) fm/c, \( c = 2.2 \) (jet emanating from the center of the medium) [Th. Renk: Phys.Rev.C 78, 034908 (2008)]

\[ \int_{t_0}^{t_f} \hat{q}(t) dt = \Delta Q^2 \]

Parameter fixing the jet-medium coupling

2. Evolutions are initiated starting from a HQ with energy \( E_{ini} \) and a virtuality ranging from \( Q^\uparrow = E_{ini} \) down to \( Q_0 \approx 1 \) GeV

3. For the following results: no further evolution in the QGP once partons are on-shell
Basic results for jet particles: humped back plateau

All model including radiative energy loss show a strong enhancement for $\xi > 1.5$...

Comparing model C & A: drag reduce these extra soft gluons, but transverse forces (D) help to maintain the production
Basic results for jet particles: absolute distributions

All model including radiative energy loss show a strong enhancement for small $||p||$ (difficult to detect unless jet tagging)

Pure collisional model leads to much less quenching... However: effect of gluon thermal mass (not included) which could reduce the difference
Basic results for jet particles: angular distributions

With radiative energy loss: large excess of small energy gluons, radiated at large angles (rediffusion in model D leads to the largest angles \(\Delta / \theta \text{ jet direction}\)).

Transverse forces lead to angular broadening which shows the less dependence on the \(p_T\) range.
Basic results for HQ quark: quenching

Quenching:

\[ R_{MV}(\|\vec{p}\|) := \frac{\left(\frac{dN}{d\|\vec{p}\|}\right)_{\text{medium}}}{\left(\frac{dN}{d\|\vec{p}\|}\right)_{\text{vacuum}}} \]

Proxy for \( R_{AA} \)

Again, radiative energy loss dominates. However, for \( p_T > 3 \text{ GeV} \), same shape found at the price of \( \Delta Q^2 \) rescaling:

\[ \text{RMV(elast.) for } \Delta Q^2 = 20 \text{ GeV}^2 \approx \text{RMV(radiat.) for } \Delta Q^2 = 3 \text{ GeV}^2 \]

Reminds of « universality » found in part 1

Missing: ensuing evolution of on shell HQ
Basic results for HQ quark: back to back

\[ \frac{dN}{d\Delta \phi_{Q\bar{Q}}} \]

\( Q_{\parallel} = E_{\text{ini}} = 20 \text{ GeV}, \)
\( Q_{\perp} = 0.6 \text{ GeV}, \)
\( \Delta Q^2 = 10 \text{ GeV}^2. \)

Confirms previous observations: elastic scatterings are more effective to smear HQ angular correlations… but absolute effect is small as compared to vacuum
Angular correlations: azimuthal

Correlations of heavy quark & any light particle:

$$\cos(\Delta \phi) = \frac{\vec{p}_h \cdot \vec{p}_l}{||\vec{p}_h|| ||\vec{p}_l||} ,$$

Angular correlations: relative $\Delta \theta$

Correlations of heavy quark & any light particle:

$$\cos(\Delta \phi) = \frac{\vec{p}_h \cdot \vec{p}_l}{||\vec{p}_h|| ||\vec{p}_l||},$$

from physical viewpoint pretty equivalent to

$$\cos(\Delta \theta) = \frac{\vec{p}_h \cdot \vec{p}_l}{||\vec{p}_h|| ||\vec{p}_l||}.$$
Angular correlations: relative $\Delta \theta$

$\frac{dN}{d \cos(\Delta \theta)}$

$Q^+_i = E_{\text{ini}} = 20 \text{ GeV},$
$Q^- = 0.6 \text{ GeV}, \|p\| > 2 \text{ GeV},$
inelastic.

$\Delta Q^2 = 3 \text{ GeV}^2$
$vacuum$

$\Delta Q^2 = 10 \text{ GeV}^2$

$Q^+_i = E_{\text{ini}} = 20 \text{ GeV},$
$Q^- = 0.6 \text{ GeV}, \|p\| > 2 \text{ GeV},$
elastic.

$Q^+_i = E_{\text{ini}} = 20 \text{ GeV},$
$Q^- = 0.6 \text{ GeV}, \|p\| > 2 \text{ GeV},$
model C.

$Q^+_i = E_{\text{ini}} = 20 \text{ GeV},$
$Q^- = 0.6 \text{ GeV}, \|p\| > 2 \text{ GeV},$
model D.

Stronger broadening for models including transverse forces.
Angular correlations: relative $\Delta \theta$

$$\langle \Delta \theta \rangle [\text{rad}]$$

$B = 1.5, C = 2.2, L = 10 \text{ fm},$

$Q_T = E_{\text{lab}} = 20 \text{ GeV},$

$Q_L = 0.6 \text{ GeV},$

$\|p\| > 0 \text{ GeV}.$

$\langle \Delta \theta \rangle [\text{rad}]$
Conclusions and Prospects

• Combining HF and jet physics is a great opportunity to better understand how HF couple to QGP and then, ultimately, to better understand this phase of strong matter

• Heavy-light observables might be a good observable to further constrain some models (and kill others)

• Complete our jet HF model (embedding in a realistic medium event + …)
Back up
Angular correlations: relative $\Delta \phi$

Model D shows the largest broadening.
Double differential angular correlations

Angle between jet and HQ
Important facts about radiative *induced* energy loss

QCD:

1. QCD analog of Bethe Heitler result established by Gunion & Bertsch (M=0) at high energy; third diagram involved…

   \[ \Delta E \propto \hat{q} L^2 \]

   Yes, but…

   … important as it contributes to populate the mid rapidity gap (large angle radiation)

2. QCD analog of LPM effects: BDMPS; main difference: dominant process are the ones for which *the emitted gluon is rescattered*:

   … leads to a complete modification of the formation times and radiation spectra, but these concepts still apply
Important facts about radiative *induced* energy loss

LHC: the realm for coherence!

3 regimes and various path length (L) dependences: (light q)

\[ \frac{\omega}{\lambda} \times \text{Gunion Bertsch} \]

\[ \omega \frac{dN_{\text{ind}}}{d\omega} \]

\[ \omega < \omega_{\text{LPM}} := \frac{q\lambda^2}{2} \]

\[ \text{Incoherent Gunion-Bertsch radiation} \]

→ a) Low energy gluons: Typical formation time \( \omega/k_t^2 \) is smaller than mean free path \( \lambda \):
Important facts about radiative induced energy loss

LHC: the realm for coherence!

3 regimes and various path length (L) dependences: (light q)

- a) Low energy gluons: Typical formation time $\omega/k_t^2$ is smaller than mean free path $\lambda$:
  \[ \omega < \omega_{LPM} := \frac{\hat{q} \lambda^2}{2} \]  
  Incoherent Gunion-Bertsch radiation

- b) Inter. energy gluons: Produced coherently on $N_{coh}$ centers after typical formation time $t_f = \sqrt{\frac{\omega}{\hat{q}}} \Rightarrow N_{coh} = \frac{t_f}{\lambda} = \sqrt{\frac{\omega}{\omega_{LPM}}} \] leading to an effective reduction of the GB radiation spectrum by a factor $1/N_{coh}$
Important facts about radiative *induced* energy loss

**LHC: the realm for coherence!**

**3 regimes and various path length \((L)\) dependences:** (light \(q\))

a) Low energy gluons: **Incoherent** Gunion-Bertsch radiation

b) Inter. energy gluons: Produced **coherently** on \(N_{\text{coh}}\) centers after typical formation time \(t_f = \sqrt{\frac{\omega}{q}}\)

c) High energy gluons: Produced mostly outside the QGP... nearly as in vacuum **do not contribute significantly to the induced energy loss**
Important facts about radiative induced energy loss

LHC: the realm for coherence!

3 regimes and various path length (L) dependences: (light q)

Bulk part of the spectrum still scales like path length L

Only this tail makes the L² dependence in the average Eloss integral ...

...provided the higher boundary ω=E > ωc.

Otherwise, everything α L

Concrete values @ LHC

\[ \omega_c \approx 100 \text{GeV} \quad \text{Huge value!} \]

A large part of radiative energy loss @ LHC still scales like the path length

=>$ \text{Still makes sense to speak about energy loss per unit length (for a typical event)}$

\[ \Delta E \simeq \pi C_\alpha C_A \alpha^3 N L^2 \left[ \ln \left( \frac{q_A L}{m_D^2} \right) + \ln \left( \frac{E}{\hat{q} A L^2} \right) \right] \]