Energy loss of hard partons in cold and hot QCD media

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Parton energy loss in cold and hot QCD media

Outline

✗ Motivations
  ➔ Energy loss and deconfinement

✗ Quenching weight $D(\epsilon)$
  ➔ Results
  ➔ Discussion

✗ Phenomenology
  ➔ DIS on nuclear targets
  ➔ High energy heavy ion collisions

✗ Summary

References
F. Arleo, JHEP 11 (2002) 044
F. Arleo, Phys Lett B532 (2002) 231
F. Arleo, to appear
Motivations

Phase transition occurs at high temperature and/or density from hadronic matter to quark-gluon plasma

How to achieve such conditions?

Ultra-relativistic heavy ion collisions

Where?

\(\times\) SPS (CERN):
- Pb-Pb at \(\sqrt{s_{NN}} = 17.3\) GeV
- NA44, NA49, NA50, WA97, WA98, CERES ...

\(\times\) RHIC (BNL, since 2000):
- Au-Au at \(\sqrt{s_{NN}} = 200\) GeV
- BRAHMS, PHENIX, PHOBOS, STAR

\(\times\) LHC (CERN, starting from 2007):
- Pb-Pb at \(\sqrt{s_{NN}} = 5.5\) TeV
- ALICE, CMS
Parton energy loss in cold and hot QCD media

Parton energy loss in a QCD medium

Baier, Dokshitzer, Mueller, Peigné, Schiff
Gyulassy, Lévai, Vitev, Wang
Zakharov
Wiedemann

Multiple soft collisions

→ Strong gluon radiation $dI/d\omega$

proportional to the medium density

Huge energy loss in quark gluon plasma
Evidence for parton energy loss

A clear experimental signal

Quenching of jets in heavy ion collisions

Gyulassy, Wang
Quenching factor $R_{AA}(p_{\perp})$

$$R_{AA}(p_{\perp}) \approx \int_{0}^{+\infty} d\epsilon \, D(\epsilon) \times \frac{d\sigma(p_{\perp}+\epsilon)}{dp_{\perp}^2} \bigg/ \frac{d\sigma(p_{\perp})}{dp_{\perp}^2}$$

$D(\epsilon) =$ probability for a hard parton to lose an energy $\epsilon$

→ Knowledge of $D(\epsilon)$ essential

Problem

How to relate $D(\epsilon)$ to the medium-induced gluon spectra $dI/d\omega$?

Baier, Dokshitzer, Mueller, Schiff
Parton energy loss in cold and hot QCD media

Quenching weight $D(\epsilon)$

[BDMS, JHEP 09 (2001) 033]

Independent gluon radiation $\rightarrow$ Poisson approximation

\[ D(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta \left( \epsilon - \sum_{i=1}^{n} \omega_i \right) \]

Relevant scale for the induced gluon spectrum $dI/d\omega$

\[ \omega_c = \frac{1}{2} \hat{q} L^2 \]

$\hat{q}$ : transport coefficient

$\rightarrow$ scattering property of the medium ($\sim$ density)

$L$ : length of matter covered by the fast parton
Integral representation \[ \text{[BDMS, JHEP 09 (2001) 033]} \]

Resummation of the Poisson series

\[
D(\epsilon) = \int_C \frac{d\nu}{2\pi i} e^{\nu \epsilon} \times \exp \left[ -\nu \int_0^\infty d\omega e^{-\nu \omega} N(\omega) \right]
\]

with \( N(\omega) = \) gluon multiplicity

\[
N(\omega) = \int_0^\infty d\omega' \frac{dI(\omega')}{d\omega'}
\]

Two options

1. Analytic determinations of \( N(\omega) \)
   - Spectrum \( dI/d\omega \) approximated for \( \omega \ll \omega_c \)

2. Numerical determination of \( N(\omega) \)
   - “Exact” spectrum \( dI/d\omega \)
Gluon multiplicity radiated by hard quarks


Sensitive in the infrared sector
Analytic approximations fail for hard gluon emission
Much smaller gluon emission for incoming quarks
Quenching weight $D(\varepsilon)$ for outgoing quarks

- Peaked at small energy loss $\rightarrow$ bias!
- Long energy tail
- Hypergeometric function does a good job
Beyond the soft limit: finite quark energy $E$

Calculations done so far assuming $\omega_i \ll E$ in the spectrum

In the general case

$$\frac{dI(\omega, E)}{d\omega} = (1 - \frac{\omega}{E}) \times \frac{dI(\omega)}{d\omega} \times \Theta(E - \omega)$$

Suppression of hard gluon emission

Kinematically forbidden region $D(\epsilon > E) \neq 0$

Eikonal approximation breaks down at $E \simeq \omega_c/2$
Infrared sensitivity

BDMPS spectrum describes LPM effect in QCD

Interference occurs for long lived gluons

\[ t = \frac{\omega}{k_{\perp}^2} \gtrsim \lambda \quad \text{with} \quad k_{\perp}^2 = \hat{q} L \simeq \hat{q} \lambda \]

No LPM suppression below \( \omega \lesssim \omega_{\text{min}} = \hat{q} \lambda^2 \)

\[ \rightarrow \text{Independent Bethe-Heitler gluon radiation} \]

Qualitative estimate in a hot medium

\[ \hat{q} = 1 \text{ GeV}^2/\text{fm}, \quad \lambda = 0.25 \text{ fm} \rightarrow \omega_{\text{min}} \simeq 300 \text{ MeV} \]
Gluon spectrum truncated in the infrared

\[ \frac{dI(\omega < \omega_{\text{min}})}{d\omega} = 0 \]

\[ \omega_{\text{min}} / \omega_c = 0 \]

\[ \omega_{\text{min}} / \omega_c = 1 / 100 \]

- Strong decrease of the mean energy loss
- Discrete contribution \( D(\epsilon) = p_0 \times \delta(\epsilon) + d(\epsilon) \) with \( p_0 \simeq \exp(-L/\lambda_q) \)
- Structure at \( \epsilon \sim \omega_{\text{min}} \)
Threshold at $\epsilon = \omega_{\text{min}}$

New channels at $\epsilon/\omega_{\text{min}} = 2, \ldots, n$

$\rightarrow$ Multiple gluon emission

Huge combinatorics at $\epsilon \gg \omega_{\text{min}}$

$\rightarrow d(\epsilon)$ becomes “smooth”
A simple analytic parameterization

\[ D(\epsilon) \text{ follows log-normal distributions} \]

\[ \begin{align*}
\omega_c D(\epsilon) \\
\epsilon / \omega_c
\end{align*} \]

\[ \times \] Identical behavior for finite quark energy

\[ \times \] Identical behavior for incoming and outgoing quarks

Easy to use for future practical applications

Conjecture on its origin

Statistical behavior from the combinatorics of gluon radiation?
Energy loss in DIS

Multiple scatterings shift quark energy from $\nu$ to $\nu - \epsilon$

Model for modified fragmentation functions

[Mathematical expression]

[Wang, Huang, Sarcevic, PRL 77, 231 (1996)]
Transport coefficient $\hat{q}$ for nuclear matter

$\rightarrow$ Perturbative estimate

[BDMPS, Nucl Phys B484 (1997) 265]

$\hat{q}$ related to gluon density

\[
\hat{q} = \frac{4\pi^2\alpha_s N_c}{N_c^2 - 1} \rho x G(x, Q^2) 
\approx 0.25 \text{ GeV/fm}^2
\]

$\rightarrow$ Constraints from Drell-Yan data


large energy loss

RULED OUT

$\hat{q} = 0.72 \pm 0.54 \text{ GeV/fm}^2$
Comparing with HERMES data

![Graph showing comparison with HERMES data]

- Pretty good agreement (except pions)
- Isospin effects in the kaon channel reproduced
- “Easier” to fragment $u \rightarrow K^+$ than $u \rightarrow K^-$
Energy loss in heavy ion collisions

Medium no longer static!

Color charge density \( ( \leftrightarrow \hat{q} ) \)

\[
n(\tau) = n(\tau_0) \times \left( \frac{\tau_0}{\tau} \right)^\alpha
\]

Equivalence with a static medium

[Salgado, Wiedemann, PRL89 (2002) 092303]

\[
\langle \hat{q} \rangle = \frac{2}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau' \left( \tau' - \tau_0 \right) \times \hat{q}(\tau_0) \left( \frac{\tau_0}{\tau'} \right)^\alpha
\]

Quenching factor

\[
R_{AA}(p_\perp) = \int_0^{+\infty} d\epsilon \, D(\epsilon, p_\perp + \epsilon) \times \frac{d\sigma(p_\perp + \epsilon)}{dp_\perp^2} / \frac{d\sigma(p_\perp)}{dp_\perp^2}
\]

Illustration

\( \times \) \( d\sigma/dp_\perp^2 \) given by PHENIX

\( \times \) \( L \simeq 5 \text{ fm} \quad \tau_0 \simeq 1 \text{ fm} \quad \alpha = 1 \)
Infrared and Ultraviolet sensitivity

Modelling of the quenching
Comparing with PHENIX $\pi^0$ data

Taking $\hat{q}(\tau_0) = 3.5$ GeV/fm$^2$ ($-dE/dz \simeq 3$ GeV/fm at $\tau = \tau_0$)

$\times$ opposite to the trend of the data !
$\times$ many effects compete at low $p_\perp$
Formation time effects

Imagine hadronization occurs inside the medium...

The larger the $p_{\perp}$ (hence, $t_h$), the stronger the quenching

$t_h \sim \frac{p_{\perp}}{\sigma}$

X Trend reproduced ($\hat{q} = 4.5$ GeV/fm$^2$)

X No (yet) pion absorption
Summary

✗ Energy loss useful to probe QCD media
  ➔ Proportional to gluon density

✗ Quenching weight $D(\epsilon)$
  ➔ Essential for the phenomenology
  ➔ IR and UV sensitivity investigated
  ➔ Analytic parameterization

✗ Applications in DIS and heavy ions
  ➔ Good description of HERMES data
  ➔ Possible formation time effects in PHENIX data