Medium–induced jet evolution

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May 8th, 2012
1 Motivation
2 Setting up the problem
3 In–medium emissions
New forms of partonic matter

Prior to the collision: 2 Lorentz–contracted nuclei (‘pancakes’)
  - ‘Color Glass Condensate’ (CGC)

Right after the collision: non–equilibrium partonic matter
  - ‘Glasma’ (from ‘Glass’ + ‘Plasma’)

At later stages ($\Delta t \gtrsim 1$ fm/c): local thermal equilibrium
  - ‘Quark–Gluon Plasma’ (QGP)
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- At later stages ($\Delta t \gtrsim 1$ fm/c): local thermal equilibrium
  - ‘Quark–Gluon Plasma’ (QGP)
- How to probe the intermediate stages (Glasma, QGP)?
Two–hadron (or ‘di–jets’) correlations:
a measurement of the medium (QGP ?) created at intermediate stages

‘Jet’: ‘leading particle’ + ‘products of fragmentation’
Studies of jet quenching at RHIC have focused on ‘leading particles’.

The “away–side” peak has disappeared! Absorption (or energy loss, or “jet quenching”) in the medium.

The matter produced in a heavy ion collision is opaque.

High density, or strong interactions (‘sQGP’), ... or both.
Jet production at the LHC

The LHC gives us access to real jets
Central Pb+Pb: ‘mono–jet’ events

The secondary jet cannot be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV
Central Pb+Pb: the secondary jet is barely visible

In-medium radiation of relatively soft quanta at large angles
Medium–induced gluon radiation

- Additional radiation triggered by interactions in the medium

*Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov ~ 1996*

- Naturally leads to emissions at large angles
  - the emitted gluons receive transverse kicks from the medium

- How to compute multiple gluon emissions / jet evolution?
Medium–induced gluon radiation

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How to compute multiple gluon emissions / jet evolution?

Ideally: Monte Carlo generator $\Rightarrow$ classical branching process
Factorization issues

- Parton branching is a quantum phenomenon, which implies ...
  - a finite formation (or branching) time $\tau_f$

interference between emissions by different sources
**Interferences in the vacuum**

- **1 → 2 gluon splitting**: the daughter gluons remain in the same overall colour state until the next emission — they are colour coherent

\[ \begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \quad \begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \quad + \\
\begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \]

- A large angle emission sees the **overall** colour charge

\[ \implies \text{it can be formally treated as an emission by the parent dipole} \]

\[ \begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \quad + \\
\begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \quad = \\
\begin{array}{c}
\text{2} \\
\text{2} \\
\end{array} \]

- Equivalent classical branching process but with **angular ordering**
Angular ordering (vacuum)

For a jet propagating through the vacuum, destructive interference between different sources leads to angular ordering:

$$\theta_1 > \theta_2 > \theta_3 > \ldots$$

What about medium–induced radiation?
Medium–induced jet evolution

- The mathematical problem looks very complicated ...
- medium rescattering and gluon emissions should be treated to all orders

... but there is hope that the physical answer could be simple!

- Medium rescattering destroys the coherence of the radiating system and thus can enhance radiation and reduce interferences
A few words on the formalism

- Quantum emission: amplitude $\times$ the complex conjugate amplitude

- ‘Medium’ = independent scattering centers with Debye screening
- Medium rescattering resummed to all orders in the eikonal approximation (Wilson lines, one for each gluon)
- $1 \rightarrow 2$ gluon branching $\Leftrightarrow$ 3–point and 4–point correlation functions of the Wilson lines (Gaussian average)
The formation time

- The gluon must lose quantum coherence with respect to its source.
- The quark–gluon transverse separation $r_\perp$ at the formation time $\tau_f$ should be comparable with the gluon transverse wavelength $\lambda_\perp$

\[ r_\perp \simeq \theta \tau_f \gtrsim \lambda_\perp \simeq 1/k_\perp \]

\[ k_\perp \simeq \omega \theta \]

\[ \tau_f \simeq \frac{\omega}{k^2_\perp} \simeq \frac{1}{\omega \theta^2} \]
The loss of coherence is accelerated by medium rescattering

Random kicks leading to transverse momentum broadening

- Parton mean free path $\ell$
- Average $(momentum)^2$ transfer per scattering $m_D^2$ (Debye mass)

\[
\frac{d\langle k_\perp^2 \rangle}{dt} \simeq \frac{m_D^2}{\ell} \equiv \hat{q} \quad \text{‘jet quenching parameter’}
\]
The gluon acquires a \((\text{momentum})^2 \sim \hat{q}\) per unit time ...

... and hence a momentum \(k_f^2 \sim \hat{q} \tau_f\) during its formation.

The condition of quantum decoherence requires \(\tau_f \sim \omega/k_f^2\)

\[
\tau_f \sim \sqrt{\frac{\omega}{\hat{q}}}, \quad \theta_f \equiv \frac{k_f}{\omega} \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}
\]

N.B. The energy \(\omega\) and the transverse momentum \(k_\perp\) are not independent kinematical variables anymore!

Medium favors the emission of soft gluons (small \(\omega\)) at large angles

\(\Longrightarrow\) the right trend to explain the LHC data!
Successive emissions

- \( P(L) \simeq \alpha_s(L/\tau_f) \): probability for one emission over a distance \( L \)
- When \( P(L) \gtrsim 1 \), multiple emissions are bound to occur

\[
P(L) \sim \alpha_s \frac{L}{\tau_f} \gtrsim 1 \implies \tau_f \lesssim \alpha_s L \ll L
\]

Successive in–medium emissions do not overlap with each other ✓
Already during formation, the daughter gluons independently scatter off (and exchange colour with) the medium constituents.

By definition, the ‘formation time’ $\tau_f$ is when the daughter gluons have lost coherence w.r.t. their parent gluon.

By that time, they also lose coherence w.r.t. each other! $\implies$ interference effects are suppressed by a factor $\tau_f/L \ll 1$.

By the same token, the branching process looks quasi-local.
Towards Monte–Carlo generators

- In-medium jet evolution: a classical, probabilistic, branching process
- One additional emission: quantum process
- Direct emissions plus interference effects
- One additional emission: classical process
- Medium effects explicit in effective vertices and propagators
The BDMPS–Z spectrum

- So long as $\omega \ll \omega_c \equiv \hat{q}L^2$, one has $\tau_f \ll L$

- After formation, the gluon can still acquire momentum via scattering in the plasma (transverse momentum broadening)

  $\implies$ final momentum $Q_s^2 = \hat{q}L$ & final angle $\theta_s = Q_s/\omega$
Nuclear modification factor at RHIC & the LHC

$$R_{A+A} \equiv \frac{1}{A^2} \frac{dN_{A+A}/d^2p_\perp d\eta}{dN_{p+p}/d^2p_\perp d\eta}$$

- Strong suppression ($R_{AA} \lesssim 0.2$) in central collisions
- Large energy loss in the medium
Event fraction as a function of the di–jet energy imbalance in p+p (a) and Pb+Pb (b–f) collisions for different bins of centrality

\[ A_J = \frac{E_1 - E_2}{E_1 + E_{21}} \]

Additional energy loss of 20 to 30 GeV due to the medium
Event fraction as a function of the azimuthal angle $\Delta \phi$.

Typical event topology: still a pair of back–to–back jets.
Event fraction as a function of the azimuthal angle $\Delta \phi$.

Typical event topology: still a pair of back–to–back jets

The secondary jet loses energy without being deflected

Additional radiation of relatively soft quanta at large angles
Bremsstrahlung

- Gluon emission by an off–shell quark **in the vacuum**!

\[ d\mathcal{P}_{\text{Brem}} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{d^2 k_\perp}{k_\perp^2} \propto \alpha_s \frac{d\omega}{\omega} \frac{d\theta}{\theta} \]

- Phase–space enhancement for the emission of
  - soft (low–energy) \((\omega \to 0)\)
  - and/or collinear \((\theta \to 0)\) gluons

- No similar enhancement for the emission of soft quarks
Radiation requires acceleration

\[ \Rightarrow \text{in–vacuum emissions occur only after a hard scattering} \]

Successive emissions are ordered in energy and in angle, hence in time

\[ \omega_1 > \omega_2 > \omega_3 \ldots \ & \theta_1 > \theta_2 > \theta_3 \ldots \ \Rightarrow \ \tau_1 < \tau_2 < \tau_3 \ldots \]
In–vacuum fragmentation

- Radiation requires acceleration

\[ \Rightarrow \text{in–vacuum emissions occur only after a hard scattering} \]

\[ d\mathcal{P}_{\text{Brem}} \approx \alpha_s C_R \frac{d\omega}{\omega} \frac{d\theta}{\theta} \]

- Successive emissions are ordered in energy and in angle, hence in time

\[ \omega_1 > \omega_2 > \omega_3 \ldots \ \& \ \theta_1 > \theta_2 > \theta_3 \ldots \ \Rightarrow \ \tau_1 < \tau_2 < \tau_3 \ldots \]

- This ordering is typically strong \((\omega_1 \gg \omega_2, \text{etc})\)

\[ \Rightarrow \text{the overlapping between successive emissions is negligible} \]
If the emission angle is sufficiently small (for a given $\omega$), then the gluon can be also emitted outside the medium:

$$\tau_q \sim \frac{2}{\omega \theta_q^2} \gtrsim L$$

The coherence between the sources is washed out by color rotations $\Rightarrow$ no interference, no angular ordering

Additional bremsstrahlung outside the antenna: $\theta_q \gtrsim \theta_{q\bar{q}}$ $\Rightarrow \theta_{q\bar{q}}$ itself must be relatively small