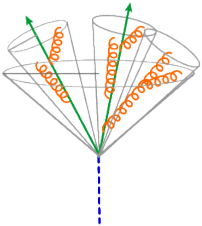
Coherence effects in medium-induced radiation

Víctor Vila

Universidade de Santiago de Compostela

BNL - Upton, NY; July 25, 2018

Motivation: jet substructure



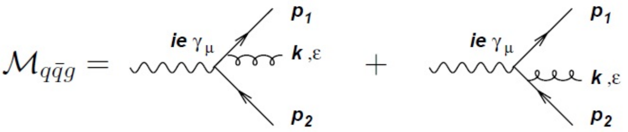
- Jets have substructure:
  - Dynamics of an energetic parton in matter [Jean-Paul Blaizot's talk].
  - We need theoretical tools to compute multiparticle scenarios from first principles.
  - Keys: Coherence, medium-induced radiation, jet fragmentation...

Motivation: unifying existing knowledge

- Existing knowledge well understood separately:
  - Vacuum jets.
  - BDMPS-Z spectrum and energy loss [Jean Paul Blaizot's talk].
  - Color coherence phenomenon in original antenna setups.
- How can we combine it? [Edmond Iancu's talk]
- Further studies towards an unified description:
  - (1) color coherence in multiple emissions setups.
  - (2) finite formation time corrections.

Color coherence in vacuum

- Is radiation independent?: $q\bar{q}$ antenna as a laboratory.

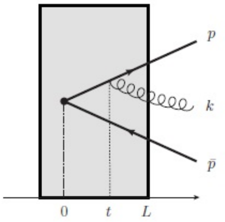


$$dN = \frac{d\omega}{\omega}\frac{d\Omega}{2\pi}\frac{\alpha_s C_F}{2\pi}\left[R_q + R_{\bar{q}} - 2\mathcal{J}\right]$$

- The spectrum is suppressed at large angles due to the presence of destructive inteferences (coherence).
- Angular ordering.

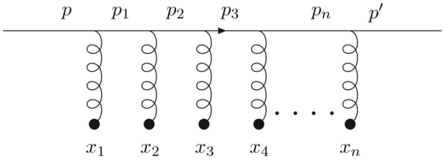
Color coherence in a medium

- How does the medium change this picture?



- A parton can change color through interaction with the medium, breaking the correlation between emitted gluons.

Particle propagation in matter

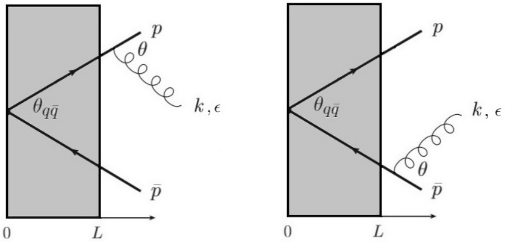


$$W(\vec{x}) = \mathcal{P}\ exp\left[ig \int dx_+ A_-(x_+, \vec{x})\right]$$

- The effect of the medium is to induce color rotation at each scattering center.
- The quark (a high energy quark) loses a negligible amount of energy and propagates in straight lines (*eikonal* propagation).

In-medium antenna radiation

- To study the degree of coherence we a take a very soft gluon $\omega \to 0$ (out-out radiation).



The decoherence parameter

- The interaction of the $q\bar{q}$ pair with the medium is described by the survival probability $\mathcal{S}$.

$$\mathcal{S} \equiv \frac{1}{N_c^2 - 1} \left\langle W(\vec{x}_\perp) W^\dagger(\vec{y}_\perp) \right\rangle$$

$$\mathcal{S} \equiv 1 - \Delta_{med}(t)$$

$$\Delta_{med} \equiv 1 - exp\left[-\frac{1}{4} \hat{q} L (\vec{x}_\perp - \vec{\bar{x}}_\perp)^2 \right]$$

- This factor determines a characteristic time-scale for decoherence of the $q\bar{q}$ pair.

The resulting spectrum

$$dN = \frac{d\omega}{\omega}\frac{d\Omega}{2\pi}\frac{\alpha_s C_F}{2\pi}\left[R_q + R_{\bar{q}} - (1-\Delta_{med})\, 2\mathcal{J}\right]$$

$$\begin{cases} \Delta_{med} \to 0 : dN \sim R_q + R_{\bar{q}} - 2\mathcal{J} \\ \boxed{Dilute\ \ medium : coherence\ (angular\ ordering)} \\ \\ \Delta_{med} \to 1 : dN \sim R_q + R_{\bar{q}} \\ \boxed{Opaque\ \ medium : decoherence\ (two\ \ independent\ \ emitters)} \end{cases}$$

[The radiation pattern of a QCD antenna in a dilute/dense medium, Yacine Mehtar-Tani, Carlos A. Salgado and Konrad Tywoniuk]

Main limitations

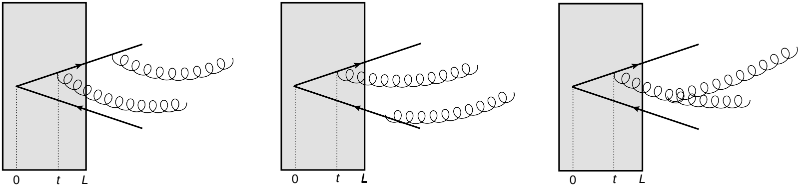
- We have to deal with more realistic settings:
  - Non-eikonal antenna.
  - Multiple emissions.
  - Finite formation time.

Main limitations

- We have to deal with more realistic settings:
    - Non-eikonal antenna.
    - **Multiple emissions.**
    - Finite formation time.

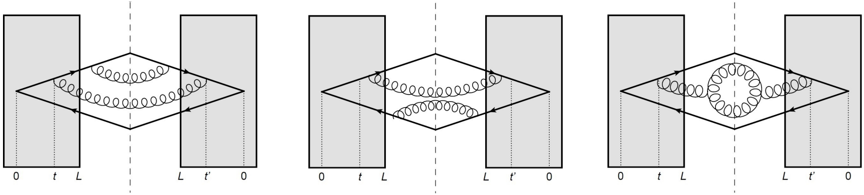
Multiple emissions

- The antenna provides a simple and intuitive picture.
- Does it hold for more than two emitters?



[In preparation: Factorization of color coherence for gluon radiation of a double QCD antenna, Fabio Domínguez, Carlos A. Salgado and Víctor Vila]

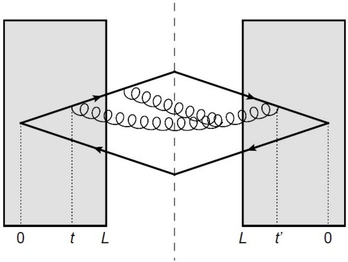
Direct terms

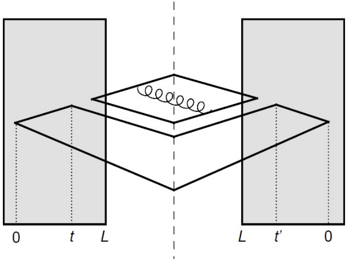


$|\mathcal{M}_1|^2 \propto C_F^2$ $|\mathcal{M}_2|^2 \propto C_F^2$ $|\mathcal{M}_3|^2 \propto N_c\ C_F^2$

- The direct terms are proportional to a color factor, i.e., no medium effects appear.

Interference terms

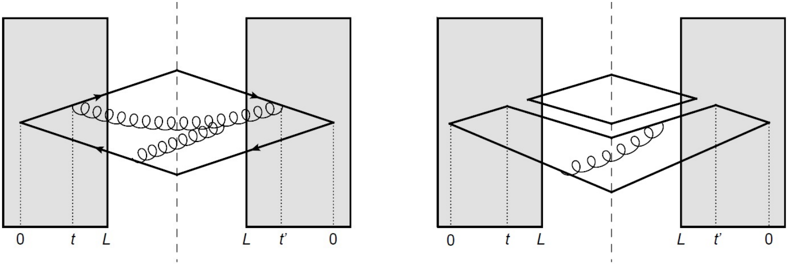




Large N_c limit

$$\mathcal{M}_1 \otimes \mathcal{M}_3^* \propto \mathcal{S}(t, L)$$

Interference terms



Large N_c limit

$$\mathcal{M}_2 \otimes \mathcal{M}_3^* \propto \mathcal{S}(0,t)\ \mathcal{S}(t,L)$$

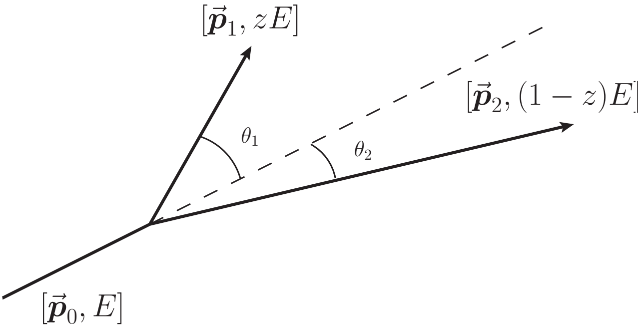
Multiple emissions summary

- We have considered the case of three emitters.
- **The interference terms are proportional to the survival probabilities $\mathcal{S}$ in the $(0, t)$ and (t, L) regions: the general result of the antenna is valid for each of the smaller antennas.**
- **If coherence is not preserved after the in-medium splitting, the antenna won't radiate coherently in the following emission.**
- These computations can be generalized to the problem of *n* emitters.

Main limitations

- We have to deal with more realistic settings:
  - Non-eikonal antenna.
  - Multiple emissions.
  - **Finite formation time.**

In-medium finite formation time antenna



[In preparation: Mapping collinear in-medium parton splittings, F. Domínguez, G. Milhano, C. A. Salgado, K. Tywoniuk and V. Vila]

$\gamma \to q\bar{q}$: amplitude

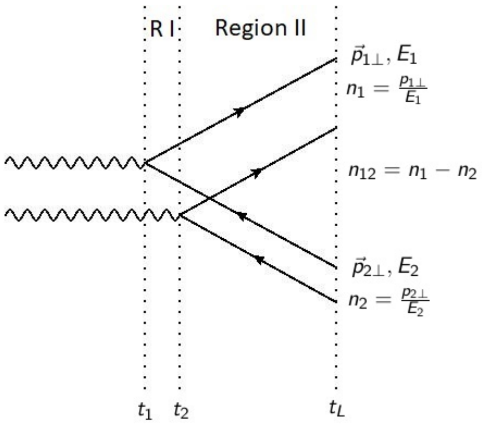
$$\bar{\mathcal{M}}^{in}_{\gamma\to q\bar{q}} = \frac{1}{2E}\int_0^L dt \int_{\vec{k}_1,k_2} \left[\mathcal{G}(\vec{p}_1, L; \vec{k}_1, t|zE)\ \bar{\mathcal{G}}(\vec{p}_2, L; \vec{k}_2, t|(1-z)E)\right]_{ij} \times \Gamma^{\gamma\to q\bar{q}}_{\lambda,s,s'}(\vec{k}, z)\ \mathcal{G}_0(\vec{k}_1 + \vec{k}_2, t|E) \tag{1}$$

$$\mathcal{G}(\vec{p}_1, t_1; \vec{p}_0, t_0) = \int_{\vec{x}_1,\vec{x}_2} e^{-i\vec{p}_1\cdot\vec{x}_1 + i\vec{p}_0\cdot\vec{x}_0}\ \mathcal{G}(\vec{x}_1, \vec{x}_0) \tag{2}$$

$$\mathcal{G}(\vec{x}_1, \vec{x}_0) = \int_{\vec{r}(t_0)=\vec{x}_0}^{\vec{r}(t_1)=\vec{x}_1} \mathcal{D}\vec{r}\ exp\left[i\frac{E}{2}\int_{t_0}^{t_1} ds\ \dot{\vec{r}}^2\right]\ V(t_1, t_0; \vec{r}[s]) \tag{3}$$

$$\mathcal{G}^{(0)}(\vec{x}_1, \vec{x}_0) = \mathcal{G}_0(\vec{x}_1 - \vec{x}_2, \tau)\ V(t_1, t_0; [\vec{x}_{cl}(s)]) \tag{4}$$

Finite formation time antenna



Finite formation time antenna

- **Region I**:
  - q and $\bar{q}$ phases: $exp\Big\{ i\frac{p_{i\perp}^2}{2E_i}(t_2 - t_1)\Big\}$.
  - Average of the Wilson lines: $exp\Big\{ -\frac{1}{12}\hat{q}n_{12}^2(t_2 - t_1)^3\Big\}$.
- **Region II**:
  - Average of a trace of four Wilson lines:

$$Q(t_L, t_2) = \frac{1}{N_c}\Big\langle Tr\Big[W_1(t_L, t_2)W_2^\dagger(t_L, t_2)W_{\bar{2}}(t_L, t_2)W_{\bar{1}}^\dagger(t_L, t_2)\Big]\Big\rangle$$

  - Additional momentum broadening both during the formation time and afterwards.

The time-scales

- Kinematical formation time:

$$t_f = \frac{z(1-z)E}{\vec{p}^2} \tag{5}$$

- Decoherence time:

$$t_d \sim \left(\frac{1}{\hat{q}\theta^2}\right)^{1/3} \tag{6}$$

- Broadening time:

$$t_{broad} \sim \left(\frac{1}{\hat{q}\theta^2 L}\right)^{1/2} \tag{7}$$

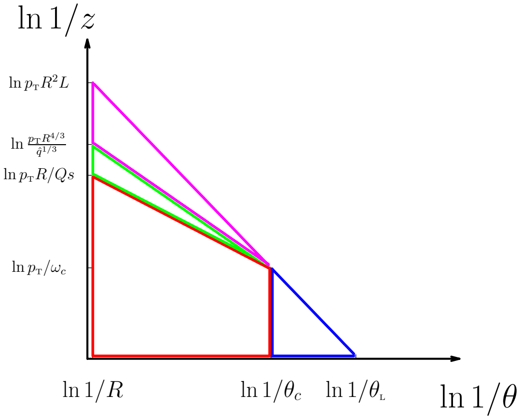
- Length of the medium: L.

The *real* formation time

$$\tau \lesssim min[t_f, t_d, t_{br}]$$

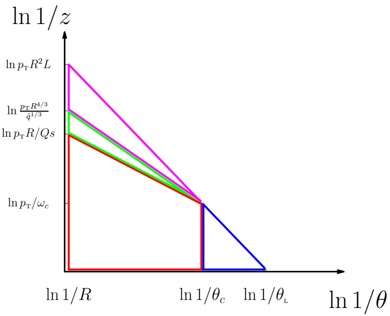
- The **real formation time** is governed by **the smallest** of the three **physical time scales** of the problem: either the kinematical formation time, the decoherence time or the broadening time.

The Lund diagram



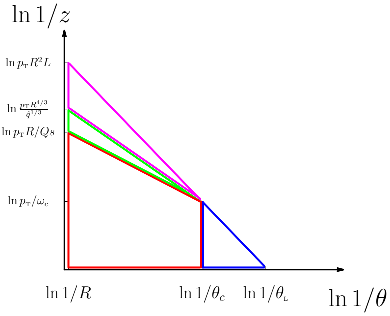
[Konrad Tywoniuk's talk]

Discussion of time-scales



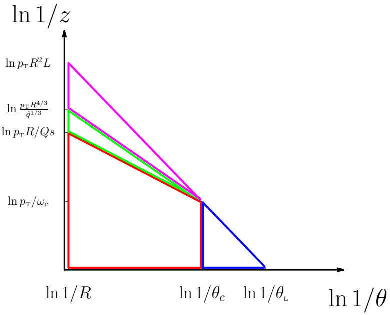
- (A.1) $t_f < t_{broad} < t_d < L$: particles decohere at a finite distance.

Discussion of time-scales



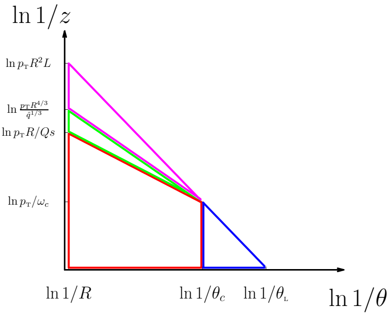
- (A.2) $t_{broad} < t_f < t_d < L$: medium effects.
- (A.3) $t_{broad} < t_d < t_f < L$: medium effects.

Discussion of time-scales



- (A.4) $t_f < L < t_d < t_{broad}$: the created partons will never decohere in color. Splittings should follow a vacuum emission pattern.

Discussion of time-scales



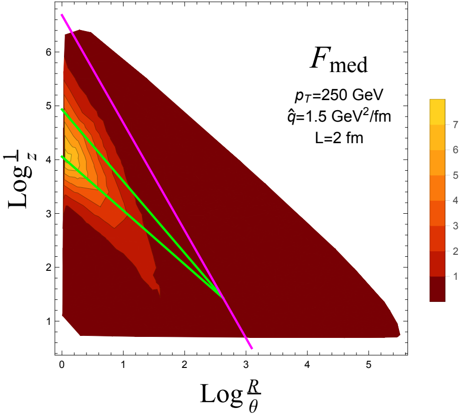
- (B) $t_f > L$: no medium modification is expected.

The medium modification factor

$$\frac{dI^{med}}{dz\ d\vec{p}^2} = \frac{dI^{vac}}{dz\ d\vec{p}^2}\left(1 + F_{med}\right) \tag{8}$$

- The medium modifications factor out into F_{med}.

Numerics: F_{med} in the Lund plane



Outlook

- Color coherence is essential to understand the jet constituents' energy loss (are they independent or not?).
- In spite of the singlet antenna limitations (eikonal propagation, zero formation time, only one splitting...), it is a very convenient *laboratory*.
- The general result of the singlet antenna is valid for the subsequent antennas in the multiple emissions case.
- The finite formation time scenario shows us an interesting theoretical guidance for MC.
- These computations go a step forward to obtain a complete description of a QCD cascade.

Thanks for your attention