

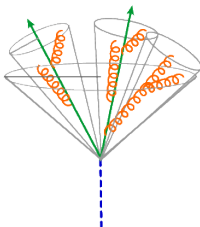
Coherence effects in multiple medium-induced radiation

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Motivation: jet substructure



- Jets have substructure:
 - Dynamics of an energetic parton in matter.
 - 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.
 - Color coherence phenomenon in original antenna setups.
- How can we combine it?
- 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.

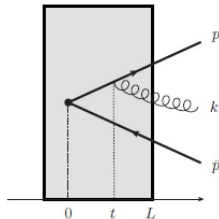
$$\mathcal{M}_{q\bar{q}g} = \text{Diagram 1} + \text{Diagram 2}$$

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

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

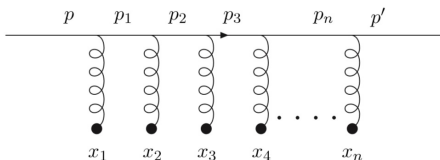
Color coherence in a medium

- 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

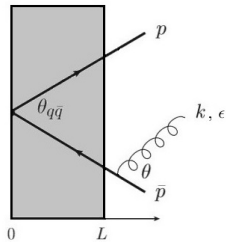
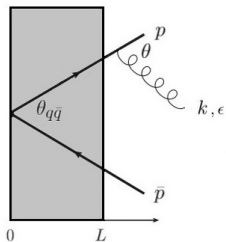


$$W(\vec{x}) = \mathcal{P} \exp \left[ig \int dx_+ A_-(x_+, \vec{x}) \right]$$

- 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 take a very soft gluon $\omega \rightarrow 0$ (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} .

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

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

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

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

The resulting spectrum

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

$$\left\{ \begin{array}{l} \Delta_{med} \rightarrow 0 : dN \sim R_q + R_{\bar{q}} - 2\mathcal{J} \\ \quad \boxed{\text{Dilute medium : coherence (angular ordering)}} \\ \\ \Delta_{med} \rightarrow 1 : dN \sim R_q + R_{\bar{q}} \\ \quad \boxed{\text{Opaque medium : decoherence (two independent emitters)}} \end{array} \right.$$

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

Main limitations

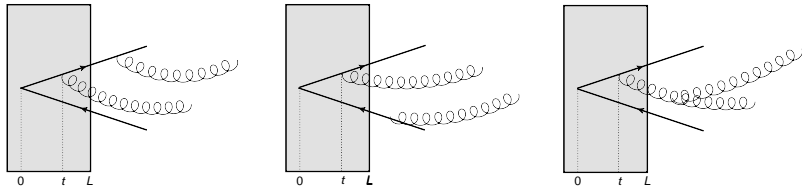
- We have to deal with more realistic settings:
 - Non-eikonal antenna.
 - Multiple emissions.
 - Finite formation time.

Main limitations

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 - Non-eikonal antenna.
 - **Multiple emissions.**
 - Finite formation time.

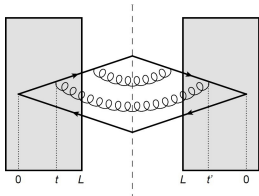
Multiple emissions

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

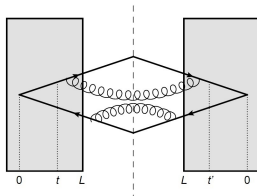


[In preparation: Factorization of color coherence for gluon radiation of a double QCD antenna, Fabio Domínguez, Carlos A. Salgado and Víctor Vila]

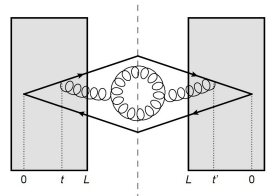
Direct terms



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



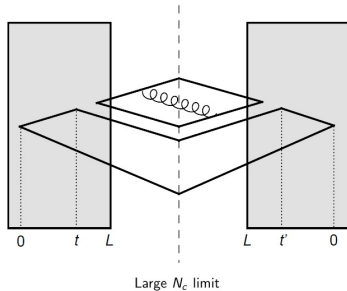
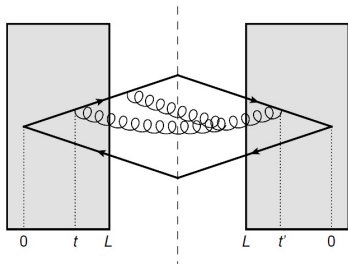
$$|\mathcal{M}_2|^2 \propto C_F^2$$



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

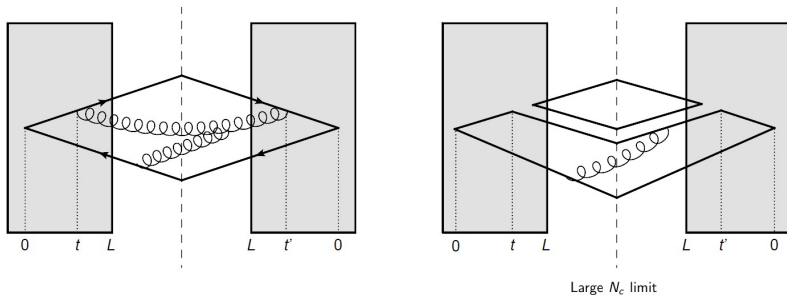
- The direct terms are proportional to a color factor, i.e., no medium effects appear.

Interference terms



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

Interference terms



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

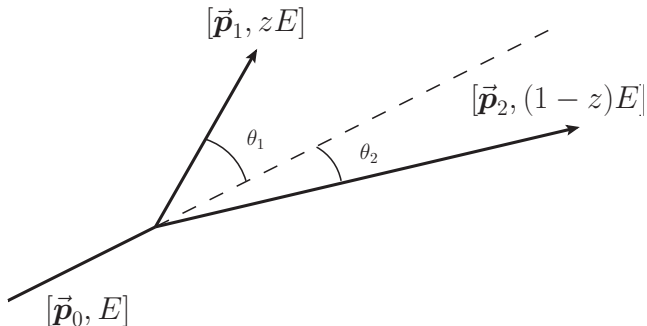
Multiple emissions summary

- 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

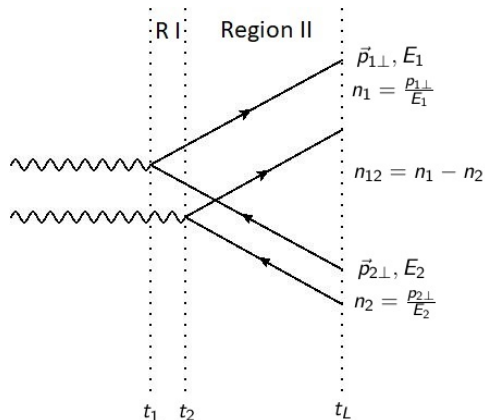
- We have to deal with more realistic settings:
 - Non-eikonal antenna.
 - Multiple emissions.
 - **Finite formation time.**

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]

Finite formation time antenna



Finite formation time antenna

- **Region I:**

- q and \bar{q} phases: $\exp\left\{i\frac{p_{T\perp}^2}{2E_i}(t_2 - t_1)\right\}$.
- Average of the Wilson lines: $\exp\left\{-\frac{1}{12}\hat{q}n_{12}^2(t_2 - t_1)^3\right\}$.

- **Region II:**

- Average of a trace of four Wilson lines:

$$Q(t_L, t_2) = \frac{1}{N_c} \left\langle \text{Tr} \left[W_1(t_L, t_2) W_2^\dagger(t_L, t_2) W_2(t_L, t_2) W_1^\dagger(t_L, t_2) \right] \right\rangle$$

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

The time-scales

- Kinematical formation time:

$$t_f = \frac{z(1-z)E}{\bar{p}^2} \quad (1)$$

- Decoherence time:

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

- Broadening time:

$$t_{\text{broad}} \sim \left(\frac{1}{\hat{q}\theta^2 L} \right)^{1/2} \quad (3)$$

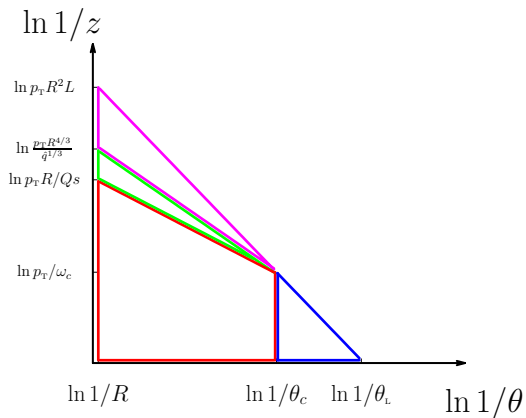
- Length of the medium: L .

The *real* formation time

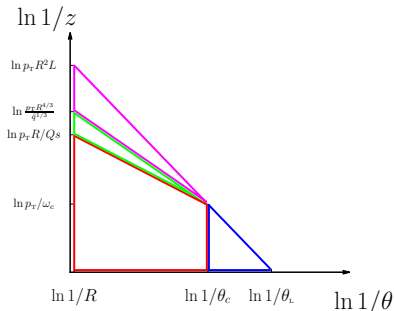
$$\tau \lesssim \min[t_f, t_d, t_{br}]$$

- 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

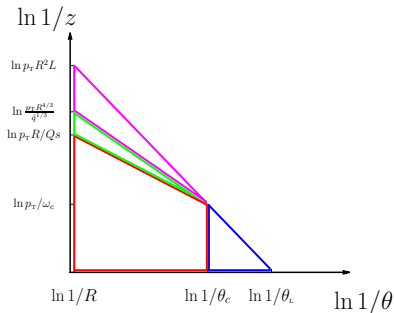


Discussion of time-scales



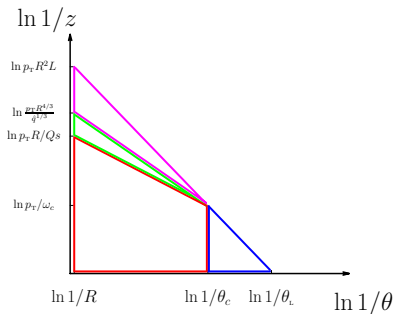
- (A.1) $t_f < t_{broad} < t_d < L$: particles decohere at a finite distance.

Discussion of time-scales



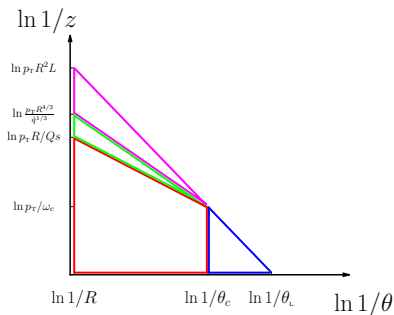
- (A.2) $t_{broad} < t_f < t_d < L$: medium effects.
- (A.3) $t_{broad} < t_d < t_f < L$: medium effects.

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



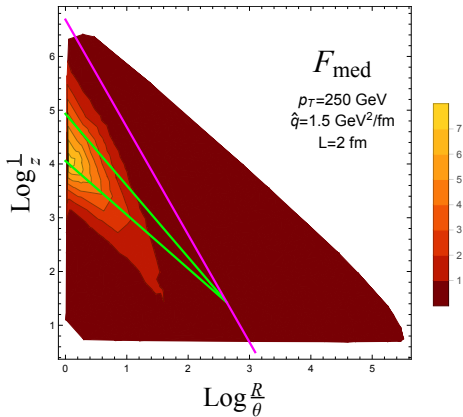
- (B) $t_f > L$: no medium modification is expected.

The medium modification factor

$$\frac{dI^{med}}{dz d\vec{p}^2} = \frac{dI^{vac}}{dz d\vec{p}^2} (1 + F_{med}) \quad (4)$$

- 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