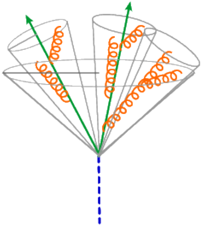
Coherence effects in a QCD parton cascade

Víctor Vila

Universidade de Santiago de Compostela

8th International Conference on Physics Opportunities at an ElecTron-Ion-Collider - POETIC 8, Regensburg - 19-22/03/2018

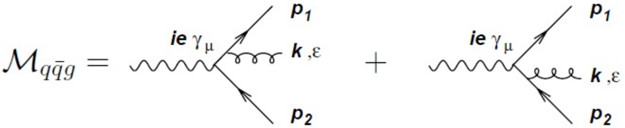
Motivation: jet substructure



- Ideal techniques for heavy ion collisions.
- More direct access to the underlying dynamics:
    - QGP properties.
    - Energy loss.
    - Coherence.

Color coherence in vacuum

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

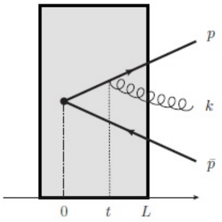


$$dN = \frac{d\omega}{\omega}\frac{d\Omega}{2\pi}\frac{\alpha_s C_F}{2\pi}\left[R_q + R_{\bar{q}} - 2\mathcal{J}\right]$$

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

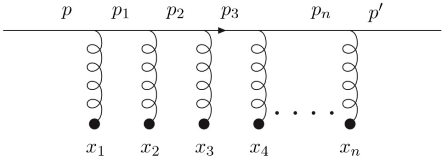
Color coherence in a medium

- 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

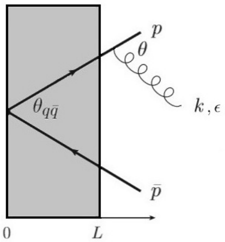


$$W(\vec{x}) = \mathcal{P}\ exp\left[ig \int dx_+ A_-(x_+, \vec{x})\right]$$

- 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 $\mathcal{S}$.

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

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

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

- 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 diluite/dense medium, Yacine Mehtar-Tani, Carlos A. Salgado and Konrad Tywoniuk]

Main limitations

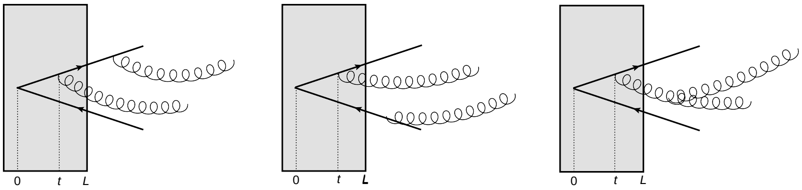
- We have to deal with more realistic settings:
    - Non-eikonal antenna.
    - Multiple emissions.
    - Finite formation time.

Main limitations

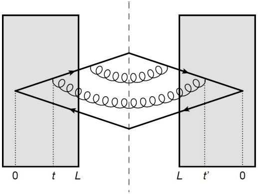
- We have to deal with more realistic settings:
    - Non-eikonal antenna.
    - **Multiple emissions.**
    - Finite formation time.

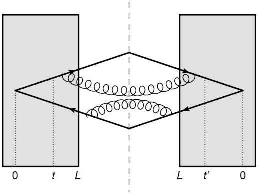
Multiple emissions

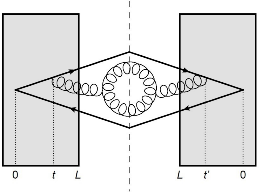
- The antenna provides a simple and intuitive picture.
- Does it hold for more than two emitters?



Direct terms



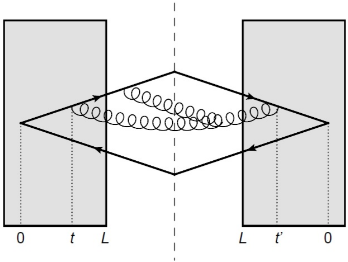


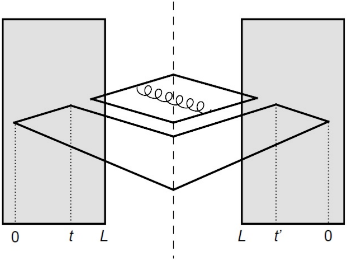


$$|\mathcal{M}_1|^2 \propto C_F^2 \qquad |\mathcal{M}_2|^2 \propto C_F^2 \qquad |\mathcal{M}_3|^2 \propto N_c \; C_F^2$$

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

Interference terms

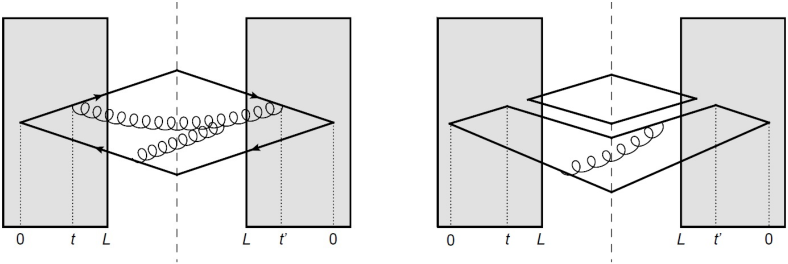




Large N_c limit

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

Interference terms



Large N_c limit

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

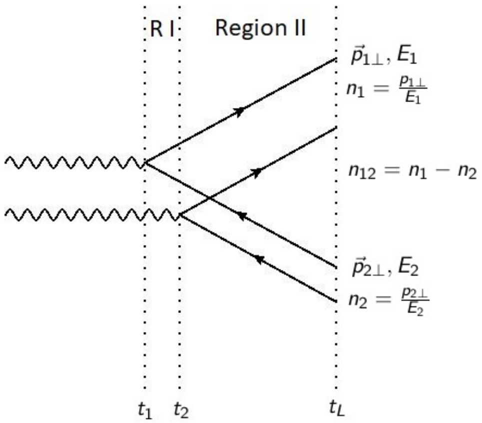
Multiple emissions results

- 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.**

Finite formation time antenna



Finite formation time antenna

- **Region I**:
  - q and $\bar{q}$ phases: $exp\left\{ i\frac{p_{i\perp}^2}{2E_i}(t_2 - t_1)\right\}$.
  - Average of the Wilson lines: $exp\left\{ -\frac{1}{12}\hat{q}n_{12}^2(t_2 - t_1)^3\right\}$.
  - Competing process between t_f and t_d:
    - $t_f << t_d$: vacuum propagation.
    - $t_f >> t_d$: medium effects.

Finite formation time antenna

- **Region II**:

  - All phases cancel out.

  - Average of a trace of four Wilson lines:

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

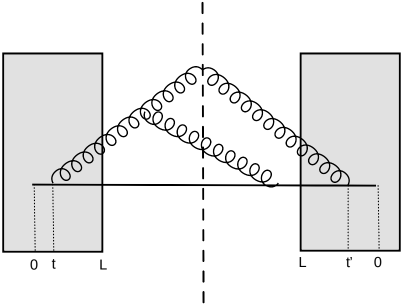
$$Q(t_L, t_2) = e^{-\frac{1}{4}\hat{q}(n_1^2+n_2^2)(t_2-t_1)^2(t_L-t_2)}\left[1-\hat{q}(n_1\cdot n_2)(t_2-t_1)^2\int_{t_2}^{t_L} dt_3\ e^{-\frac{1}{6}n_{12}^2(t_3-t_2)^3}\right]$$

- Competing process between p_T and Q_s.

Finite formation time antenna

- We have studied a singlet antenna with **short formation time** considering separately two different regions:
  - **Region I** contains information about **local scales** (t_f vs. t_d).
  - **Region II** compares **global scales** (p_T vs. Q_s).
- Both **regions are well connected**.
- We are studying the details of the relation between these regions to obtain general results about finite formation time setups.

A hard quark propagating through a medium



$$\propto \frac{1}{N_c\,(N_c^2-1)} \left\langle W^{ai}(\vec{0})\, W^{ai}(\vec{r}_3) \right\rangle_{(t,t')} \left\langle f^{ijc}\, f^{\alpha bz}\, W^{i\alpha}(\vec{r}_3)\, W^{jb}(\vec{0})\, W^{\dagger zc}(\vec{r}_3^{\,\prime}) \right\rangle_{(t',L)}$$

Summary

- HIC are key to go further in the study of the QCD matter formed in the collisions.
- 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.
- Finite formation time setups showed us some interesting preliminary results about the evolution of these systems.
- These computations go a step forward to obtain a complete description of a QCD cascade.

Thanks for your attention