# Jet multiplicities in a dense QCD medium

P. Caucal, E. Iancu, A.H. Mueller and G. Soyez

Institut de Physique Théorique, CEA, France

January 7, 2018 at JETSCAPE workshop

# Motivations and goal of the talk

- Jet evolution in a dense medium : medium induced emissions versus vacuum-like emissions. How can we include both mechanisms ?
- The simplest possible approximation in parton shower : keep all **leading double-logarithm** (DL) terms and resum them.
- Within this approximation, the time scales in the evolution **factorize**.

# Where does double-logarithmic phase space come from ?

## Vacuum-like emissions inside the medium

- Bremsstrahlung $\Longrightarrow$ energy and angle logarithms. Formation time due to the virtuality of the parent parton : $t_{vac} \sim \omega/k_\perp^2 \sim 1/(\omega\theta^2)$.
- BDMPS-Z (Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov 1996–97) Medium-induced formation time and broadening characteristic time scale : $t_f \sim \sqrt{\omega/\hat{q}}$.

If $t_{vac} \ll t_f$ : emission triggered by the virtuality and not yet affected by the momentum broadening.
$\Longrightarrow$ **double-logarithmic enhancement of the probability**.

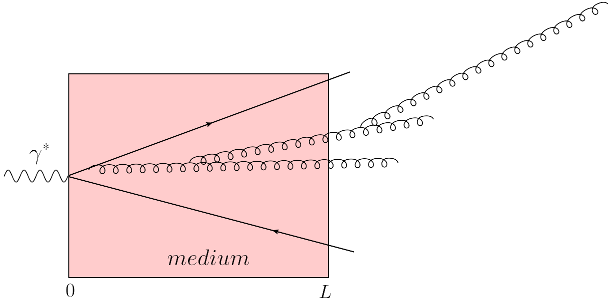
### Equivalent conditions

- $k_\perp^2 \gg k_f^2 = \sqrt{\hat{q}\omega}$
- $\omega \gg (\hat{q}/\theta^4)^{1/3} \equiv \omega_0(\theta)$

# Where does double-logarithmic phase space come from ?

## Vacuum-like emissions outside the medium

- $t_{vac} \geq L \Longrightarrow$ vacuum-like emission outside the medium triggered by the virtuality of the parent parton.
- In terms of energy : $\omega \leq 1/(L\theta^2)$.



# How to resum these double logarithms in the medium ?

## Iteration of vacuum-like emissions

### Large $N_c$ limit

Emission of a soft gluon by an antenna $\Leftrightarrow$ splitting of the parent antenna into two daughter antennae.

### Decoherence time

- In the medium, an antenna loses its color coherence after a time $t_{coh} = 1/(\hat{q}\theta^2_{q\bar{q}})^{1/3}$.

  (Mahtar-Tani, Salgado, Tywoniuk, 2010-11 ; Casalderrey-Solana, Iancu, 2011)
- Important angular scale, $\theta_c^2$ such that $t_{coh}(\theta_c^2) = L$.
- Reminder : color coherence is responsible for **angular ordering** in vacuum cascades.

# How to resum these double logarithms in the medium ?

In the leading double-logarithmic approximation, **successive in-medium vacuum-like emissions form angular-ordered cascades**.

## Proof

- First case : $t_{vac}(\omega_i, \theta_i^2) \leq t_{coh}(\omega_{i-1}, \theta_{i-1}^2)$, the parent antenna did not lose its coherence during the time required by the next antenna to be formed $\Rightarrow$ $\theta_i^2 \ll \theta_{i-1}^2$.
- Second case : $t_{vac}(\omega_i, \theta_i^2) \geq t_{coh}(\omega_{i-1}, \theta_{i-1}^2)$. This inequality can be rewritten $\omega_i \leq (\hat{q}/\theta_i^4)^{1/3} \times \left(\frac{\theta_{i-1}^2}{\theta_i^2}\right)^{1/3} = \omega_0(\theta_i) \times \left(\frac{\theta_{i-1}^2}{\theta_i^2}\right)^{1/3}$ Then, necessarily $\theta_i^2 \leq \theta_{i-1}^2$, otherwise the condition $t_{vac}(\omega_i, \theta_i^2) \leq t_f(\omega_i, \theta_i^2)$ is not fulfilled.

# Consequences on the emissions outside the medium

- The precedent proof does **not** apply if the antenna $i-1$ is the **last inside the medium**.
- In that case, the formation time of the next antenna is larger than $L$.

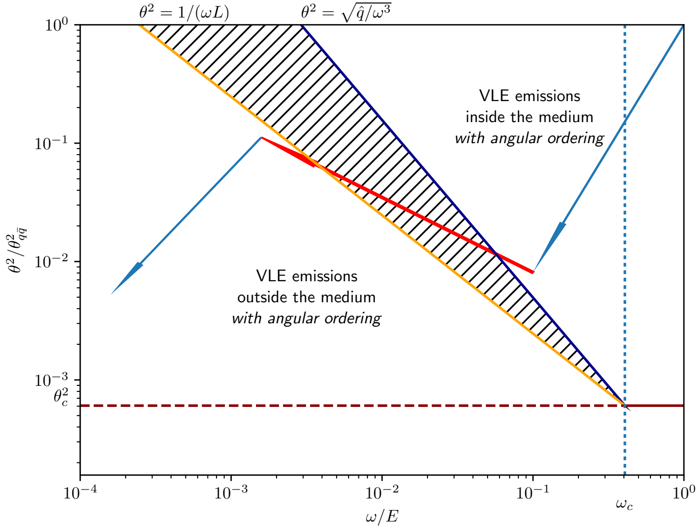
## Last emission inside the medium

- If $\theta^2_{i-1} \leq \theta^2_c$ : the decoherence time is also larger than $L$ $\Rightarrow$ angular ordering is preserved.
- If $\theta^2_{i-1} \geq \theta^2_c$ : the antenna has lost its coherence during the formation time of the next antenna $\Rightarrow$ **no constraint** on the angle of the next antenna.

(Y. Mehtar-Tani, K. Tywoniuk, Physics Letters B 744, 2015)

# Phase space

## Long story short



# What about the energy loss ?

Energy loss is **negligible** for any parton of the cascade inside the medium (except for the last one)

- $\omega_{loss} \sim \hat{q}t^2$ energy of the hardest medium induced emission that can develop during $t$.
- By the inequality $t_{vac}(\omega_i, \theta_i^2) \ll t_f(\omega_i, \theta_i^2)$, one finds that $\omega_{loss} \ll \omega_i$.

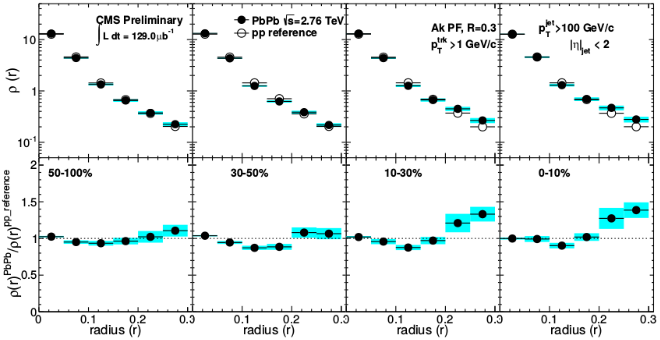
However...

- Energy loss is not negligible for the last antenna inside the medium since it will cross the medium along a distance of order $L$.
- Medium induced gluon cascades are important for large angle radiations.

# Experimental data

## CMS data (CMS PAS HIN-12-013, CMS collaboration)

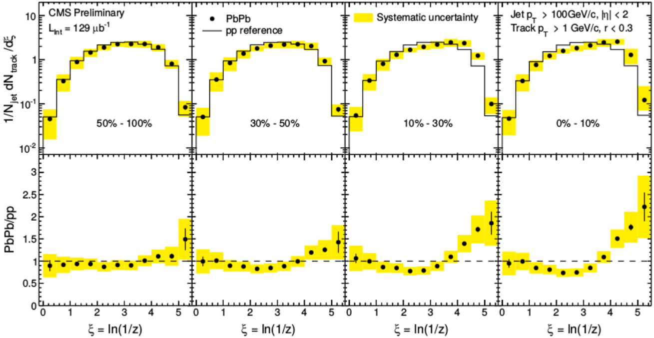
Differential jet shapes for different centrality bins for jets with $p_T \geq 100$ GeV/c in PbPb collisions.



# Experimental data

## CMS data (CMS PAS HIN-12-013, CMS collaboration)

Fragmentation function in bins of increasing centrality for jets with $p_T \geq 100$ GeV/c in PbPb collisions.



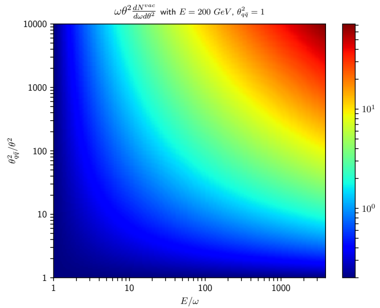

*Similar results by the ATLAS collaboration* *(Physics Letters B 739 (2014) 320–342)*

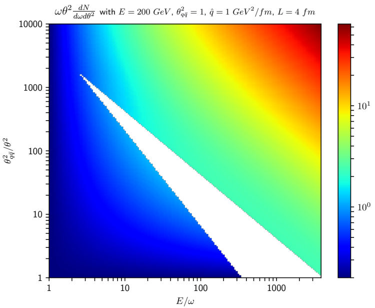
# Preliminary analytical results

Vacuum DLA cascades :

$$\omega\theta^2 \frac{dN^{vac}}{d\omega d\theta^2} = \bar{\alpha} I_0\left(2\sqrt{\bar{\alpha}\log(E/\omega)\log(\theta_{q\bar{q}}^2/\theta^2)}\right)$$

We have similar analytical formulae for DLA cascades with medium constraints.

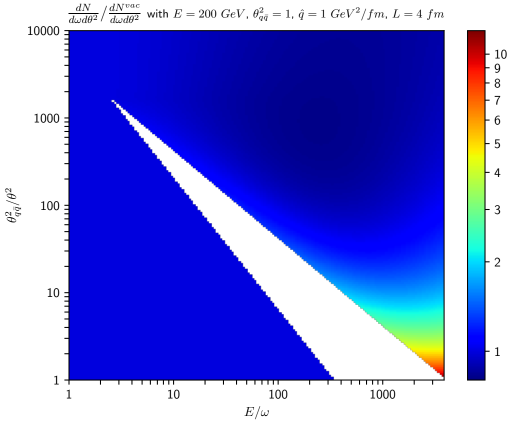


# Preliminary analytical results

## Qualitative behavior, in agreement with data

- Enhancement of the multiplicity at large angles inside the jet and small energy fractions.
- Small suppression at intermediate energy fractions.



# Conclusion

## In perspective

- Calculate the fragmentation function in order to compare more precisely our results with data.
- Go beyond DLA by including full splitting functions (hence, energy conservation) for the VLE's.
- Include medium-induced radiation not only as a constraint on the VLE's $\Longrightarrow$ energy loss.

Thank you for listening !