

Jet fragmentation in a dense QCD medium

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

Institut de Physique Théorique, CEA

October 4, 2018 at the **Hard Probes 2018** conference,
Aix-Les-Bains, France



Jet fragmentation
in a dense QCD
medium

Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion

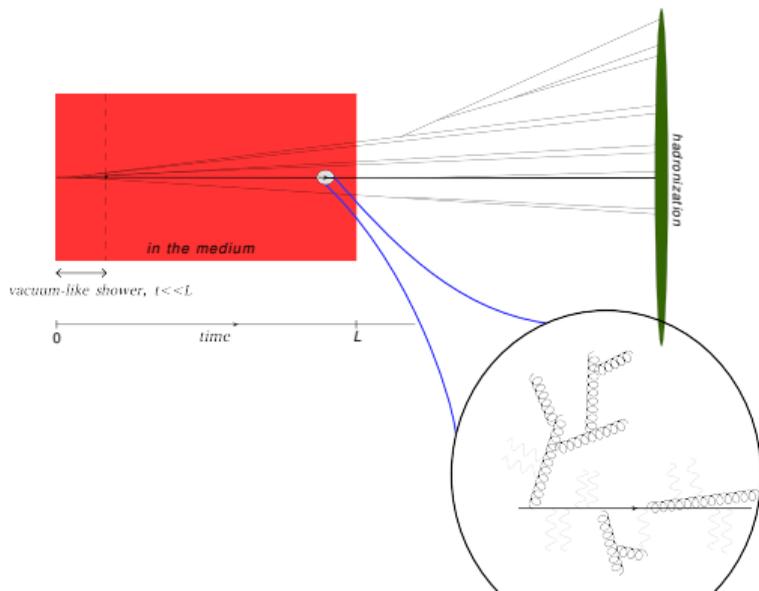
- ▶ Jets are important probes of the quark-gluon plasma (QGP) produced in heavy-ions collisions at LHC or at RHIC.

- ▶ Understanding observables such that the jet R_{AA} or the jet fragmentation function helps to better characterize the QGP.

Important messages

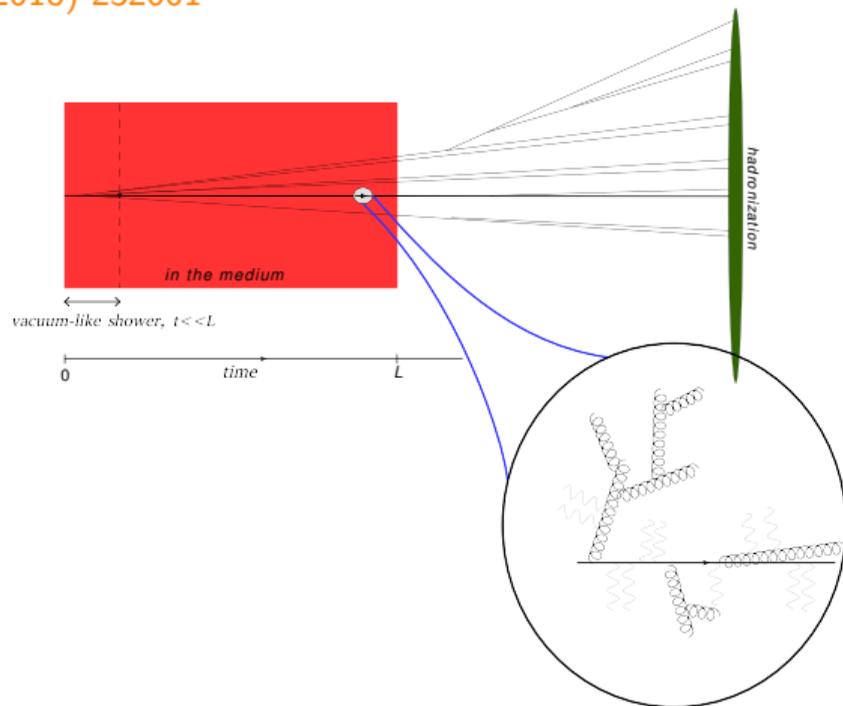
Phys.Rev.Lett. 120 (2018) 232001

- Within the double-log approximation of **perturbative QCD**, the evolution of a jet **factorizes** into three steps:
- one *vacuum-like shower* inside the medium,
 - followed by *medium-induced mini-jets* from by previous sources;
 - finally, a *vacuum-like shower* outside the medium.



Important messages

Phys.Rev.Lett. 120 (2018) 232001



- ▶ Because of **decoherence** induced by the medium, the first emission outside the medium has no angular constraint. This reopening of the phase space leads to an increase of soft particles inside the jet.

Jet fragmentation
in a dense QCD
medium

Introduction

Jets in the vacuum
at DLA

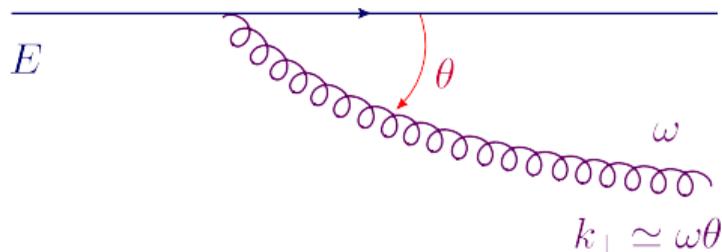
Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion

Bremsstrahlung spectrum

- ▶ Logarithmic enhancement for soft and collinear emissions.



$$d\mathcal{P} \simeq \frac{\alpha_s C_R}{\pi} \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

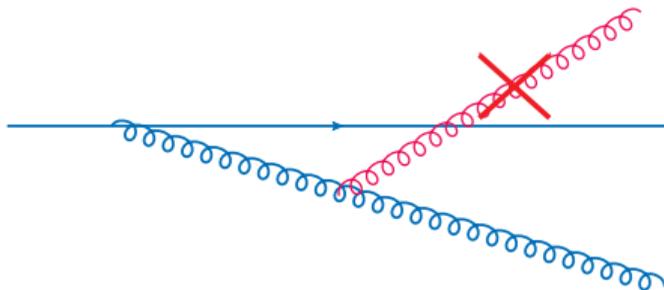
- ▶ Formation time due to the virtuality $\simeq \omega\theta^2$ of the parent parton:

$$t_{\text{vac}} \sim \omega/k_{\perp}^2 \sim 1/(\omega\theta^2)$$

Iteration of Bremsstrahlung emissions

Angular ordering at DLA

Quantum color coherence implies angular ordering: a jet is described in terms of a **classical shower picture** with successive Bremsstrahlung emissions forming the Markov chains of independent elementary radiation events.



Phase space and evolution at DLA

Transverse momentum cut-off

Evolution is stopped by hadronisation: $k_{\perp}^2 \simeq \omega^2 \theta^2 > \Lambda_{\text{QCD}}^2$.

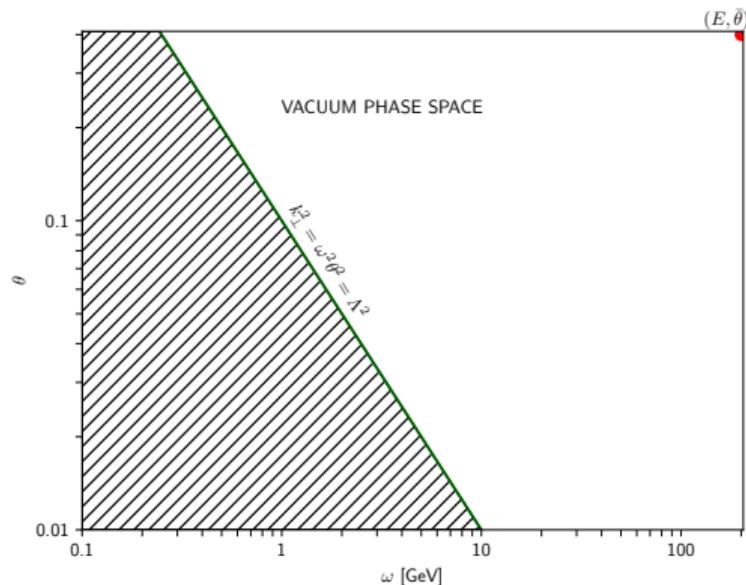
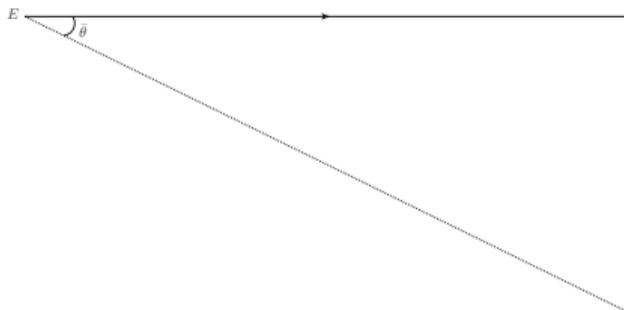
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion



Phase space and evolution at DLA

Transverse momentum cut-off

Evolution is stopped by hadronisation: $k_{\perp}^2 \simeq \omega^2 \theta^2 > \Lambda_{\text{QCD}}^2$.

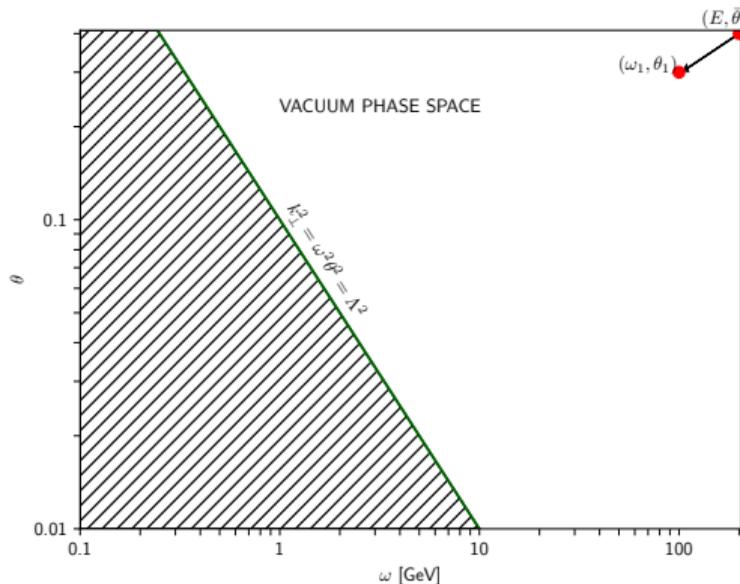
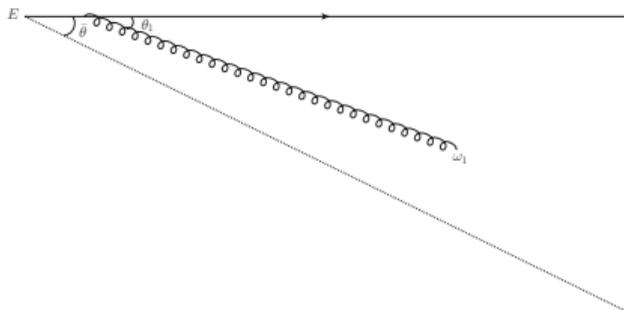
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion



Phase space and evolution at DLA

Transverse momentum cut-off

Evolution is stopped by hadronisation: $k_{\perp}^2 \simeq \omega^2 \theta^2 > \Lambda_{\text{QCD}}^2$.

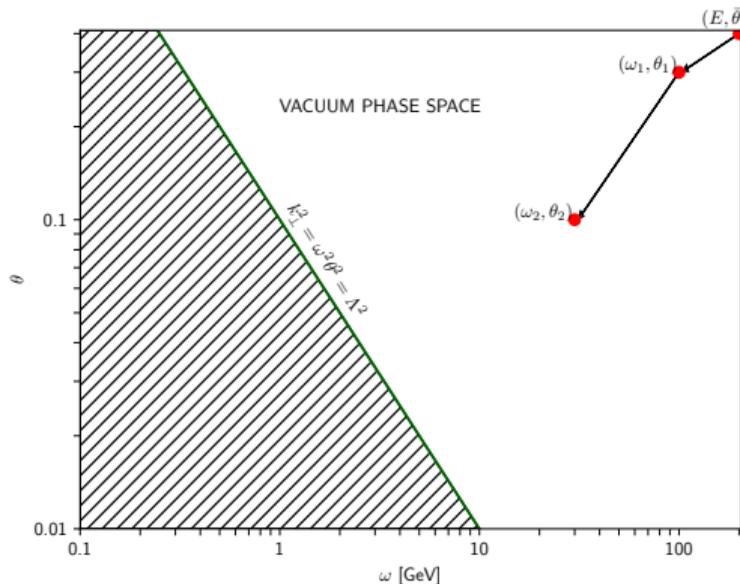
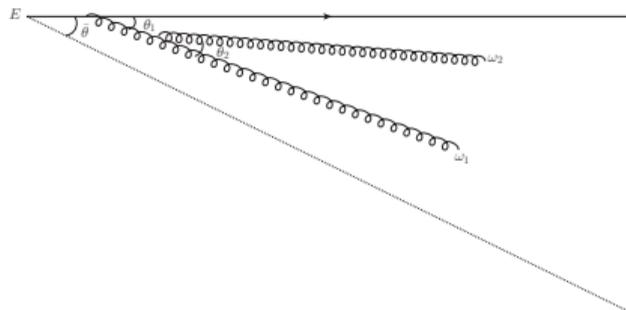
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion



Phase space and evolution at DLA

Transverse momentum cut-off

Evolution is stopped by hadronisation: $k_{\perp}^2 \simeq \omega^2 \theta^2 > \Lambda_{\text{QCD}}^2$.

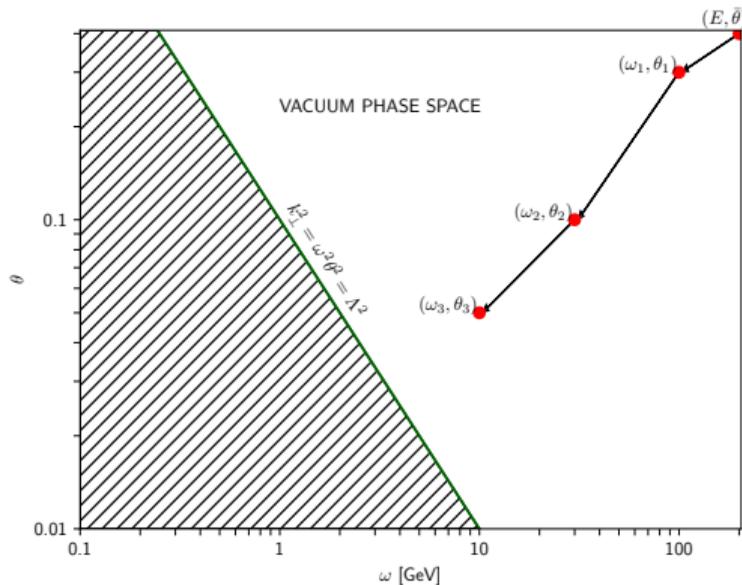
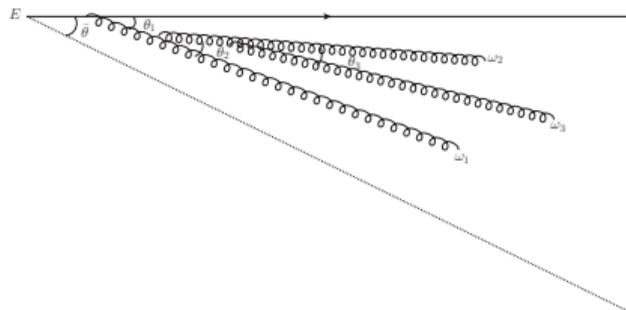
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

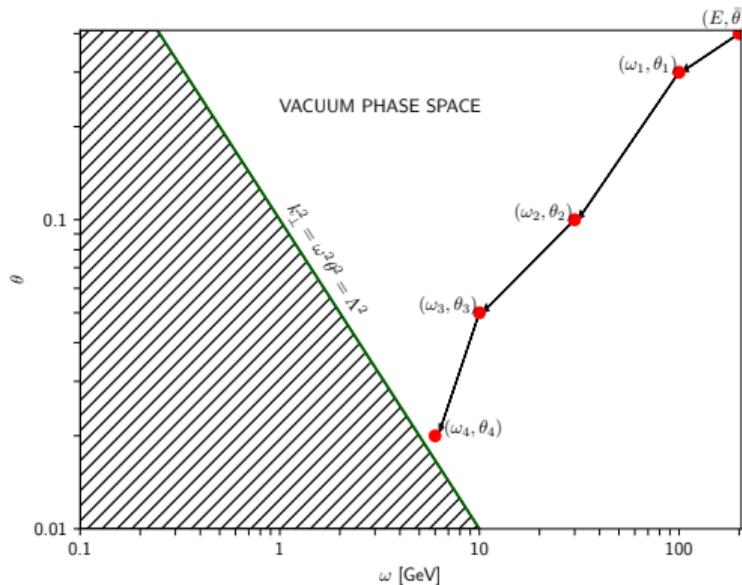
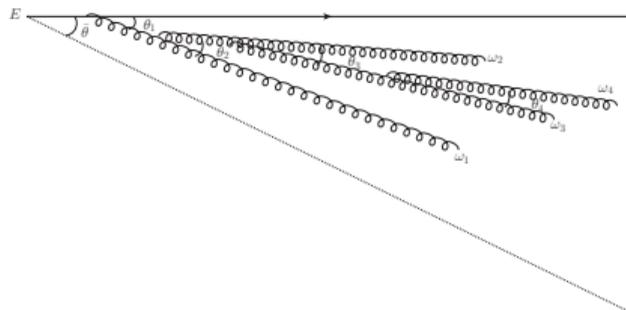
Conclusion



Phase space and evolution at DLA

Transverse momentum cut-off

Evolution is stopped by hadronisation: $k_{\perp}^2 \simeq \omega^2 \theta^2 > \Lambda_{\text{QCD}}^2$.

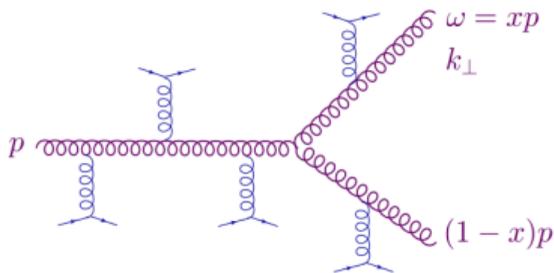


Description of the dense QCD medium

- ▶ Dense, weakly coupled quark-gluon plasma.
- ▶ Medium induced radiation “BDMPS-Z”:
 - formation time $t_{med} \gg$ mean free path.
 - multiple soft scattering during one emission.
- ▶ For present purposes, our medium is characterized by two parameters:
 - the jet quenching parameter \hat{q} :
 $\langle k_{\perp}^2 \rangle = \hat{q} \Delta t$, transverse momentum acquired by multiple collisions during time Δt .
 - the distance L travelled by the jet in the medium.

Medium induced radiation

- ▶ BDMPS-Z spectrum (Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov 1996–97)



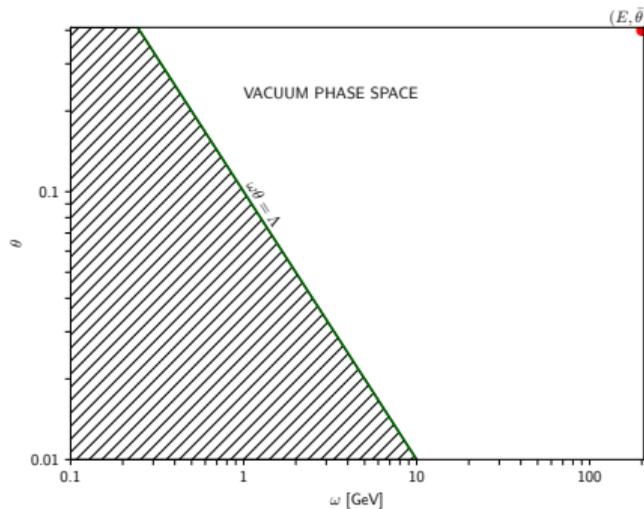
$$d\mathcal{P} \simeq \bar{\alpha}_s \frac{d\omega}{\omega} \frac{L}{t_{med}(\omega)} \simeq \bar{\alpha}_s L \sqrt{\frac{\hat{q}}{\omega^3}} d\omega$$

\implies No energy nor collinear log !

- ▶ Medium-induced formation time and broadening characteristic time scale:
 $t_{med} \sim \sqrt{\omega/\hat{q}}$.

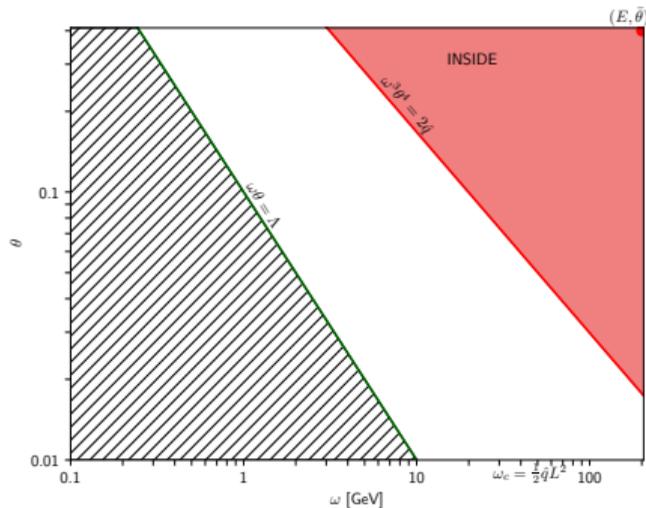
Phase space for vacuum-like emissions (VLEs)

- ▶ Let's start with the vacuum phase space.



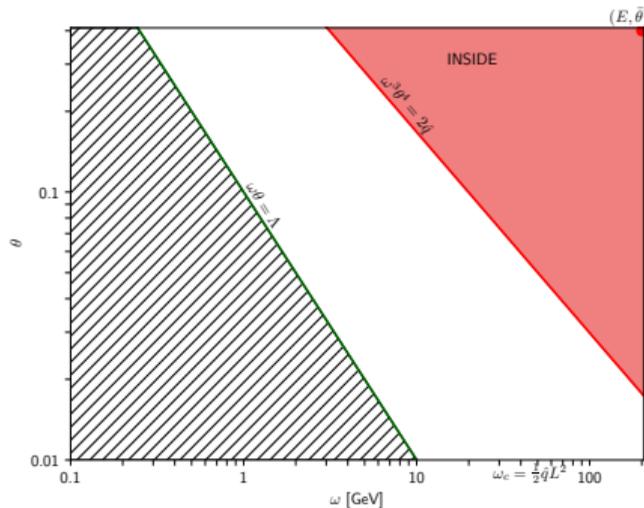
Phase space for vacuum-like emissions (VLEs)

- ▶ VLE in the medium: $t_{vac} \ll t_{med}$.



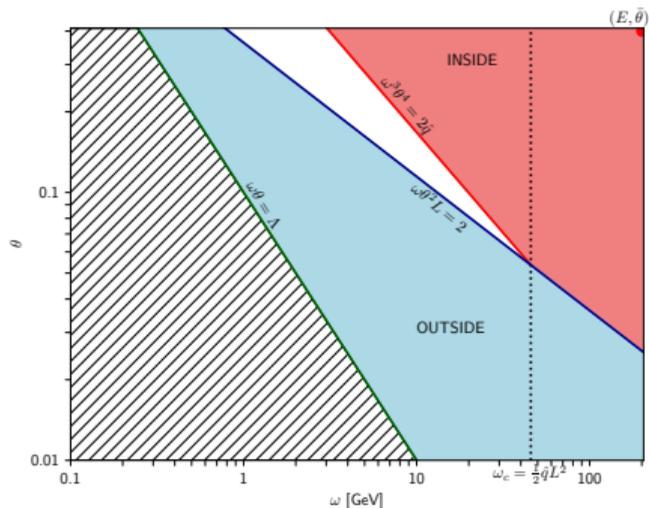
Phase space for vacuum-like emissions (VLEs)

- ▶ VLE in the medium: $t_{vac} \ll t_{med}$.
 - extends to N emissions strongly ordered in energy.
 - $t_{vac,1} \ll \dots \ll t_{vac,N} \ll t_{med,N} \ll \dots \ll t_{med,1}$.



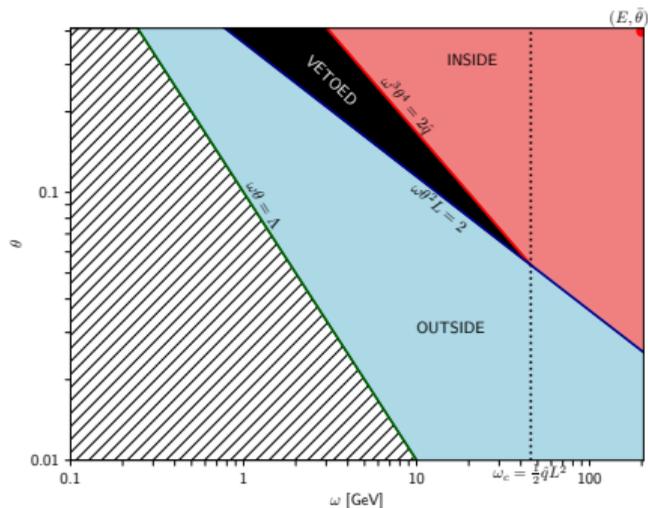
Phase space for vacuum-like emissions (VLEs)

- ▶ VLE in the medium: $t_{vac} \ll t_{med}$.
- ▶ VLE outside the medium: $t_{vac} \geq L$.



Phase space for vacuum-like emissions (VLEs)

- ▶ VLE in the medium: $t_{vac} \ll t_{med}$.
- ▶ VLE outside the medium: $t_{vac} \geq L$.



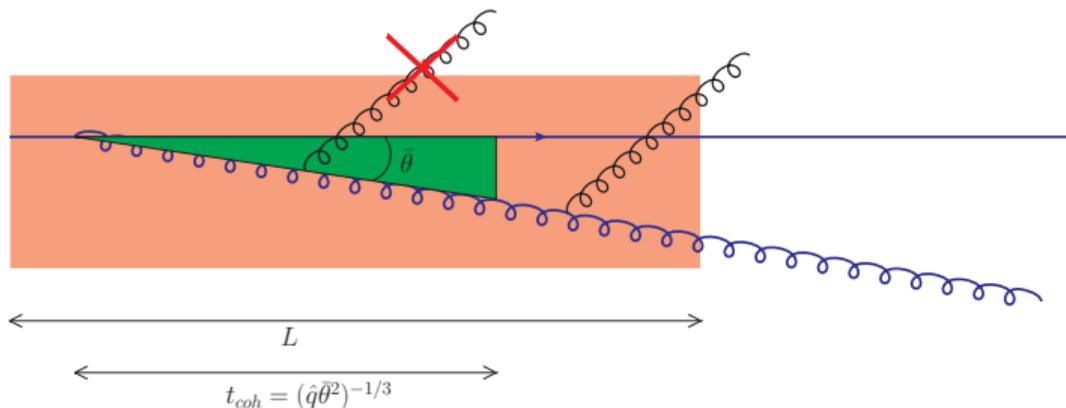
Vetoed region for VLEs

Reduction of the phase space available with respect to the vacuum case: emissions with $t_{med} \leq t_{vac} \leq L$ are forbidden.

(De)coherence in the medium

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

(Mahtar-Tani, Salgado, Tywoniuk, 2010-1 ; Casalderey-Solana, Iancu, 2011)



▶ However, **no consequences for VLEs in the medium** (PC, Iancu, Mueller, Soyez 2018)

- VLE ($t_{vac} \leq t_{med}$) at large angle ($\theta \geq \bar{\theta}$) $\Rightarrow t_{vac} \leq t_{coh}$.
- Large angle emissions forbidden by color coherence.
- Gluon cascades are **angular ordered** as in the vacuum.

▶ **DLA cascades develop also inside the medium.**

DLA phase space and evolution with QGP

Jet fragmentation
in a dense QCD
medium

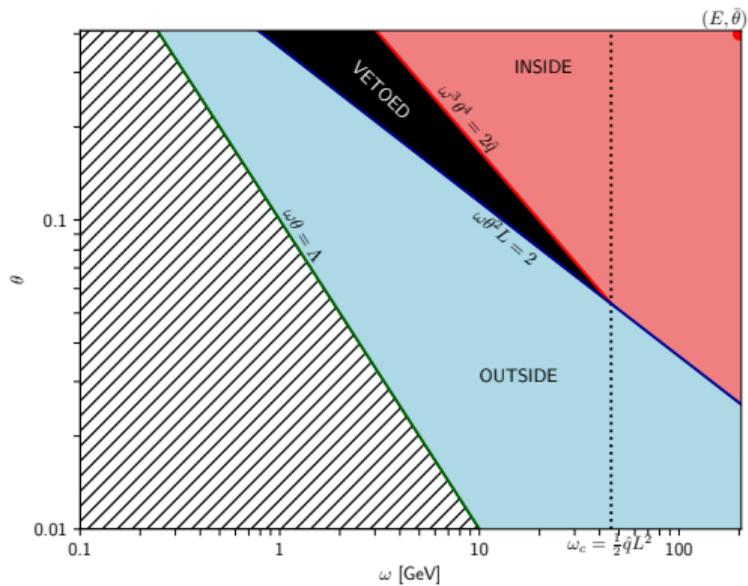
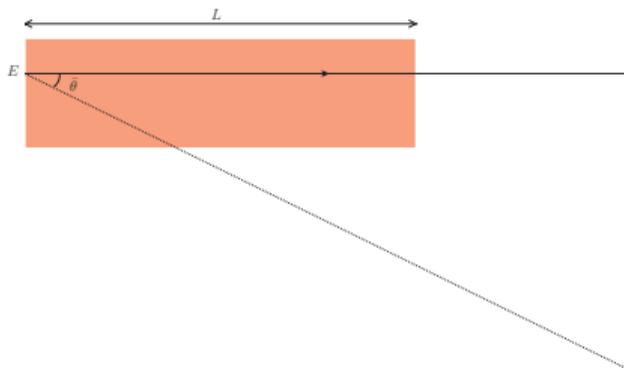
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion



DLA phase space and evolution with QGP

Jet fragmentation
in a dense QCD
medium

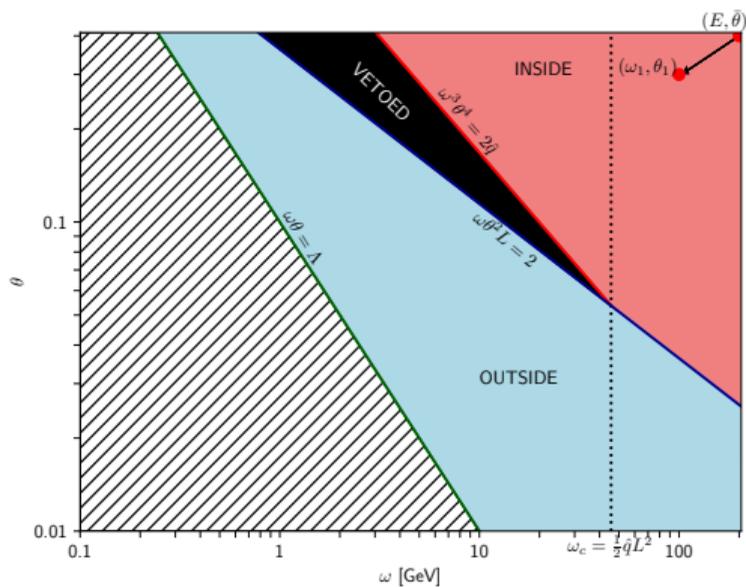
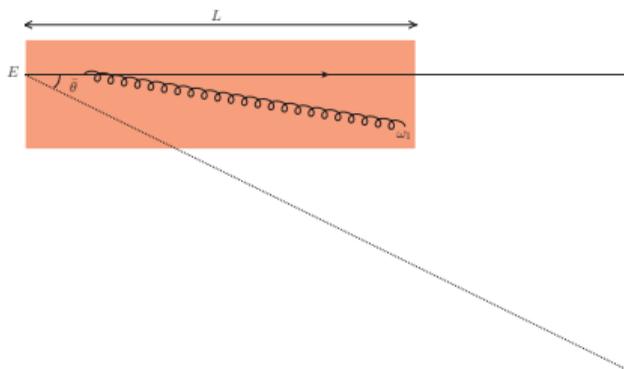
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion



DLA phase space and evolution with QGP

Jet fragmentation
in a dense QCD
medium

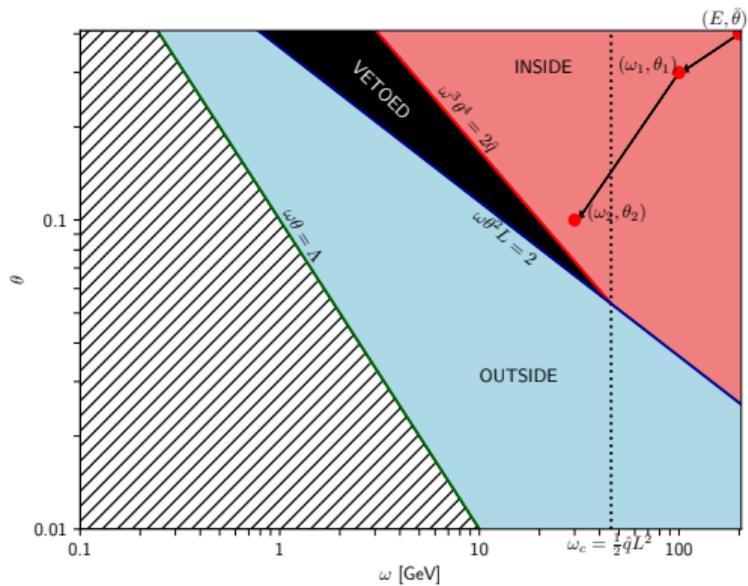
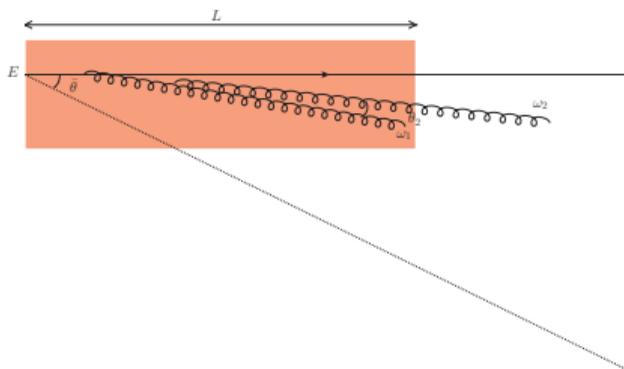
Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

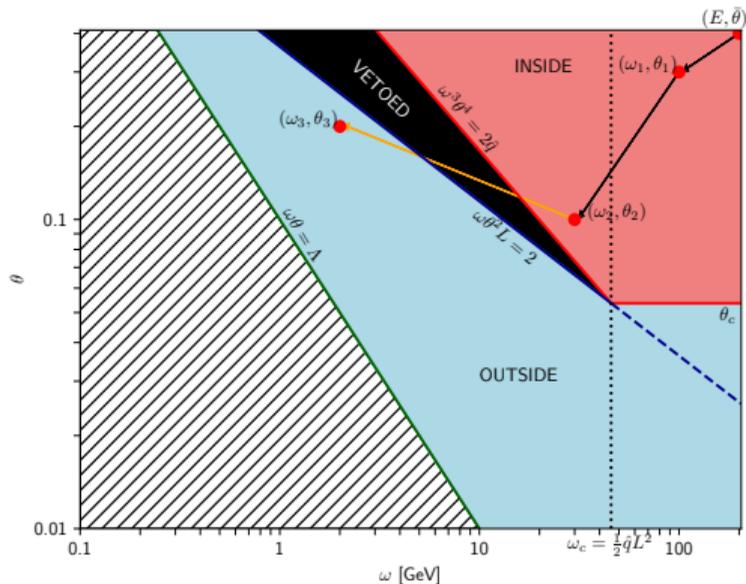
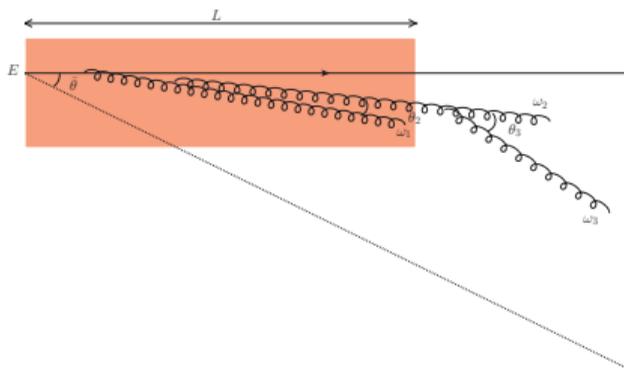
MonteCarlo results
beyond DLA

Conclusion



First emission outside the medium

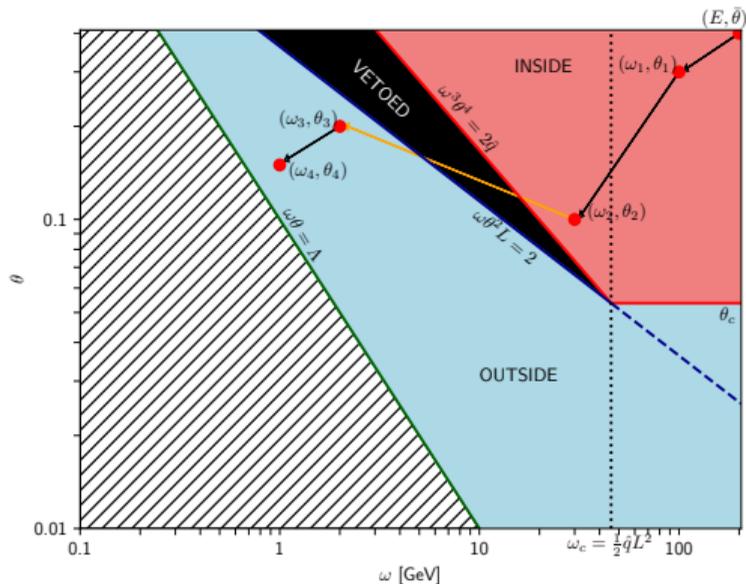
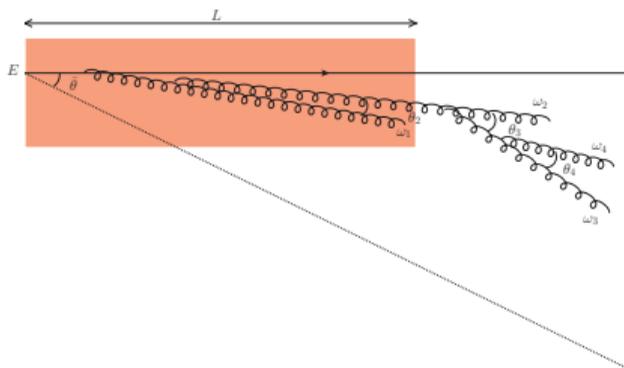
- ▶ $t_{vac} \geq L$: parent gluon has lost its color coherence
 \implies **no angular ordering**



- ▶ Critical angle θ_c such that $t_{coh}(\theta_c) = L$.

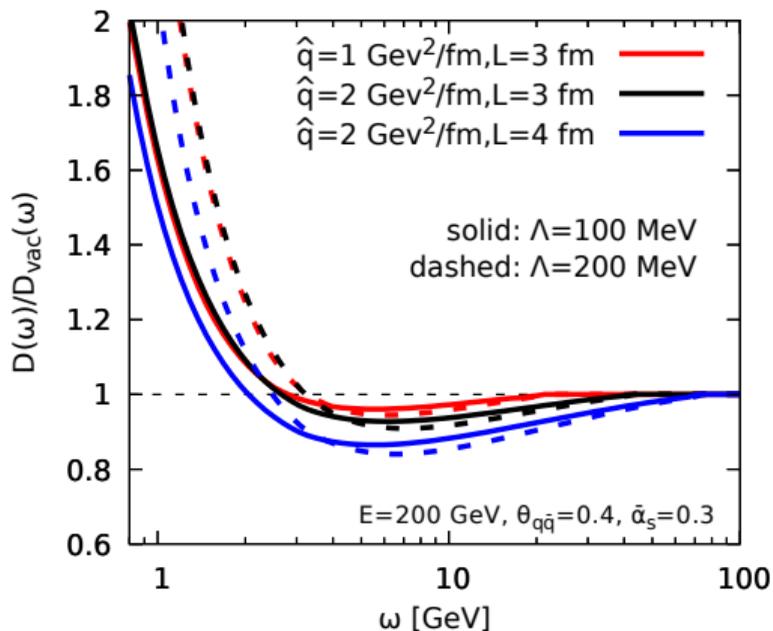
Parton shower outside the medium

- ▶ Subsequent emissions in the vacuum are angular ordered.



- ▶ Evolution is stopped by hadronisation.

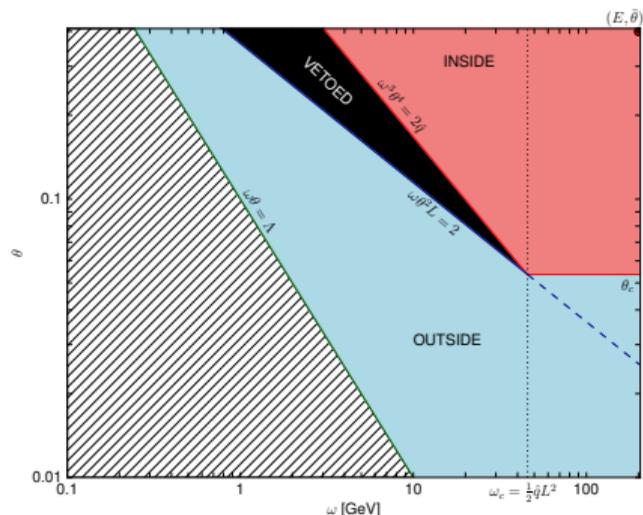
Analytical results for the DLA fragmentation function



Small z behavior

The enhancement at small energy is a consequence of **decoherence** and the re-opening of the **angular** phase space for the first VLE outside the medium.

MonteCarlo implementation



Convolution of three showers

Vacuum cascade in the medium (red region)

with full splitting function, running coupling and color representations



Medium-induced mini-jets with fixed coupling

(Blaizot, Iancu, Mehtar-Tani, 2013)



Vacuum cascade outside the medium
(blue region) after reopening the phase space

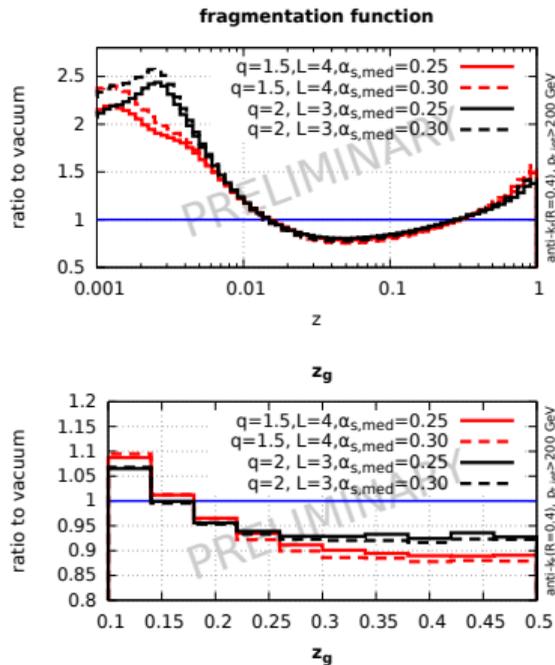
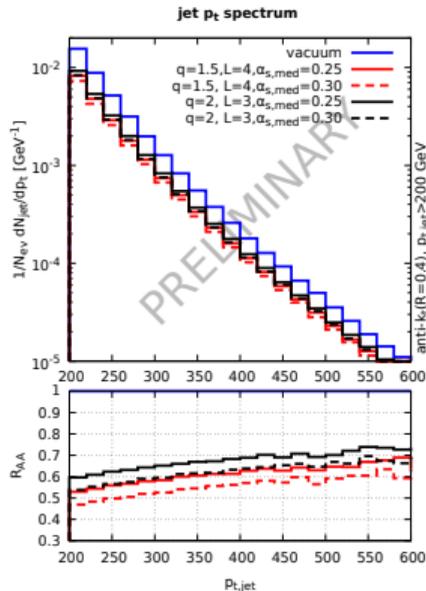
Pros

Based on pQCD
Any jet observables
Include hard matrix elements

Cons

Fixed medium length
No geometry/fluctuations
No hadrons

Preliminary results



- Good overall qualitative behavior w.r.t data.
- Saturation of R_{AA} due to vacuum-like fragmentation inside the medium.
- Enhancement at small z of the fragmentation function due to decoherence of the last emission inside the medium (vacuum-like or rare medium-induced still inside the jet).

Summary

- ▶ A pQCD approach of jet evolution leads to a factorization of vacuum-like emissions inside the medium from the medium-induced radiations.
- ▶ This picture is well-suited for MonteCarlo implementation which gives qualitatively good preliminary results.

In perspective

- ▶ Systematic applications to the phenomenology.
- ▶ Implementation of the medium expansion and geometry.
- ▶ Effects of hadronization.

Introduction

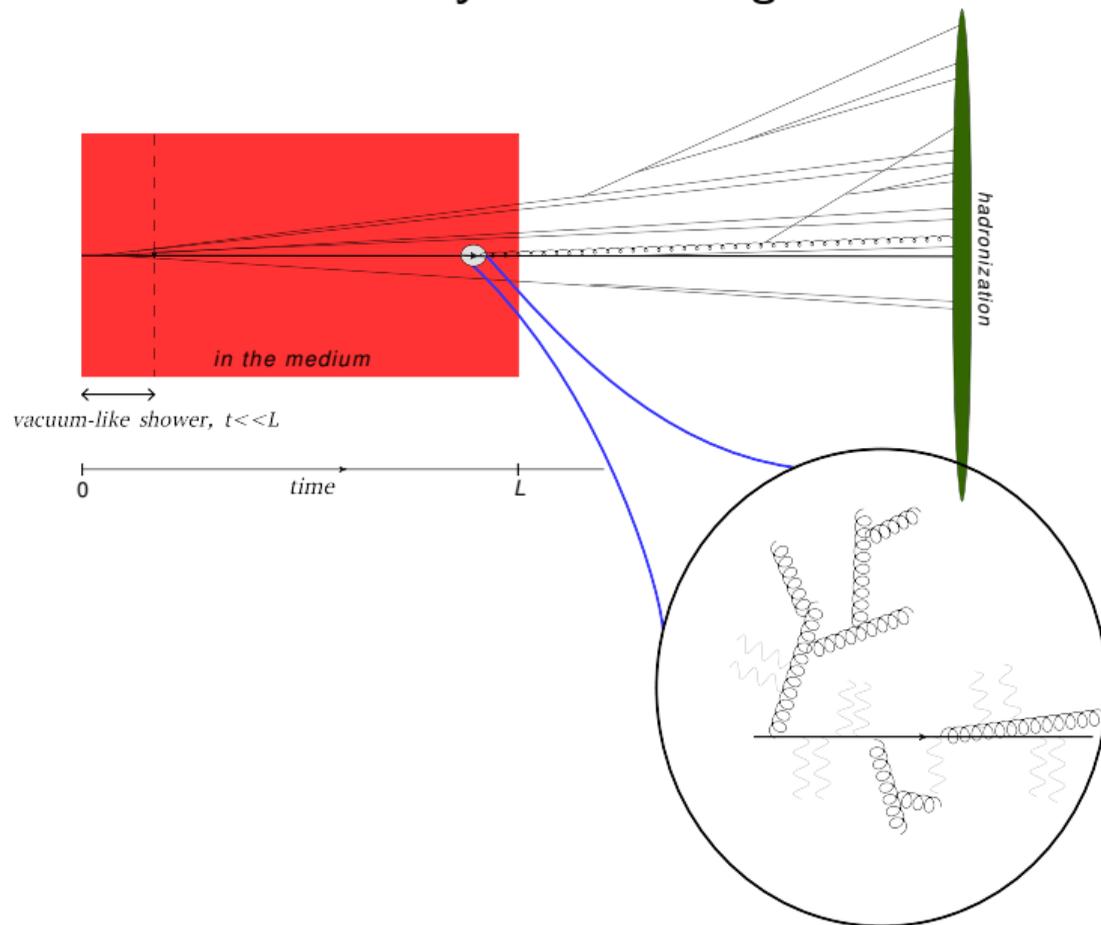
Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion

Thank you for listening !



Jet fragmentation
in a dense QCD
medium

Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion

Analytical study of jets at DLA

Double differential gluon distribution

$$T(\omega, \theta^2 | E, \theta_{q\bar{q}}^2) \equiv \omega \theta^2 \frac{d^2 N}{d\omega d\theta^2}$$

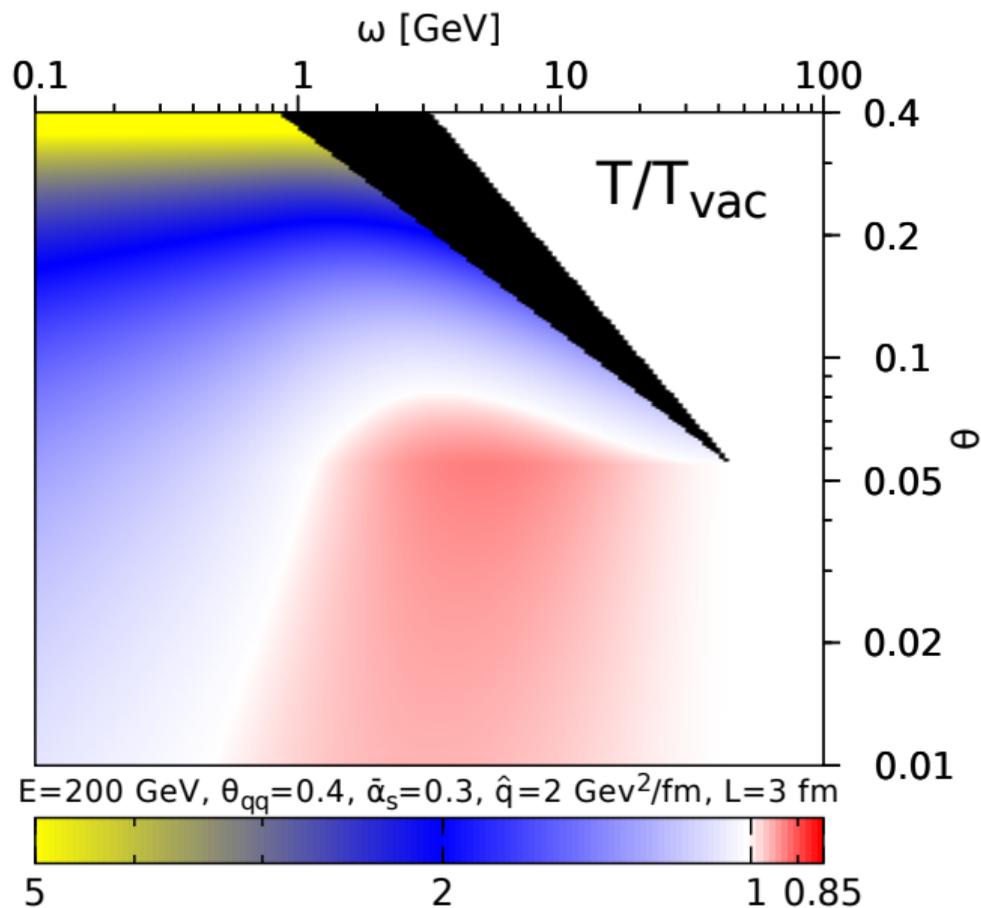
\Rightarrow probability of emission of a gluon with energy ω and angle θ^2 from an antenna with energy E and opening angle $\theta_{q\bar{q}}^2$.

In the vacuum at DLA, this quantity satisfies the simple master equation

$$T_{\text{vac}}(\omega, \theta^2 | E, \theta_{q\bar{q}}^2) = \bar{\alpha}_s + \int_{\theta^2}^{\theta_{q\bar{q}}^2} \frac{d\theta_1^2}{\theta_1^2} \int_{\omega/E}^1 \frac{dz_1}{z_1} \bar{\alpha}_s T_{\text{vac}}(\omega, \theta^2 | z_1 E, \theta_1^2)$$

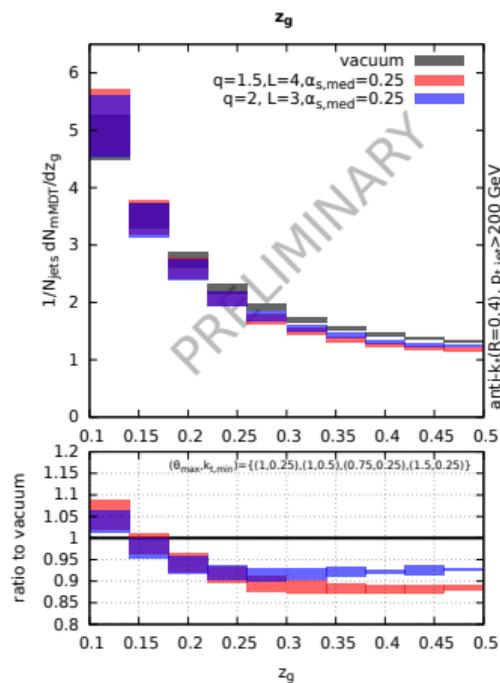
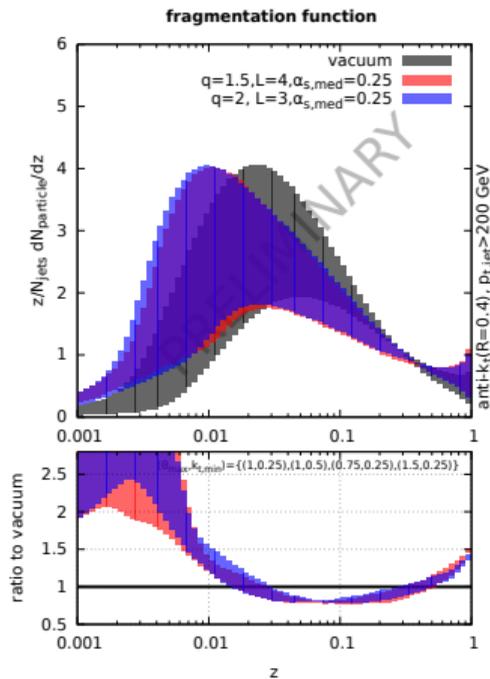
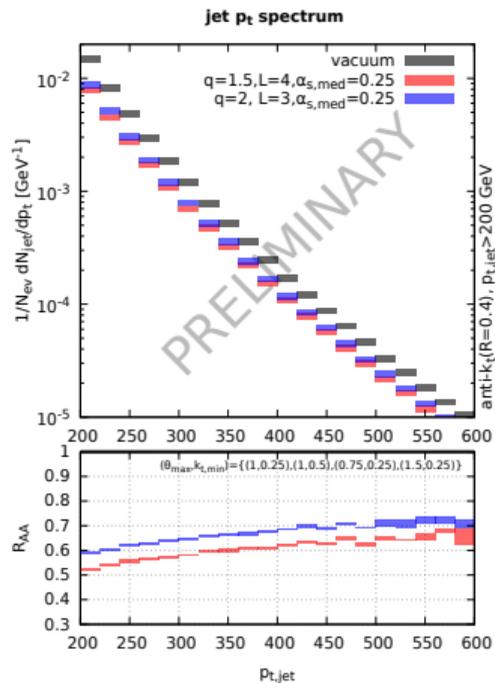
With a medium, this equation holds only inside the medium \Rightarrow mathematically, one must take into account “jumps” over the vetoed region.

Ratio $T(\omega, \theta^2)/T_{vac}(\omega, \theta^2)$



Dependence of MonteCarlo results on θ_{max} and $k_{t,min}$

Estimation of uncertainties



Jet fragmentation
in a dense QCD
medium

Introduction

Jets in the vacuum
at DLA

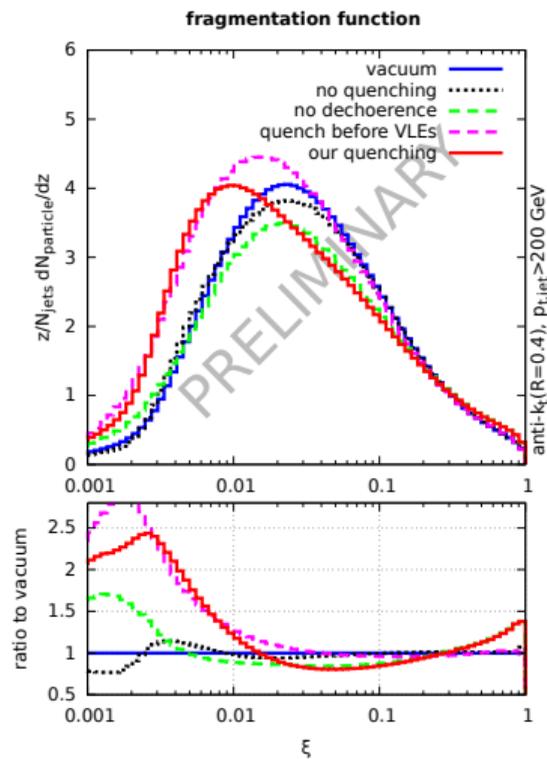
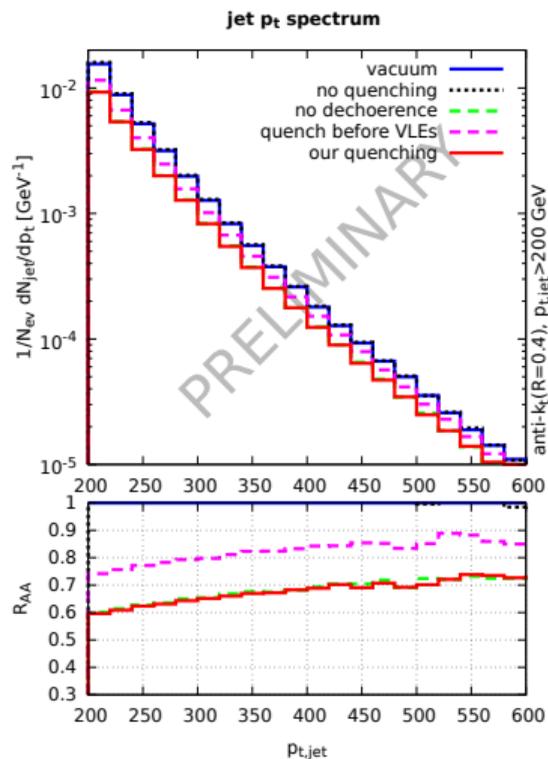
Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion

In-medium intrajet multiplicity and decoherence effects

Jet fragmentation
in a dense QCD
medium



Introduction

Jets in the vacuum
at DLA

Jet evolution with
a medium at DLA

MonteCarlo results
beyond DLA

Conclusion