Jet fragmentation function: pQCD and phenomenological aspects

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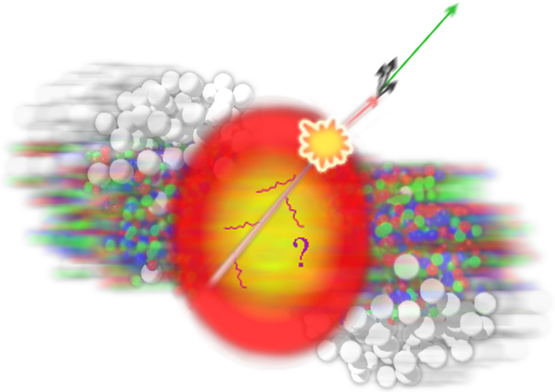
Outline

- Introduction
- General pQCD picture
- Energy loss and R_{AA} ratio for jets
- Jet fragmentation function

Jets in heavy-ion collisions as hard probes

- Jets are collimated spray of particles.
- The hard scattering occurs early in the collision prior to the formation of the QGP.
- Jets are then used as probes of the medium.



pQCD approach to jets in the plasma

- **High-p_T** jets are valuable because it is possible to rely on **pQCD** to predict their properties.
  The difficulties come from these two mechanisms of radiation:
  - the usual, "vacuum-like" bremsstrahlung through which a parton evacuates its virtuality.
  - medium-induced radiations because of the multiple collisions with the medium constituents.
- How can we include both mechanisms ?

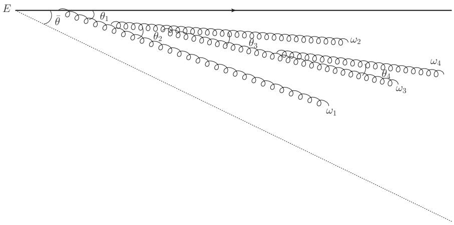
General pQCD picture

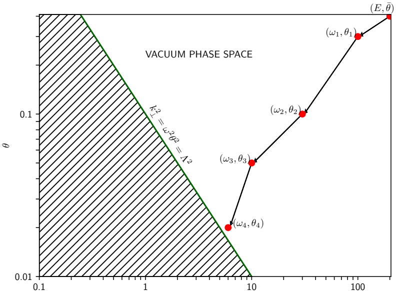
Emissions in QCD: vacuum-like

- **Vacuum-like emissions** (VLEs) triggered by the virtuality according to the Bremsstrahlung law:

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

- Includes soft and collinear divergences.
- Markovian process with angular ordering of successive emissions to account for **quantum** interferences.



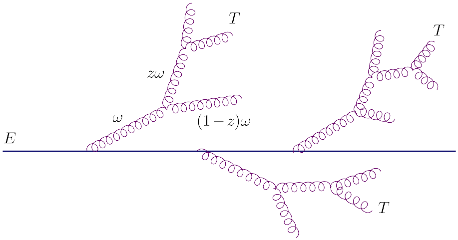


Emissions in QCD: medium-induced emissions

- Quenching parameter $\hat{q}$: $\langle k_\perp^2 \rangle$ transferred from the medium to a parton per unit time because of collisions with medium-consituents.
- **Medium-induced emissions** (MIEs) triggered by these interactions:

$$\mathrm{d}^2\mathcal{P}_{\text{mie}}(\omega,\theta) = \frac{\alpha_s C_R}{\pi}\sqrt{\frac{\hat{q}L^2}{\omega^3}}\mathcal{P}_{\text{broad}}(\omega,\theta)\,\mathrm{d}\omega\mathrm{d}\theta$$

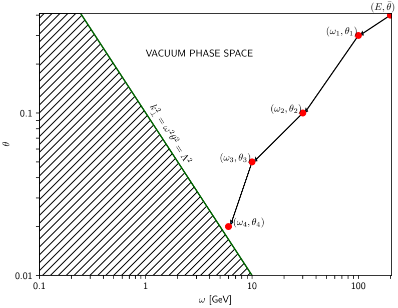
- **No** collinear divergences.
- Markovian process in formation time $t_f = \omega/k_\perp^2$ / no angular ordering.

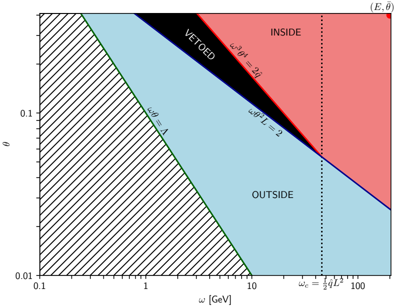


How does the dense QCD medium change the evolution ?

Phase space constraint for VLEs

- During $t_f = 1/(\omega\theta^2)$, a parton acquires a transverse momentum: $\Delta k_\perp^2 = \hat{q} t_f$
- For the vacuum-like shower *inside*, it provides a **lower bound** on the $k_\perp$ of VLEs: $k_\perp^2 > \hat{q} t_f$

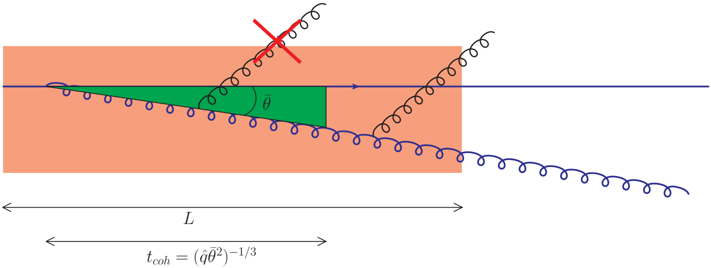




How does the dense QCD medium change the evolution ?

Decoherence

- In the medium, an antenna loses its color coherence after a time $t_{\text{decoh}} = (\hat{q}\bar{\theta}^2)^{-1/3}$. (Mehtar-Tani, Salgado, Tywoniuk, 2010-1 ; Casalderrey-Solana, Iancu, 2011)



- However, no consequences for VLEs in the medium (PC, Iancu, Mueller, Soyez 2018)
  - VLE ($k_\perp^2 \geq \hat{q}t_f$) at large angle ($\theta \geq \bar{\theta}$) $\Rightarrow t_f \leq t_{\text{decoh}}$.
  - Large angle emissions forbidden by color coherence.
  - Gluon cascades are angular ordered as in the vacuum.

How does the dense QCD medium change the evolution ?

Decoherence

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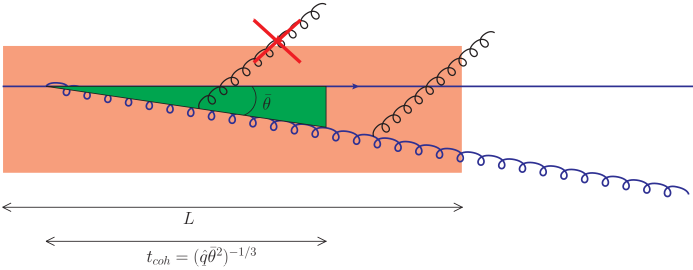
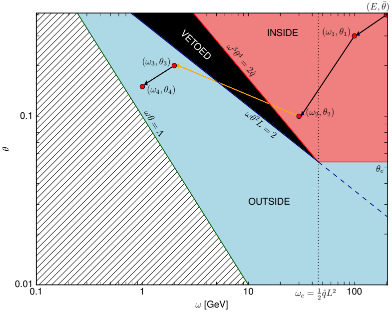


- But an important consequence for the first emission outside:
  - Critical angle $\theta_c = 2/\sqrt{\hat{q}L^3}$ such that $t_{\rm decoh}(\theta_c) = L$.
  - If the angle of the last emission inside is larger than θ_c, then the first emission outside can have any angle.

What about the medium-induced radiations ?

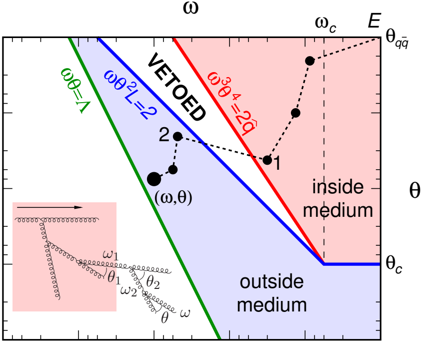
- Via multiple soft scattering, the medium may also trigger additional emissions, called **medium-induced radiations**. (Baier, Dokshitzer, Mueller, Peigné, and Schiff; Zakharov 1996–97)
- Transverse momentum comes from multiple scatterings: $k_\perp^2 = \hat{q} t_f$.
- Consequently, they can only occur once the vacuum like shower inside the medium has evacuated the initial virtuality until $k_\perp^2 \sim \hat{q} t_f$.



Jet evolution in a dense QCD medium

Summary

- The evolution of a jet **factorizes** into three steps:
  - (1) one **angular ordered** *vacuum-like shower* inside the medium ,
  - (2) *medium-induced emissions* triggered by previous sources,
  - (3) finally, a *vacuum-like shower* outside the medium.
- Re-opening of the phase space for the first emission outside the medium.



- $\omega_c = \frac{1}{2}\hat{q}L^2$
- $\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$

Monte-Carlo implementation in a nutshell

- Two modules required:
  - **Vacuum-like shower**: angular ordered shower of VLEs with DGLAP splitting function and running coupling to produce the VLEs inside and outside the medium.
  - **Medium-induced shower**: time-ordered shower of MIEs with angle set by the momentum broadening during propagation through the medium.
- The factorization is very suitable for MC implementation.

Leading parton produced by the hard process

↓

Vacuum-like shower inside

↓

Medium-induced shower during a time L

↓

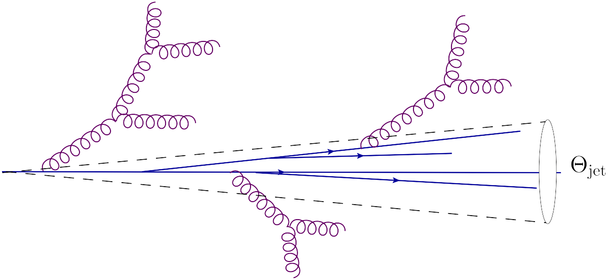
Vacuum-like shower outside

Energy loss and R_{AA} ratio

Basic features of energy loss

- The energy is lost by the jet because of the medium-induced cascade transporting the energy at **large angle** via multiple branchings.

  - Energy is transferred to softer and softer gluons which are deviated outside the jet.

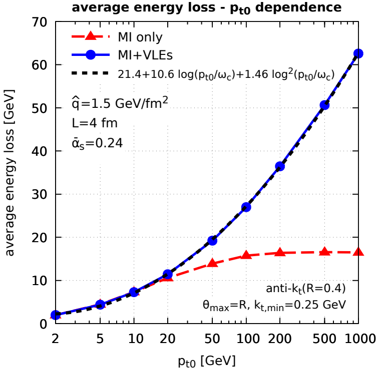


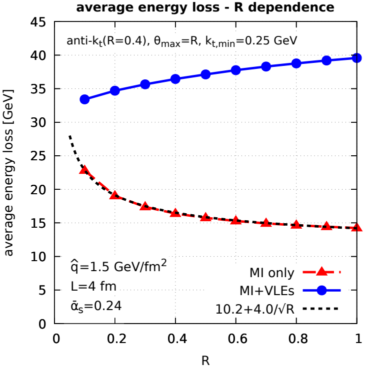
- Typical scale of energy loss is $\omega_{br} = \bar{\alpha}_s^2 \omega_c$, the scale below which multiple medium-induced branchings become important.

Energy loss $\mathcal{E}(p_T, R)$ for medium-induced jets

Red curves

- For $p_T \gg \omega_{br}$, the energy loss via MIEs is constant and $\simeq \omega_{br}$.
- As a function of R, the energy loss decreases since one recovers more and more the large angles MIEs.



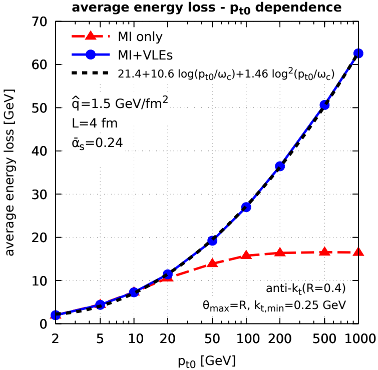


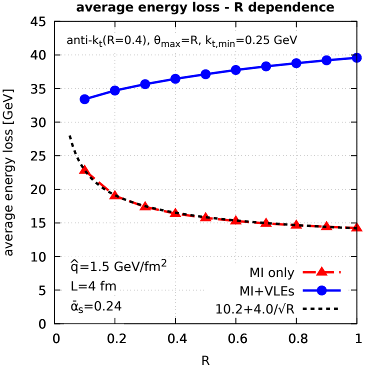
Energy loss $\mathcal{E}(p_T, R)$ for full jets

Blue curves

- As a function of p_T and R, the energy loss increases because the VLEs multiplicity **inside** the medium increases:

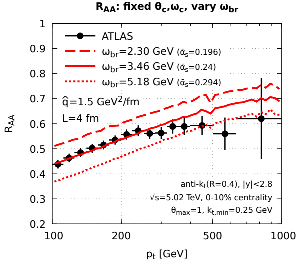
$$\mathcal{E}(p_T, R) \propto \omega_{br} \int_0^{p_T} d\omega \int_{\theta_c}^{R} d\theta \frac{d^2 N}{d\omega d\theta} \Theta_{in}$$

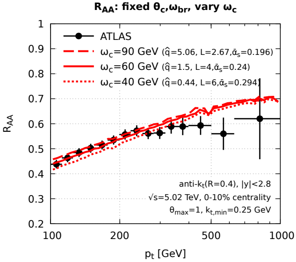


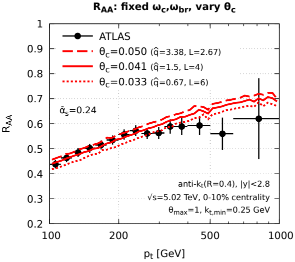


R_{AA} ratio: jet cross section in PbPb/ jet cross section in pp

The nuclear modification factor is controlled by $\omega_{br} = \bar{\alpha}_s^2 \omega_c$







Summary

- In-medium multiplicity of VLEs keeps R_{AA} small.

- R_{AA} mostly controlled by the multiple branchings scale $\omega_{br} = \bar{\alpha}_s^2 \hat{q} L^2/2$.

Nuclear modification of the jet fragmentation function

Definition

- Energy ($\simeq$ transverse momentum) distribution of particles within jets.

$$D(z) = \frac{1}{N_{\mathrm{jets}}} \frac{dN}{dz}$$

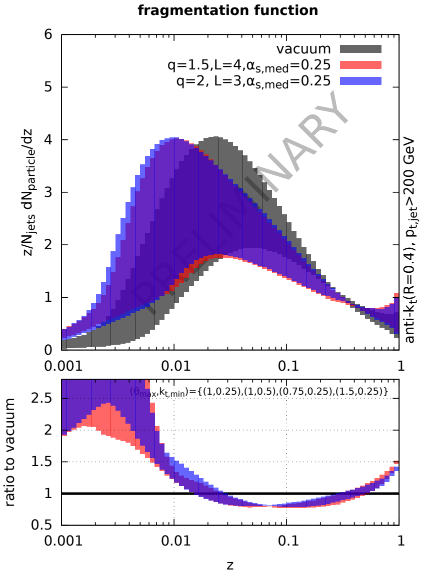
with $z = p_T \cos(\Delta R)/p_{T,\mathrm{jet}} \sim p_T/p_{T,\mathrm{jet}}$

- Nuclear modification of the jet fragmentation function:

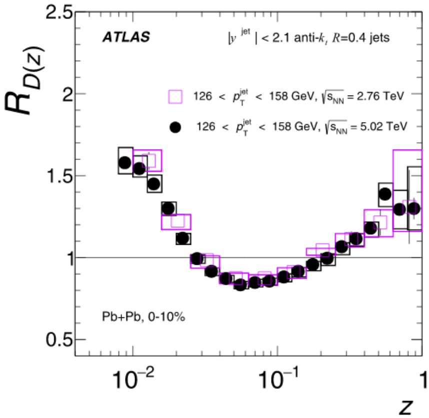
$$R_{D(z)} = \frac{D_{\mathrm{PbPb}}(z)}{D_{\mathrm{pp}}(z)}$$

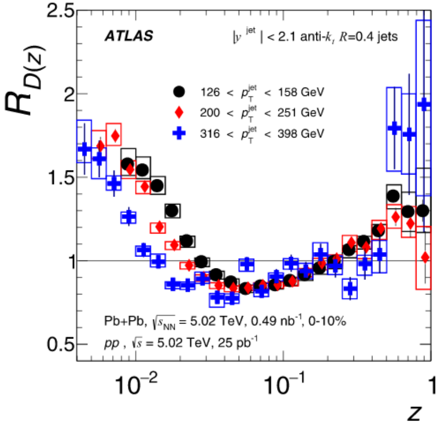
This observable is not IRC safe !

- Simple argument: the integral over z of $D(z)$ is the **total intrajet multiplicity** which is obviously not infrared nor collinear safe.
- Nevertheless, $D(z)$ is **calculable** $\Rightarrow$ **but** strong dependence upon the cut-off of the calculation.
- Two way out: make "qualitative" statement and focus on the ratio $R_{D(z)}$ which is less sensitive to the cut-off.



The unfolded ATLAS data





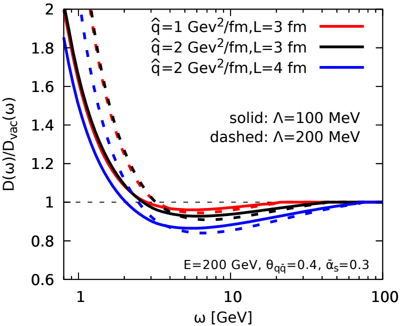
- Robust pattern when varying $\sqrt{s}$.
- Enhancement of low z and $z \sim 1$.
- Suppression at intermeditate z.

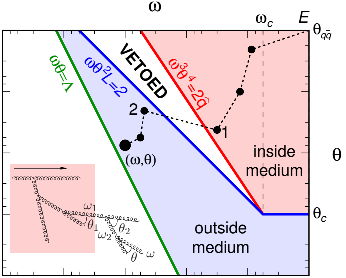
Enhancement at low z: decoherence effect

Double-logarithmic resummation

At low z, the multiplicity of soft fragments comes from the outside cascades triggered by decoherence of in-medium sources. At DLA:

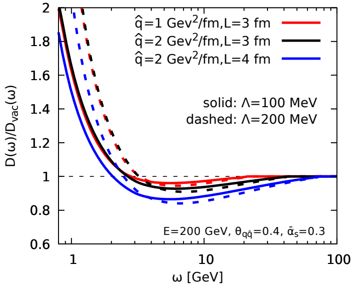
$$D_{\rm PbPb}(p_T) = \frac{\sqrt{\bar{\alpha}_s}}{2} \overbrace{\mathcal{N}_{\rm med}}^{\text{number of "in" sources}} \overbrace{\exp(\bar{\alpha}_s \log(2p_T/\Lambda^2 L))}^{\text{DL cascade}}$$

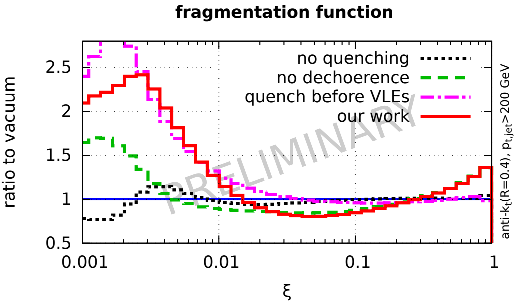




Enhancement at low z: MC results beyond DLA

- $D_{\rm PbPb}(p_T) = \frac{\sqrt{\bar{\alpha}_s}}{2}\mathcal{N}_{\rm med}\overbrace{\exp(\bar{\alpha}_s \log(2p_T/\Lambda^2 L))}^{\text{poor estimate at DLA !}}$
- However, when MIEs are switched on, additional sources increase the $\mathcal{N}_{\rm med}$ factor.
- If decoherence swichted off, the enhancement at low z disappears.





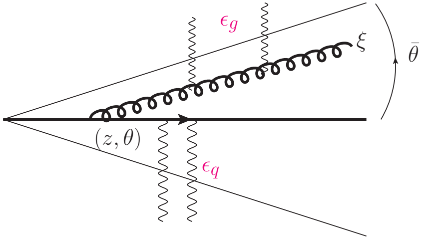
$z \sim 1$ behavior

Leading-log calculation for “monochromatic” jets

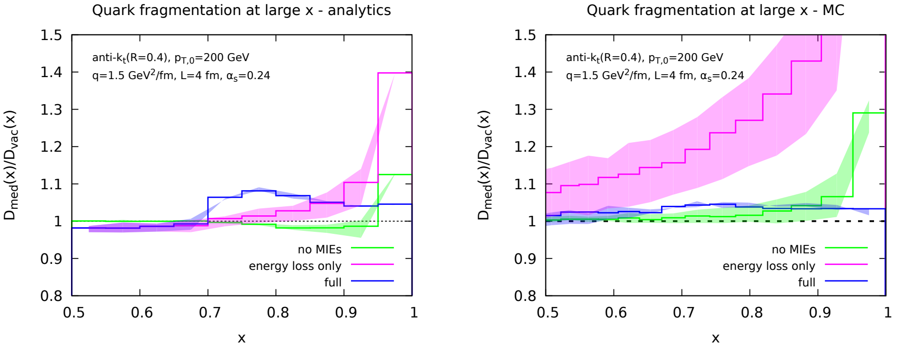
- Consider the cumulative distribution $\Sigma(x) = \int_x^1 dz D(z)$.
- At leading-log accuracy in the vacuum,

$$\Sigma_R^{\mathrm{VLE}}(x) = \exp\left(-\frac{2C_R}{\pi} \int_{1-x}^1 \frac{dz}{z} \int_0^{\bar{\theta}} \frac{d\theta}{\theta} \alpha_s(zE\theta)\Theta(zE\theta - Q_0)\right)$$

- In the presence of the medium, 3 effects:
  - vetoed region: $\Theta(zE\theta - Q_0) \to \Theta(zE\theta - Q_0)\Theta_{\mathrm{not\ vetoed}}(z,\theta)$
  - energy loss shift: $z \to \xi = (zE - \epsilon_g)/(E - \epsilon_g - \epsilon_R)$
  - intrajet medium-induced emissions: $\Sigma_R = \Sigma_R^{\mathrm{VLE}} \underbrace{\Sigma_R^{\mathrm{MIE}}}_{\propto \exp(-\bar{\alpha}_s \sqrt{\bar{\theta}/\theta_c})}$



MC vs analytics for "monochromatic" quark jets



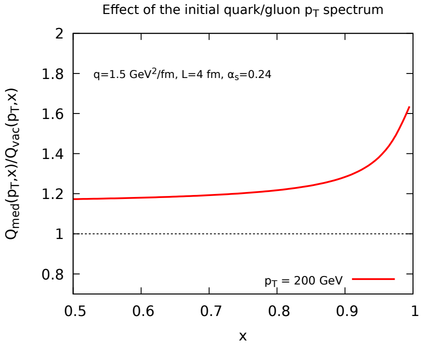
Comments

- Good qualitative agreement between MC and data.
- Dependence upon cut-off Q_0 smaller in the ratio $R_{D(z)}$.
- Stronger enhancement in the MC calculation for the "energy loss only" case because all MIEs are sent outside the jet cone.

Effect of the steeply falling spectrum

For a given jet p_T,

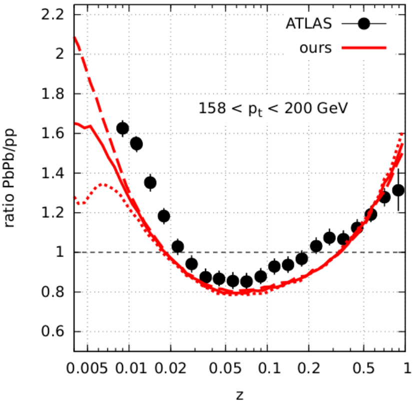
$$R_{D(x)} = \overbrace{\frac{\mathcal{Q}_{\rm med}(p_T, x)}{\mathcal{Q}_{\rm vac}(p_T)}}^{\text{effect of the spectrum}} \quad \underbrace{\frac{D_{q,\rm med}(x|p_T)}{D_{q,\rm vac}(x|p_T)}}_{\text{already estimated}}$$

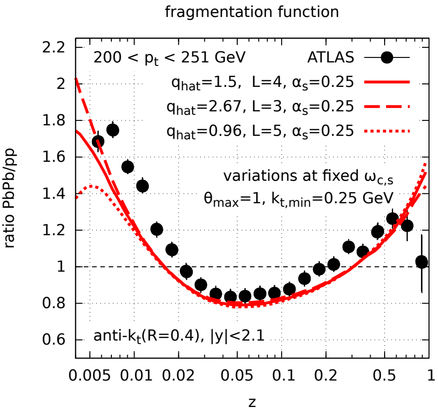


→ $\mathcal{Q}_{\rm med}$ encompasses the idea that a jet with few fragments loses less energy than an average jet.

$$\mathcal{Q}_{\rm med}(p_T, x) = \frac{\frac{d\sigma_q}{dE}(p_T + \epsilon_q + \epsilon_g)}{\frac{d\sigma_q}{dE}(p_T + \mathcal{E}_q(p_T)) + \frac{d\sigma_g}{dE}(p_T + \mathcal{E}_g(p_T))}$$

Full MC results





Comments

- Low z and high z enhancement well captured.
- Depletion in between: effect of normalization.

Conclusion

Take-home messages

- pQCD picture for jet evolution in a dense QCD medium with **factorization** between vacuum-like emissions and medium-induced emissions.

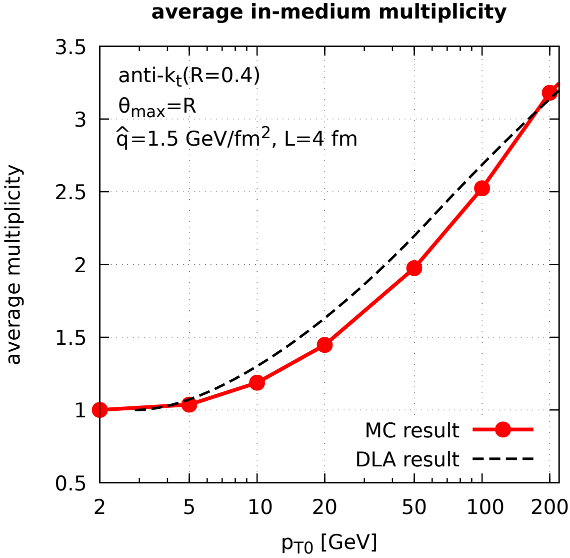
- R_{AA} ratio controlled by the scale $\omega_{br} \sim \alpha_s^2 \hat{q} L^2$. Strongly suppressed even at high p_T because of the **increasing number of VLEs inside the medium**.

- Jet fragmentation function: enhancement at low z due to **decoherence** of sources created inside the medium.

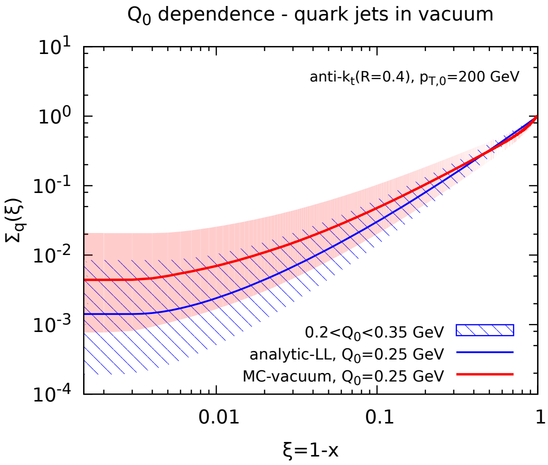
- z close to 1 behavior of the jet fragmentation function: **competition** between several effects...

THANK YOU !

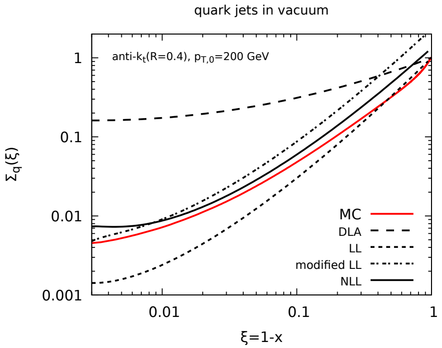
In-medium multiplicity of VLEs

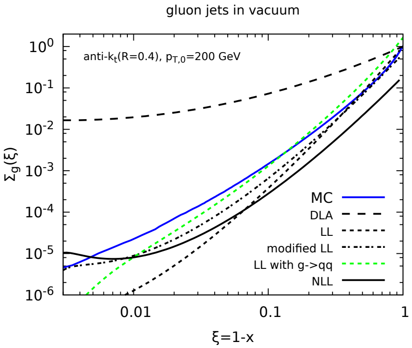


Cut-off dependence of the cumulative fragmentation function



Cumulative fragmentation distribution for q/g jets in vacuum





Full formula for the fragmentation function at $z \sim 1$

Using $\xi_0 = 1 - x$,

$$xD(x) = \frac{\int_0^\infty dE \sum_{i=q,g} \frac{d\sigma_i}{dE} \int_0^1 d\xi \int_0^R d\theta \delta(\Xi(\xi,\theta) - \xi_0) \frac{x dN_i}{d\xi d\theta} \delta(p_T - E + \epsilon(\xi,\theta))}{\int_0^\infty dE \sum_{i=q,g} \frac{d\sigma_i}{dE} \delta(p_T - E + \mathcal{E}_i(E))}$$

with

$$\begin{aligned} \epsilon(\xi,\theta) &= \epsilon_g(\xi E) + \epsilon_i((1-\xi)E) && \text{if } (z,\theta) \in \text{ inside region} \\ &= \epsilon_i(E) && \text{if } (z,\theta) \in \text{ outside region} \end{aligned}$$

and

$$\frac{dN_i}{d\xi d\theta} = \frac{2C_i \alpha_s(\xi \tilde{E} \theta)}{\pi} \frac{1}{\xi\theta} \Theta(\xi \tilde{E}\theta - Q_0) \Theta_{\text{not vetoed}}(\xi,\theta)$$
$$\times \exp\left(- \int_\xi^1 dz \int_0^{\bar{\theta}} d\theta' \frac{2C_i \alpha_s(z\tilde{E}\theta')}{\pi} \frac{1}{z\theta'} \Theta(z\tilde{E}\theta' - Q_0) \Theta_{\text{not vetoed}}(z,\theta') \right)$$