JET EVOLUTION IN A DENSE QCD MEDIUM

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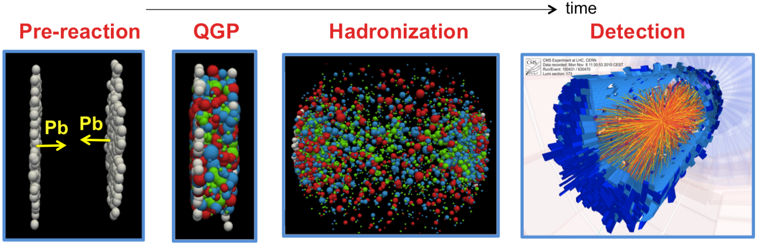
My PhD thesis: jets in heavy-ion collisions
Quark Gluon Plasma

- The QGP is re-created in high energy collisions of large nuclei (LHC, RHIC).

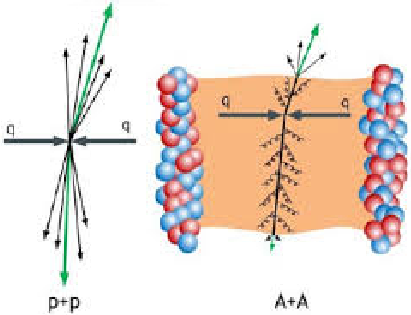


- Extremely short lifetime! Difficult to measure directly its property.

My PhD thesis: jets in heavy-ion collisions

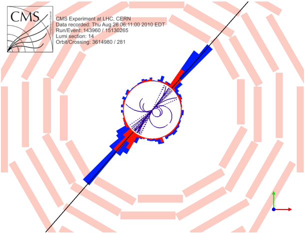
Jets as hard probes

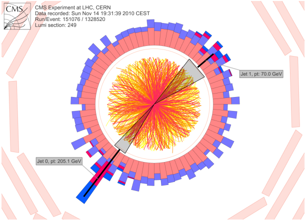
- A hard scattering produces a pair of highly energetic partons.
- The subsequent evolution of the parton ⇒ jets.

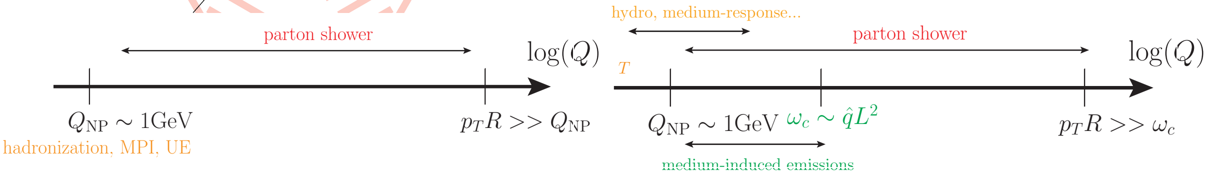


- In PbPb, interaction with the plasma during propagation.

Jets in *pp* vs jets in heavy-ions collisions







A complicated physical system

Jets are sensitive to a broad range of scales and thus to many medium-induced mechanisms.

pQCD picture of jet fragmentation in dense QCD media

with Edmond Iancu, Al Mueller and Gregory Soyez

Key idea: find an approximation consistent with pQCD

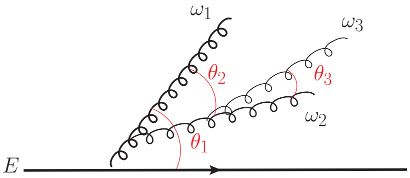
- Rely on a suitable approximation under pQCD control.
- Most simple approximation: **double logarithmic limit**!

How does a vacuum jet look like within the DLA?

- **Vacuum-like emissions** (VLEs) = Bremsstrahlung triggered by the virtuality:

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

- Duration of the process: $t_f \sim 1/(\omega\theta^2)$.
- Markovian process with angular ordering to



$\theta_1 \gg \theta_2 \gg \theta_3$

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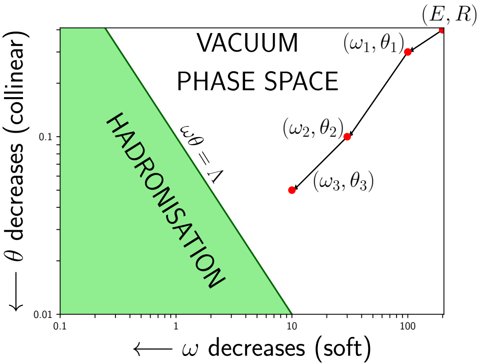
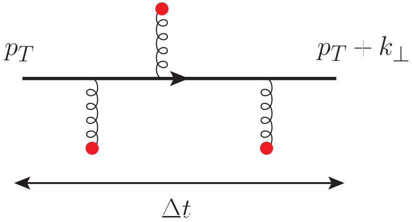


Parton propagation in dense media

(1) Transverse momentum broadening: $\langle k_\perp^2 \rangle = \hat{q}\Delta t$



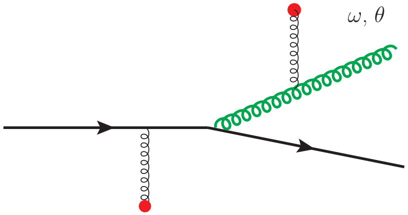
Parton propagation in dense media

(1) Transverse momentum broadening: $\langle k_\perp^2 \rangle = \hat{q}\Delta t$

(2) Medium-induced emissions. Baier, Dokshitzer, Mueller, Peigne, Schiff, 1997 - Zakharov,1997

$$\mathrm{d}^3\mathcal{P}_{\mathrm{mie}} \sim \frac{\alpha_s C_R}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}t}{t_{f,\mathrm{med}}}\underbrace{\mathcal{P}_{\mathrm{broad}}(\theta)\mathrm{d}\theta}_{\mathrm{Gaussian}}, \qquad \text{with} \qquad t_{f,\mathrm{med}} = \sqrt{\omega/\hat{q}}$$

⇒ **No** collinear divergence when $\theta \longrightarrow 0$.
⇒ Typical $k_\perp^2 \sim \sqrt{\hat{q}\omega}$.

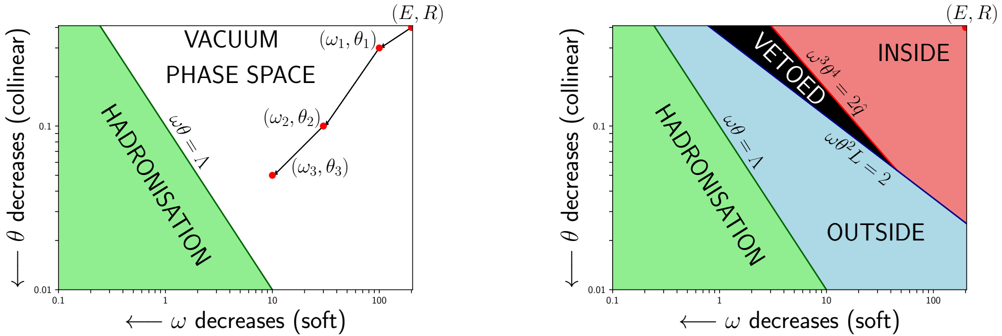


How does an in-medium jet look like at DLA?

Phase space constraint for vacuum-like emissions

- During $t_f = 1/(\omega\theta^2)$, in-medium partons acquire $k_\perp^2 = \hat{q} \times \overbrace{t_f}^{1/(\omega\theta^2)}$
- For VLEs *inside*, **lower bound** on the $k_\perp \simeq \omega\theta$ of emission:

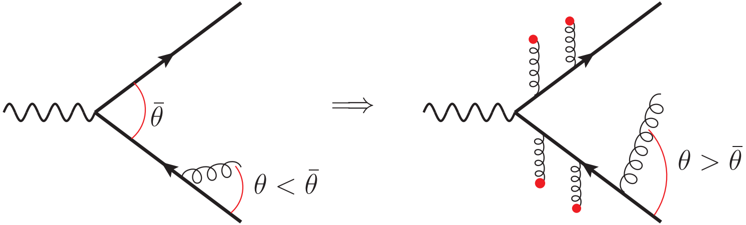
$$k_\perp^2 > \hat{q} t_f$$



- No VLEs allowed for formation times $\sqrt{\omega/\hat{q}} < t_f < L$. PC, Iancu, Mueller, Soyez, 2018

How does an in-medium jet look like at DLA?
Decoherence

- **Color decoherence:** after $t_d = (\hat{q}\bar{\theta}^2)^{-1/3}$, $\Rightarrow$ independent sources of soft large angle gluons. Mehtar-Tani, Salgado, Tywoniuk, 2011 - Casalderrey-Solana, Iancu, 2011



- However, no consequences for VLEs **in the medium**
  PC, Iancu, Mueller, Soyez, 2018
  - Large angle in-medium VLEs occur very fast $\Rightarrow t_f < t_d$.
  - Gluon cascades are angular ordered as in the vacuum.

How does an in-medium jet look like at DLA?

Decoherence

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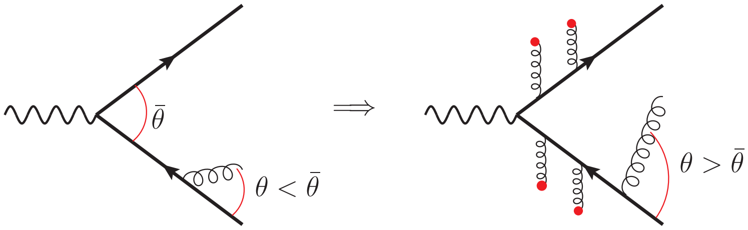
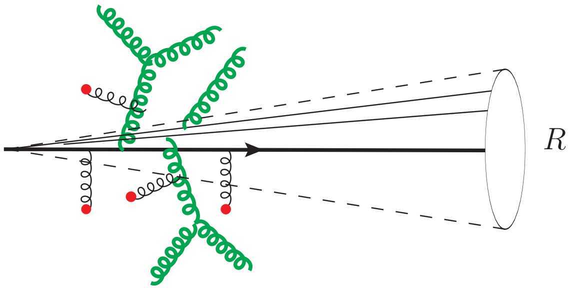


- But an important consequence for the first emission **outside** $t_f > L$:
  - Critical angle θ_c such that $t_\mathrm{d}(\theta_c) = L$.
  - If $\bar{\theta} > \theta_c = 2/\sqrt{\hat{q}L^3}$, the first emission **outside** can have any angle. Mehtar-Tani, Salgado, Tywoniuk, 2011

Beyond DLA: including medium-induced emissions

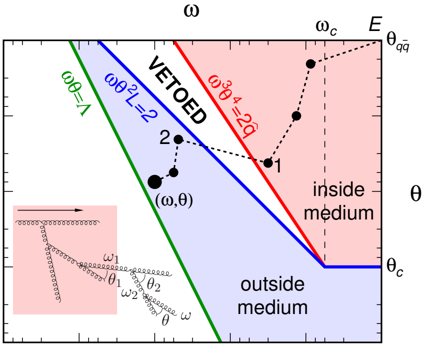
- MIEs satisfy $k_\perp^2 \sim \hat{q} t_f \Longleftrightarrow t_{f,\mathrm{med}} = \sqrt{\omega/\hat{q}}$.
- Each VLE inside **with** $\theta \geq \theta_c$ radiates MIEs.
- Markovian process in time and no angular ordering, with rate:

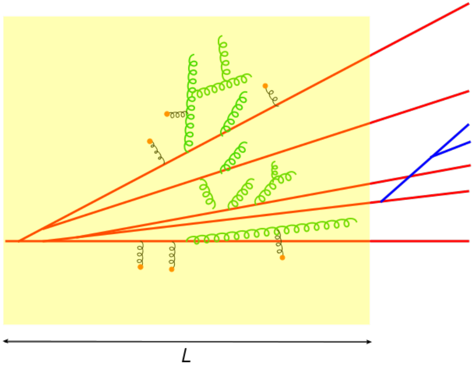
$$\mathrm{d}^2\mathcal{P}_{\mathrm{mie}} = \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}t}{t_{f,\mathrm{med}}}$$



Summary: jet evolution to leading-log accuracy

- 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.

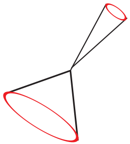




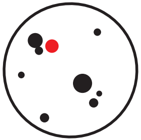
Phenomenology at the LHC: jet quenching in Pb-Pb collisions

Jet observables discussed in this presentation

- Jet cross-section



- Fragmentation function

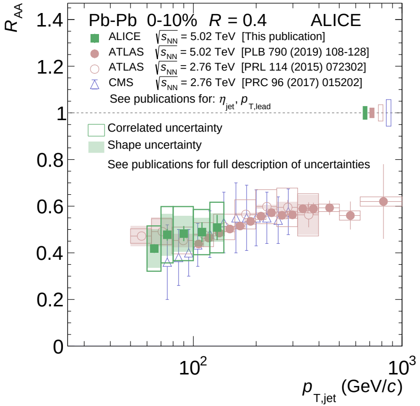


Calculations with **3 parameters** $\hat{q}$, L and $\alpha_{s,\mathrm{med}}$.

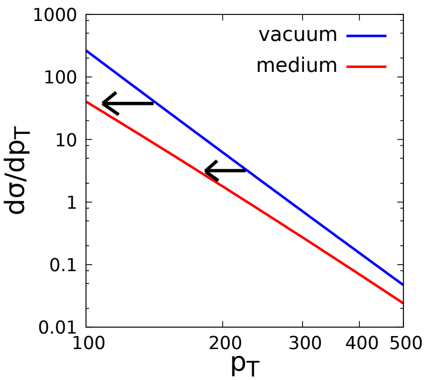
The inclusive jet cross section in Pb-Pb collisions

Definition

$$R_{\rm AA}(p_T) = \frac{\text{cross-section for jets with } p_T \text{ in PbPb}}{\text{cross-section in pp} \times \text{number of binary collisions}} < 1 \; !$$



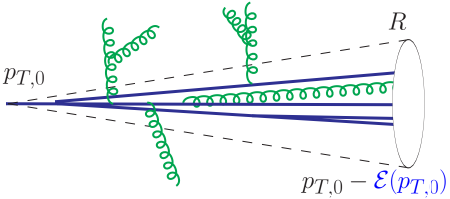
Steeply falling spectrum + energy loss

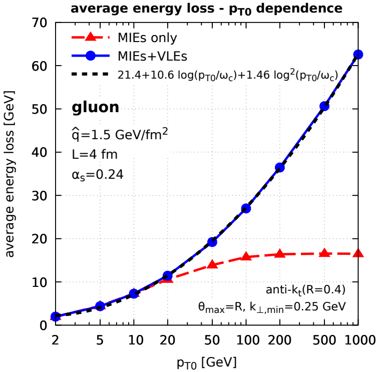


Physical interpretation: large number of in-medium VLEs

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

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

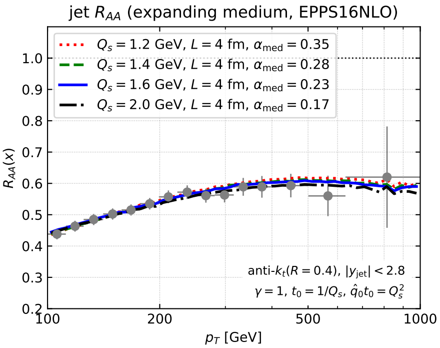


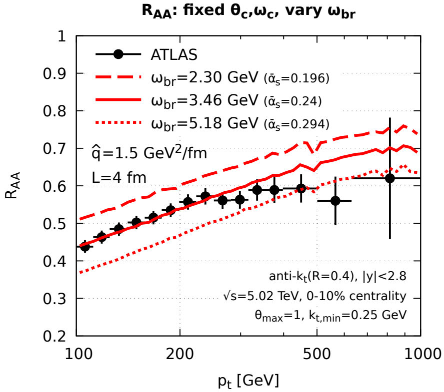


R_{AA} ratio: jet cross section in PbPb/ jet cross section in pp

- In-medium multiplicity of VLEs keeps R_{AA} small (+non negligible nPDFs effets at large p_T)
- R_{AA} is controlled by $\omega_{br} = \alpha_s^2 \hat{q} L^2$.

PC, Iancu, Soyez, 2019-2020



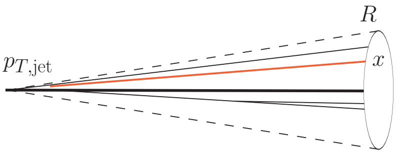


Fragmentation function (FF): definition

- Energy distribution of particles within jets.

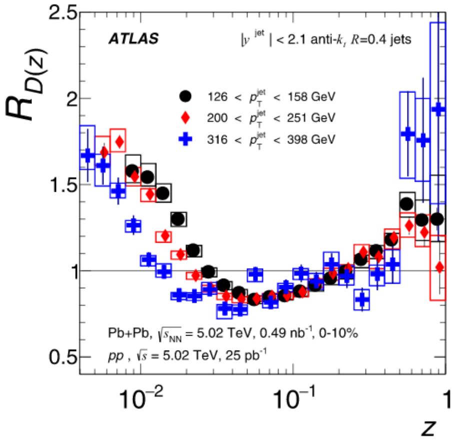
$$\mathcal{D}(x) = \frac{1}{N_{\mathrm{jets}}} \frac{dN}{dx}$$

with $x \sim p_T / p_{T,\mathrm{jet}}$



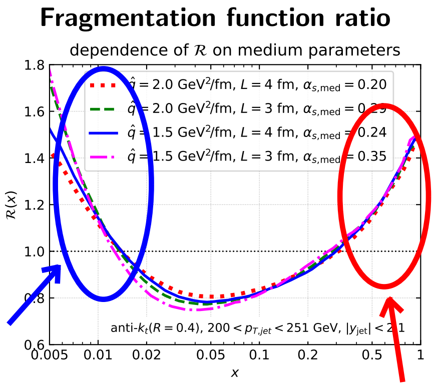
- Nuclear modification:

$$\mathcal{R}(x) = \frac{\mathcal{D}_{\mathrm{PbPb}}(x)}{\mathcal{D}_{\mathrm{pp}}(x)}$$



ATLAS Collaboration, Phys. Rev. C98, 2018

Monte-Carlo calculations PC, Mueller, Iancu, Soyez, 2020



Two regimes

Nuclear **enhancement** at large x and low x: same behaviour seen in the data.

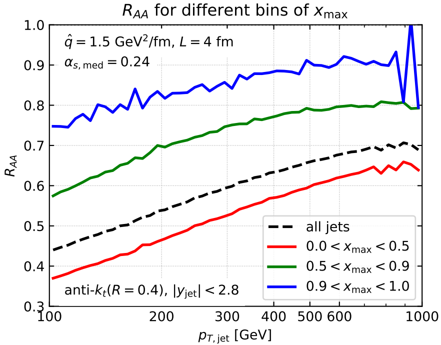
Large-x behaviour: bias towards "hard-branching" jets

- Change in the statistics of hard-fragmenting jets induced by the steeply falling spectrum.

- Hard-fragmenting jets have less structure, hence they lose less energy.

see also Casalderrey-Solana et al.(1808.07386) 2019,

Spousta and Cole, (1504.05169) 2016



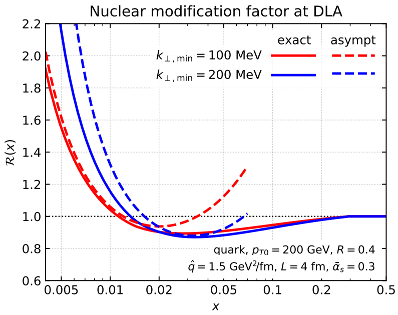
PC, Iancu, Mueller, Soyez (2005.05852), 2020

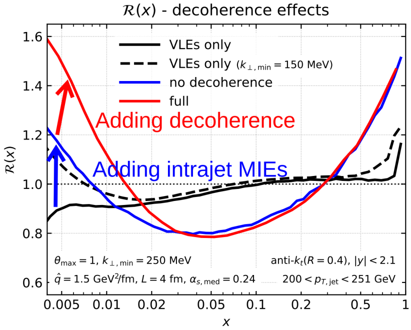
$\longrightarrow x_{\max}$ *momentum fraction of the leading particle in jets.*

Enhancement at low x: colour decoherence and MIEs

Monte Carlo and analytic tests of various mechanisms

- Black curve: no MIEs.
- VLEs and MIEs no colour decoherence,
- Full MC including decoherence.





Outlook

Two directions

- **Find qualitative new physics.**
  - Use jet substructure to pin down specific aspects of in-medium jet dynamics.
  - Medium-induced turbulent behaviour, thermalization.

    Blaizot, Iancu, Mehtar-Tani, 2013, Iancu, Wu 2015, Schlichting, Soudi 2020,...
  - NLO corrections to $\hat{q}$, anomalous $k_\perp$ diffusion in large systems.

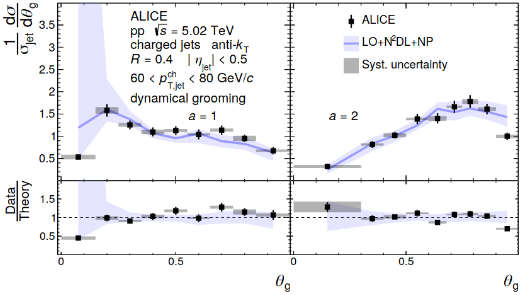
    Liou, Mueller, Wu, 2013, Blaizot, Mehtar-Tani, 2014, Iancu, 2014, PC, Mehtar-Tani 2021,...

    See also talk by E. Weitz this afternoon
  - ...
- **Towards precision phenomenology of jet quenching.**

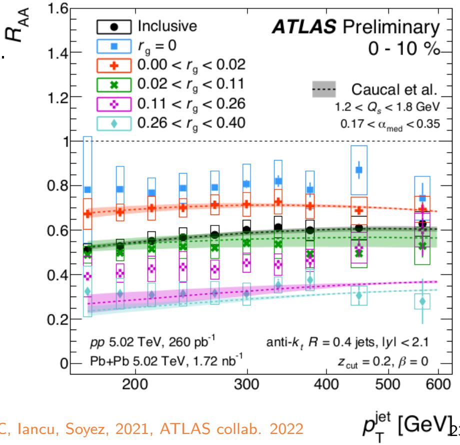
Use jet substructure techniques to reveal color coherence

Example: θ_g distribution

- Basic idea: groom soft large angle emissions to find hard branches, and measure the angle θ_g of this hard branch.
- Jet substructure observable under pQCD control.
- In AA, strong sensitivity to the coherence angle θ_c.



PC, Soto-Ontoso, Takacs, 2021 - ALICE collab. 2021



PC, Iancu, Soyez, 2021, ATLAS collab. 2022

Towards precision jet physics in HIC

New theoretical and numerical developments

- Improve the in-medium vacuum-like cascade:
    - Full LL, NLL?
    - Use dipoles.

      Barata, PC, Soto-Ontoso (in progress)

- Improve medium-induced physics
    - Account for (rare) hard scatterings in a consistent way.

      Barata, PC, Soto-Ontoso, Takacs, Tywoniuk (in progress)
    - Include recent exciting developments in the computation of medium-induced emissions spectra.
      See talk by C. Andres this afternoon
    - ...

- Improve modeling aspects: geometry, medium response, in-medium hadronization,...

A big thank to the GDR QCD for this prize!