The "Saclay approach" to jet quenching: factorization and role of color coherence

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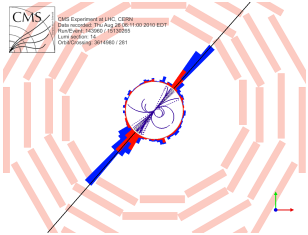
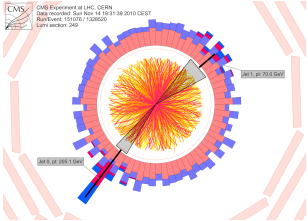
with E. Iancu, A. H. Mueller, G. Soyez

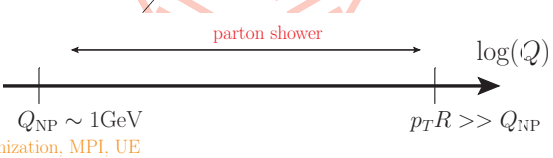
Workshop: "jet quenching in the QGP", ECT* Trento, June 14th 2022

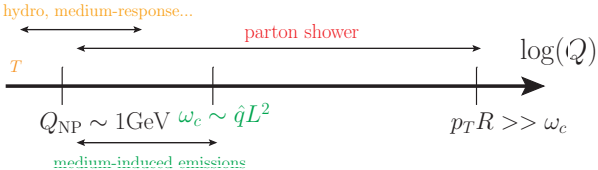
Brookhaven National Laboratory

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









See also talk by A. Soto-Ontoso.

Jets are sensitive to a broad range of scales

In heavy-ion collisions: how to organize the treatment of all these physical mechanisms?

The Saclay approach in a nutshell

- Rely on well defined approximations in pQCD: double logarithmic limit.
- Factorization between vacuum-like cascades ("leading twist") and medium induced emissions.
- Include color de/coherence effects.

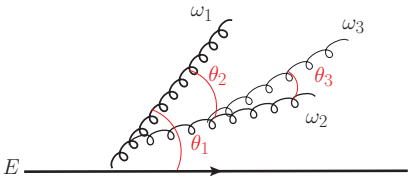
PC, Iancu, Mueller, Soyez, 1801.09703

How does a vacuum jet look like within the DLA?

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

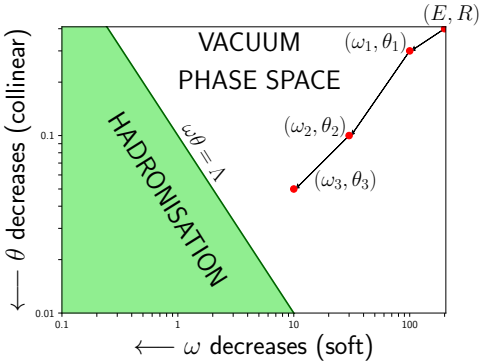
$$\mathrm{d}^2\mathcal{P}_{\mathsf{vle}} \simeq \frac{\alpha_s C_R}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\theta^2}{\theta^2}$$

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



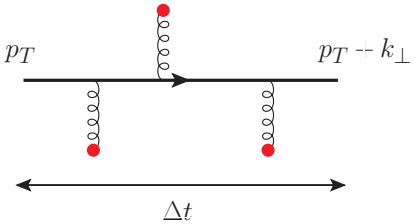
$\theta_1 \gg \theta_2 \gg \theta_3$

$\omega_1 \gg \omega_2 \gg \omega_3$



Parton propagation in dense media

- Dense QCD medium: needs to account for multiple soft scatterings ("all twist" corrections).
- Interaction between the hard partons and the plasma described by an *effective* parameter $\hat{q}$.
- Transverse momentum broadening: $\langle k_\perp^2 \rangle = \hat{q}\Delta t$

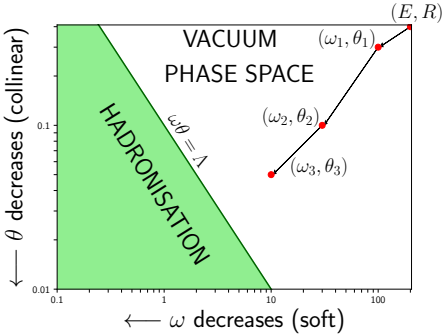


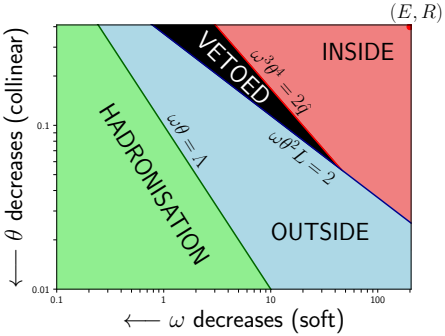
How does an in-medium jet look like at DLA?

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:

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





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

More on the in-medium constraint and veto region

- A **leading twist** effect induced by multiple soft scattering. (Similar to the quantum evolution of $\hat{q}$)
- Manifest in BDMPS-Z type calculations in the $L \to \infty$ limit:

$$\frac{d^3 N^{q\to qg}}{d\omega d^2 \boldsymbol{k}_\perp} \approx \frac{\alpha_s C_F}{\pi^2} \frac{1}{\omega \boldsymbol{k}_\perp^2} \Theta\left(\boldsymbol{k}_\perp^2 - \sqrt{\hat{q}\omega}\right) + \text{"non-singular"}$$

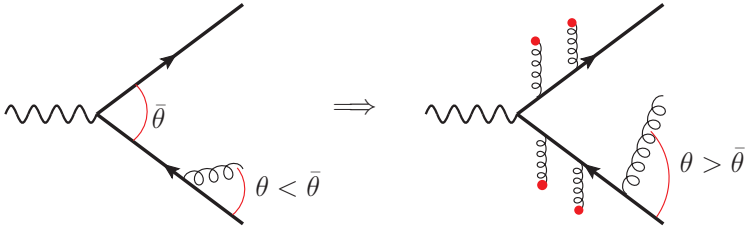
Also manifest as competitive phases in the in-medium effective propagator.

- For finite L, the cross-section displays additional singular pieces coming from
  - "VLEs" triggered by the interaction with the medium, with $\boldsymbol{k}_\perp^2 \lesssim \sqrt{\hat{q}\omega}$.
  - VLEs with $t_f \geq L$.
- In a leading twist approximation, only VLEs with $\boldsymbol{k}_\perp^2 \gg \sqrt{\hat{q}\omega}$ and $t_f \gg L$ should be iterated.

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.

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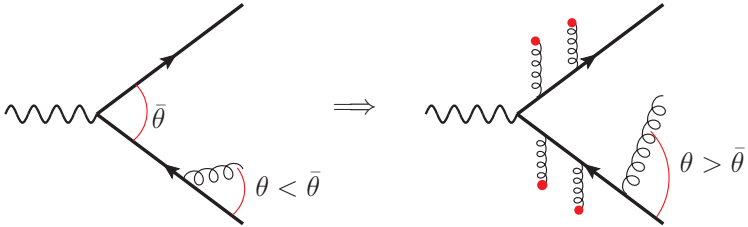


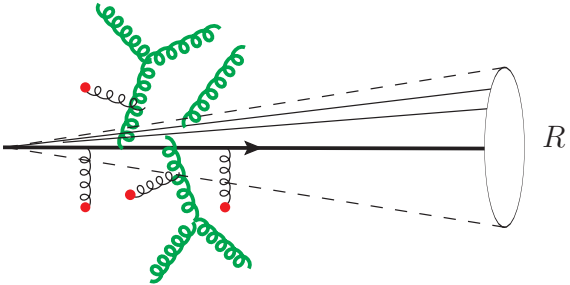
- But an important consequence for the first emission **outside** $t_f > L$:
  - Critical angle θ_c such that $t_{\rm d}(\theta_c) = L$.
  - If $\bar{\theta} > \theta_c = 2/\sqrt{\hat{q}L^3}$, the first emission **outside** can have any angle.

Mehtar-Tani, Salgado, Tywoniuk, 2011

Beyond DLA: including medium-induced emissions

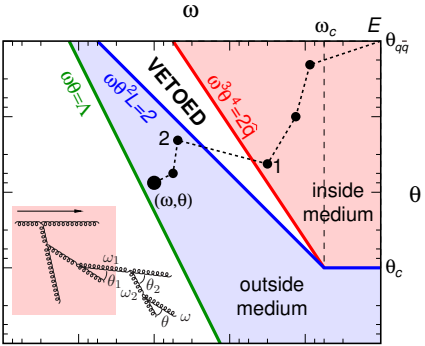
- MIEs satisfy $k_\perp^2 \sim \hat{q} t_f \iff t_{f,\mathrm{med}} = \sqrt{\omega/\hat{q}}$.
- Each VLE inside **with** $\theta \geq \theta_c$ radiates MIEs.
- Markovian process in time and no angular ordering, with rate:

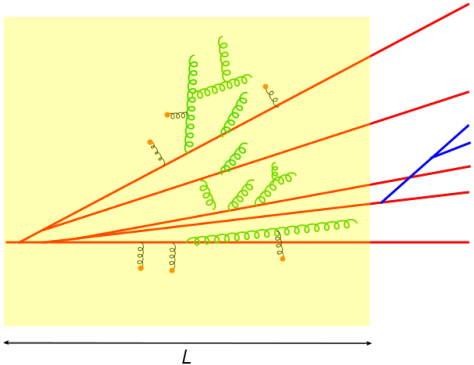
$$\mathrm{d}^2\mathcal{P}_{\mathrm{mie}} = \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}t}{t_{f,\mathrm{med}}}$$



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.





Recent developments including longitudinal expansion

- In a Bjorken expanding medium, $\hat{q} \to \hat{q}(t)$:

$$\hat{q}(t) = \hat{q}_0 (t_0/t)^\gamma$$

with $\gamma \sim 1$.

- The longitudinal expansion may affect:
  (1) the phase space for Brehmsstralung,
  (2) the emission rate of medium-induced radiations.

The DL boundary in a Bjorken expanding medium

PC, Iancu, Soyez, 2012.01457

- The criterion for an emission to be VL:

$$k_\perp^2 \simeq \omega^2\theta^2 \gg \int_{t_0}^{t_f} \hat{q}(t)dt \overset{\text{ideal gas}}{=} \hat{q}(t_0)t_0 \ln(t_f/t_0)$$

- At leading log, one can neglect the slowly varying function $\ln(\ln(t_f/t_0))$ and get

$$\omega\theta \gg \hat{q}_0 t_0$$

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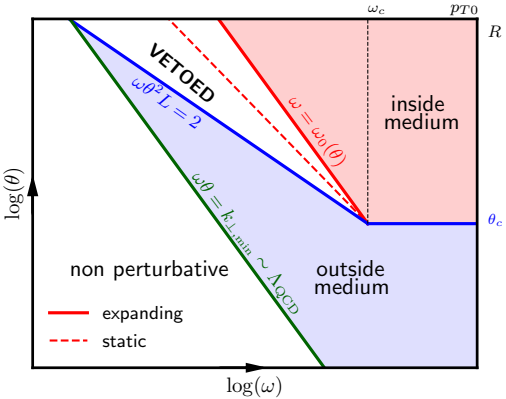


Effect of the longitudinal expansion on the MIEs

- Quasi-local process: essentially a change in the emission *rate*:

$$\mathrm{d}P = \frac{\alpha_s C_R}{\pi}\sqrt{\frac{\hat{q}(t)}{\omega}}\mathrm{d}t$$

- This change can be absorbed by a redefinition of the "time"

$$\mathrm{d}\tau = \sqrt{\frac{\hat{q}(t)}{E}}\mathrm{d}t$$

- Equivalently, one can define the quenching parameter of an equivalent static medium

$$\hat{q}_{\mathrm{stat}} = \left(\frac{1}{L-t_0}\int_{t_0}^{L}\mathrm{d}t\,[\hat{q}(t)]^{1/2}\right)^2$$

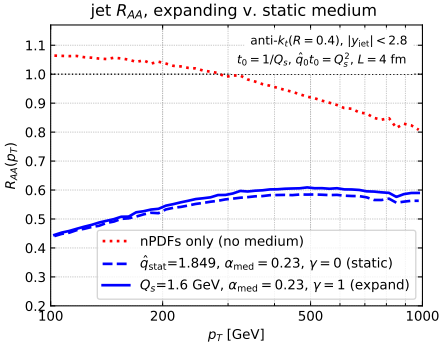
which satisfies $\tau(L) = \sqrt{\hat{q}_{\mathrm{stat}}}(L-t_0)$ Adhya, Salgado, Spousta, Tywoniuk, arxiv:1911.12193

See also talks by C. Andres and S. Adhya

Effect of the expansion on R_{AA}

PC, Iancu, Soyez, 2012.01457

- This rescaling behaviour is (mildly) violated by transverse diffusion and VLEs.

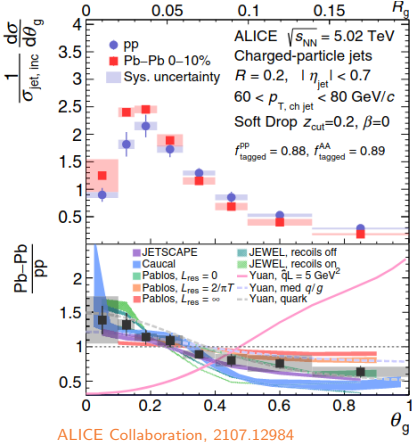


- Also violated by single hard scattering contributions. Adhya, Salgado, Spousta, Tywoniuk, arxiv:1911.12193

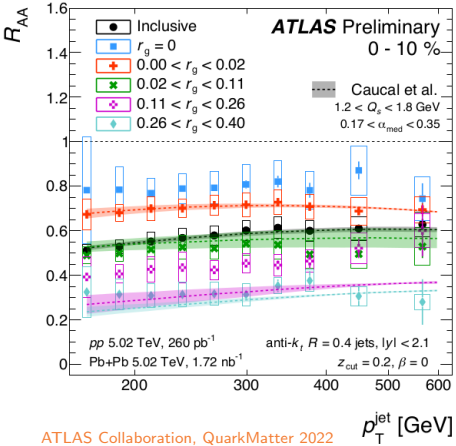
Color coherence in phenomenology: "filter" effect revealing θ_c

- Substructure observable like the SoftDrop θ_g distribution.
- Correlation between R_{AA} and θ_g.

See talks by M. Verweij, L. Havener and R. Ehlers

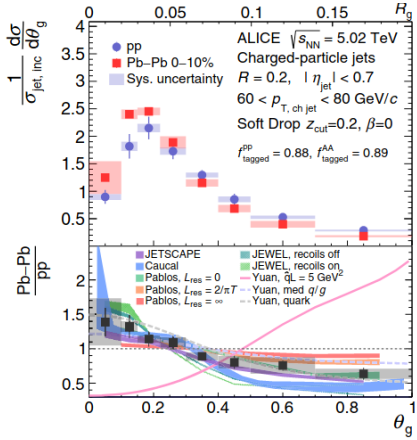


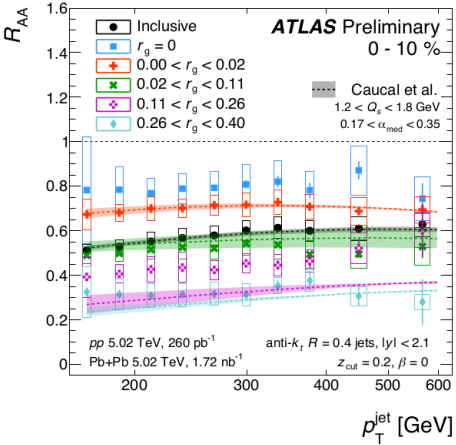
ALICE Collaboration, 2107.12984



ATLAS Collaboration, QuarkMatter 2022

Color coherence in phenomenology: "filter" effect revealing θ_c





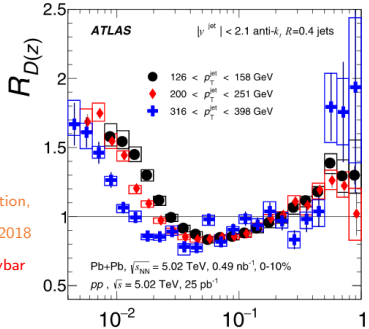
Towards a measurement of θ_c?

Bias toward jets losing less energy leads to a filter effects for jets with $\theta \leq \theta_c$, therefore revealing the θ_c angular scale. See also talk by A. Takacs

Color decoherence in phenomenology: soft particles multiplicity

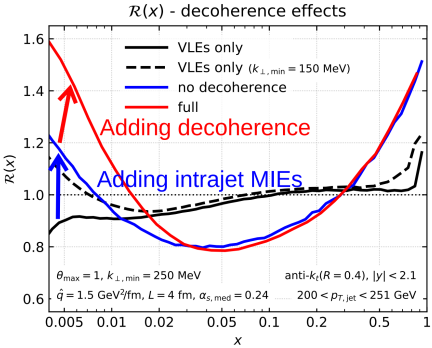
Monte Carlo and analytic tests of various mechanisms PC, Iancu, Mueller, Soyez, 2005.05852

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



ATLAS Collaboration, Phys. Rev. C98, 2018

See talk by M. Rybar



Towards a complete event generator in HIC

New theoretical and numerical developments

- Improve the in-medium vacuum-like cascade:
  - Logarithmic accuracy: full LL, NLL?
  - Use dipoles. $\Rightarrow$ dijet asymmetry and γ-jet $x_{\gamma J}$.
- Improve medium-induced physics
  - Account for (rare) hard scatterings in a consistent way.
  - Include recent exciting developments in the computation of medium-induced emissions spectra.

    See talks by F. Dominguez, I. Soudi, J. Isaksen, Y. Mehtar-Tani,...
  - ...
- Improve modeling aspects: geometry, in-medium hadronization,...

Summary

- Factorized picture of jet evolution in a dense QCD medium.
- Systemically improvable both on the vacuum-like or medium-induced sides.
- Displays good qualitative agreement for jet observables under pQCD control
  $\Rightarrow$ needs global studies to disentangle the contributions of each mechanism.

THANK YOU!