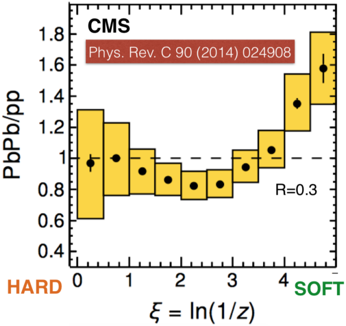
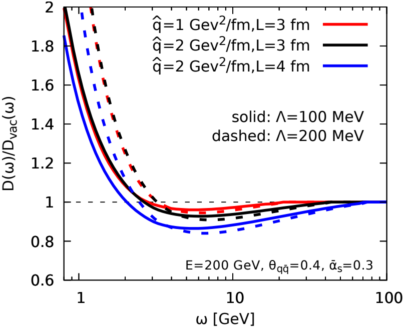
Vacuum-like jet fragmentation in a dense QCD medium

Edmond Iancu
IPhT Saclay & CNRS

with P. Caucal, A. H. Mueller and G. Soyez, PRL 120 (2018) 232001



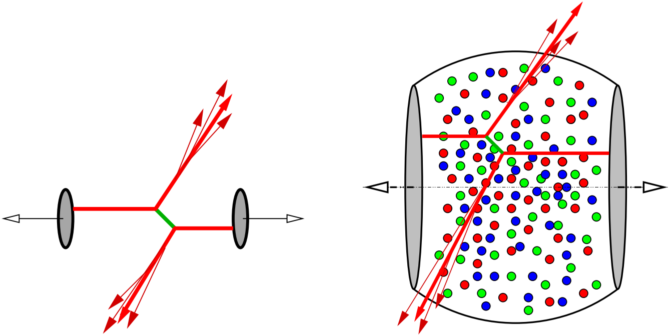


Outline

- A (very) brief introduction
  - jets in p+p and Pb+Pb collisions at the LHC
  - di-jet asymmetry in Pb+Pb collisions
- Medium-induced radiation
  - transverse momentum broadening, BDMPS-Z spectrum
  - multiple branchings and di-jet asymmetry
- Vacuum-like emissions in Pb+Pb collisions
  - medium effects on phase-space and angular ordering
  - factorization in the double logarithmic approximation
- Consequences for the jet fragmentation function
- Conclusions and perspectives

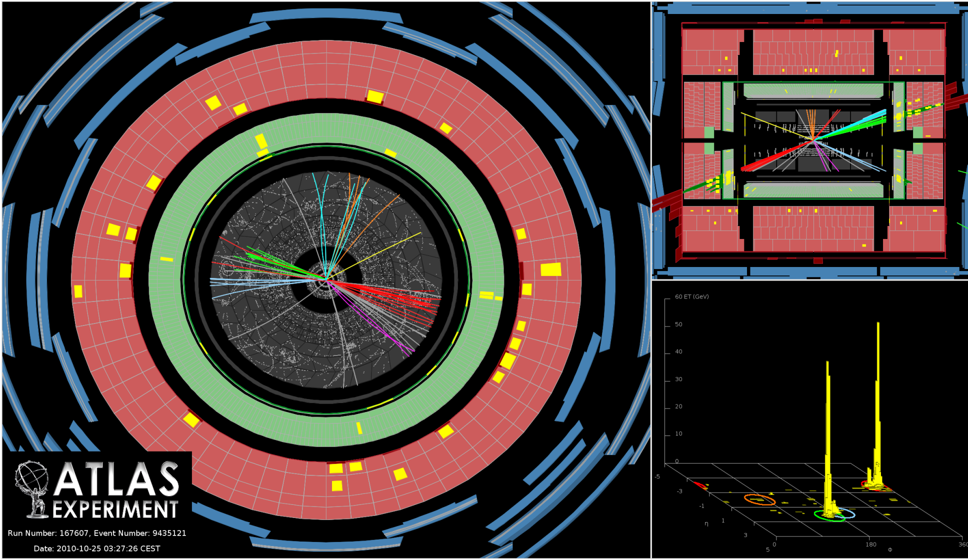
Jets: pp vs. AA collisions at the LHC

- Hard processes in QCD typically create pairs of partons which propagate back–to–back in the transverse plane
- In the "vacuum" (pp collisions), this leads to a pair of symmetric jets
- A spray of collimated particles produced via radiation (parton branching)

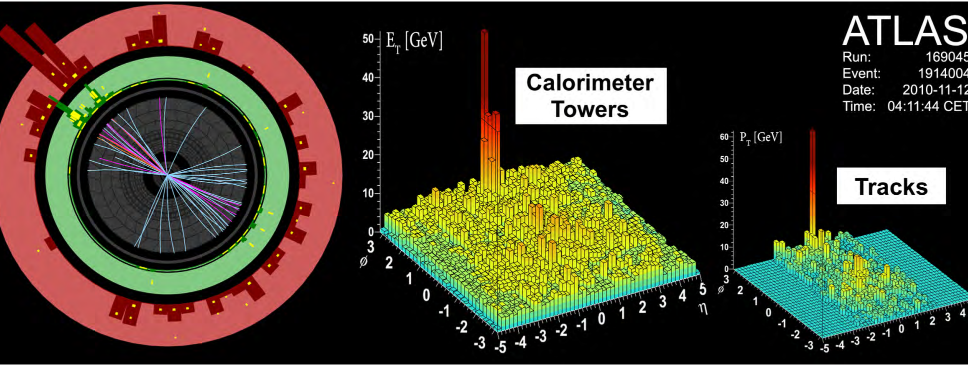


- In AA collisions, the two jets can be differently affected by their interactions with the surrounding, partonic, medium: quark-gluon plasma

From di–jets in p+p collisions ...

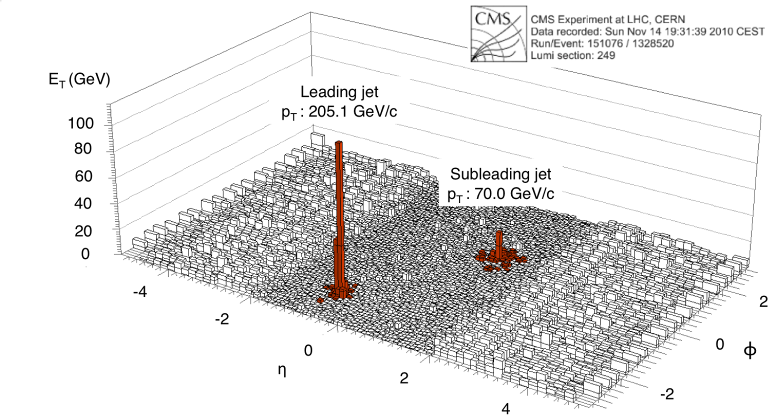


... to "mono-jets" in Pb+Pb collisions



- Central Pb+Pb: 'mono–jet' events
- The secondary jet can barely be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV

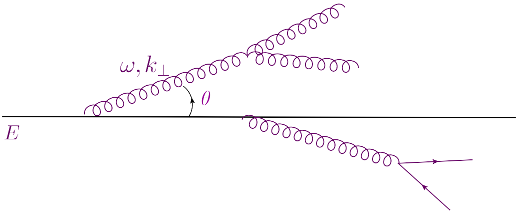
Di–jet asymmetry at the LHC



- Huge difference between the energies of the two jets
- The missing energy is found in the underlying event:
    - many soft ($p_\perp < 2$ GeV) hadrons propagating at large angles
- Very different from the usual jet fragmentation pattern in the vacuum

Bremsstrahlung in the vacuum

- In-vacuum radiation is triggered by the parton virtualities
  - via collisions, particles are created "off-shell" (in an excited state)
  - they radiate gluons in order to return "on-shell" (in the stable state)
- Bremsstrahlung favors soft & collinear splittings



$$\mathrm{d}\mathcal{P} = \frac{\alpha_s C_R}{\pi}\,\frac{\mathrm{d}\omega}{\omega}\,\frac{\mathrm{d}k_\perp^2}{k_\perp^2}$$

  - small angle emissions $k_\perp \simeq \omega\theta$ with $\theta \ll 1 \Rightarrow$ jets are collimated
  - many soft gluons ... but they carry very little energy
  - most of the energy remains in the few partons with large $x \equiv \omega/E$

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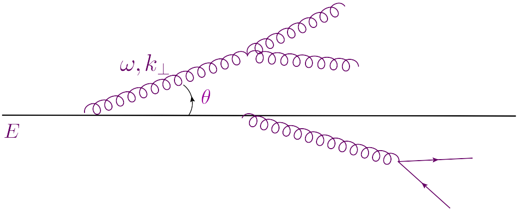
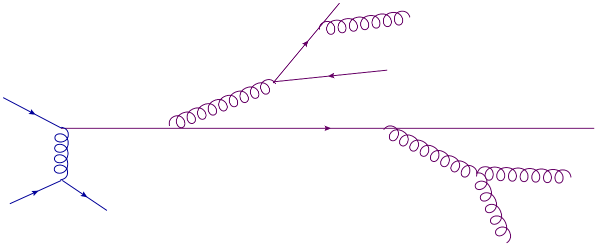


$$\mathrm{d}\mathcal{P} = \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}$$

- The main question: how to transfer a large fraction of the jet energy to (necessarily many) soft constituents ?

Medium-induced jet evolution

- The leading particle (LP) is produced by a hard scattering
- It subsequently evolves via radiation (branchings) ...



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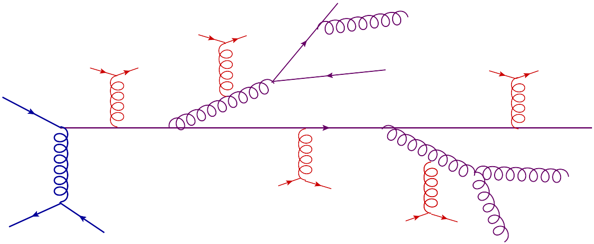

- ... and via collisions off the medium constituents

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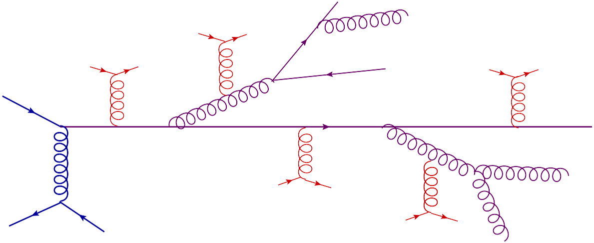
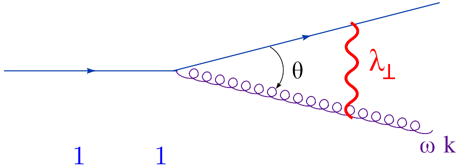


- ... and via collisions off the medium constituents
- Collisions can have several effects
  - transfer energy and momentum between the jet and the medium
  - trigger additional radiation
- If the medium is dense enough, the QCD coupling is weak $\Longrightarrow$ pQCD

Radiation: Formation time

- Uncertainty principle: quantum particles are delocalized
- The gluon has been emitted when it has no overlap with its source



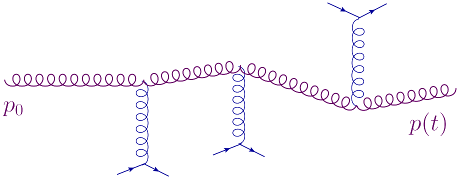
$$\lambda_\perp = \frac{1}{k_\perp} \simeq \frac{1}{\omega\theta}$$

$$\Delta x_\perp \simeq \theta\,\Delta t \gtrsim \lambda_\perp \Longrightarrow \Delta t \gtrsim t_f \equiv \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\theta^2}$$

- "Formation time" : the time it takes to emit a gluon
- This argument universally applies to radiation: in vacuum & in the medium
- In vacuum, t_f is measured from the hard scattering

Transverse momentum broadening

- In medium, there is additional radiation triggered by the collisions
- Collisions randomly transfer energy and momentum
- Energy loss (drag) and broadening of the momentum distribution (diffusion)



$$\langle p_z(t)\rangle \simeq p_0 - \eta t$$

$$\langle p_\perp^2(t)\rangle \simeq \hat{q} t$$

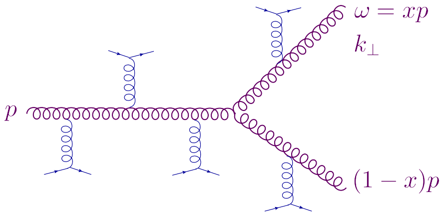
- Jet quenching parameter $\hat{q}$: squared momentum transfer per unit time

$$\hat{q} \simeq \alpha_s^2 T^3 \ln \frac{1}{\alpha_s}$$

- An average value (theory and data): $\hat{q} \simeq 1 \div 2\,\mathrm{GeV}^2/\mathrm{fm}$

Medium induced radiation

- In the medium, there is a lower limit on the transverse momentum ...



$$t_f = \frac{\omega}{k_\perp^2} \quad \& \quad k_\perp^2 \gtrsim \hat{q} t_f$$

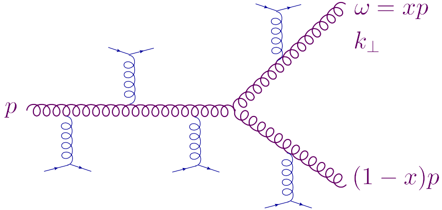
$$t_f \lesssim \sqrt{\frac{\omega}{\hat{q}}}$$

$$t_f < L \implies \omega \le \omega_c \equiv \hat{q} L^2$$

- ... hence an upper limit on the formation time !
- Two types of emissions:
  - vacuum-like: $k_\perp^2 \gg \sqrt{\hat{q}\omega}$, or $t_f \ll \sqrt{\omega/\hat{q}}$
  - medium-induced: $k_\perp^2 \simeq \sqrt{\hat{q}\omega}$, or $t_f \simeq \sqrt{\omega/\hat{q}}$
- Medium-induced gluons have $\omega \le \omega_c$ ... but $\omega_c \simeq 50$ GeV for $L = 4$ fm

The BDMPS-Z spectrum

(Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov; 1996-97)



$$t_{\rm f} \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

$$t_{\rm f} < L \implies \omega \le \omega_c \equiv \hat{q}L^2$$

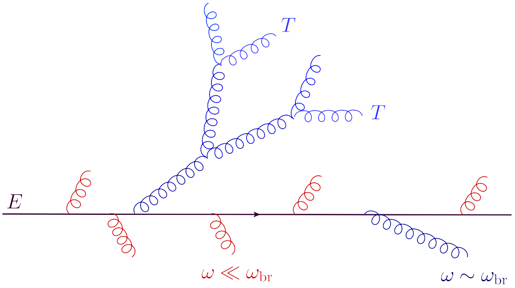
- Medium-induced emissions can occur anywhere inside the medium:

$$\mathrm{d}\mathcal{P} \sim \alpha_s \frac{\mathrm{d}\omega}{\omega}\frac{L}{t_{\rm f}(\omega)} \sim \alpha_s \sqrt{\hat{q}L^2}\,\frac{\mathrm{d}\omega}{\omega^{3/2}}$$

- The average energy loss by the leading particle: $\langle \Delta E\rangle_{\rm LP} \sim \alpha_s\omega_c = \alpha_s\hat{q}L^2$
  - a relatively hard, $\omega \sim \omega_c$, but rare, $\mathcal{P} \sim \mathcal{O}(\alpha_s)$, emission
- Multiple branching becomes important when $\omega \lesssim \omega_{\rm br} \equiv \alpha_s^2\hat{q}L^2$

Multiple branching & wave turbulence

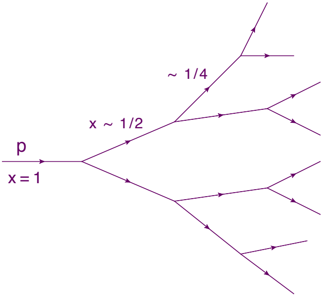
J.-P. Blaizot, E. I., Y. Mehtar-Tani, PRL 111, 052001 (2013)

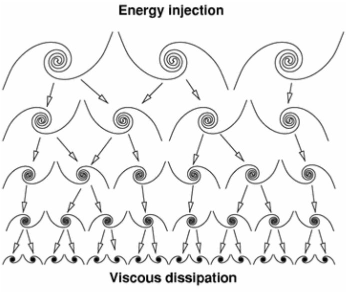


- In a typical event, the LP emits a number of $\mathcal{O}(1)$ of gluons with $\omega \sim \omega_{\rm br}$
- Primary gluons generate 'mini-jets' via democratic branchings: $x \sim 1-x$
  - energy is transmitted to many soft quanta which thermalize: $\omega \sim T$
- Energy loss by the jet at large angles: $\langle \Delta E \rangle_{_{\rm J}} \sim \omega_{\rm br} \sim \alpha_s^2 \hat{q} L^2$
- A natural explanation for the di-jet asymmetry

Wave turbulence

- Democratic branchings lead to wave turbulence
  - energy flows from one parton generation to the next one, at a rate which is independent of the generation
  - it eventually dissipates into the medium, via thermalization



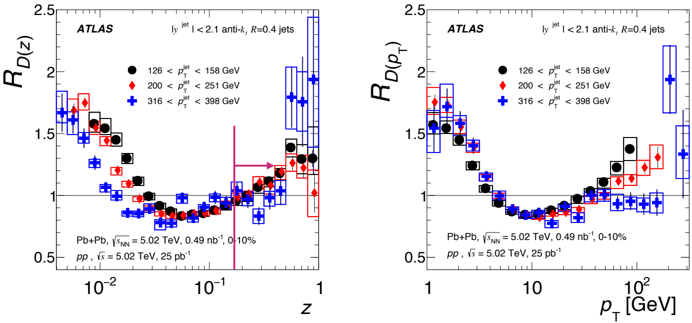


- Exact solutions $D = 1 + 1$ (time+energy): strong fluctuations, KNO scaling

Intra-jet nucler modifications

- The LHC data also show nuclear modifications for the energy distribution inside the jet cone $(\theta < R = 0.4)$

ratios of fragmentation functions in PbPb / pp



1805.05424 Martin Rybar, Wednesday 7

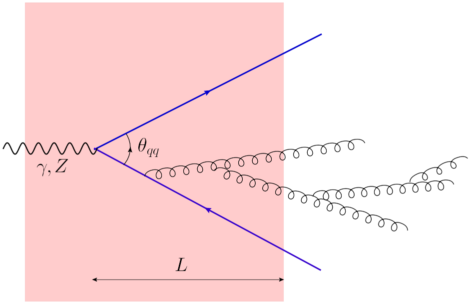
Jet fragmentation function: $D(\omega) \equiv \omega \frac{\mathrm{d}N}{\mathrm{d}\omega}$

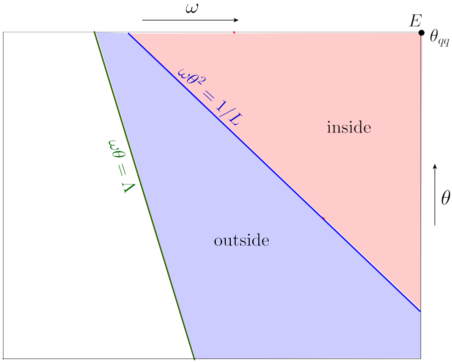
- Can vacuum-like radiation be modified by the medium ?

Vacuum-like emissions (VLE)

P. Caucal, E.I., A. H. Mueller and G. Soyez, arXiv:1801.09703 (PRL)

- A jet initiated by a colorless $q\bar{q}$ antenna (decay of a boosted γ or Z)
- The antenna propagates through the medium along a distance L





- Emissions $\left(t_f = \frac{1}{\omega\theta^2}\right)$ can occur either inside $(t_f \le L)$, or outside $(t_f > L)$
- Evolution stopped by hadronisation: $k_\perp \simeq \omega\theta \gtrsim \Lambda_{QCD}$

The vetoed region

- Remember: the medium introduces an upper limit on the formation time

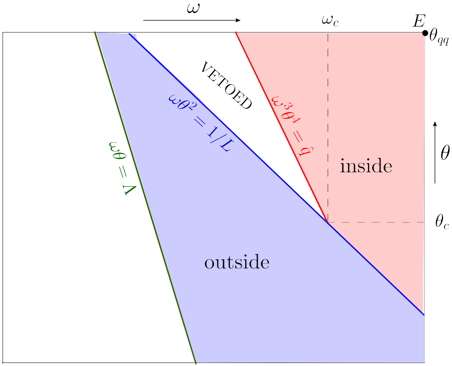
$$t_{\rm f} \lesssim \sqrt{\frac{\omega}{\hat{q}}} \leq L$$

- No emission within the range

$$\sqrt{\frac{\omega}{\hat{q}}} < \frac{1}{\omega\theta^2} < L$$

- End point of VETOED at

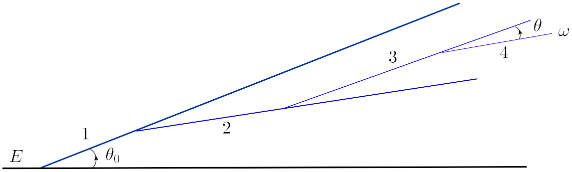
$$\omega_c = \hat{q}L^2\,, \quad \theta_c = \frac{1}{\sqrt{\hat{q}L^3}}$$



- VLEs in medium occur like in vacuum, but with a smaller phase-space
  - gluons within VETOED should have $k_\perp^2 \ll \hat{q}t_{\rm f}$, which is not possible
  - a leading-twist effect: DGLAP splitting functions
  - typical values: $\hat{q} = 1\,{\rm GeV}^2/{\rm fm}$, $L = 4\,{\rm fm}$, $\omega_c = 50\,{\rm GeV}$, $\theta_c = 0.05$

Jet in the vacuum (DLA)

- Radiation triggered by the parton virtualities: bremsstrahlung



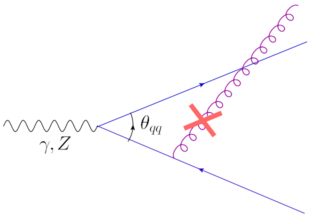
$$\mathrm{d}\mathcal{P} \simeq \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2}$$

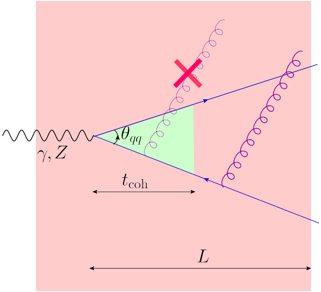
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons
- Parton cascades: successive emissions are ordered in
  - energy ($\omega_i < \omega_{i-1}$), by energy conservation
  - angle ($\theta_i < \theta_{i-1}$), by color coherence
- Double-logarithmic approximation (DLA): strong double ordering

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2} \simeq \frac{\bar{\alpha}}{\omega\, \theta^2} \sum_{n\geq 0} \bar{\alpha}^n \left[\frac{1}{n!}\left(\ln\frac{E}{\omega}\right)^n\right] \left[\frac{1}{n!}\left(\ln\frac{\theta_0^2}{\theta^2}\right)^n\right]$$

Color (de)coherence

- In vacuum, wide angle emissions ($\theta > \theta_{q\bar{q}}$) are suppressed by color coherence
  - the gluon has overlap with both the quark and the antiquark





- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

$$\hat{q}t \gtrsim \frac{1}{r_\perp^2(t)} \sim \frac{1}{(\theta_{q\bar{q}}t)^2} \implies t \gtrsim t_{\rm coh} = \frac{1}{(\hat{q}\theta_{q\bar{q}}^2)^{1/3}}$$

(Mehtar-Tani, Salgado, Tywoniuk; Casalderrey-Solana, E. I., 2010–12)

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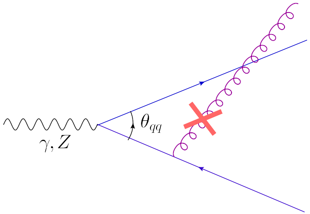
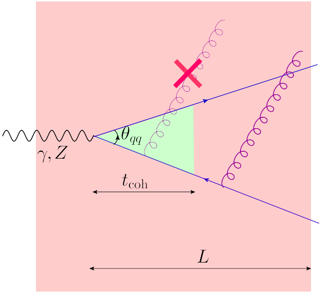




- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

$$t_{\rm coh} = \frac{1}{(\hat{q}\theta_{q\bar{q}}^2)^{1/3}} \ll L \quad \text{if} \quad \theta_{q\bar{q}} \gg \theta_c \simeq 0.05$$

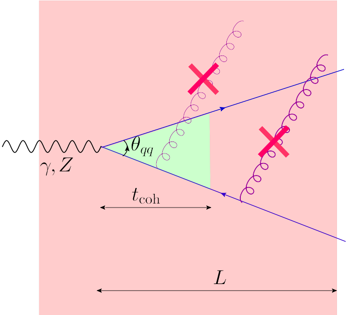
- Standard lore: "Angular ordering is violated for emissions in the medium."

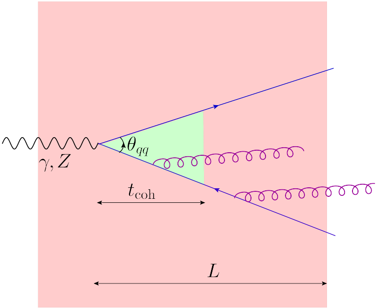
Angular ordering strikes back

- ... But this is not the case for VLEs inside the medium !

$$\theta > \theta_{q\bar{q}} \quad \& \quad \omega \gg \left(\frac{\hat{q}}{\theta^4}\right)^{\frac{1}{3}} \implies t_{\rm f} = \frac{1}{\omega\theta^2} \ll t_{\rm coh}$$

- Wide angle emissions ($\theta > \theta_{q\bar{q}}$) are still suppressed, like in the vacuum



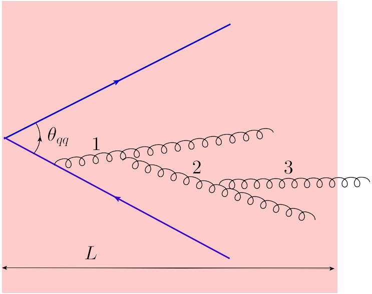


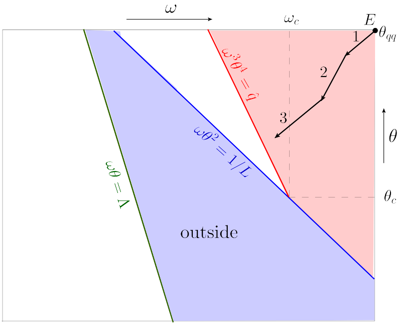
- Emissions at smaller angles ($\theta < \theta_{q\bar{q}}$) can occur at any time

- DLA cascades inside the medium are still strongly ordered in angles

There is a life after formation ...

- The VLEs inside the medium have short formation times $t_{\rm f} \ll L$
- After formation, gluons propagate in the medium along a distance $\sim L$

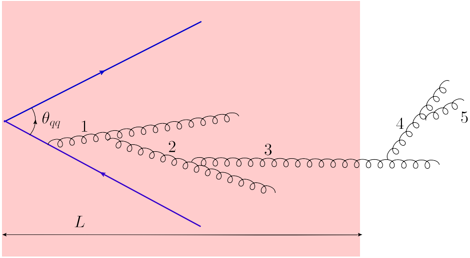


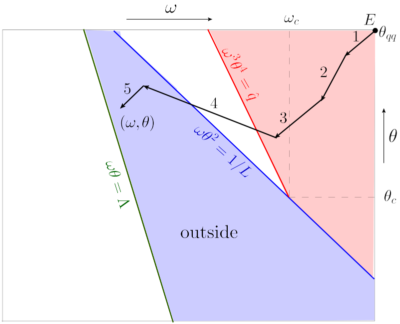


- They can suffer significant energy loss and momentum broadening
  - additional sources for medium-induced radiation
- They contribute to the jet multiplicity (fragmentation function)
- They can emit (vacuum-like) gluons outside the medium

First emission outside the medium

- The respective formation time is necessarily large: $t_{\rm f} \gtrsim L$
- An antenna with opening angle $\theta \gg \theta_c$ loses coherence in a time $t_{\rm coh} \ll L$



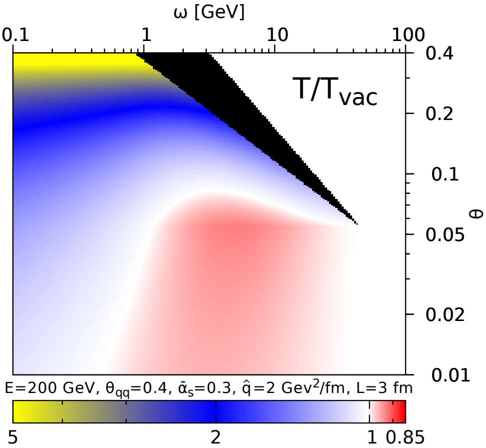


- In-medium sources lose color coherence and can also radiate at larger angles
- After the first "outside" emission, one returns to angular-ordering, as usual
- Medium effects at DLA (leading twist):
  vetoed region + lack of angular-ordering for the first "outside" emission

Gluon distribution at DLA

- Double differential distribution in energies and emission angles:

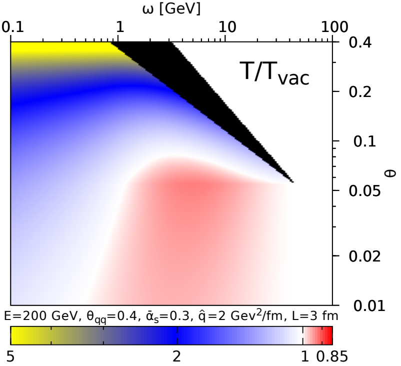
$$T(\omega,\theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$$

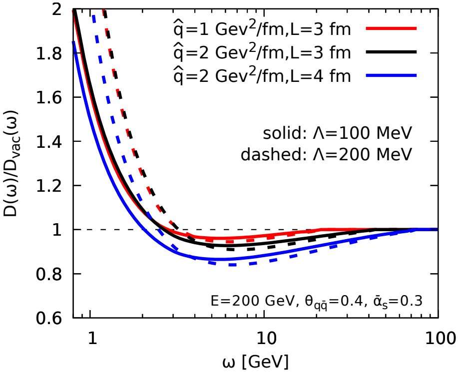


- $E = 200\,\mathrm{GeV}, \quad \theta_{q\bar{q}} = 0.4$
- $\hat{q} = 2\,\mathrm{GeV}^2/\mathrm{fm}, \quad L = 3\,\mathrm{fm}$
- $T/T_{\rm vac} = 0$ in the excluded region
- $T/T_{\rm vac} = 1$ inside the medium and also for $\omega > \omega_c$ and any θ
- $T/T_{\rm vac} < 1$ outside the medium at small angles $\lesssim \theta_c$
- $T/T_{\rm vac} > 1$ outside the medium at large angles $\sim \theta_{q\bar{q}}$

Jet fragmentation function at DLA

$$D(\omega) \equiv \omega \frac{\mathrm{d}N}{\mathrm{d}\omega} = \int_{\Lambda^2/\omega^2}^{\theta^2_{q\bar{q}}} \frac{\mathrm{d}\theta^2}{\theta^2} T(\omega, \theta)$$

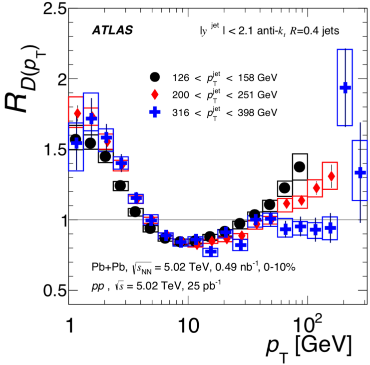


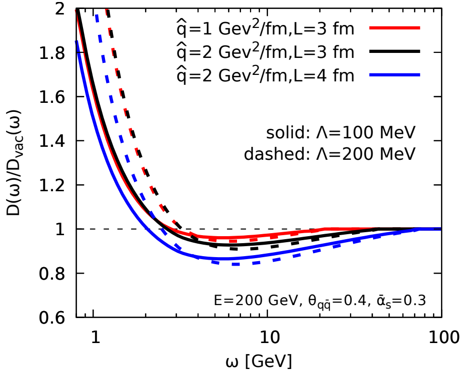


- Slight suppression at intermediate energies (from 3 GeV up to ω_c)
  - the phase-space is reduced by the vetoed region
  - the amount of suppression increases with L, $\hat{q}$ and E

Jet fragmentation function at DLA

$$D(\omega) \equiv \omega \frac{\mathrm{d}N}{\mathrm{d}\omega} = \int_{\Lambda^2/\omega^2}^{\theta_{q\bar{q}}^2} \frac{\mathrm{d}\theta^2}{\theta^2} T(\omega, \theta)$$





- Significant enhancement at low energy (below 2 GeV)
  - lack of angular ordering for the first emission outside the medium
- Qualitative agreement with data ... but more studies are needed

Conclusions & perspectives

- Vacuum-like emissions inside the medium can be factorized from the medium-induced radiation via systematic approximations in pQCD
- Medium effects enter already at leading-twist level :
  - reduction in the phase-space for VLEs inside the medium
  - violation of angular ordering by the first emission outside the medium
- Angular ordering is preserved for VLEs inside the medium, like in the vacuum
- Qualitative agreement with the LHC data for jet fragmentation
- VLEs inside the medium act as sources for medium-induced radiation
- DLA: fine for multiplicity, but not for energy flow
- Probabilistic picture, well suited for Monte-Carlo implementations