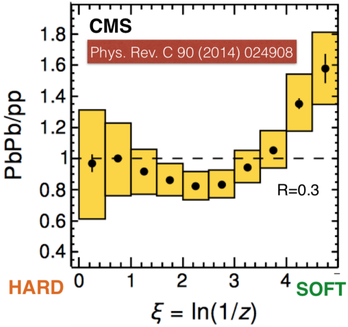
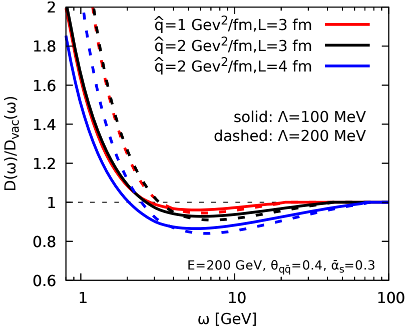
Jet evolution in a dense QCD medium

Edmond Iancu
IPhT Saclay & CNRS

based on work with J.-P. Blaizot, P. Caucal, F. Dominguez, Y. Mehtar-Tani, A. H. Mueller, and G. Soyez (2013-18)



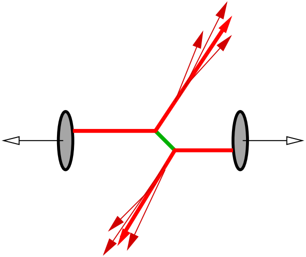


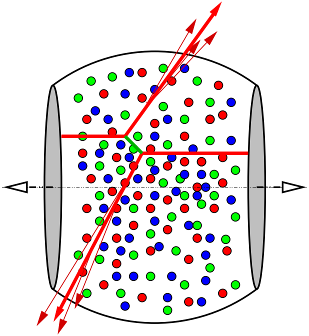
Outline

- Jets in heavy ion collisions
  - jet quenching
  - di-jet asymmetry, fragmentation functions
- Two types of radiation
  - vacuum-like: bremsstrahlung (parton virtualities)
  - medium-induced radiation : BDMPS-Z (collisions in the plasma)
- Separately well understood
- How to combine them together (within pQCD) ?
- How is the "vacuum-like" radiation modified by the medium ?

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)

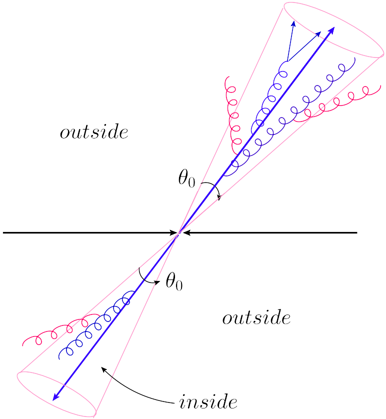




- In AA collisions, the two jets can be differently affected by their interactions with the surrounding, partonic, medium: quark-gluon plasma

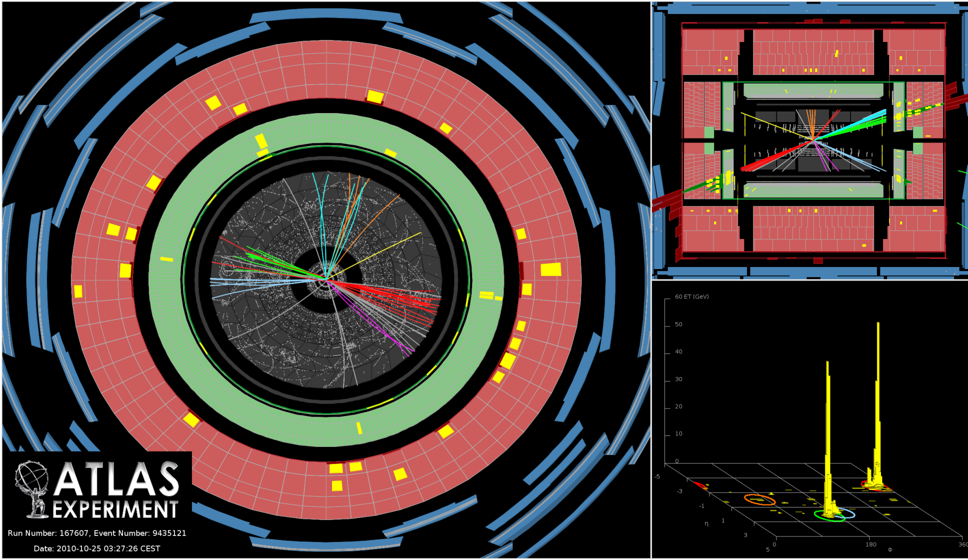
Jets in practice

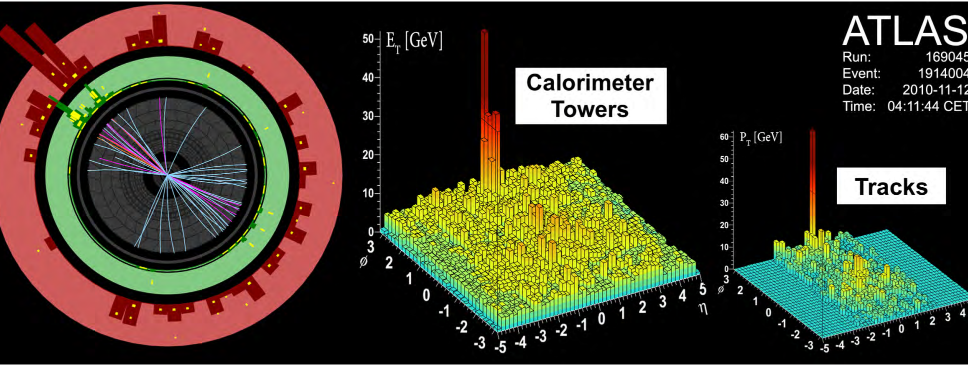
- Experimentally, jets are constructed by grouping together hadrons which propagate at nearby angles
- The jet opening angle θ_0 (a.k.a. R) is the same for both jets



- Medium modifications refer both to the jets and to the outer regions

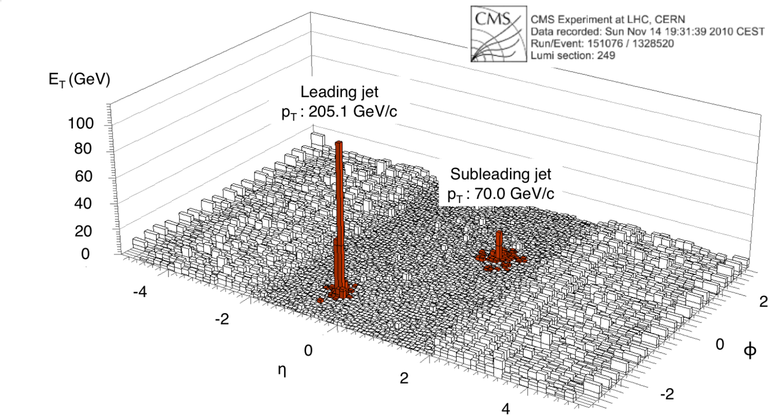
From di–jets in p+p collisions ...





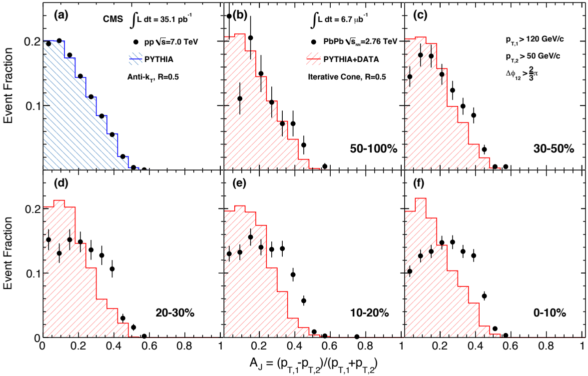
- Central Pb+Pb: ‘mono–jet’ events
- The secondary jet can barely be distinguished from the background: $E_{T1} \geq 100$ GeV, $E_{T2} > 25$ GeV

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

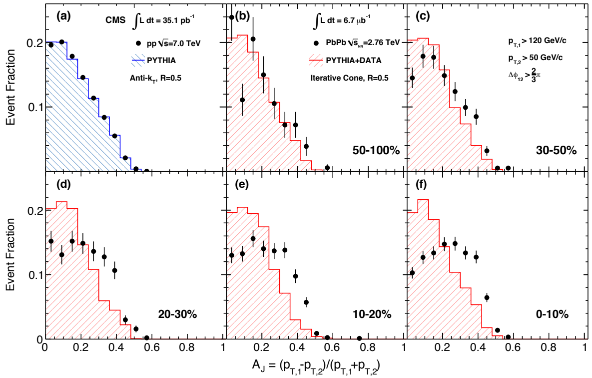
Di–jet asymmetry : A_J



- Event fraction as a function of the di–jet energy imbalance in p+p (a) and Pb+Pb (b–f) collisions for different bins of centrality

$$A_J = \frac{E_1 - E_2}{E_1 + E_2} \qquad (E_i \equiv p_{T,i} = \text{ jet energies})$$

Di–jet asymmetry : A_J

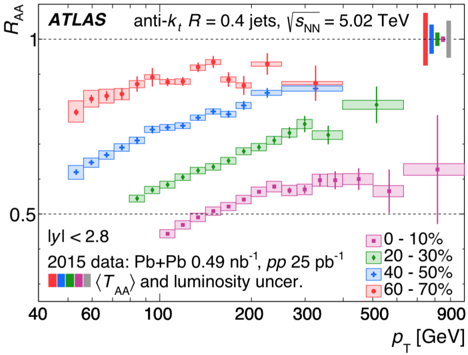


- N.B. A pronounced asymmetry already in p+p collisions !
  - 3-jets events, fluctuations in the branching process
- Central Pb+Pb : the asymmetric events occur more often

The nuclear modification factor for jets

- The jet yield in Pb+Pb collisions normalized by p+p times the average nuclear thickness function $\langle T_{AA} \rangle$

$$R_{AA} \equiv \frac{\frac{1}{N_{\mathrm{evt}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}y}\Big|_{AA}}{\langle T_{AA} \rangle \frac{\mathrm{d}^2 \sigma_{\mathrm{jet}}}{\mathrm{d}p_T \mathrm{d}y}\Big|_{pp}}$$



- R_{AA} would be equal to one in the absence of nuclear effects
- stronger suppression for more central collisions

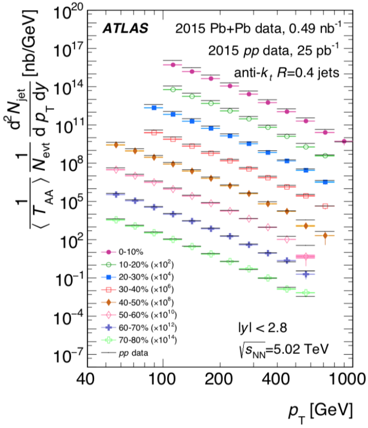
- Naturally interpreted as a consequence of energy loss inside the medium

The nuclear modification factor for jets

- The jet yield in Pb+Pb collisions normalized by p+p times the average nuclear thickness function $\langle T_{AA} \rangle$

$$R_{AA} \equiv \frac{\frac{1}{N_{\rm evt}} \frac{{\rm d}^2 N_{\rm jet}}{{\rm d}p_T {\rm d}y}\Big|_{AA}}{\langle T_{AA} \rangle \frac{{\rm d}^2 \sigma_{\rm jet}}{{\rm d}p_T {\rm d}y}\Big|_{pp}}$$

- jet spectra are rapidly decreasing with p_T
- they are shifted towards lower p_T due to in-medium energy loss



- R_{AA} is almost flat at very high p_T: energy loss increases with p_T

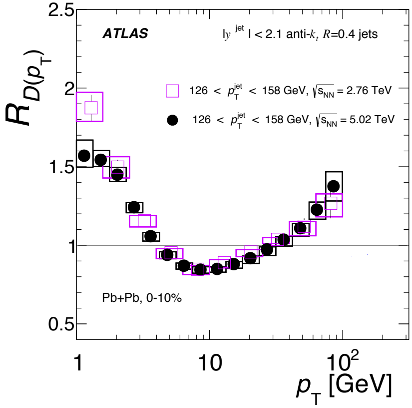
Intra-jet nuclear modifications

- Jet fragmentation function: energy distribution of hadrons inside the jet

$$D(\omega) \equiv \omega \frac{\mathrm{d}N}{\mathrm{d}\omega}$$

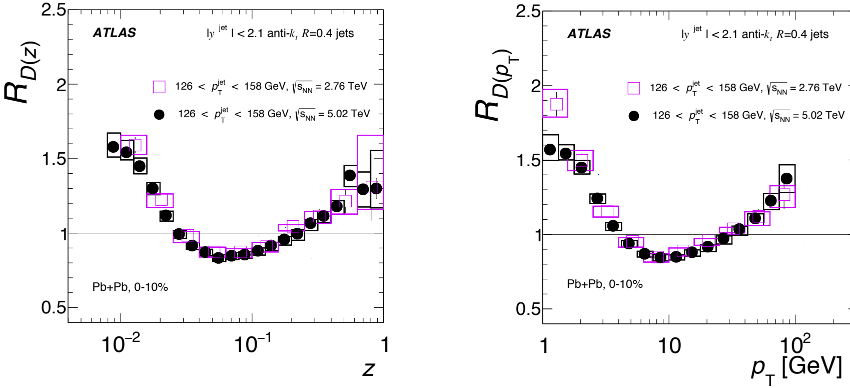
$$= \int_0^R \mathrm{d}\theta \; \omega \frac{\mathrm{d}N}{\mathrm{d}\theta \mathrm{d}\omega}$$

- $\omega \equiv p_T$ of a hadron inside the jet
- ratio of FFs in Pb+Pb and p+p
- slight suppression at intermediate energies
- enhancement at low energies ($z \ll 1$)



Intra-jet nuclear modifications

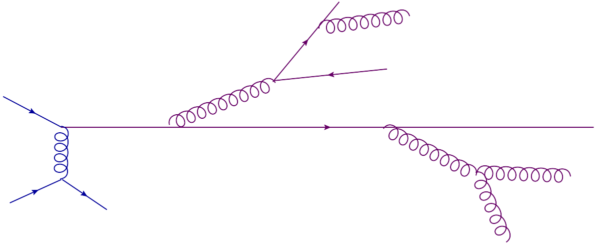
- Jet fragmentation function: energy distribution of hadrons inside the jet
- Similar pattern when the distribution is plotted vs. p_T or vs. $z = p_T/p_T^{jet}$



- Two classes of nuclear modifications: inside & outside the jet cone
- We shall argue that they refer to two different types of radiation

Medium-induced jet evolution

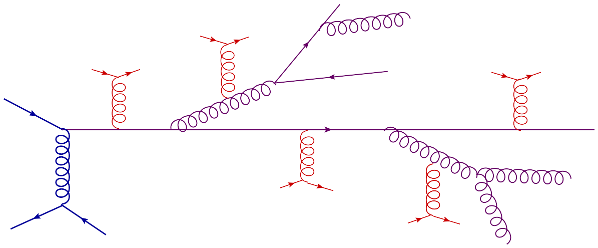
- The leading particle (LP) is produced by a hard scattering
- It subsequently evolves via radiation (branchings) ...



- ... 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 ("medium-induced")
  - wash out the color coherence (destroy interference pattern)

Medium-induced jet evolution

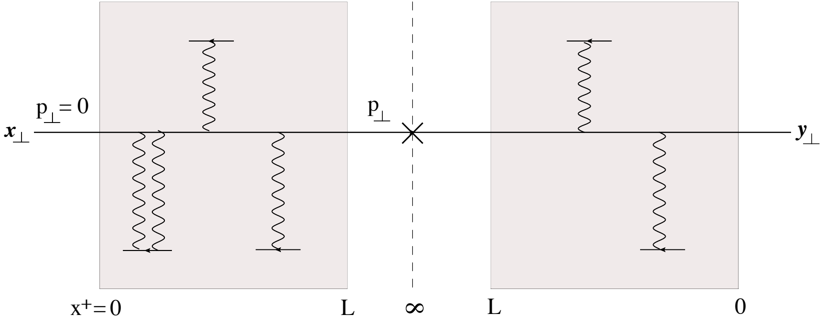
- The leading particle (LP) is produced by a hard scattering
- It subsequently evolves via radiation (branchings) ...



- ... 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 ("medium-induced")
  - wash out the color coherence (destroy interference pattern)

Transverse momentum broadening

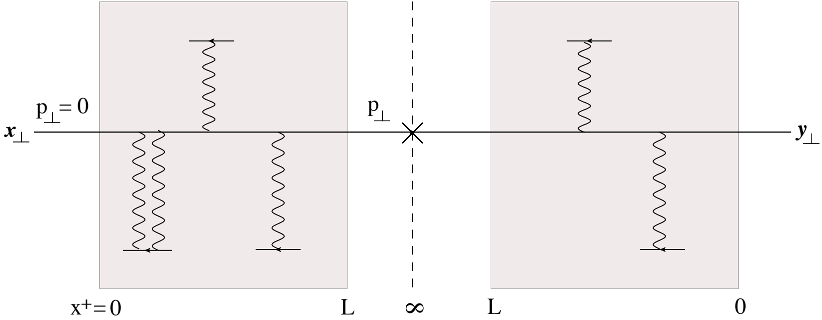
- An energetic quark acquires a transverse momentum $p_\perp$ via collisions in the medium, after propagating over a distance L



- Direct amplitude (DA) $\times$ Complex conjugate amplitude (CCA)
- Weakly coupled medium $\Longrightarrow$ independent scattering centers
- A random walk in $p_\perp$: $\langle p_\perp^2 \rangle \simeq \hat{q}\, L$

Dipole picture

- The individual collisions are relatively soft : $k_\perp \sim m_D \ll E$

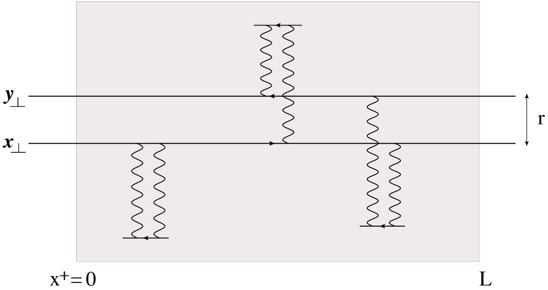


- Scattering can be computed in the eikonal approximation: Wilson lines

$$V^\dagger(\boldsymbol{x}) = \mathrm{P}\exp\left\{ \mathrm{i}g \int \mathrm{d}x^+ A_a^-(x^+, \boldsymbol{x}) t^a \right\}$$

- Two such Wilson lines (DA $\times$ CCA) $\Longrightarrow$ a $q\bar{q}$ color dipole

Dipole picture



$$\frac{dN}{d^2\boldsymbol{p}} = \frac{1}{(2\pi)^2}\int_{\boldsymbol{r}} e^{-i\boldsymbol{p}\cdot\boldsymbol{r}}\langle\hat{S}_{\boldsymbol{xy}}\rangle\,, \qquad \hat{S}_{\boldsymbol{xy}} \equiv \frac{1}{N_c}\,\mathrm{tr}\big(V_{\boldsymbol{x}}^\dagger V_{\boldsymbol{y}}\big)$$

- Average over the Gaussian distribution of the color fields $A_a^-(x^+, \boldsymbol{x})$:

$$\big\langle A_a^-(x^+, \boldsymbol{k})\, A_b^-(y^+, -\boldsymbol{k})\big\rangle_0 = n\,\delta_{ab}\delta(x^+ - y^+)\,\frac{g^2}{(\boldsymbol{k}^2 + m_D^2)^2}$$

- $n = C_F n_q + N_c n_g \sim T^3$: color weighted density of thermal quarks & gluons

The tree-level approximation ("MV model")

$$\langle \hat{S}_{\boldsymbol{xy}} \rangle_0 \simeq \exp\left\{ -\frac{1}{4} L\hat{q}_0(1/r^2)\, \boldsymbol{r}^2 \right\}$$

- The tree-level jet quenching parameter $\hat{q}_0$ (logarithmic scale dependence):

$$\hat{q}_0(Q^2) \equiv n g^4 C_F \int^{Q^2} \frac{\mathrm{d}^2\boldsymbol{k}}{(2\pi)^2} \frac{\boldsymbol{k}^2}{(\boldsymbol{k}^2 + m_D^2)^2} \simeq 4\pi\alpha_s^2 C_F n \ln \frac{Q^2}{m_D^2}$$

- The cross–section for $p_\perp$–broadening at tree-level:

$$\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{p}} = \frac{1}{(2\pi)^2} \int_{\boldsymbol{r}} \mathrm{e}^{-\mathrm{i}\boldsymbol{p}\cdot\boldsymbol{r}}\, \mathrm{e}^{-\frac{1}{4}L\hat{q}_0(1/r^2)\,\boldsymbol{r}^2} \simeq \frac{1}{\pi Q_s^2}\, \mathrm{e}^{-p_\perp^2/Q_s^2}$$

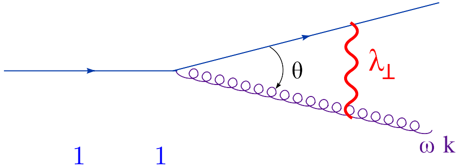
- A random walk in transverse momentum: $\langle p_\perp^2 \rangle = Q_s^2(L) \equiv L\hat{q}_0(Q_s^2)$

- Power-law tail at large $p_\perp \gg Q_s$: single hard scattering

$$\frac{\mathrm{d}N}{\mathrm{d}^2\boldsymbol{p}} \simeq \frac{1}{(2\pi)^2} \int_{\boldsymbol{r}} \mathrm{e}^{-\mathrm{i}\boldsymbol{p}\cdot\boldsymbol{r}} \left\{ -\frac{1}{4} L\hat{q}_0(1/r^2)\, \boldsymbol{r}^2 \right\} \simeq \frac{4\pi\alpha_s^2 C_F n}{p_\perp^4}$$

Radiation: Formation time

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



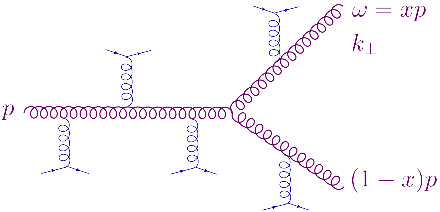
$$\lambda_\perp = \frac{1}{k_\perp} \simeq \frac{1}{\omega\theta}$$

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

- "Formation time" : the time it takes to emit a gluon
- This argument universally applies to radiation: in vacuum & in the medium
- In vacuum, $t_{\rm f}$ is measured from the hard scattering

Medium-induced radiation

- Collisions introduce a lower limit on the transverse momentum ...



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

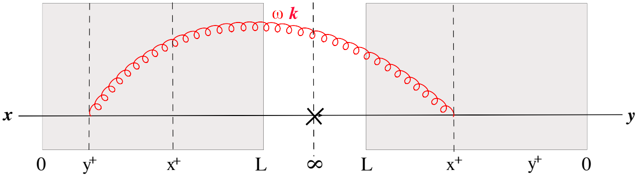
$$t_f \lesssim \sqrt{\frac{\omega}{\hat{q}}}$$

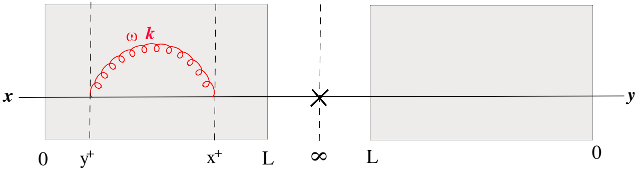
$$t_f < L \implies \omega \le \omega_c \equiv \hat{q} L^2$$

- ... hence an upper limit on the formation time !
- Three types of emissions:
  - vacuum-like (usual bremsstrahlung): $k_\perp^2 \gg \hat{q} t_f$, or $t_f \ll \sqrt{\omega/\hat{q}}$
  - medium-induced, single hard scattering: $k_\perp^2 \gg \hat{q} t_f$, or $t_f \ll \sqrt{\omega/\hat{q}}$
  - medium-induced, multiple soft scattering: $k_\perp^2 \simeq \hat{q} t_f$, or $t_f \simeq \sqrt{\omega/\hat{q}}$

Radiative corrections to $p_\perp$–broadening

- Medium-induced emissions contribute to momentum broadening via recoil
- Formally, a higher-order effect, but amplified by logarithms: “evolution”

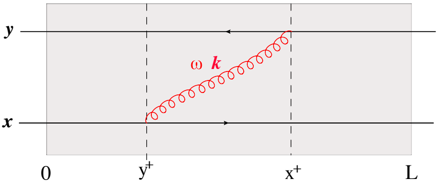


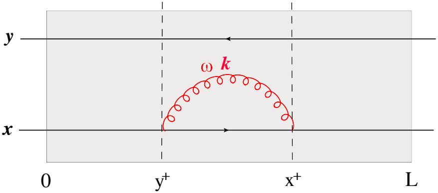


- The quark ‘evolves’ by emitting a soft gluon (‘real’ or ‘virtual’)
  - ‘soft’ $\Longleftrightarrow \omega \equiv k^+ \ll E \Longrightarrow$ eikonal emission vertices

In-medium BK/JIMWLK evolution

- 'Exchange graphs' between q and $\bar{q}$, or 'self–energy' graphs





- All partons undergo multiple scattering: non–linear evolution
- However, and unlike for a shockwave (DIS, pA), the multiple scattering cannot be computed in the eikonal approximation
- Eikonal scattering: transverse deviation $\Delta x_\perp$ during collision time Δt should be small compared to the transverse wavelength $\lambda_\perp = 1/p_\perp$:

$$\Delta x_\perp = \frac{p_\perp}{\omega}\Delta t \ll \lambda_\perp = \frac{1}{p_\perp} \implies \Delta t \ll \frac{\omega}{p_\perp^2} = t_{\rm f}$$

- But for the soft gluon emissions at hand, one rather has $\Delta t = t_{\rm f}$

The single scattering approximation

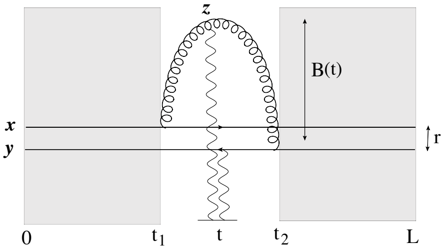
- The dominant radiative corrections are associated with fluctuations which undergo only a single scattering *(Liou, Mueller, Wu, 2013)*
- Power-law spectrum $\propto 1/k_\perp^4$ yielding a logarithmic enhancement of the recoil

- single scattering

$$k_\perp^2 \gg \hat{q} t_{\rm f} \quad \text{or} \quad t_{\rm f} \ll \sqrt{\omega/\hat{q}}$$

- Gunion-Bertsch (or GLV) spectrum

$$\omega \frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} \simeq \frac{\alpha_s N_c}{\pi^2} \frac{\hat{q}_0 L}{k_\perp^4}$$



- The one-loop contribution to $p_\perp$-broadening to double-log accuracy:

$$\langle p_\perp^2 \rangle_{\rm rad} = \int_{\omega,\boldsymbol{k}} \boldsymbol{k}^2 \frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} = \bar{\alpha}\hat{q}_0 L \int \frac{{\rm d}\omega}{\omega} \int \frac{{\rm d}k_\perp^2}{k_\perp^2} \equiv L\, \Delta\hat{q}$$

A renormalization group equation for $\hat{q}$

(Liou, Mueller, Wu, 2013; Blaizot and Mehtar-Tani, 2014; E.I., 2014)

- The limits of the double-logarithmic phase–space are simpler in terms of the formation time $t_{\rm f} = 2\omega/k_\perp^2$ *(below, $\lambda \equiv 1/T$)*

$$\frac{\Delta\hat{q}}{\hat{q}_0} = \bar{\alpha}\int_\lambda^L \frac{{\rm d}t_{\rm f}}{t_{\rm f}}\int_{\hat{q}t_{\rm f}}^{\hat{q}L}\frac{{\rm d}k_\perp^2}{k_\perp^2} = \frac{\bar{\alpha}}{2}\ln^2\frac{L}{\lambda}$$

  - a relatively large correction $\Longrightarrow$ needs for resummation
  - the general ('BK') equation reduces to a linear equation : 'DLA'

$$\hat{q}(L) = \hat{q}_0 + \bar{\alpha}\int_\lambda^L \frac{{\rm d}t_{\rm f}}{t_{\rm f}}\int_{\hat{q}t_{\rm f}}^{\hat{q}L}\frac{{\rm d}k_\perp^2}{k_\perp^2}\,\hat{q}(t_{\rm f}, k_\perp^2)$$

  - not the standard DLA equation: medium-dependent integration limits

$$\hat{q}(L) = \hat{q}_0\,\frac{1}{\sqrt{\bar{\alpha}}\ln\left(L/\lambda\right)}\,{\rm I}_1\left(2\sqrt{\bar{\alpha}}\ln\frac{L}{\lambda}\right) \propto L^{2\sqrt{\bar{\alpha}}}$$

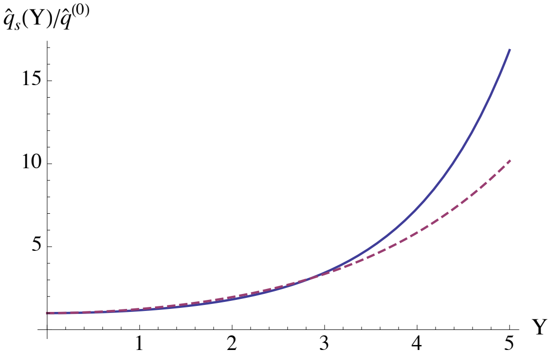
  - large anomalous dimension $\gamma_s = 2\sqrt{\bar{\alpha}} \sim 1$

Using a running coupling *(E.I., D.N. Triantafyllopoulos, 2014)*

- The running coupling slows down the evolution at large $Y \equiv \ln(L/\lambda)$

$$\hat{q}(L) = \hat{q}_0 + \int_{\lambda}^{L} \frac{\mathrm{d}t_{\rm f}}{t_{\rm f}} \int_{\hat{q}t_{\rm f}}^{\hat{q}L} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\, \bar{\alpha}(k_\perp^2)\, \hat{q}(t_{\rm f}, k_\perp^2)$$

$$\Longrightarrow \ \ln \hat{q}(L) \simeq 4\sqrt{b_0 \ln \frac{L}{\lambda}} \qquad \text{(slower than any exponential)}$$



Radiation from multiple soft scattering

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

- The single hard scattering regime does not also control the energy loss

$$\langle \Delta E \rangle_{\rm rad} = \int_{\omega,\boldsymbol{k}} \omega \frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} = \bar{\alpha}\hat{q}_0 L \int^{\omega_c} {\rm d}\omega \int_{\hat{q}t_{\rm f}}^{\hat{q}L} \frac{{\rm d}k_\perp^2}{k_\perp^4}$$

  - without the $k_\perp^2$-weighting, the integral is controlled by its lower limit

$$k_\perp^2 \sim \hat{q}t_{\rm f} \sim \sqrt{\hat{q}\omega} \;\;\&\;\; t_{\rm f} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

- The BDMPS-Z spectrum for medium-induced radiation

$$\omega \frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} \simeq \bar{\alpha}\, \frac{L}{t_{\rm f}(\omega)}\, \frac{1}{\sqrt{\hat{q}\omega}}\, {\rm e}^{-\frac{k_\perp^2}{\sqrt{\hat{q}\omega}}}$$

  - the emission can occur anyway inside the medium: a factor $L/t_{\rm f}(\omega)$
  - transverse momentum broadening during formation: $\langle k_\perp^2 \rangle \simeq \sqrt{\hat{q}\omega}$

- Maximal ω for this mechanism: $t_{\rm f} \leq L \;\Rightarrow\; \omega \leq \omega_c \equiv \hat{q}L^2$

Angular distribution

- Transverse momentum broadening during formation & after formation

- formation angle:

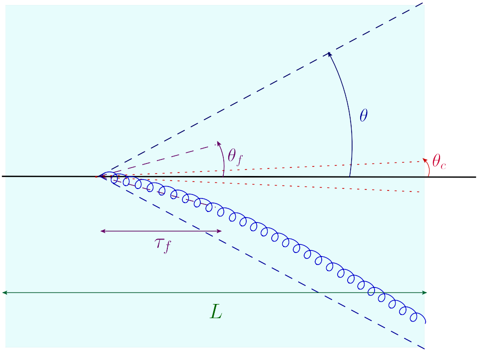
$$\theta_{\rm f}(\omega) \simeq \frac{(\hat{q}\omega)^{1/4}}{\omega} \simeq \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

- the minimal angle

$$\theta_c = \theta_{\rm f}(\omega_c) = \frac{1}{\sqrt{\hat{q}L^3}}$$

- final angle

$$\theta(\omega) \simeq \frac{\sqrt{\hat{q}L}}{\omega} = \theta_c \frac{\omega_c}{\omega}$$



- Soft gluons $\omega \ll \omega_c$: small formation times $(t_{\rm f} \ll L)$ & large angles $(\theta \gg \theta_c)$
- Gluons with angles larger than the jet opening angle θ_0 move outside the jet

The average energy loss

- Differential probability for one emission (integrated over $k_\perp$)

$$\omega \frac{\mathrm{d}P}{\mathrm{d}\omega} \simeq \bar{\alpha} \frac{L}{t_{\mathrm{f}}(\omega)} \simeq \bar{\alpha}\sqrt{\frac{\omega_c}{\omega}} \qquad (\omega < \omega_c \equiv \hat{q}L^2/2)$$

- The average energy loss by a particle with energy $E > \omega_c$

$$\Delta E = \int^{\omega_c} \mathrm{d}\omega\, \omega \frac{\mathrm{d}P}{\mathrm{d}\omega} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$$

  - integral dominated by its upper limit $\omega = \omega_c$

- Hard emissions with $\omega \sim \omega_c$: probability of $\mathcal{O}(\alpha_s)$
  - rare events but which take away a large energy
  - small emission angle $\theta_c \Rightarrow$ the energy remains inside the jet

- Irrelevant for the di-jet asymmetry and also for the typical events

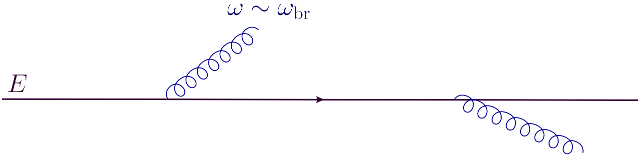
Multiple branching

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

- When $\omega(\mathrm{d}\mathcal{P}/\mathrm{d}\omega) \sim 1$, multiple branching becomes important

$$\omega \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\omega} \simeq \bar{\alpha}\sqrt{\frac{\omega_c}{\omega}} \sim 1 \implies \omega \lesssim \omega_{\rm br}(L) \equiv \bar{\alpha}^2 \hat{q} L^2$$

- LHC: the leading particle has $E \sim 100\,\mathrm{GeV} \gg \omega_{\rm br} \sim 5\,\mathrm{GeV}$



- In a typical event, the LP emits ...
  - a number of $\mathcal{O}(1)$ of gluons with $\omega \sim \omega_{\rm br}$

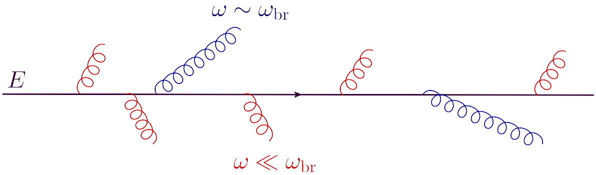
Multiple branching

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

- When $\omega(\mathrm{d}\mathcal{P}/\mathrm{d}\omega) \sim 1$, multiple branching becomes important

$$\omega \frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\omega} \simeq \bar{\alpha}\sqrt{\frac{\omega_c}{\omega}} \sim 1 \Longrightarrow \omega \lesssim \omega_{\rm br}(L) \equiv \bar{\alpha}^2 \hat{q} L^2$$

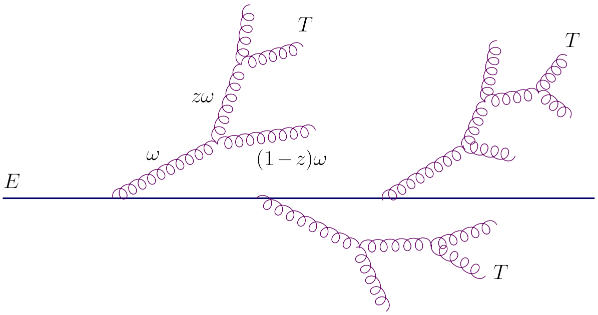
- LHC: the leading particle has $E \sim 100\,\mathrm{GeV} \gg \omega_{\rm br} \sim 5\,\mathrm{GeV}$



- In a typical event, the LP emits ...
  - a number of $\mathcal{O}(1)$ of gluons with $\omega \sim \omega_{\rm br}$
  - a large number of softer gluons with $\omega \ll \omega_{\rm br}$
- The primary gluons with $\omega \lesssim \omega_{\rm br}$ keep splitting

Democratic branchings

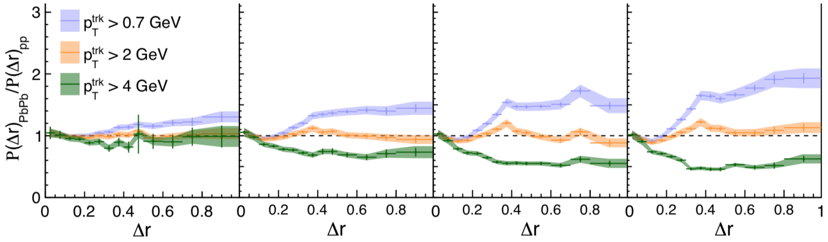
- The primary gluons generate 'mini-jets' via democratic branchings
  - daughter gluons carry comparable energy fractions: $z \sim 1 - z \sim 1/2$
  - contrast to asymmetric splittings in the vacuum: $z \ll 1$
- Via successive democratic branchings, the energy is efficiently transmitted to softer and softer gluons, which eventually thermalize



- Energy appears in many soft quanta propagating at large angles ✓

Democratic branchings

- The primary gluons generate 'mini-jets' via democratic branchings
  - daughter gluons carry comparable energy fractions: $z \sim 1 - z \sim 1/2$
  - contrast to asymmetric splittings in the vacuum: $z \ll 1$
- Via successive democratic branchings, the energy is efficiently transmitted to softer and softer gluons, which eventually thermalize

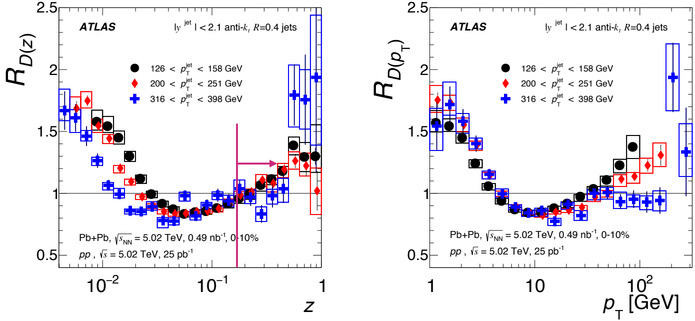


- CMS: The jet transverse momentum profile $P(\Delta r)$ (p_T in annular rings)
- A natural explanation for the di-jet asymmetry and for jet shapes

Intra-jet nucler modifications

- How to understand the excess of soft particles inside the jet cone $(\theta < R)$?

ratios of fragmentation functions in PbPb / pp



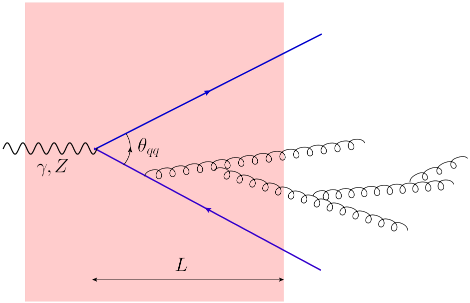
1805.05424 Martin Rybar, Wednesday 7

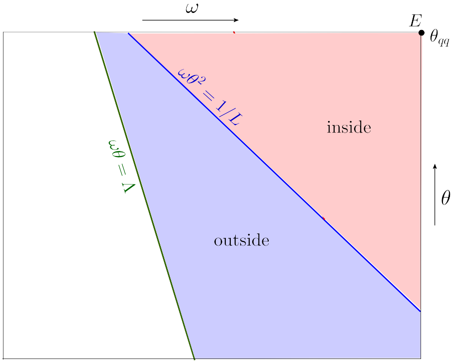
- Medium-induced soft radiation should be pushed at large angles $\theta > R$
- Can vacuum-like radiation be modified by the medium ?

Vacuum-like emissions (VLE)

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

- 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 $(t_f \leq L)$, 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

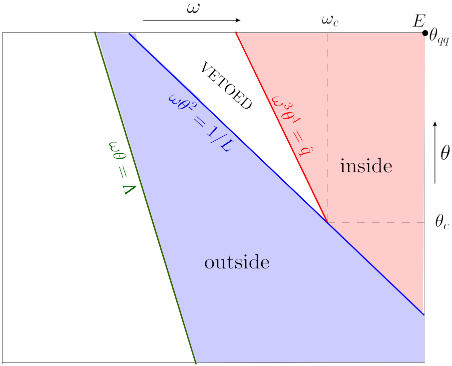
$$t_{\rm f} \lesssim \sqrt{\frac{\omega}{\hat{q}}} \leq L$$

- No emission within the range

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

- End point of VETOED at

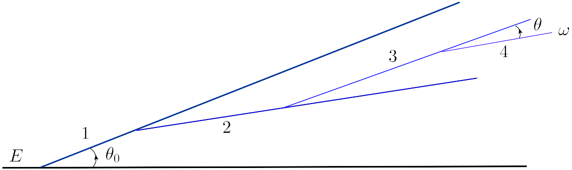
$$\omega_c = \hat{q}L^2\,, \quad \theta_c = \frac{1}{\sqrt{\hat{q}L^3}}$$



- 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



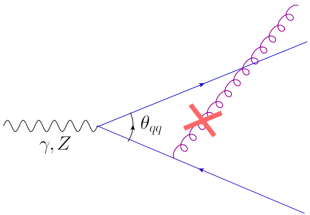
$$\mathrm{d}\mathcal{P} \simeq \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2}$$

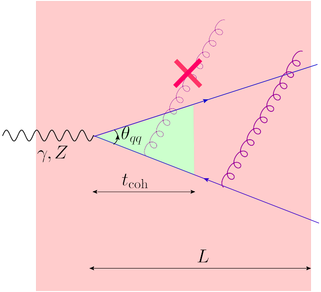
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons
- Parton cascades: successive emissions are ordered in
  - energy ($\omega_i < \omega_{i-1}$), by energy conservation
  - angle ($\theta_i < \theta_{i-1}$), by color coherence
- Double-logarithmic approximation (DLA): strong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





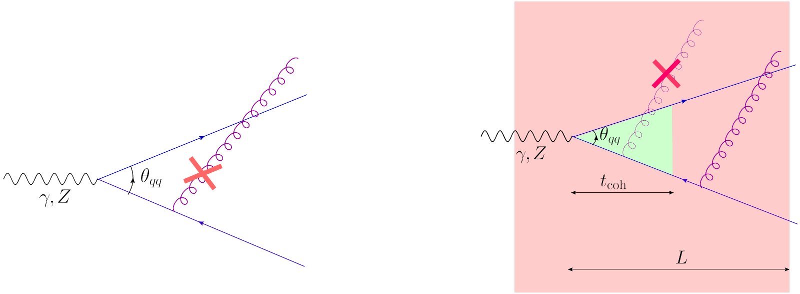
- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

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

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

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 $t_{\rm coh}$

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

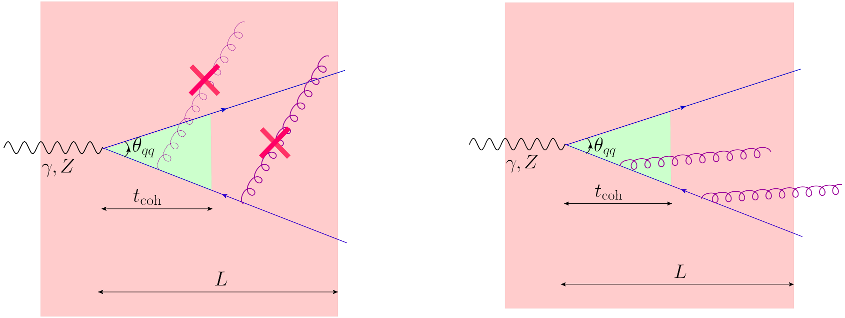
- Angular ordering could be violated for emissions inside the medium

Angular ordering strikes back

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

$$\theta > \theta_{q\bar{q}} \quad \& \quad t_{\rm f} = \frac{1}{\omega\theta^2} > t_{\rm coh} \implies t_{\rm f} \gg \sqrt{\frac{\omega}{\hat{q}}}$$

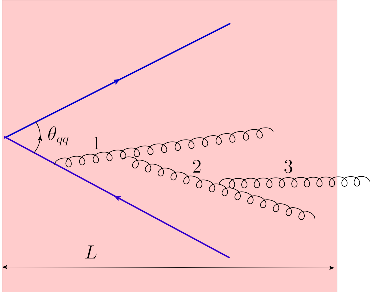
- Wide angle emissions $(\theta > \theta_{q\bar{q}})$ have $t_{\rm f} \ll t_{\rm coh}$, hence they are suppressed

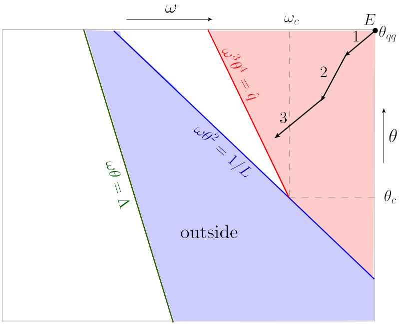


- Emissions at smaller angles $(\theta < \theta_{q\bar{q}})$ can occur at any time
- DLA cascades inside the medium are still strongly ordered in angles

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 $\sim L$

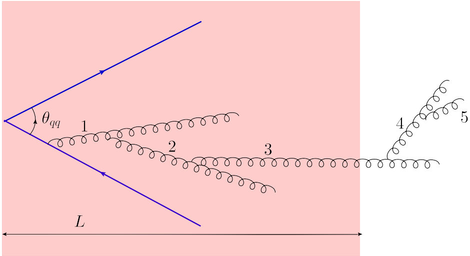


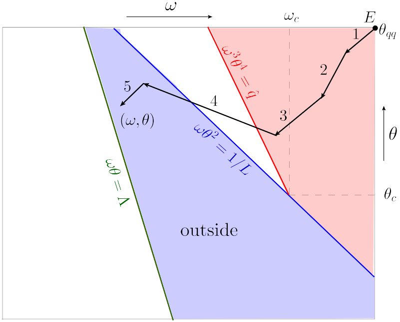


- They can suffer significant energy loss and momentum broadening
  - additional sources for medium-induced radiation
- They contribute to the jet multiplicity (fragmentation function)
- They can emit (vacuum-like) gluons outside the medium

First emission outside the medium

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



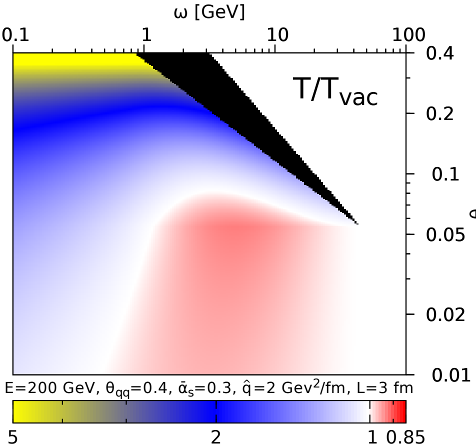


- In-medium sources lose color coherence and can also radiate at larger angles
- After the first "outside" emission, one returns to angular-ordering, as usual
- Medium effects at DLA (leading twist):
  vetoed region + lack of angular-ordering for the first "outside" emission

Gluon distribution at DLA

- Double differential distribution in energies and emission angles:

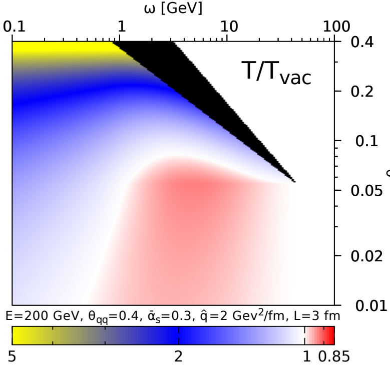
$$T(\omega,\theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$$

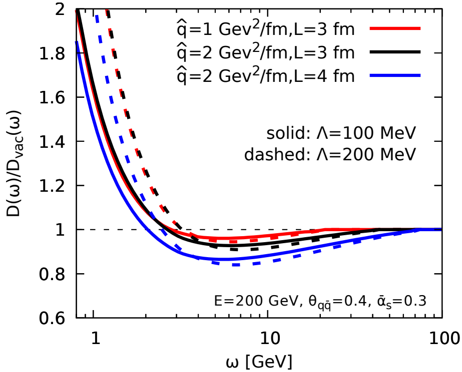


- $E = 200\,\mathrm{GeV}, \quad \theta_{q\bar{q}} = 0.4$
- $\hat{q} = 2\,\mathrm{GeV}^2/\mathrm{fm}, \quad L = 3\,\mathrm{fm}$
- $T/T_{\mathrm{vac}} = 0$ in the excluded region
- $T/T_{\mathrm{vac}} = 1$ inside the medium and also for $\omega > \omega_c$ and any θ
- $T/T_{\mathrm{vac}} < 1$ outside the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

Jet fragmentation function at DLA

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

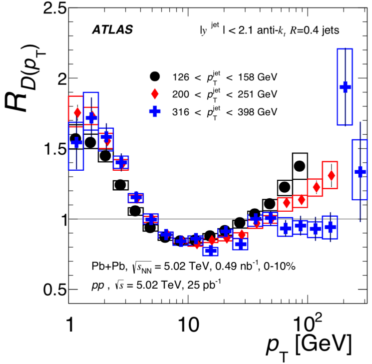


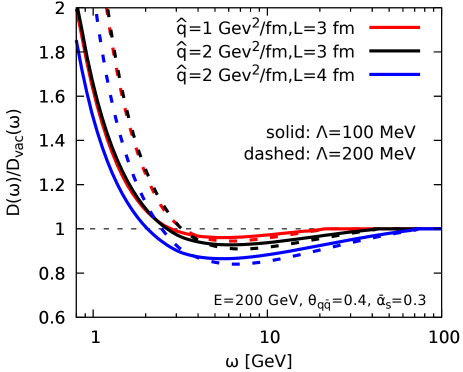


- Slight suppression at intermediate energies (from 3 GeV up to ω_c)
  - the phase-space is reduced by the vetoed region
  - the amount of suppression increases with L and $\hat{q}$

Jet fragmentation function at DLA

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

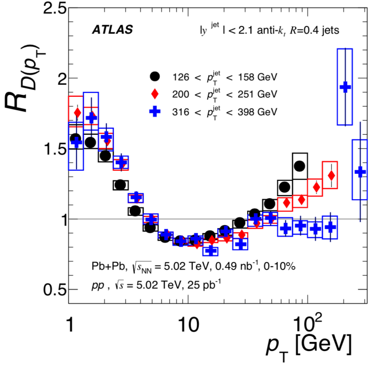


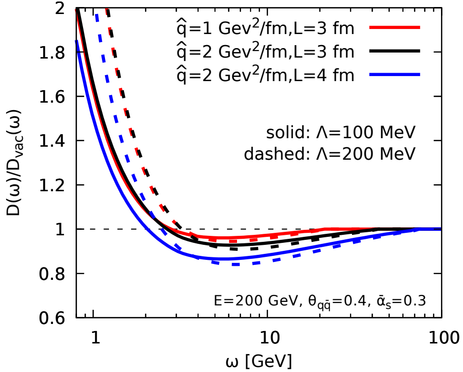


- Significant enhancement at low energy (below 2 GeV)
  - lack of angular ordering for the first emission outside the medium
  - the enhancement is slowly increasing with the jet energy $E\ (= p_T)$

Jet fragmentation function at DLA

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

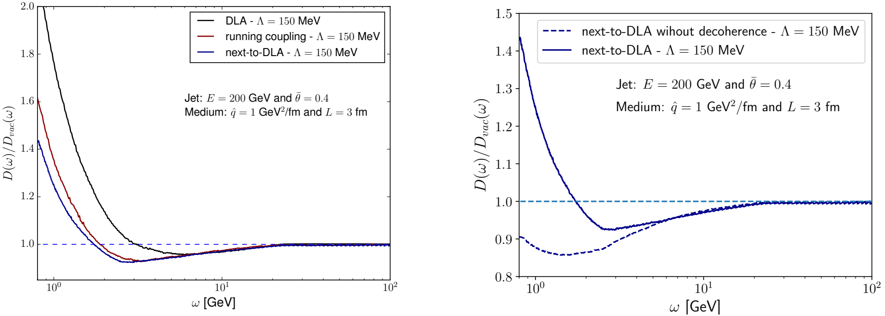




- Significant enhancement at low energy (below 2 GeV)
- A related proposal by *Mehtar-Tani and Tywoniuk, arXiv:1401.8293*

Beyond DLA: Running coupling & NDLA

- Remember the double-logarithmic approximations:
  - strong ordering in both energies ($P_{gg} \simeq 1/z$) and angles
  - fixed coupling $\bar{\alpha}$
  - no "higher-twist" effects: no collisions, no medium-induced radiation



- Adding a running coupling: $\bar{\alpha}(k_\perp^2) = \frac{1}{\bar{b}\ln\frac{\omega^2\theta^2}{\Lambda^2}}$, $\bar{b} = 11/12$
- Finite-part of the splitting function: $P_{gg}(z) \simeq \frac{1}{z} + \int_0^1 \mathrm{d}z'\left(P_{gg}(z') - \frac{1}{z'}\right)$

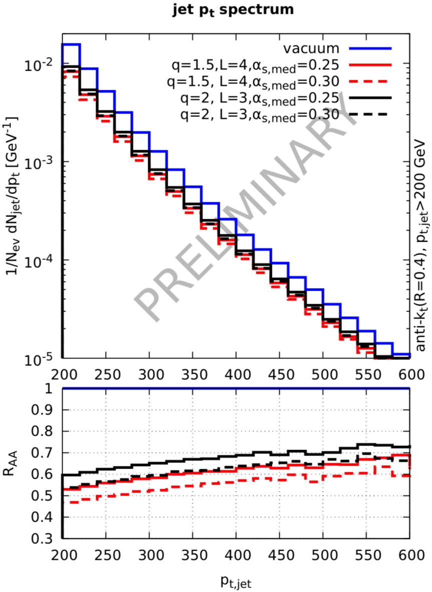
Beyond DLA: Monte Carlo implementation

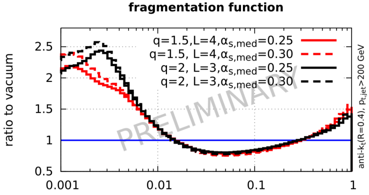
(P. Caucal, E.I., A. H. Mueller and G. Soyez, in preparation)

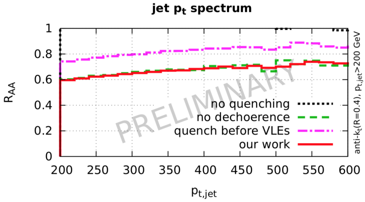
- Convolution of three showers:
  - vacuum cascades inside the medium but outside the vetoed region
    - full splitting functions, running coupling, quarks and gluons, $N_c = 3$
  - medium-induced cascade in energy with democratic branchings
    - fixed coupling $\bar{\alpha}$, energy loss, transverse momentum broadening
    - partons with angles $\theta > \theta_0$ are leaving the jet
  - vacuum cascade outside the medium
    - no angular ordering for the first emission outside the medium
    - all the partons inside the jet (vacuum-like & medium-induced) can act as sources
    - cascades stop at the hadronisation line

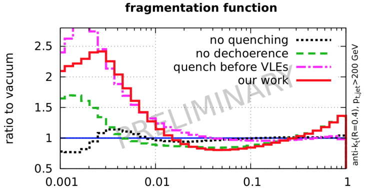
- Leading parton selected according to the cross-section for $pp \to 2$ partons
  - experimental bias towards events with small energy loss
  - typical energy loss: $\Delta E \sim \bar{\alpha}^2 \omega_c$, rather than average: $\langle \Delta E \rangle \sim \bar{\alpha} \omega_c$

MC: preliminary results

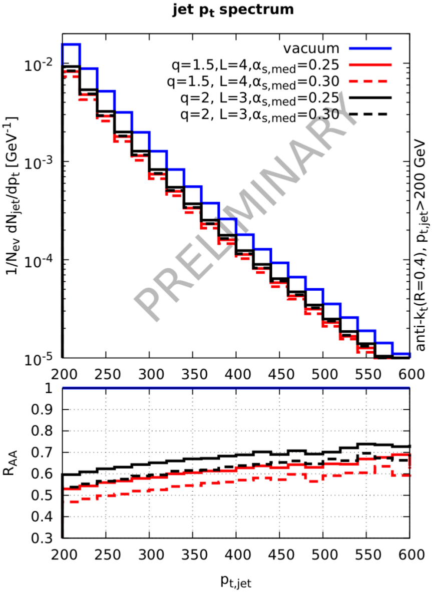


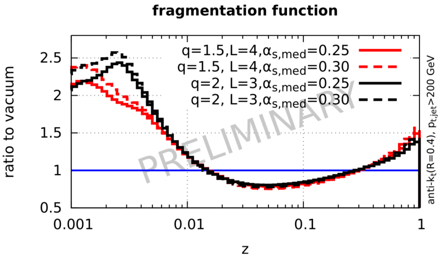






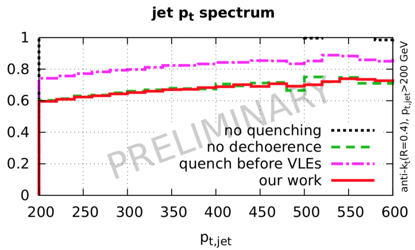
MC: preliminary results (2)

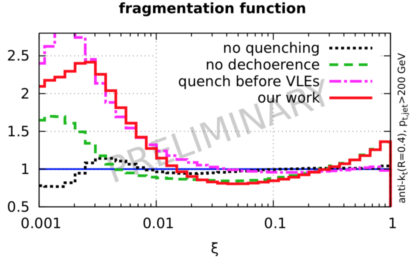




- Focus on 2 observables:
  - R_{AA}: jet yield in AA normalized to pp
  - ratio of FFs in AA and pp
- Various choices for $\hat{q}$, L and $\alpha_{s,\,\mathrm{med}}$

MC: preliminary results (3)





- "No quenching": just VLEs
  - no energy loss: $R_{AA} = 1$
  - suppression in FF at small ξ
- "No decoherence": strict angular ordering (including first "outside" emission)
  - no effect on energy loss (R_{AA})
  - little enhancement at small ξ
- "Quenching before VLEs": no VLEs inside the medium
  - R_{AA} larger & increasing with $p_{T,\text{jet}}$

- Partons created inside the medium via medium-induced emissions significantly contribute to the soft radiation outside the medium

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