Vacuum-like jet fragmentation in a dense QCD medium

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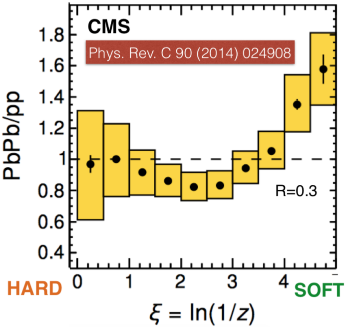
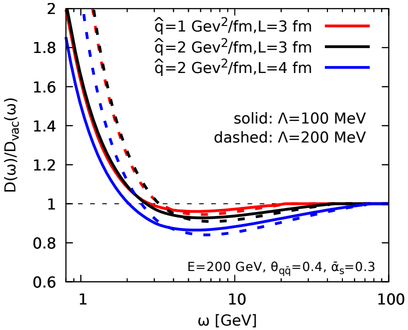
with P. Caucal, A. H. Mueller and G. Soyez, PRL 120 (2018) 232001





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  - di-jet asymmetry
  - in-medium fragmentation functions

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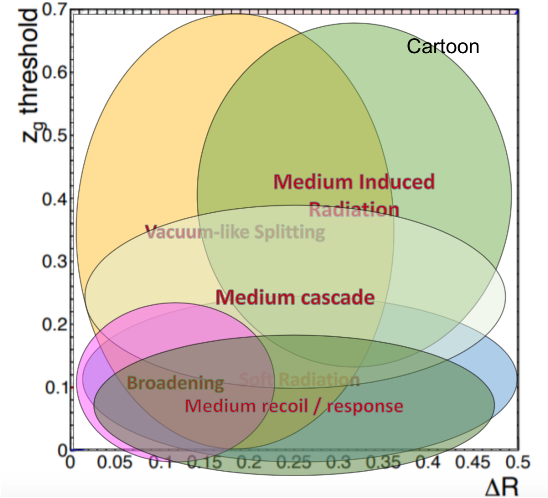
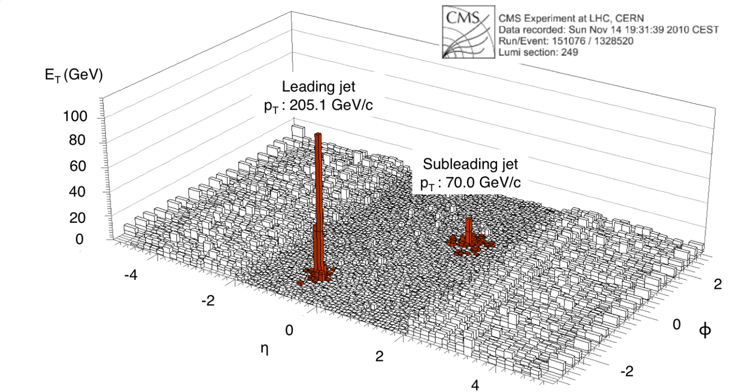
- Semi-quantitative agreement with the data via first principles calculations

Outline

- Going towards that !



Di–jet asymmetry at the LHC

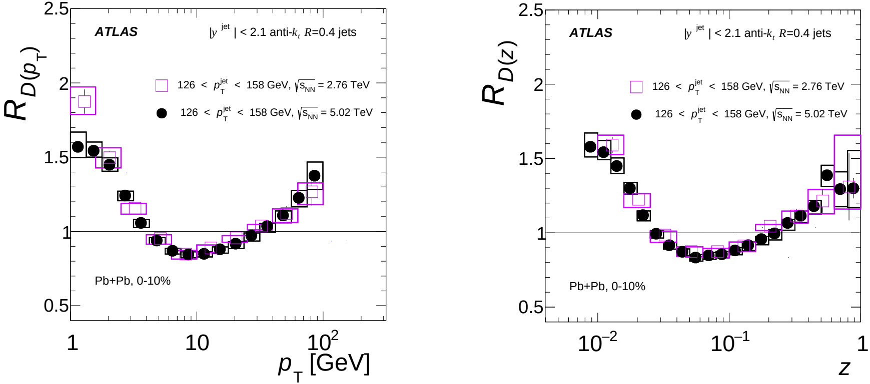


(cf. the yesterday talk by Yen-Jie Lee)

- 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

In-medium jet fragmentation: PbPb/pp

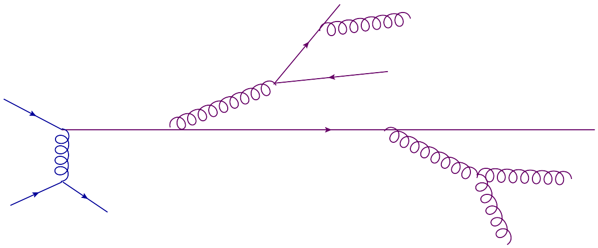
- Energy distribution of hadrons inside the jet (vs. p_T or vs. $z = p_T/p_T^{jet}$)



  - slight suppression at intermediate energies
  - enhancement at low energies ($z \ll 1$)
- We shall argue that these two types of nuclear modifications (inside/outside the jet cone) 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) ...



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
- many soft gluons ... but they carry very little energy
- energy remains in the (few) large $x \equiv \omega/E$ partons, at small angles

Medium-induced jet evolution

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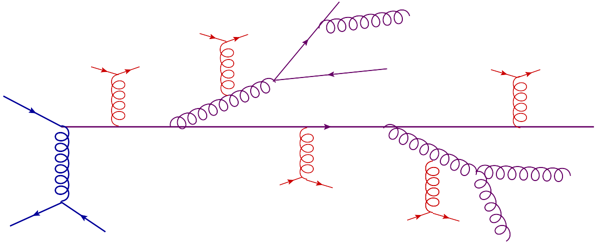
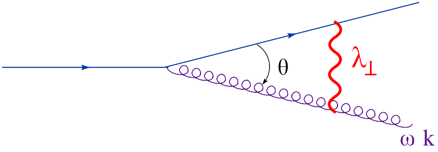


- ... and via collisions off the medium constituents
- Collisions can have several effects *(cf. the talk by Jean-Paul Blaizot)*
  - transverse momentum broadening: $\Delta k_\perp^2 \simeq \hat{q}\Delta t$
  - medium-induced radiation
  - wash out the color coherence (destroy interference pattern)

Radiation: Formation time

- The time it takes the daughter partons to lose their mutual coherence



$$\Delta r_\perp \sim \theta \Delta t \gtrsim \lambda_\perp \sim \frac{1}{k_\perp}$$

$$k_\perp \simeq \omega\theta$$

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

- This argument universally applies to radiation: in vacuum & in the medium
- In vacuum, decoherence follows from parton virtualities: $t_{\rm f} \sim E/Q^2$
- $t_{\rm f}$ is measured from the hard scattering

Radiation: Formation time

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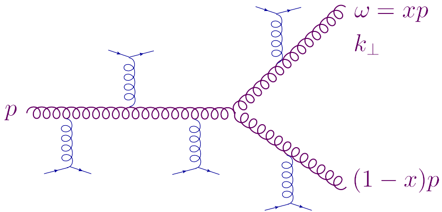


$$t_{\rm f} = \frac{\omega}{k_\perp^2} \quad \& \quad k_\perp^2 \gtrsim \hat{q} t_{\rm f}$$

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

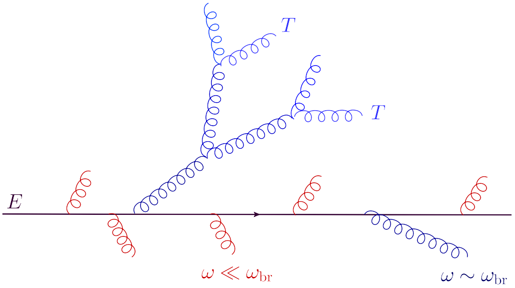
$$t_{\rm f} < L \implies \omega \le \omega_c \equiv \hat{q} L^2$$

- In medium: collisions introduce a lower limit on the transverse momentum ...
- ... hence an upper limit on the formation time !
- Two types of emissions:
  - vacuum-like: $k_\perp^2 \gg \hat{q} t_{\rm f}$, or $t_{\rm f} \ll \sqrt{\omega/\hat{q}}$
  - medium-induced: $k_\perp^2 \simeq \hat{q} t_{\rm f}$, or $t_{\rm f} \simeq \sqrt{\omega/\hat{q}}$

Medium induced radiation

$$\mathrm{d}\mathcal{P} \sim \alpha_s \frac{\mathrm{d}\omega}{\omega}\frac{L}{t_{\rm f}(\omega)} \sim \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}\,\frac{\mathrm{d}\omega}{\omega} \qquad \text{(BDMPS-Z)}$$

- Multiple branching becomes important when $\omega \lesssim \omega_{\rm br} \equiv \alpha_s^2 \hat{q} L^2$
- Primary gluons disappear via democratic branchings: $x \sim 1-x$
  - energy is transmitted to many soft quanta which thermalize: $\omega \sim T$



- A natural explanation for the di-jet asymmetry

Medium induced radiation

$$\mathrm{d}\mathcal{P} \sim \alpha_s \frac{\mathrm{d}\omega}{\omega} \frac{L}{t_{\mathrm{f}}(\omega)} \sim \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}} \frac{\mathrm{d}\omega}{\omega} \quad \text{(BDMPS-Z)}$$

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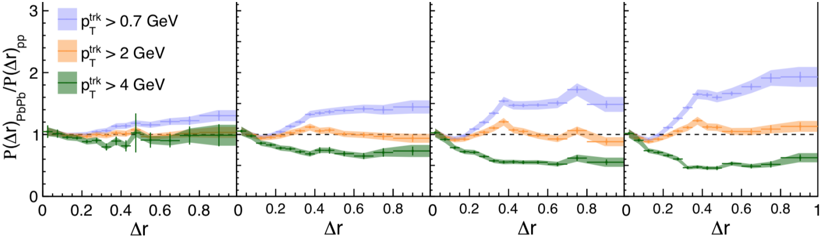
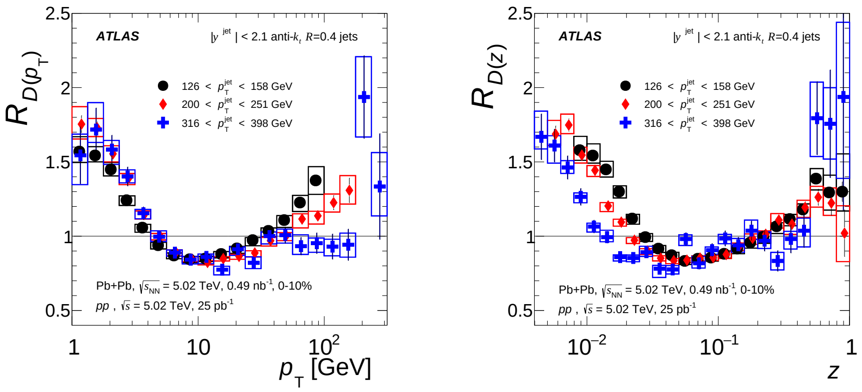


- A natural explanation for the di-jet asymmetry

Intra-jet nucler modifications

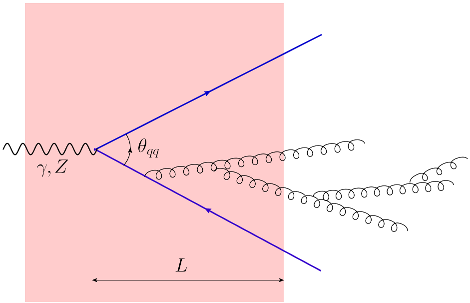
- Medium-induced radiation propagates at large angles, outside the jet cone
- The LHC data also show nuclear modifications for the energy distribution inside the jet cone

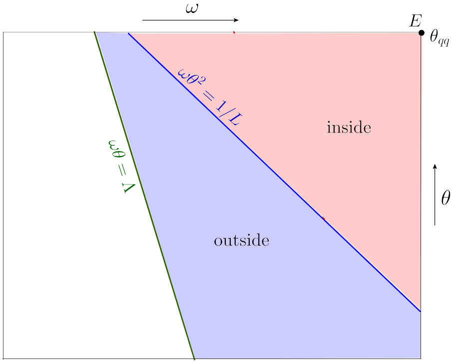


- Can vacuum-like radiation be modified by the medium ?

Vacuum-like emissions (VLE)

- 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





- Lund diagram: energy (ω)/emission angle (θ) phase-space in log units
- Emissions $(t_f = \frac{1}{\omega\theta^2})$ 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

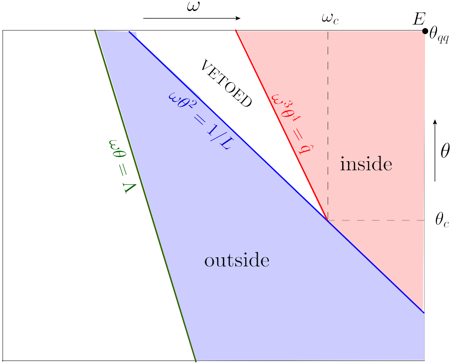
$$t_{\rm f} \lesssim \sqrt{\frac{\omega}{\hat{q}}} \leq L$$

- No emission within the range

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

- End point of VETOED at

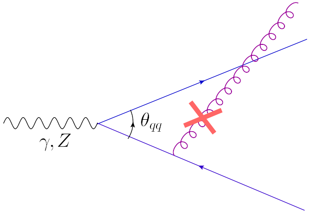
$$\omega_c = \hat{q}L^2\,, \quad \theta_c = \frac{1}{\sqrt{\hat{q}L^3}}$$

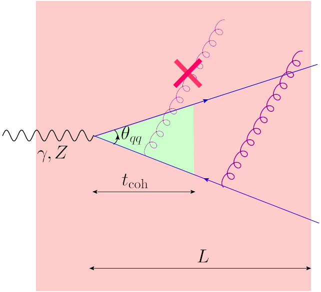


- VLEs in medium occur like in vacuum, but with a smaller phase-space
  - gluons within VETOED should have $k_\perp^2 \ll \hat{q}t_{\rm f}$, which is not possible
  - a leading-twist effect: DGLAP splitting functions
  - typical values: $\hat{q} = 1\,{\rm GeV}^2/{\rm fm}$, $L = 4\,{\rm fm}$, $\omega_c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

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 $t_{\rm coh}$

$$\hat{q}\Delta t \gtrsim \frac{1}{(\theta_{q\bar{q}}\Delta t)^2} \quad \Longrightarrow \quad \Delta t \gtrsim t_{\rm coh} = \frac{1}{(\hat{q}\theta_{q\bar{q}}^2)^{1/3}}$$

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

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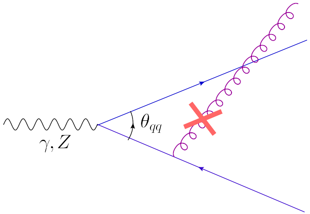
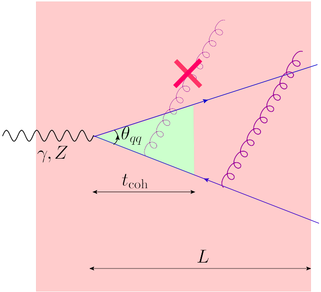




- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

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

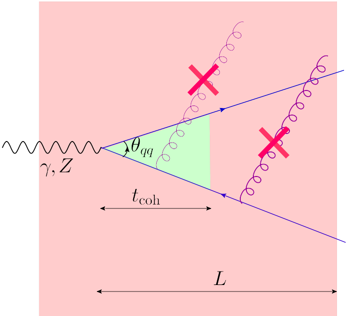
- Angular ordering could be violated for emissions inside the medium

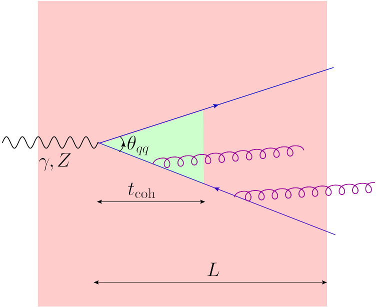
Angular ordering strikes back

- ... 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

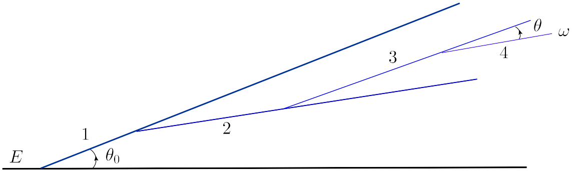




- Emissions at smaller angles $(\theta < \theta_{q\bar{q}})$ can occur at any time
- Color decoherence via collisions plays no role for the VLEs

Double Logarithmic Approximation

- In-medium parton cascades are angular-ordered, like in the vacuum



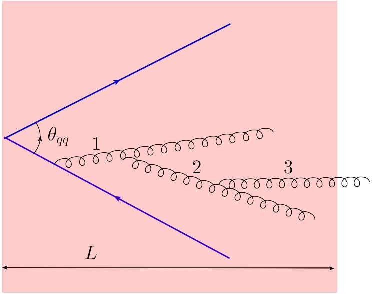
$$\mathrm{d}\mathcal{P} \simeq \frac{\alpha_s C_R}{\pi} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta^2}{\theta^2}$$

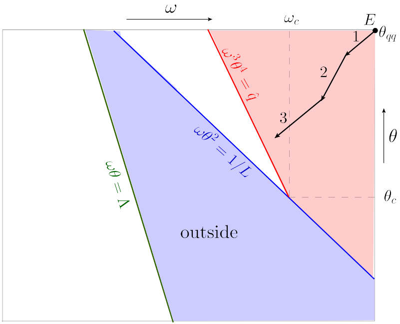
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons
- Parton cascades: successive emissions are ordered in
  - energy ($\omega_i < \omega_{i-1}$), by energy conservation
  - angle ($\theta_i < \theta_{i-1}$), by color coherence
- Double-logarithmic approximation (DLA): strong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

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

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 $\sim L$

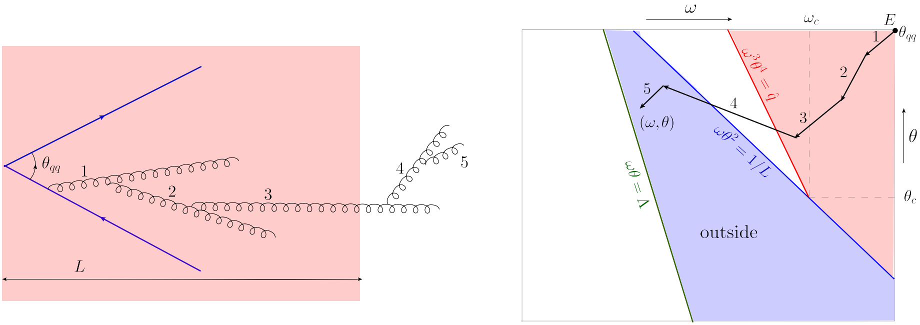




- They can suffer significant energy loss and momentum broadening
  - additional sources for medium-induced radiation
- They contribute to the jet multiplicity (fragmentation function)
- They can emit (vacuum-like) gluons outside the medium

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 $t_{\rm coh} \ll L$

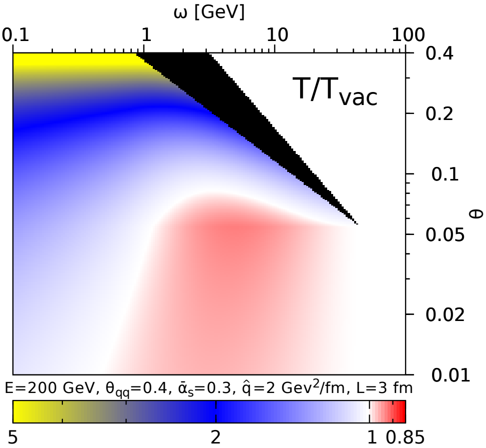


- In-medium sources lose color coherence and can also radiate at larger angles
- After the first "outside" emission, one returns to angular-ordering, as usual
- Medium effects at DLA (leading twist):
  vetoed region + lack of angular-ordering for the first "outside" emission

Gluon distribution at DLA

- Double differential distribution in energies and emission angles:

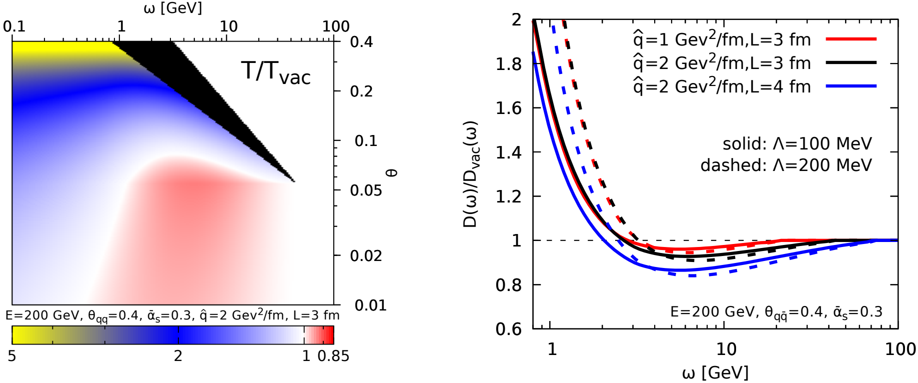
$$T(\omega,\theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$$



- $E = 200\,\mathrm{GeV}, \quad \theta_{q\bar{q}} = 0.4$
- $\hat{q} = 2\,\mathrm{GeV}^2/\mathrm{fm}, \quad L = 3\,\mathrm{fm}$
- $T/T_{\mathrm{vac}} = 0$ 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

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



- 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 and $\hat{q}$

Jet fragmentation function at DLA

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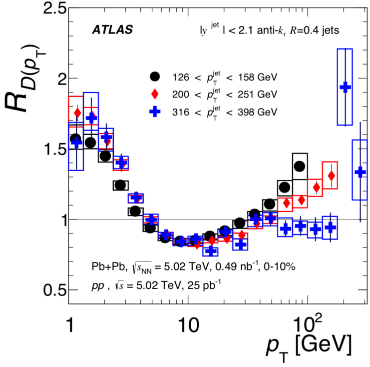
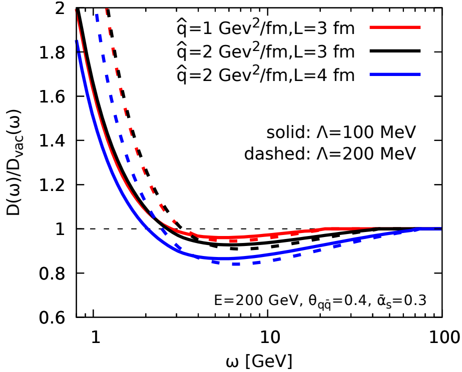
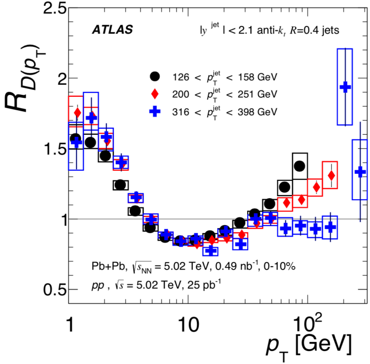


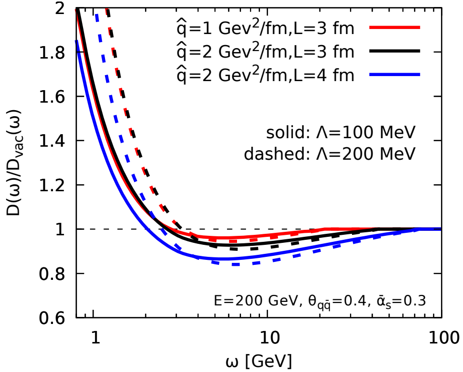


- Significant enhancement at low energy (below 2 GeV)
  - lack of angular ordering for the first emission outside the medium
  - the enhancement is slowly increasing with the jet energy $E\ (= p_T)$

Jet fragmentation function at DLA

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

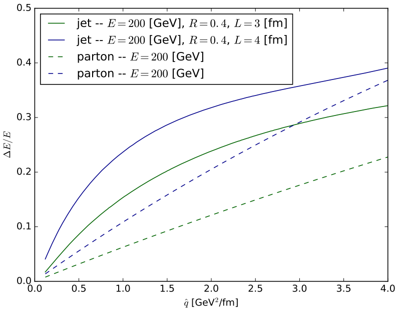


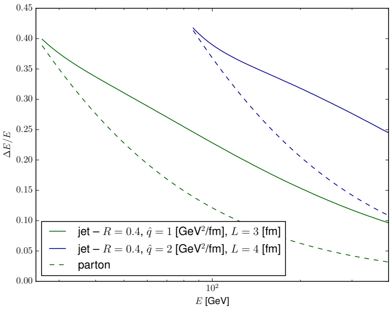


- Significant enhancement at low energy (below 2 GeV)
- A related proposal by *Mehtar-Tani and Tywoniuk, arXiv:1401.8293*

Energy loss by the jet (preliminary)

- Partons produced inside the medium via VLEs act as sources for medium-induced radiation
- A gluon ω will typically lose an energy $\varepsilon = \min(\omega, \omega_{\rm br})$ with $\omega_{\rm br} \equiv \alpha_s^2 \hat{q} L^2$





- Energy loss by the jet is considerably higher than that by a parton
- $\Delta E/E$ for the jet is less rapidly decreasing with increasing E
- Recall: R_{AA} for jets is not approaching unity with increasing p_T $(= E)$

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