A unified picture for in-medium jet evolution in pQCD

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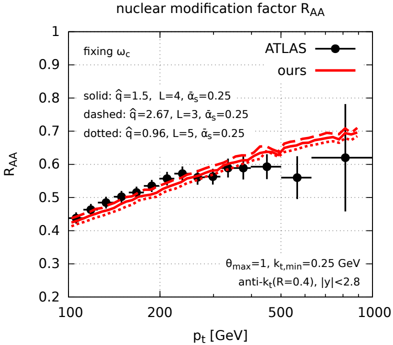
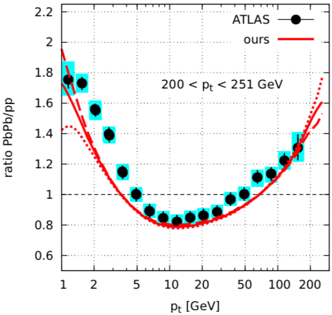
with P. Caucal, A. H. Mueller and G. Soyez *(PRL 120 (2018) 232001 + w.i.p.)*



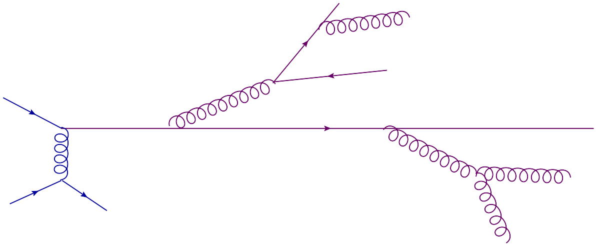


Outline

- Jet evolution in a quark-gluon plasma at weak coupling
- Two types of radiation...
  - vacuum-like: bremsstrahlung (parton virtualities)
  - medium-induced radiation : BDMPS-Z (collisions in the plasma)
- ... which are separately well understood
- They can be factorized within controlled approximations in pQCD
- The "vacuum-like" radiation too is modified by the medium (constraints on the associated phase-space)
- Probabilistic picture allowing for Monte-Carlo implementation
- Encouraging preliminary results (jet R_{AA}, fragmentation function)

Jet evolution in a quark-gluon plasma

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



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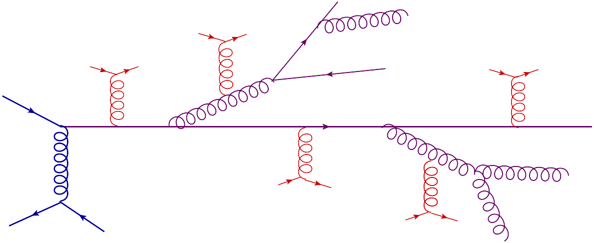
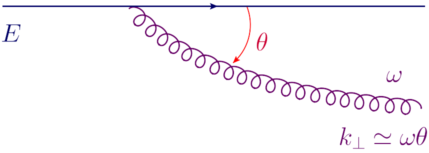


- ... and via collisions off the medium constituents, leading to...
  - transverse momentum broadening: $\Delta k_{\perp}^2 \simeq \hat{q}\Delta t$
  - additional, medium-induced, radiation
  - wash out the colour coherence (destroy interference pattern)

Jets in the vacuum



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

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

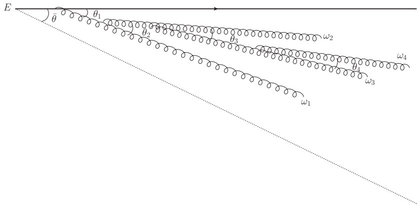
- Formation time $t_{\rm f}$: the time it takes the daughter partons to lose their quantum coherence (overlap in transverse direction)
- Determined by the virtuality Q^2 of the original parton: $t_{\rm f} \sim E/Q^2$
- Log enhancement for soft ($\omega \ll E$) and collinear ($\theta \ll 1$) gluons
- 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

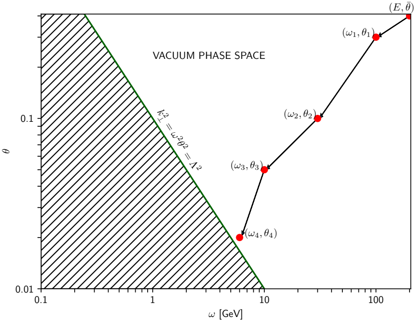
Lund plot for vacuum emissions at DLA

- Strong ordering in both energies and angles: $\left[\alpha_s \ln(E/\omega)\ln(\bar{\theta}/\theta)\right]^n$

$$E \gg \omega_1 \gg \omega_2 \gg \cdots \gg \omega \quad \& \quad \bar{\theta} \gg \theta_1 \gg \theta_2 \gg \cdots \gg \theta$$

- $\bar{\theta}$: the maximal angle allowed for the first emission
- Each emission $(\omega_i,\, \theta_i)$: a point in the phase-space diagram

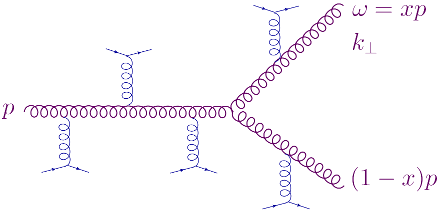




- Evolution stopped by hadronisation: $k_\perp \simeq \omega\theta \gtrsim \Lambda_{\rm QCD}$

Medium-induced radiation

- In medium: collisions introduce a lower limit on the transverse momentum ...



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

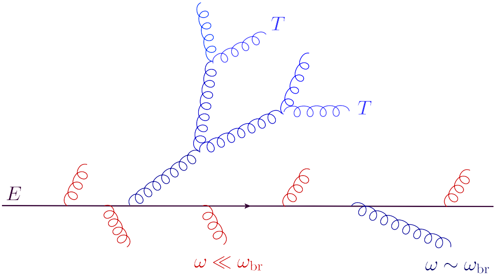
$$t_{\rm f} \lesssim \sqrt{\frac{\omega}{\hat{q}}}$$

- ... hence an upper limit on the formation time !
- Effective only so long as $t_{\rm f} < L$ (medium size), hence for $\omega \le \omega_c \equiv \hat{q} L^2$
- Two types of emissions occurring inside the medium $(t_{\rm f} < L)$:
  - 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 $t_{\rm f} \simeq \sqrt{\omega/\hat{q}}$

Mini-jets from multiple branching

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

- Multiple branching becomes important when $\omega \lesssim \omega_{br} \equiv \alpha_s^2 \hat{q} L^2$
- Soft primary gluons with $\omega \lesssim \omega_{br}$ occur event by event



- In turn, they generate mini-jets via democratic branchings: $x \sim 1-x$
  - energy transmitted to many soft quanta which thermalize: $\omega \sim T$
  - typical energy loss by the jet $\Delta E \sim \omega_{br}$, large fluctuations

Mini-jets from multiple branching

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

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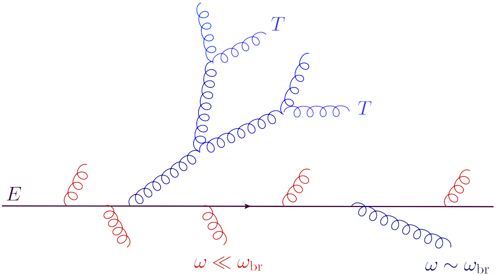
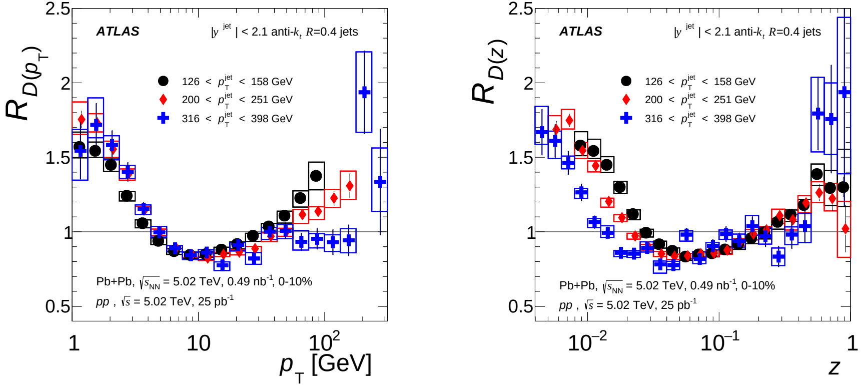


- Energy loss at large angles: a natural explanation for di-jet asymmetry

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

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

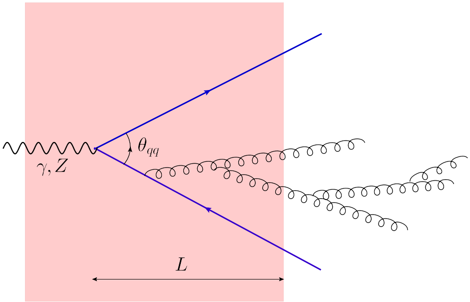


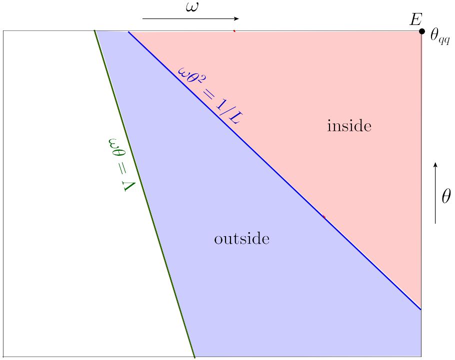
- Can vacuum-like radiation be modified by the medium ?

Vacuum-like emissions (VLE)

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)
  - just to simplify the arguments about color coherence
- The antenna propagates through the medium along a distance L





- Emissions $\left(t_{\rm f} = \frac{1}{\omega\theta^2}\right)$ can occur either inside $(t_{\rm f} \leq L)$, or outside $(t_{\rm f} > L)$

VLEs inside the medium

- For $\omega \leq \omega_c$, the medium introduces an upper limit on $t_{\rm f}$:

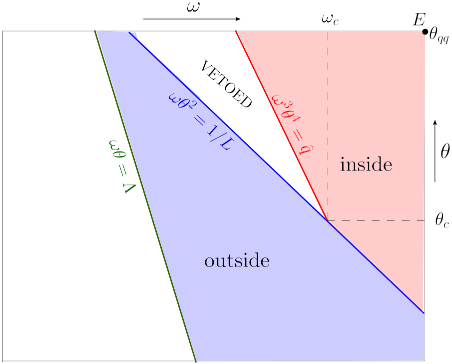
$$t_{\rm f} \lesssim \sqrt{\frac{\omega}{\hat{q}}} \leq L$$

- No emission within the range

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

- End point of VETOED at

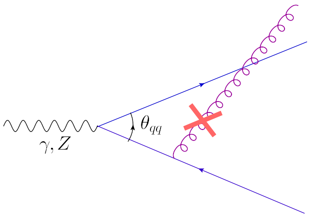
$$\omega_c = \hat{q}L^2\,, \quad \theta_c = \frac{1}{\sqrt{\hat{q}L^3}}$$

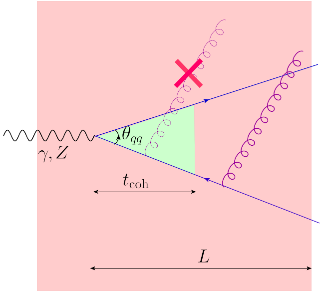


- VLEs in medium occur like in vacuum, but with a smaller phase-space
  - typical values: $\hat{q} = 1\,\mathrm{GeV}^2/\mathrm{fm}$, $L = 4\,\mathrm{fm}$, $\omega_c = 50\,\mathrm{GeV}$, $\theta_c = 0.05$
- Energy loss & $p_\perp$-broadening during formation are negligible

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 $t_{\rm coh}$

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

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

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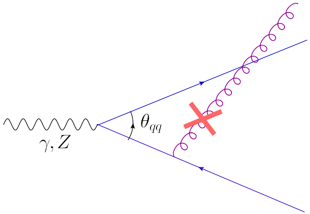
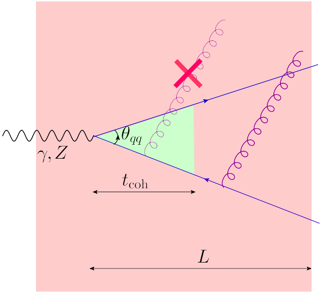




- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

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

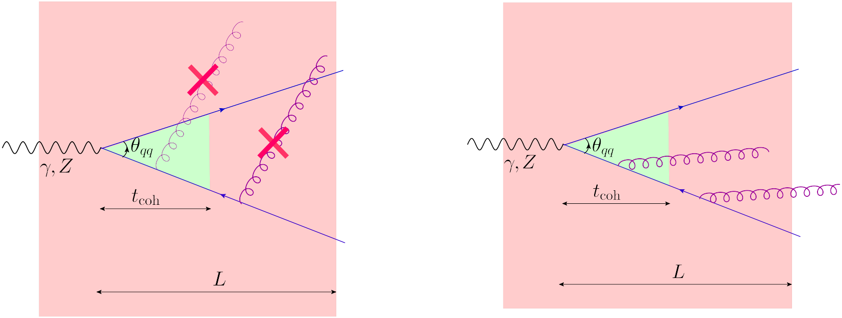
- Angular ordering could be violated for emissions inside the medium

Angular ordering strikes back

- But this is not the case for the VLEs !

$$\theta > \theta_{q\bar{q}} \quad \& \quad t_f = \frac{1}{\omega\theta^2} > t_{coh} \implies t_f \gtrsim \sqrt{\frac{\omega}{\hat{q}}} \; : \quad \text{not a VLE}$$

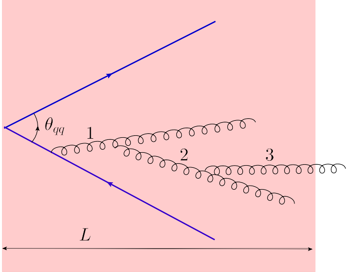
- Wide angle VLEs $(\theta > \theta_{q\bar{q}})$ have $t_f \ll t_{coh}$, hence they are suppressed

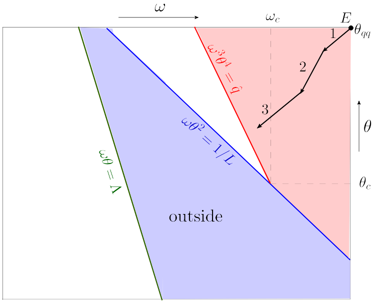


- Emissions at smaller angles $(\theta < \theta_{q\bar{q}})$ can occur at any time
- Color decoherence via collisions plays no role for the VLEs

Vacuum-like cascades at DLA

- Previous arguments extend to a sequence of angular-ordered VLEs
  - rigorous in the double-logarithmic approximation
- Formation time for the cascade ≈ that of the last gluon
  - a typical VL cascade has a formation time $\ll L$

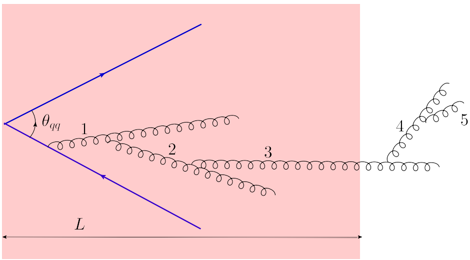


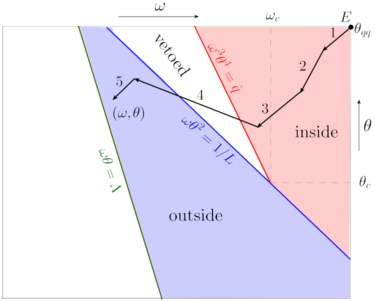


- After formation, gluons propagate in the medium along a distance $\sim L$
  - additional sources for medium-induced radiation
  - ... and for vacuum-like emissions outside the medium

First emission outside the medium

- The respective formation time is necessarily large: $t_f \gtrsim L$
- In-medium sources with $\theta \gg \theta_c$ lose coherence in a time $t_{coh} \ll L$
- First outside emission can violate angular ordering
  - re-opening of the angular phase-space
- Subsequent "outside" emissions obey angular-ordering, as usual



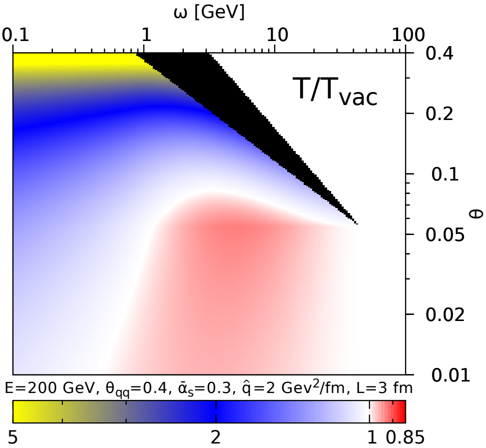


- Vetoed region + lack of angular-ordering for the first "outside" emission

Gluon distribution at DLA

- Double differential distribution in energies and emission angles:

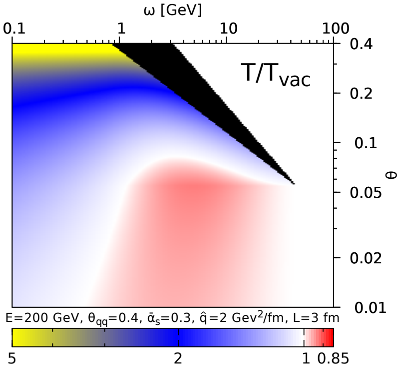
$$T(\omega, \theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$$

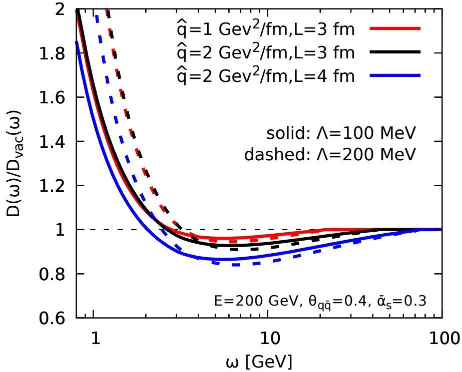


- $E = 200\,\mathrm{GeV}, \quad \theta_{q\bar{q}} = 0.4$
- $\hat{q} = 2\,\mathrm{GeV}^2/\mathrm{fm}, \quad L = 3\,\mathrm{fm}$
- $T/T_{\rm vac} = 0$ in the excluded region
- $T/T_{\rm vac} = 1$ inside the medium and also for $\omega > \omega_c$ and any θ
- $T/T_{\rm vac} < 1$ outside the medium at small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

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

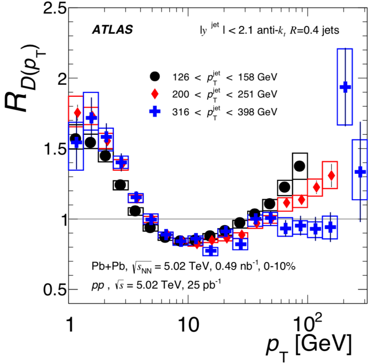


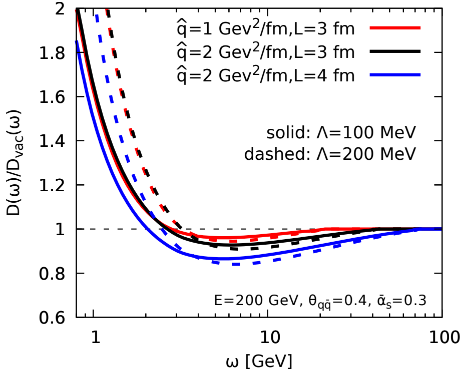


- Slight suppression at intermediate energies (from 3 GeV up to ω_c)
  - the phase-space is reduced by the vetoed region
  - the amount of suppression increases with L and $\hat{q}$

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)
    - reopening of the phase-space by the first emission outside the medium
- Related proposal by *Mehtar-Tani and Tywoniuk, arXiv:1401.8293*

Monte Carlo implementation

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

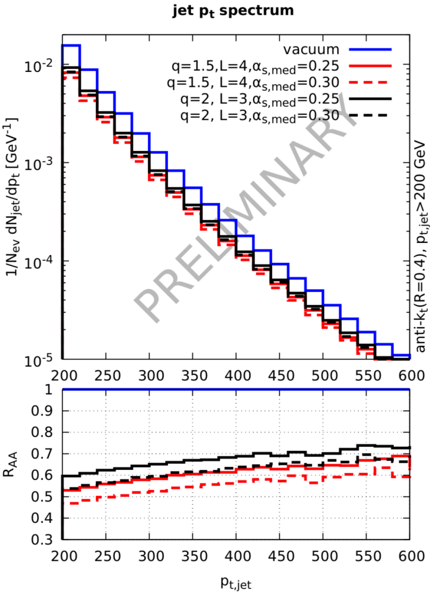
- So far, conceptually simple, but DLA approximations are very crude:
  - no energy conservation (small-x, gluons only), fixed coupling
  - no $k_\perp$-broadening, no medium-induced radiation
- Factorization remains true when assuming strong angular ordering alone
- Probabilistic (Markovian) description separately for
  - vacuum-like parton cascades with angular ordering
  - medium-induced cascades with BDMPS-Z branching rates
- MC implementation: convolution of three showers:
  - vacuum cascade inside the medium but outside the vetoed region
  - medium-induced cascade (in energy)
  - vacuum cascade outside the medium, down to the hadronisation line
- Leading parton selected according to the cross-section for $pp \to 2$ partons

Monte Carlo implementation

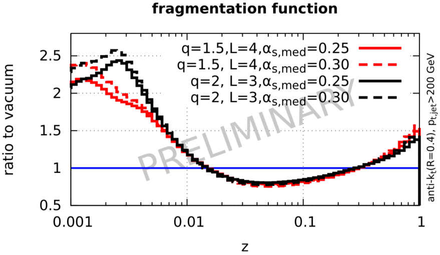
(P. Caucal, E.I., A. H. Mueller and G. Soyez, in preparation)

- So far, conceptually simple, but DLA approximations are very crude:
  - no energy conservation (small-x, gluons only), fixed coupling
  - no $k_\perp$-broadening, no medium-induced radiation
- Leading-logarithmic approximation (angular ordering), with obvious benefits
  - full splitting functions, running coupling, quarks and gluons, $N_c = 3$
  - Gaussian $k_\perp$-broadening ascribed by hand
  - reconstruction of the geometry in 3 dimensions
  - energy loss: partons with angles $\theta > \bar{\theta}$ are leaving the jet
  - no angular ordering for the first emission outside the medium
  - all the partons inside the medium can act as sources for it
- Not yet fully realistic for phenomenology:
  - over-simplified medium description: no expansion, no hydro, just $\hat{q}$
  - no hadrons, just partons

MC: preliminary results

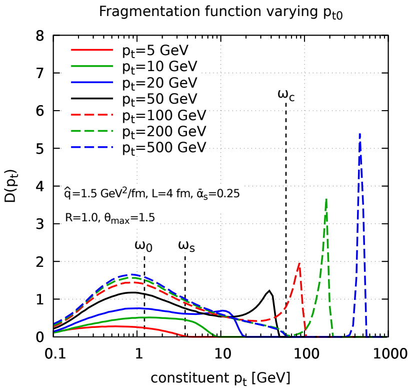


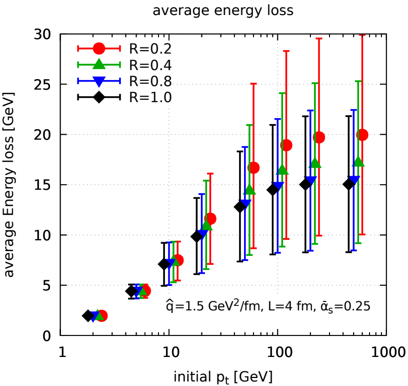
- Focus on 2 observables:
  - nuclear modification factor R_{AA}
  - ratio of FFs in AA and pp
- Various choices for $\hat{q}$, L and $\alpha_{s,\,\mathrm{med}}$



Medium-induced radiation alone

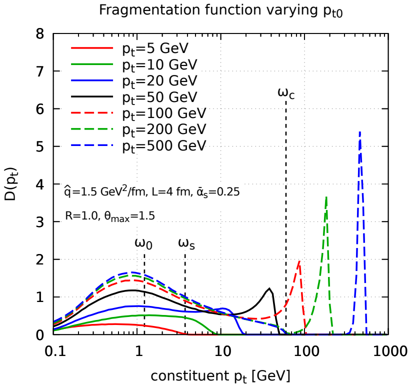
- Initial parton with energy $E \equiv p_{t0}$ generating a medium-induced cascade
- Left: fragmentation function (or spectrum) $D(\omega) = \omega \frac{\mathrm{d}N}{\mathrm{d}\omega}$
  - pronounced leading-particle peak so long as $E \gg \omega_s = \alpha_s^2 \omega_c$
  - BDMPS-Z spectrum $D(\omega) \propto \frac{1}{\sqrt{\omega}}$ at $\omega < \omega_c$

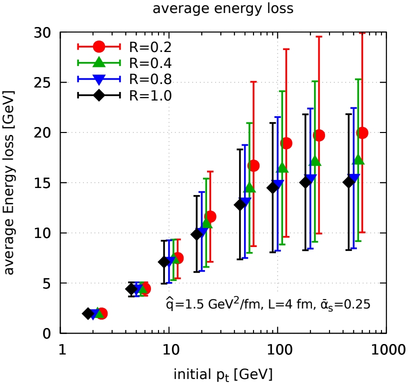




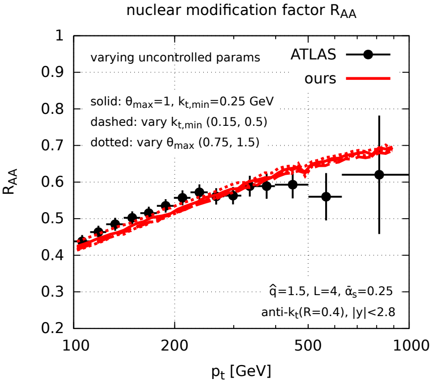
Medium-induced radiation alone

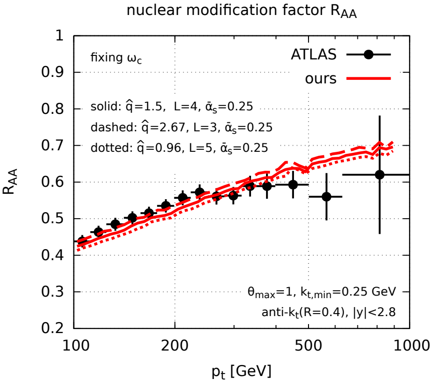
- Initial parton with energy $E \equiv p_{t0}$ generating a medium-induced cascade
- Right: average energy loss by the jet + its fluctuations
  - $\langle \Delta E \rangle$ becomes independent of E when $E \gg \omega_s$
  - sizeable dependence upon the jet opening angle for $R \leq 0.8$





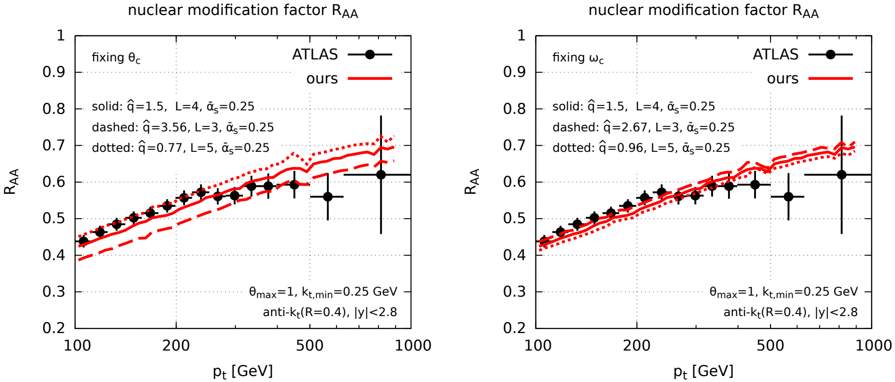
- Not a fit: just a set of "reasonable" values for the physical parameters
- "Uncontrolled parameters" = kinematical cuts: $k_{t,\mathrm{min}} \equiv \Lambda$, $\theta_{\mathrm{max}} \equiv \bar{\theta}$
    - results are remarkably robust
- Right plot: R_{AA} depends upon the medium only via $\omega_c = \hat{q}L^2/2$





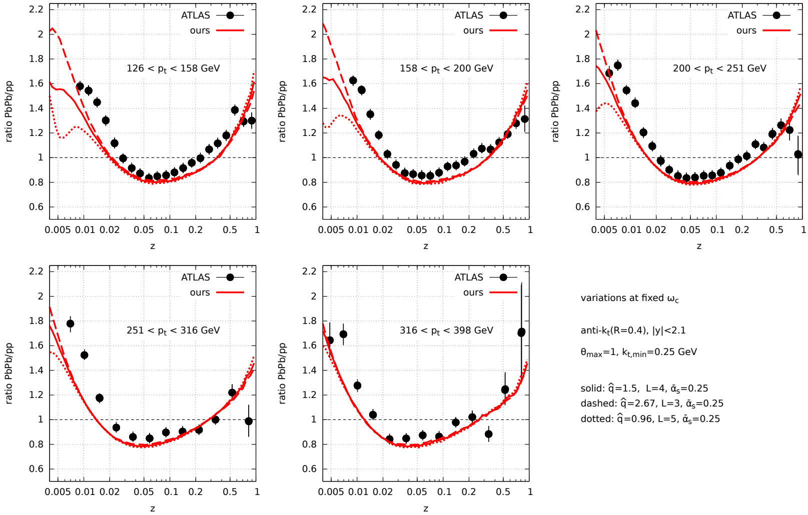
Boldly adding the data: R_{AA}

- Not a fit: just a set of "reasonable" values for the physical parameters
- Left plot: fixing θ_c, that is, the product $\hat{q}L^3$
  - results are changing, as expected
- Right plot: R_{AA} depends upon the medium only via $\omega_c = \hat{q}L^2/2$



Boldly adding the data: Fragmentation

- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- Fixing $\omega_c = \hat{q}L^2/2$: very small variations (except at very low z)



variations at fixed ω_c

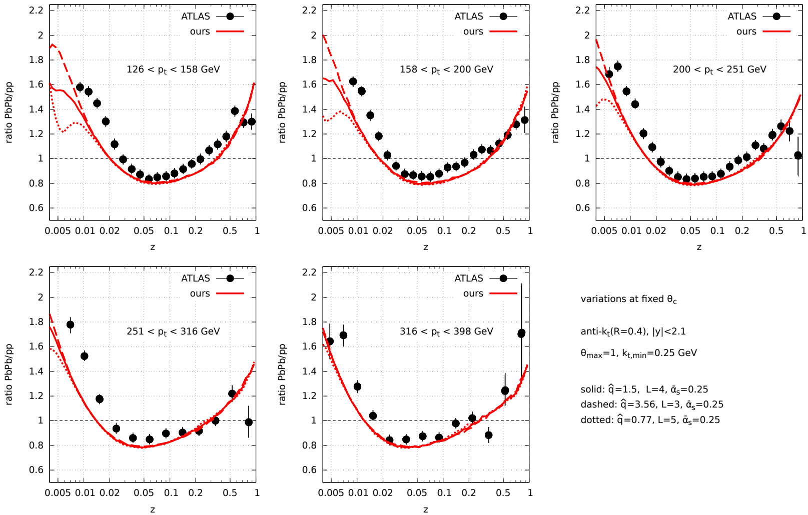
anti-k_t(R=0.4), |y|<2.1

θ_{max}=1, $k_{t,min}$=0.25 GeV

solid: $\hat{q}$=1.5, L=4, $\bar{\alpha}_s$=0.25
dashed: $\hat{q}$=2.67, L=3, $\bar{\alpha}_s$=0.25
dotted: $\hat{q}$=0.96, L=5, $\bar{\alpha}_s$=0.25

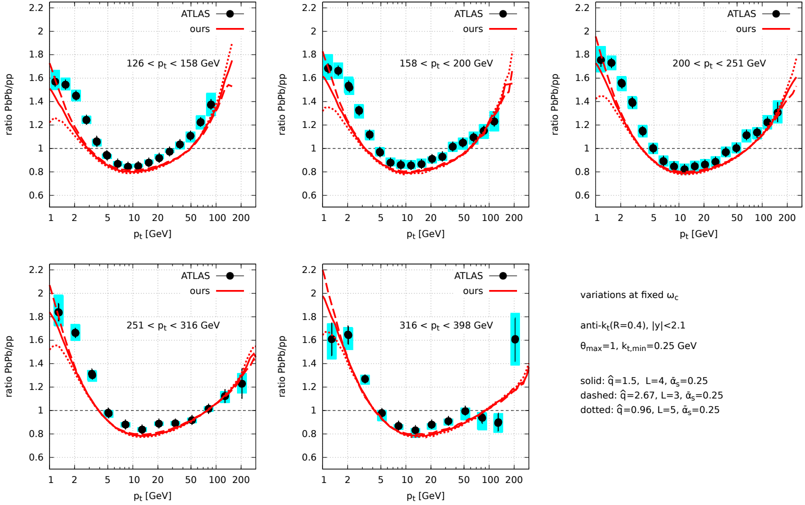
Boldly adding the data: Fragmentation

- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- Fixing θ_c, that is, $\hat{q}L^3$: very small variations as well ...



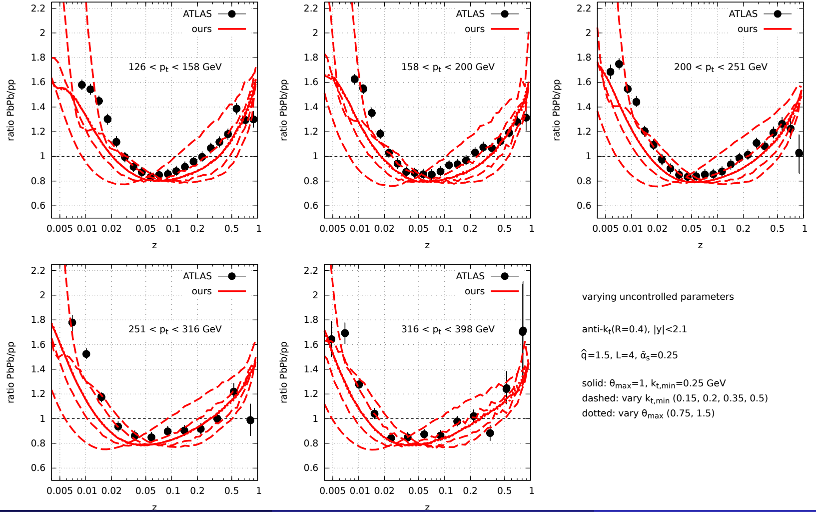
Boldly adding the data: Fragmentation

- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- Equally good results when plotted as a function of the constituent p_t ...



Boldly adding the data: Fragmentation

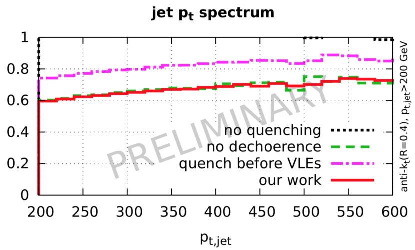
- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- ... but stronger variability with respect to the "uncontrolled parameters" :

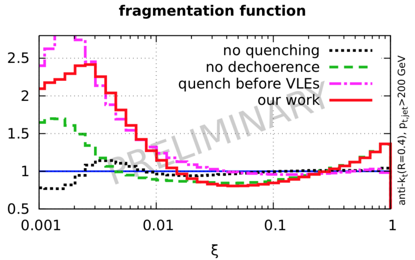


Conclusions & perspectives

- 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
- VLEs inside the medium act as sources for medium-induced radiation
- Probabilistic picture, well suited for Monte-Carlo implementations
- Preliminary MC results, which look promising
  - qualitative and even semi-quantitative agreement with the LHC data for jet fragmentation and the nuclear modification factor
- Perspectives: more realistic description of the medium, implementation in JETSCAPE

MC: preliminary results (2)





- "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