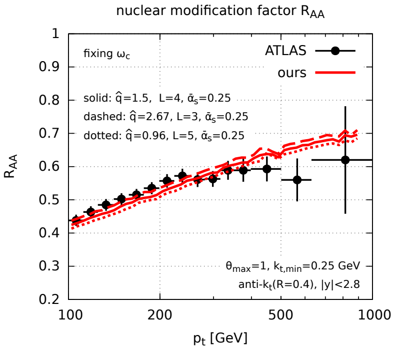
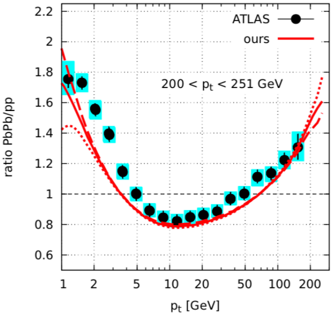
A unified picture for jet evolution in a dense QCD medium

Edmond Iancu
IPhT Saclay & CNRS

with P. Caucal, A. H. Mueller and G. Soyez





Outline

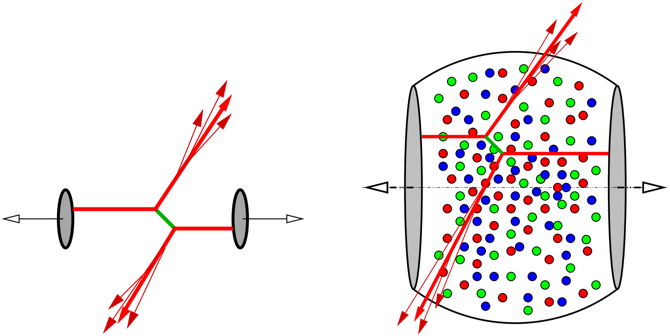
- Introduction to jet quenching (very short)
  - one slide on experimental motivations
  - the general picture & our main conclusions
- Two types of radiation...
  - vacuum-like (bremsstrahlung): parton virtualities
  - medium-induced radiation: collisions in the plasma
- ... and their factorization within perturbative QCD
  - probabilistic (Markovian) descriptions
- Our original discussion: the leading double-logarithmic approximation

  P. Caucal, E.I., A. H. Mueller and G. Soyez, PRL 120 (2018) 232001
- Here: our preliminary results from the Monte-Carlo implementation

Jet quenching

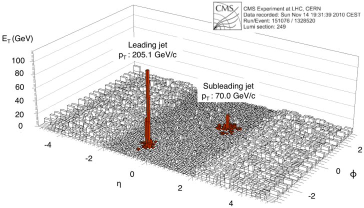
- Hard processes in QCD typically create pairs of partons which propagate back–to–back in the transverse plane

- In the "vacuum" (pp collisions), this leads to a pair of symmetric jets

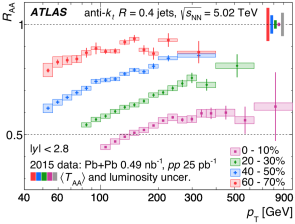


- In AA collisions, the two jets can be differently affected by their interactions with the surrounding, partonic, medium: quark-gluon plasma

Jet quenching in Pb+Pb collisions at the LHC

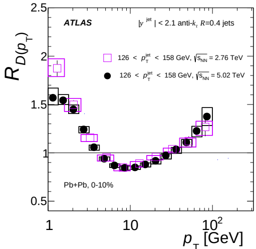


- Di-jet asymmetry: energy imbalance
- carried by many soft (< 2 GeV) hadrons propagating at large angles



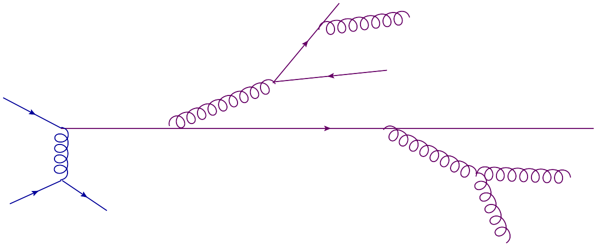
- Nuclear modification factor for jets R_{AA}
- stronger suppression for more central collisions
- it flattens out at large jet p_T

- Jet fragmentation function
- ratio of FFs in Pb+Pb and p+p
- an interesting pattern



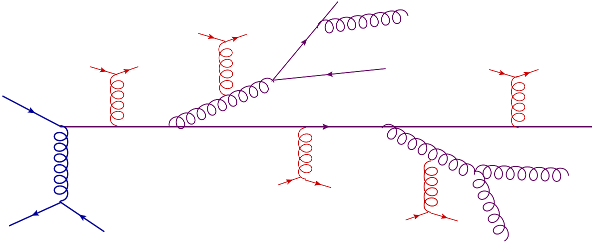
Jet evolution in a quark-gluon plasma

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



Jet evolution in a quark-gluon plasma

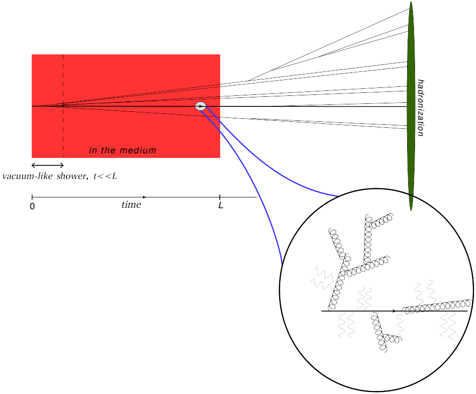
- The leading particle (LP) is produced by a hard scattering
- It subsequently evolves via radiation (branchings) ...
  - Bremsstrahlung triggered by the parton virtualities



- ... 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 (energy loss)
  - wash out the colour coherence (destroy interference pattern)

Our main conclusions

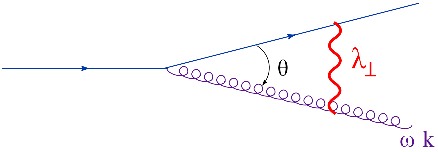
- The two types of radiation ("vacuum-like" and "medium-induced") can be factorized from each other, via controlled approximations in pQCD



- The "vacuum-like" radiation too is modified by the medium: phase-space constraints, color decoherence

Formation time

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



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

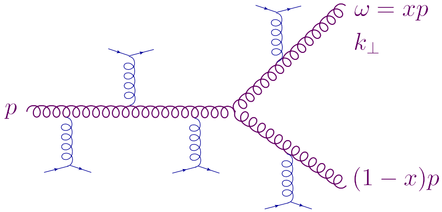
$$k_\perp \simeq \omega\theta$$

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

- 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
- In the medium: additional decoherence introduced by collisions: $k_\perp^2 \gtrsim \hat{q} t_{\rm f}$
  - $\hat{q}$: jet quenching parameter (a property of the medium)

Medium-induced radiation

- The collisions introduce a lower limit on the transverse momentum ...

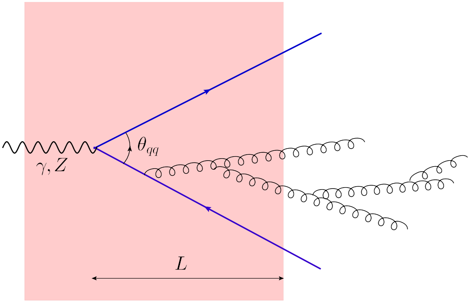


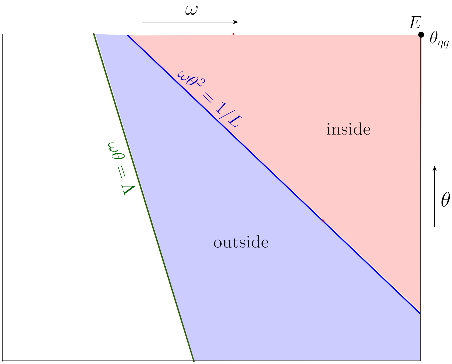
$$t_{\rm f} = \frac{\omega}{k_\perp^2} \quad \& \quad k_\perp^2 \gtrsim \hat{q} t_{\rm f}$$

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

- ... 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 $t_{\rm f} \simeq \sqrt{\omega/\hat{q}}$

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

Vacuum-like emissions (VLE)

- Recall: the medium introduces an upper limit on $t_{\rm f}$ for VLEs:

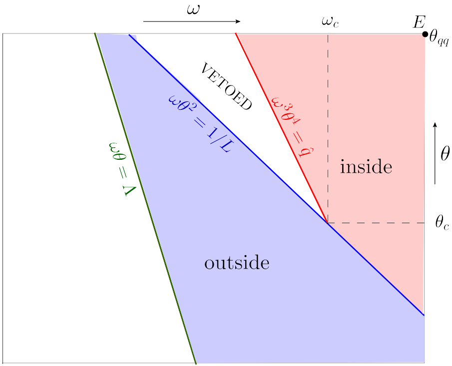
$$t_{\rm f} = \frac{1}{\omega\theta^2} \lesssim \sqrt{\frac{\omega}{\hat q}}$$

- No emission within the range

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

- End point of VETOED at

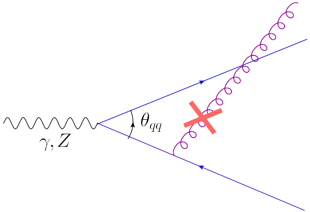
$$\omega_c = \hat q L^2\,, \quad \theta_c = \frac{1}{\sqrt{\hat q L^3}}$$

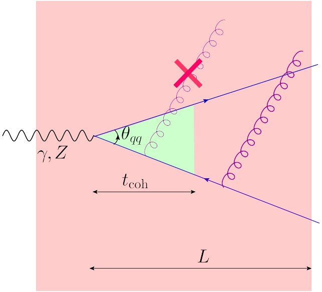


- VLEs in medium occur like in vacuum, but with a smaller phase-space
  - typical values: $\hat q = 1\,{\rm GeV^2/fm}$, $L = 4\,{\rm fm}$, $\omega_c = 50\,{\rm GeV}$, $\theta_c = 0.05$
- Energy loss & $p_\perp$-broadening during formation are negligible

Color (de)coherence

- In vacuum, wide angle emissions ($\theta > \theta_{q\bar{q}}$) are suppressed by color coherence
  - successive emissions are ordered in the emission angle





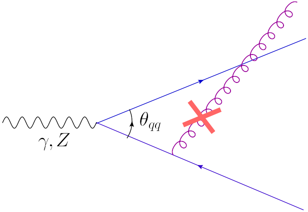
- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

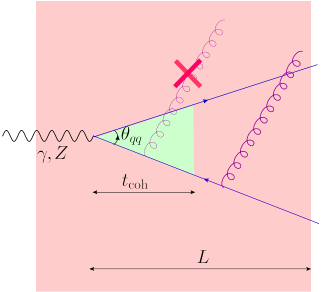
$$\hat{q}\Delta t \gtrsim \frac{1}{(\theta_{q\bar{q}}\Delta t)^2} \implies \Delta t \gtrsim t_{\rm coh} = \frac{1}{(\hat{q}\theta_{q\bar{q}}^2)^{1/3}}$$

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

Color (de)coherence

- In vacuum, wide angle emissions ($\theta > \theta_{q\bar{q}}$) are suppressed by color coherence
  - successive emissions are ordered in the emission angle





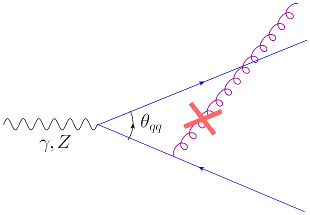
- In medium, color coherence is washed out by collisions after a time $t_{\rm coh}$

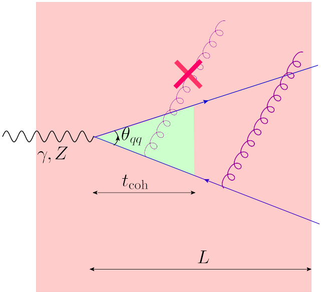
$$t_{\rm coh} = \frac{1}{(\hat{q}\theta_{q\bar{q}}^2)^{1/3}} \ll L \quad \text{if} \quad \theta_{q\bar{q}} \gg \theta_c \simeq 0.05$$

- Angular ordering could be violated for emissions inside the medium

Color (de)coherence

- In vacuum, wide angle emissions ($\theta > \theta_{q\bar{q}}$) are suppressed by color coherence
  - successive emissions are ordered in the emission angle





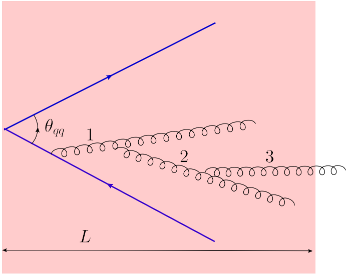
- But this is not the case for the VLEs !

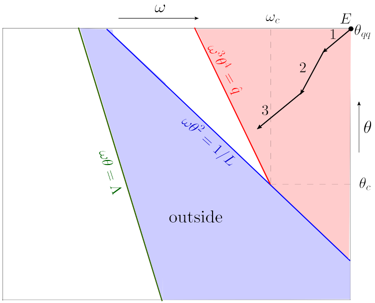
$$\theta > \theta_{q\bar{q}} \quad \& \quad t_{\rm f} = \frac{1}{\omega\theta^2} \ll \sqrt{\frac{\omega}{\hat{q}}} \Longrightarrow t_{\rm f} \ll t_{\rm coh}$$

- Wide-angle VLEs ($\theta > \theta_{q\bar{q}}$) are still suppressed $\Longrightarrow$ angular ordering

Vacuum-like cascades inside the medium

- Previous arguments extend to a sequence of angular-ordered VLEs
  - angular ordering $\Longrightarrow$ formation times are strongly increasing
  - leading-logarithmic approximation: strong angular ordering for VLEs
- Formation time for the whole cascade $\approx$ that of the last gluon
  - a typical VL cascade has a formation time $\ll L$

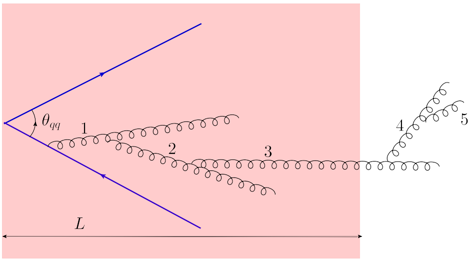


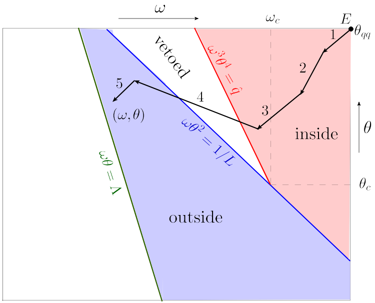


- After formation, partons propagate in the medium along a distance $\sim L$

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
  - enhanced radiation at low energies and large angles





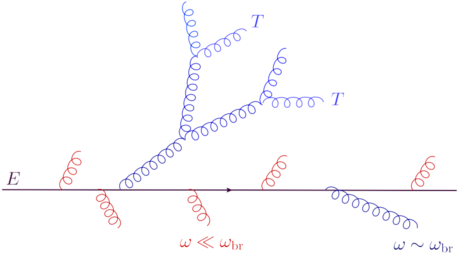
- Subsequent "outside" emissions obey angular-ordering, as usual

Medium-induced radiation: mini-jets

- Emissions can occur anywhere inside the medium: emission rate $\propto 1/t_{\rm f}$

$$\omega\frac{{\rm d}\mathcal{P}}{{\rm d}\omega{\rm d}k_\perp^2{\rm d}t} \sim \frac{\alpha_s}{t_{\rm f}(\omega)}\,\frac{1}{\hat q \Delta t}\,{\rm e}^{-\frac{k_\perp^2}{\hat q \Delta t}}\,, \quad t_{\rm f}(\omega) \simeq \sqrt{\frac{\omega}{\hat q}}$$

- After emission, transverse momentum broadening: $\langle k_\perp^2 \rangle = \hat q (L-t)$
  - no energy (soft) logs, nor collinear logs



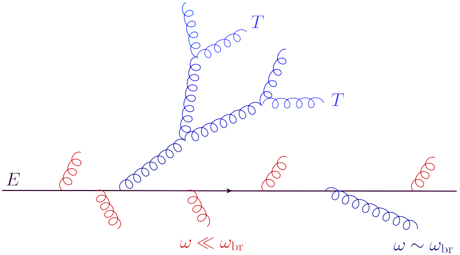
- Multiple branching when $t_{\rm f}(\omega)/\alpha_s < L \implies \omega \lesssim \omega_{\rm br} \equiv \alpha_s^2 \hat q L^2$
  - successive emissions are incoherent: no angular ordering

Medium-induced radiation: mini-jets

- Emissions can occur anywhere inside the medium: emission rate $\propto 1/t_{\rm f}$

$$\omega \frac{{\rm d}\mathcal{P}}{{\rm d}\omega {\rm d}k_\perp^2 {\rm d}t} \sim \frac{\alpha_s}{t_{\rm f}(\omega)} \frac{1}{\hat{q}\Delta t} {\rm e}^{-\frac{k_\perp^2}{\hat{q}\Delta t}}, \quad t_{\rm f}(\omega) \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

- Energy gets transmitted to many soft quanta at large angles: $\theta > \theta_{q\bar{q}}$
  - typical energy loss by the jet: $\Delta E \sim \omega_{\rm br} = \alpha_s^2 \hat{q} L^2$



- A natural explanation for di-jet asymmetry (energy loss at large angles)

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

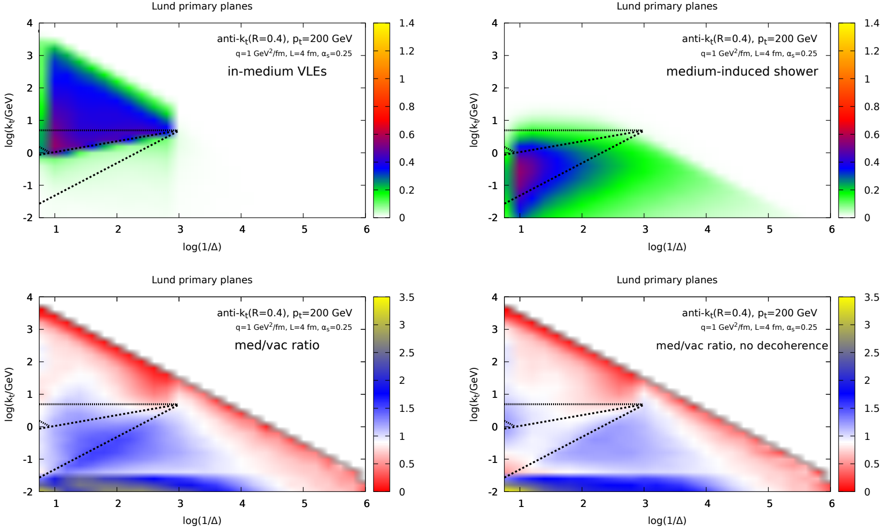
Monte Carlo implementation

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

- Medium-induced emissions can be factorized from the vacuum-like ones
- Probabilistic (Markovian) descriptions for both mechanisms
- Well defined MC implementation: two modules
  - vacuum-like angular-ordered showers (inside & outside the medium)
  - medium-induced emissions: energy loss, no angular ordering
  - no angular ordering for the first emission outside the medium
- For substructure studies: jet declustering with Cambridge/Aachen algorithm
  - angular ordering $\Rightarrow$ problems with medium-induced radiation
- Leading parton selected according to the cross-section for $pp \to 2$ partons
- Promising preliminary results, but further developments are still needed
  - more realistic medium description: expansion, back-reaction, hydro
  - hadronization

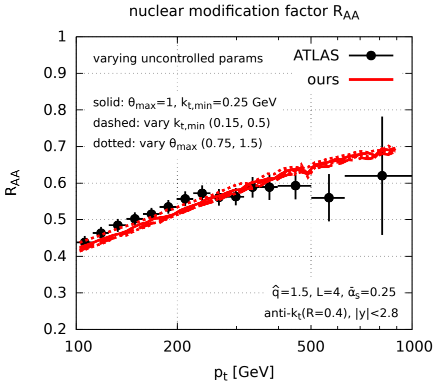
Monte Carlo: Lund primary plane

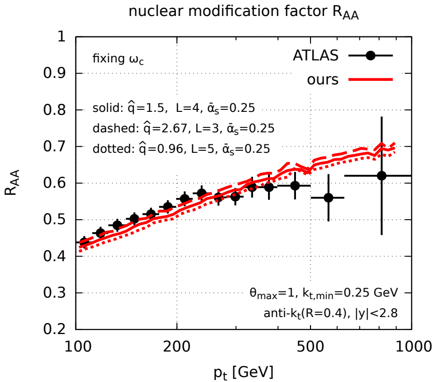
- Average density of points per jet and per unit area in the $(\ln k_t,\ \ln \frac{1}{\theta})$ plane



Monte Carlo: R_{AA}

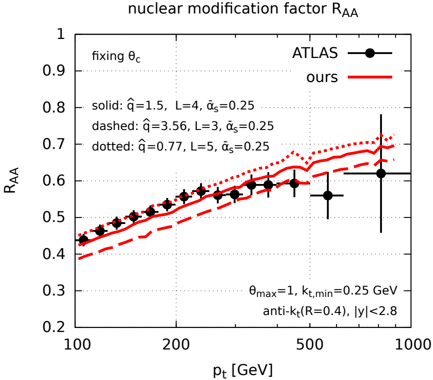
- Not a fit: just a set of "reasonable" values for the physical parameters
- "Uncontrolled parameters" = kinematical cuts: $k_{t,\min} \equiv \Lambda$, $\theta_{\max} \equiv \theta_{q\bar{q}}$
  - results are remarkably robust
- Right plot: R_{AA} depends upon the medium only via $\omega_c = \hat{q}L^2$

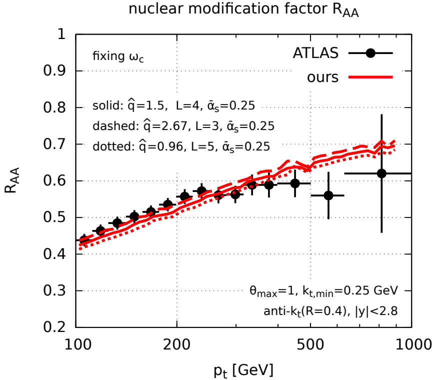




Monte Carlo: R_{AA}

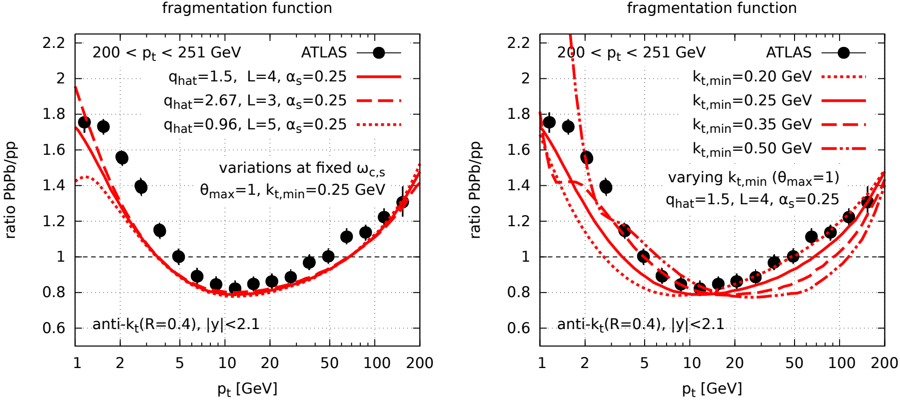
- Not a fit: just a set of "reasonable" values for the physical parameters
- Left plot: fixing θ_c, that is, the product $\hat{q}L^3$
  - results are changing, as expected
- Right plot: R_{AA} depends upon the medium only via $\omega_c = \hat{q}L^2$





Monte Carlo: Fragmentation function

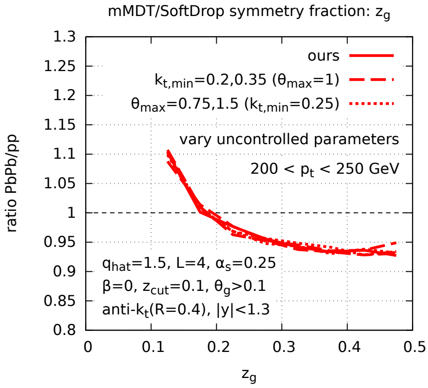
- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- Fixing $\omega_c = \hat{q}L^2$: very small variations (except at very low p_t)
- ... but stronger variability with respect to the "uncontrolled parameters"

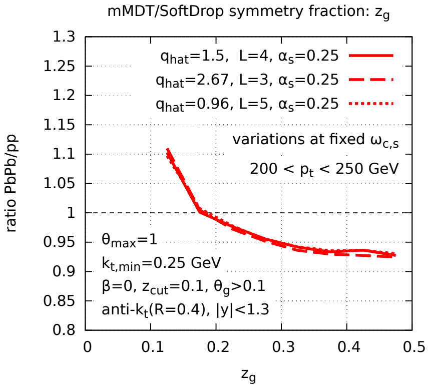


- z_g: splitting fraction for the first hard splitting (in our MC: typically a VLE)

$$z_g \equiv \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R}\right)^\beta \quad \text{with} \quad z_{cut} = 0.1, \ \Delta R_{ij} > 0.1, \ \beta = 0$$

- Qualitatively similar to CMS data *(arXiv:1708.09429)* (smeared p+p)



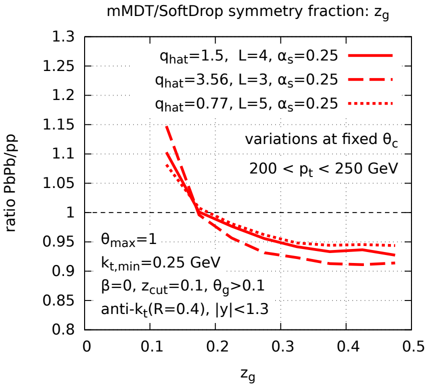


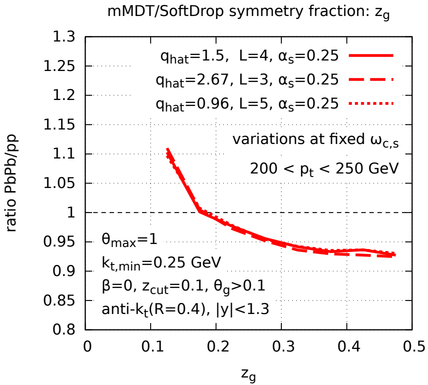
Monte Carlo: Soft Drop

- z_g: splitting fraction for the first hard splitting (in our MC: typically a VLE)

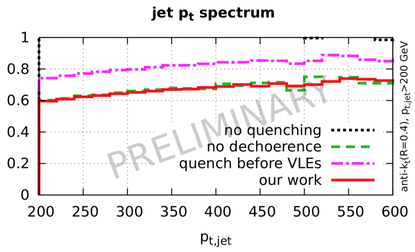
$$z_g \equiv \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R}\right)^{\beta} \quad \text{with} \quad z_{\text{cut}} = 0.1,\ \Delta R_{ij} > 0.1,\ \beta = 0$$

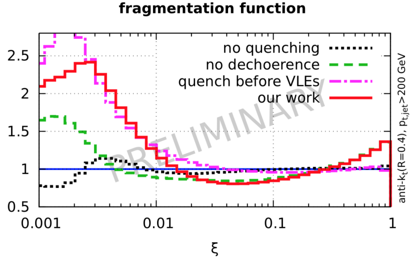
- Qualitatively similar to CMS data *(arXiv:1708.09429)* (smeared p+p)





More exclusive studies





- "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 $p_{T,\mathrm{jet}}$

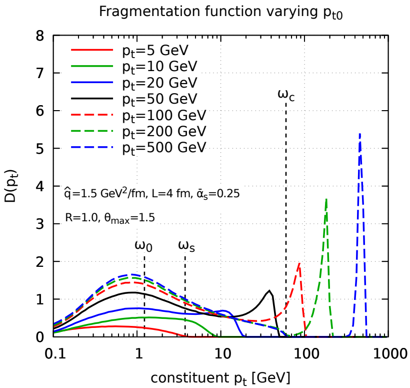
- Partons created inside the medium via medium-induced emissions significantly contribute to the soft radiation outside the medium

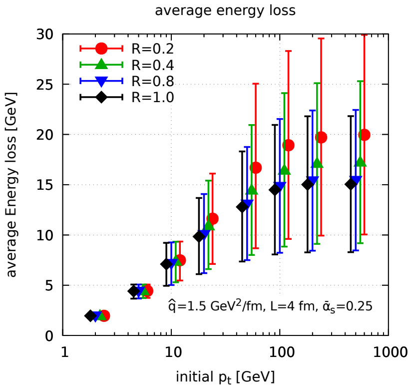
Conclusions & perspectives

- 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
- Probabilistic picture, well suited for Monte-Carlo implementations
- Preliminary MC results, which look promising
  - qualitative and semi-quantitative agreement with the LHC data for the jet R_{AA}, jet fragmentation functions, and jet substructure ($z_{\rm g}$)
- Perspectives: more realistic description of the medium, implementation in JETSCAPE

Monte Carlo: Medium-induced radiation only

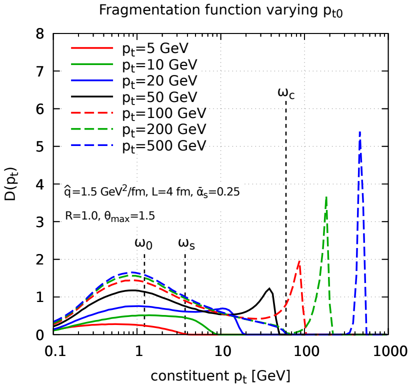
- Initial parton with energy $E \equiv p_{t0}$, jet with opening angle $\theta_{q\bar{q}} \equiv R$
- Left: fragmentation function (or spectrum) $D(\omega) = \omega \frac{\mathrm{d}N}{\mathrm{d}\omega}$
  - pronounced leading-particle peak so long as $E \gg \omega_s = \alpha_s^2 \hat{q} L^2$
  - medium-induced radiation: $D(\omega) \propto \frac{1}{\sqrt{\omega}}$ at $\omega < \omega_c = \hat{q} L^2$

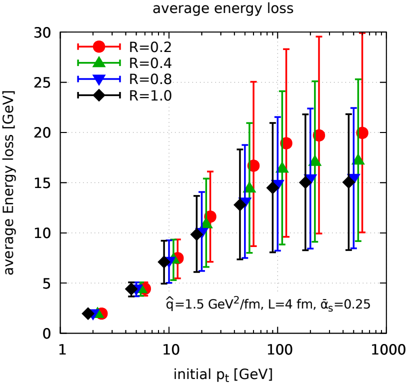




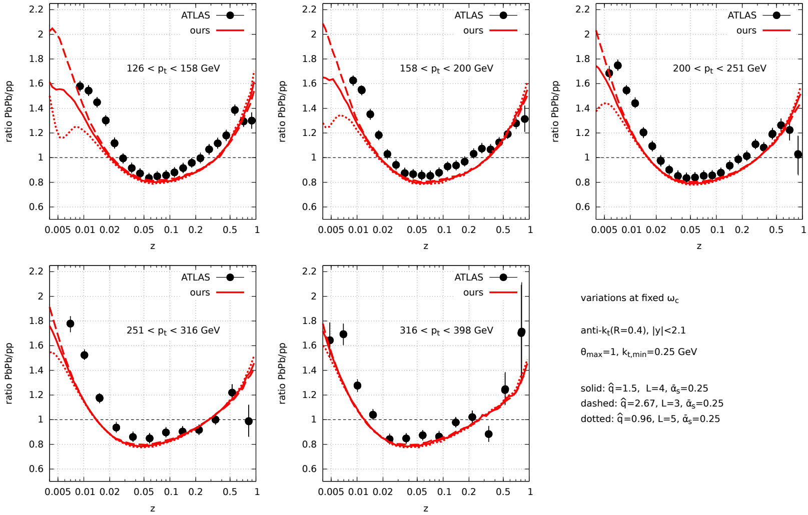
Monte Carlo: Medium-induced radiation only

- Initial parton with energy $E \equiv p_{t0}$, jet with opening angle $\theta_{q\bar{q}} \equiv R$
- Right: average energy loss by the jet + its fluctuations
  - $\langle \Delta E \rangle$ becomes independent of E when $E \gg \omega_s$
  - energy is recovered when increasing R ... but very slowly



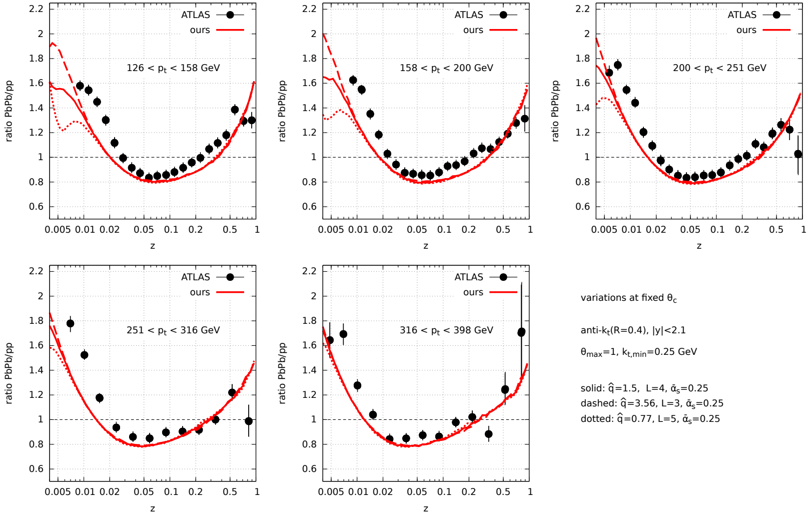


- The same "canonical" values for the medium parameters as in the "best" description of R_{AA} *(ATLAS data from arXiv:1805.05424)*
- Fixing $\omega_c = \hat{q}L^2$: very small variations (except at very low z)



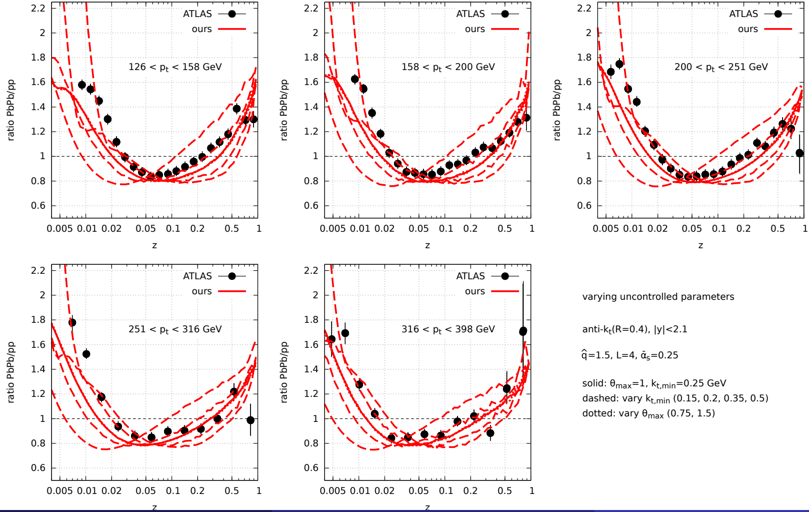
Fragmentation function: as a function of z

- 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 ...



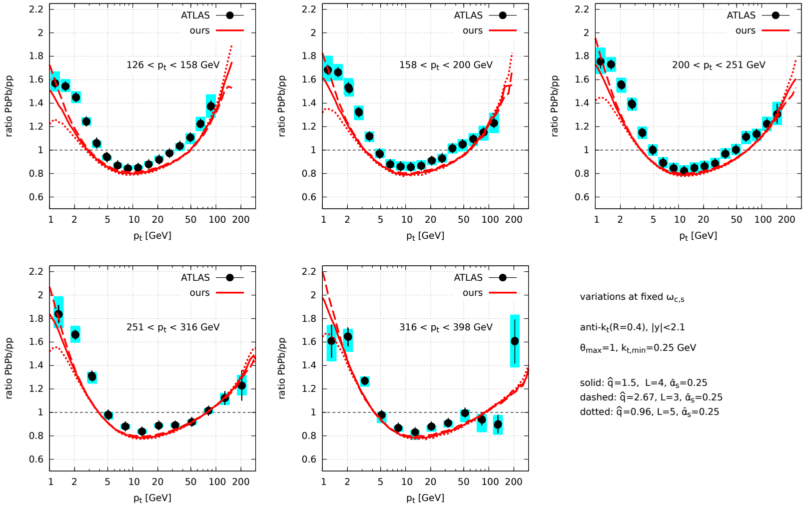
Fragmentation function: as a function of z

- 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" :



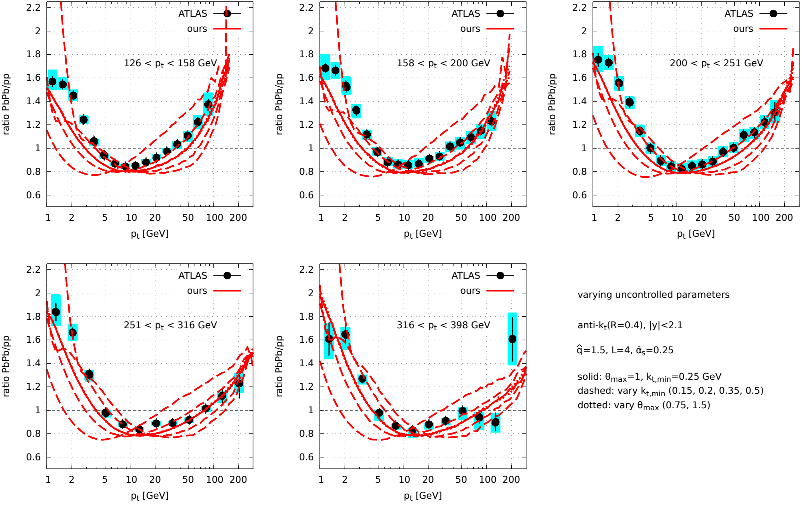
Fragmentation function: as a function of p_t

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

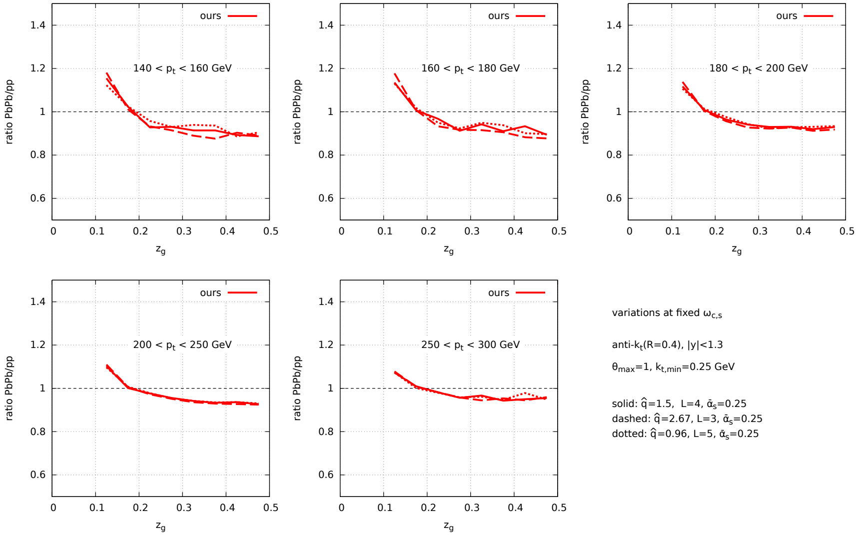


Fragmentation function: as a function of p_t

- 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" :



Monte Carlo: Soft Drop



variations at fixed $\omega_{c,s}$

anti-k_t(R=0.4), |y|<1.3

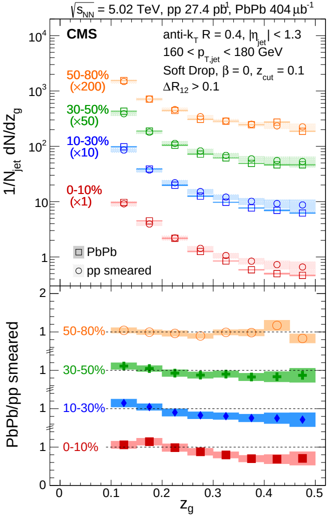
θ_{max}=1, $k_{t,min}$=0.25 GeV

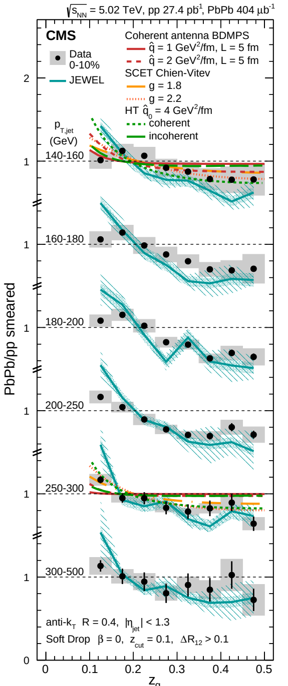
solid: $\hat{q}$=1.5, L=4, $\bar{\alpha}_s$=0.25
dashed: $\hat{q}$=2.67, L=3, $\bar{\alpha}_s$=0.25
dotted: $\hat{q}$=0.96, L=5, $\bar{\alpha}_s$=0.25

- Stronger variations at lower values of p_{t0}

z_g distribution by CMS

(arXiv:1708.09429)

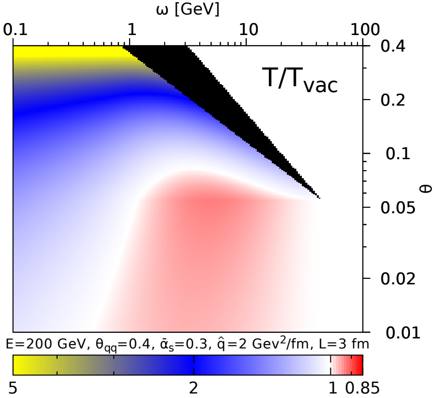




Gluon distribution at DLA

- So far, medium effects on the vacuum-like emissions only
  - vetoed region + lack of angular-ordering for the first "outside" emission

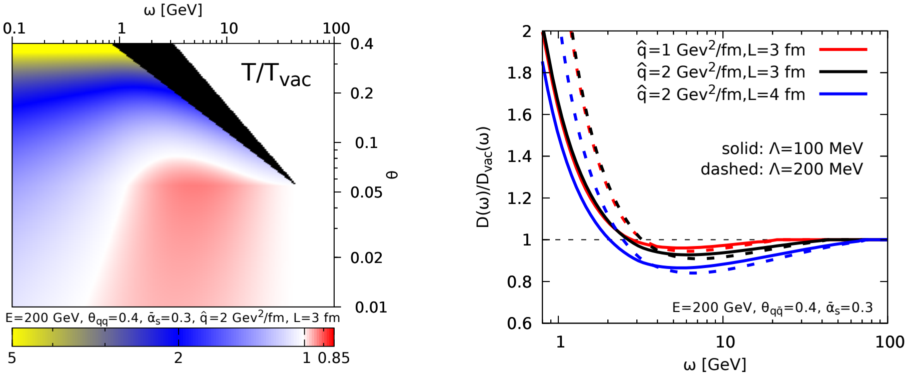
Gluon distribution: $T(\omega, \theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$



- $T/T_{\text{vac}} = 0$ in the vetoed region
- $T/T_{\text{vac}} = 1$ inside the medium and also for $\omega > \omega_c$ and any θ
- $T/T_{\text{vac}} < 1$ outside the medium at small angles $\lesssim \theta_c$
- $T/T_{\text{vac}} > 1$ outside the medium at large angles $\sim \theta_{q\bar{q}}$

Jet fragmentation function at DLA

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



- Slight suppression at intermediate energies: vetoed region
- Significant enhancement at low energy (below 2 GeV)
  - reopening of the phase-space by the first emission outside the medium