Adding vacuum branching to jet evolution in a dense medium

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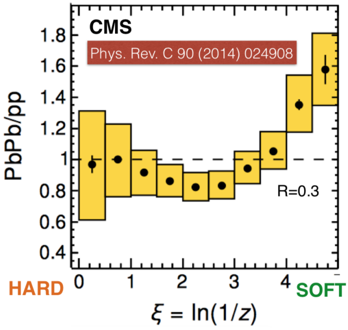
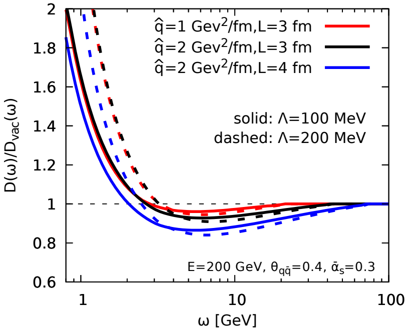
with P. Caucal, A. H. Mueller and G. Soyez, arXiv:1801.09703 [hep-ph]



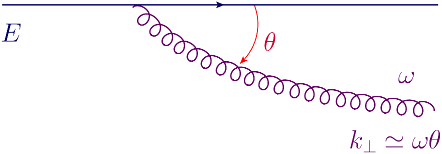


Outline

- A (very) brief introduction
  - jets in the vacuum: bremsstrahlung
  - medium-induced radiation: BDMPS-Z
  - ... and why it seems so hard to marry them
- Vacuum-like emissions inside the medium
  - phase-space, angular ordering, and all that
  - factorization in the double logarithmic approximation
- The first emission outside the medium
  - ... which needs a special treatment
- Overall picture & its consequences for the jet fragmentation function
- Conclusions and perspectives
- A back-up on Jet shapes (preliminary results)

Jet in the vacuum

- Radiation triggered by the parton virtualities: bremsstrahlung



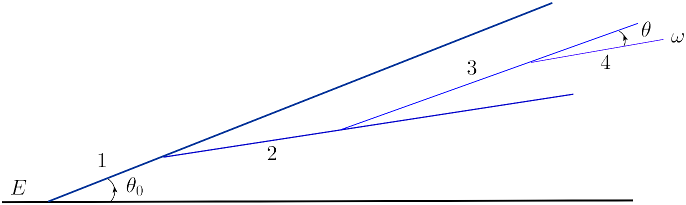
$$\mathrm{d}\mathcal{P} \simeq \frac{\alpha_s C_R}{\pi}\,\frac{\mathrm{d}\omega}{\omega}\,\frac{\mathrm{d}\theta^2}{\theta^2}$$

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

- 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

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

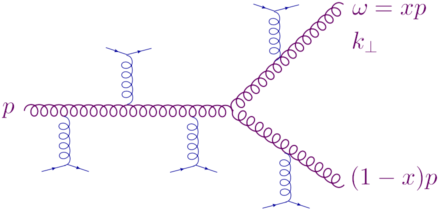
Jets in vacuum at DLA



- Strong ordering in energy: $\omega_i \ll \omega_{i-1}$
- Strong ordering in angles: $\theta_i \ll \theta_{i-1}$
- Very strong ordering in formation times: $t_{\mathrm{f},\,i} \simeq \frac{1}{\omega_i \theta_i^2} \ggg t_{\mathrm{f},\,i-1} \simeq \frac{1}{\omega_{i-1}\theta_{i-1}^2}$
- Evolution stopped by hadronisation: $k_\perp \simeq \omega\theta \gtrsim \Lambda_{\mathrm{QCD}}$

Medium induced radiation

- Additional emissions triggered by collisions in the medium: $k_\perp^2 \simeq \hat{q} t_\mathrm{f}$



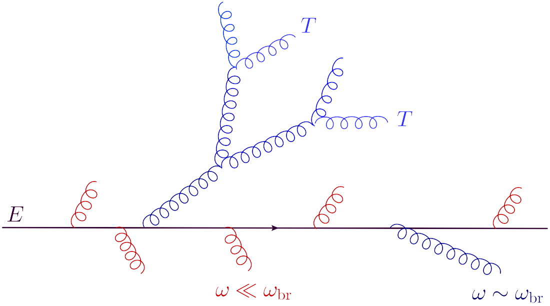
$$t_\mathrm{f}(\omega) \simeq \sqrt{\frac{\omega}{\hat{q}}}$$

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

$$\mathrm{d}\mathcal{P} \simeq \bar{\alpha}\, \frac{\mathrm{d}\omega}{\omega}\, \frac{L}{t_\mathrm{f}(\omega)} \simeq \bar{\alpha}\, L \sqrt{\frac{\hat{q}}{\omega^3}}\, \mathrm{d}\omega \quad \text{(“BDMPS-Z”)}$$

- Multiple branching becomes important when $\omega \lesssim \omega_\mathrm{br} \equiv \bar{\alpha}^2 \hat{q} L^2$
- Independent emissions : collisions wash out the color coherence
- Democratic branchings $(x \sim 1-x)$: energy is transmitted to many soft quanta propagating at large angles (wave turbulence)

Medium-induced jets



- A number of $\mathcal{O}(1)$ of gluons with $\omega \sim \omega_{\rm br}$
- A vaste number of softer gluons with $\omega \ll \omega_{\rm br}$
- Mini-jets generated via democratic branchings, down to the medium scale T

"Bottom-up thermalization", Baier, Mueller, Schiff, Son, 2001

Mehtar-Tani, Salgado, Tywoniuk, 2010; Casalderrey-Solana, E. I., 2011

Blaizot, Dominguez, E.I., Mehtar-Tani, 2012; E.I., Wu, 2015

Apolinário, Armesto, Milhano, Salgado, 2014; Kurkela, Wiedemann, 2014

Towards a unified description

- Can one encode the two mechanisms for radiation in a unified description ?
  - different evolution variables, different coherence properties ...

- Vacuum-like
  - virtuality/emission angles
  - coherent/angular ordering
  - DGLAP equation

- Medium-induced
  - time
  - incoherent
  - rate equation

- Heuristic, pQCD-inspired, approaches which treat them simultaneously
  - medium-modified splitting functions (higher twist) *(K. Kauder's talk)*
  - JEWEL: Monte-Carlo, formation-time selection *(cf. K. Zapp's lecture)*

- Factorization: vacuum-like emissions occur prior to medium-induced ones
  - MARTINI: PYTHIA + AMY + hydro *(talk by C. Park this afternoon)*
  - "Hybrid", strong/weak coupling, model *(cf. D. Pablos' talk)*

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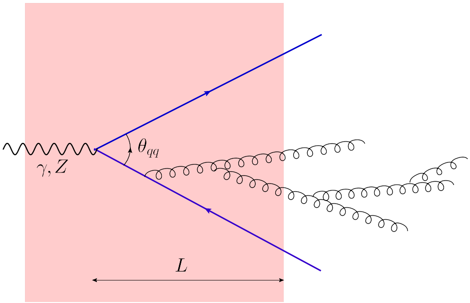
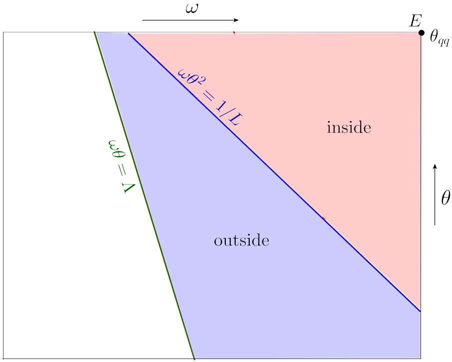
- Factorization: vacuum-like emissions occur prior to medium-induced ones

- There is some truth in that ...

  P. Caucal, E.I., A. H. Mueller and G. Soyez, arXiv:1801.09703 [hep-ph]

- 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





- Vacuum-like emissions (VLE): driven by virtuality, formation time $t_{\mathrm{f}} = \frac{1}{\omega\theta^2}$
- Emissions can occur inside the medium $(t_{\mathrm{f}} \leq L)$, or outside it $(t_{\mathrm{f}} > L)$
- Evolution stopped by hadronisation: $k_\perp \simeq \omega\theta \gtrsim \Lambda_{\mathrm{QCD}}$

VLEs inside the medium

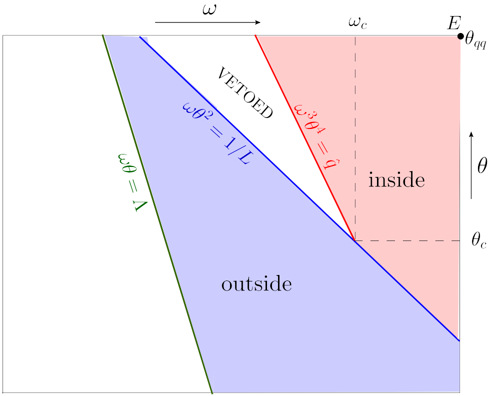
- Collisions introduce a lower limit on the $k_\perp$ of an emitted gluon: $k_\perp^2 \gtrsim \hat{q} t_\mathrm{f}$
- When $k_\perp^2 \simeq \hat{q} t_\mathrm{f}$, the emission is necessarily medium-induced
- A gluon emission can be vacuum-like only if it is much harder
  - $k_\perp^2 \gg \hat{q} t_\mathrm{f}$: momentum broadening is negligible

$$t_\mathrm{f}\,\big|_\mathrm{vac} \equiv \frac{1}{\omega\theta^2} \ll t_\mathrm{f}\,\big|_\mathrm{med} \equiv \sqrt{\frac{\omega}{\hat{q}}} \Longleftrightarrow \omega \gg \left(\frac{\hat{q}}{\theta^4}\right)^{\frac{1}{3}}$$

  - $\omega \gg \hat{q} t_\mathrm{f}^2$: energy loss (during formation) is negligible as well
- This constraint applies only so long as $t_\mathrm{f}\,\big|_\mathrm{med} < L$, that is, $\omega < \omega_c = \hat{q} L^2$
- More energetic gluons with $\omega > \omega_c$ are always vacuum-like
- A vetoed region in phase-space for $\omega < \omega_c$
  - no VLEs with formation times within the range $t_\mathrm{f}\big|_\mathrm{med} < t_\mathrm{f} < L$

The vetoed region

- 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
  - this restriction is a "leading-twist" effect: standard splitting functions



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

- some typical values:

$$\hat{q} = 1 \div 2\,\mathrm{GeV}^2/\mathrm{fm} \qquad L = 4\,\mathrm{fm}$$

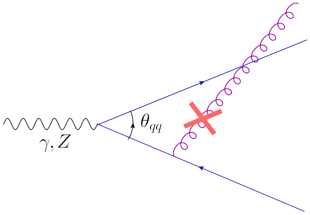
$$\omega_c = 40 \div 80\,\mathrm{GeV}$$

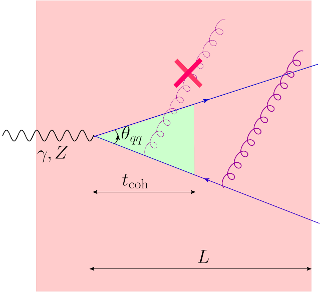
$$\theta_c = 0.03 \div 0.05$$

- Notice the upper limit $\theta_{q\bar{q}}$ (antenna opening) on the emission angle: Why ?

Color (de)coherence

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





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

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

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

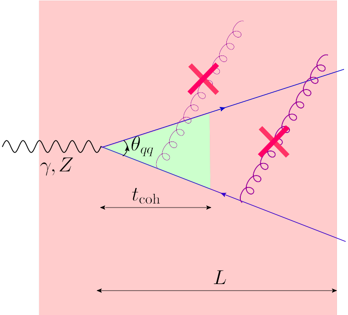
- Wide angle emissions with $t_{\rm f} > t_{\rm coh}$ are in principle allowed

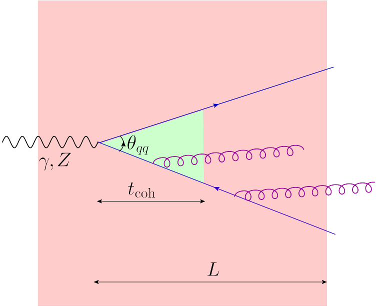
Angular ordering for VLEs

- ... But this can not be the case for the VLEs !

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

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





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

The DLA cascade inside the medium

- The previous considerations generalize to a gluon cascade with strong double ordering (energies and angles):

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

- The whole cascade is vacuum-like if so is the very last (softest) gluon:

$$\frac{1}{\omega_i \theta_i^2} \ll \frac{1}{\omega\theta^2} \ll \sqrt{\frac{\omega}{\hat{q}}} \ll \sqrt{\frac{\omega_i}{\hat{q}}}$$

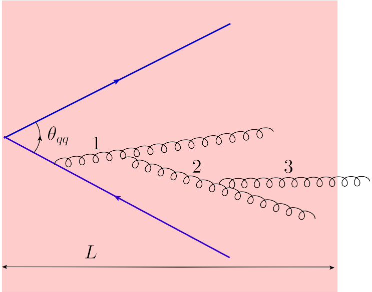
  - $t_{\rm f}|_{\rm vac}$ is strongly increasing down the cascade, while the corresponding values for $t_{\rm f}|_{\rm med}$ are rather decreasing

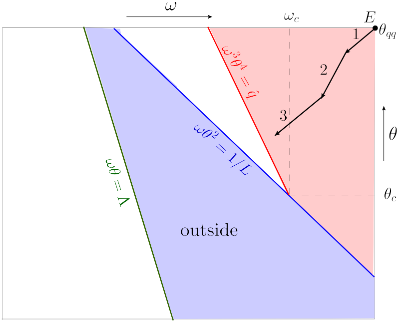
- Angular ordering is once again guaranteed by color coherence
  - obvious in the large N_c limit where gluon emission $\Leftrightarrow$ dipole splitting

- Formation time for the cascade $\approx$ that of the last gluon: $t_{\rm f} = 1/(\omega\theta^2)$
  - the energy loss is negligible ($\ll \omega$) for any parton in the cascade

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 $\sim L$

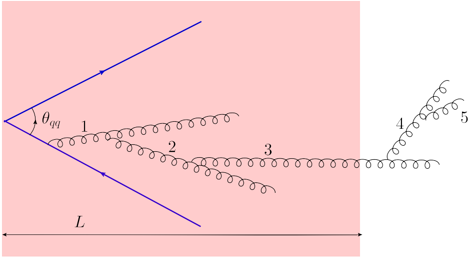


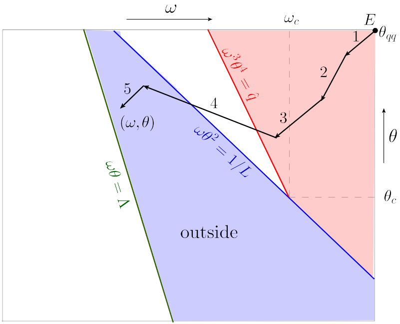


- They can suffer significant energy loss and momentum broadening
  - additional sources for medium-induced radiation
- They contribute to the jet multiplicity (fragmentation function)
- They can emit (vacuum-like) gluons outside the medium

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 $t_{\rm coh} \ll L$



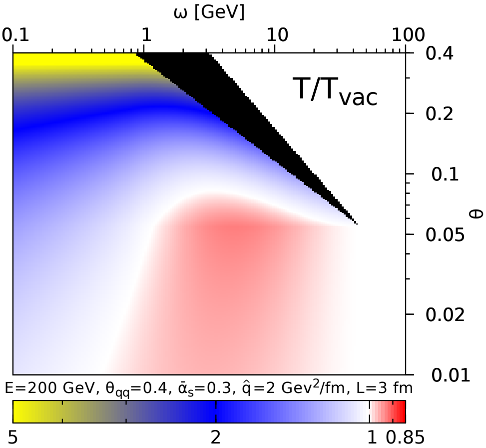


- In-medium sources lose color coherence and can also radiate at larger angles
- After the first "outside" emission, one returns to angular-ordering, as usual
- Medium effects at DLA (leading twist):
  vetoed region + lack of angular-ordering for the first "outside" emission

Gluon distribution at DLA

- Double differential distribution in energies and emission angles:

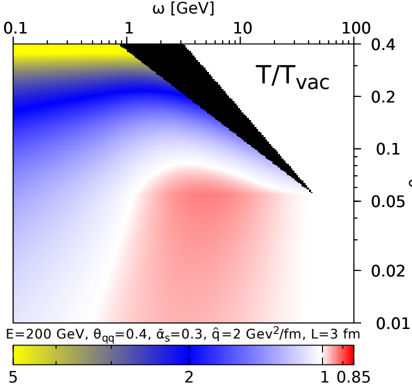
$$T(\omega,\theta) \equiv \omega\theta^2 \frac{\mathrm{d}^2 N}{\mathrm{d}\omega \mathrm{d}\theta^2}$$

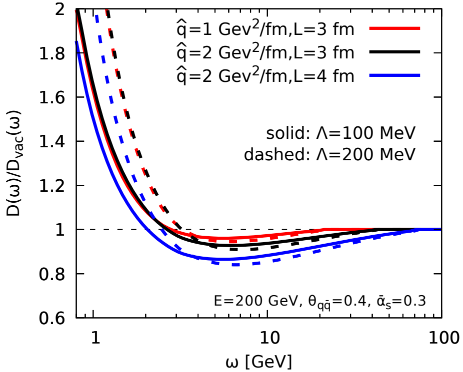


- $E = 200\,\mathrm{GeV}, \quad \theta_{q\bar{q}} = 0.4$
- $\hat{q} = 2\,\mathrm{GeV}^2/\mathrm{fm}, \quad L = 3\,\mathrm{fm}$
- $T/T_{\mathrm{vac}} = 0$ in the excluded region
- $T/T_{\mathrm{vac}} = 1$ inside the medium and also for $\omega > \omega_c$ and any θ
- $T/T_{\mathrm{vac}} < 1$ outside the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

Jet fragmentation function at DLA

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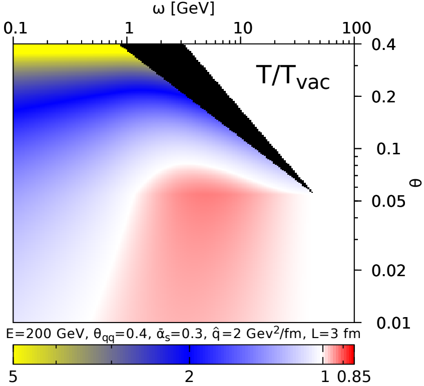
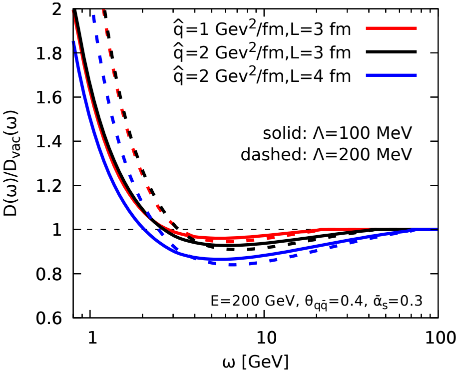
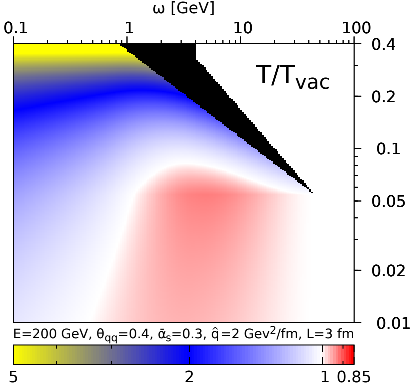


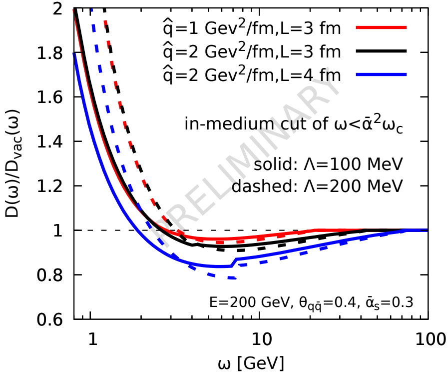


- Significant enhancement at low energy (below 2 GeV)
  - lack of angular ordering for the first emission outside the medium
- A related proposal by *Mehtar-Tani and Tywoniuk, arXiv:1401.8293*

Adding energy loss (preliminary !)

- So far, we have neglected the energy loss by the in-medium sources
- One expects a typical energy loss $\Delta\omega \sim \omega_{\rm br} \equiv \bar{\alpha}^2\hat{q}L^2$ per source
- A simple estimate of this effect: remove all sources with $\omega \leq \omega_{\rm br}$



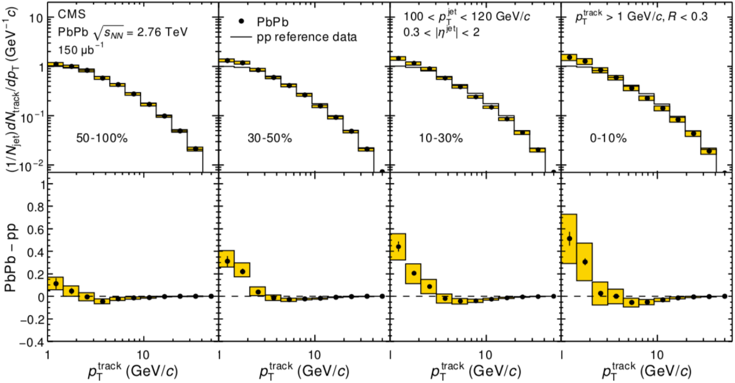


- The results are not significantly changed ... but more studies are needed

A look at the data

- Qualitatively similar to the trend shown by the LHC data

  CMS (arXiv:1406.0932, 1803.00042); ATLAS (arXiv:1406.2979, 1702.00674)



- Encouraging ... but again, more studies are needed

Conclusions & perspectives

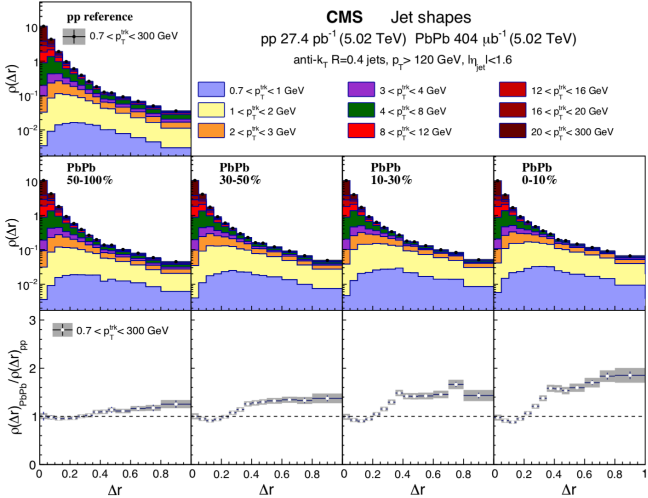
- Vacuum-like emissions inside the medium can be factorized from the medium-induced radiation via systematic approximations in pQCD
- Medium effects enter already at leading-twist level :
  - reduction in the phase-space for VLEs inside the medium
  - violation of angular ordering by the first emission outside the medium
- Angular ordering is preserved for VLEs inside the medium, like in the vacuum
- Qualitative agreement with the LHC data for jet fragmentation
- VLEs inside the medium act as sources for medium-induced radiation
- DLA is inappropriate for studies of energy flow (violates energy conservation)
- Generalization to full (energy-conserving) DGLAP splitting functions possible
- Probabilistic picture, well suited for Monte-Carlo implementations

There is much more to come ...

Thank you for listening!

Jet shapes

- The LHC data also show an excess of low p_T hadrons correlated with the jet axis and extending at large angles *(below: CMS, arXiv:1803.00042)*



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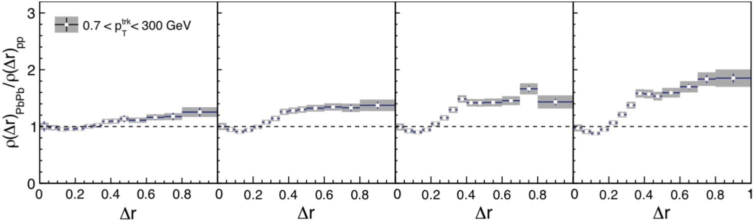
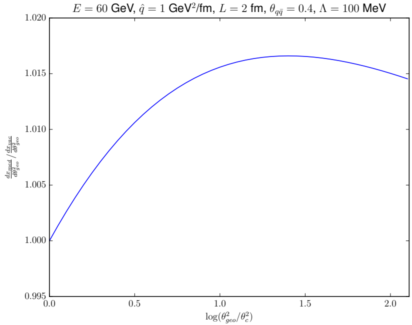
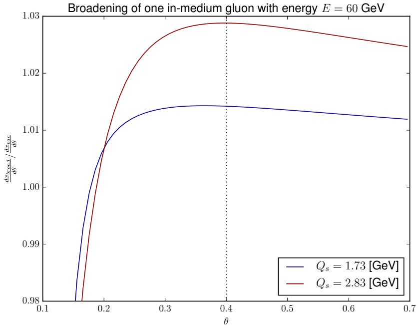


- The excess starts already inside the jet cone and keeps increasing outside it
- The excess at very large angles (outside the jet) is naturally understood as medium-induced radiation: multiple quasi-democratic branchings
- The excess near the edge of the jet seems more difficult to explain

Jet shape from gluon cascades at DLA

- Within our DLA vacuum-like cascades, there are 2 mechanisms that could naturally create (some) energy excess towards the edge of the jet:
  - the violation of angular ordering by the first "outside" emission
  - the transverse momentum broadening of VLEs inside the medium
- Preliminary results to DLA: the effects are indeed present but they look small





- N.B. DLA is not optimal for studying energy flow (no energy conservation)