# Jet Structure in Heavy Ion Collisions

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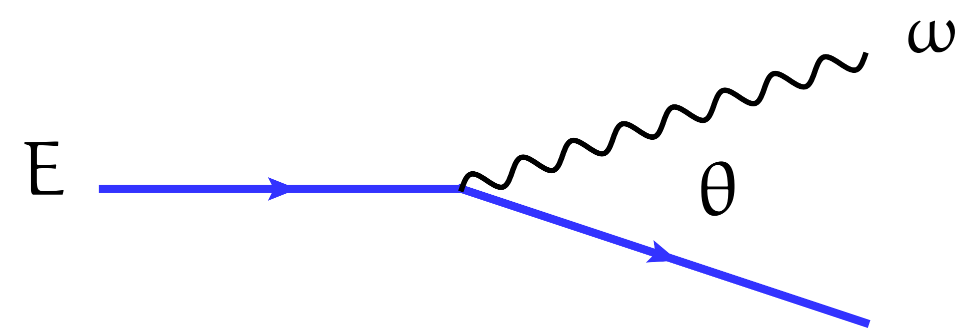
# Outline

- Parton cascades of two kinds: vacuum and medium-induced cascades
- Radiative corrections: renormalization of $\hat{q}$
- Color decoherence of the intrajet structure (interferences)
- A new class of jet-quenching observables: in-medium splitting function

# Jet events in pQCD

- Jets originate from an initial hard scattering (off-shell leading parton). Successive branchings of energetic and virtual partons

$$dP \sim \alpha_s C_R \frac{d\theta}{\theta} \frac{d\omega}{\omega}$$




- Probability for collinear branching enhanced:

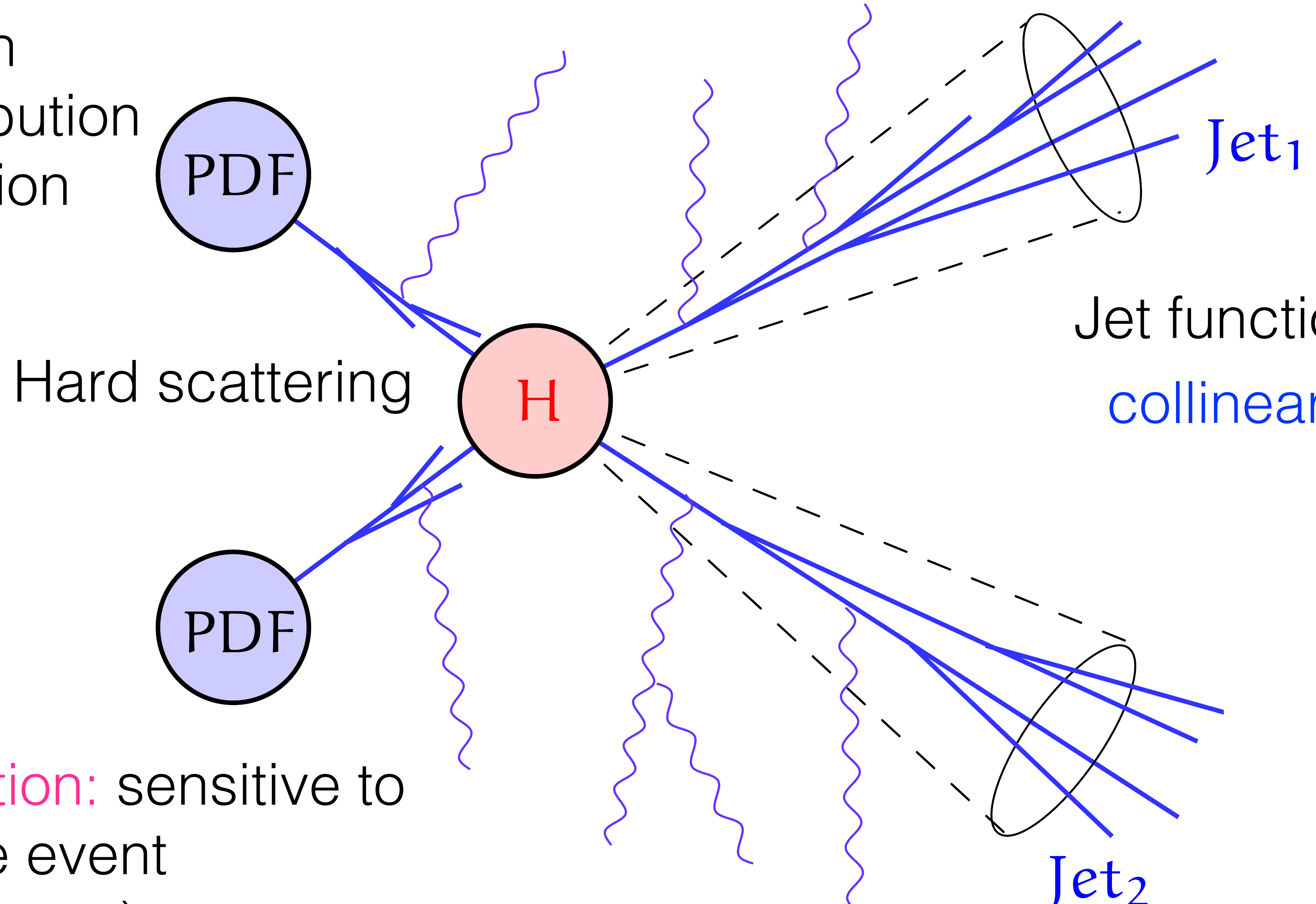
$\Longrightarrow$ collimation of jets

- Large phase space for multiple branching (vacuum cascade): in a typical event many particles are measured. Implemented in Monte-Carlo Event generators: PYTHIA, HERWIG, SHERPA, etc.

# Jet events in pQCD

coherent soft radiation

Parton Distribution Function




Jet function: universal

collinear splittings

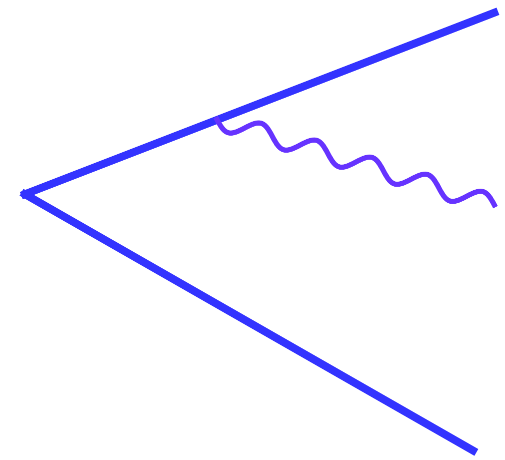
Soft function: sensitive to the whole event (interferences)

Factorization of the cross-section

$$\sigma \sim \mathrm{PDF} \times H \times J_1 \times J_2 \times S$$

# Jet events in pQCD

- Building block of QCD evolution: antenna. Coherent radiation: suppression of large angle radiation sensitive to the the event shape ⟶ Angular ordering, soft function



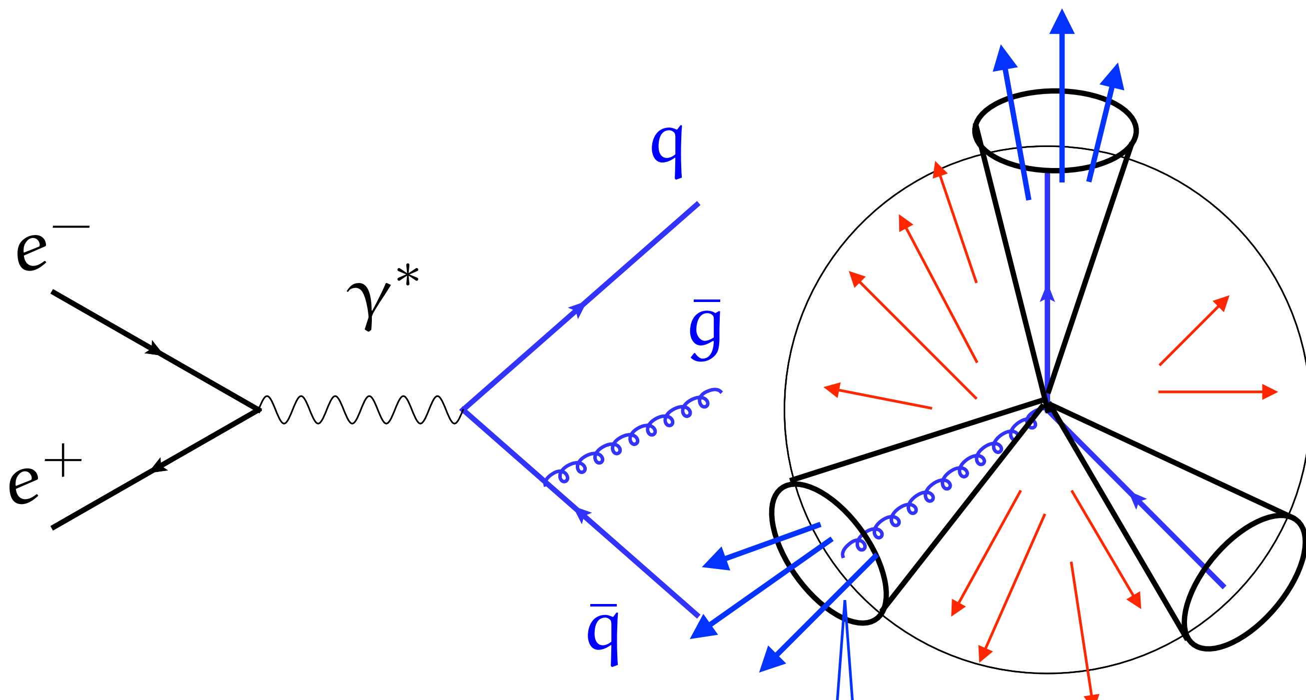

Large angle radiation sensitive to total color charge

- Intranet structure: independent multiple branching ordered in angle

- Two types of observables:
  — Infrared-Collinear (IRC) safe observables: sum over final state hadrons ⟶ cancellations of divergences. Ex: event shape: thrust, jet mass, jet spectra, etc. Resummation of large logs, e.g. log R can be necessary
  — Collinear sensitive observables: pQCD still predictive (factorization theorems). Ex: Fragmentation Functions

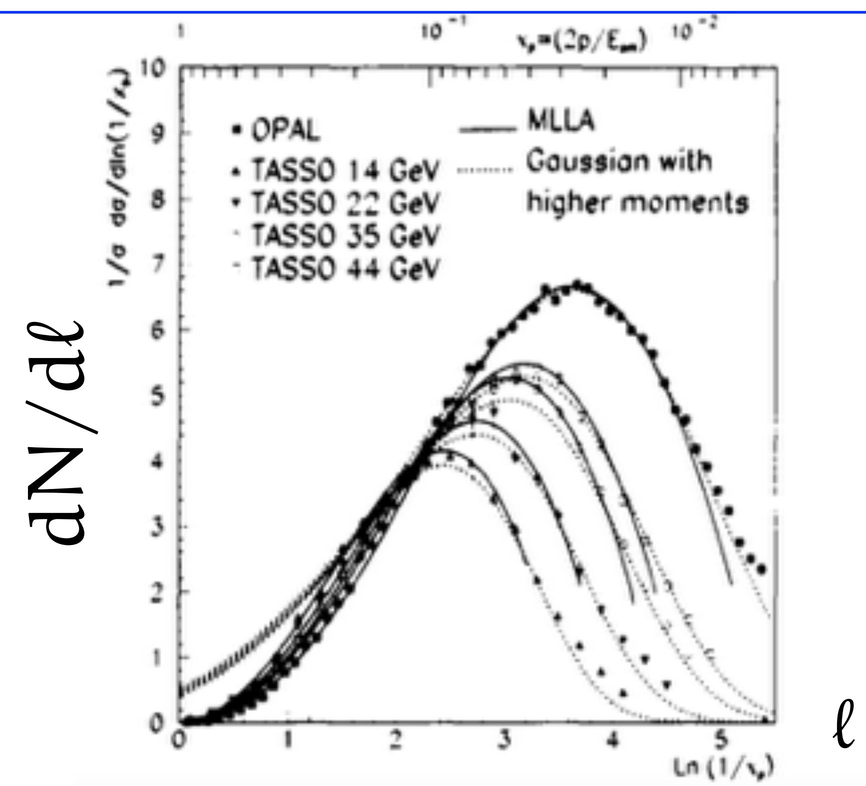
# Color coherence in $e^+ e^-$ : intra/inter jet activity

[Azimov, Dokshitzer, Khoze, Troyan (1985)]

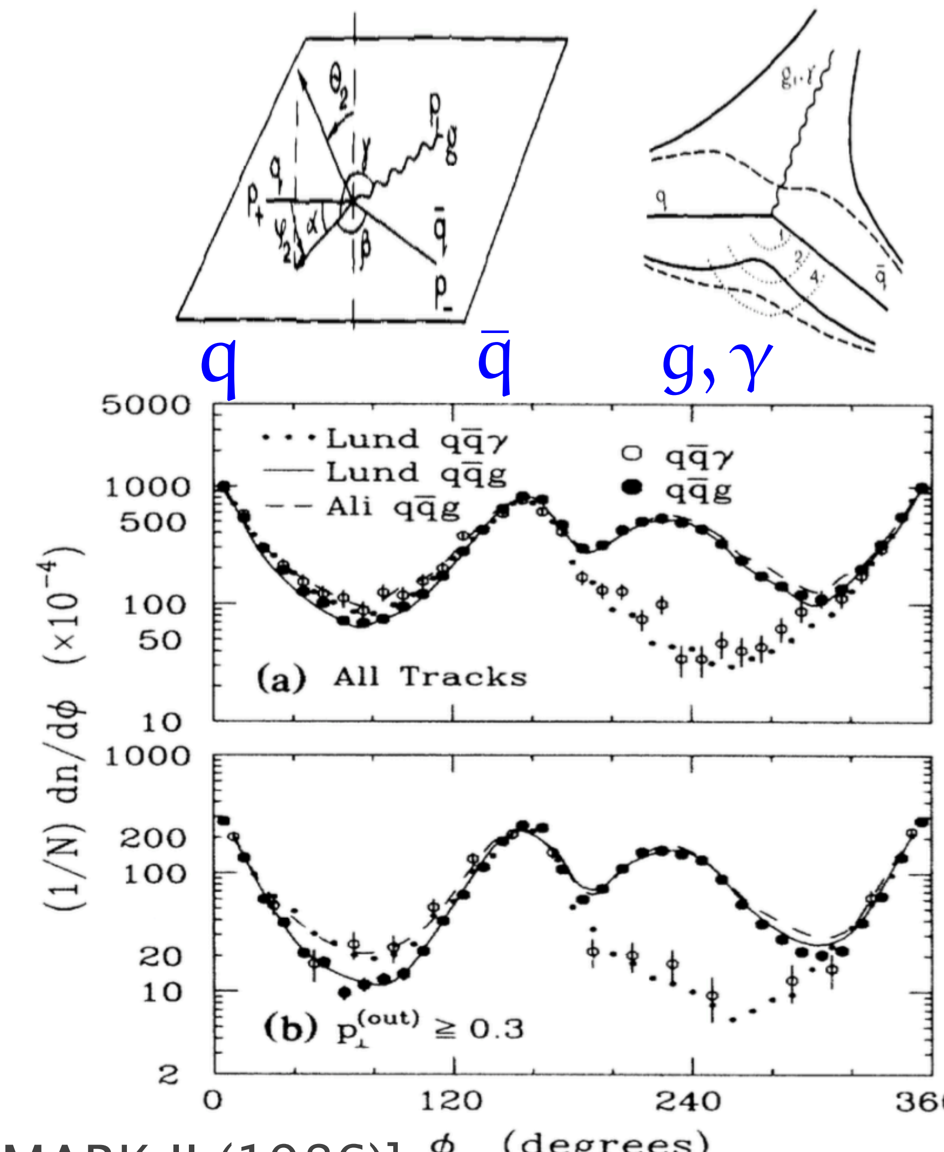



Interjet hadronic activity:
"Stringy" fragmentation
from pQCD

Fragmentation Function




$$\ell = \ln \frac{1}{z}$$




[MARK II (1986)]

# Fragmentation and hadronization in vacuum

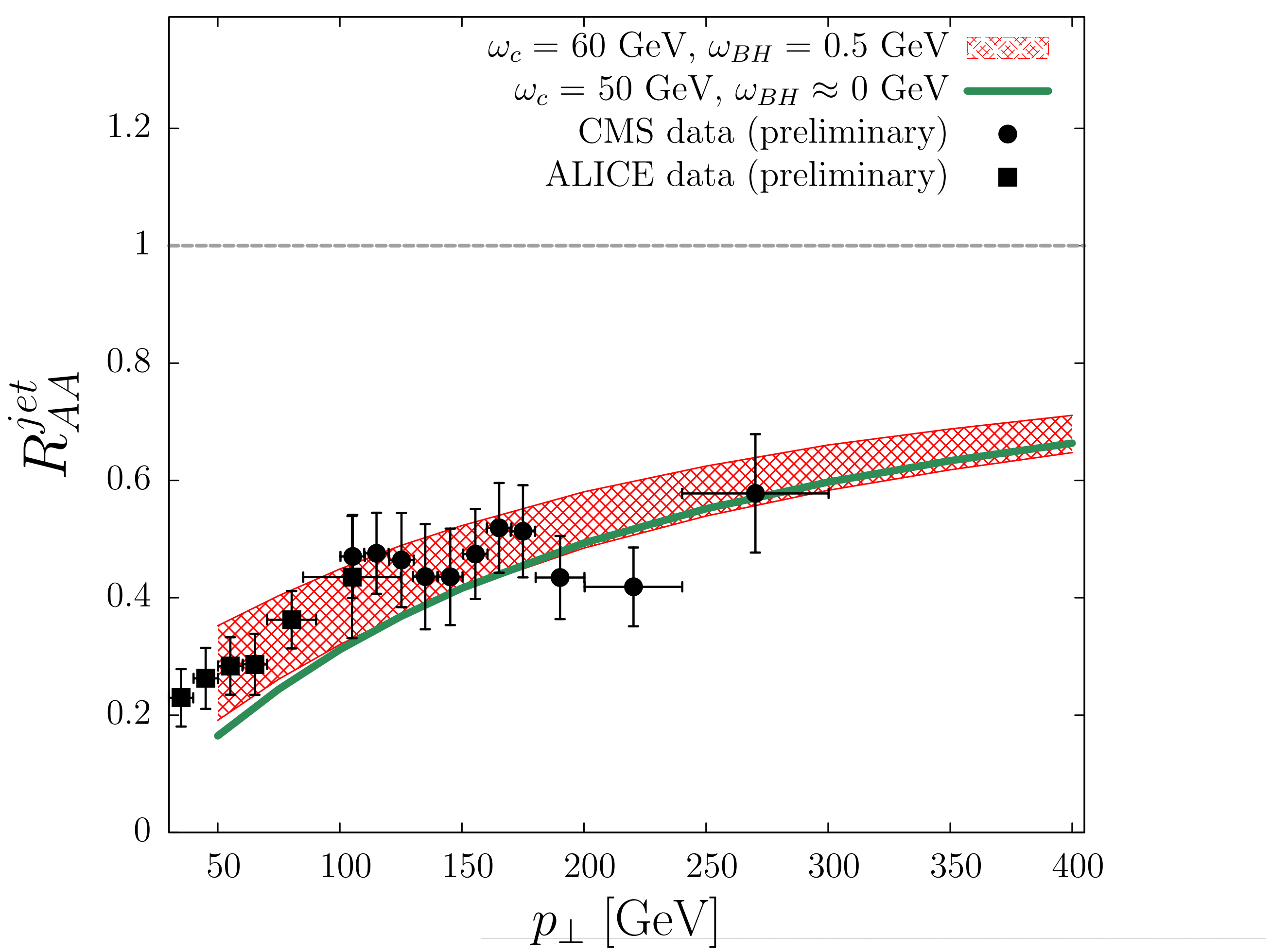
- At high energy hadronic and partonic observables are similar: local hadron-pardon duality (good agreement with data but doesn't say anything about hadrons!)

- Hadronization models matched onto pQCD evolution at low virtuality in Monte Carlo Event Generators: PYTHIA, HERWIG, SHERPA: Lund String model, Cluster model,…

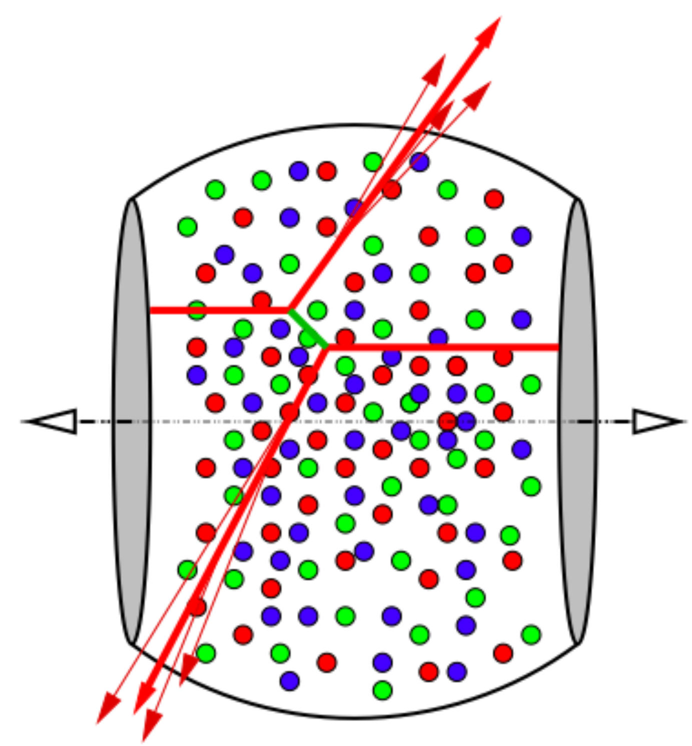
- Precision physics (IRC safe observables) ⟶ Next-to-Leading-Order (NLO), Next-to-Leading-Log (LO)

# Jet physics in HIC

- In the presence of dense colored medium jets are expected to be strongly modified: energy loss, pt-broadening, etc
- Example: Suppression of the nuclear modification factor




$$R_{AA} \equiv \frac{1}{N_{coll}} \frac{dN_{AA}}{dN_{pp}}$$



# Coupling to the medium

- The jet couples to the medium via (local) transport coefficients

$$\hat{q} \equiv \frac{m_D^2}{\lambda} \sim \frac{(\text{Debye mass})^2}{\text{mean free path}}$$

pt-broadening $\langle k_\perp^2 \rangle \sim \hat{q}\, L$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000)]

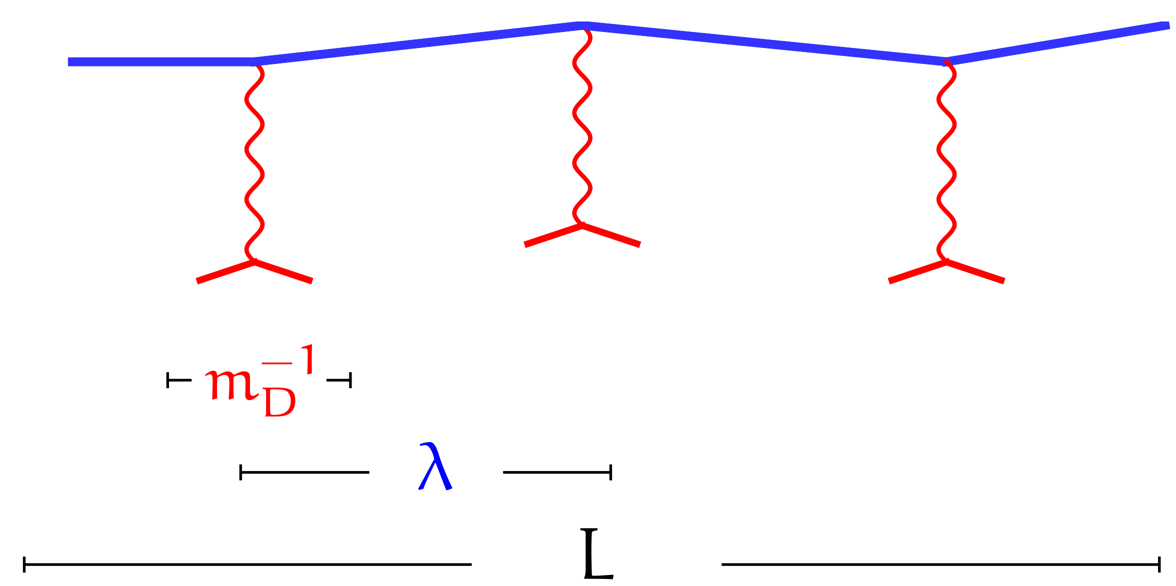
$$\hat{e} \equiv \frac{\hat{q}}{T}$$

collisional energy loss (drag) $\langle \Delta E \rangle_{coll} \sim \hat{e}\, L$

[Majumder (2008)]

- Weak coupling:
  Independent multiple scattering approximation

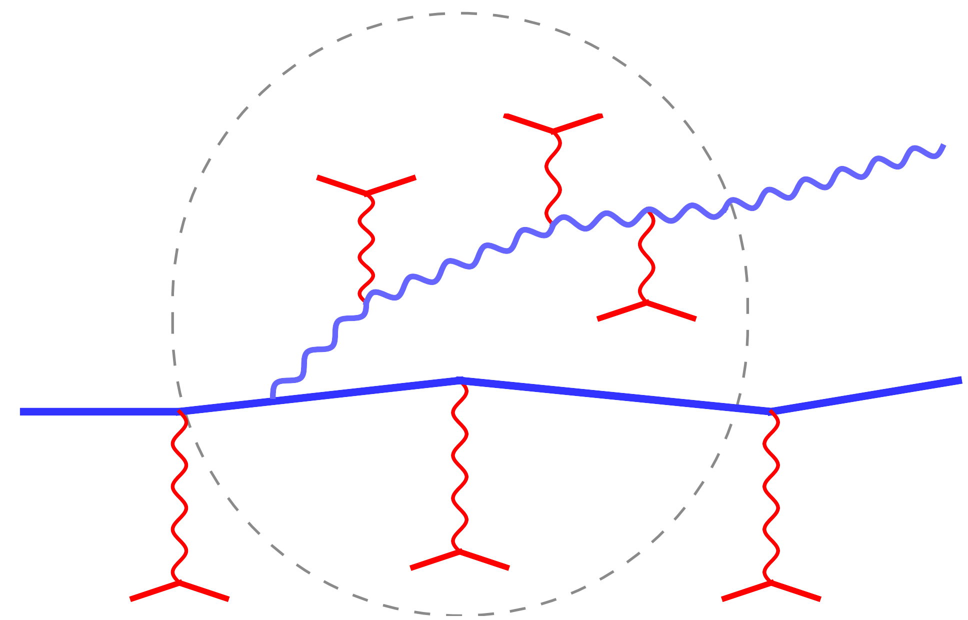
correlation length « mean-free-path « L



# In-medium radiation mechanism (LPM effect)

- Radiation triggered by multiple scatterings

- Landau-Pomeranchuk-Migdal suppression (coherent radiation)



$$\omega \frac{dN}{d\omega} = \alpha_s \frac{L}{t_f} \equiv \alpha_s N_{eff}$$

$$t_f = \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

formation time

- Maximum suppression when $t_f \gtrsim L \Rightarrow \omega > \omega_c = \hat{q} L^2$

- Minimum radiation angle $\theta > \theta_c \equiv 1/\sqrt{\hat{q} L^3}$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)]

[Wiedemann (2001) Arnold, Moore,Yaffe (2002)]

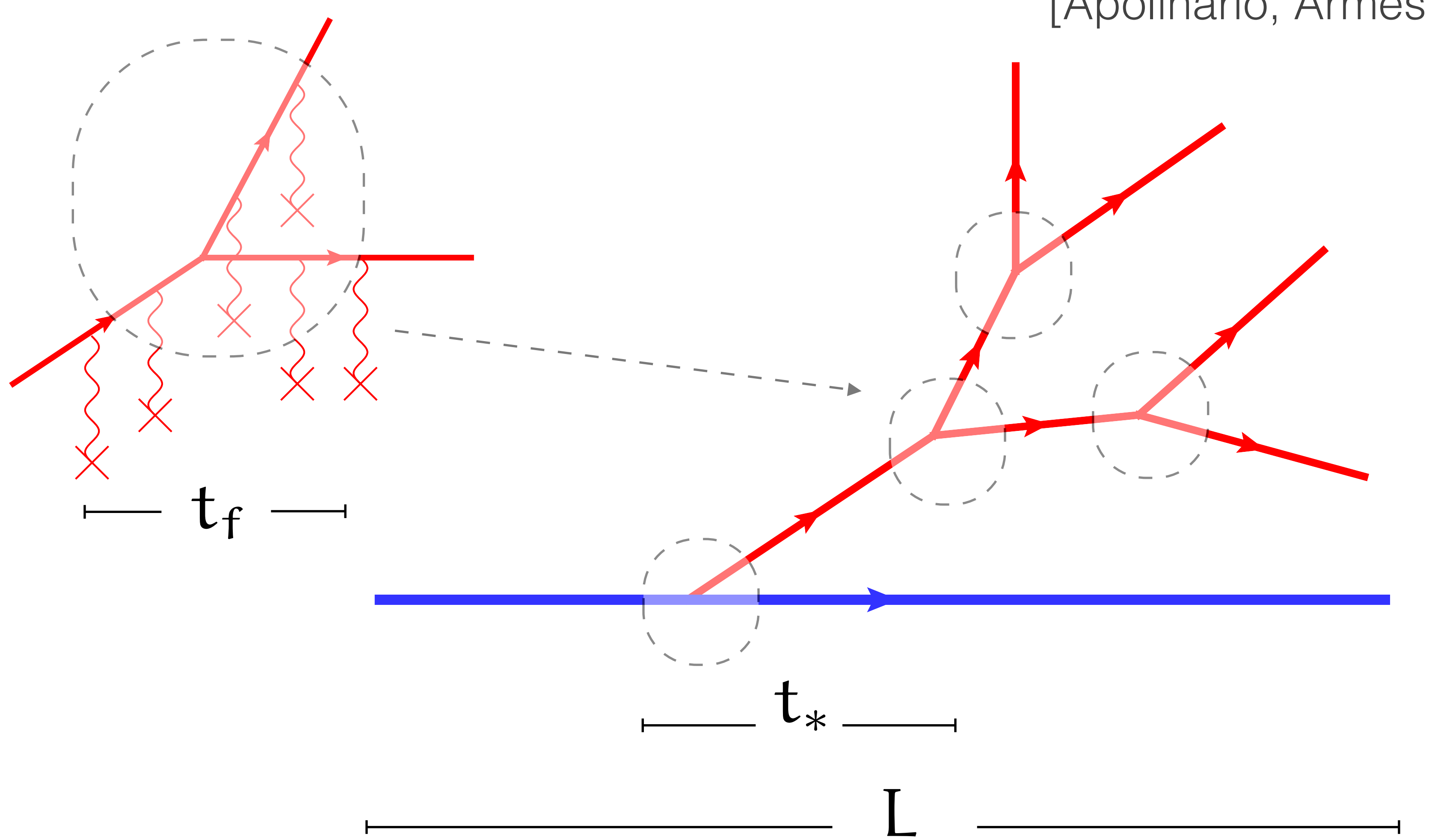
# Probabilistic picture

- Multiple (independent) branchings regime:

$$t_f \ll t_* \ll L$$

- Incoherent branchings: randomization of color due to rescatterings

[Blaizot, Dominguez, Iancu, MT (2013-2014)]
[Apolinário, Armesto, Milhano, Salgado (2014)]




effective inelastic mean free path

$$t_*(\omega) \sim \frac{1}{\alpha_s} t_f(\omega)$$

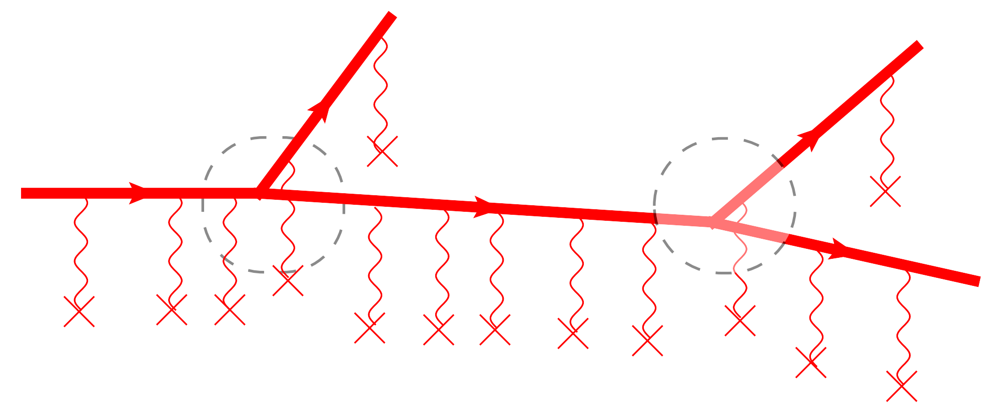
# Probabilistic picture

[Baier, Mueller, Schiff, Son (2001) Jeon, Moore (2003) Blaizot, Dominguez, Iancu, MT (2014)]

- The inclusive gluon distribution obeys a rate equation

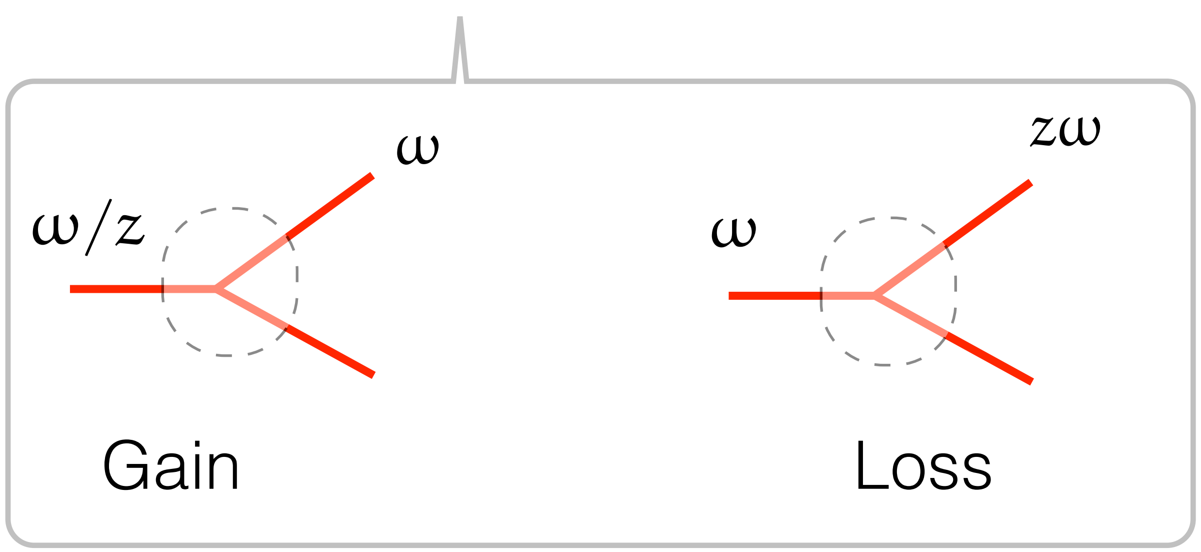
$$\omega \frac{dN}{d\omega\, d^2\theta} \equiv D(\omega,\theta)$$

- Momentum broadening during the branching process is suppressed: **effective collinear branching**

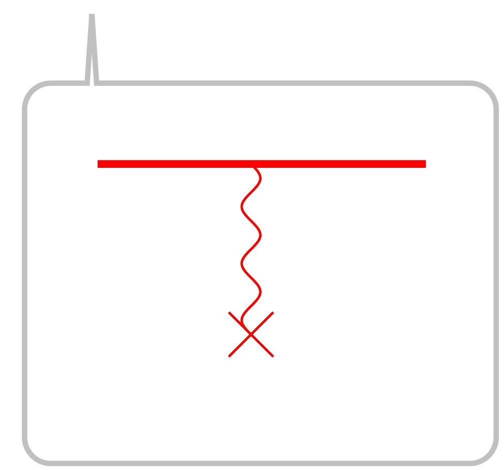


$$\frac{\partial}{\partial t} D(\omega,\theta) = \int_0^1 dz\, K(z) \left[ \frac{D(\omega/z,\theta)}{t_*(\omega/z)} - z\frac{D(\omega,,\theta)}{t_*(\omega)} \right] + \frac{1}{4}\frac{\hat{q}}{\omega^2}\nabla^2_\theta D(\omega,\theta) + \hat{e}\frac{\partial}{\partial\omega} D(\omega,\theta)$$

$$t_*(\omega) \equiv \frac{1}{\alpha_s}\sqrt{\frac{\omega}{\hat{q}}}$$




inelastic process: radiative energy loss



elastic process:
angular broadening
collisional Eloss

# Energy flow at large angle

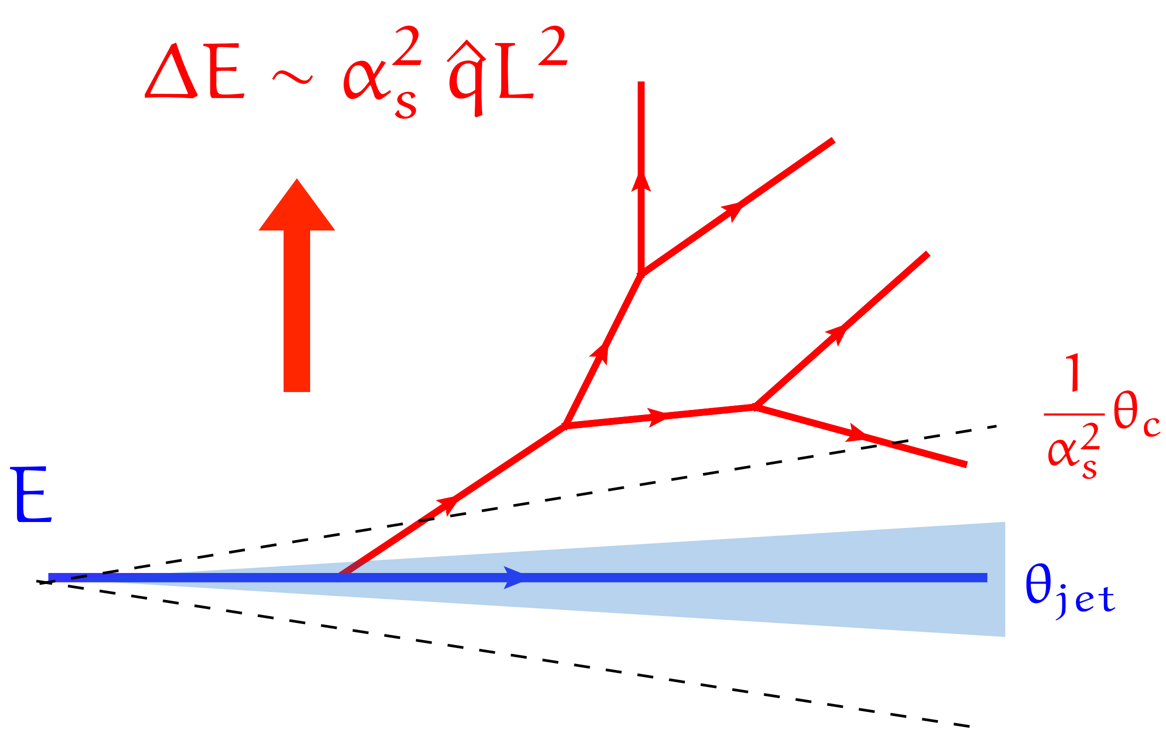
[Blaizot, Iancu, Fister, Torres, MT (2013-2014) Kurkela, Wiedemann (2014)]

- Multiple branchings at parametrically **large angle**

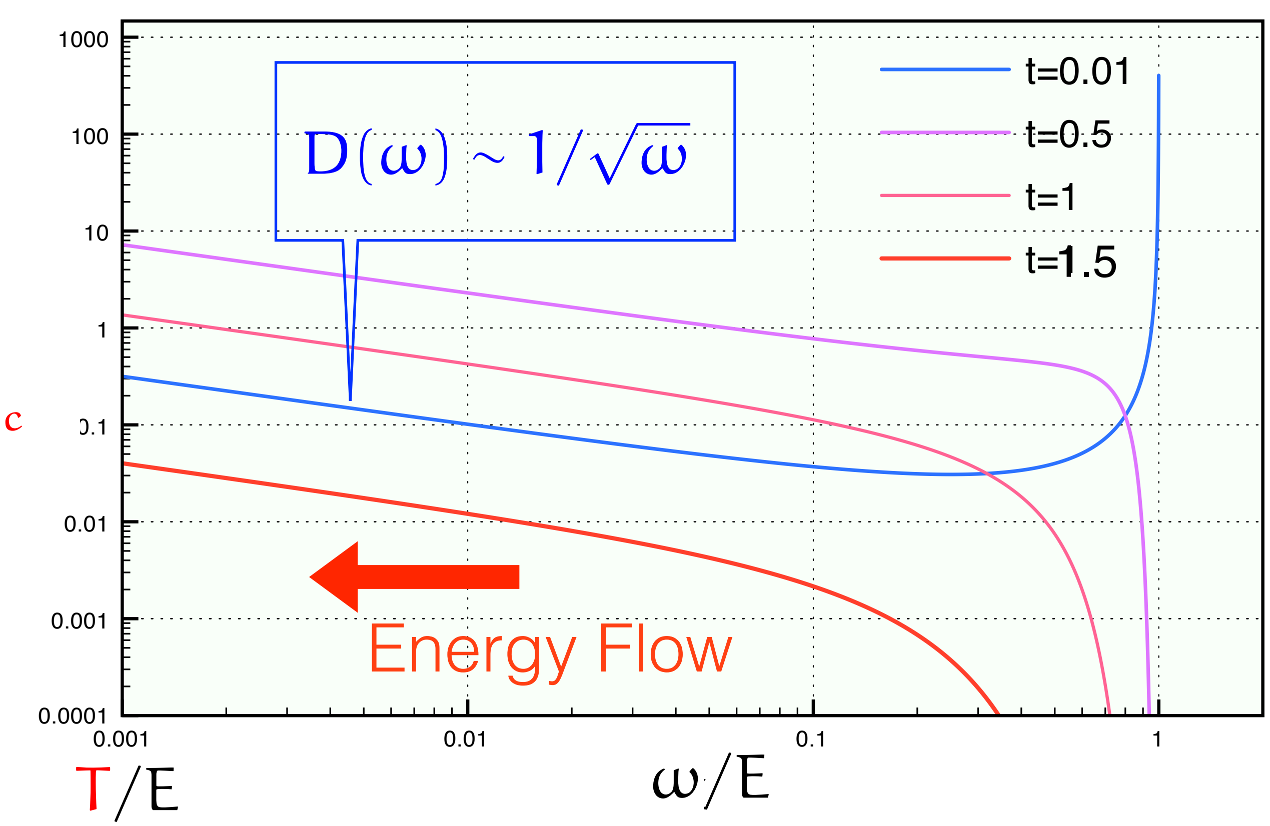
$$\theta_*(\omega) \gg \frac{1}{\alpha_s^2}\theta_c \gg \theta_{jet}$$

- **Constant energy flow** from jet energy scale $E$ energy down to the medium temperature scale $\omega \sim T$

Energy lost to the medium




Energy distribution as function of time

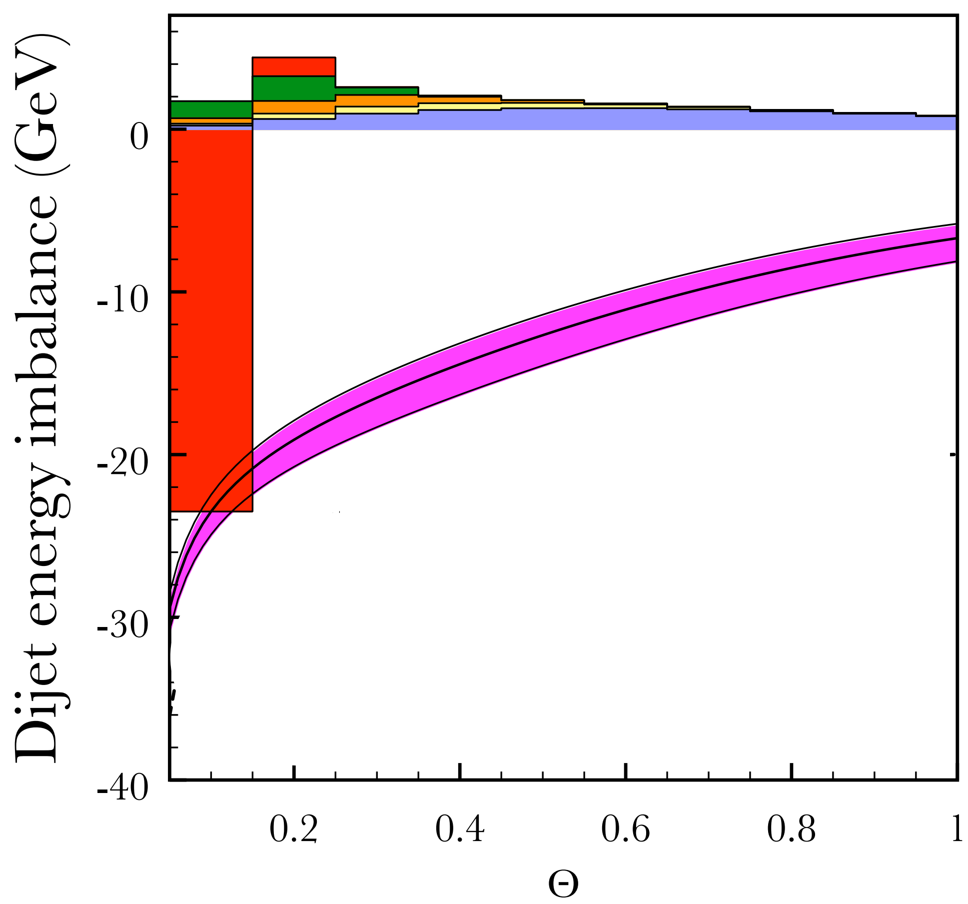


# In-medium cascade

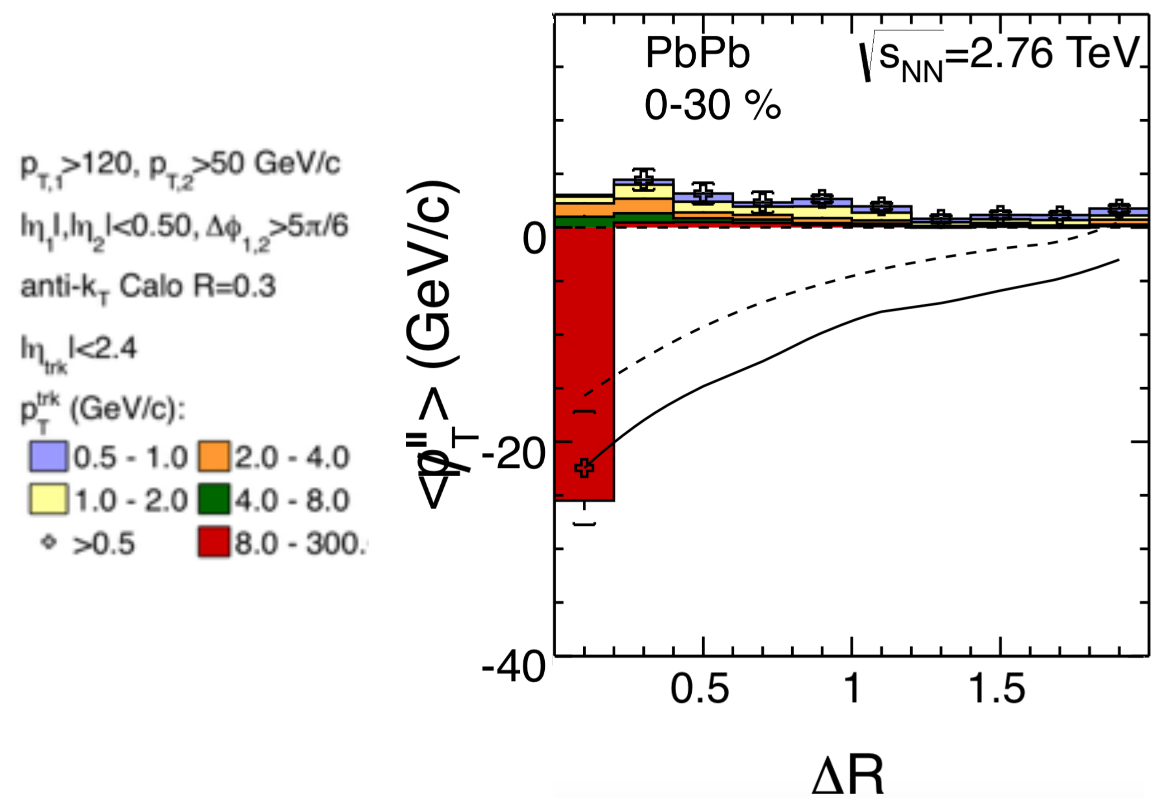
Turbulent transport of energy to large angles

Might explain missing $p_T$ in dijet events (CMS 2011-2014)

[Blaizot, MT, Torres PRL (2014)]




CMS DATA



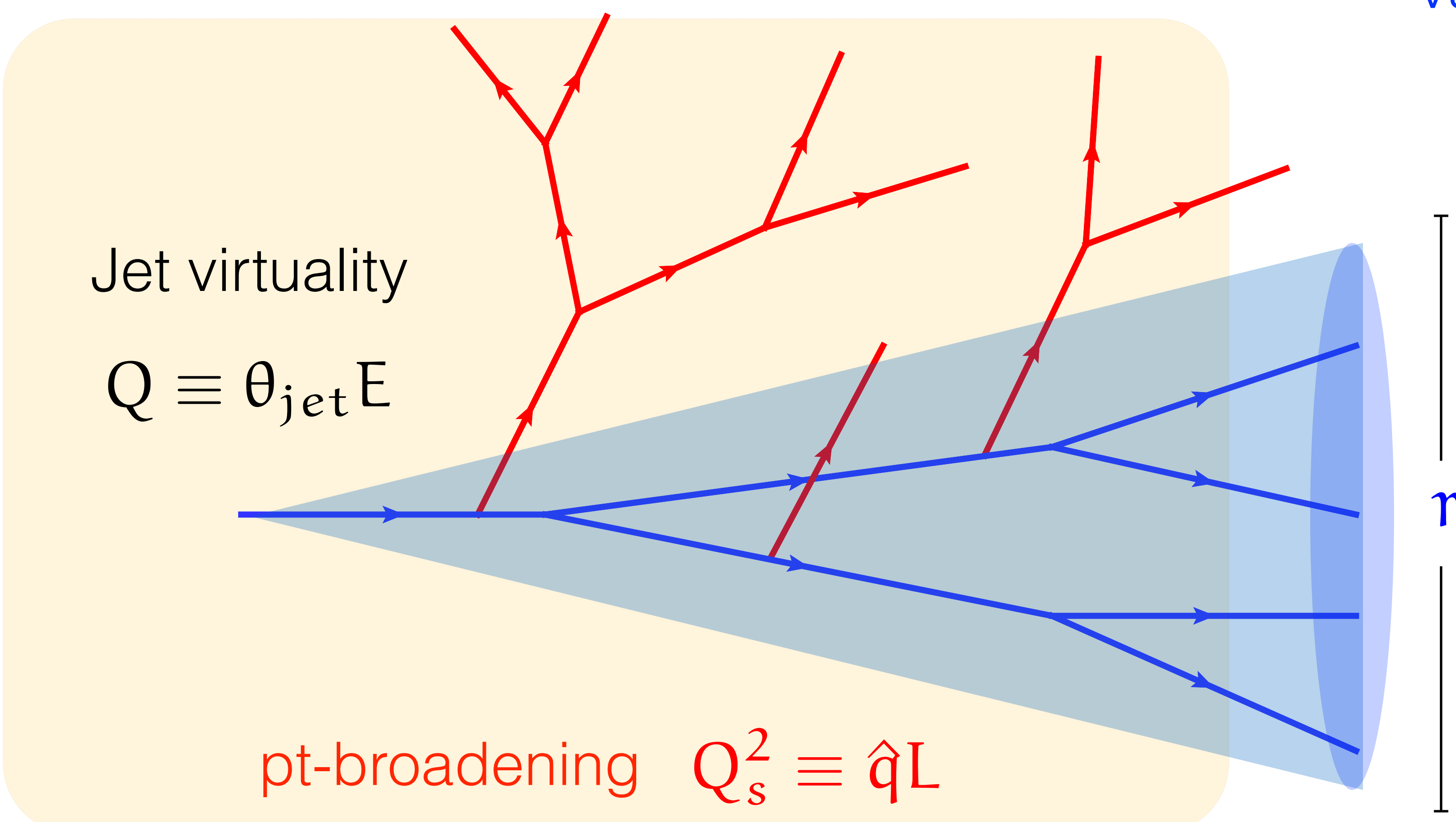
# Multi-scale problem

- Parton cascades of two kinds. Independent evolution variables:

$t \sim L$ in-medium cascade

$t \equiv \ln Q^2 \sim \ln \theta_{jet}^2$

vacuum cascade




$r_\perp \equiv \theta_{jet} L$

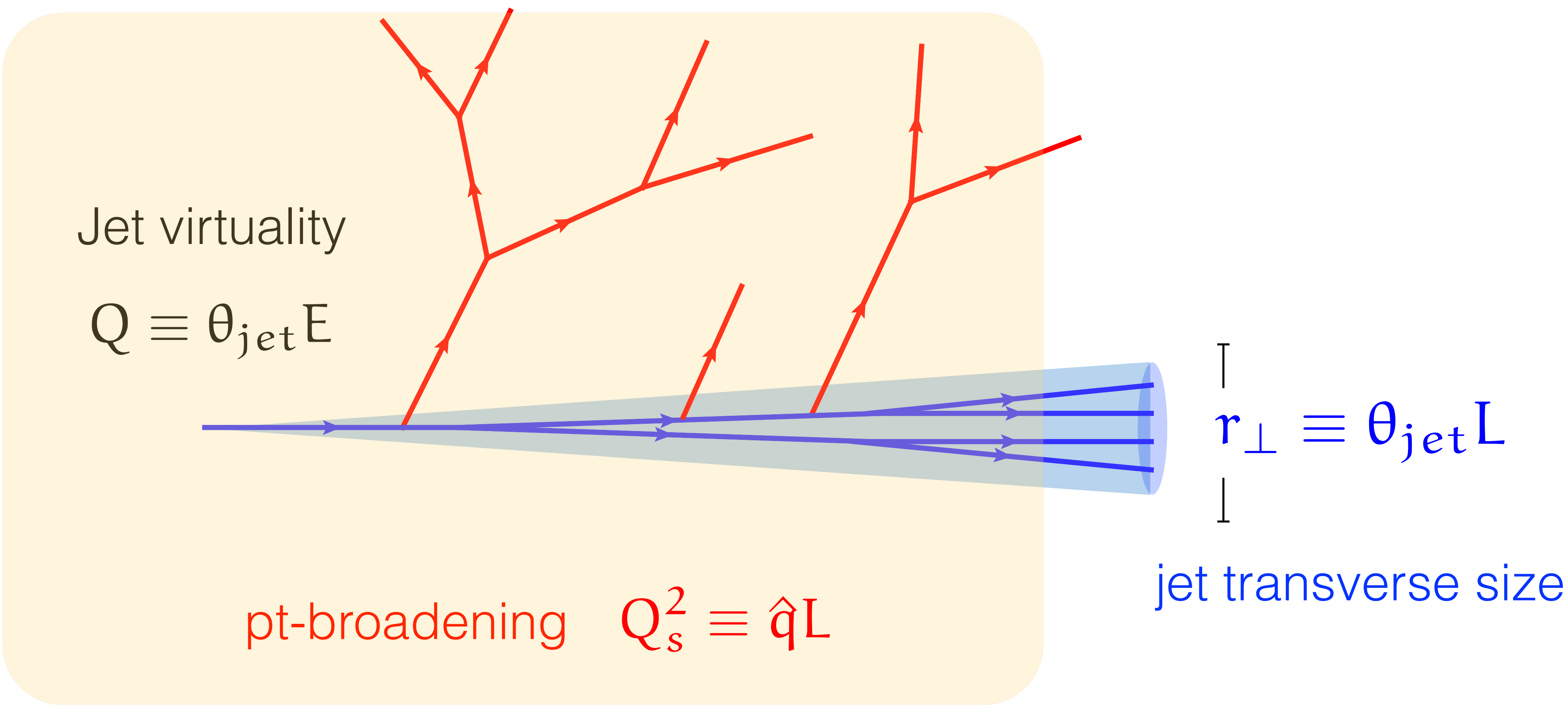
jet transverse size

**How does a jet, as a multi-partonic system, lose energy in the medium?**

**It depends on the resolution of the medium**

# Coherent limit in pQCD

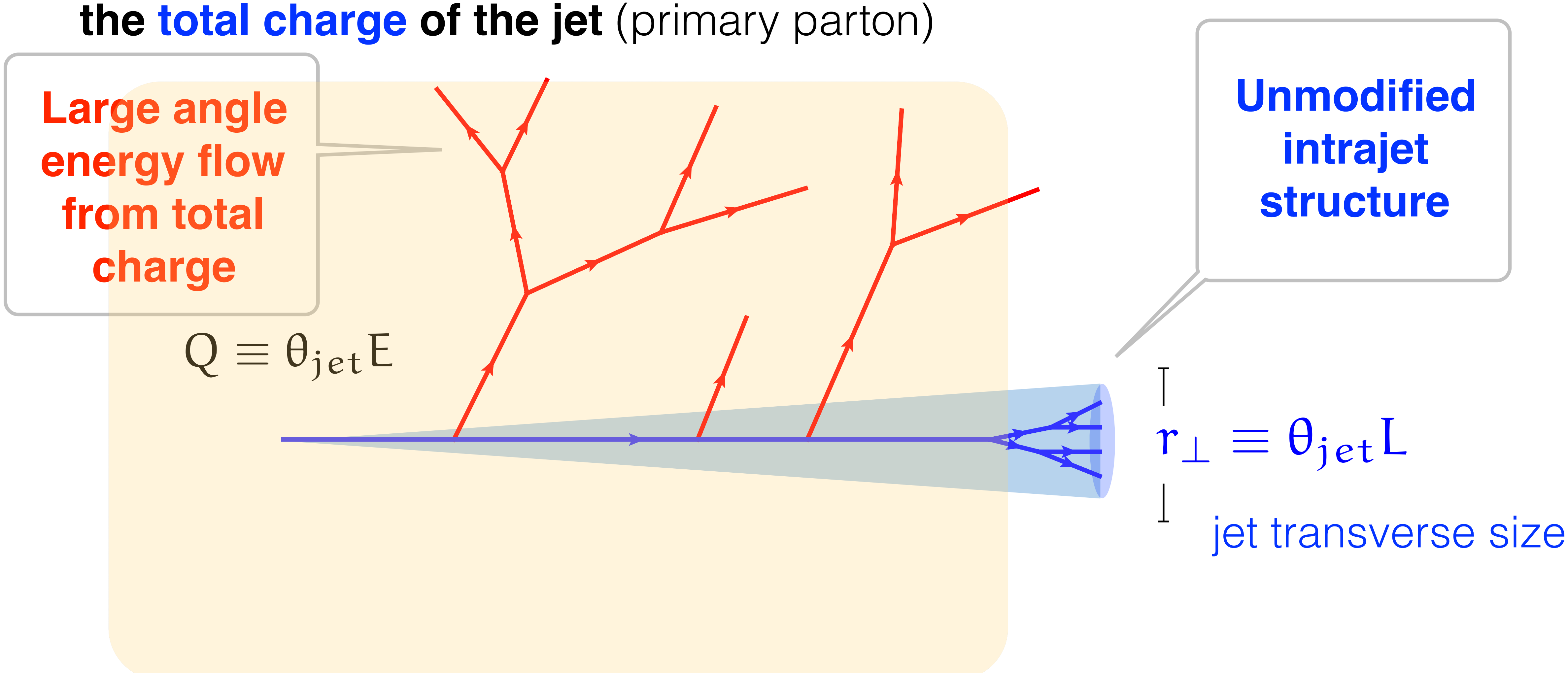
- When the transverse size $r_\perp$ of the jet is smaller than medium resolution scale $Q_s^{-1}$ **the medium interacts "effectively" with the total charge of the jet** (primary parton)




$$r_\perp \ll Q_s^{-1} \quad \Longrightarrow \quad \theta_{jet} \ll \theta_c \equiv (\hat{q} L^3)^{-1/2}$$

# Coherent limit in pQCD

- When the transverse size $r_\perp$ of the jet is smaller than medium resolution scale $Q_s^{-1}$ **the medium interacts "effectively" with the total charge of the jet** (primary parton)

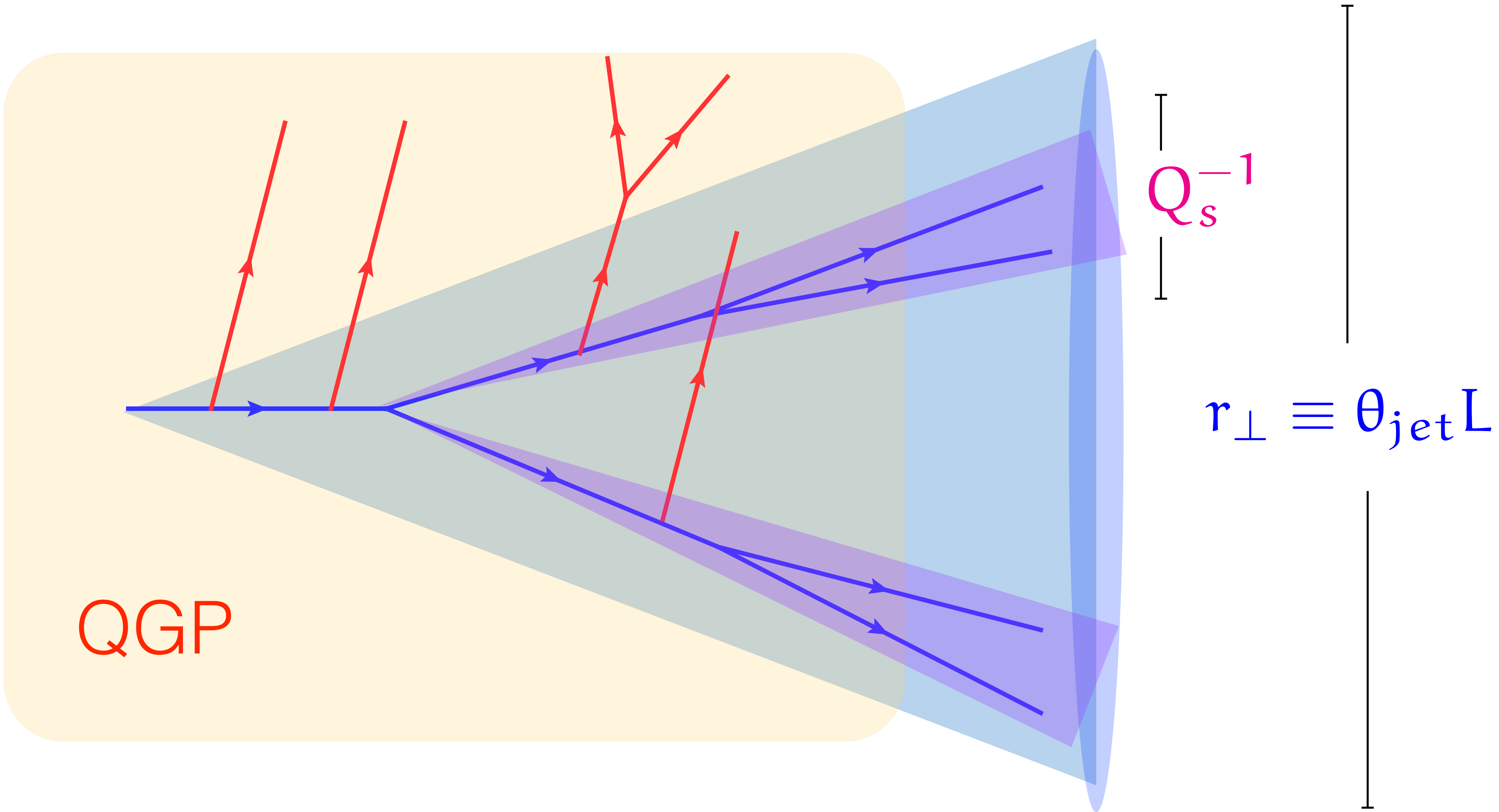



MC prescription (for unresolved jets): medium t-evolution then collinear Q-evolution

[Casalderrey-Solana, MT, Salgado, Tywoniuk (2013)]

# Coherent limit in pQCD

- When the transverse size $r_\perp$ of the jet is larger than medium resolution scale $Q_s^{-1}$ **the medium interacts with multiple (resolved) color charges in the jet** (in the sketch below, two)

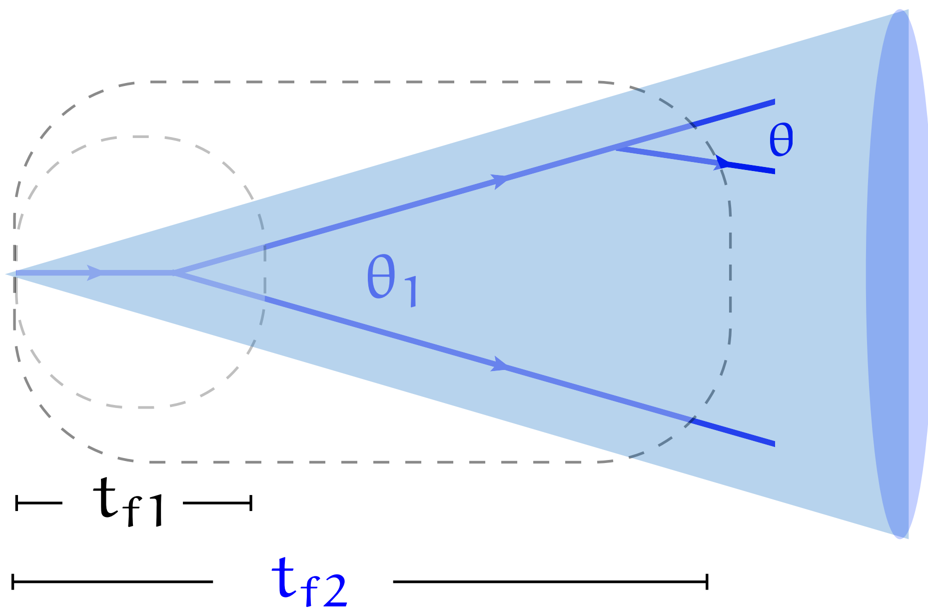



- Energy loss increases with the number of resolved sub-jets

[Casalderrey-Solana, MT, Salgado, Tywoniuk (2013)]

# Color (de)coherence of intrajet structure

- Consider two subsequent splittings in vacuum (antenna radiation pattern)




Q-evolution: strong ordering in formation time

$$t_{f1} \ll t_{f2}$$

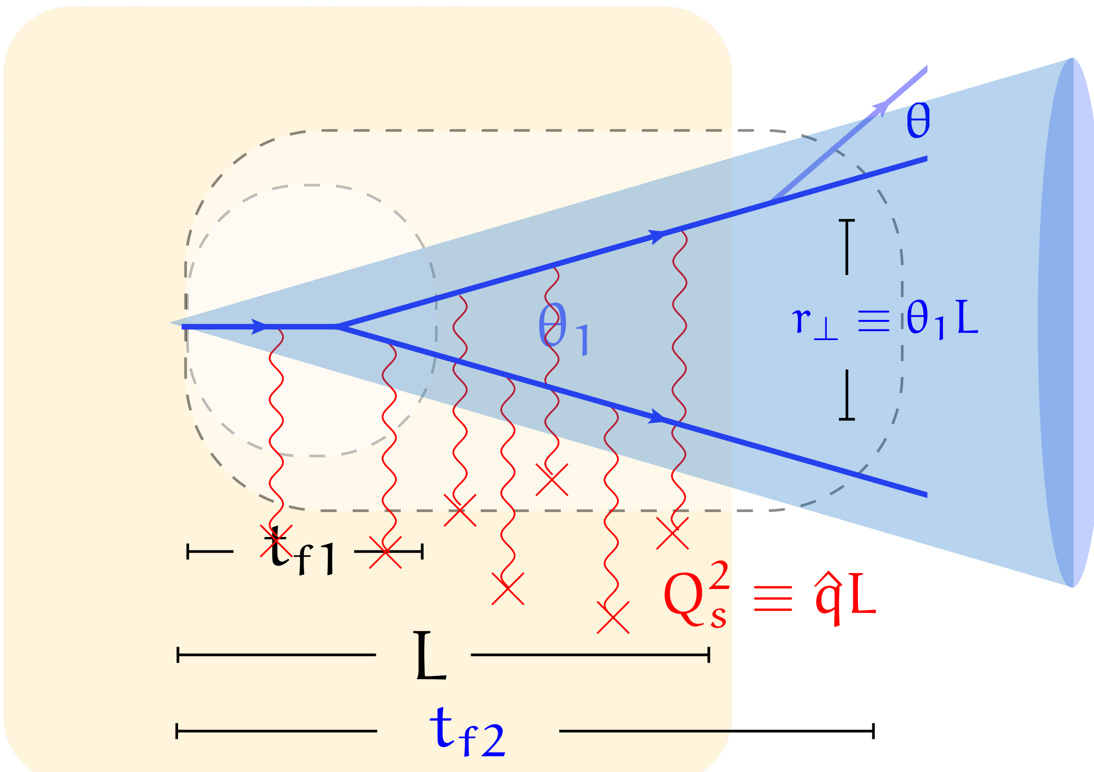
- **Color coherence** $\Longrightarrow$ **strict angular ordering** of the secondary branchings for inclusive parton distribution D(z)

$$dP_2 \sim \alpha_s \frac{d\theta}{\theta} \frac{d\omega}{\omega} \Theta(\theta_1 - \theta)$$

[At the basis of PYTHIA and HERWIG event generators]

# Color (de)coherence of intrajet structure

- Consider two subsequent splittings in medium (antenna radiation pattern)




soft radiation off a hard antenna

$$t_{f1} \ll L \ll t_{f2}$$

Decoherence parameter

$$\Delta_{med} \equiv 1 - e^{-r_\perp^2 Q_s^2}$$

0: coherence: unresolved jet

1: decoherence: resolved substructure

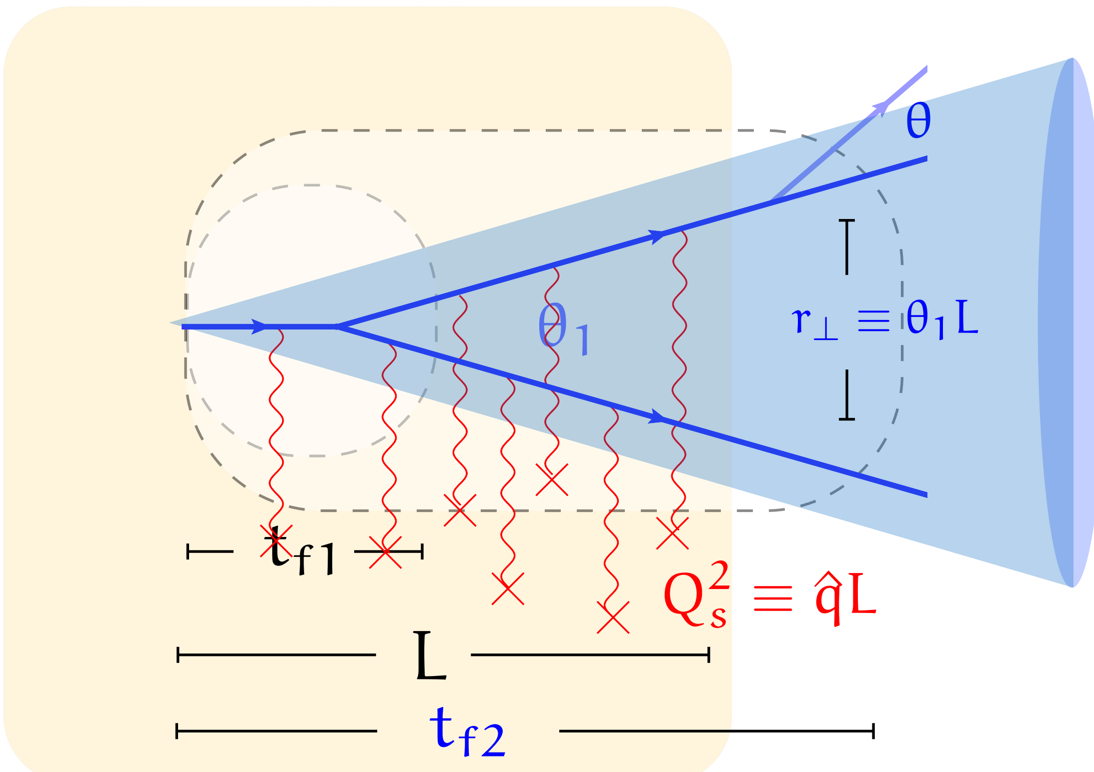
- In-Medium Interactions suppress color coherence of the two charges system freeing extra in-cone soft radiation

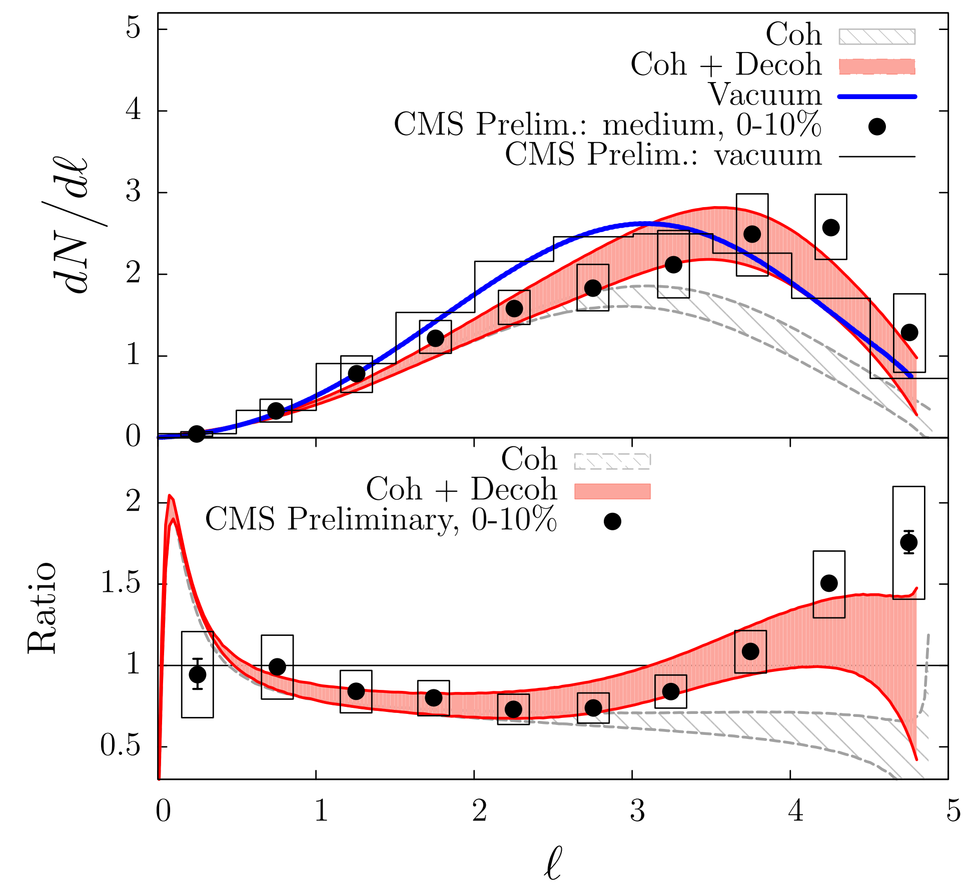
$$dP_2 \sim \alpha_s \frac{d\theta}{\theta} \frac{d\omega}{\omega} \left[\Theta(\theta_1 - \theta) + \Delta_{med}\, \Theta(\theta - \theta_1)\right]$$

[MT, Salgado, Tywoniuk (2010-2011) Casalderrey-Solana, Iancu (2011)]

# Color (de)coherence of intrajet structure

- Consider two subsequent splittings in medium (antenna radiation pattern)




⟹ Possible mechanism for the observed soft particle excess in medium modified fragmentation functions by CMS and ATLAS

[MT, Tywoniuk (2014)]

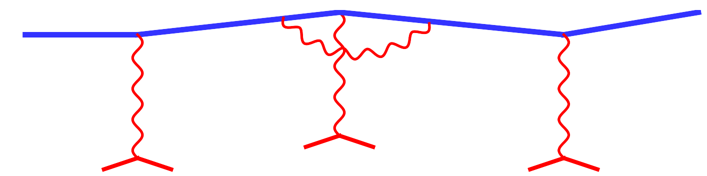
NB: Also, recoil of medium partons (back reaction)

[He, Wang, Zhu, Chen, Pang (2012-2014)] [also in JEWEL]

# (Universal) radiative corrections

- Radiative corrections to pt-broadening to Double Log accuracy

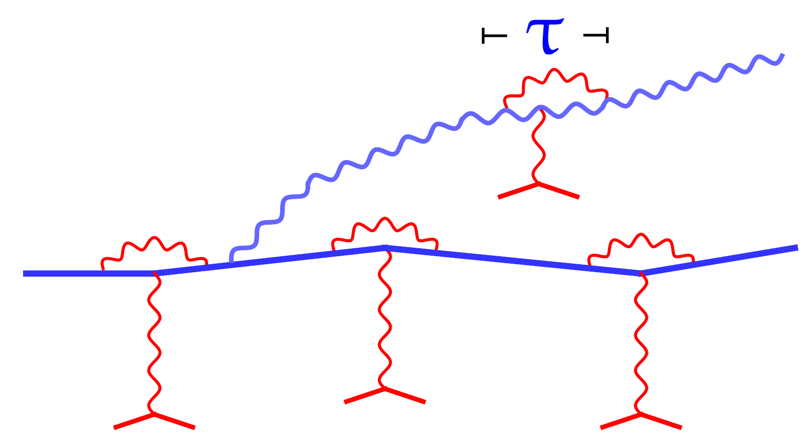
$$\langle k_\perp^2 \rangle = \hat{q} L \left( 1 + \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{L}{\tau_0} \right)$$



[Wu (2011) Liou, Mueller, Wu (2014) Blaizot, Iancu, Dominguez, MT (2014)]

- Radiative corrections to energy loss

$$\Delta E \sim \alpha_s C_R \hat{q} L^2 \left( 1 + \frac{\alpha_s N_c}{2\pi} \ln^2 \frac{L}{\tau_0} \right)$$




[Blaizot, MT (2014) Wu (2014)]

- Universality and renormalization of $\hat{q}$

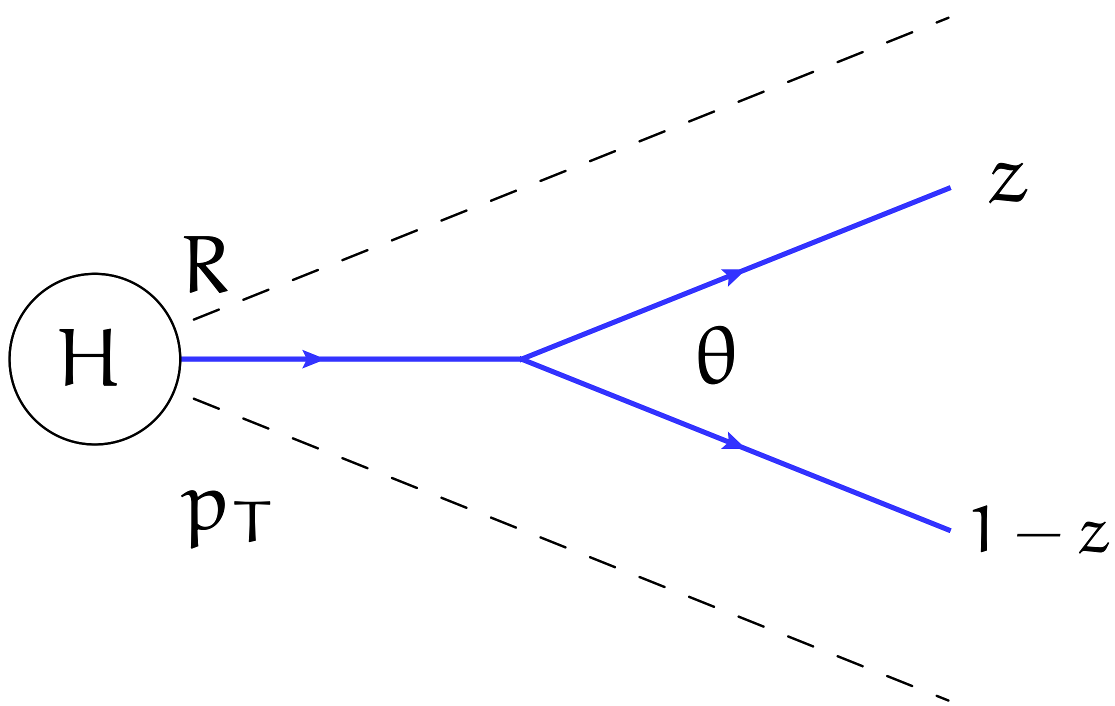
$$\frac{\partial}{\partial \tau} \hat{q}(\mathbf{k}, \tau) = \frac{\alpha_s N_c}{\pi} \int_{\hat{q}\tau}^{\mathbf{k}^2} \frac{d\mathbf{k}'^2}{\mathbf{k}'^2} \hat{q}(\mathbf{k}', \tau)$$

[Blaizot, MT (2014) Iancu (2014)]

# In-medium splitting function

- The splitting function can be measured using the grooming method (Soft Drop) that allows to trace back the first hard splitting in the jet evolution by removing soft particles that do not make a given cut $z > z_{\rm cut}\theta^\beta$

Larkoski, Marzani, Soyez, Thaler (2014)]




$$\frac{1}{N_{jet}}\frac{dN}{dz} \equiv p(z) \sim \frac{1}{z}$$

$$p(z) \equiv \int d\theta\, p(\theta)\, p(z|\theta)$$

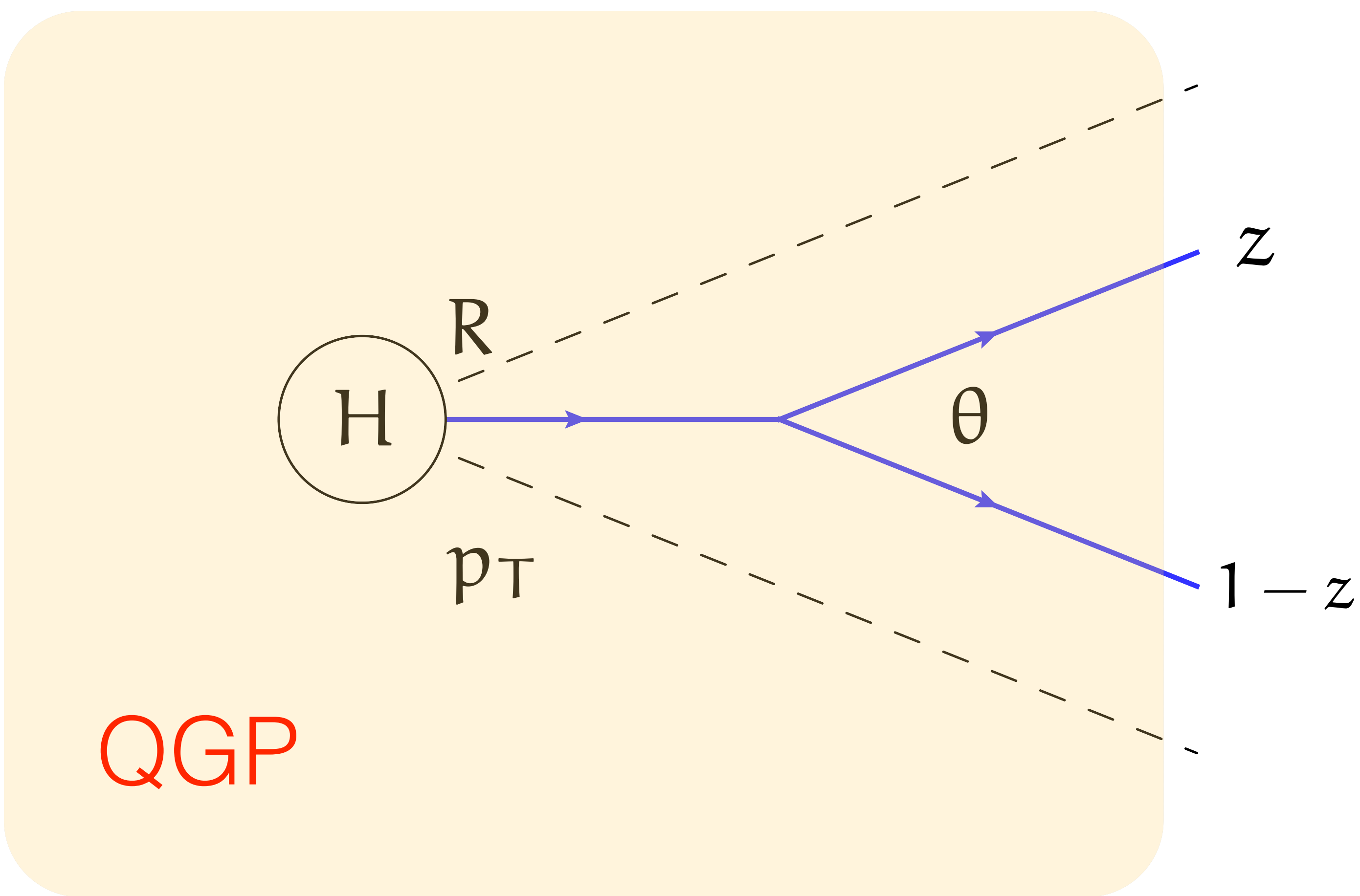
prob. to split at an angle (Sudakov suppression) $p(\theta) \sim \Delta(\theta)$

$\Longrightarrow$ Recently measured by CMS [CMS PAS HIN-16-006]

**See Matra Veweij's talk**

# In-medium splitting function

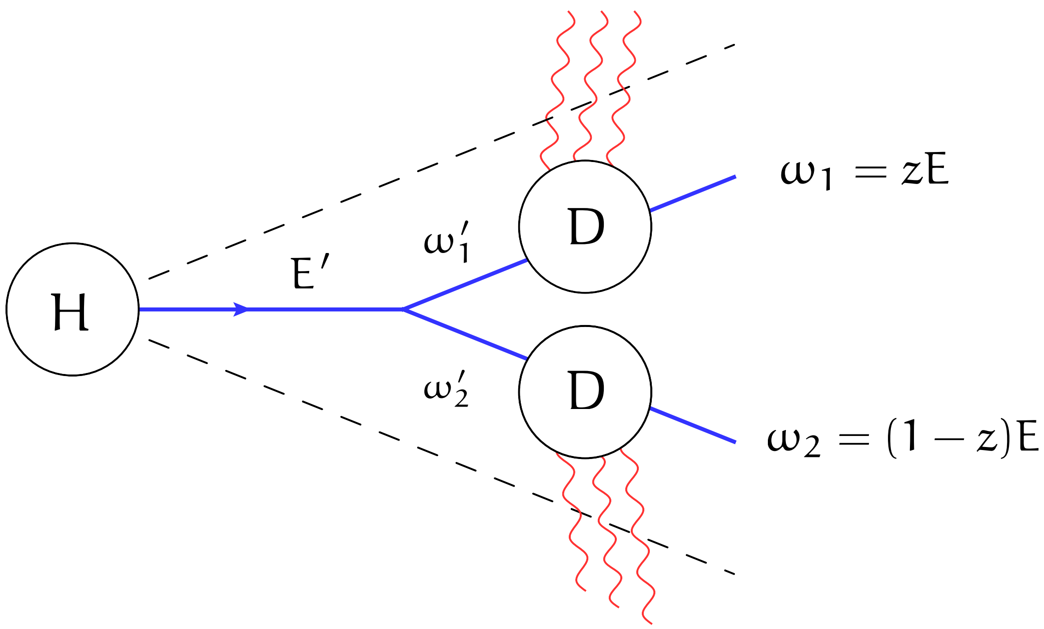
- Laboratory to probe color decoherence and LPM effects in QCD



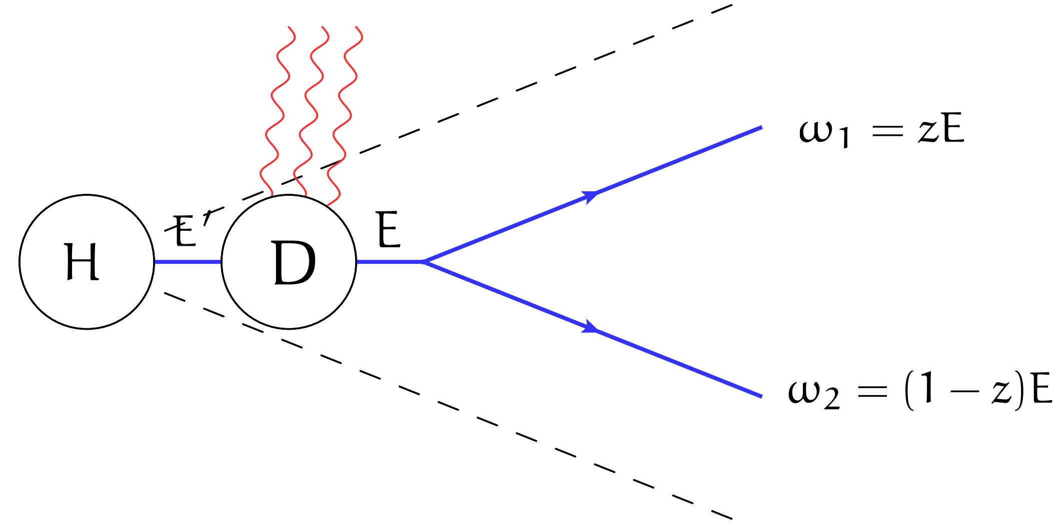

- Two types of splitting: vacuum + BDMPS (medium induced)

# In-medium splitting function

- How does the pair lose energy in the medium?
- Limiting cases: incoherent and coherent energy loss of in-vacuum splitting




Incoherent Eloss



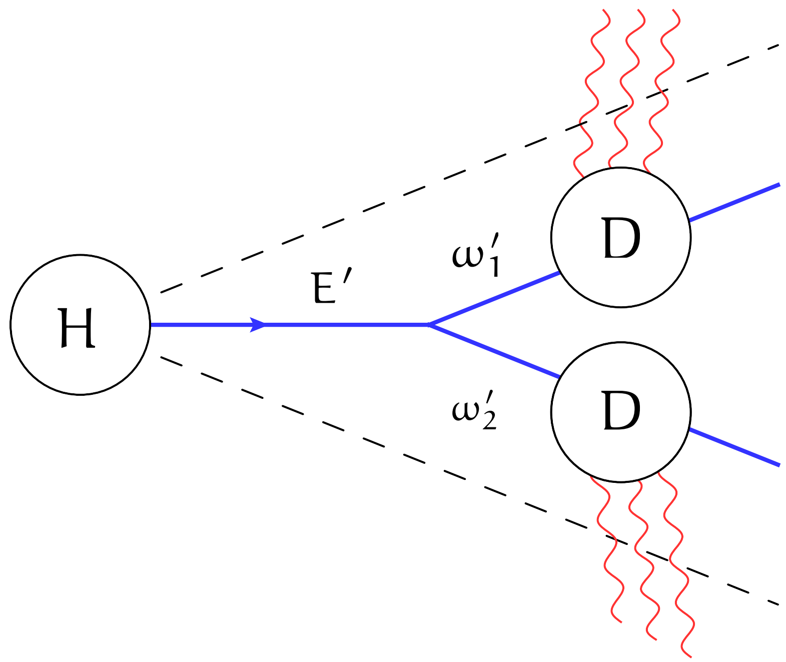

Coherent Eloss

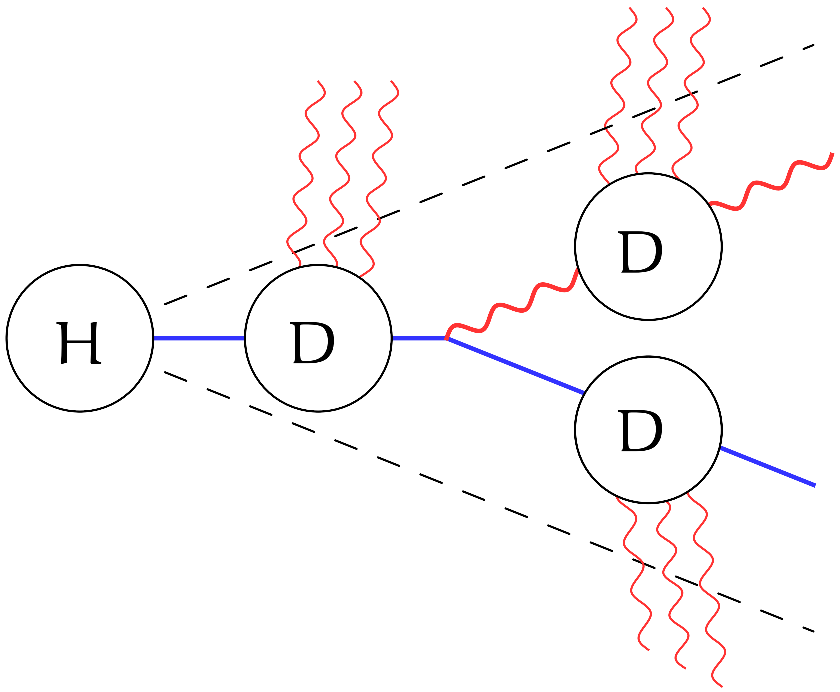
$$p_{\rm med}(z)/p_{\rm vac}(z) \sim 1$$

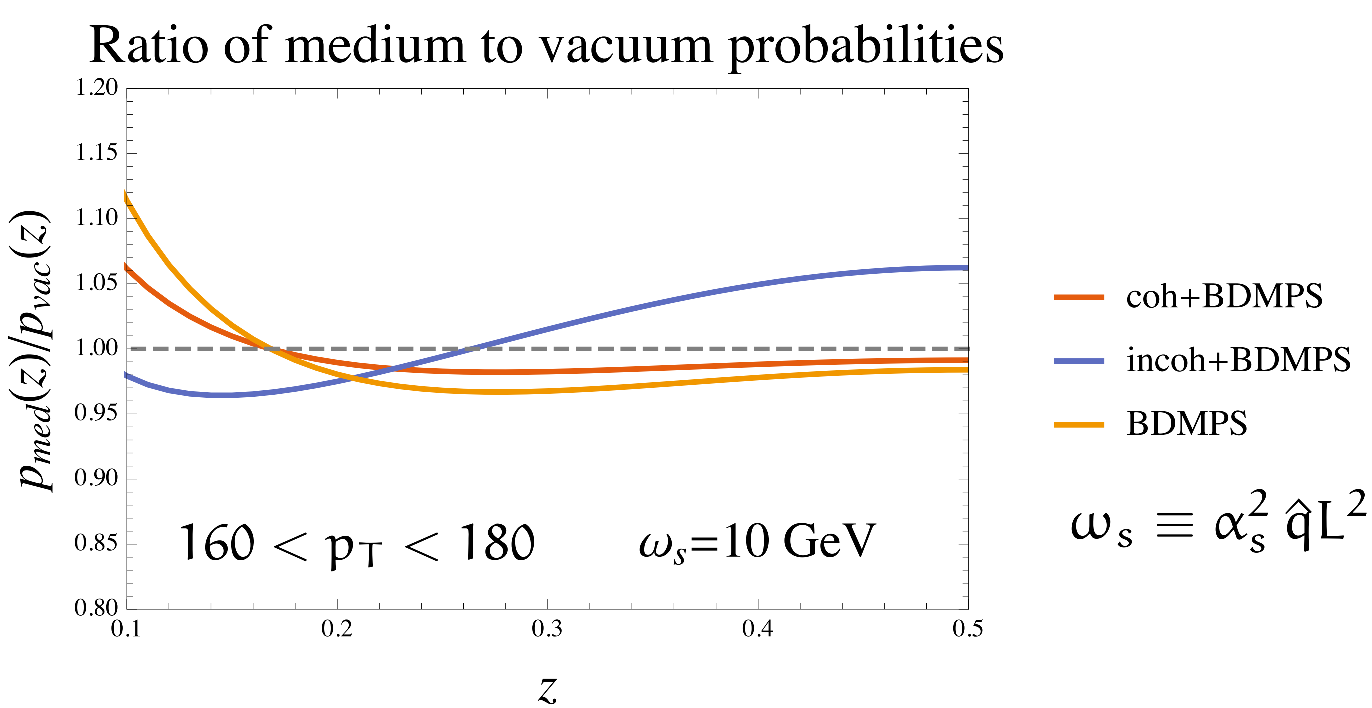
# In-medium splitting function

- Model I: incoherent energy loss + hard medium induced radiation

[Blaizot, Dominguez, Iancu, MT (2014)]




$\omega_s \equiv \alpha_s^2\, \hat{q} L^2$

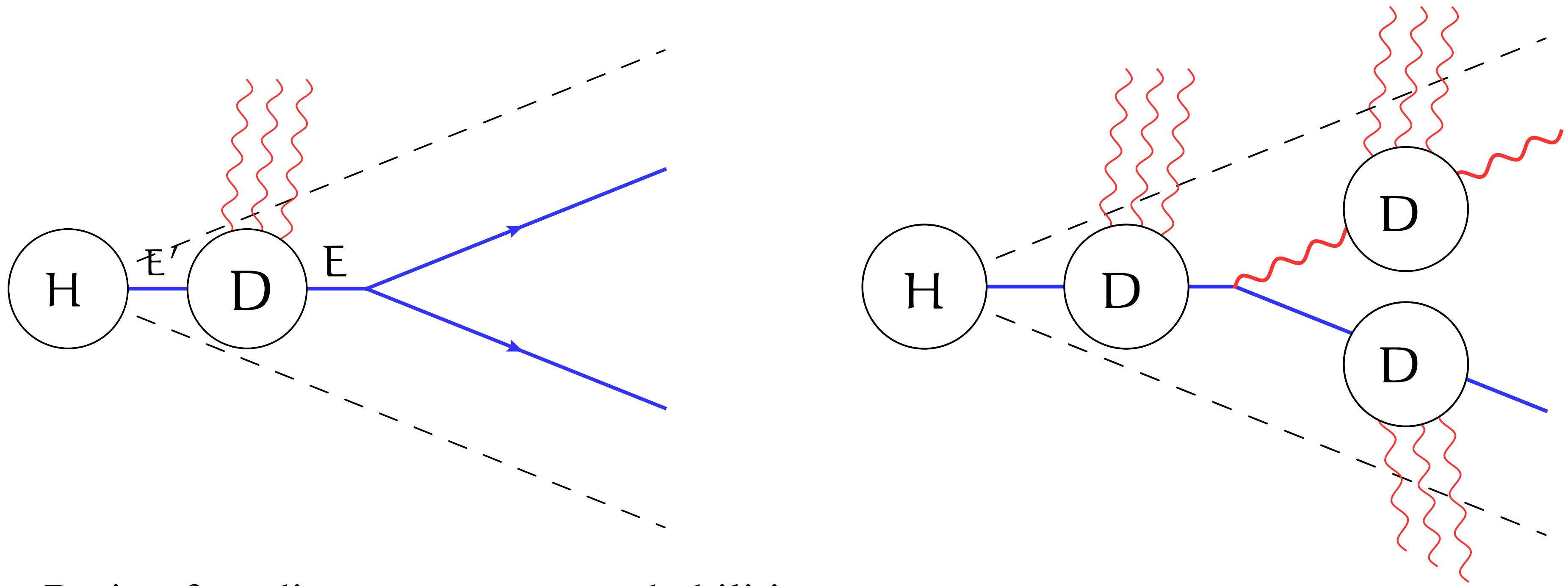
Incoherent Eloss yields a harder splitting function (blue curve)

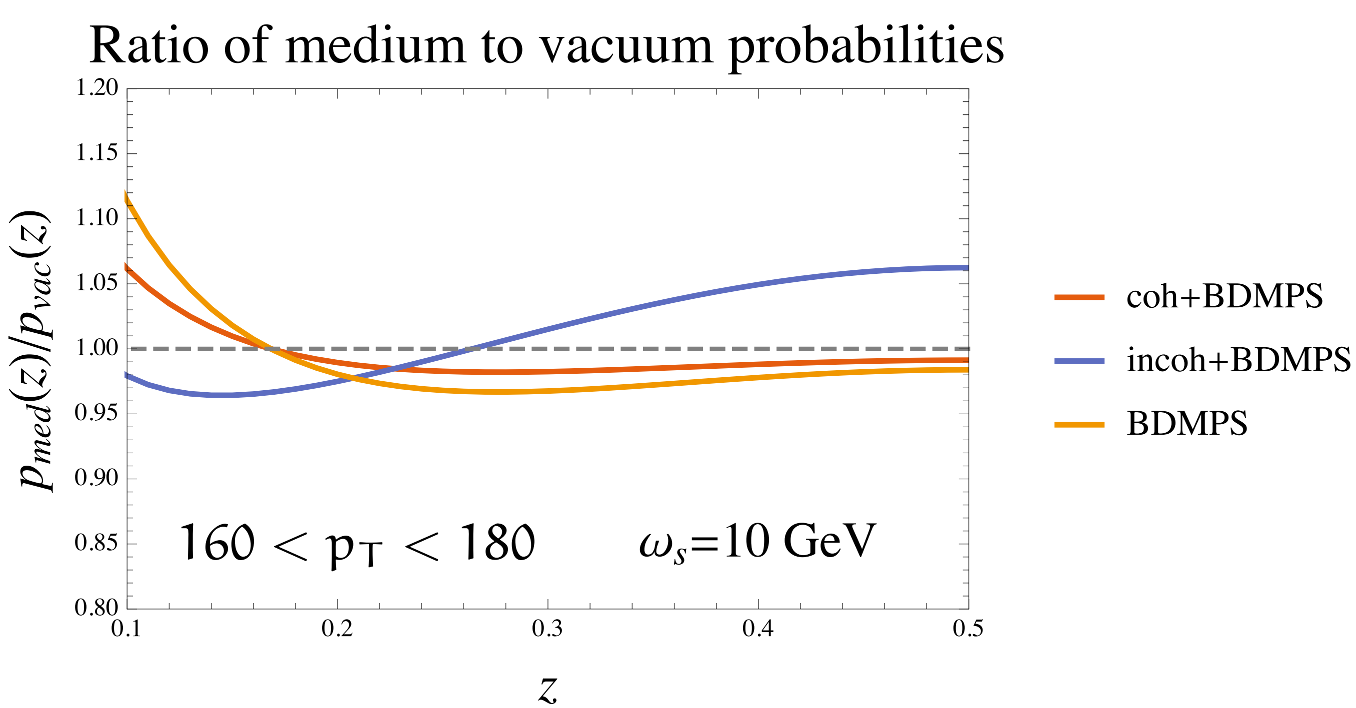
[MT, Tywoniuk (in preparation)]

# In-medium splitting function

- Model II: coherent energy loss + hard medium induced radiation

[Blaizot, Dominguez, Iancu, MT (2014)]




Softening of the splitting function in the coherent case due to the unmodified vacuum and the presence of BDMPS radiation $z^{-3/2}$

[MT, Tywoniuk (in preparation)]

# Summary

- "Jet quenching" in the LHC era: new observables (jets) and new tools (resummations, SCET,…)
- In-medium jet evolution, two major components:
    - Collimated angular ordered core (partially resolved substructures)
    - Large angle, time ordered turbulent cascade
- Radiative corrections to jet quenching observables absorbed in the renormalization of the quenching parameter
- Remaining questions: Theoretical description of the jet-medium system as a whole (factorization? back reaction). Mote Carlo implementation
- Newly measured splitting function by CMS may help analyze color (de)coherence effects and provide a measurement of the BDMPS spectrum