A overview of jet quenching from a theory perspective

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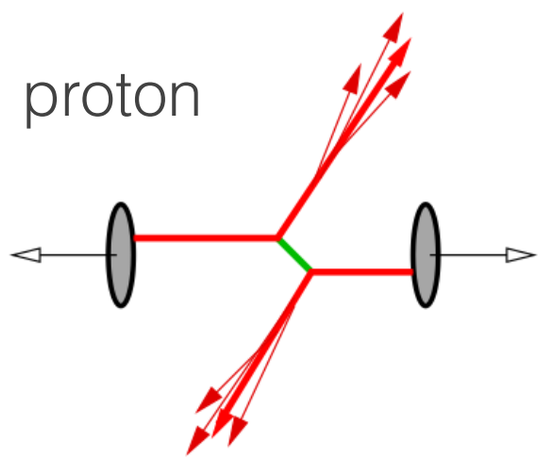
BROOKHAVEN NATIONAL LABORATORY

Outline

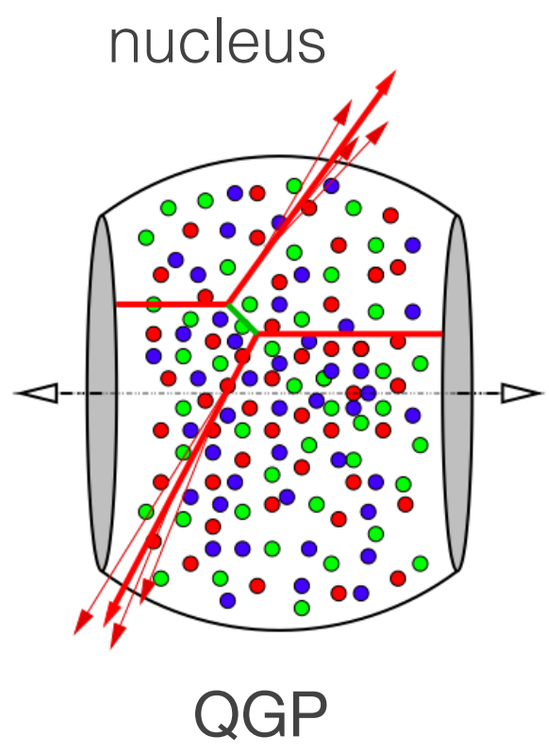
- Jet quenching
- Jet evolution in a plasma
- Medium response vs turbulent gluon cascade
- Medium modification of jet substructure

Jet quenching

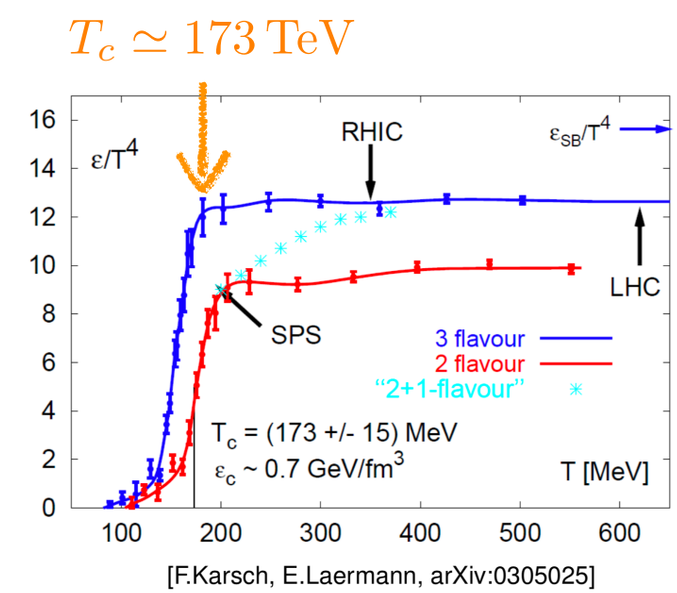
Jet physics at colliders (T=0)



Heavy Ion Collisions



Crossover phase transition (from lattice QCD)



LHC: $T \sim 600\,\mathrm{MeV}$

RHIC: $T \sim 350\,\mathrm{MeV}$

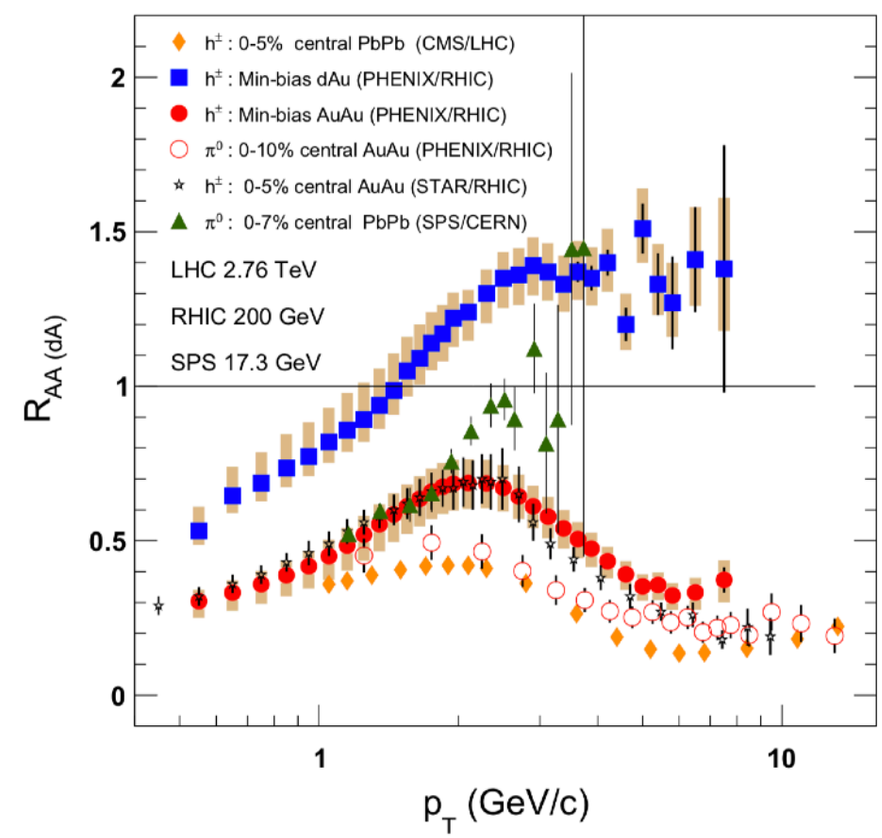
- Jet quenching refers to the suppression and modification of a jet as it propagates through hot QCD matter
- Strong final state interactions cause high pT jets to lose energy to the plasma

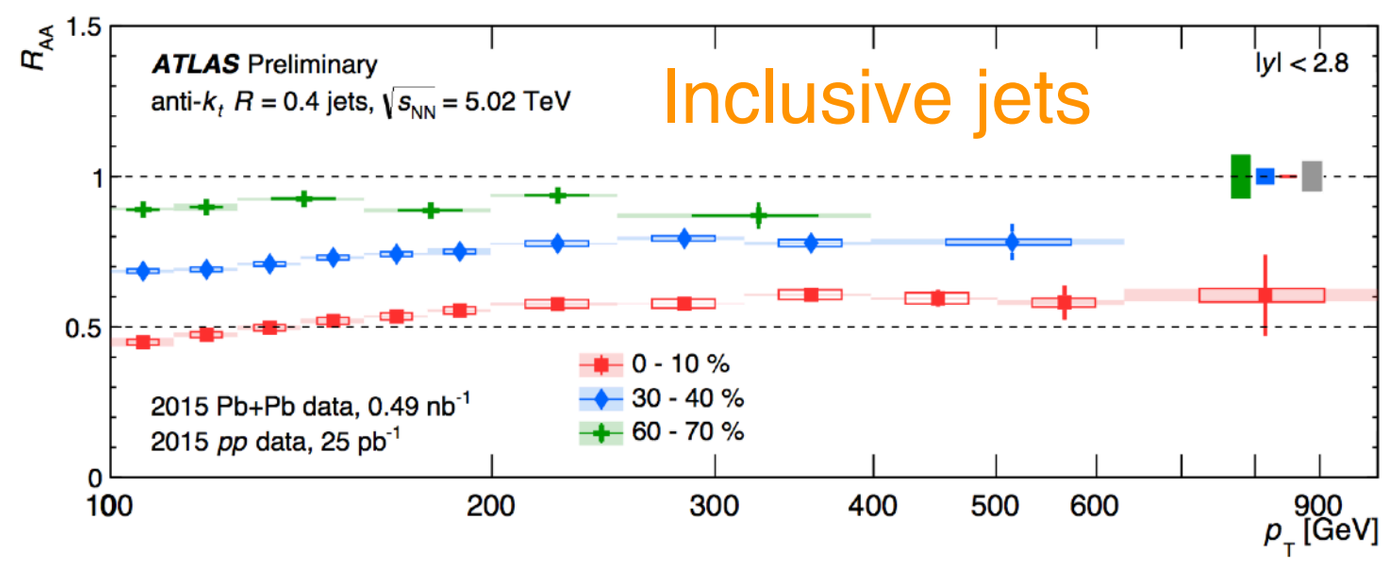
Jet quenching

- Two decades after Bjorken prediction, jet quenching phenomenon was observed at RHIC in the suppression of high-pT hadrons and confirmed at LHC where a strong suppression of 1 TeV jets was observed
- Use jets as test particles to learn about the properties of of the Quark-Gluon-Plasma (QGP)

$$R_{AA} \equiv \frac{1}{N_{coll}} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}N_{pp}/\mathrm{d}p_T}$$

Inclusive hadrons



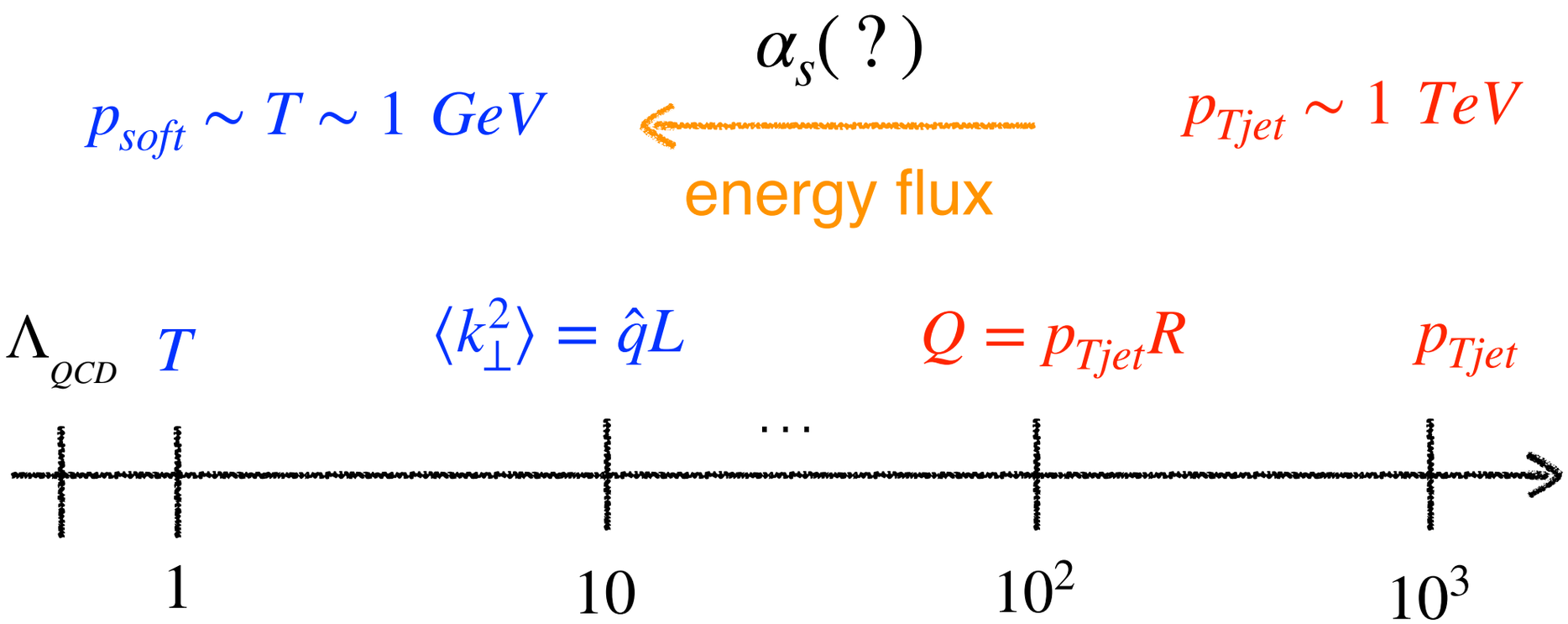


Probing high density QCD with jets

- Guidance from first principles: how does a jet as a multi-parton system interact with the QGP? Is it perturbative?

  → How is energy transported from energetic partons to low momenta and dissipated in the QGP?

  → How is the jet substructure modified?



QCD jets in a nutshell

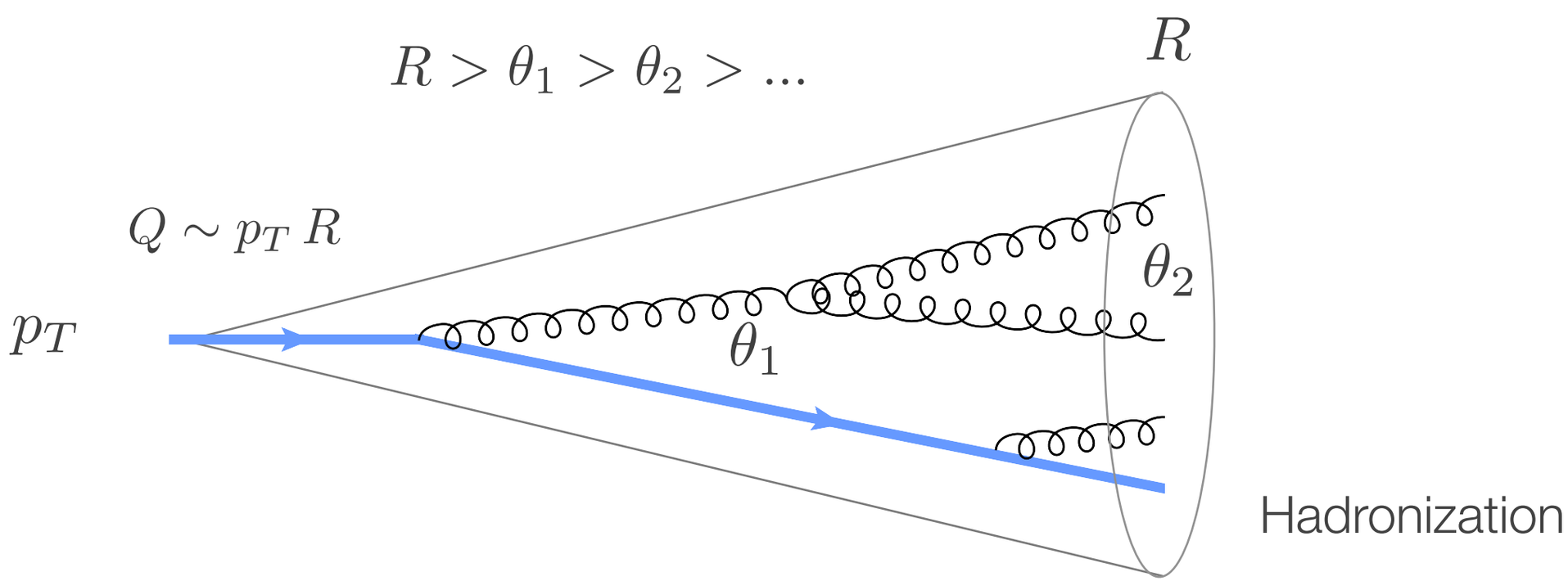
- Soft & Collinear divergences: high probability for branching

$$\mathrm{d}P \sim \alpha_s C_R \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega}$$

color factors (quark and gluon):

$$C_R \equiv C_F \quad \text{or} \quad C_A$$

- Jet collimation: jets are dominated by collinear splittings
- Color coherence: soft radiation depleted due to destructive interference



[Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer, Khoze, Toyan, Collins, Soper, Sterman … 1980's]

Multiple soft scattering and $\hat{q}$

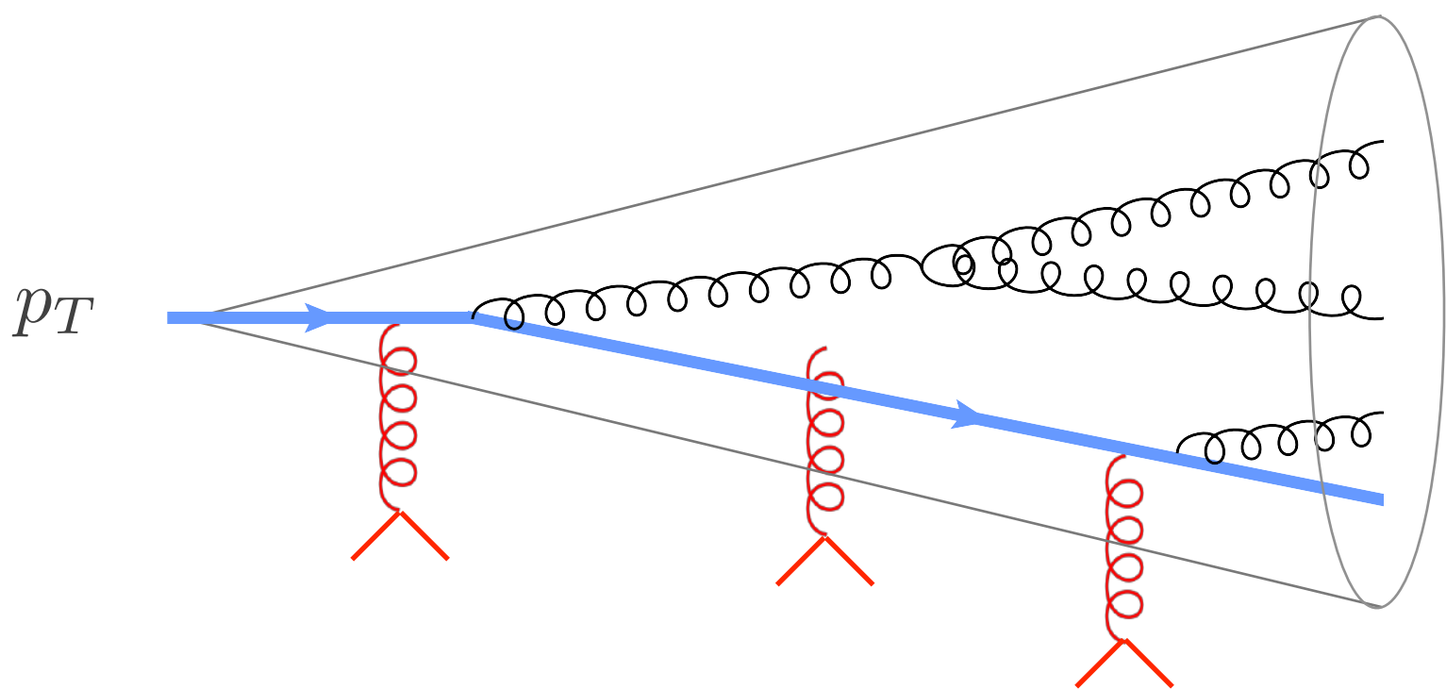
- In a dense colored medium (QGP) a high energy parton produced in a hard collision undergoes multiple interactions with the plasma constituents

$$\frac{\mathrm{d}P}{\mathrm{d}z\,\mathrm{d}q_\perp^2} \sim \alpha_s^2\, C_R\, \frac{n}{q_\perp^4}$$

→ Coulomb scattering

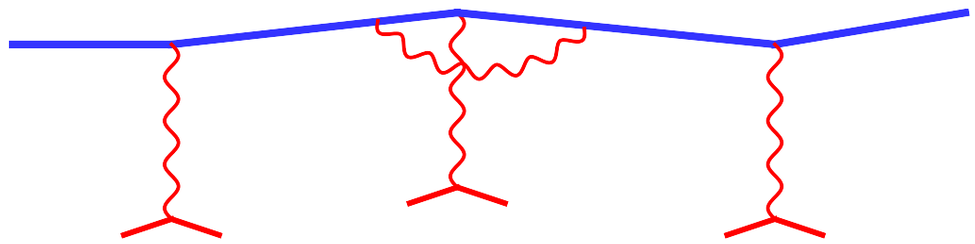
- Momentum boarding: the dominant collisions are soft. The effect is a diffusion in transverse momentum space

$$\langle k_\perp^2 \rangle \equiv \hat{q} L$$



Multiple soft scattering and $\hat{q}$ at NLO

- The next-to-leading contribution to momentum broadening and energy loss is enhanced by a (potentially large) double logarithm



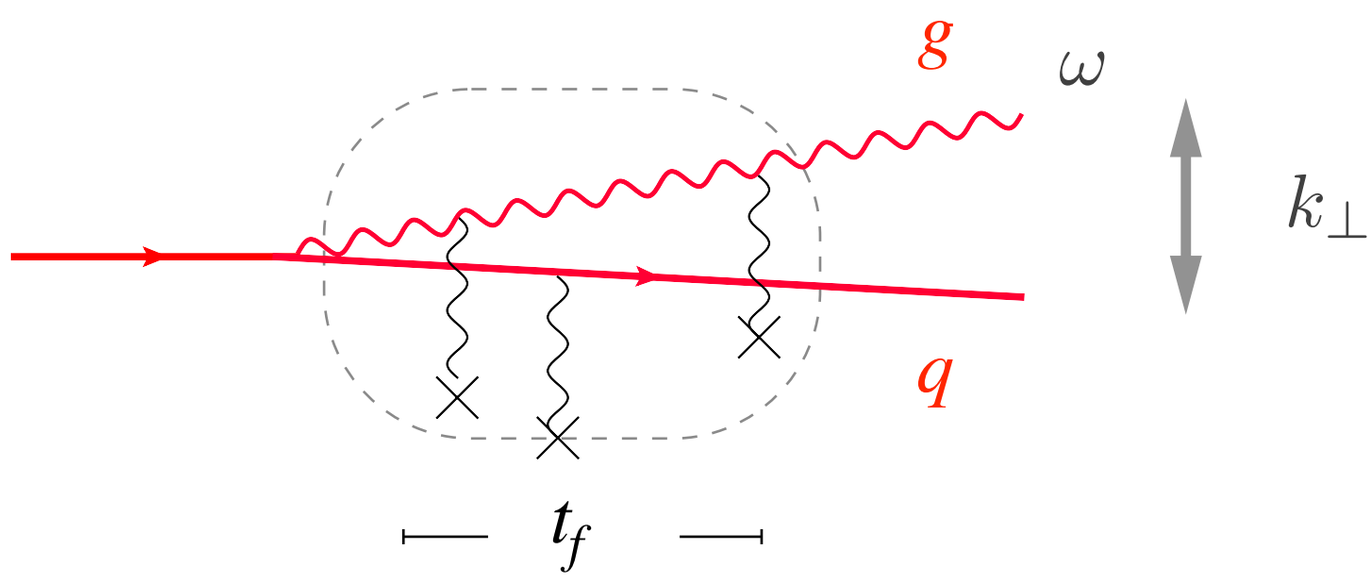
[Wu (2011) Liou, Mueller, Wu (2014) Blaizot, Iancu, Dominguez, MT (2014)]

- The double logs can be absorbed in a renormalization of the transport coefficient

$$\hat{q} \to \hat{q}\left(1 + \frac{\bar{\alpha}}{2}\ln^2\frac{L}{\ell_{mfp}}\right)$$

The LPM effect on the back of the envelop

- The energy spectrum of photons caused by the propagation of a relativistic charge in a medium is suppressed due to coherence effects (Landau-Pomeranchuk Migdal 1953)



- The radiation formation time, together with transverse momentum broadening define the LPM time scale

$$t_f \sim \omega / k_\perp^2$$

$$k_\perp^2 \sim \hat{q}\, t_f$$

$$\Longrightarrow \qquad t_f(\omega) \equiv \sqrt{\frac{\hat{q}}{\omega}}$$

The LPM effect on the back of the envelop

- During the formation time multiple scattering centers act coherently. This yields the suppression of the spectrum in the UV which corresponds to large formation times

$$t_f(\omega) = \sqrt{\frac{\omega}{\hat{q}}} \quad \text{and} \quad \omega \frac{\mathrm{d}I^{LPM}}{\mathrm{d}\omega} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}} L \propto \frac{1}{\sqrt{\omega}}$$

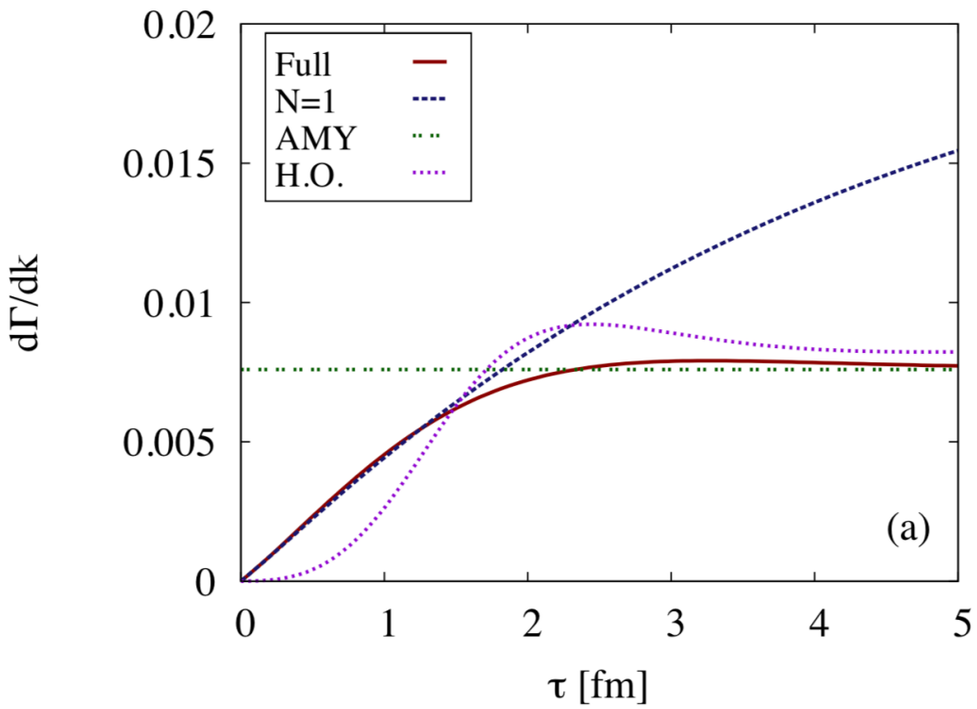
Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)

- Mean radiative energy loss scales with the square of the medium length

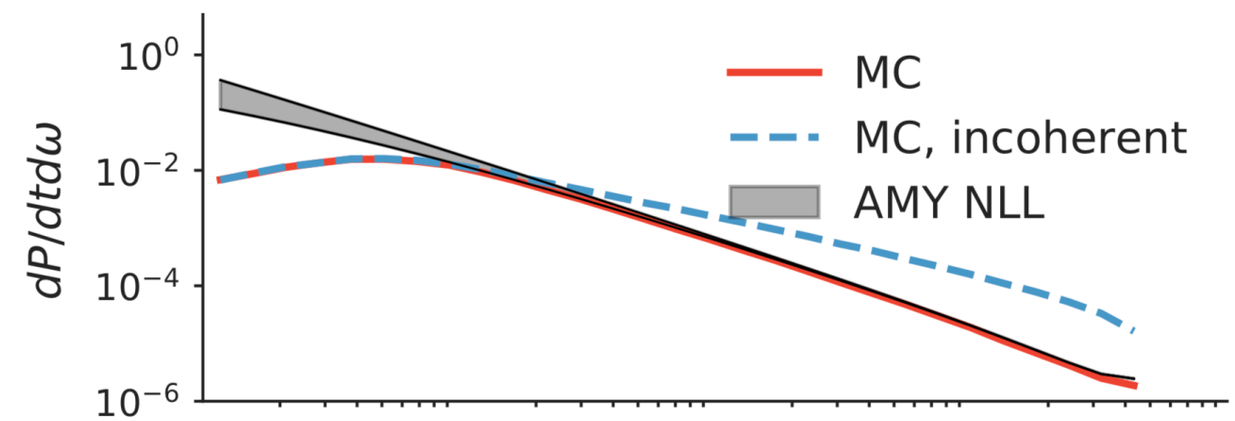
$$\Delta E_{\mathrm{rad}} \sim \int \mathrm{d}\omega \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \hat{q} L^2$$

Medium-Induced gluon radiation

- Difficult to solve. Numerical solutions



Caron-Huot and Gale (2010)



Ke , Xu, Bass (2018)

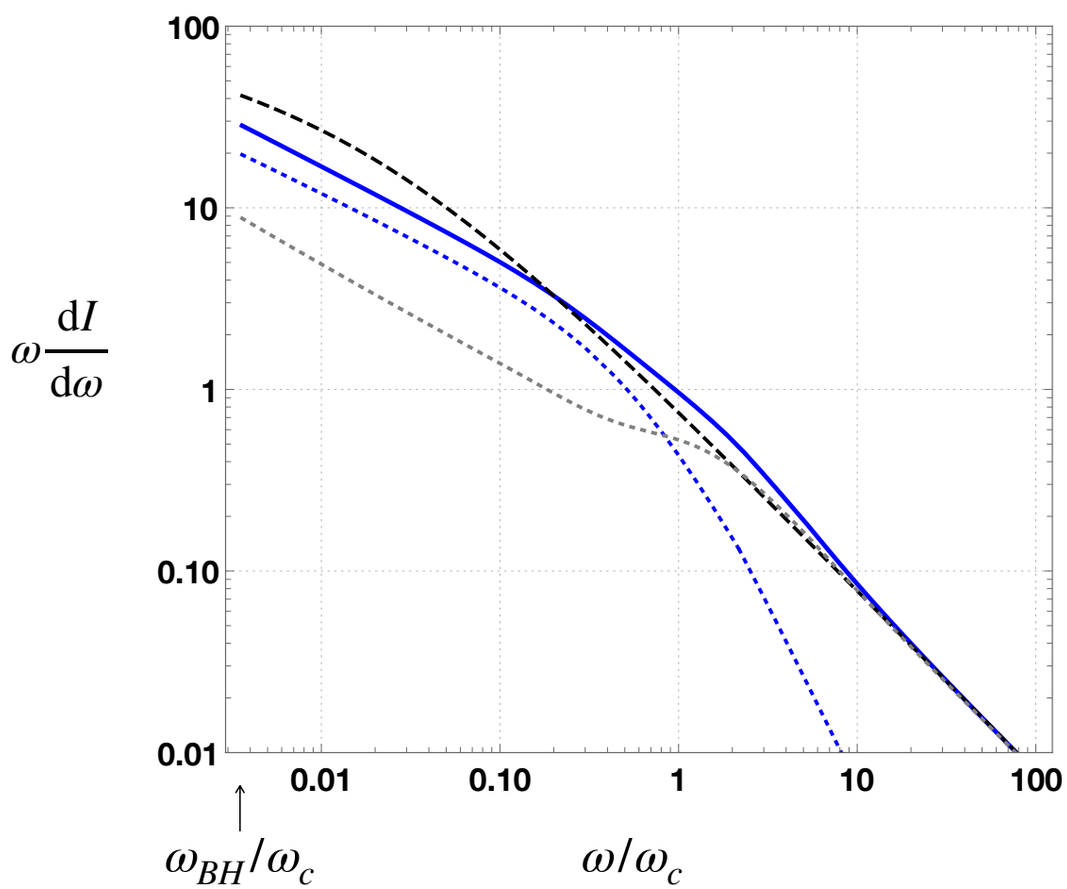
- Analytic limits:
  - N=1 opacity (GLV) dilute medium or hard radiation
  - Harmonic Oscillator (HO) (BDMPS) dense medium $\sigma(x_\perp) \sim x_\perp^2$
- Novel analytic approach: Opacity expansion around HO to account for both regimes

YMT (2019)

The LPM effect on the back of the envelop

Medium-induced gluon spectrum for $\omega_c = nL^2 = 22.5\,GeV$

$L = 3\,fm \quad \hat{q} \simeq 1.4\,GeV^2/fm$

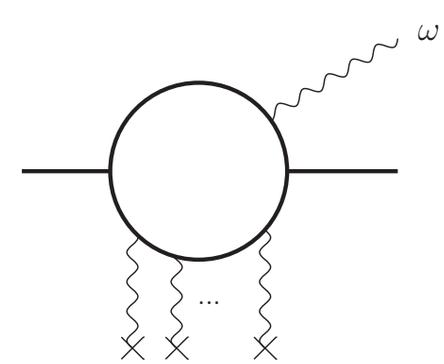


full

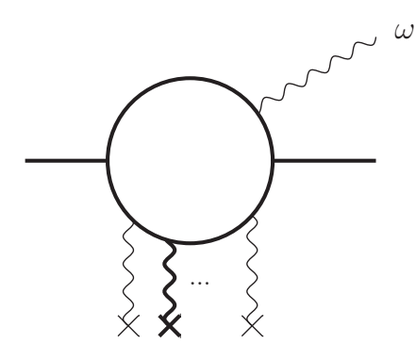
order 0 (HO)

order 1

single-hard (GLV)



Multiple-soft



Multiple-soft + 1 hard

- First two orders account for GLV-HT and BDMPS spectra

Medium-induced turbulent cascade

- Multiple scattering trigger abundant soft gluon radiation

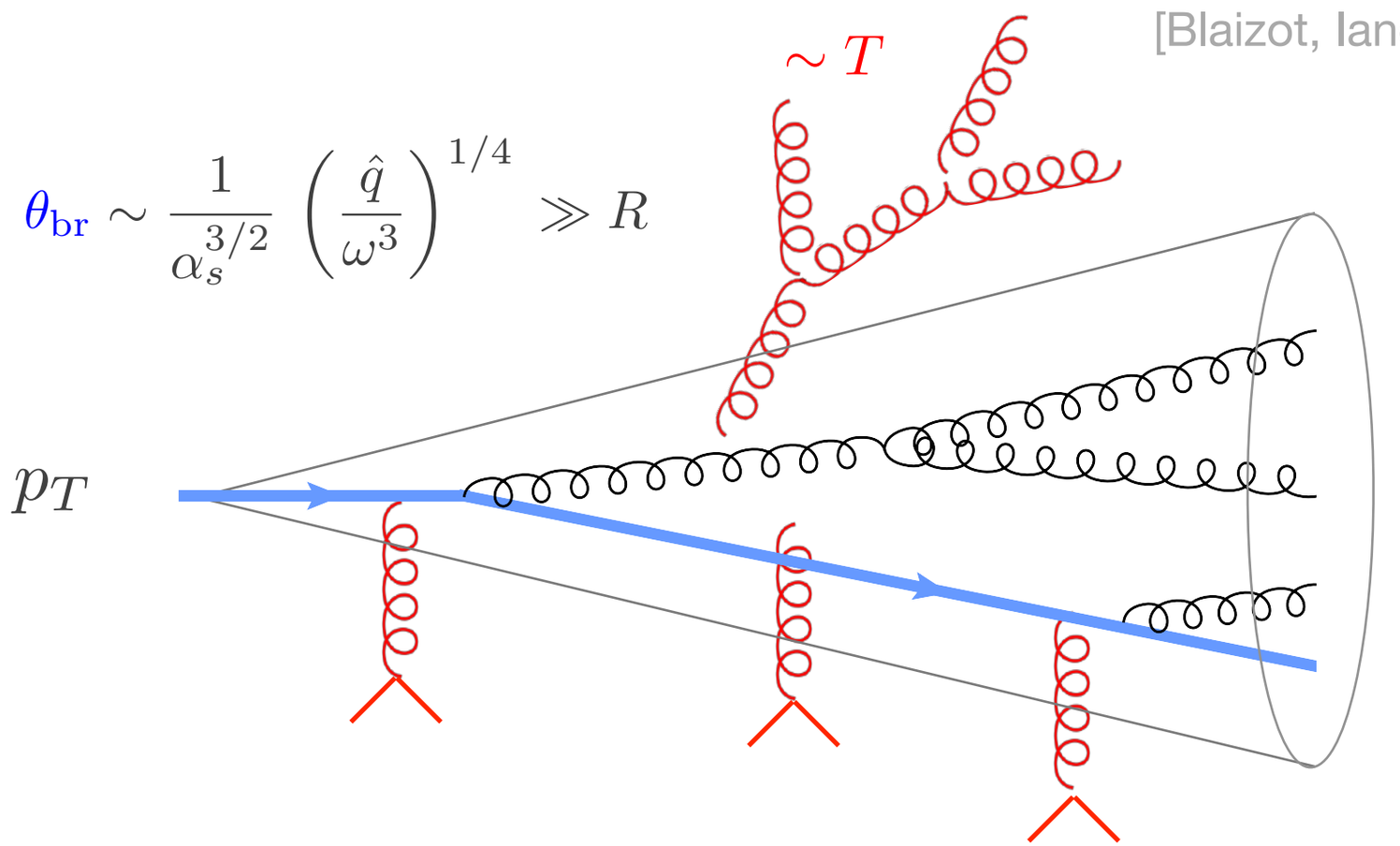
$$\omega \frac{\mathrm{d}^2 P_{\mathrm{rad}}}{\mathrm{d}\omega\, \mathrm{d}z} \sim \alpha_s\, C_R \sqrt{\frac{\hat{q}}{\omega}}$$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996) Wiedemann (2000) Arnold, Moore, Yaffe (2002), Gyulassy, Levai, Vitev (2000) Guo, Wang (2000)]

- Large angle cascade for $\omega \sim \alpha_s^2 \hat{q} L^2 \ll p_T$ → minijet thermalization

[Blaizot, Iancu, MT (2013), Iancu, Wu (2015)]

$$\theta_{\mathrm{br}} \sim \frac{1}{\alpha_s^{3/2}} \left(\frac{\hat{q}}{\omega^3}\right)^{1/4} \gg R$$

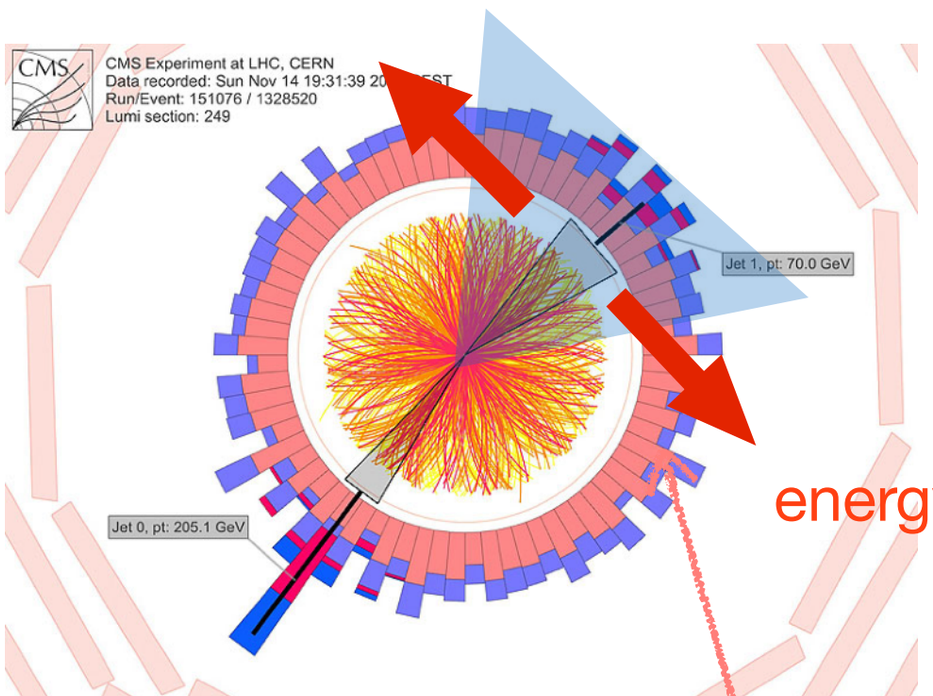


Missing pT in dijet events

- Energy flows from high to low frequencies without accusation: efficient mechanism for energy transport to large angles

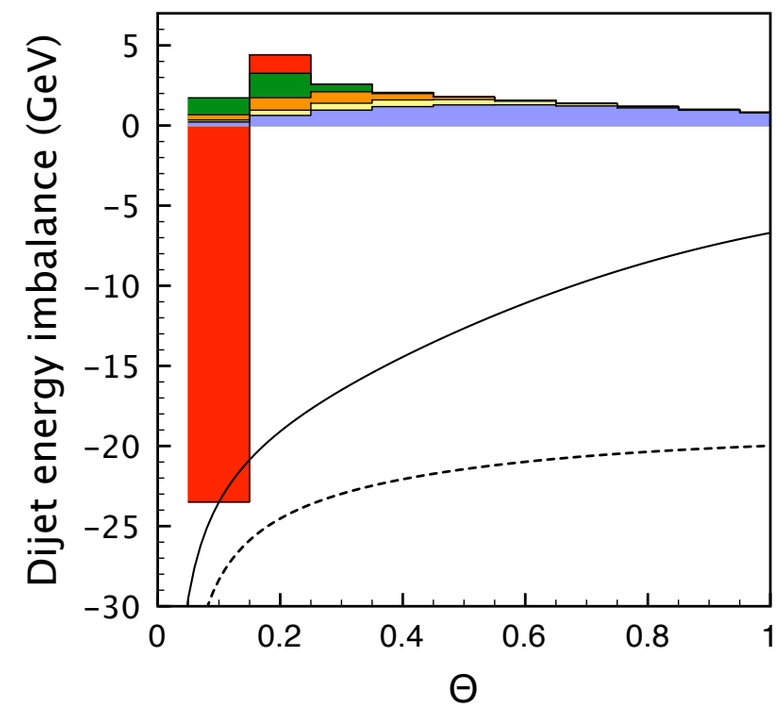
Blaizot, MT, Torres (2014)

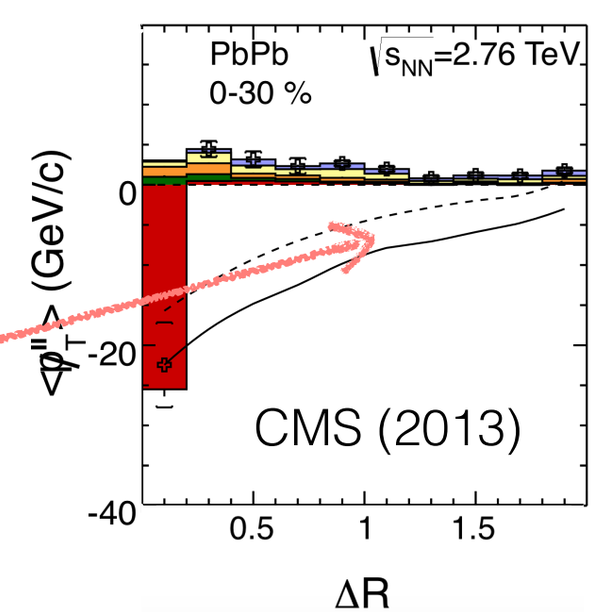
$p_{T1} = 70\,GeV$



energy flow

$p_{T1} = 205\,GeV$



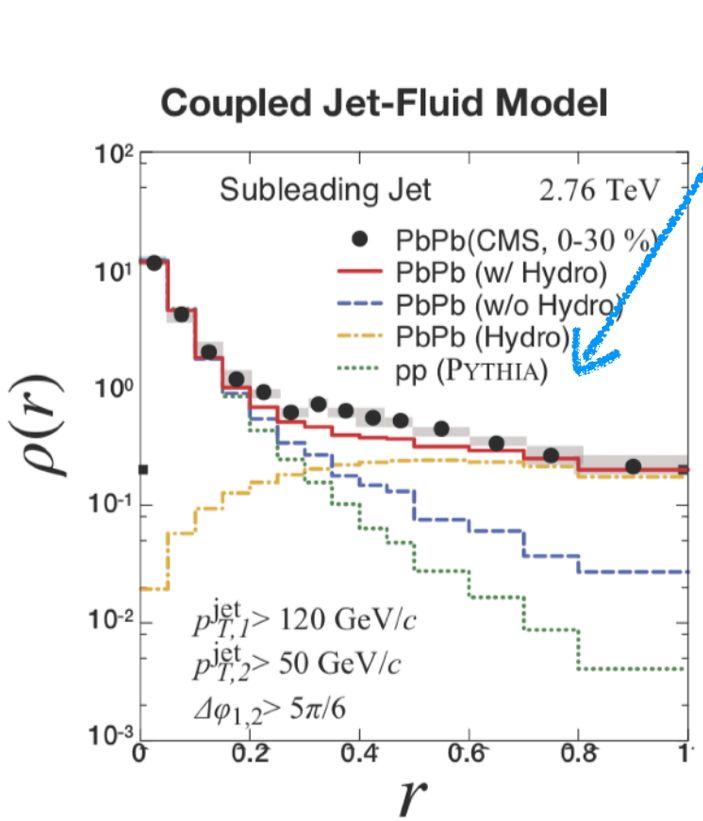


→ Energy is recovered at large angles in soft particles

Medium response

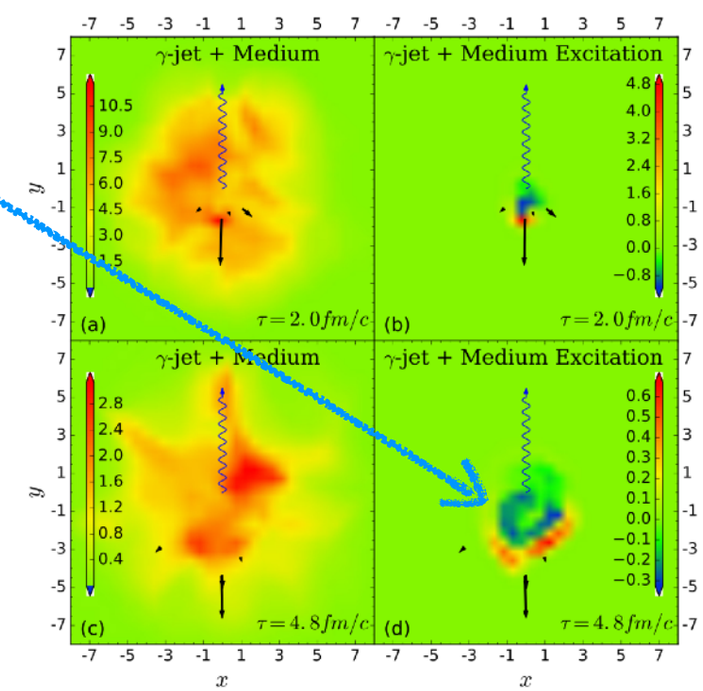
- Similar effect obtained by assuming direct energy deposition in the plasma: hydrodynamic response, linear Boltzmann

- Medium excitation correlated with the jet: may cause enhancement of soft radiation inside the jet



Y. Tachibana, N.-B. Chang, G.-Y. Qin (2017)

Hydro response



He, Liu Wang, Zhu (2015)

T. Luo, S. Cao, Y. He, X.-N. Wang (2018)

Wang, Wei, Zhang (2017)

- However, radiative processes dominate at low occupancy.

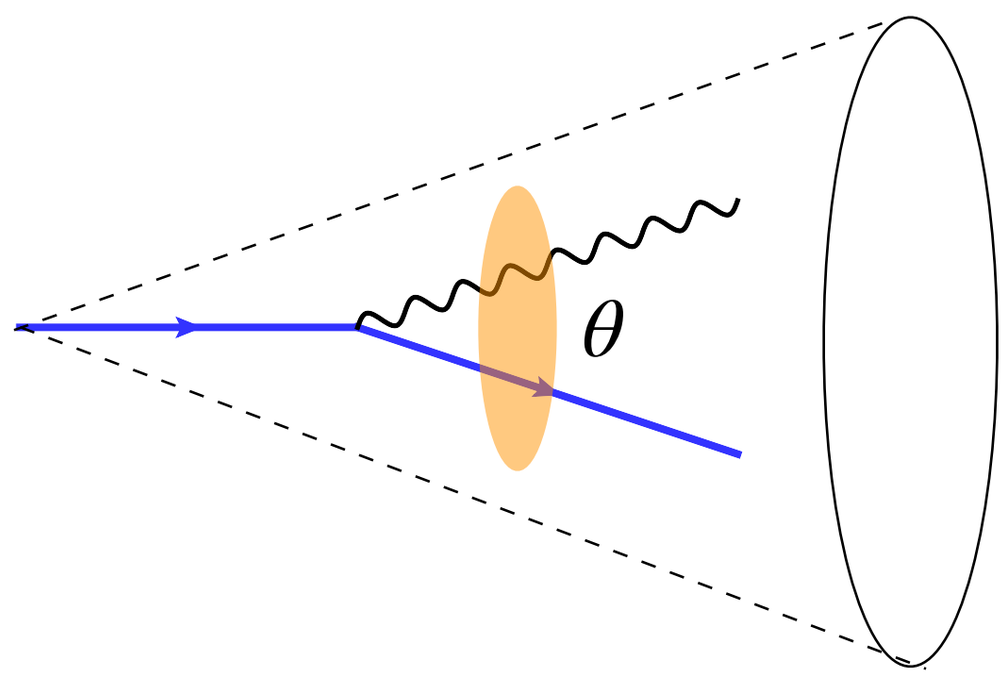
Baier, Mueller, Schiff, Son (2001) Arnold, Moore, Yaffe (2002)

Color decoherence of jet substructure

- The jet is composed of many partons as it traverses the plasma — It is tempting to assume that jet constituents interact independently with the plasma.

- However, interactions are not point-like: the medium resolves transverse distance of order

$$l_{\rm med} \sim k_\perp^{-1} \sim (\hat{q}\, t)^{-1/2}$$



Color decoherence

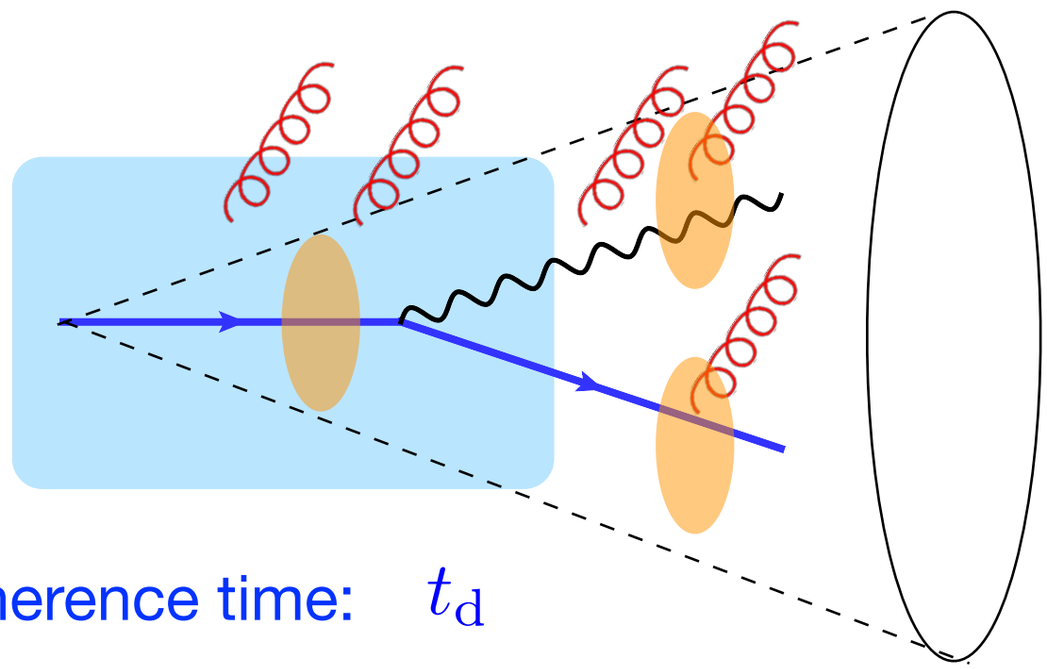
- Comparing the medium resolution scale to the transverse size of a partonic fluctuation defines a new time scale

$$l_{\rm med} \sim k_\perp^{-1} \sim (\hat{q}\, t)^{-1/2} \ll r_\perp \sim \theta\, t$$

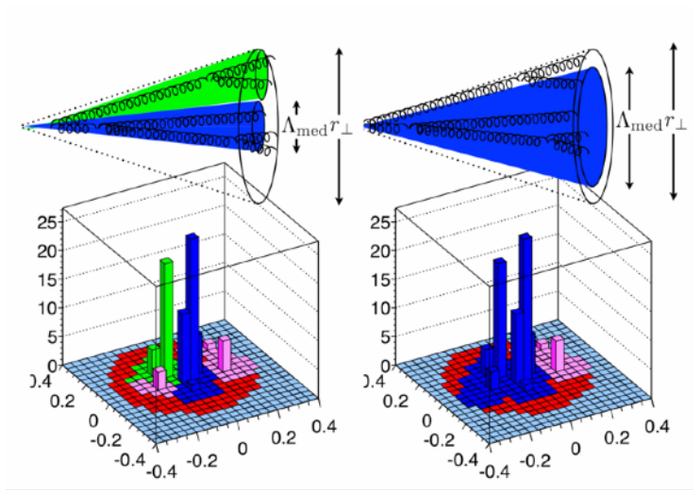
- The medium resolves jet substructure (subjets) when $\theta > \theta_c \sim (\hat{q} L^3)^{-1/3}$

$$t_{\rm d} \sim (\hat{q}\, \theta^2)^{-1/3} < L$$

MT, Salgado, Tywoniuk (2010-11)
Iancu, Casalderrey-Solana (2011)
MT, Tywoniuk (2017)



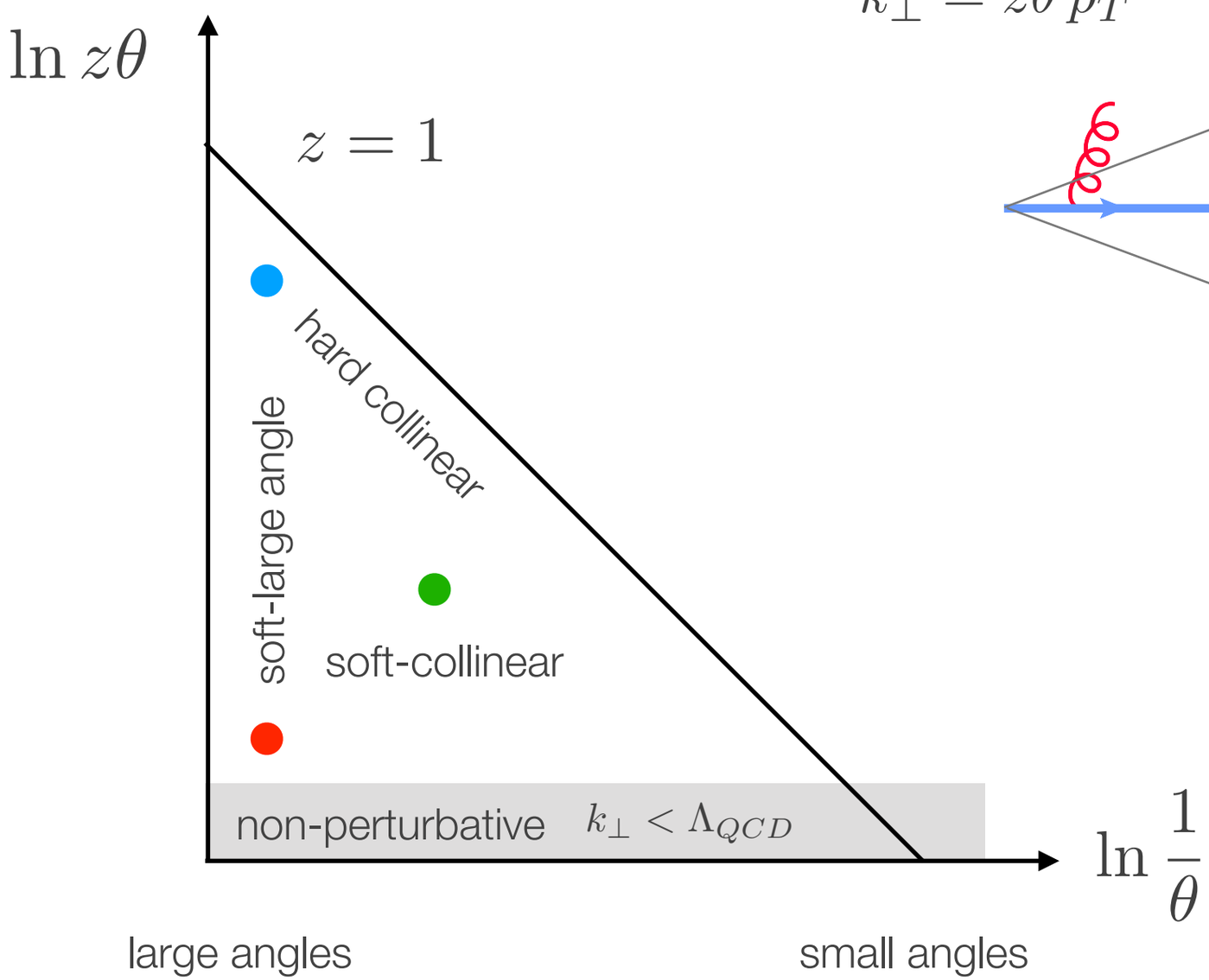
The decoherence time: $t_{\rm d}$

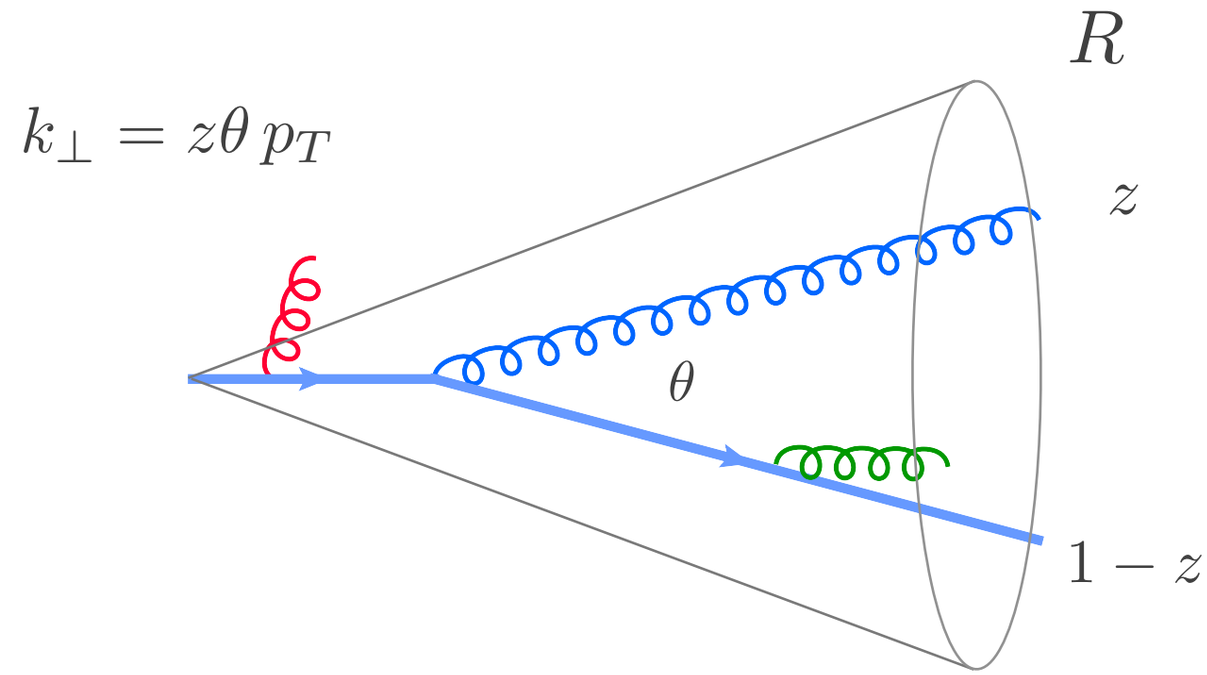


- Radiation intensity is proportional to the number of resolved color charges

Probabilistic picture and MC prescription (vacuum)

- **Lund plane:** Representation of the phase space of parton shower within jets

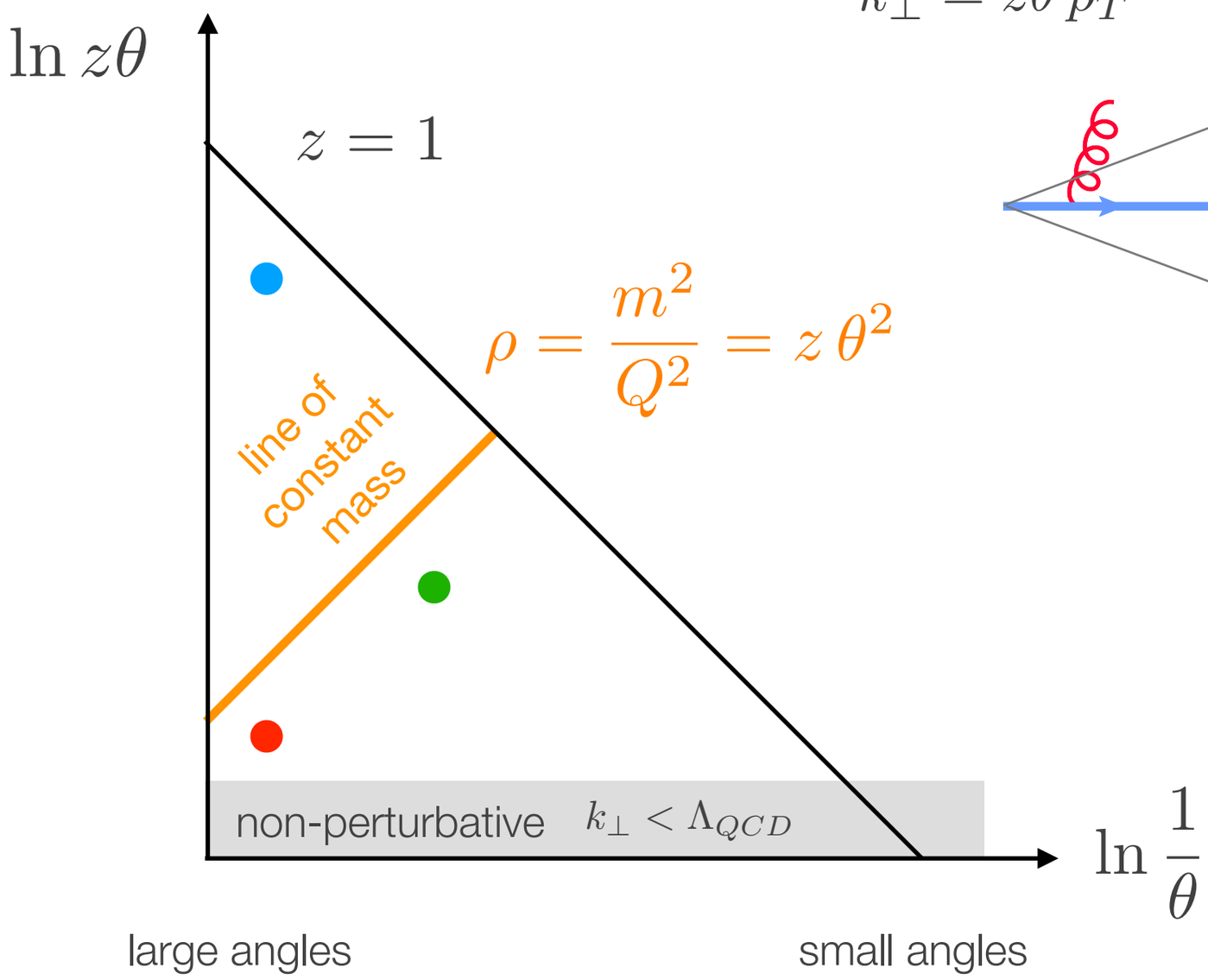




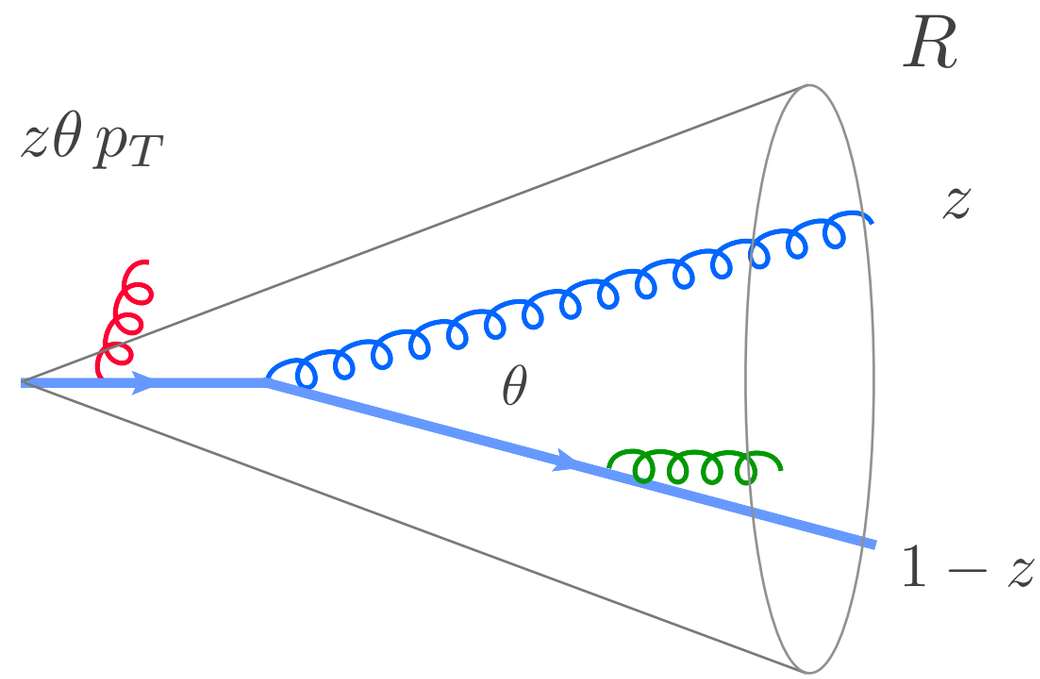
$$\mathrm{d}P = \frac{\alpha_s(k_\perp)\, C_R}{\pi}\, \mathrm{d}\ln z\theta\, \mathrm{d}\ln\theta$$

Probabilistic picture and MC prescription (vacuum)

- **Lund plane:** Representation of the phase space of parton shower within jets



$k_\perp = z\theta\, p_T$

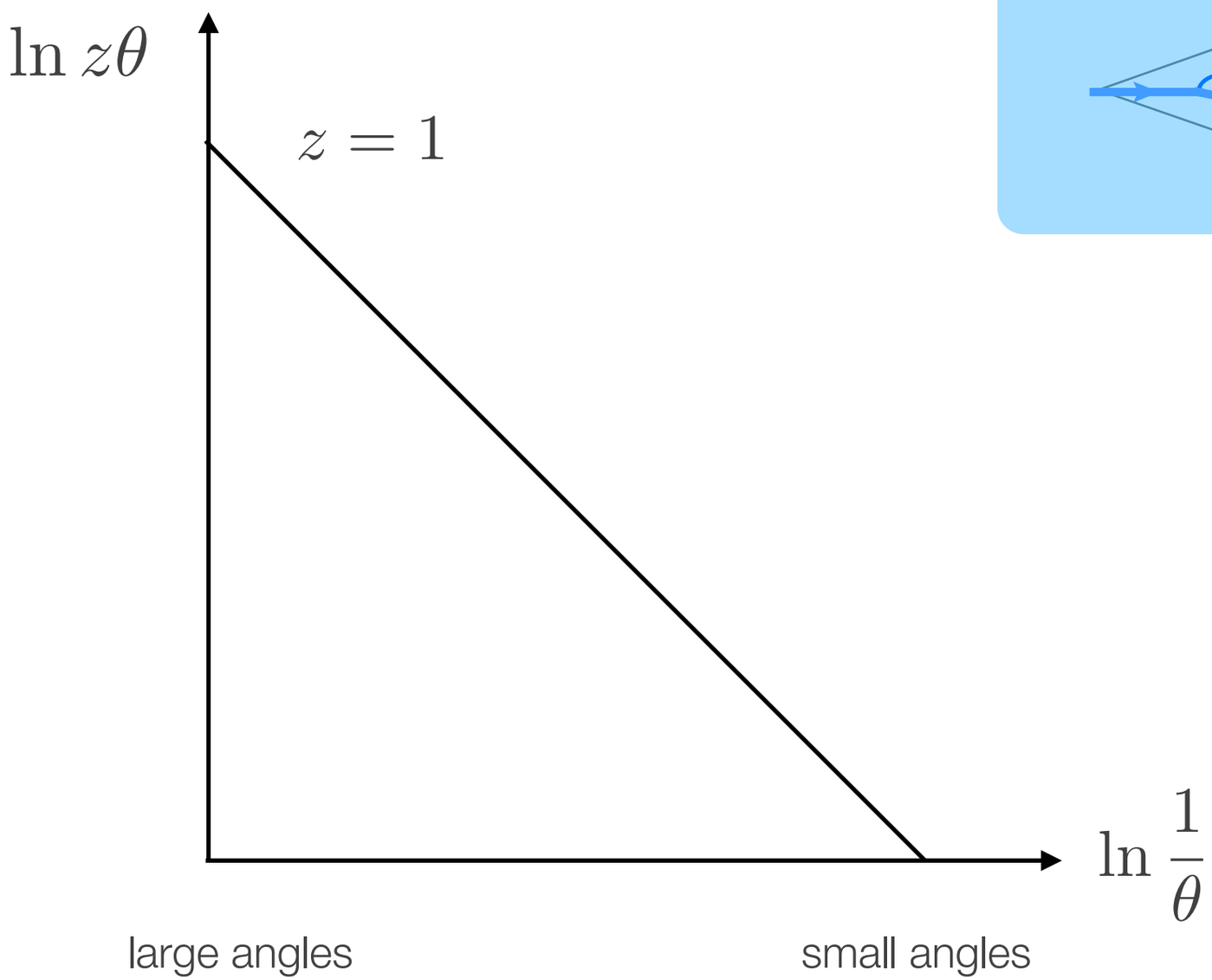


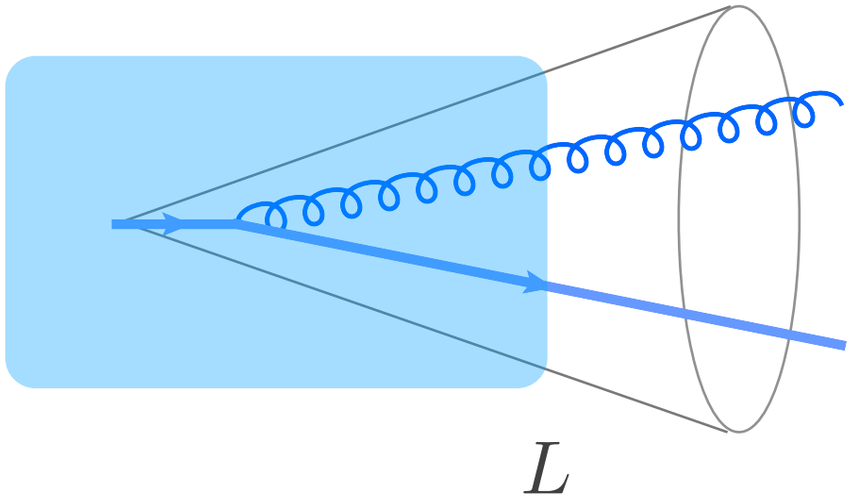
$$\mathrm{d}P = \frac{\alpha_s(k_\perp)\, C_R}{\pi}\, \mathrm{d}\ln z\theta\, \mathrm{d}\ln\theta$$

Jet substructure observables define lines on the Lund plane

Probabilistic picture and MC prescription (in-medium)

formation time: $t_f = (\omega\theta^2)^{-1}$





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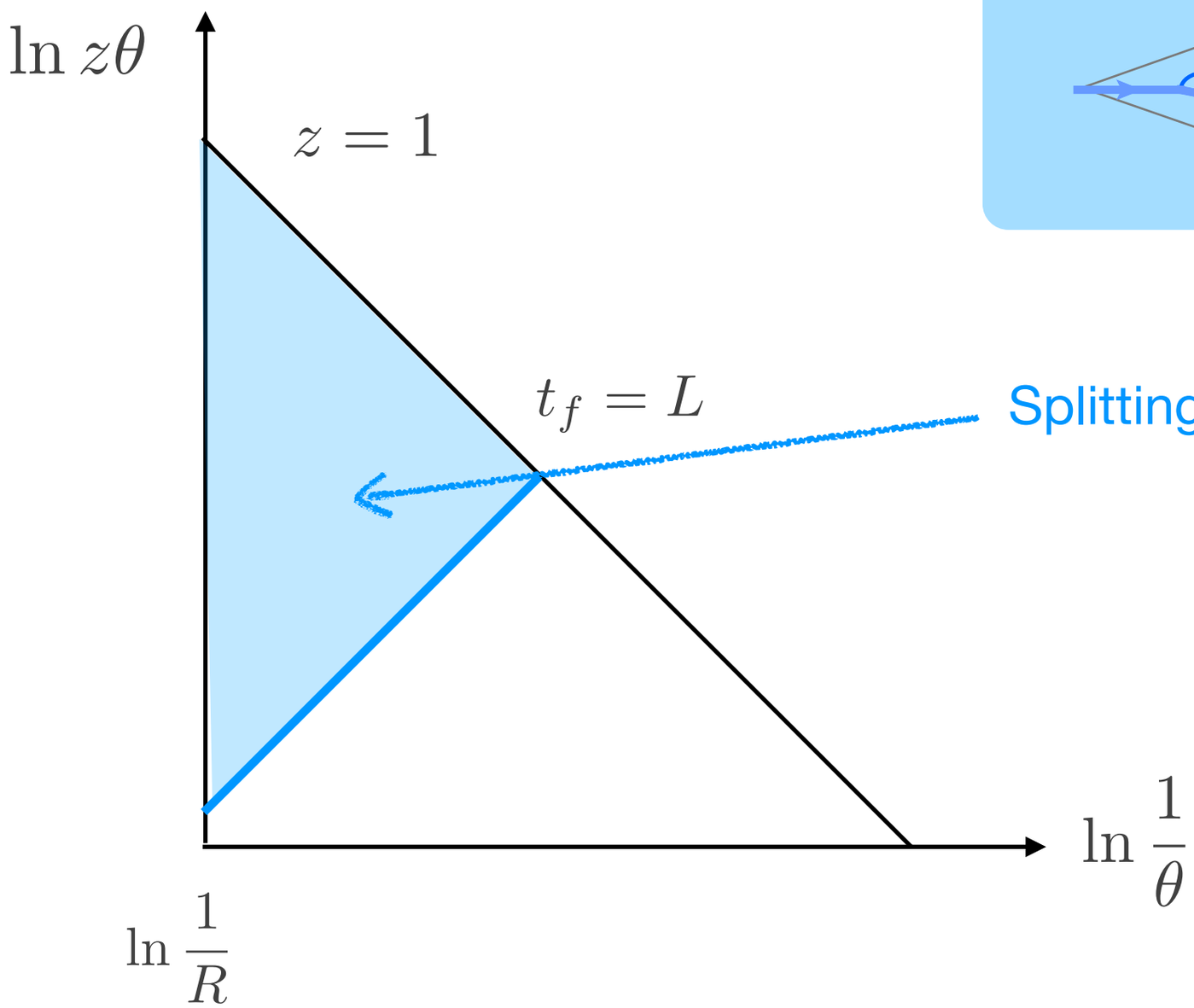
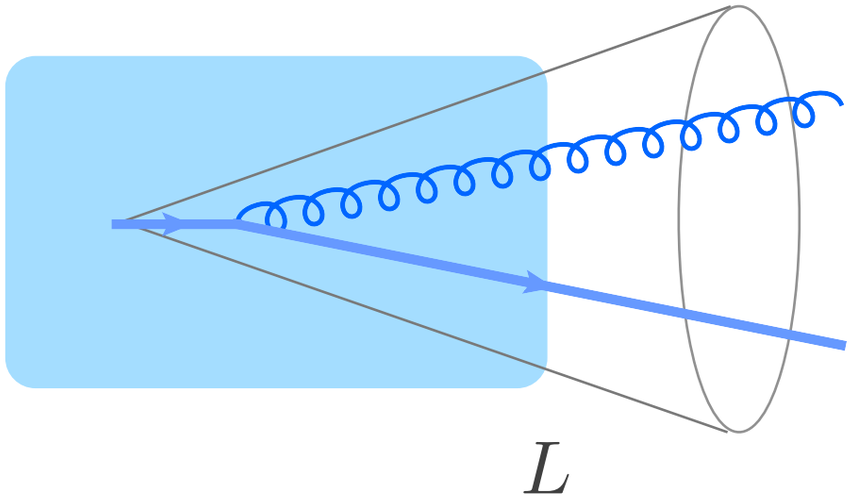
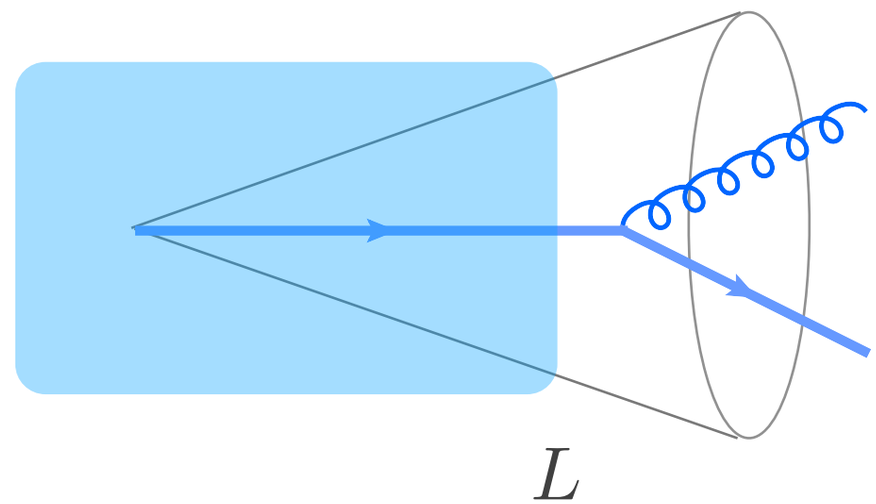


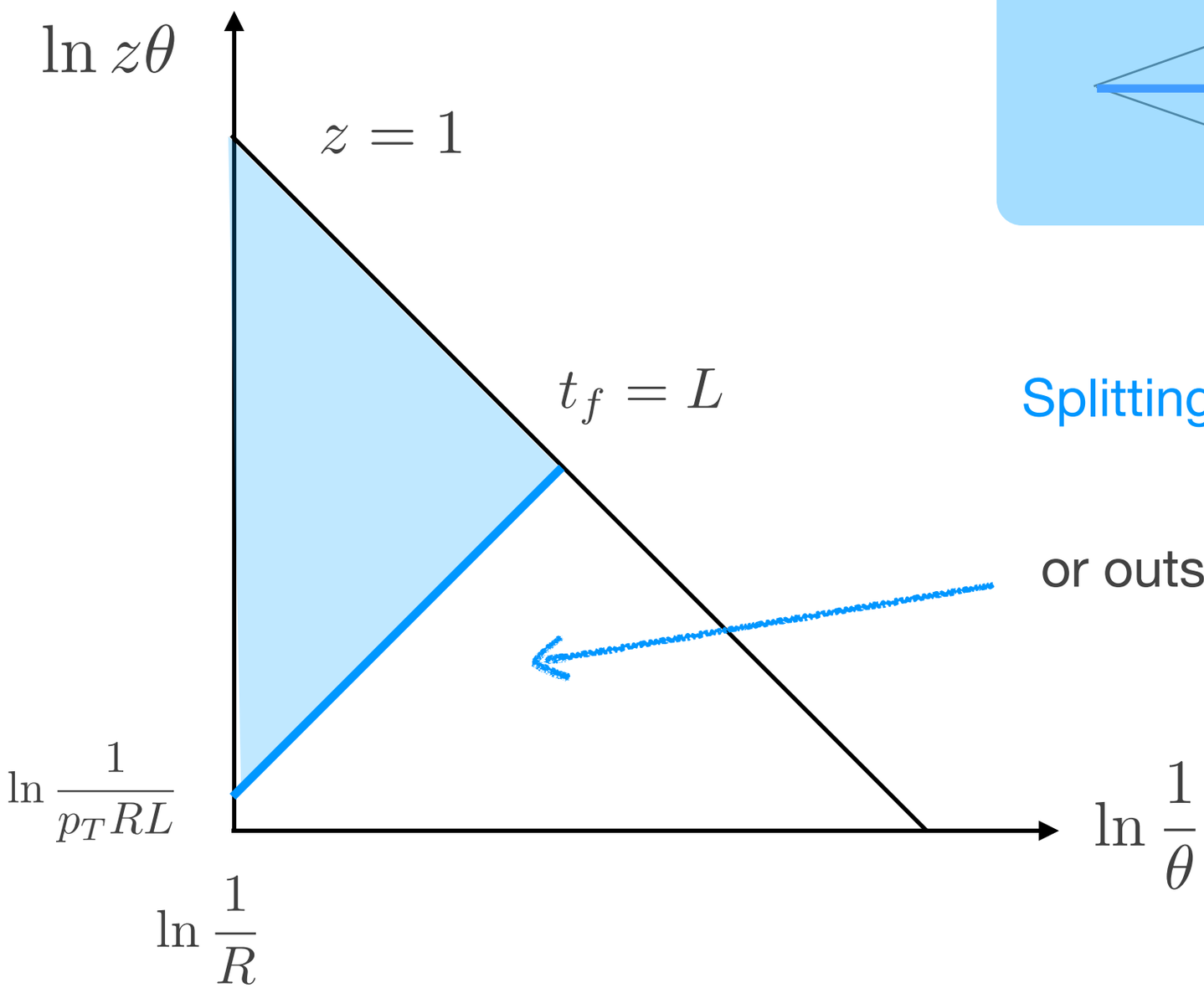


Splitting inside the medium: $t_f < L$

Probabilistic picture and MC prescription (in-medium)

formation time: $t_f = (\omega\theta^2)^{-1}$





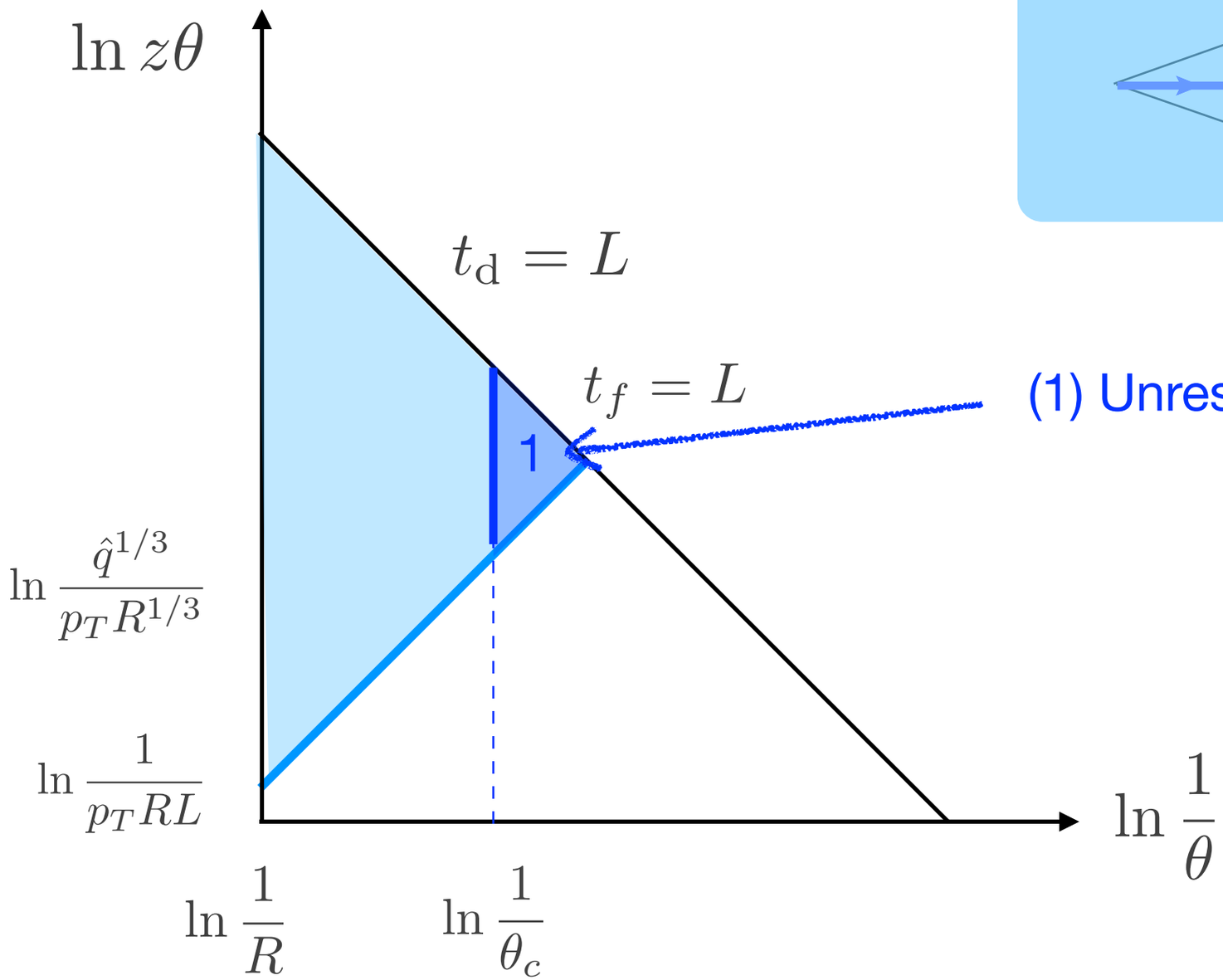
Splitting inside the medium: $t_f < L$

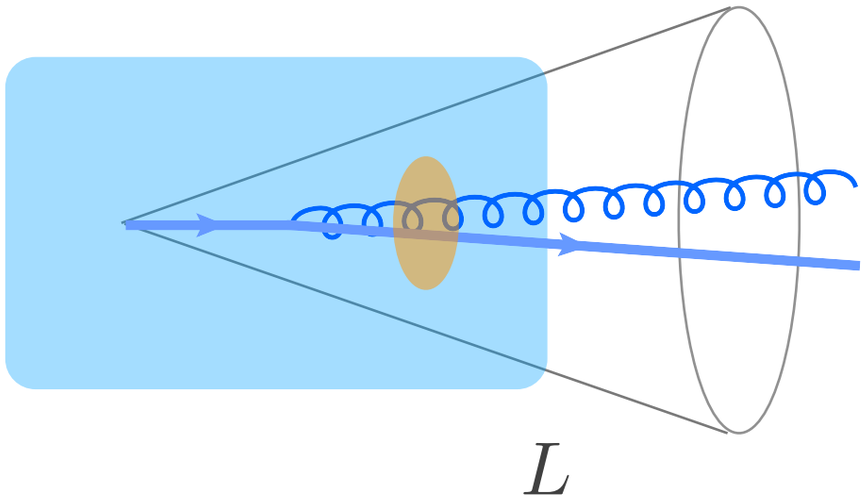
or outside: $t_f > L$

Vacuum cascade outside the medium

Probabilistic picture and MC prescription (in-medium)

formation time: $t_f = (\omega\theta^2)^{-1}$





(1) Unresolved in medium splitting

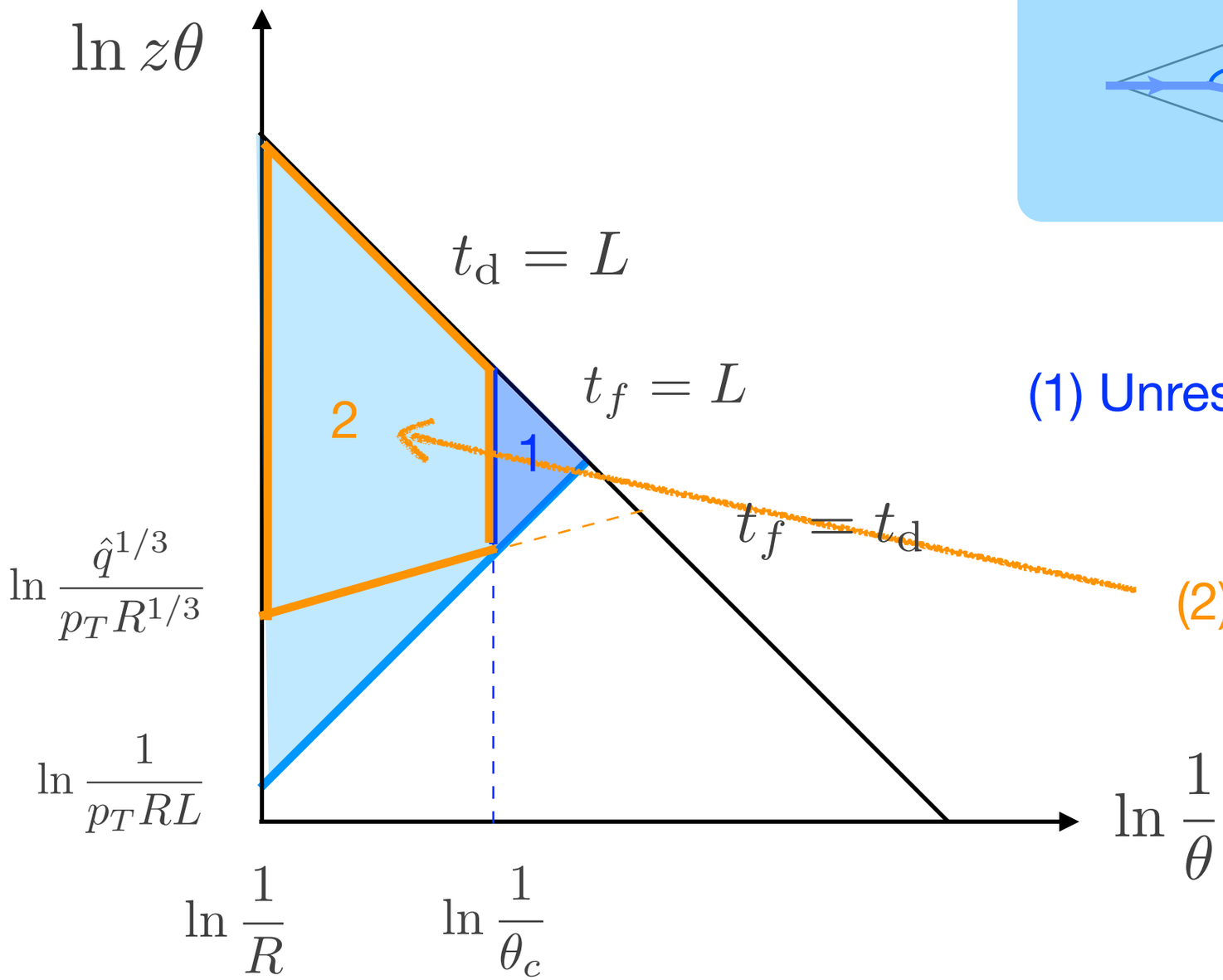
$$t_{\rm d} > L$$

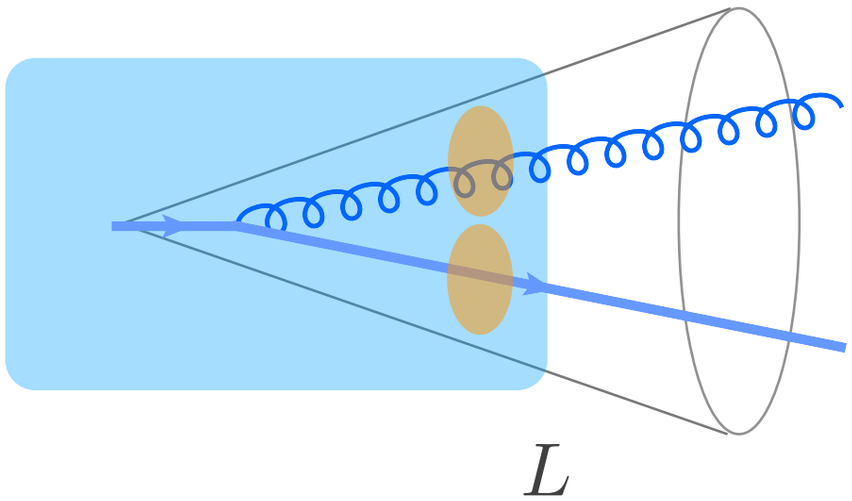
$$\theta < \theta_c \sim (\hat{q}L^3)^{-1/3}$$

Unmodified substructure, energy loss sensitive to total color charge (parent parton)

Probabilistic picture and MC prescription (in-medium)

formation time: $t_f = (\omega\theta^2)^{-1}$





(1) Unresolved in medium splitting

$t_{\rm d} > L$

(2) Resolved vacuum splitting inside the medium

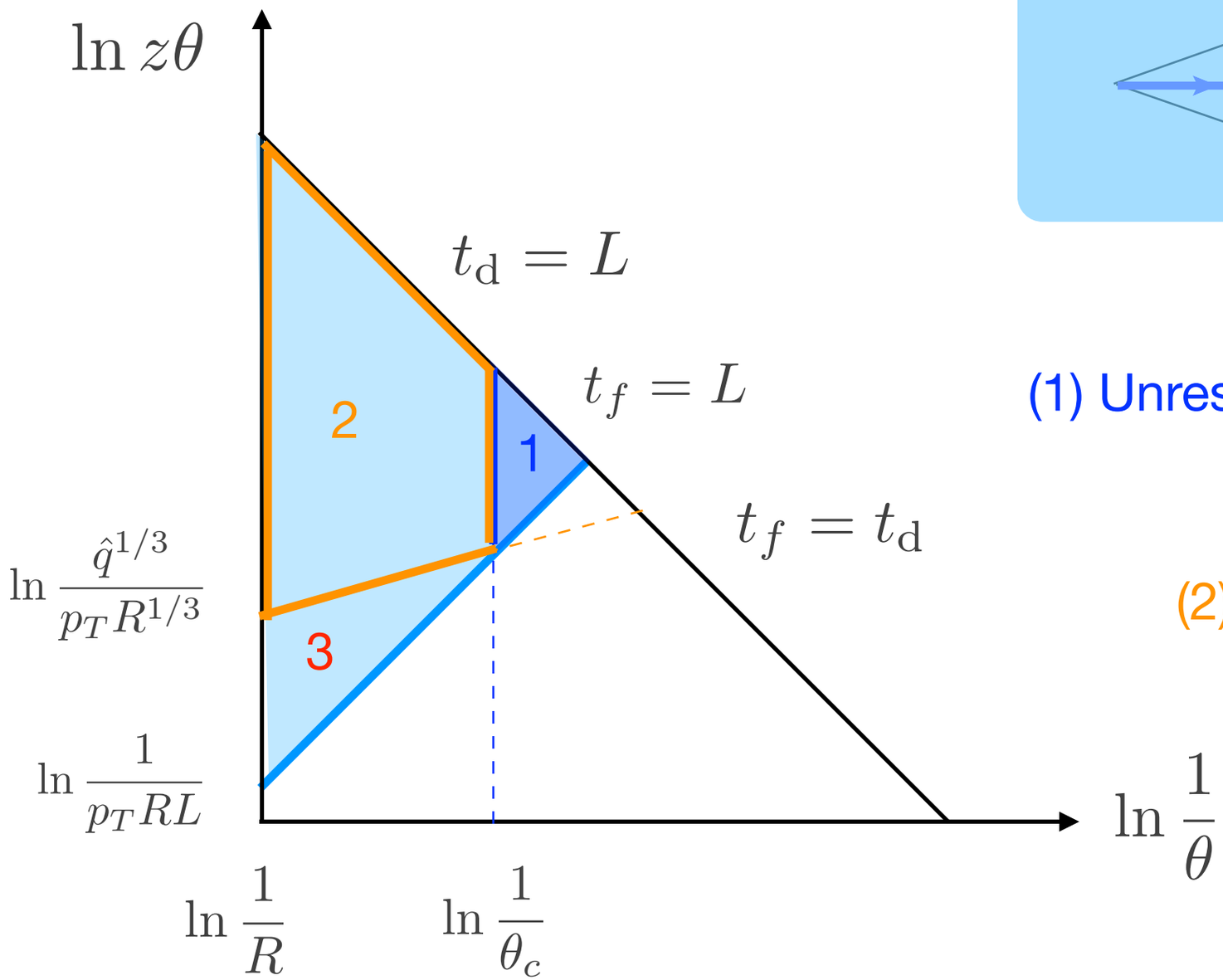
$t_f < t_{\rm d} < L$

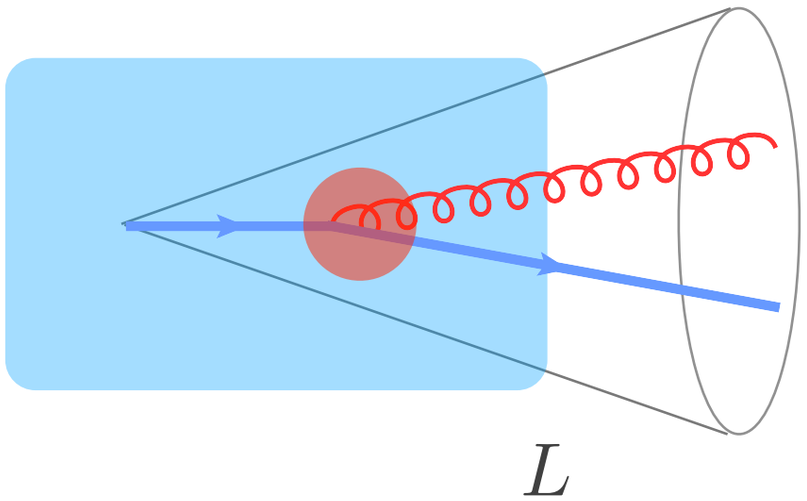
Resolved subjects lose energy independently

Probabilistic picture and MC prescription (in-medium)

[Andrews et al (2018)]

formation time: $t_f = (\omega\theta^2)^{-1}$





(1) Unresolved in medium splitting

$t_{\rm d} > L$

(2) Resolved vacuum splitting inside the medium

$t_f < t_{\rm d} < L$

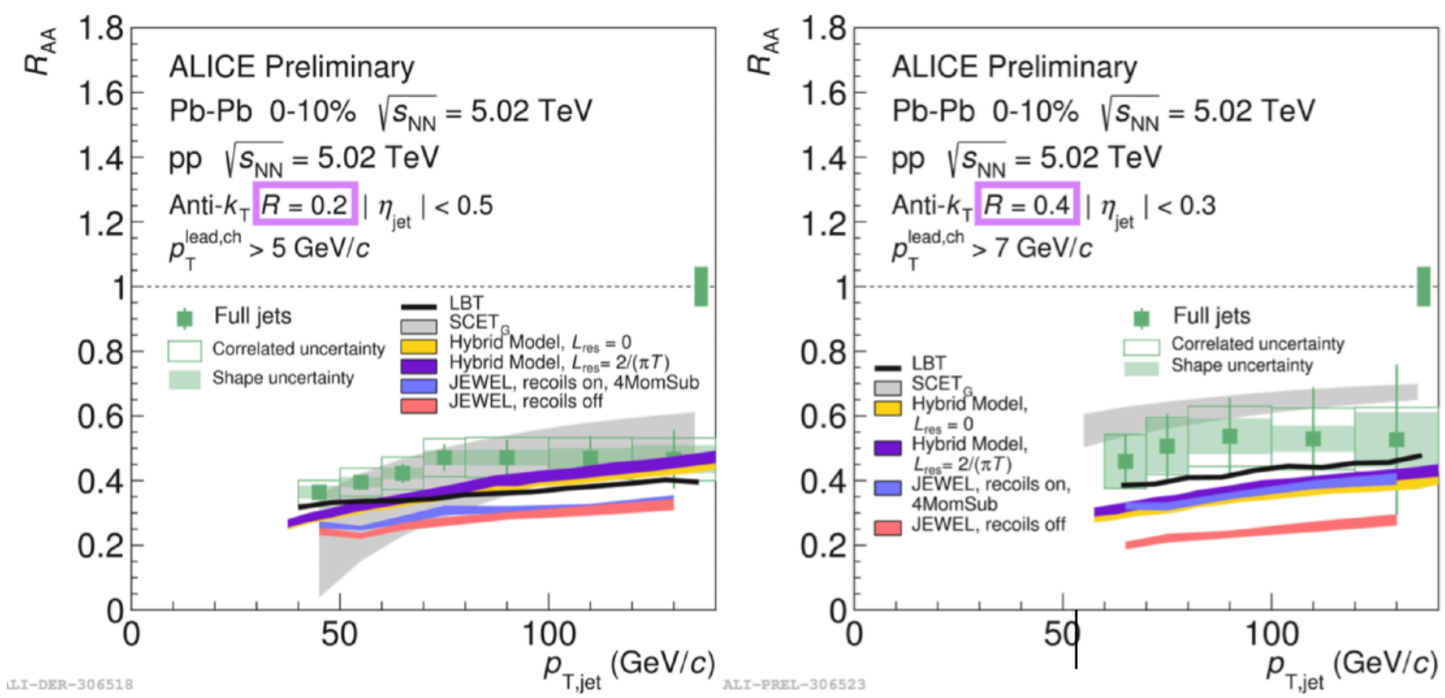
(3) Medium-induced radiation

$t_{\rm d} < t_f < L$

Monte Carlo Event Generators and data

- Several Monte Carlo event generators in the market: JEWEL, Q-Pythia, MARTINI, CoLBT, LBT, Hybrid, MATTER (some available in a common platform, JETSCAPE) → More or less successful in describing substructure observables…do not account for color coherence yet

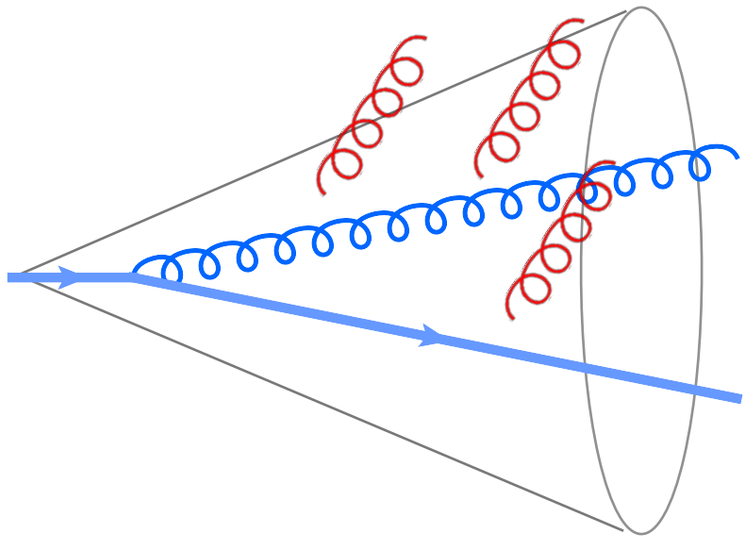
- Tension in the cone size dependence of R_{AA}. Hints of color coherence?



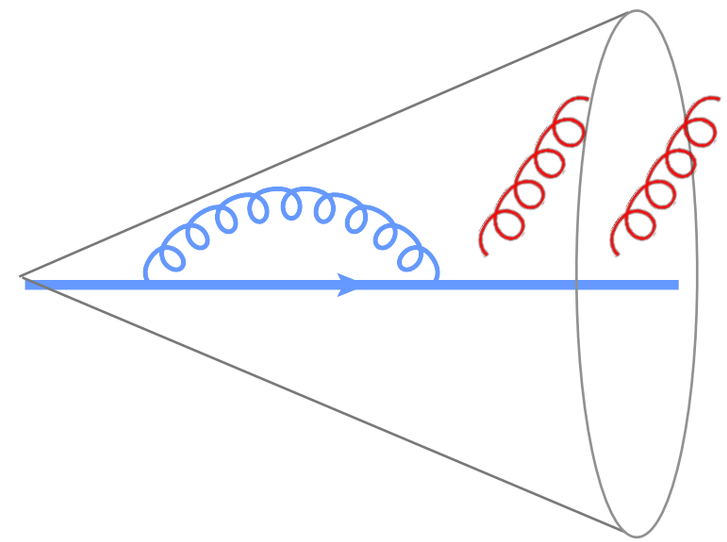
R=0.2 R=0.4

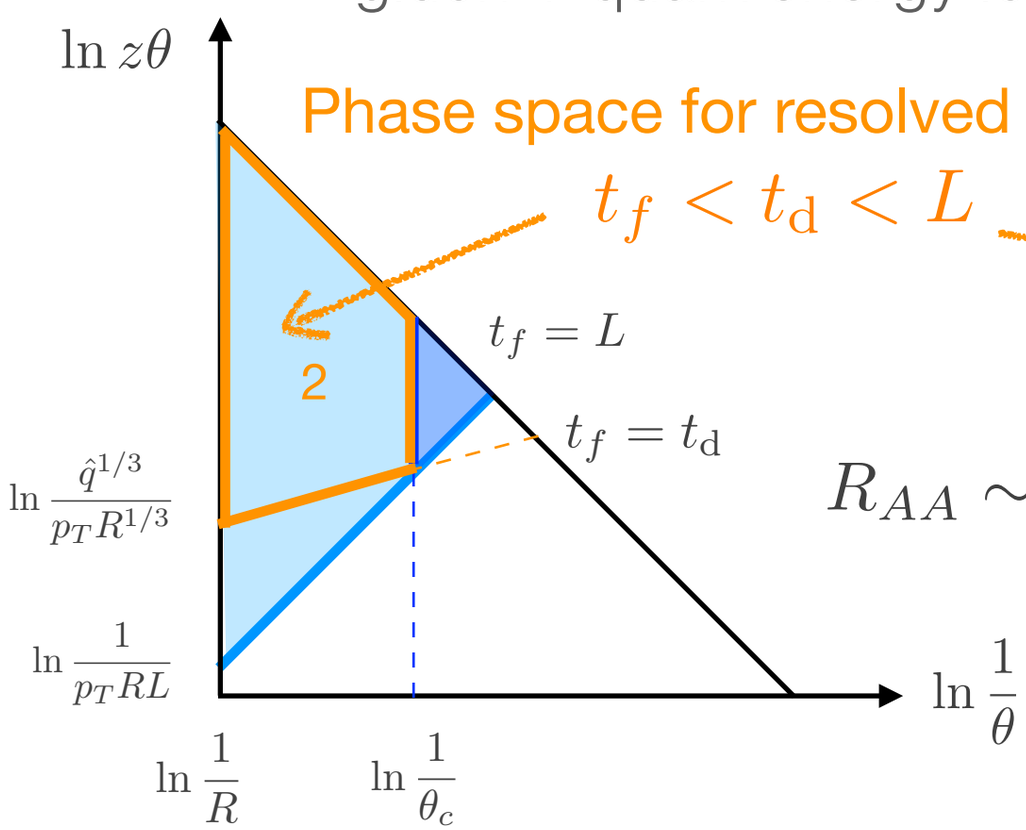
J. Mulligan (JetScape Workshop 2019)

Higher order corrections to the jet spectrum



gluon + quark energy loss $\gg$ quark energy loss





Lund Plane

Sudakov suppression of jets due to jet substructure fluctuations

$$R_{AA} \sim Q_{\rm tot}(p_T) \times \exp\left[-2\bar{\alpha}\, \ln \frac{R}{\theta_c} \left(\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right)\right]$$

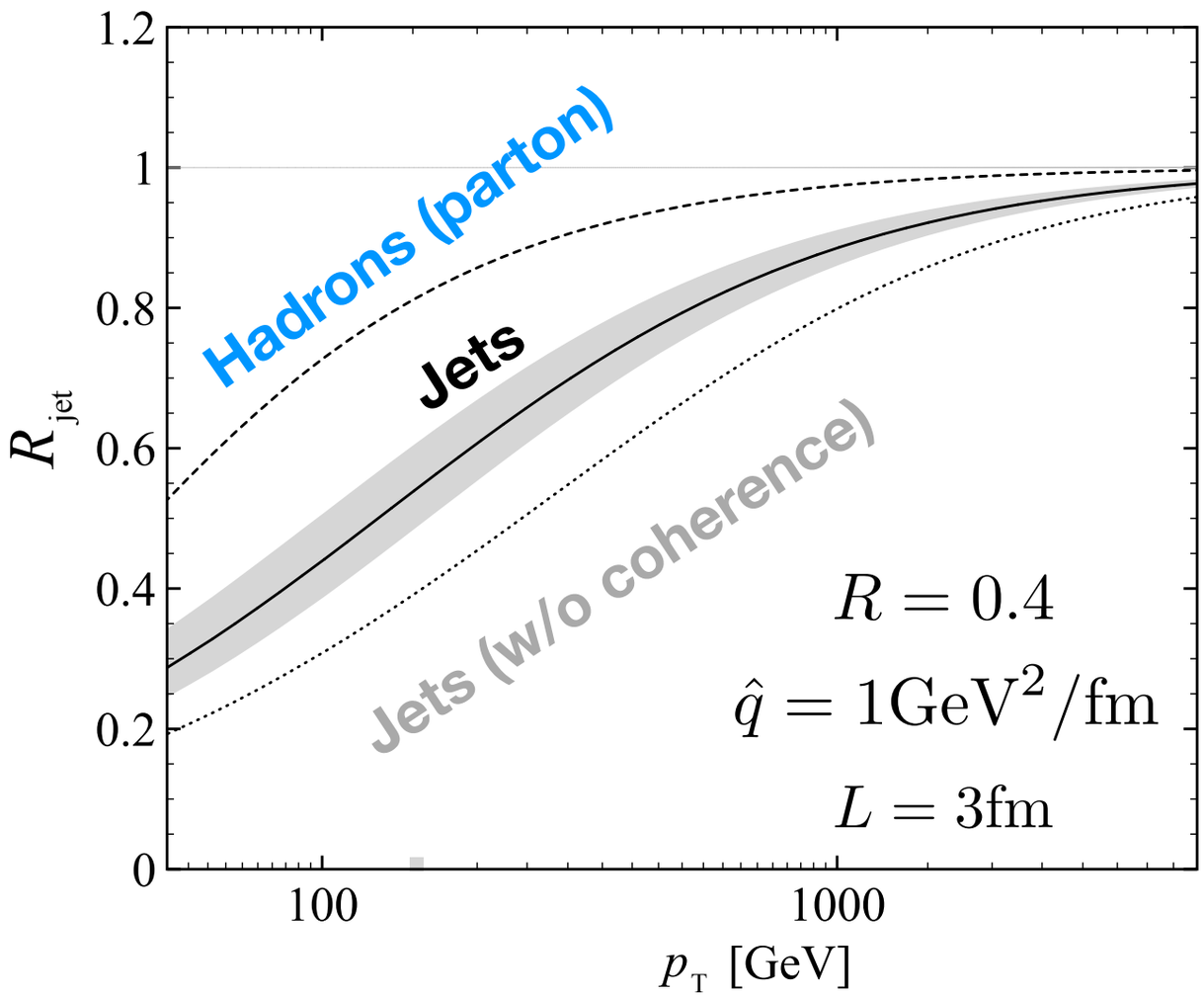
MT, Tywoniuk (2018)

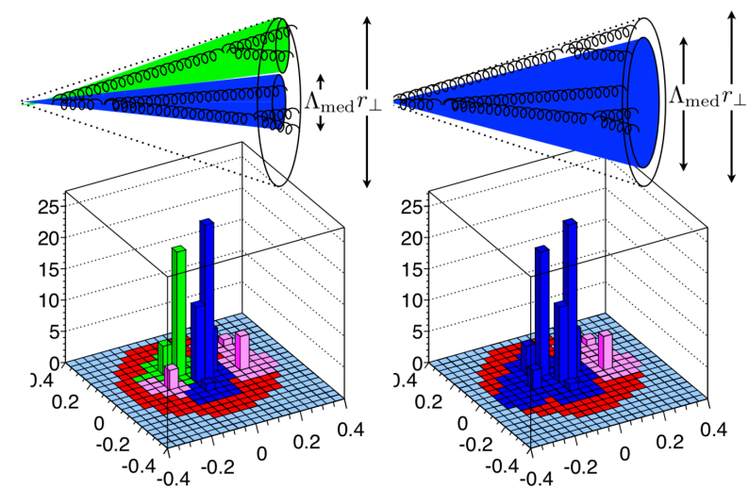
Note: θ_c sets the boundary between color coherence and decoherence

Higher order corrections to the jet spectrum

MT, Tywoniuk (2018)

- Sensitivity of the nuclear modification factor to color coherence





$$\theta_c \sim (\hat{q}L^3)^{1/3} \sim 0.1$$

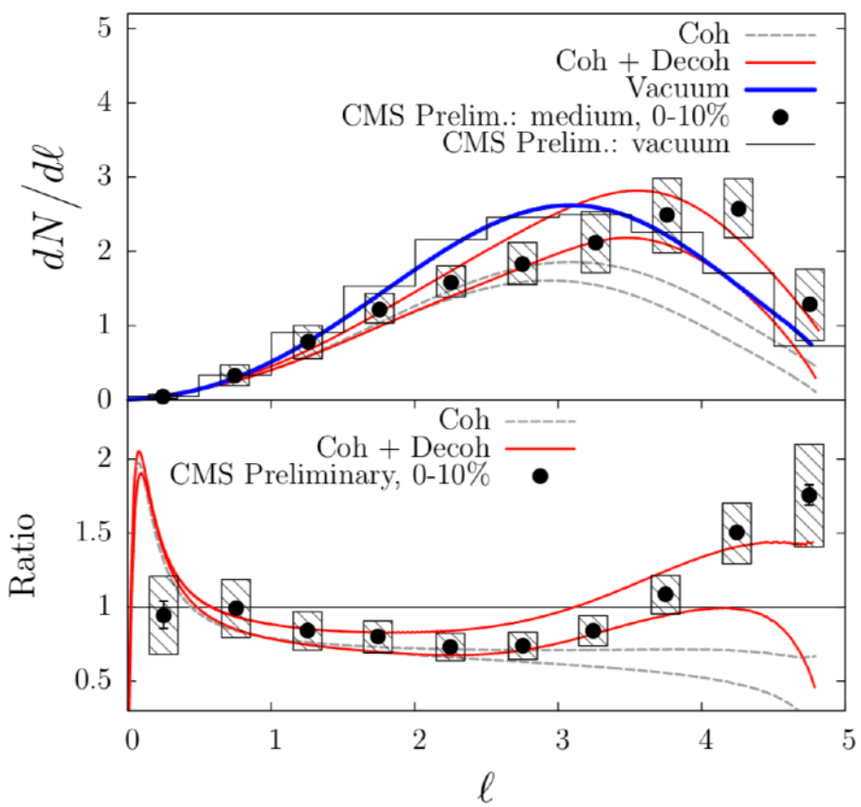
w/o color coherence: MC event generators: Hybrid Model, JEWEL and MARTINI

- **Caveat:** theoretical idealization

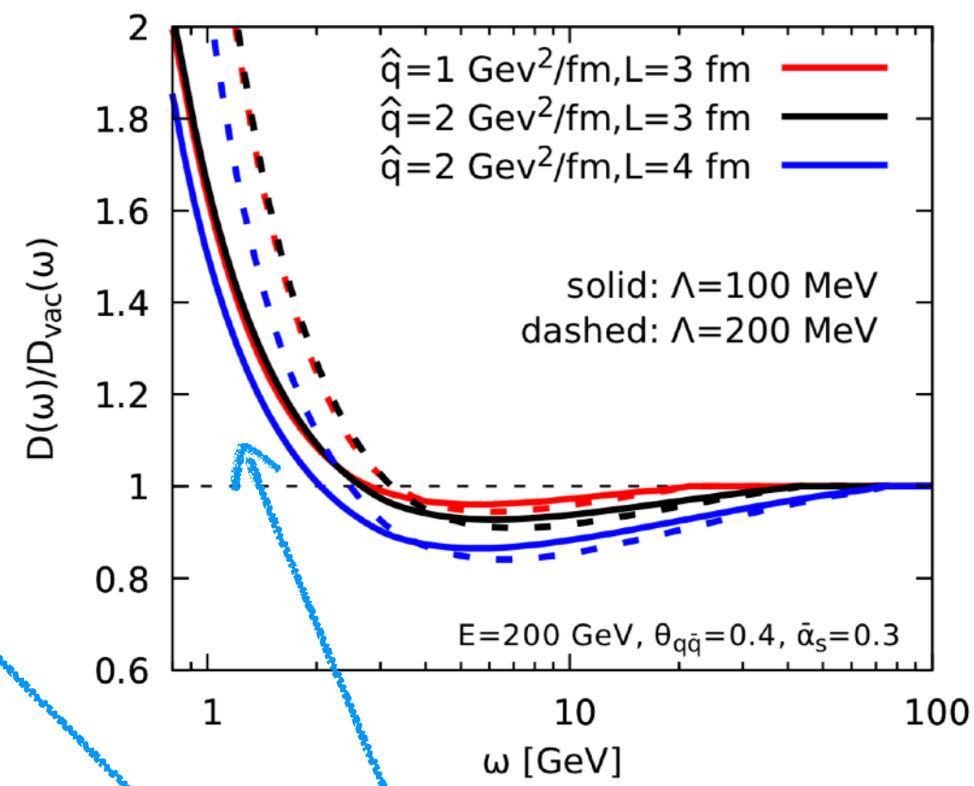
Softening of Fragmentation Function

- A softening of the Fragmentation function observed in the data

MT, Tywoniuk (2014)



Caucal, Iancu, Mueller Soyez (2018)



- Possible mechanism: in-cone decoherent vacuum radiation
- Other explanation: medium response

Summary and outlook

- QCD jet evolution in the presence of a QGP is multifaceted: in addition to the vacuum collinear cascade a medium induced shower responsible for jet quenching forms at large angles

- Jets in HIC are probes of the QGP and constitute a unique tool to study QCD far-from-equilibrium and thermalization

- QCD coherence phenomena such as the LPM effect and color (de)coherence play an important role in jet quenching and may be more directly investigated with substructure observables

- A plethora of MC event generators encoding different physics. A common picture of the perturbative component of jet evolution in a QGP remains to be achieved → Need analytic guidance to reduce dependence on modeling