UNIVERSITY OF BERGEN

QUENCHING EFFECTS FOR HIGH-P_T JET OBSERVABLES

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… in preparation (w/ Y. Mehtar-Tani)

2019 Santa Fe Jets and Heavy Flavor Workshop
28-31 Jan 2019
UCLA, Los Angeles

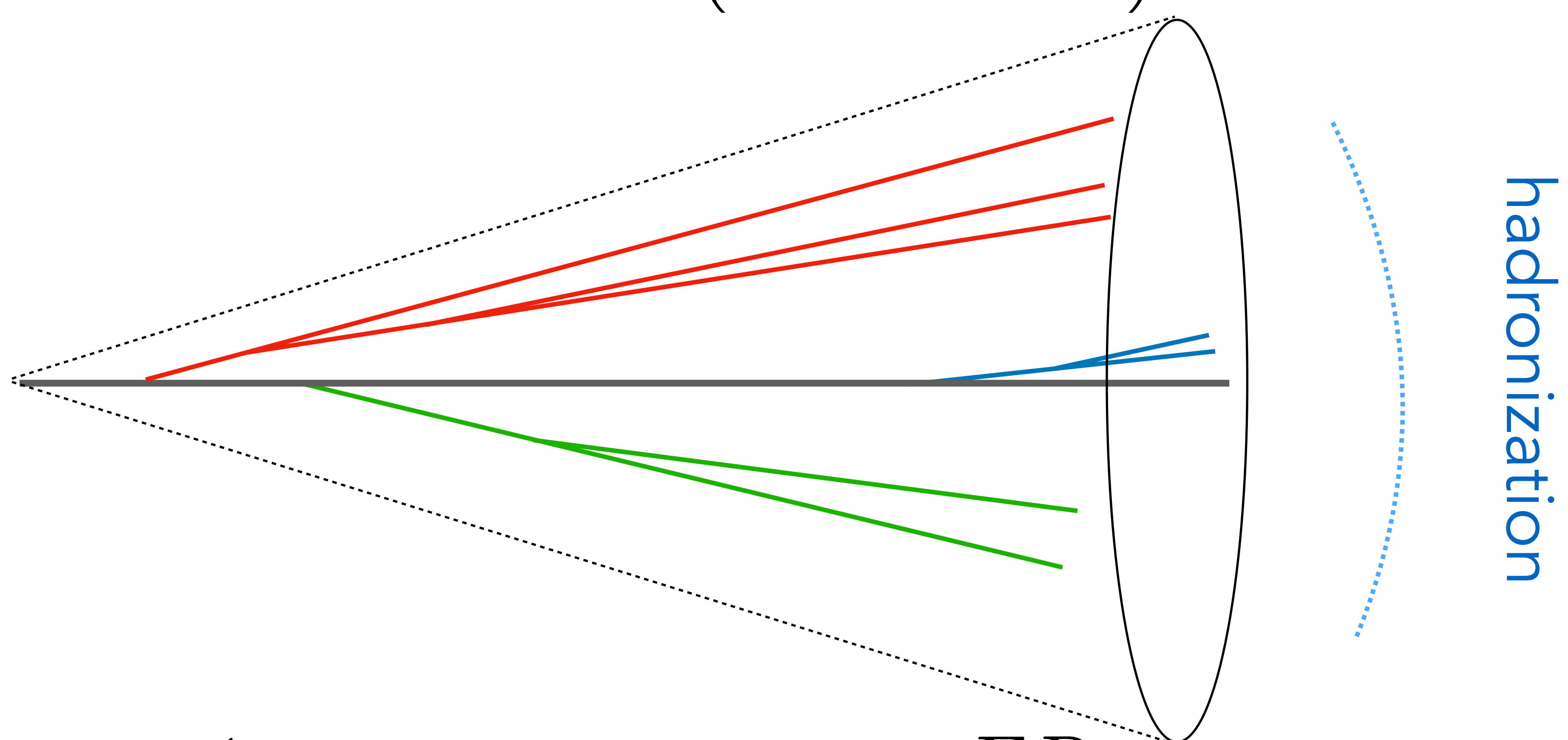
INTRODUCTION

- models of jet evolution in medium typically adopt a multi-stage framework (factorization):
  - ME/shower (in) → medium modifications → shower (out)
- modeling of jets does not only depend on the details of stage 2, but also how we separate the stages
- our motivation: theoretical guidance at high-pT
  - **what drives quenching & substructure modifications?**

QCD JETS

Dokshitzer, Khoze, Mueller, Troyan "Basics of Perturbative QCD" (1991)

- soft & collinear divergences: resummation
- color coherence: angular ordering
- strong separation of time scales (semi-classical)



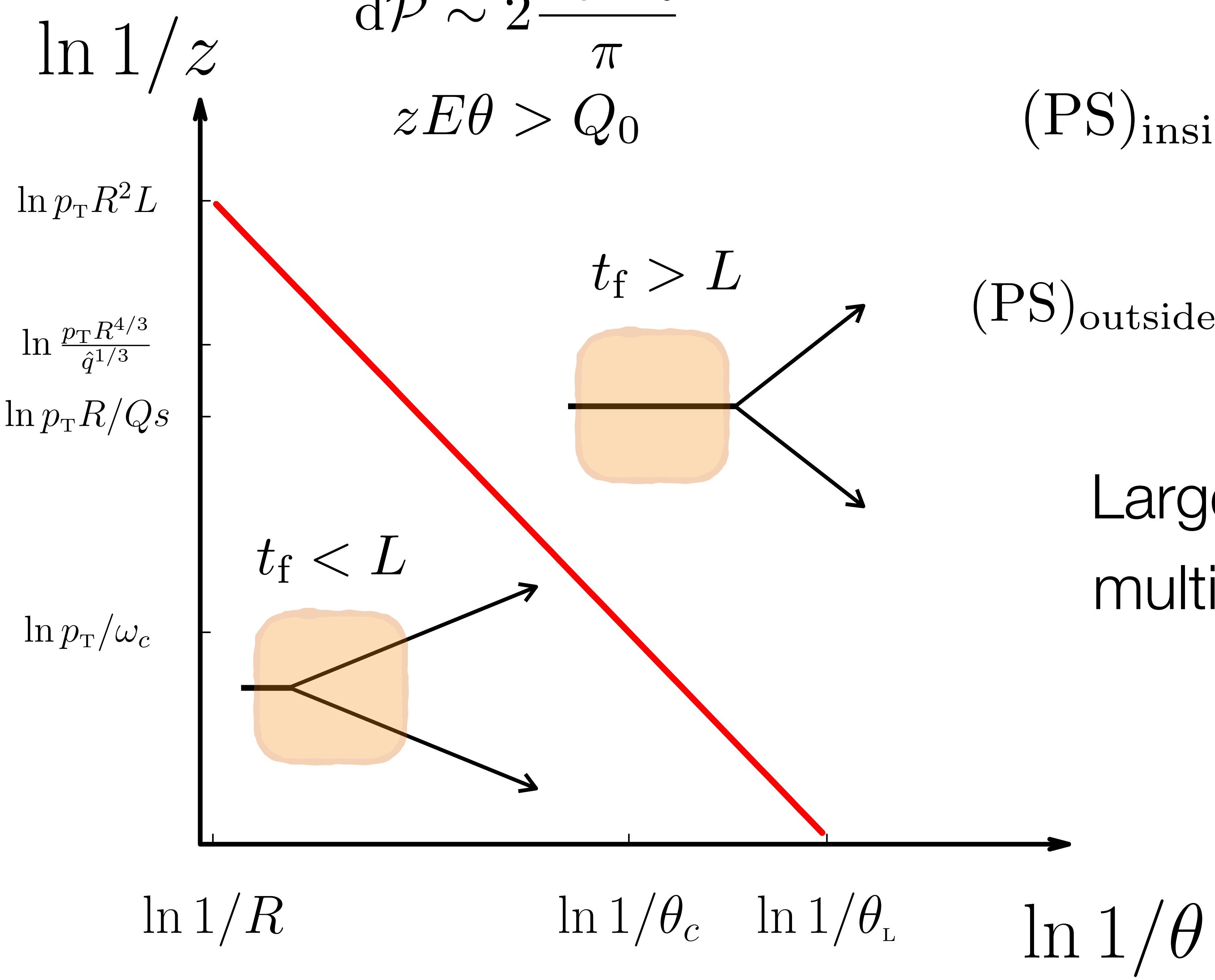
$$\frac{1}{ER^2} \ll t_\mathrm{f} \ll \frac{ER}{Q_0^2}$$

MEDIUM SCALES: LENGTH

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)

$$\mathrm{d}\mathcal{P} \sim 2\frac{\alpha_s C_R}{\pi}$$

$$zE\theta > Q_0$$



$$(\mathrm{PS})_{\text{inside}} = \frac{\bar{\alpha}}{4} \ln^2\left(p_{\mathrm{T}} R^2 L\right)$$

$$(\mathrm{PS})_{\text{outside}} = \frac{\bar{\alpha}}{2} \ln^2\left(\frac{p_{\mathrm{T}} R}{Q_0}\right) - (\mathrm{PS})_{\text{inside}}$$

Large $\sim\mathcal{O}(1)$ probability of multiple splitting inside the medium.

Andrews et al. arXiv:1808.03689
Dreyer, Salam, Soyez 1807.04758
Chien, Elayavalli arXiv:1803.03589
Cunqueiro, Płoskoń arXiv:1812.00102

Computing observables

quenching weight: probability distribution of losing energy

$$\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y} = \int_0^\infty \mathrm{d}\epsilon\, \mathcal{P}(\epsilon) \frac{\mathrm{d}\sigma_{\mathrm{vac}}(p_{\mathrm{T}}+\epsilon)}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}$$

quenching factor = nuclear modification factor

$$R_{\mathrm{jet}} = \left(\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}\right) \Big/ \left(\frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y}\right)$$

For $\epsilon/p_{\mathrm{T}} \ll 1$ and large n:

$$\frac{1}{(p_{\mathrm{T}}+\epsilon)^n} \approx \frac{1}{p_{\mathrm{T}}^n}\mathrm{e}^{-\epsilon n/p_{\mathrm{T}}}$$

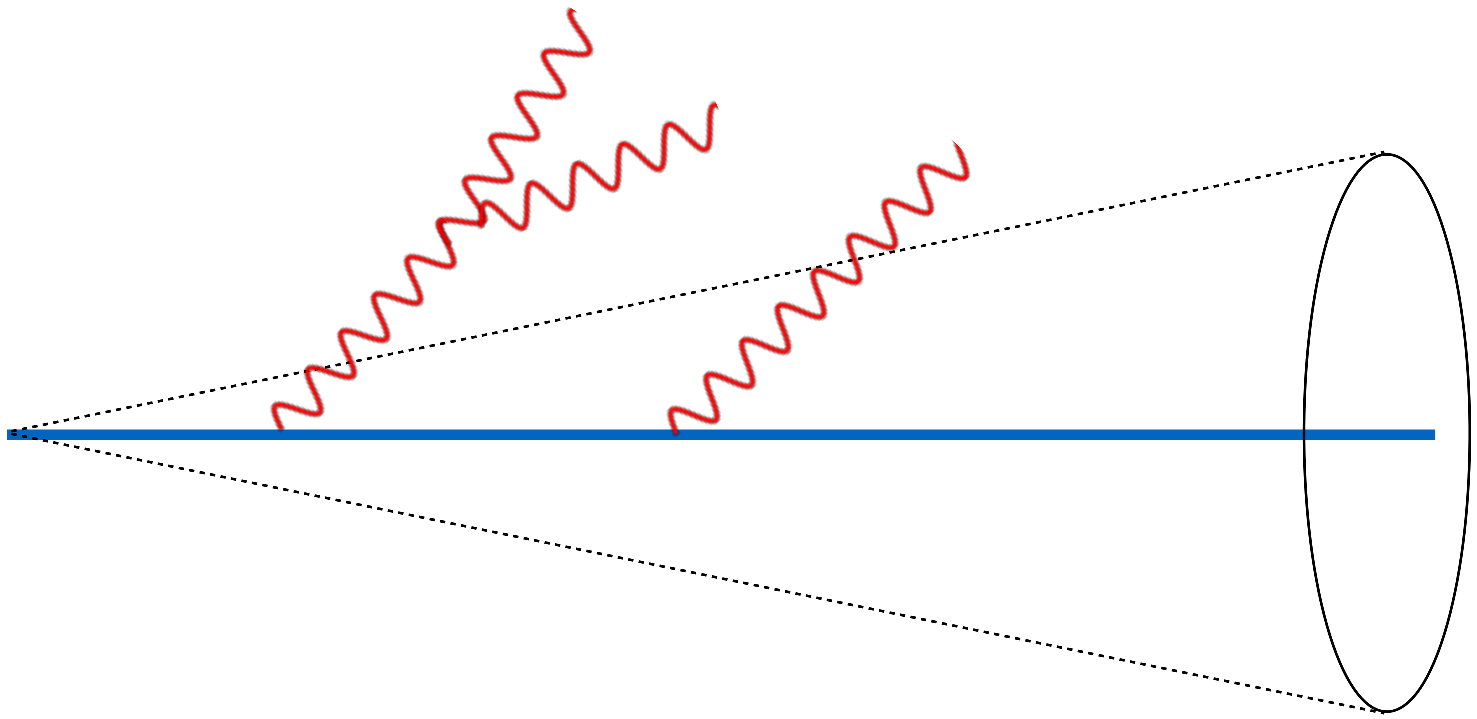
$$\mathcal{P}(\epsilon) = \int_C \frac{\mathrm{d}\nu}{2\pi i}\,\mathrm{e}^{\nu\epsilon}\tilde{\mathcal{P}}(\nu)$$

$$R_{\mathrm{jet}} \sim \tilde{\mathcal{P}}\big(n/p_{\mathrm{T}}\big) \equiv \mathcal{Q}(p_{\mathrm{T}})$$

quenching factor is Laplace transform of energy loss probability

SINGLE-PARTON QUENCHING

Baier, Dokshitzer, Mueller, Schiff JHEP 0109 (2001) 033



resummation of multiple, soft radiation at large angles

$$\mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}} \mathrm{e}^{-\frac{\pi \omega_s}{\epsilon}} \qquad \omega_s \sim \alpha_s^2 C_R^2 \hat{q} L^2$$

Sensitivity to the soft scale where multiplicity is large,
$N(\omega > \omega_s) > 1$

QUENCHING OF PARTON

Baier, Dokshitzer, Mueller, Schiff JHEP 0109 (2001) 033

$$\mathcal{Q}(p_{\mathrm{T}}) = \mathrm{e}^{-2\bar{\alpha}L\sqrt{n\pi\hat{q}/p_{\mathrm{T}}}} \qquad \bar{\alpha} = \frac{\alpha_s C_R}{\pi}$$

$$\mathcal{Q}_g(p_{\mathrm{T}}) = \big(\mathcal{Q}_q(p_{\mathrm{T}})\big)^{N_c/C_F}$$

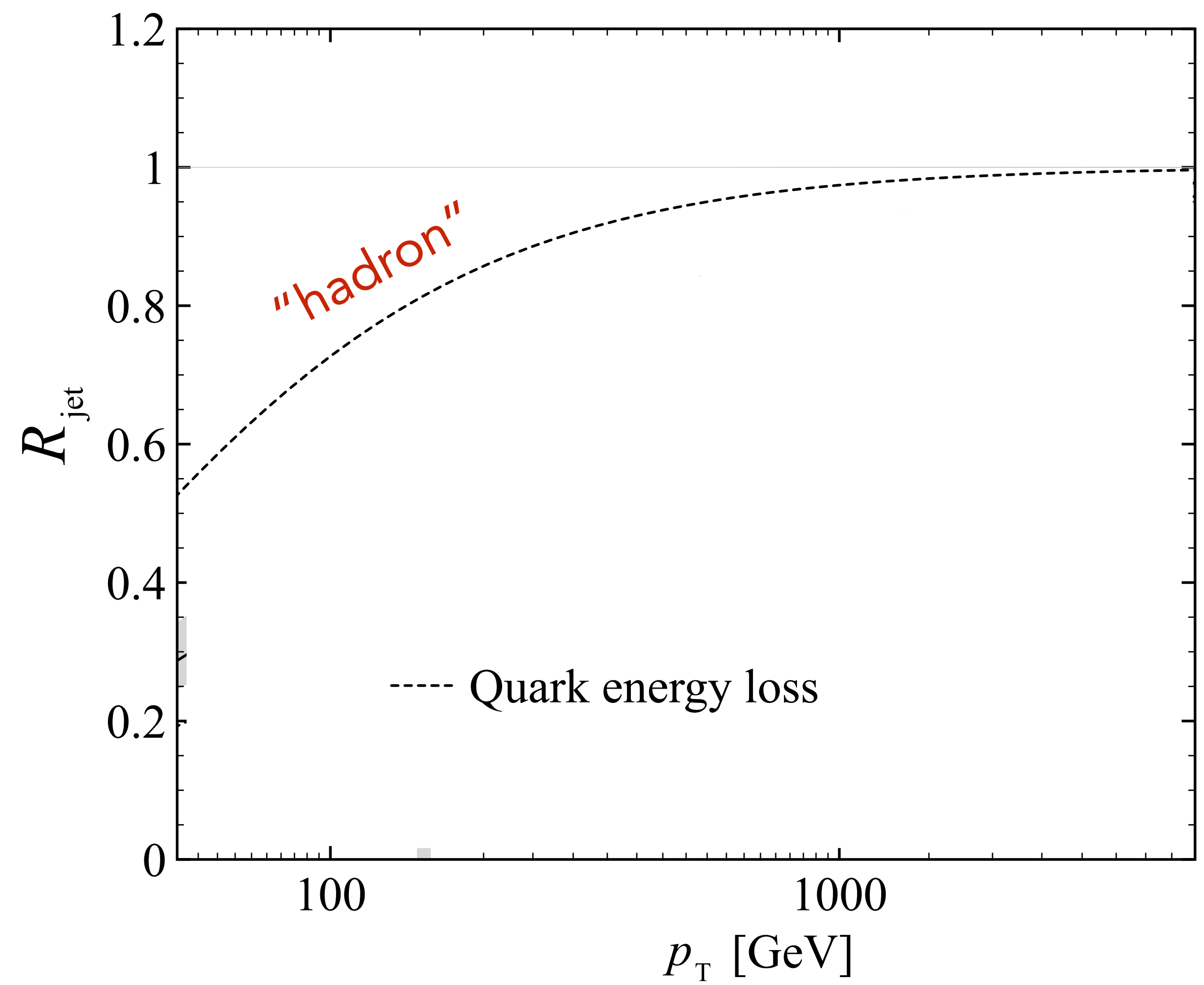
- form factor suppression related to multiplicity of virtual gluons

$$\mathcal{Q}(p_{\mathrm{T}}) \sim \mathrm{e}^{-N(\omega > p_{\mathrm{T}}/n)}$$

- strong quenching for

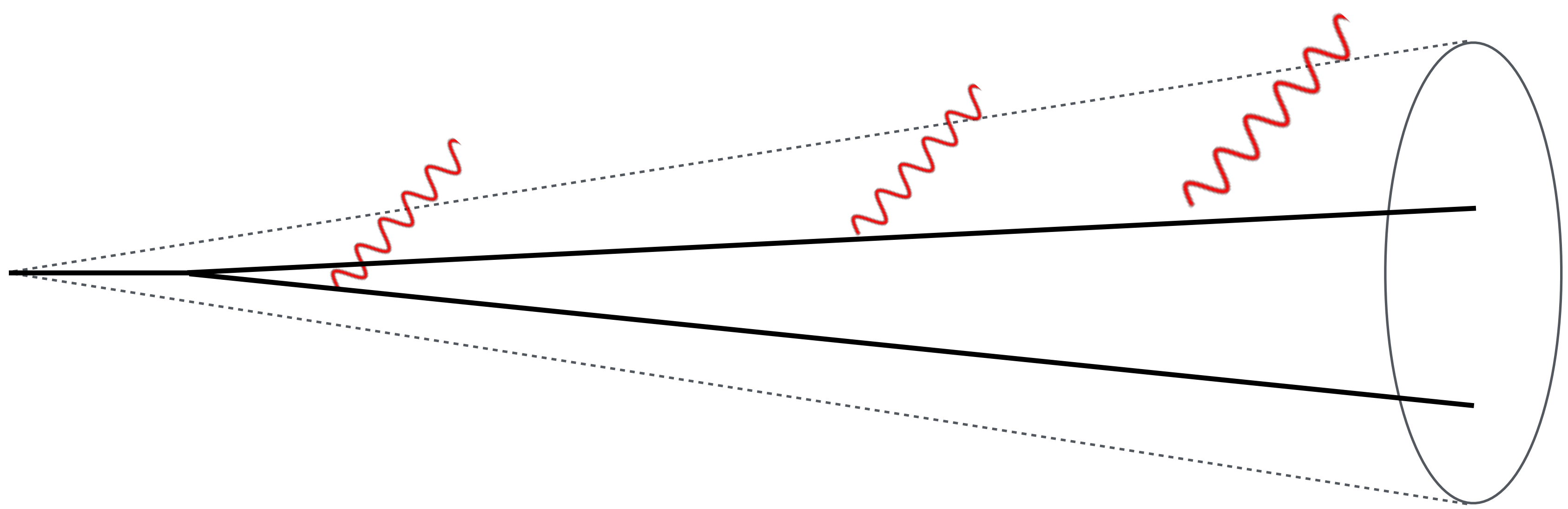
$$p_{\mathrm{T}} \ll n\bar{\alpha}^2\hat{q}L^2$$

- quark ≈ meson (rescaling)



NEIGHBORING JET ENERGY LOSS

Y. Mehtar-Tani, KT arXiv:1706.06047 [hep-ph]



$$\mathcal{P}_2(\nu) = \mathcal{P}(\nu) \times \mathcal{P}_{\rm sing}(\nu)$$

total color charge

contributions from interferences

Mehtar-Tani, Salgado, KT PLB (2012), JHEP (20132; Casalderrey, Iancu JHEP (2011)

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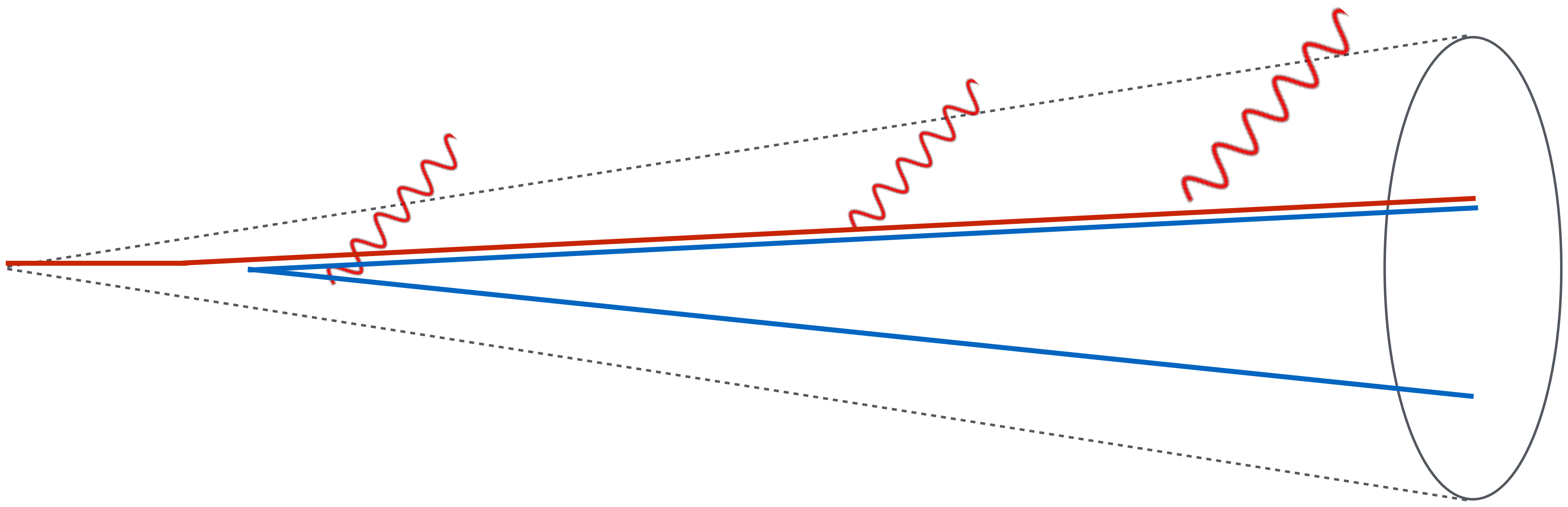

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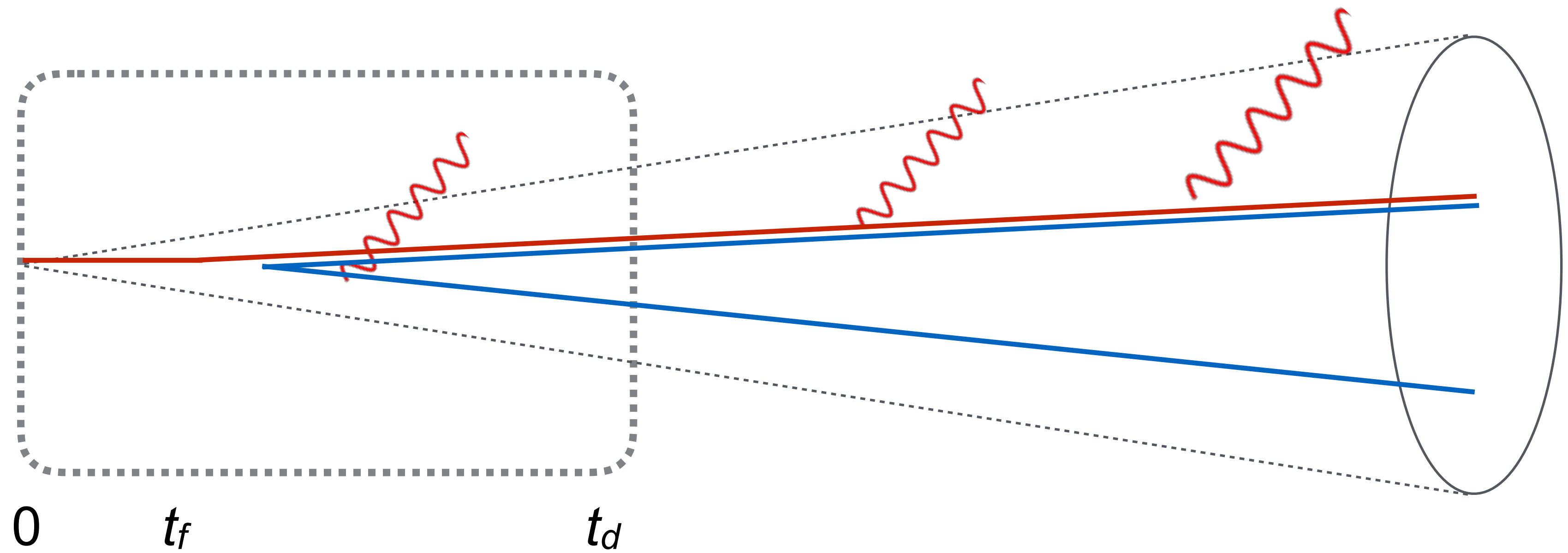


$$t_{\rm d} \sim (\hat{q}\theta_{12})^{-1/3}$$

$$\theta_c \sim \sqrt{\frac{1}{\hat{q}L^3}}$$

$$\mathcal{P}_2(\nu) = \mathcal{P}(\nu) \times \mathcal{P}_{\rm sing}(\nu)$$

total color charge

contributions from interferences

$$\mathcal{S}_2(t) = \exp\left[-\frac{1}{4}\int_0^t {\rm d}s\, \hat{q}(\boldsymbol{x}_{12},t)\boldsymbol{x}_{12}^2(s)\right]$$

decoherence parameter

color randomization of a $q\bar{q}$ pair

Mehtar-Tani, Salgado, KT PLB (2012), JHEP (20132; Casalderrey, Iancu JHEP (2011)

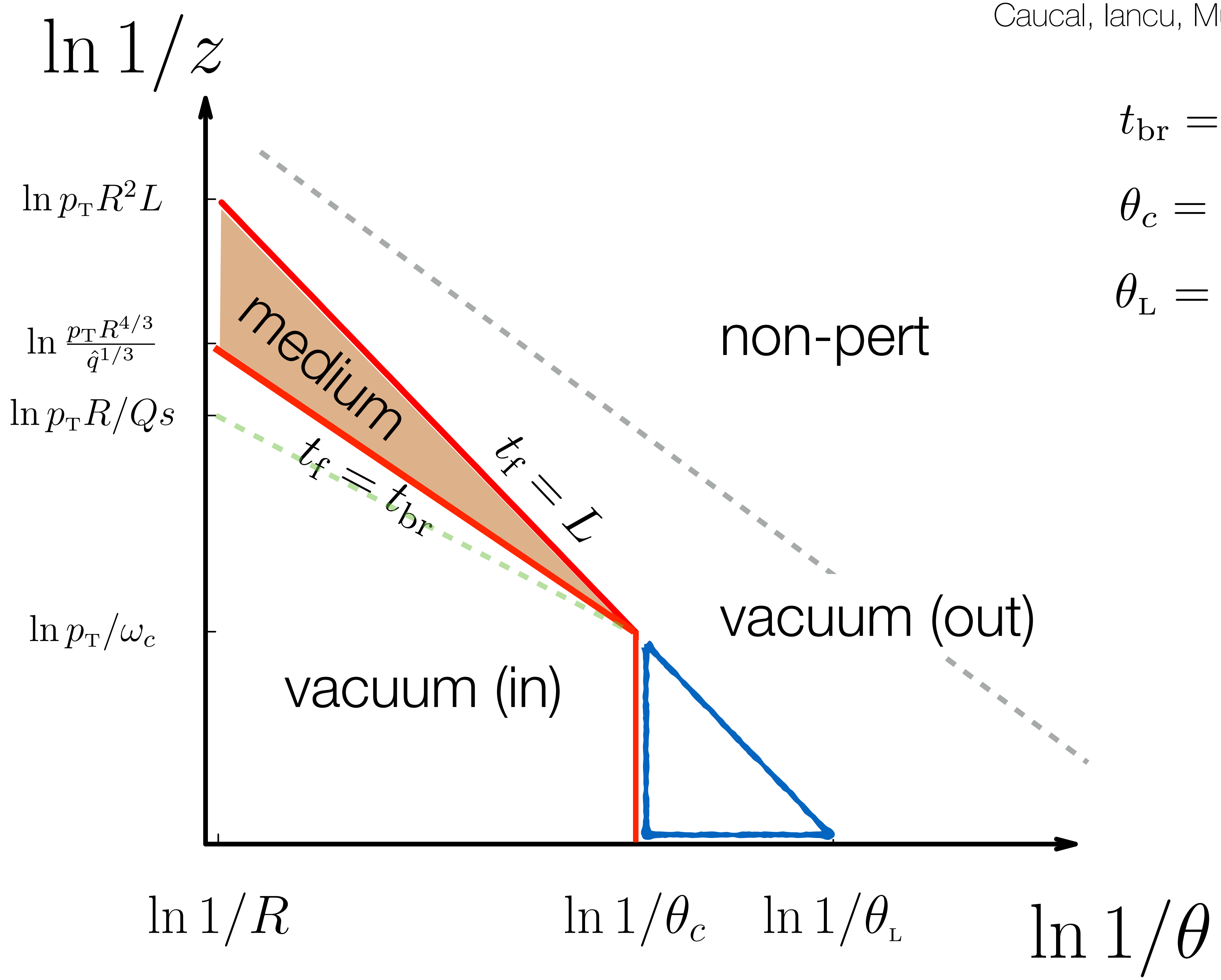
LUND PLANE IN MEDIUM

Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]
Andrews et al. arXiv:1808.03689
Caucal, Iancu, Mueller, Sozey PRL (2018)

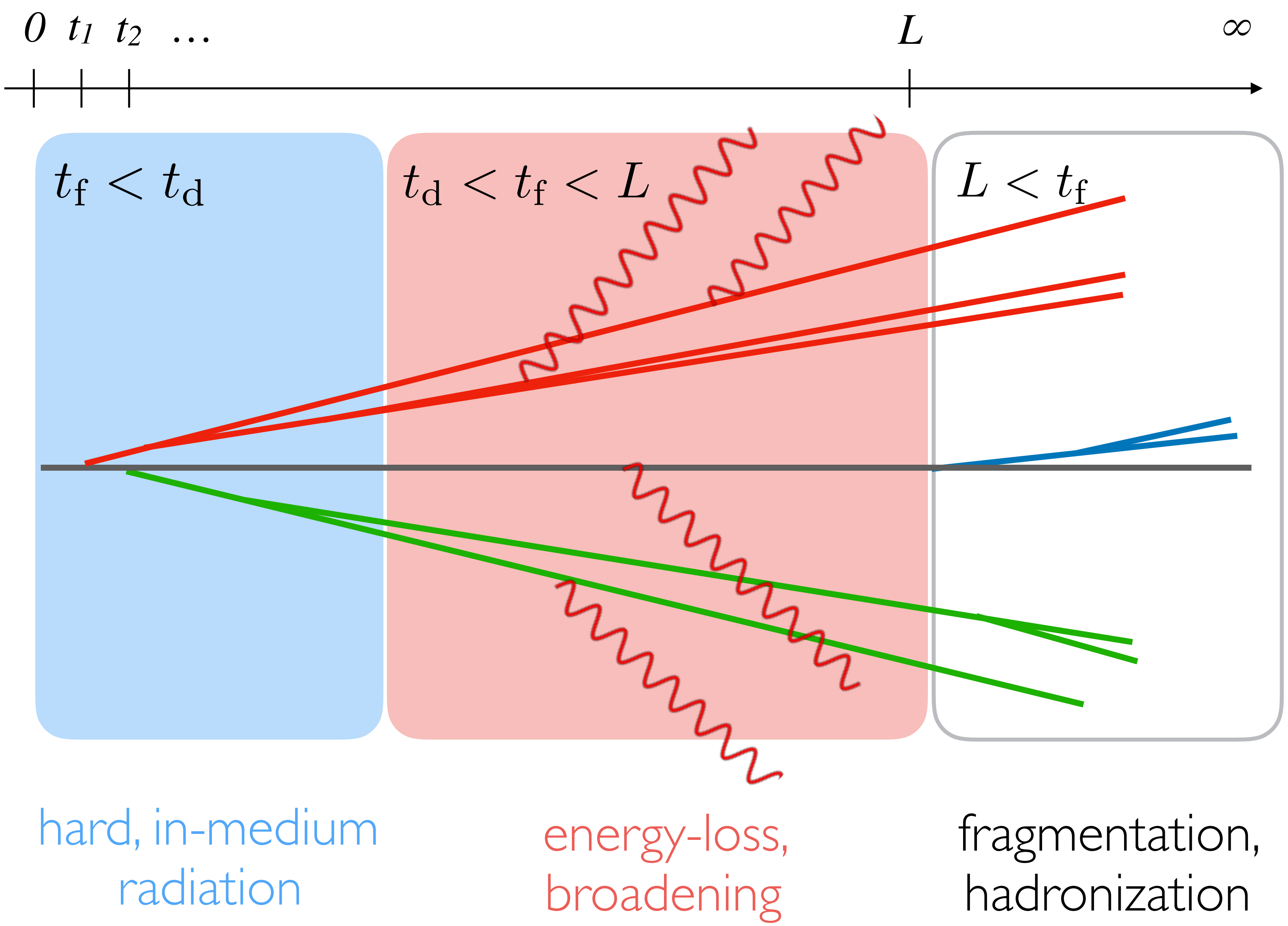
$$t_{\rm br} = (\hat{q}\theta^2)^{-1/3}$$

$$\theta_c = (\hat{q}L^3)^{-1/2}$$

$$\theta_{\rm L} = (p_{\rm T}L)^{-1/2}$$



EMERGING PICTURE



Regimes: *"logarithmic" time* | *"linear" time* | *"logarithmic", non-perturbative*

Generating functional method

Konishi, Ukawa, Veneziano Nucl. Phys. B1567 (1979); Bassetto, Ciafaloni, Marchesini Phys. Rept. 100 (1983)
Dokshitzer, Khoze, Mueller, Troyan "Basics of Perturbative QCD" (1991)

Generating function: $$G(u) = \sum_n P_n u^n$$

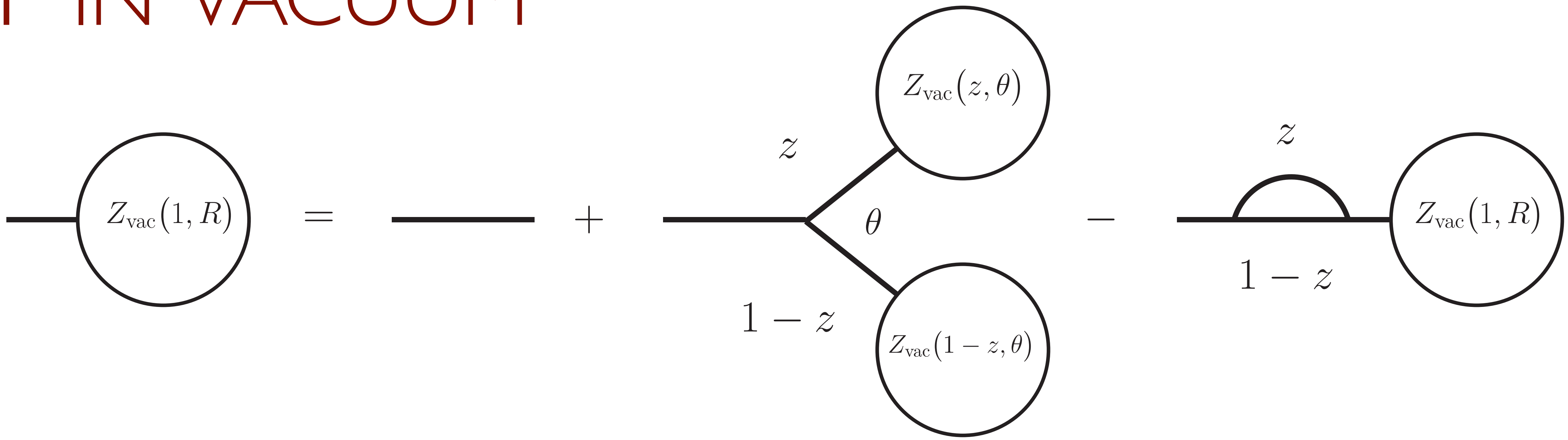
Normalization (conservation of probability) $$G(u=1) = 1$$

Applications to jets

$$P_n \to P(k_1, \ldots, k_n) \qquad u_n \to u(k_1) \ldots u(k_n)$$

Fragmentation function $$D(x|p,R) \equiv x\frac{\mathrm{d}N}{\mathrm{d}x} \equiv x\frac{\delta Z(p,R;u)/\delta u(x)\Big|_{u=1}}{Z(p,R;u)\Big|_{u=1}}$$

GF IN VACUUM



$$Z_{\rm vac}(p,R;u) = u(p) + \frac{\alpha_s}{\pi}\int_0^R \frac{{\rm d}\theta}{\theta}\int_0^1 {\rm d}z\, P(z)$$
$$\left[Z_{\rm vac}(zp,\theta)\, Z_{\rm vac}((1-z)p,\theta) - Z_{\rm vac}(p,\theta)\right]$$

Built-in angular ordering: $R > \theta > \ldots > Q_0/p$

$$\frac{\partial}{\partial \ln Q} D(x,\theta) = \int_0^1 {\rm d}z \frac{\alpha_s}{\pi} P(z) \left[D(x/z, zQ) - z D(x,Q)\right]$$

MLLA evolution equation

IMPLEMENTING QUENCHING

Assume all particles are produced and, subsequently, quenched ***independently*** in the medium

$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\mathrm{d}k_2...\mathrm{d}k_N} &= \int \mathrm{d}p \left\{ \int \prod_{i=1}^{N} \mathrm{d}\epsilon_i P(\epsilon_i) \right\} f(k_1+\epsilon_1, k_2+\epsilon_2, ..., k_N+\epsilon_N|p) \\
&\times \delta(p-\epsilon-k_1-k_2-...-k_N)\, \frac{\mathrm{d}\sigma}{\mathrm{d}p}
\end{aligned}
$$

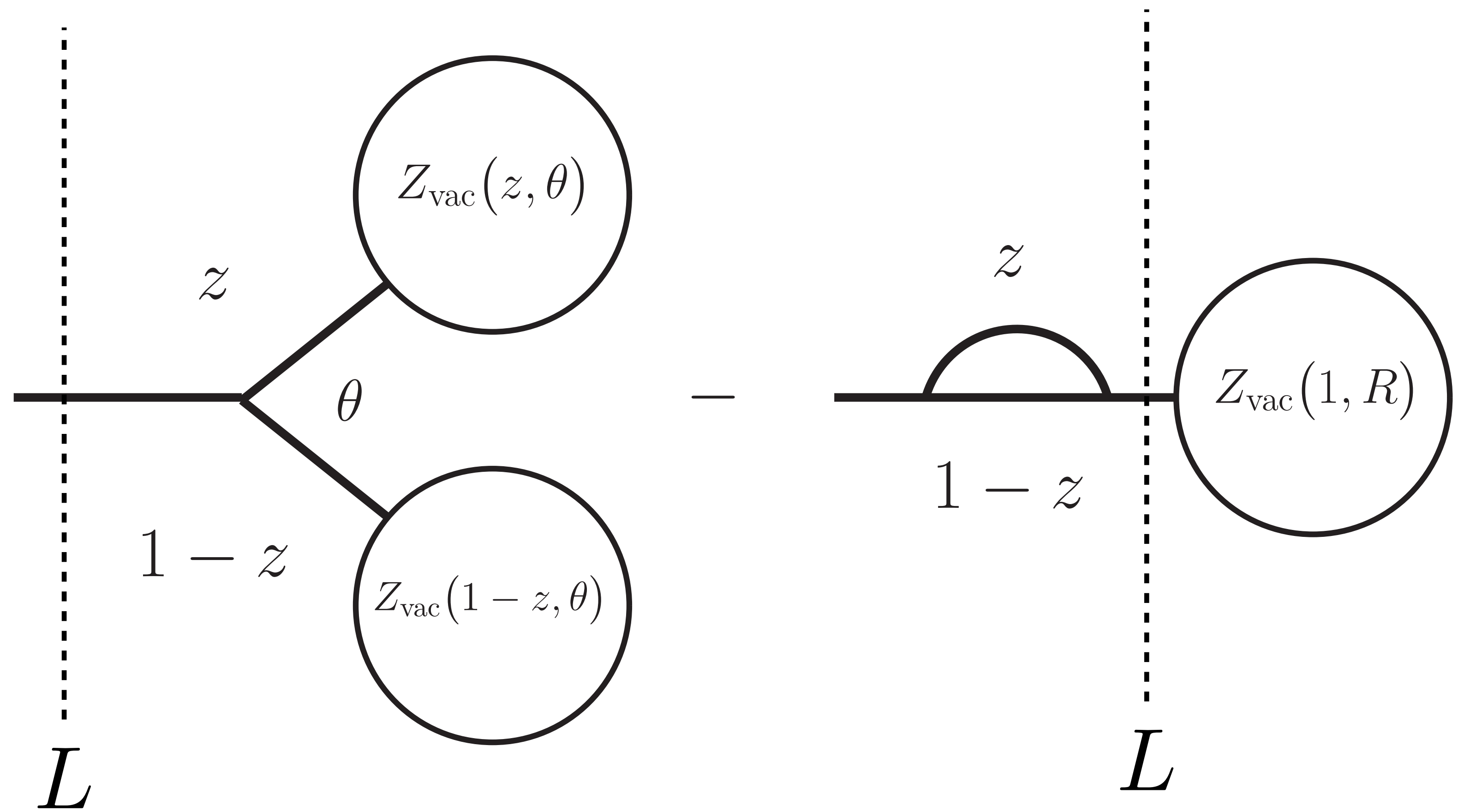
-neglect energy-loss compared to typical energies…

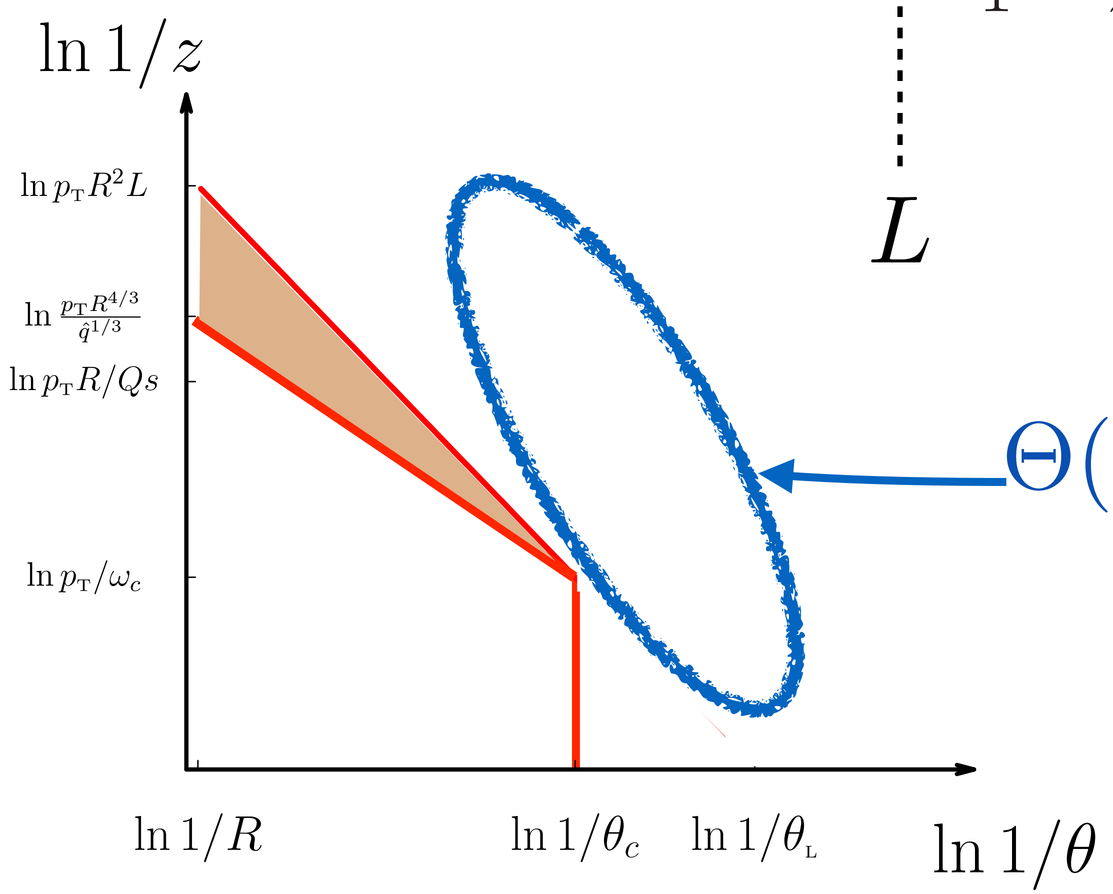
$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\mathrm{d}k_2...\mathrm{d}k_N} &\simeq \left(\int_0^\infty \mathrm{d}\epsilon P(\epsilon) \exp\left(-\frac{n\epsilon}{p_T}\right)\right)^N \frac{\mathrm{d}\sigma_{0,\mathrm{excl}}}{\mathrm{d}k_1\mathrm{d}k_2...\mathrm{d}k_N} \\
&= \mathcal{Q}(p)^N \frac{\mathrm{d}\sigma_{0,\mathrm{excl}}}{\mathrm{d}k_1\mathrm{d}k_2...\mathrm{d}k_N}.
\end{aligned}
$$

Any in-medium, resolved parton is weighted by a quenching factor!

GF IN THE MEDIUM

Fragmentation **outside** the medium



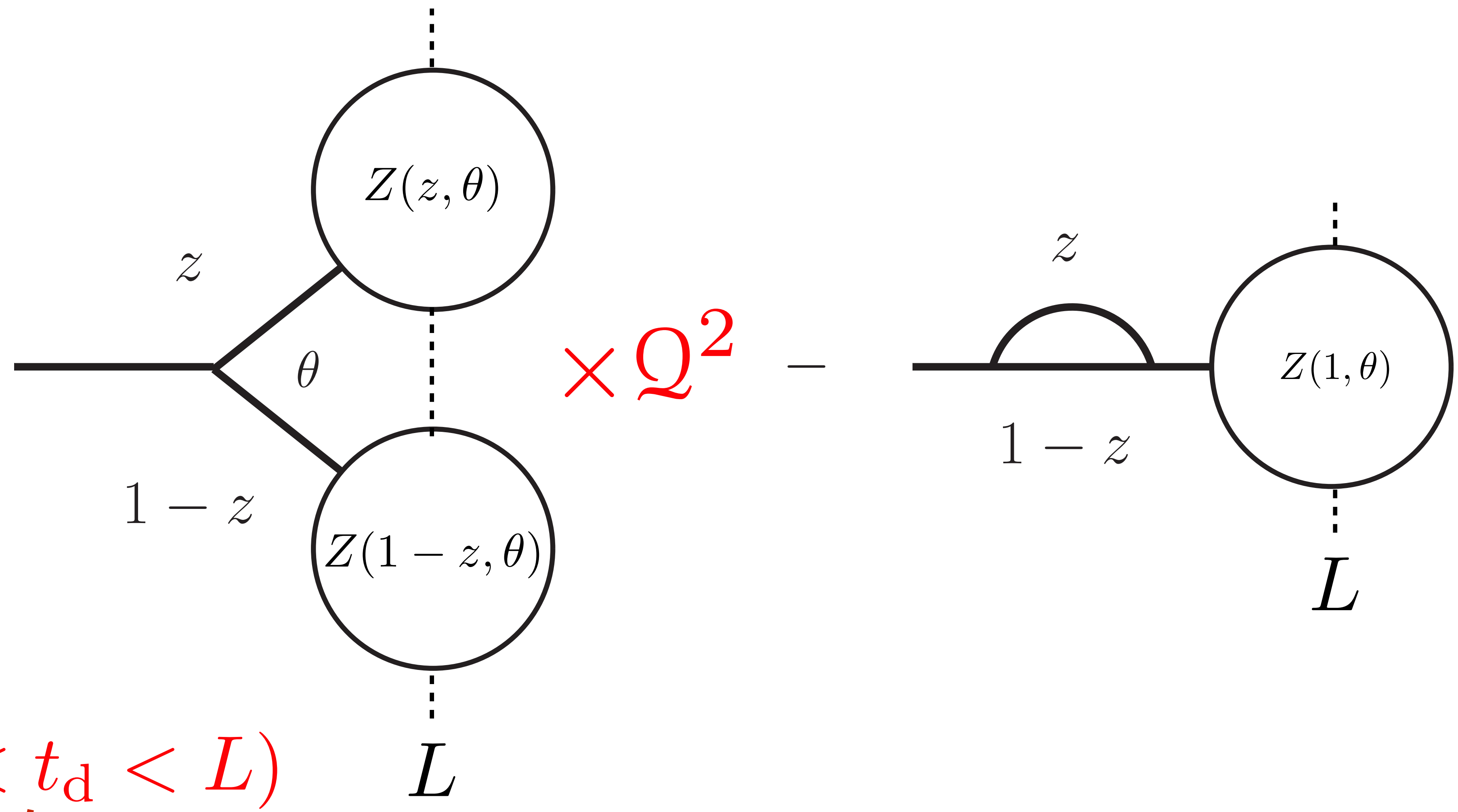


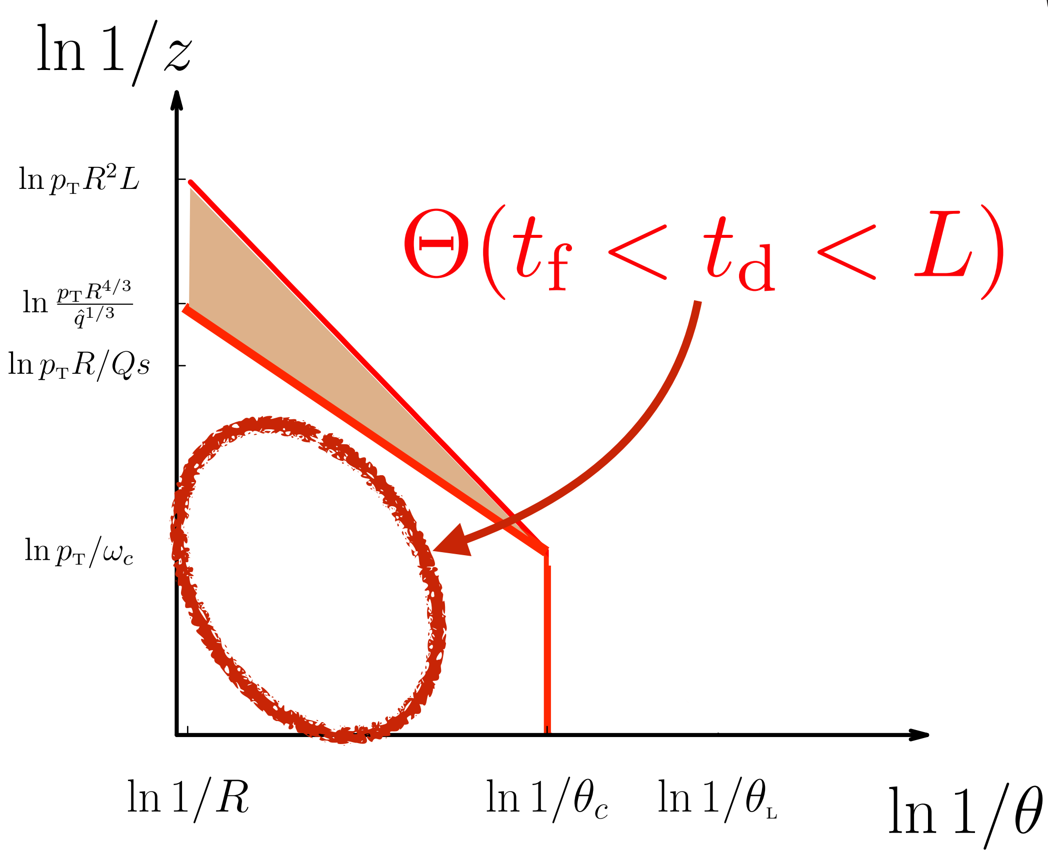
$\Theta(t_{\rm d} < L < t_{\rm f}) + \Theta(\theta < \theta_c)$

… is vacuum-like.

GF IN THE MEDIUM

Fragmentation **inside** the medium



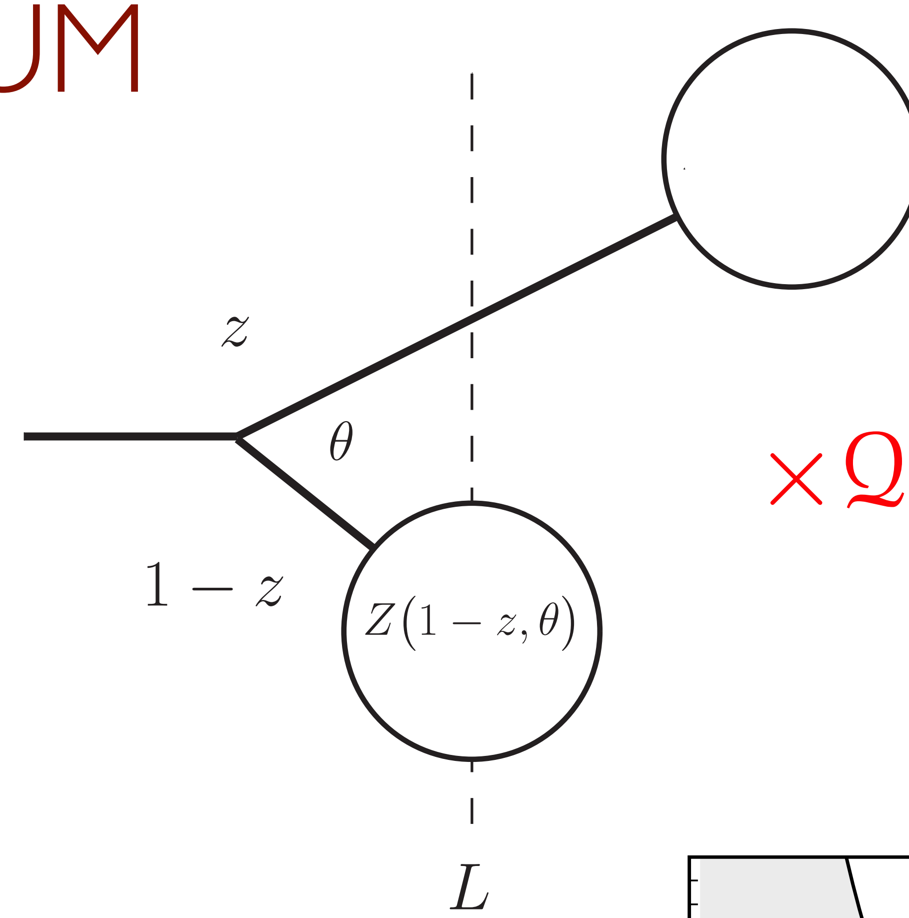


- Follows angular ordering
  - ordering of decoherence times
- Is affected by quenching (large-N$_c$)

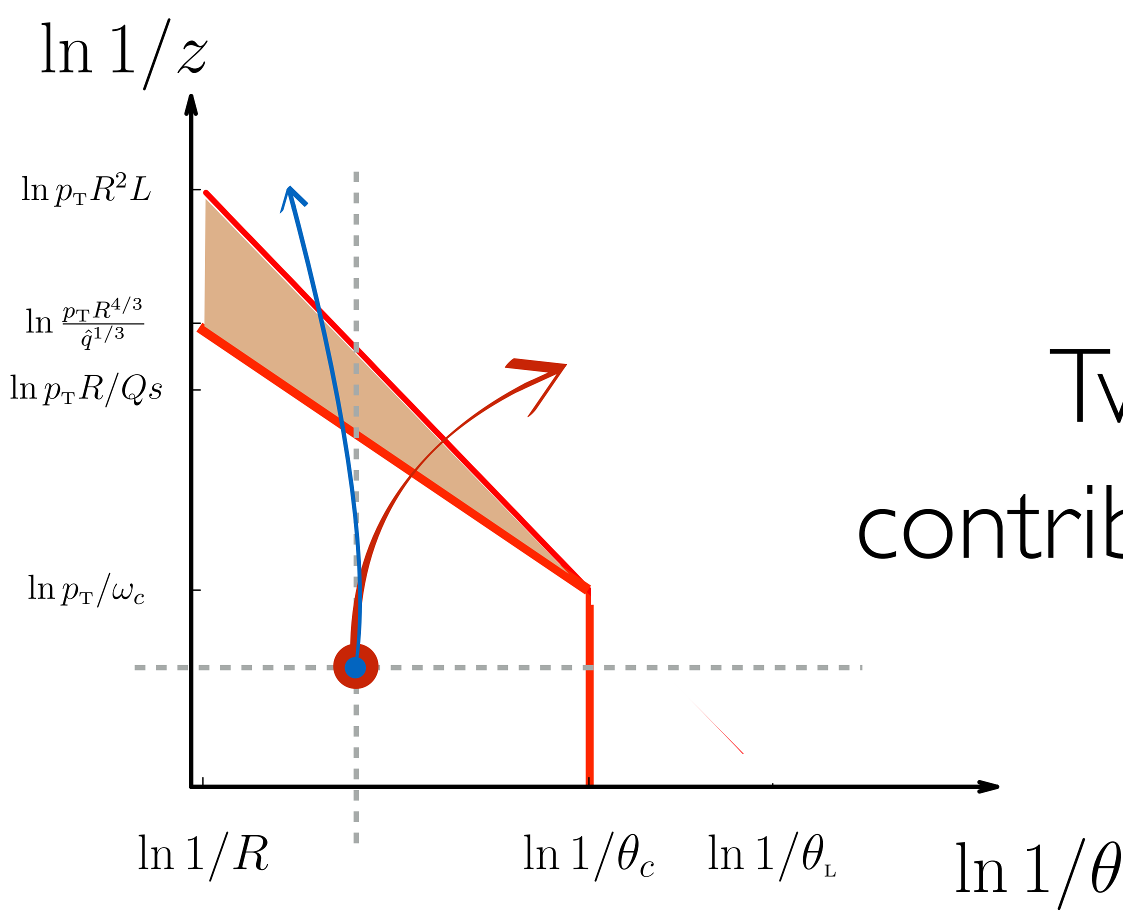
Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]
Caucal, Iancu, Mueller, Sozey PRL (2018)

GF IN THE MEDIUM

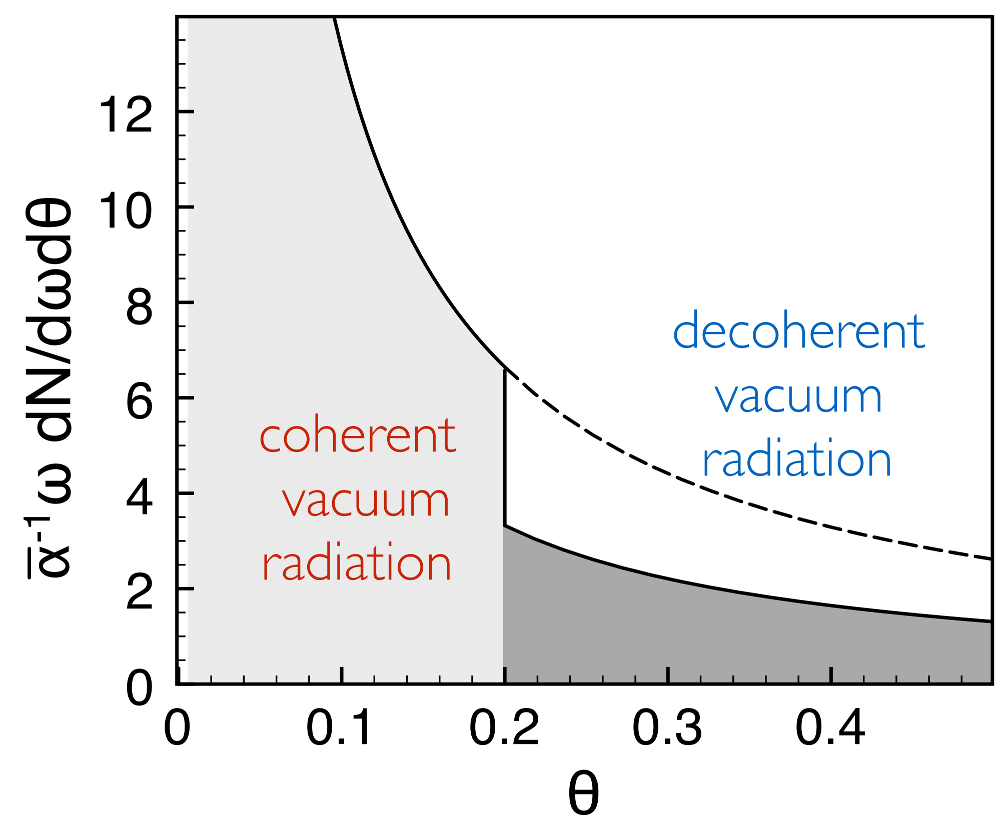
Splitting **inside** the medium, fragmentation **outside**



$$\times Q^2\,\Theta(t_f < t_d < L)$$



Two contributions:



Mehtar-Tani, Salgado, KT PRL 106 (2011) 122002, PLB (2012)

GF IN MEDIUM

Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

Putting all the pieces together: $Z(p,R;u)$

$$Z(p,R;u=1) = \mathcal{C}(p,R)$$

Non-trivial normalization: collimator function!

$$C(p,R) = 1 + \bar{\alpha} \int_0^R \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z\, P(z)\, \underline{\Theta(t_\mathrm{f} < t_\mathrm{d} < L)} \\ \times \left[C(zp,\theta)\, C((1-z)p,\theta)\, \mathcal{Q}^2(p_T) - C(p,\theta) \right]$$

Strong quenching limit $Q \ll 1$ (Sudakov factor):

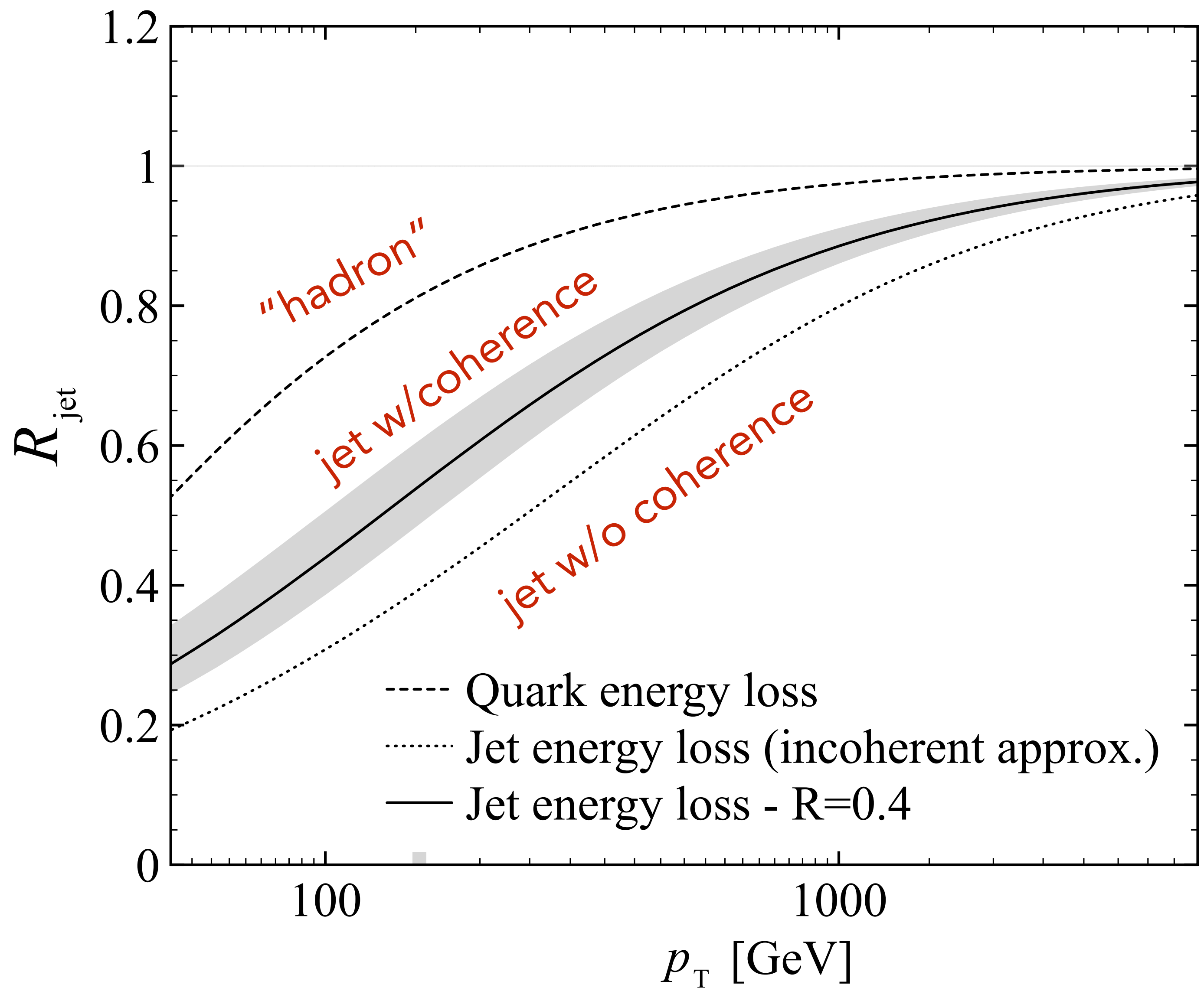
$$\mathcal{C}(p_\mathrm{T},R) \simeq \exp\left[-2\bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_\mathrm{T}}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right) \right]$$

SINGLE-INCLUSIVE SPECTRUM

Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

$$R_{\rm jet} = \mathcal{Q}_q(p_{\rm T}) \times \mathcal{C}(p_{\rm T}, R)$$

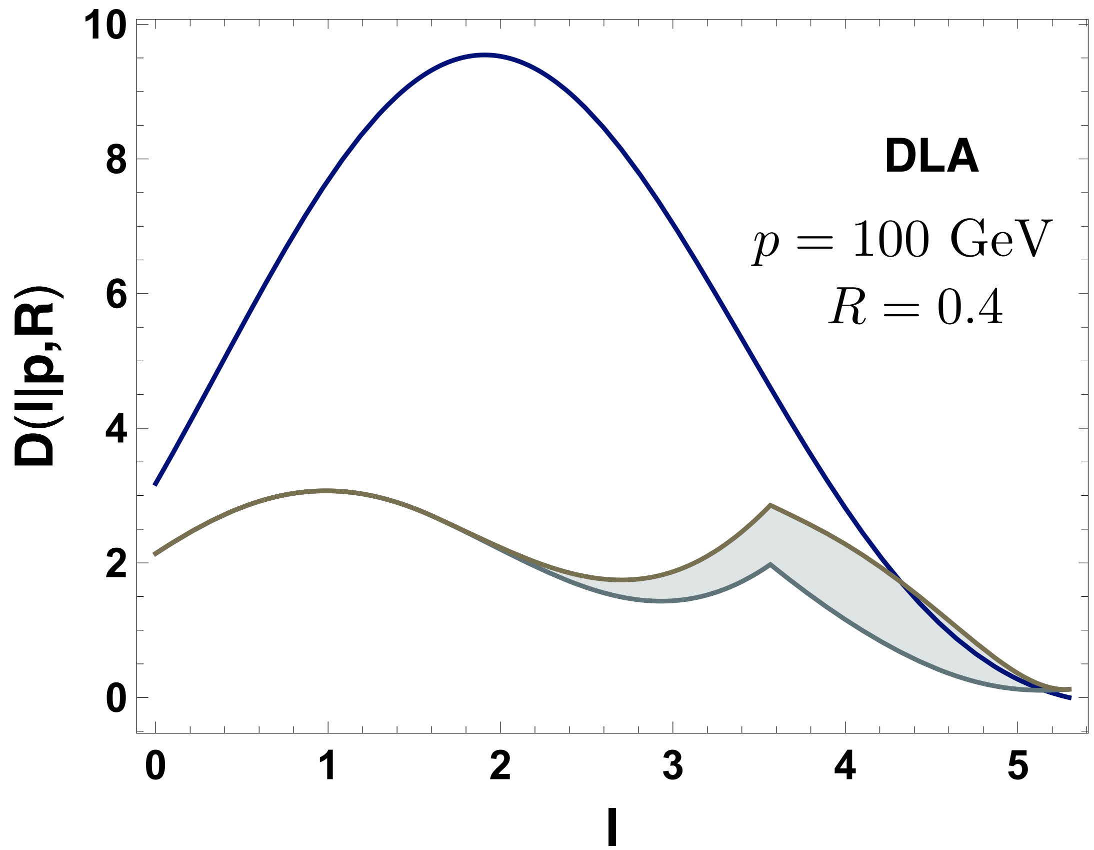
jet loses energy via total charge & resolved substructure fluctuations



EXAMPLE: STRONG QUENCHING LIMIT

All particles, except primary, quenched in the medium (*Q≪1*)

$$D(\omega|p,R) = D_{\rm vac}(\omega|p,\theta_c) + 2\bar\alpha \int_\omega^{\omega_c} \frac{{\rm d}\omega_0}{\omega_0} \int_{\theta_c}^R \frac{{\rm d}\theta_0}{\theta_0}\, \Theta(t_{\rm f} > L)\, \mathcal{C}^{-1}(p,\theta_0) D_{\rm vac}(\omega|\omega_0,\theta_0)$$



Non-trivial effect of collimator!

- coherence of high-energy modes
- enhancement of low-energy modes

OUTLOOK

- probabilistic setup combining jet & medium scales
  - generating functional
  - systematically improvable
- test bed to compare against models & MCs
- collimator function
  - non-linear evolution of quenching

JET TOOLS 2019

2nd Heavy-Ion Jet Substructure Workshop

13 - 17 May
University of Bergen

- new tools for jet physics at the frontiers
- jet substructure and heavy flavor
- splitting maps of the shower
- jet modifications in small systems
- interplay between jets and underlying event
- statistical & machine-learning techniques

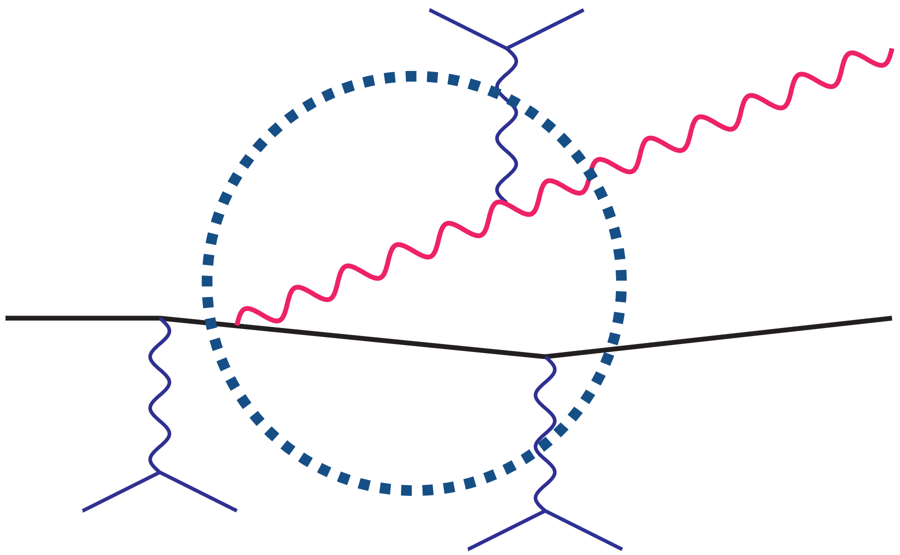
https://jettols.w.uib.no

Back-up

Medium-induced gluons

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996);…

momentum broadening $\langle k_\perp^2 \rangle \sim \hat{q} t$



modified splitting kinematics $t_\mathrm{f} = \dfrac{\omega}{k_\perp^2} \sim \sqrt{\dfrac{\omega}{\hat{q}}}$

lack of collinear singularity!

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{2\pi} \sqrt{\frac{\hat{q} L^2}{\omega}}$$

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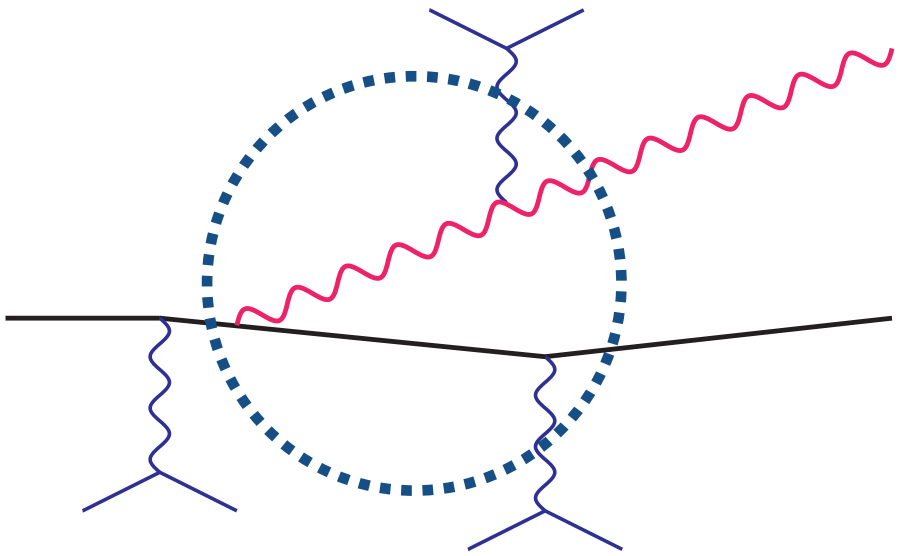

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$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{2\pi} \sqrt{\frac{\hat{q} L^2}{\omega}}$$

rare, small-angle emission $\omega_c = \hat{q} L^2$

$$\theta_\mathrm{br}(\omega_c) \sim \sqrt{\frac{1}{\hat{q} L^3}} \equiv \theta_c$$

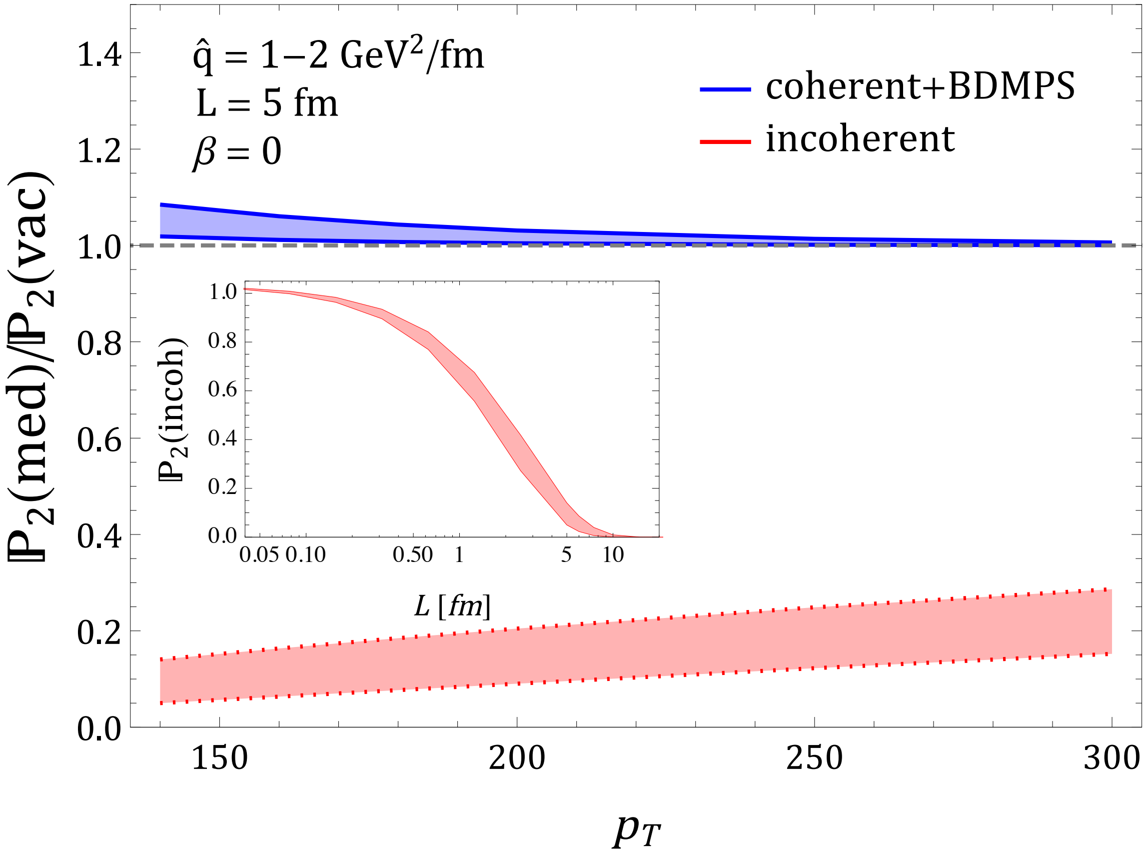
copious, large-angle emissions $\omega_s = \bar{\alpha}^2 \hat{q} L^2$

$$\theta_\mathrm{br}(\omega_s) \sim \frac{1}{\bar{\alpha}^{3/2}} \theta_c$$

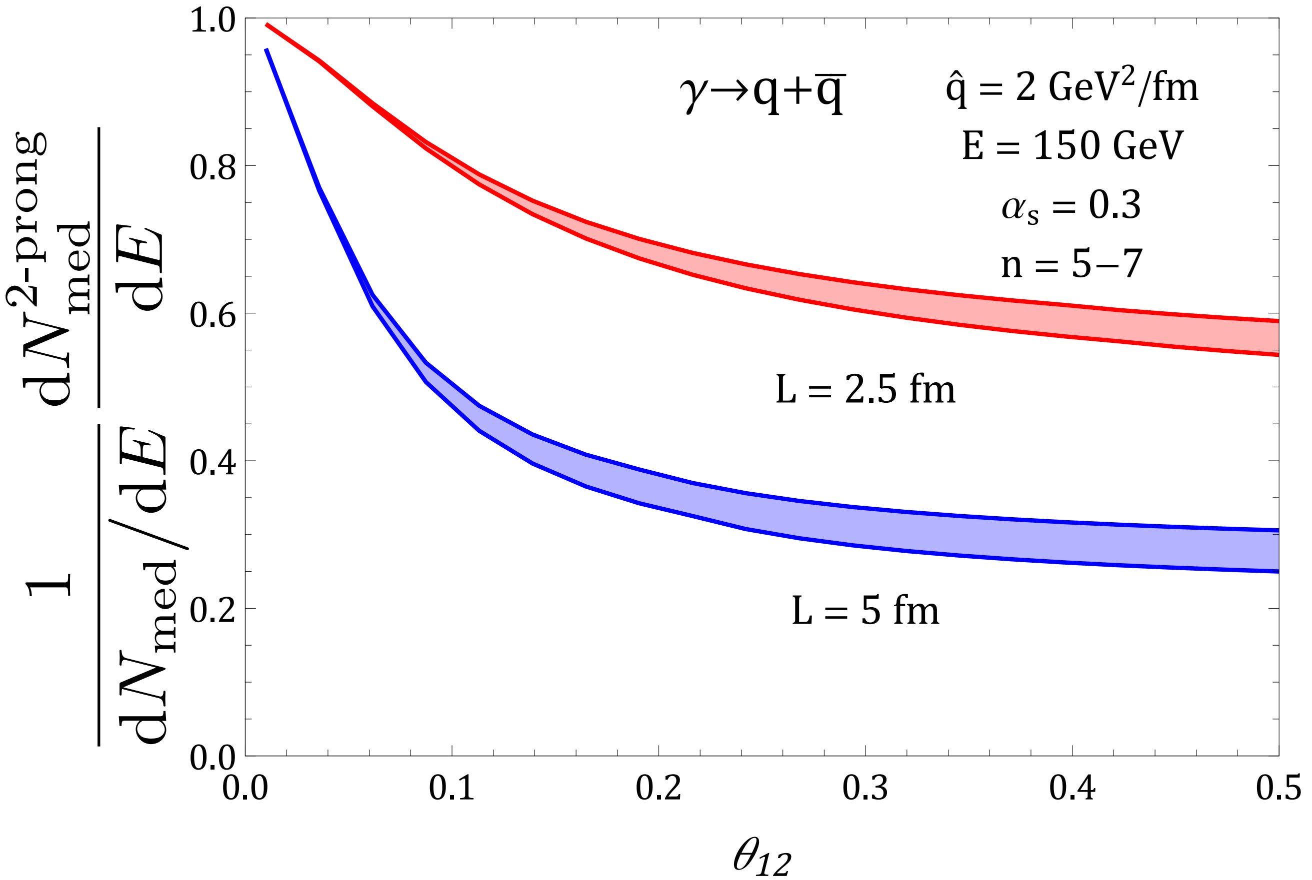
TWO-PRONG PROBABILITY

Choosing two-prong substructure using SoftDrop

Mehtar-Tani, KT arXiv:1610.08930



Casalderrey, Mehtar-Tani, Salgado KT QM2017 proceedings



Non-monotonic behavior indicative of coherence effects!

Suggestive: inclusive z_g distribution [Andrews et al. (ALICE) QM2018].