UNIVERSITY OF BERGEN

JET SUBSTRUCTURE IN HEAVY-ION COLLISIONS

Konrad Tywoniuk

BOOST 2019
21-26 July 2019, MIT, Boston

Theory challenges

- new emergent state of matter in HIC: quark-gluon plasma
- nature of quantum fields and their "space-time" structure
  - how does a quantum object ("jet") interface with a classical, extended medium?
  - light-cone perturbation theory with background field
- thermalization of non-equilibrium probes
  - how is energy/quanta transferred between modes?
  - what are the relevant medium scales that affect jet observables?

SUBSTRUCTURE IN HIC

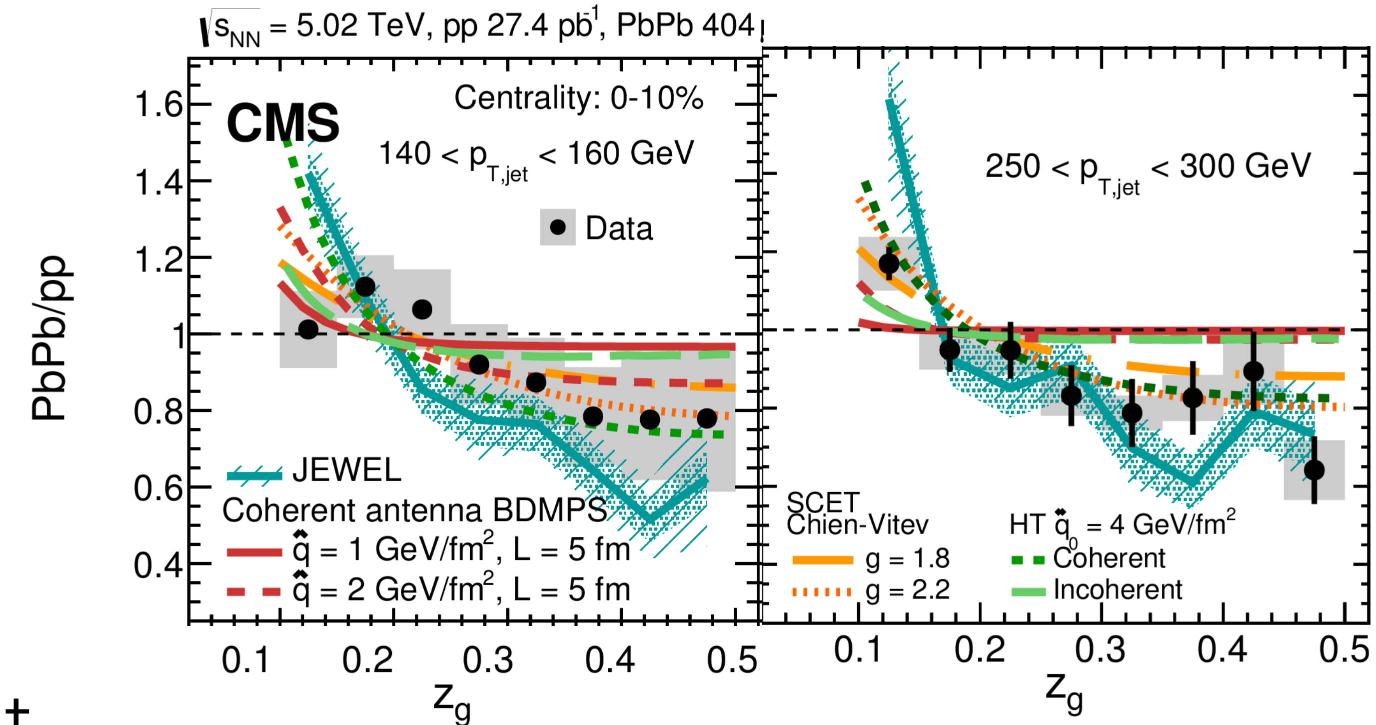
- several exists from MCs

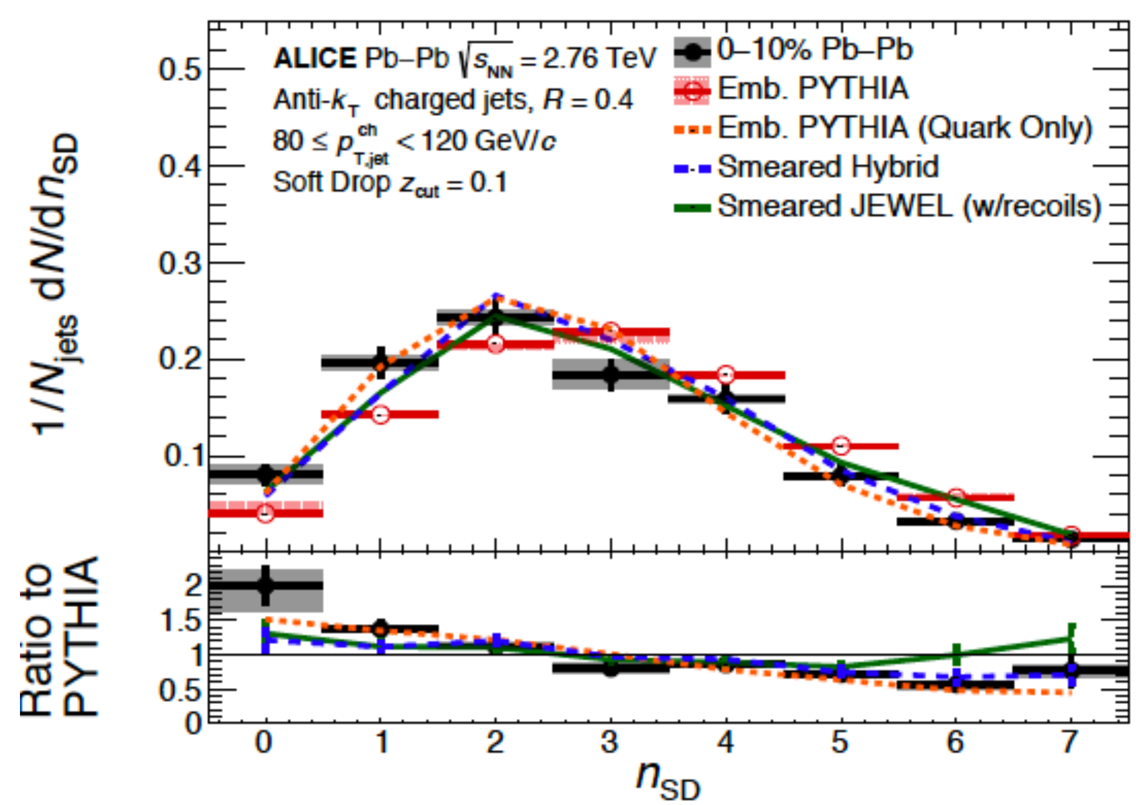
  Milhano, Zapp, Wiedemann 1707.04142
  Elayavalli, Zapp 1707.01539

- analytical computations
  - focussed on groomed observables z_g, R_g (also interest in n_{SD})
  - studied the effect from additional in-medium radiation

  Chien, Vitev 1608.07283
  Mehtar-Tani, KT 1610.08930
  Chang, Cao, Qin 1707.03767
  Caucal, Iancu, Soyez 1907.04866

see also Soyez' talk (Tue 11:30)



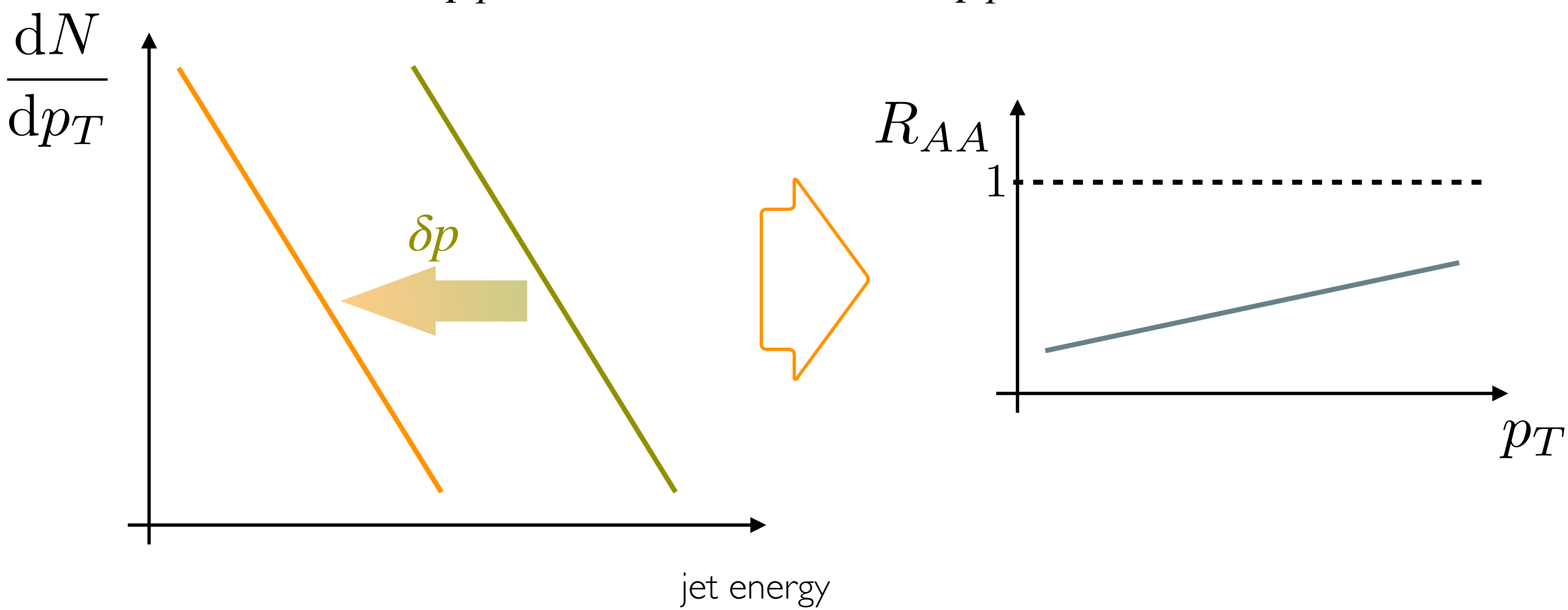


ROLE OF SUBSTRUCTURE STUDIES

- jet quenching is a multi-parton and multi-scale problem
  - maps out intricate picture of jet-medium interactions at different scales
- potential to isolate/enhance regimes
  - sensitivity to "new" physics (QCD bremsstrahlung, medium response)
  - purified samples to study microscopic properties (color, mass)
- this talk
  - sketch a systematically improvable framework to compute "benchmark" observables (including resummation & perturbative corrections)

ENERGY-LOSS BASICS

$$\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_T} = \mathcal{J}(p_T, p'_T)\frac{\mathrm{d}N_{pp}(p'_T = p_T + \delta p)}{\mathrm{d}p'_T}$$



Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

Shift dominated by radiative processes!

QCD BREMSSTRAHLUNG

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996); Gyulassy, Levai, Vitev (2001); Arnold, Moore, Yaffe (2002)

Momentum broadening $\langle \boldsymbol{k}^2 \rangle \sim \hat{q}t$ leads to modified bremsstrahlung spectrum → no collinear divergence!

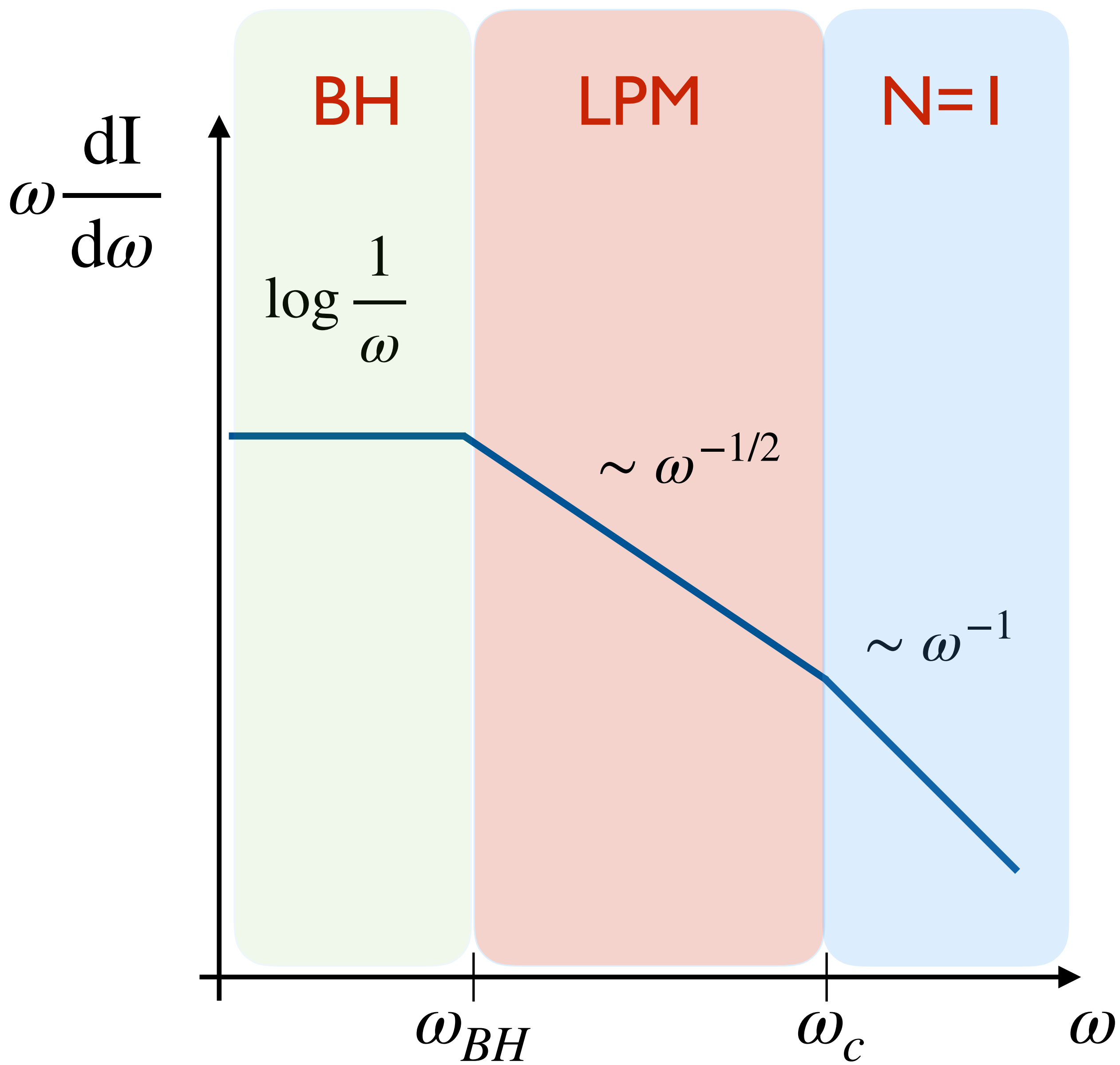
$$t_{\rm f} \sim t_{\rm br} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

QCD BREMSSTRAHLUNG

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996); Gyulassy, Levai, Vitev (2001); Arnold, Moore, Yaffe (2002)

Momentum broadening $\langle \boldsymbol{k}^2 \rangle \sim \hat{q} t$ leads to modified bremsstrahlung spectrum → no collinear divergence!

$$t_{\mathrm{f}} \sim t_{\mathrm{br}} \sim \sqrt{\frac{\omega}{\hat{q}}}$$



$$\omega \frac{dI}{d\omega} = \frac{\alpha_s C_R}{\pi} \frac{L}{t_{\mathrm{br}}}$$

- $t_{\mathrm{br}} \sim \lambda \rightarrow \quad \omega \sim \omega_{\mathrm{BH}} = \hat{q}\lambda^2 \sim T$
- $t_{\mathrm{br}} \sim L \rightarrow \quad \omega \sim \omega_c = \hat{q}L^2$
- $t_{\mathrm{br}} \sim \frac{\omega}{\mu^2} \gtrsim L \rightarrow$ N=1 dominates

Two regimes

Multi-gluon emissions are dominated by the LPM regime.

$$N_{\mathrm{LPM}}(\omega) = \int_0^\infty \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = \frac{2\alpha_s C_R}{\pi}\sqrt{\hat{q}L^2/\omega}$$

$$\omega \sim \omega_c = \hat{q}L^2$$

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

$$N \sim \mathcal{O}(\alpha_s)$$

perturbative: rare, small-angle radiation can modify intra-jet structure, N=1 also contributes

$$\omega \sim \omega_c = \alpha_s^2 \hat{q}L^2$$

$$\theta_{\mathrm{br}} \sim \frac{1}{\alpha_s^2}\theta_c$$

$$N \sim 1$$

non-perturbative: copious, large-angle emissions

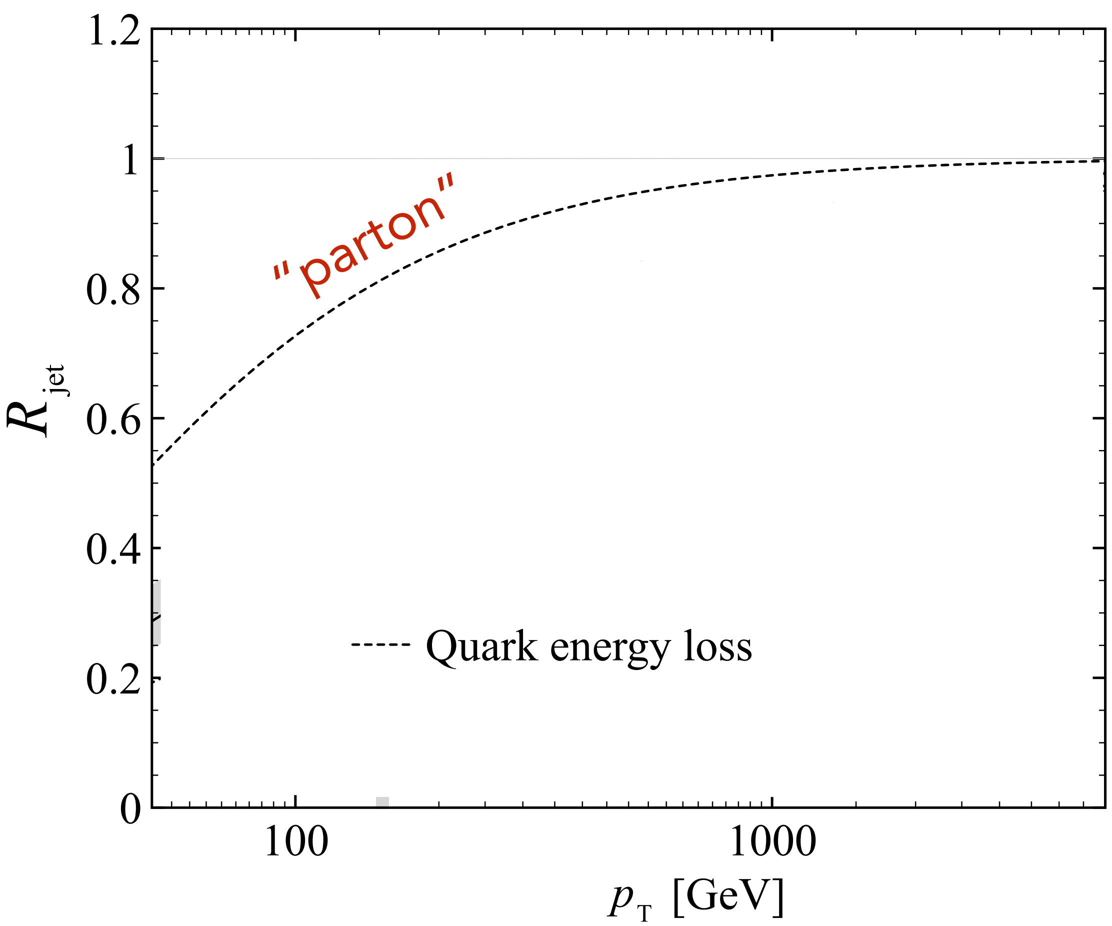
out-of-cone energy-loss, thermalization

QUENCHING WEIGHTS

$$\frac{d\sigma_{\rm med}}{dp_T^2\,dy} = \int_0^\infty d\epsilon\, \mathscr{P}(\epsilon) \frac{d\sigma_{\rm vac}(p_T+\epsilon)}{dp_T^2\,dy}$$

Resumming multiple soft gluon emissions possible via rate equation.

Expanding: $(p_T+\epsilon)^{-n} \approx e^{-n\epsilon/p_T}/p_T^n + \ldots$



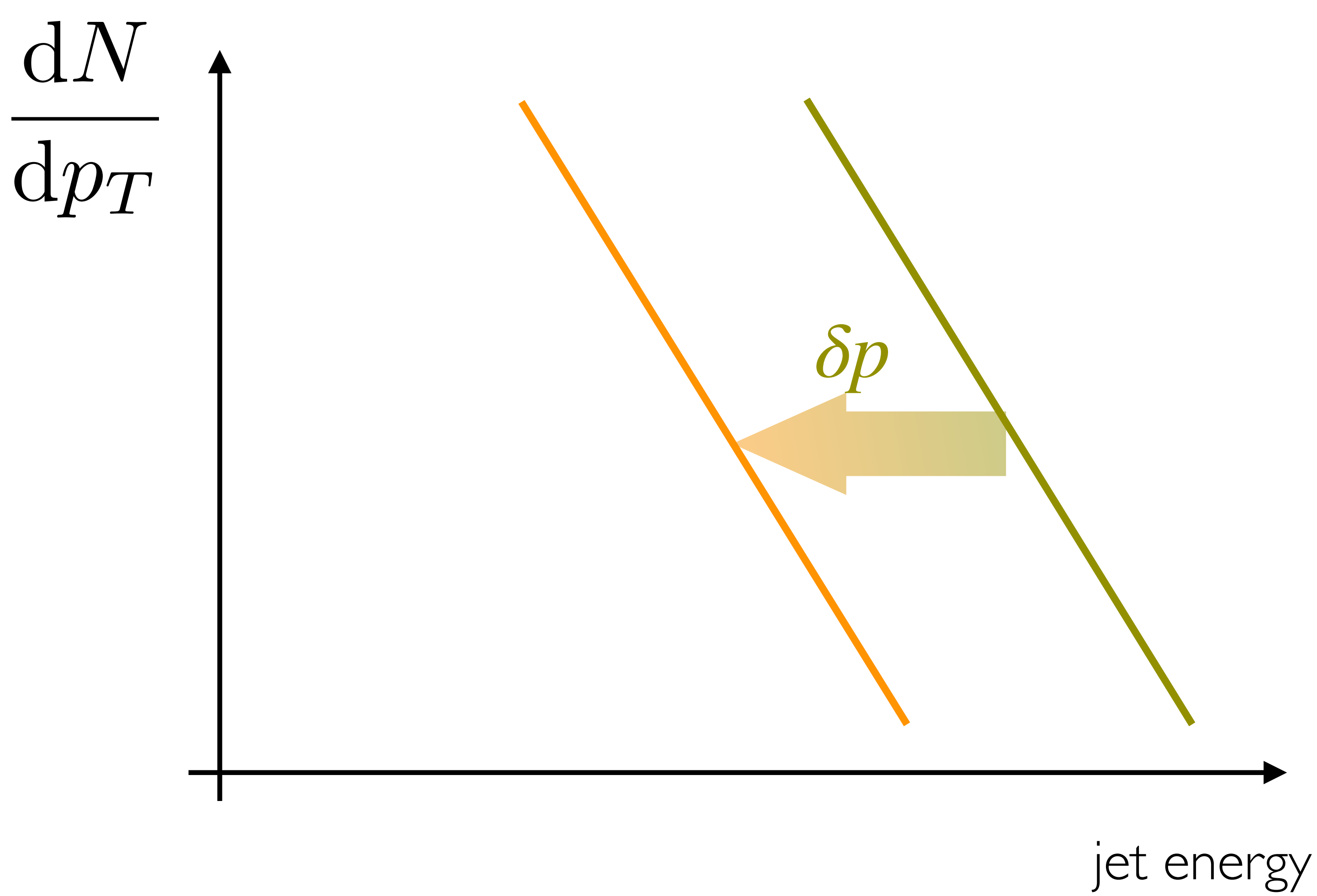
RAA is sensitive to the energy loss distribution through the Laplace transform.

$$\mathcal{Q}(p_T) = \tilde{\mathscr{P}}(n/p_T) \sim e^{-N(\omega > p_T/n)}$$

- $\delta p \sim (\alpha_s^2 \hat{q} L^2 p_T/n)^{1/2}$ for $p_T < n\hat{q}L^2$
- $\delta p \sim \alpha_s \hat{q} L^2$ for $p_T > n\hat{q}L^2$

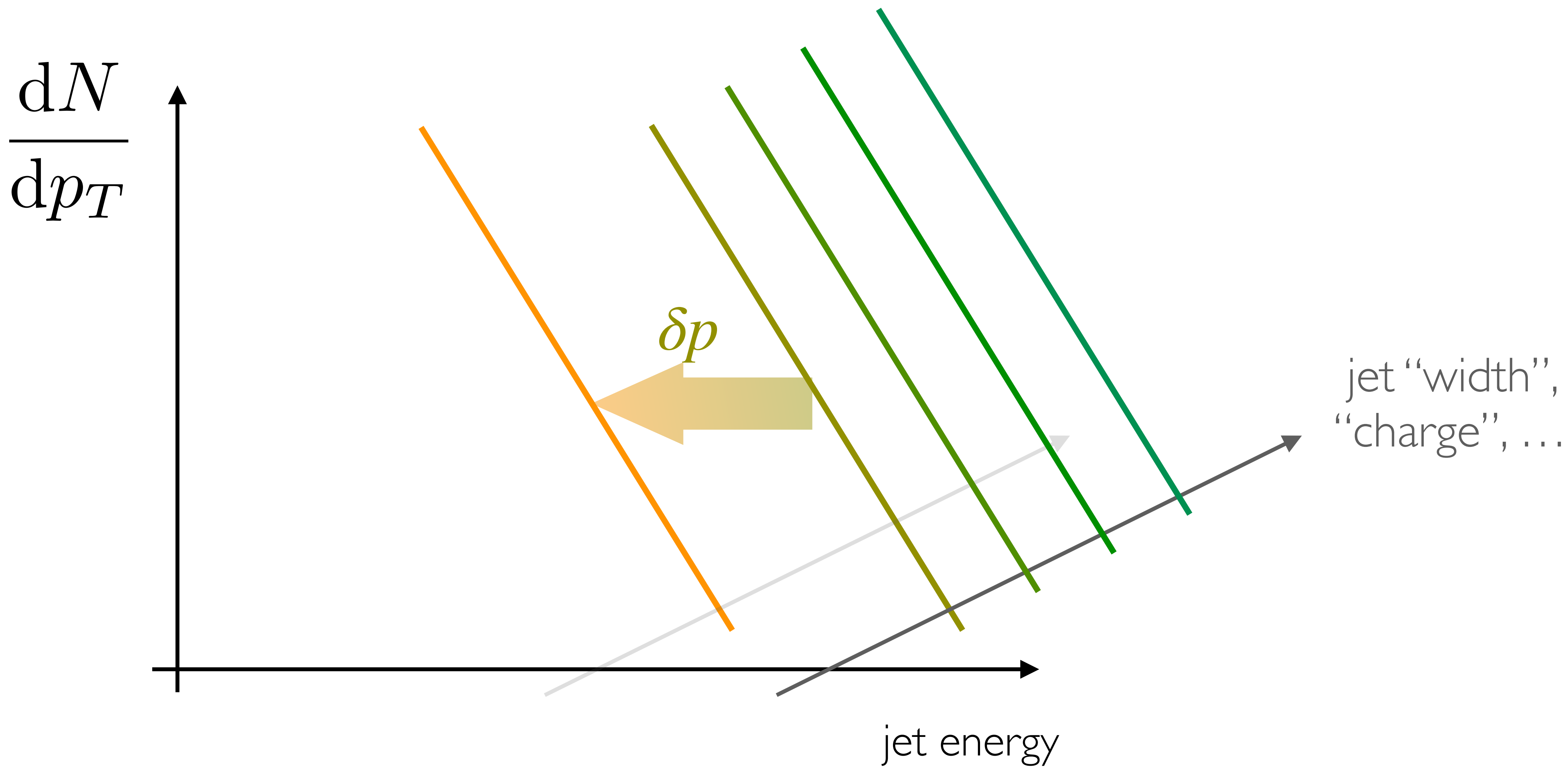
Multi-variate migration effects

Consider a two-parameter dependence of δp.



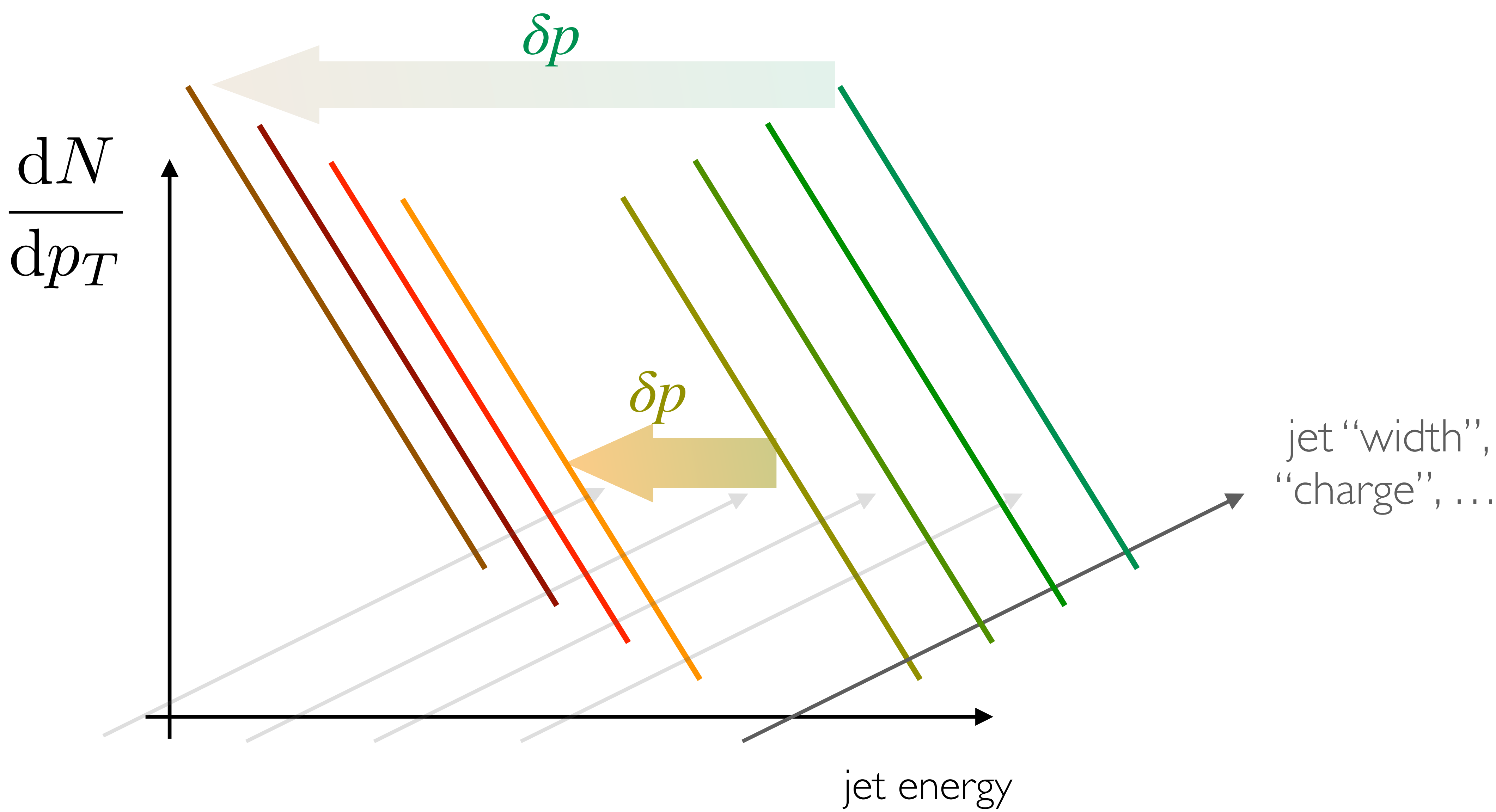
Multi-variate migration effects

Consider a two-parameter dependence of δp.



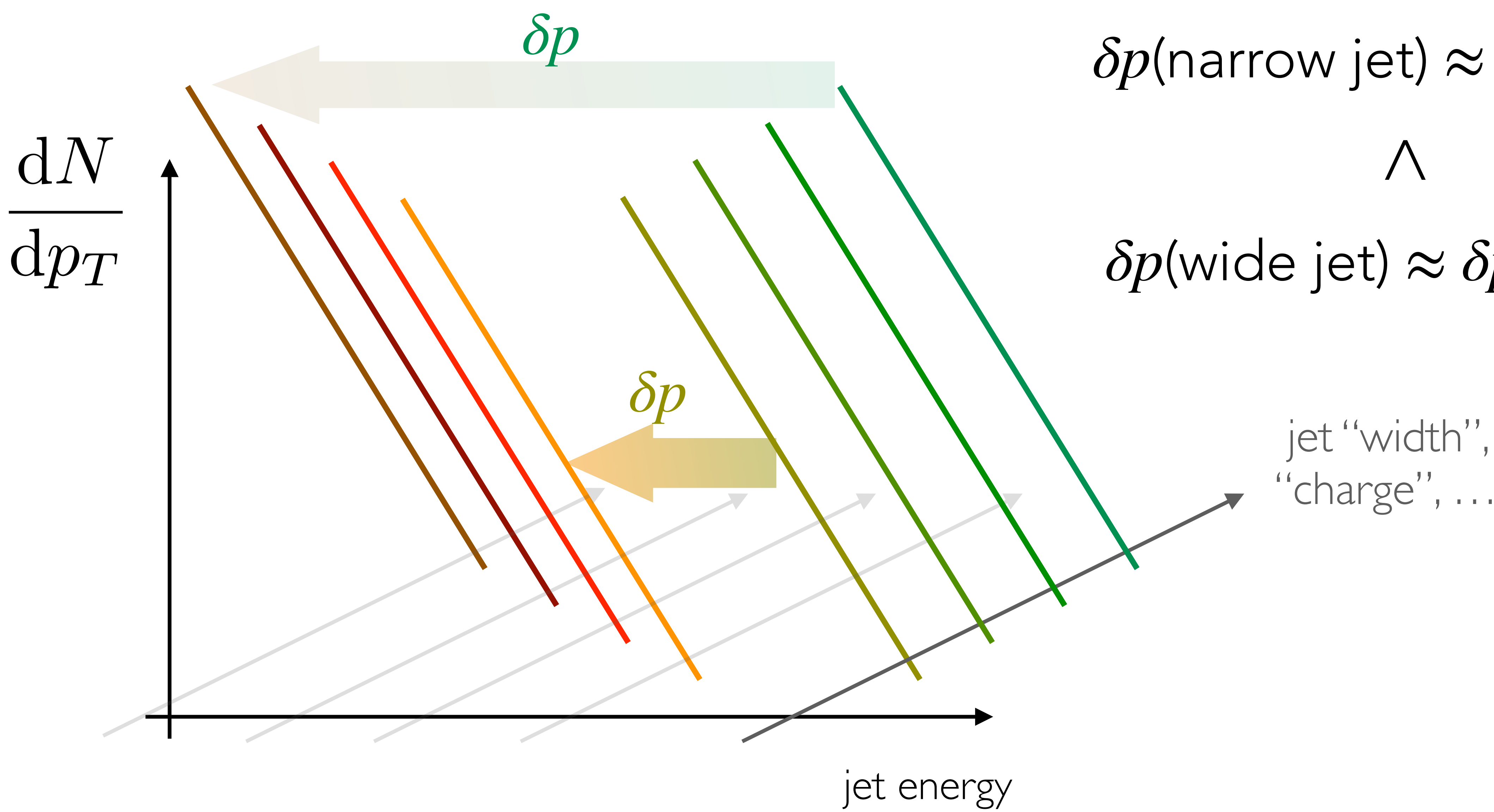
MULTI-VARIATE MIGRATION EFFECTS

Consider a two-parameter dependence of δp.



Multi-variate migration effects

Consider a two-parameter dependence of δp.



$\delta p(\text{narrow jet}) \approx \delta p(1 \text{ parton})$

$\wedge$

$\delta p(\text{wide jet}) \approx \delta p(\text{n partons})$

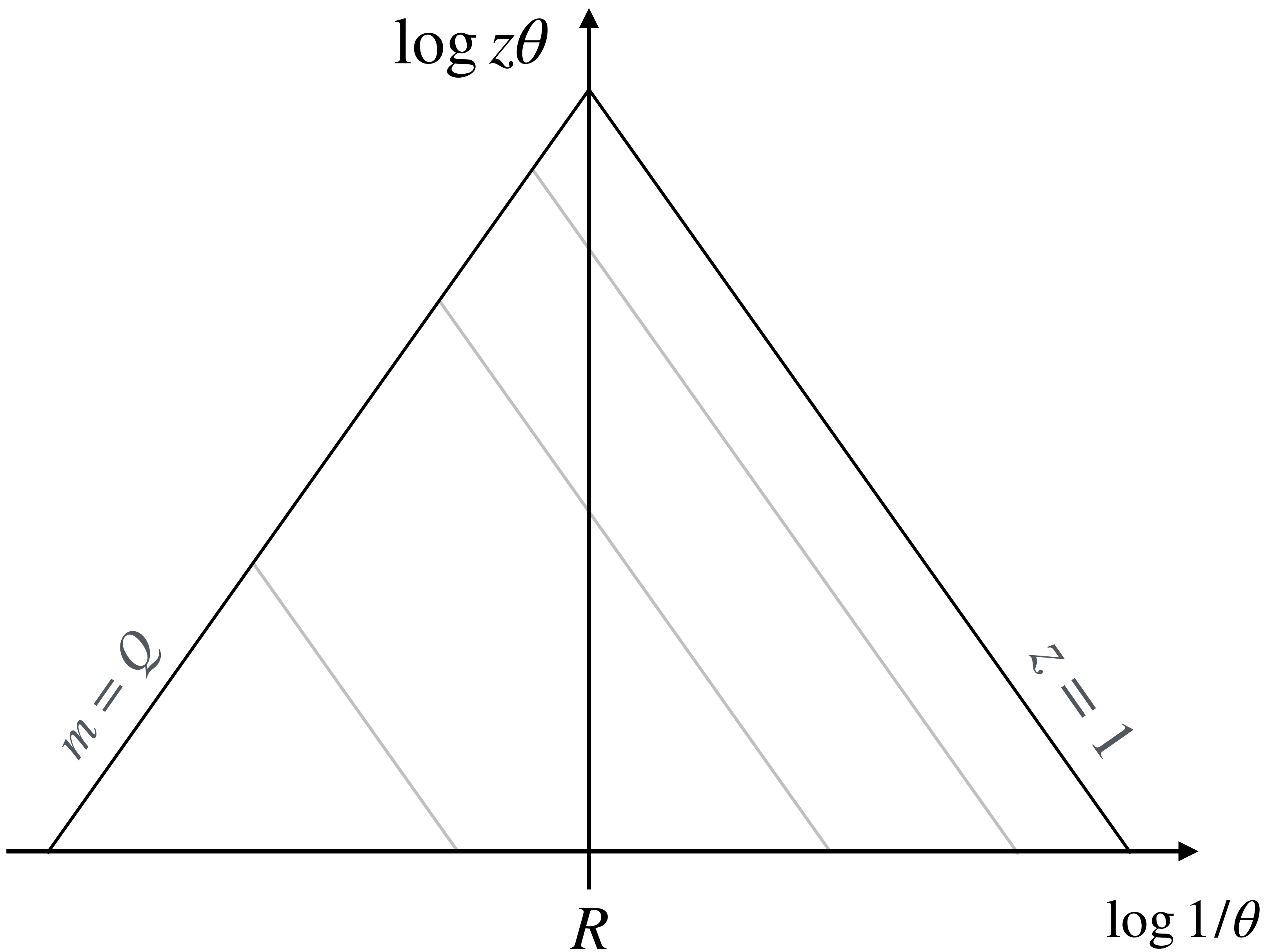
Open data/theory question: what drives quenching and substructure modifications?

HIGHER-ORDER CALCULATIONS

- so far, only one-gluon emission spectrum
  - how to generalize to higher-orders in α_s?
  - need to account for interplay of vacuum/medium spectra (two "orthogonal" showers in $\log k_\perp$ and t)
- efforts beyond
  - antenna radiation: role of color coherence
    Mehtar-Tani, Salgado, KT 1009.2965, 1102.4317, 1112.5031, 1205.5739
    Casalderrey, Iancu 1105.1760
  - two-gluon spectrum: interferences
    Arnold, Iqbal 1501.04964
    Casalderrey, Pablos, KT 1512.07561
  - for energy-loss: 1st order vacuum + n soft bremsstrahlung gluons
    Y. Mehtar-Tani, KT 1706.06047

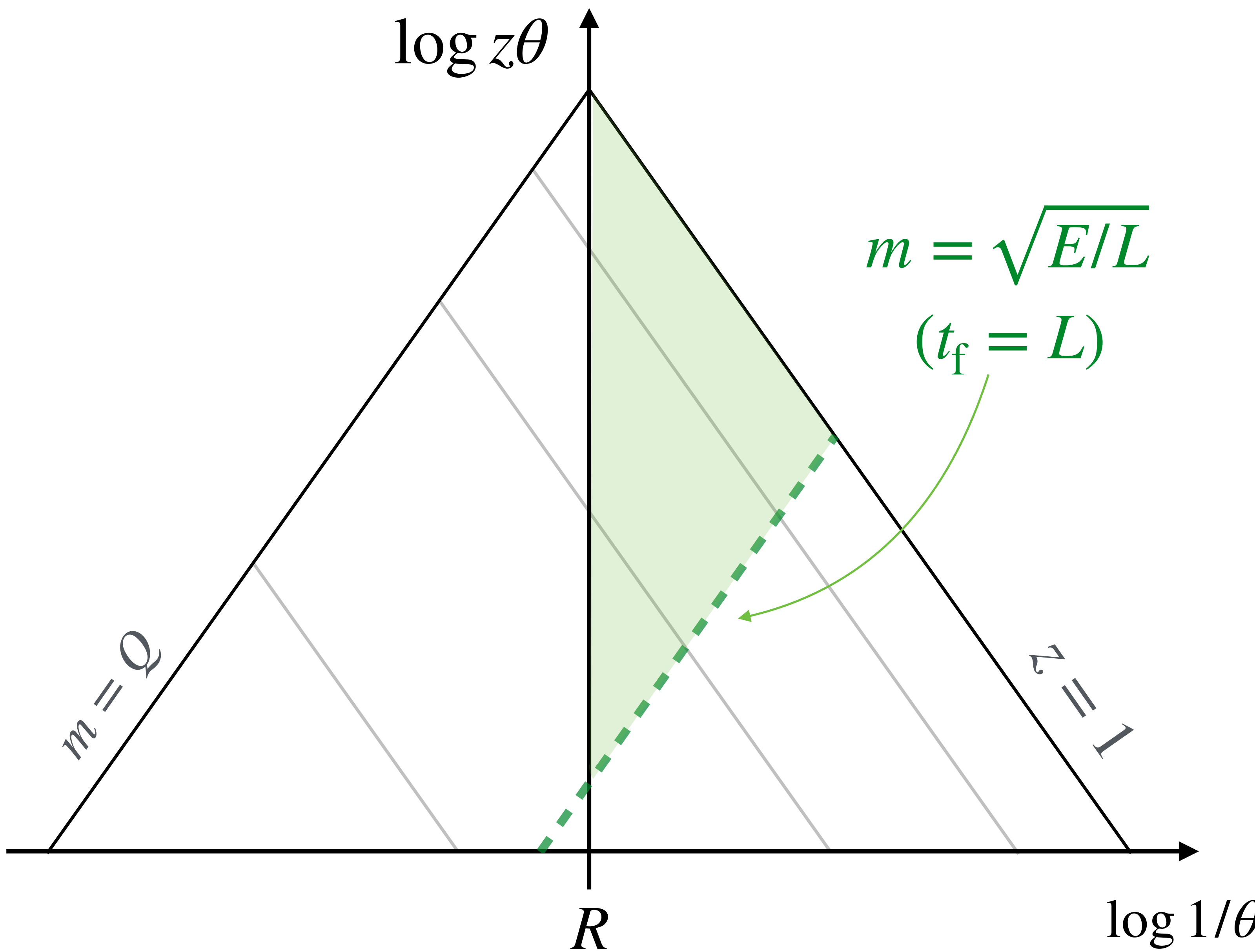
Phase space analysis

Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703
Dominguez, Milhano, Salgado, KT, Vila 1907.03653



PHASE SPACE ANALYSIS

Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703
Dominguez, Milhano, Salgado, KT, Vila 1907.03653



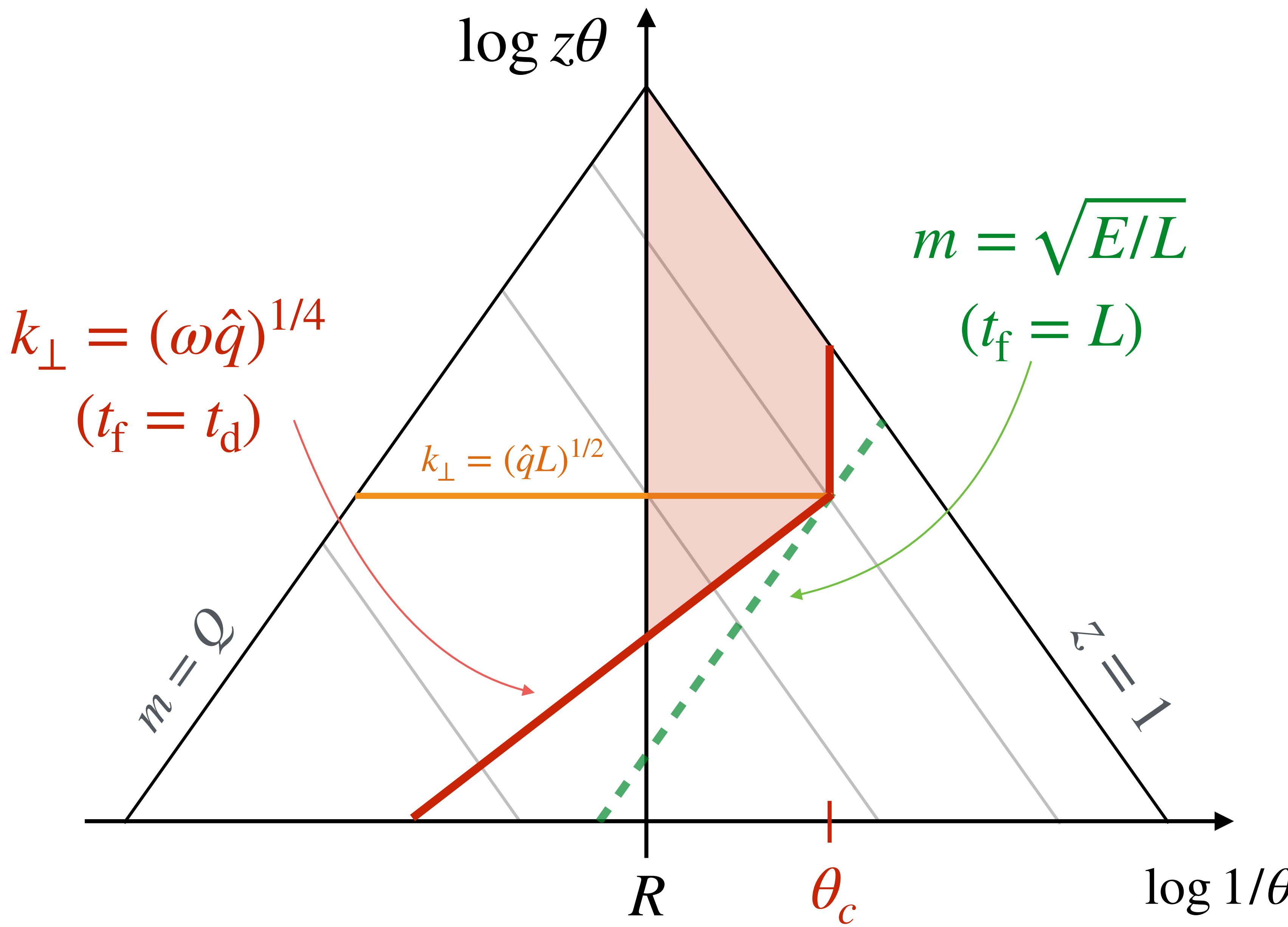
$$(PS)_{\text{in}} = \frac{\bar{\alpha}}{4} \log^2 ER^2L$$

Considering E=100GeV, R=0.4 and L=4fm, we find that $\log^2 \sim 30$!

Should expect multiple in-medium emissions for LHC kinematics.

Phase space analysis

Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703
Dominguez, Milhano, Salgado, KT, Vila 1907.03653



$$(PS)_{in} = \frac{\bar{\alpha}}{4}\log^2 ER^2L$$

Considering E=100GeV, R=0.4 and L=4fm, we find that $\log^2 \sim 30$!

Should expect multiple in-medium emissions for LHC kinematics.

Red area: identified *genuine vacuum component* w/ $k_\perp^2 > \sqrt{\hat{q}\omega}$
- modified by the medium (long-distance effects).

THEORY CONTROL: LEADING EFFECTS

Simplified example: consider a $1 \to N$ process followed by energy loss.

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} = \int \mathrm{d}p \left\{ \prod_i \int \mathrm{d}\epsilon_i \, \mathscr{P}(\epsilon_i) \right\} f_{1\to N}\left(k_1+\epsilon_1, \ldots, k_N+\epsilon_N \,|\, p\right) \delta\left(p - \sum_i k_i - \sum_i \epsilon_i\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p}$$

Theory control: leading effects

Simplified example: consider a $1 \to N$ process followed by energy loss.

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} = \int \mathrm{d}p \left\{ \prod_i \int \mathrm{d}\epsilon_i\, \mathscr{P}(\epsilon_i) \right\} f_{1\to N}\left(k_1+\epsilon_1, \ldots, k_N+\epsilon_N \,|\, p\right) \delta\left(p - \sum_i k_i - \sum_i \epsilon_i\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p}$$

Leading-order effect:

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N} \simeq \left(\int \mathrm{d}\epsilon\, \mathscr{P}(\epsilon)\, \mathrm{e}^{-n\epsilon/p} \right)^N \frac{\mathrm{d}\sigma_{0,\mathrm{excl}}}{\mathrm{d}k_1\ldots\mathrm{d}k_N}$$

THEORY CONTROL: LEADING EFFECTS

Simplified example: consider a $1 \to N$ process followed by energy loss.

$$\frac{d\sigma_{\text{excl}}}{dk_1\ldots dk_N} = \int dp \left\{ \prod_i \int d\epsilon_i \, \mathscr{P}(\epsilon_i) \right\} f_{1\to N}\left(k_1+\epsilon_1, \ldots, k_N+\epsilon_N | p\right) \delta\left(p - \sum_i k_i - \sum_i \epsilon_i\right) \frac{d\sigma_0}{dp}$$

Leading-order effect:

$$\frac{d\sigma_{\text{excl}}}{dk_1\ldots dk_N} \simeq \left(\int d\epsilon \mathscr{P}(\epsilon) e^{-n\epsilon/p} \right)^N \frac{d\sigma_{0,\text{excl}}}{dk_1\ldots dk_N}$$

systematically improvable…

$$+N\mathscr{Q}(p)^{N-1} \frac{\partial \mathscr{Q}(p)}{\partial (n/p)} \sum_i \frac{\partial}{\partial k_i} \left(\frac{d\sigma_{0,\text{excl}}}{dk_1\ldots dk_N} \right)$$

Provides a framework for studying multi-parton energy-loss effects for inclusive observables !

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)

$$G(u = 1) = 1$$

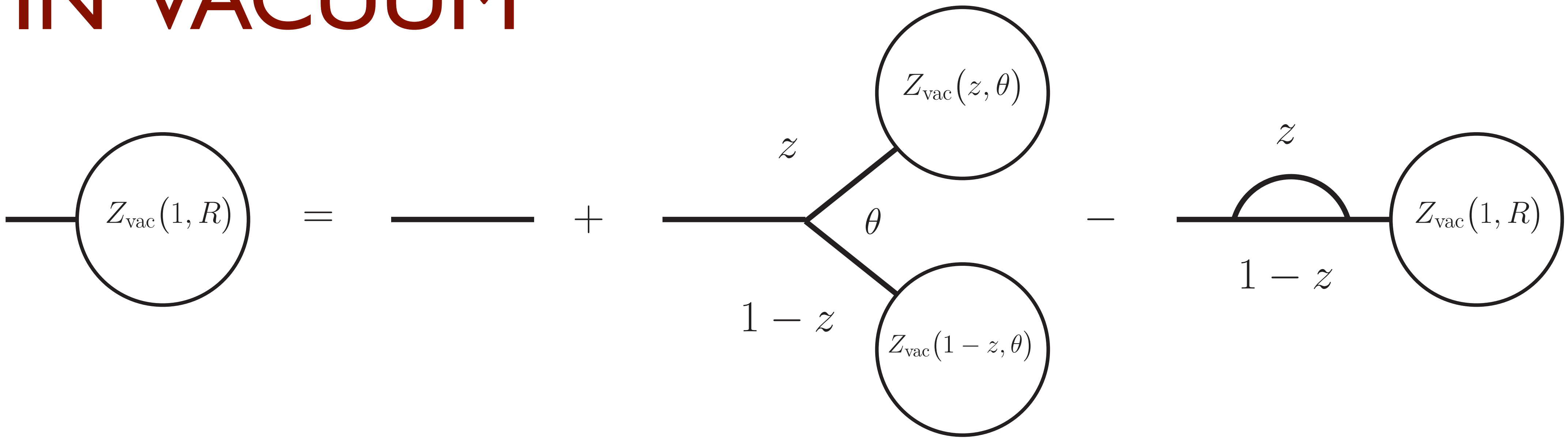
Applications to jets

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

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



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

$Z_{\rm vac}(u=1) = 1$ from probability conservation!

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

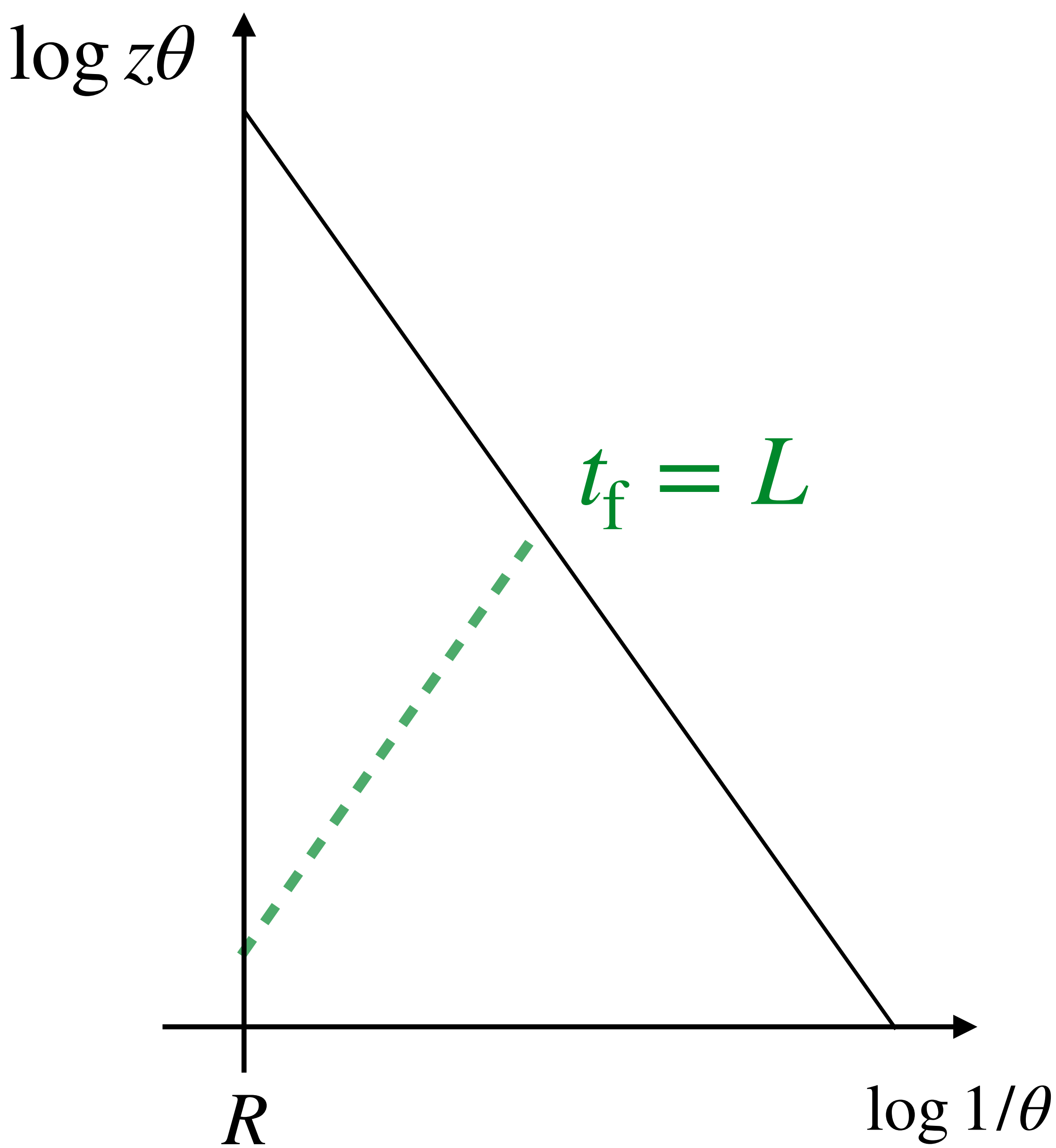
angular ordered (MLLA) evolution equation

GF FOR QUENCHED JETS

$$Z(p,R\,|\,u) = u(p) + \int^R \mathrm{d}\Omega\,\Theta_{\mathrm{in}}\big[Z_{\mathrm{io}}(zp,\theta)Z_{\mathrm{io}}((1-z)p,\theta)\mathcal{Q}(p)^2 - Z(p,\theta)\big]$$
$$+ \int^R \mathrm{d}\Omega\,\Theta_{\mathrm{out}}\,\big[Z_{\mathrm{vac}}(zp,\theta)Z_{\mathrm{vac}}((1-z)p,\theta) - Z_{\mathrm{vac}}(p,\theta)\big]$$

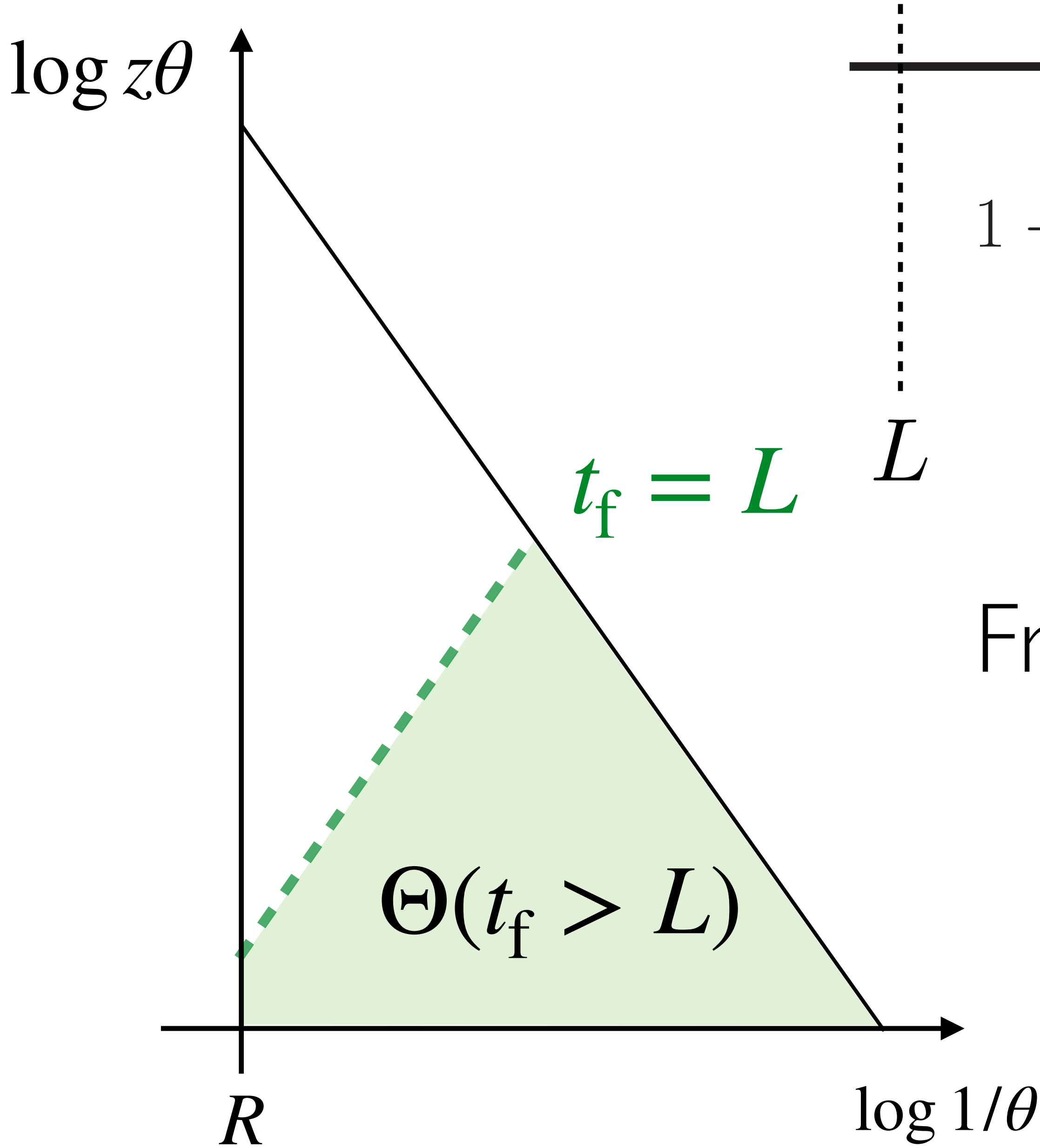
- in addition, the total charge of jet comes with $\mathcal{Q}(p)$
- couples in-medium and out-of-medium showers via $Z_{\mathrm{io}}(p,\theta) = Z(p,\theta) + Z_{\mathrm{out}}(p,\theta)$
  - including possible violations of AO
- implements quenching effects for the in-medium radiation
- Θ_{in} and Θ_{out} encode the jet/medium scale analysis

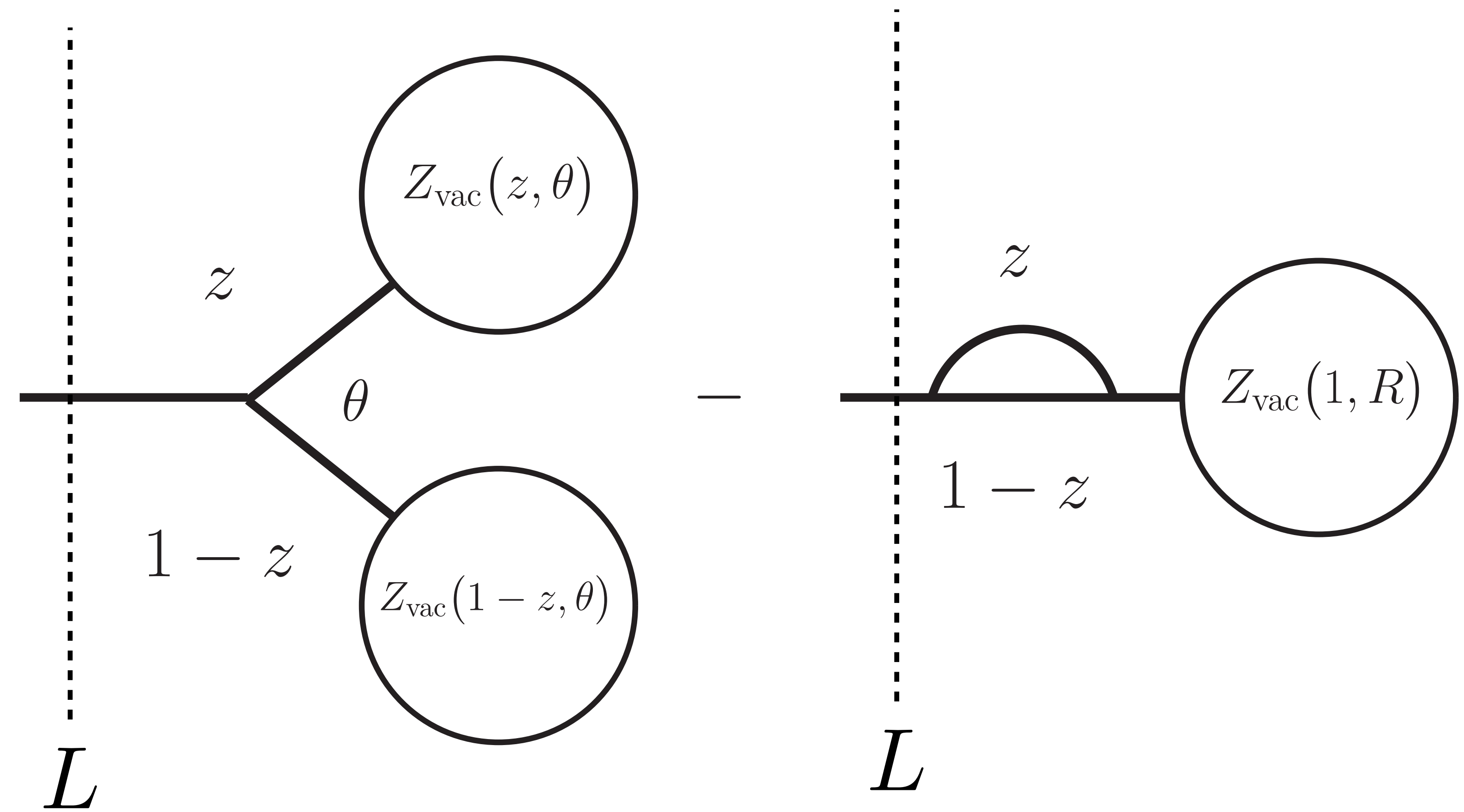
SIMPLIFIED MODEL



- consider for the moment the simpler situation: **in** or **out** of the medium
- GF differentiates between two distinct cases
  - no cross-talk

GF CONTRIBUTIONS

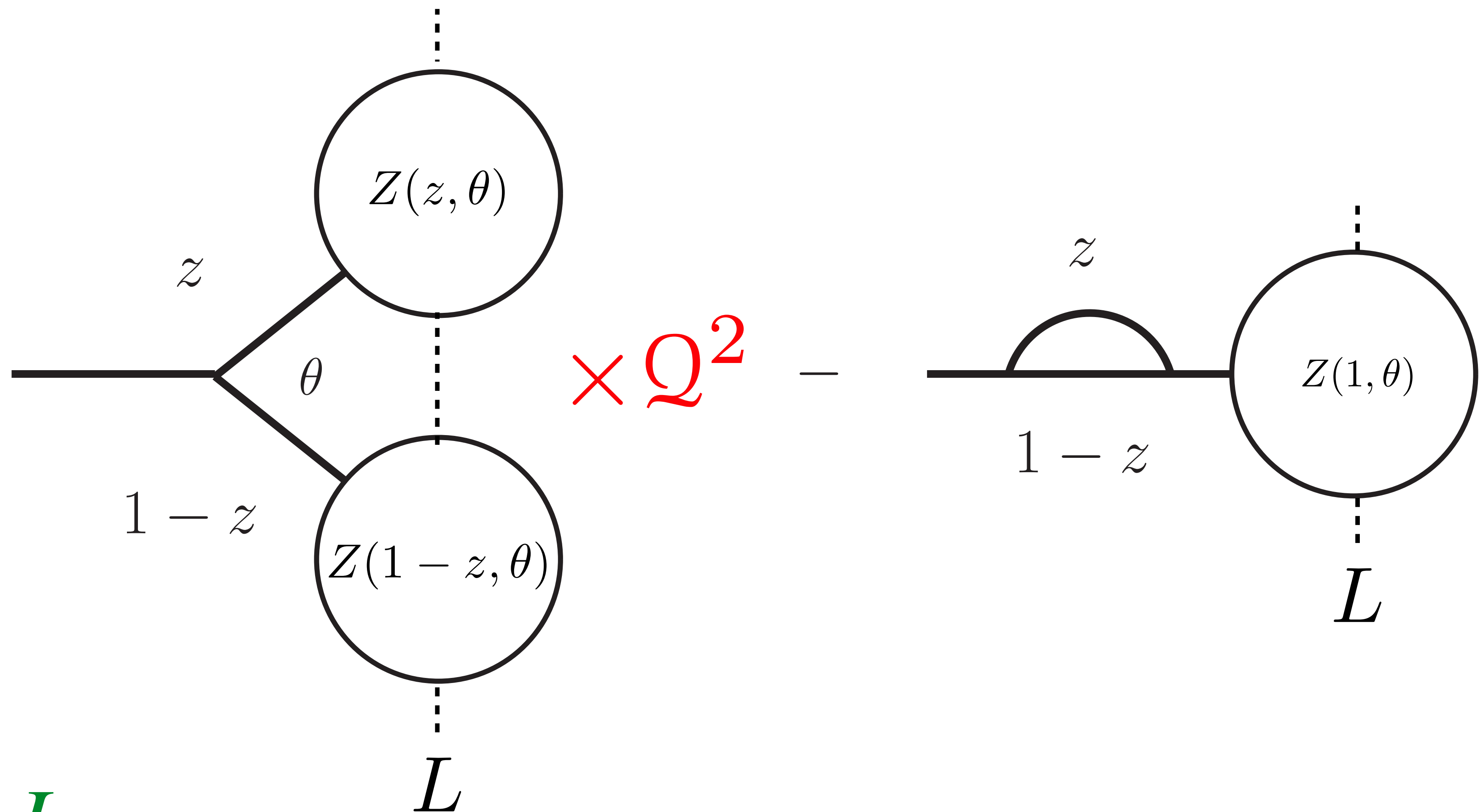


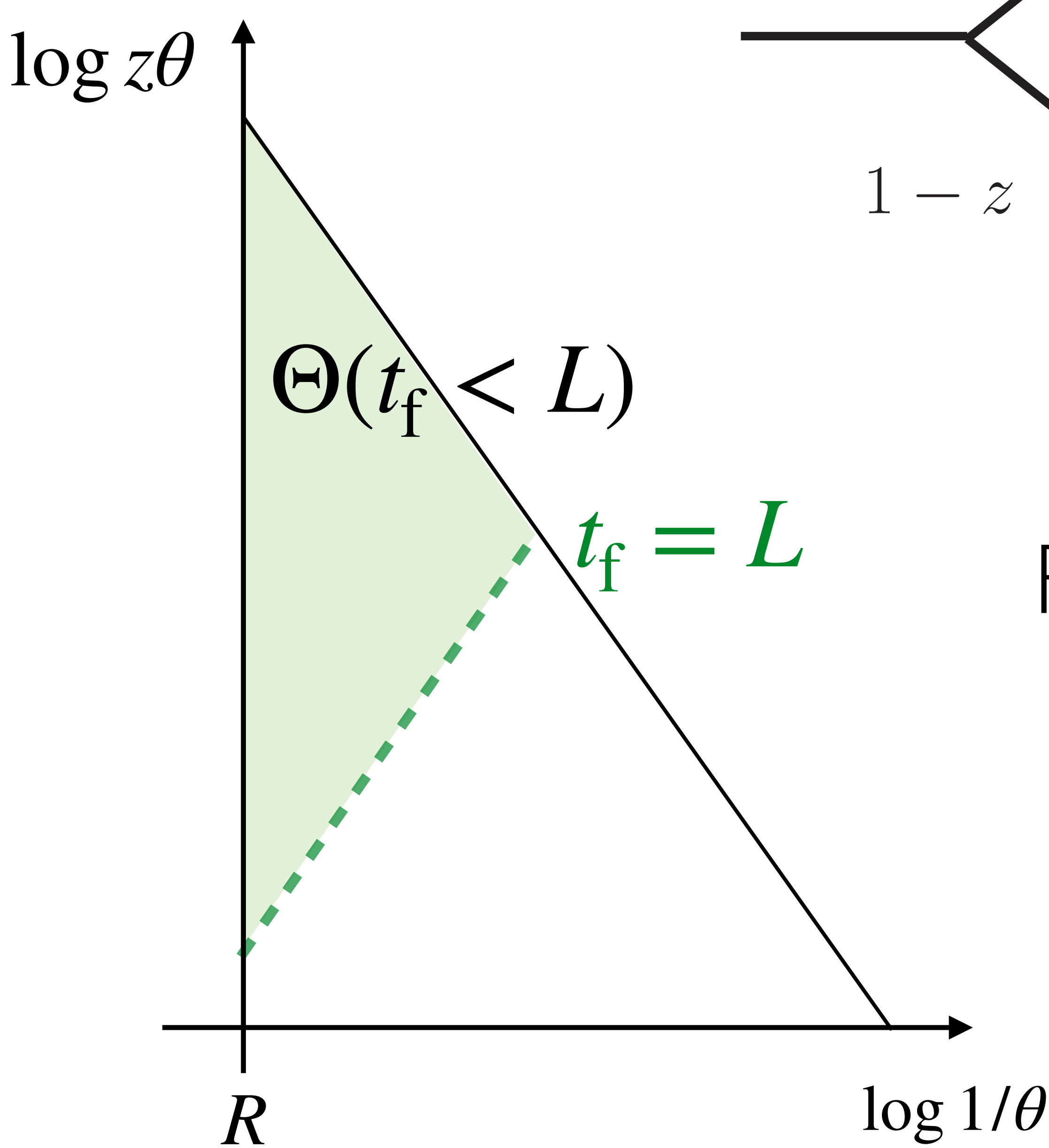


Fragmentation **outside** the medium

… is vacuum-like (AO).

GF CONTRIBUTIONS





Fragmentation **inside** the medium

… is vacuum-like (AO).

… is quenched.

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

Caucal, Iancu, Mueller, Sozey PRL (2018)

GF NORMALIZATION

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

Probability is no longer conserved: $Z(p, R\,|\,u = 1) = \mathscr{C}(p, R)$!

Mismatch between real and virtual diagrams!

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

GF NORMALIZATION

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

Probability is no longer conserved: $Z(p, R\,|\,u = 1) = \mathscr{C}(p, R)$!

Mismatch between real and virtual diagrams!

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

assumptions about medium effects (quenching)

GF NORMALIZATION

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

Probability is no longer conserved: $Z(p, R \,|\, u = 1) = \mathscr{C}(p, R)$!

Mismatch between real and virtual diagrams!

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

assumptions about medium effects (quenching) → affected phase space for vacuum radiation

GF NORMALIZATION

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

Probability is no longer conserved: $Z(p, R\,|\,u=1) = \mathscr{C}(p,R)$!

Mismatch between real and virtual diagrams!

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

assumptions about medium effects (quenching) → affected phase space for vacuum radiation → collimator function (normalization)

*) mismatch can also arise due to other processes than energy loss!

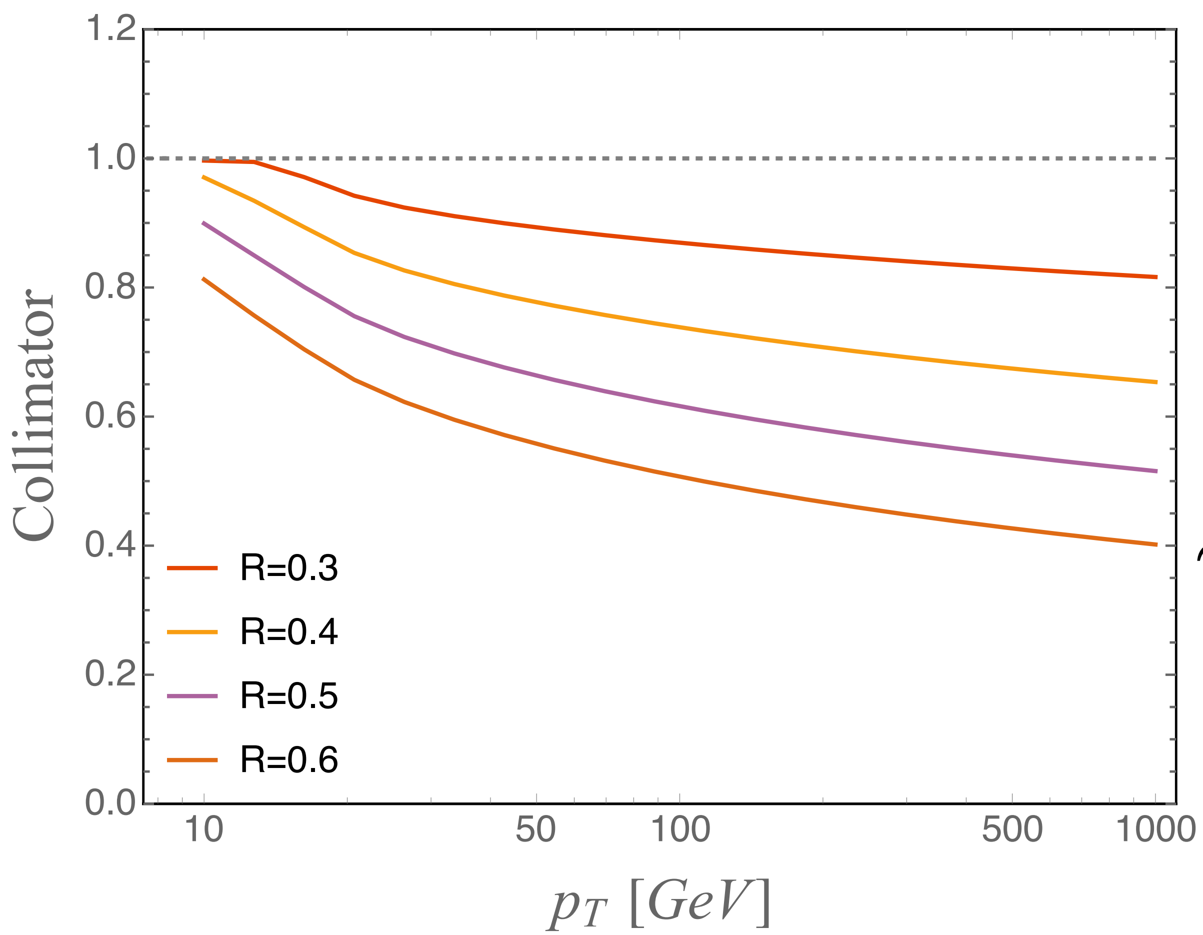
SUDAKOV SUPPRESSION

For $\mathscr{Q} = 1$ fixed point of the equation is simply $\mathscr{C} = 1$.

It is natural to expect this to be the limit at high-p_T.

SUDAKOV SUPPRESSION

For $\mathcal{Q} = 1$ fixed point of the equation is simply $\mathcal{C} = 1$.
It is natural to expect this to be the limit at high-p_T.



Strong quenching limit
$\mathcal{Q}(p_T) \ll 1$ (Sudakov factor):

$$\sim \exp\left[-2\bar{\alpha}\log\frac{R}{\theta_c}\left(\log\frac{p_T}{\omega_c} + \frac{2}{3}\log\frac{R}{\theta_c}\right)\right]$$

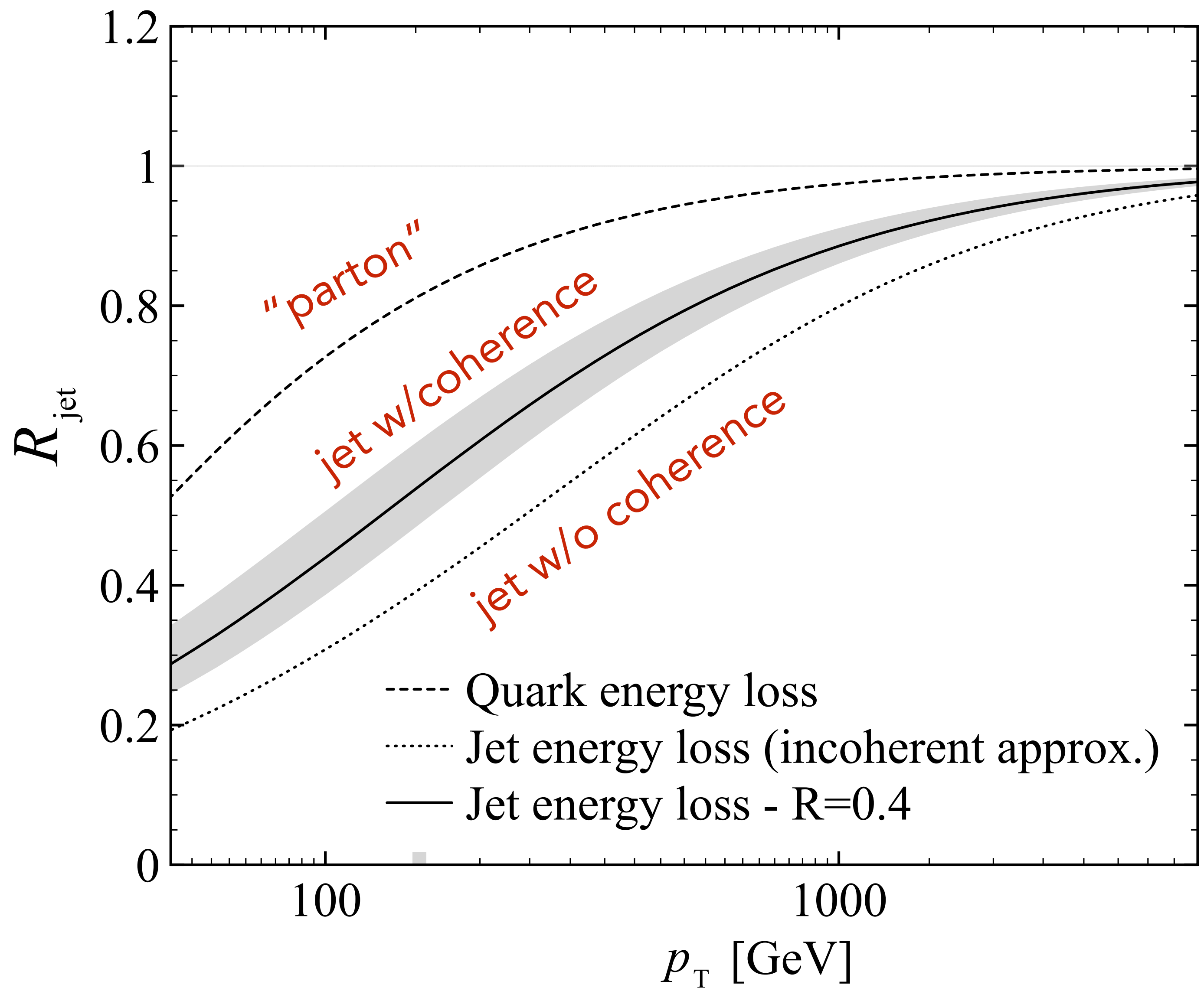
*) other fixed point possible for other types of real-virtual mismatch

SINGLE-INCLUSIVE SPECTRUM

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

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

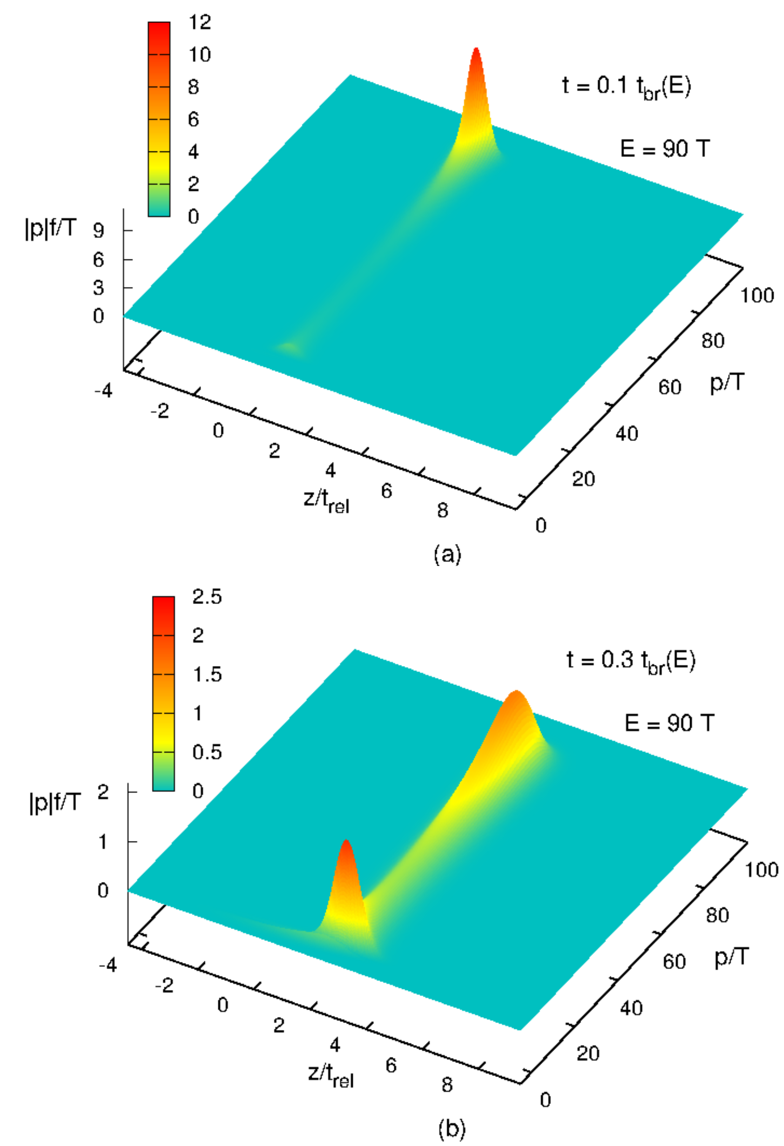
jet loses energy via total charge & resolved substructure fluctuations



BUT… WHERE DOES THE ENERGY GO?

- full solution of medium evolution equations
  - rapid depletion of energy
  - migration to large angles
  - saturation at the (global) thermal scale
- large jet radii: start to recover the energy deposited at T
  - R dependence is dampened
- expect intricate interplay that is sensitive to the details of thermalization
- pQCD can provide the "benchmark" of expected modifications in the hard sector

Iancu, Wu 1506.07871



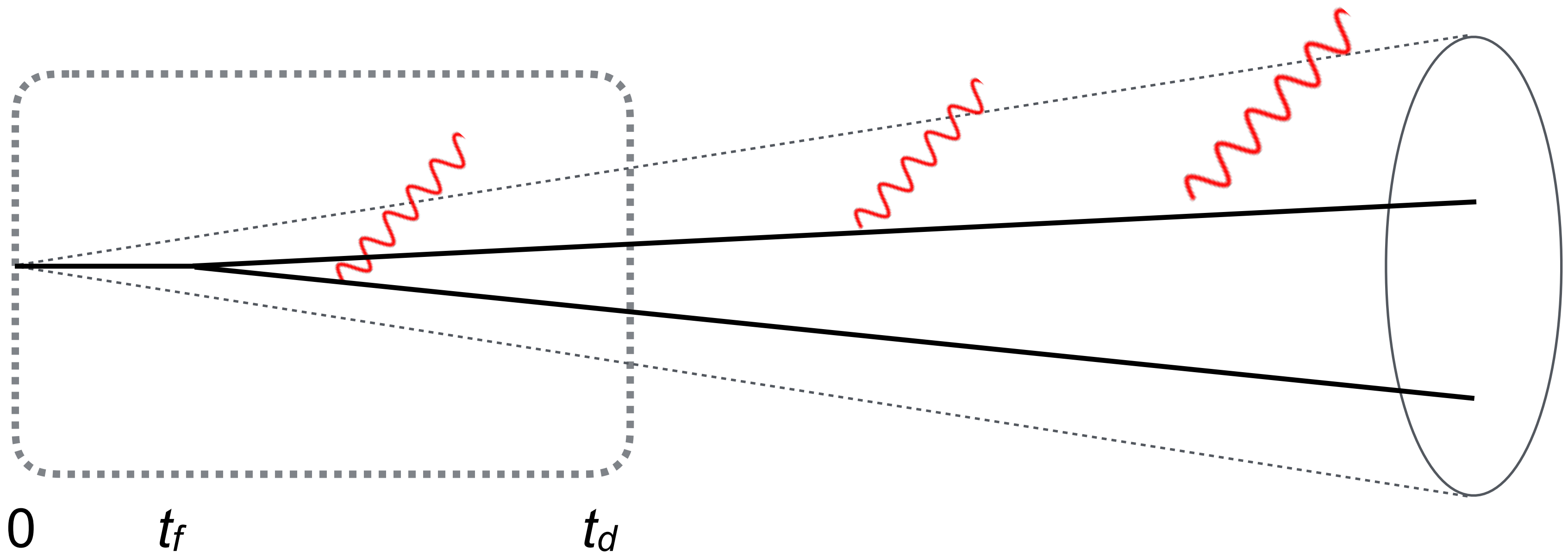
Conclusions

- substructure modifications driven by energy loss
  - also influenced by bremsstrahlung, color coherence effects, medium back-reaction
- probabilistic setup combining jet & medium scales
  - generating functional
  - systematically improvable
  - perturbative expansion to include hard, small-angle bremsstrahlung
- test bed to compare against MC model & data
  - collimator function: non-linear evolution of quenching

Back-up

NEIGHBORING JET ENERGY LOSS

Y. Mehtar-Tani, KT 1706.06047



$$t_{\rm d} \sim (\hat{q}\theta_{12}^2)^{-1/3}$$

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

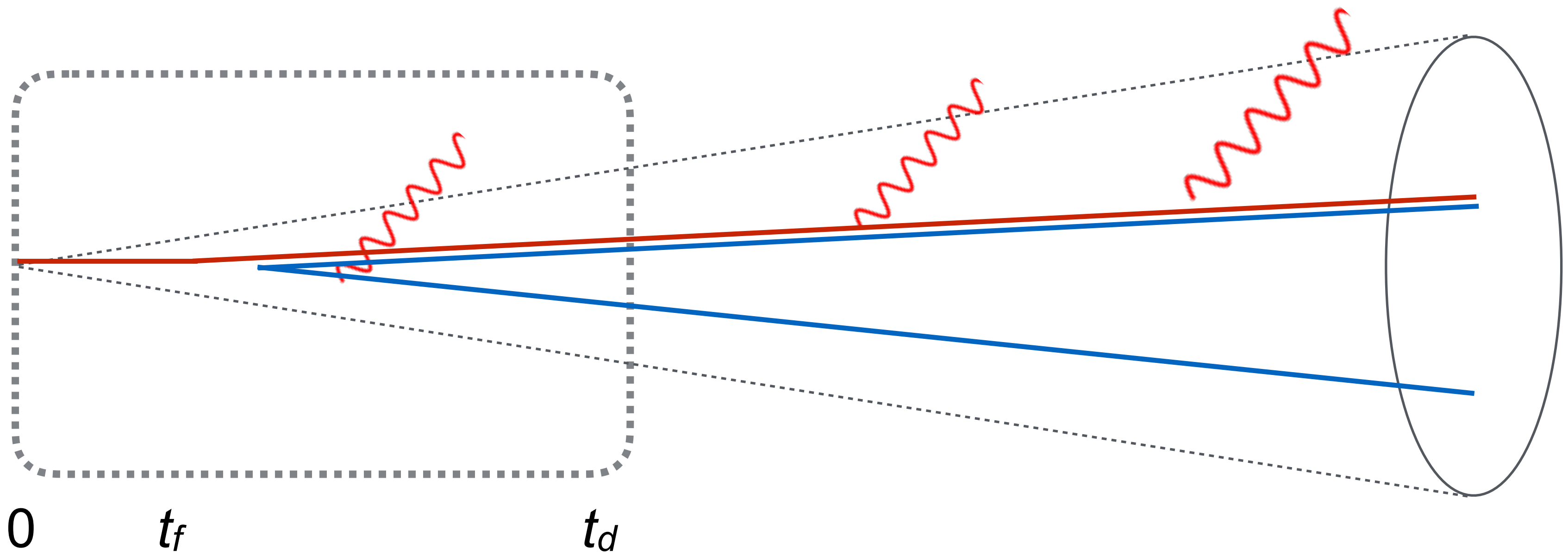
$$\mathcal{P}_2(\nu) = \mathcal{P}(\nu) \times \mathcal{P}_{\rm sing}(\nu)$$

energy loss of total color charge

delayed energy loss from resolved partons

NEIGHBORING JET ENERGY LOSS

Y. Mehtar-Tani, KT 1706.06047



$t_\mathrm{d} \sim (\hat{q}\theta_{12}^2)^{-1/3}$

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

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

energy loss of total color charge

delayed energy loss from resolved partons

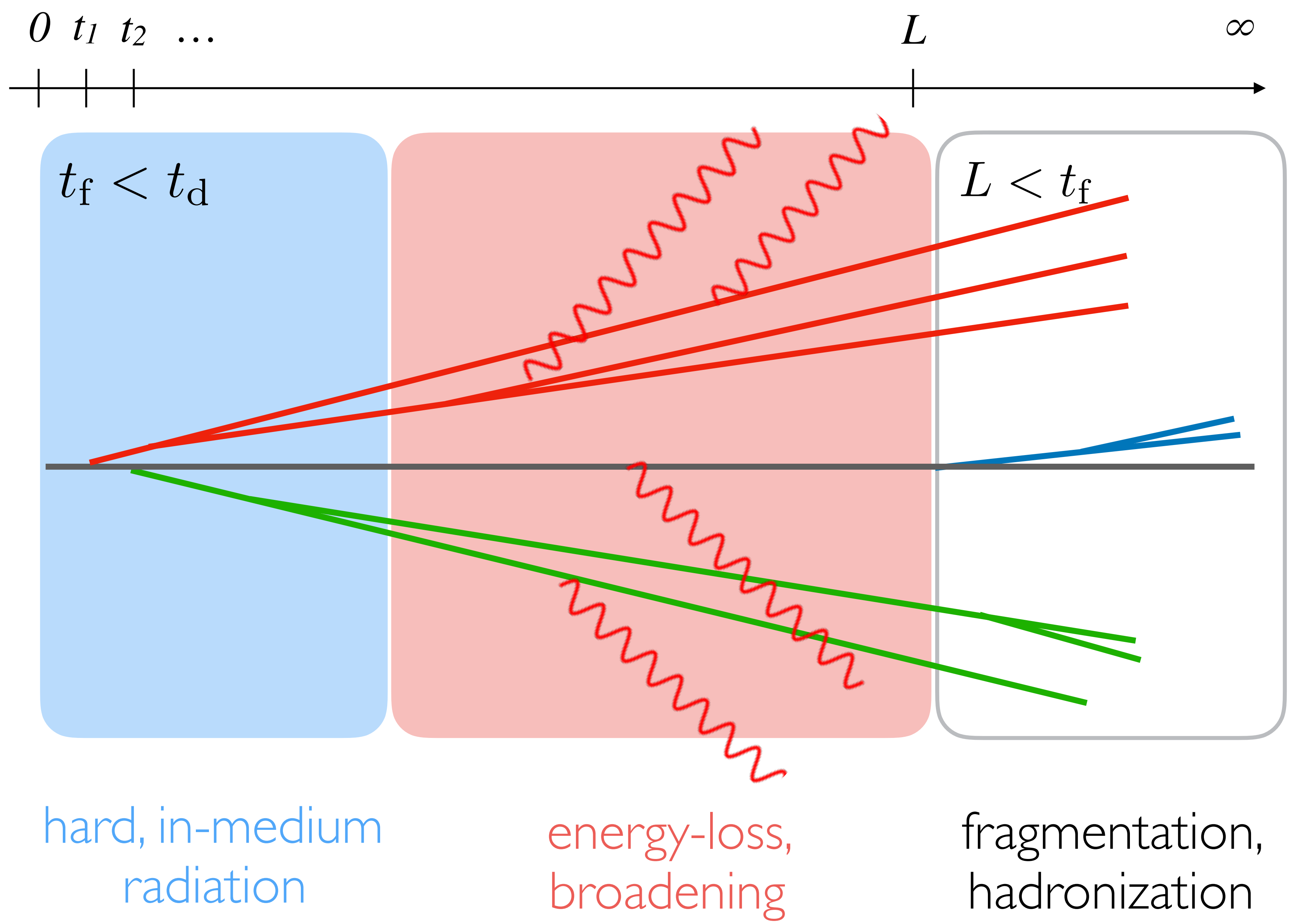
$$\mathcal{S}_2(t) = \exp\left[-\frac{1}{4}\int_0^t \mathrm{d}s\, \hat{q}(\boldsymbol{x}_{12}, t)\boldsymbol{x}_{12}^2(s)\right]$$

decoherence parameter

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

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

EMERGING PICTURE (DLA) FOR MC



Approximations @ DLA - intrinsic uncertainties (finite-length effects, etc…)

Many existing MC implementations…