Quantifying jet modifications with substructure

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In collaboration with Y. Mehtar-Tani

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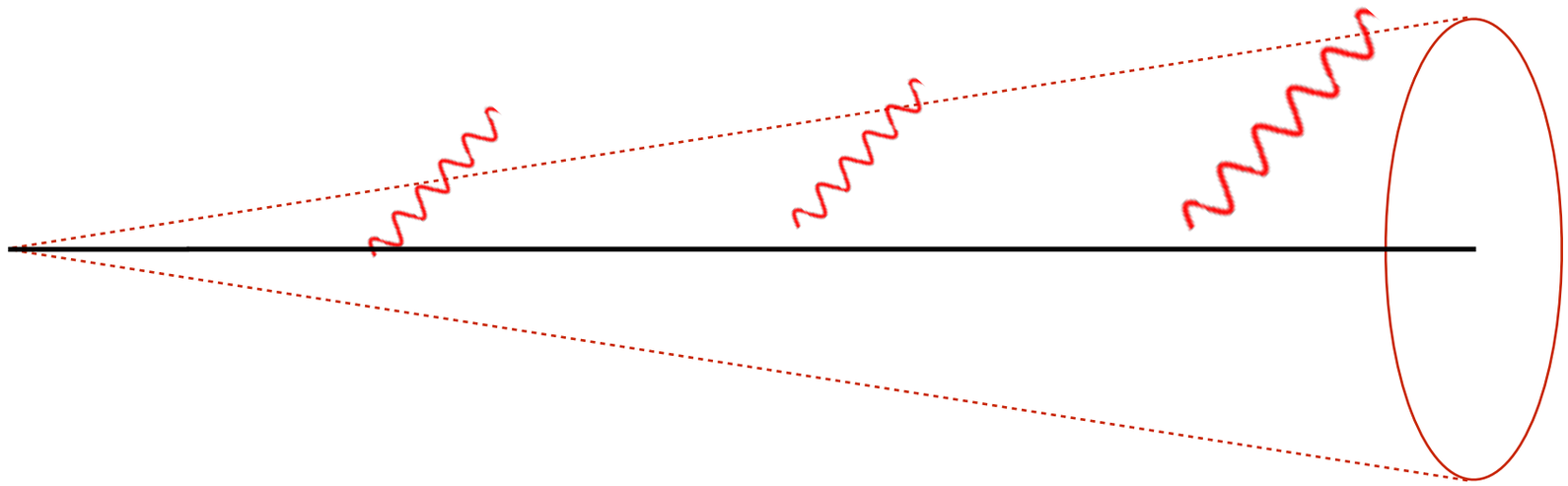
JET QUENCHING

- many experimental results & successful model implementations
  - modeling jet quenching phenomena realistically involves "multi-stage" Monte Carlo approach
  - competing effects in the soft sector
- theoretical guidance at high-pT?
  - what drives quenching & substructure modifications?
  - developing a probabilistic picture (including interferences)

QUENCHING WEIGHTS PARADIGM



- resummation necessary when the number of induced gluons become large
  - quasi-instantaneous medium-induced emissions
  - generically: QW for *any* energy loss
- **no dependence on jet scales**

Energy loss dominated by *typical* emitted energy (large medium)

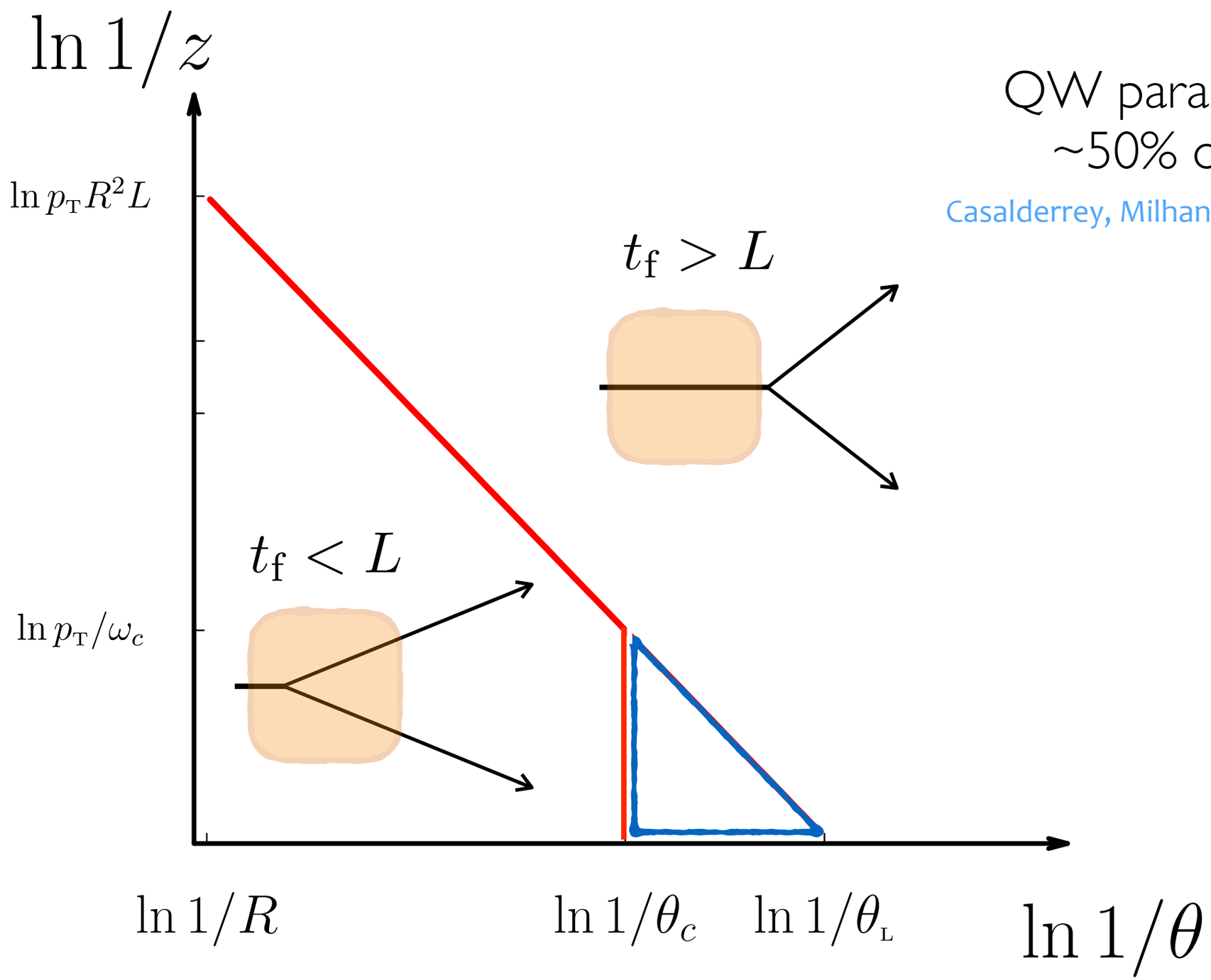
$$\mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}} \mathrm{e}^{-\frac{\pi \omega_s}{\epsilon}}$$

$$\omega_s \sim \alpha_s \hat{q} L^2$$

Baier, Dokshitzer, Mueller, Schiff JHEP 0109 (2001) 033
Salgado, Wiedemann PRD 68 (2003) 014008
Andres et al. EPJC 76 (2016) 475
Arleo PRL 119 (2017) 062302

PHASE SPACE ARGUMENTS

Consider phase space of collinear particles: $p_{\rm coll} \sim Q\left(1, \lambda^2, \lambda\right)$



QW paradigm applies only to ~50% of the full diagram!

Casalderrey, Milhano, Quiroga-Arias PLB 710 (2010) 175

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

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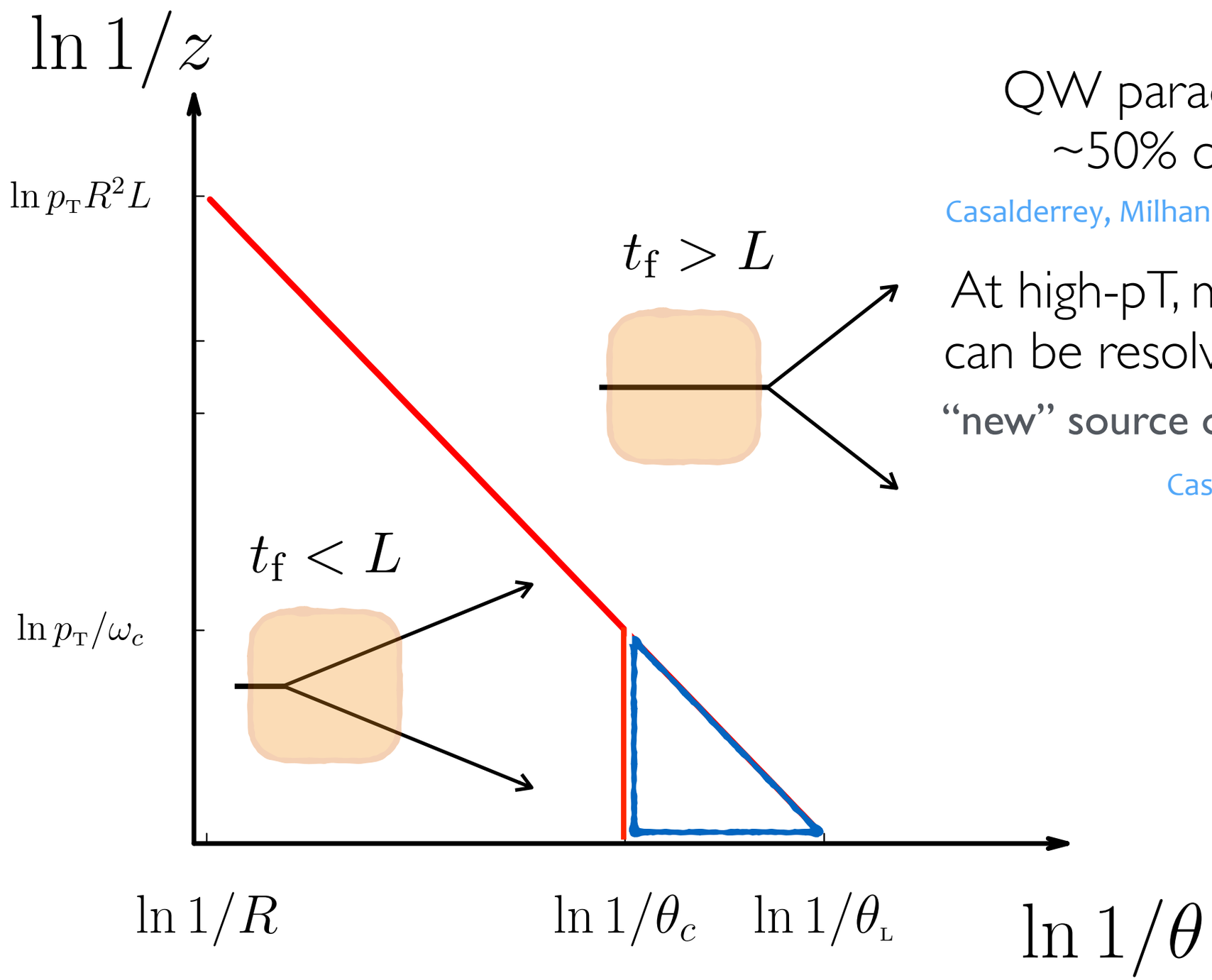

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At high-pT, many collinear particles can be resolved inside the medium.

"new" source of energy-loss fluctuations!

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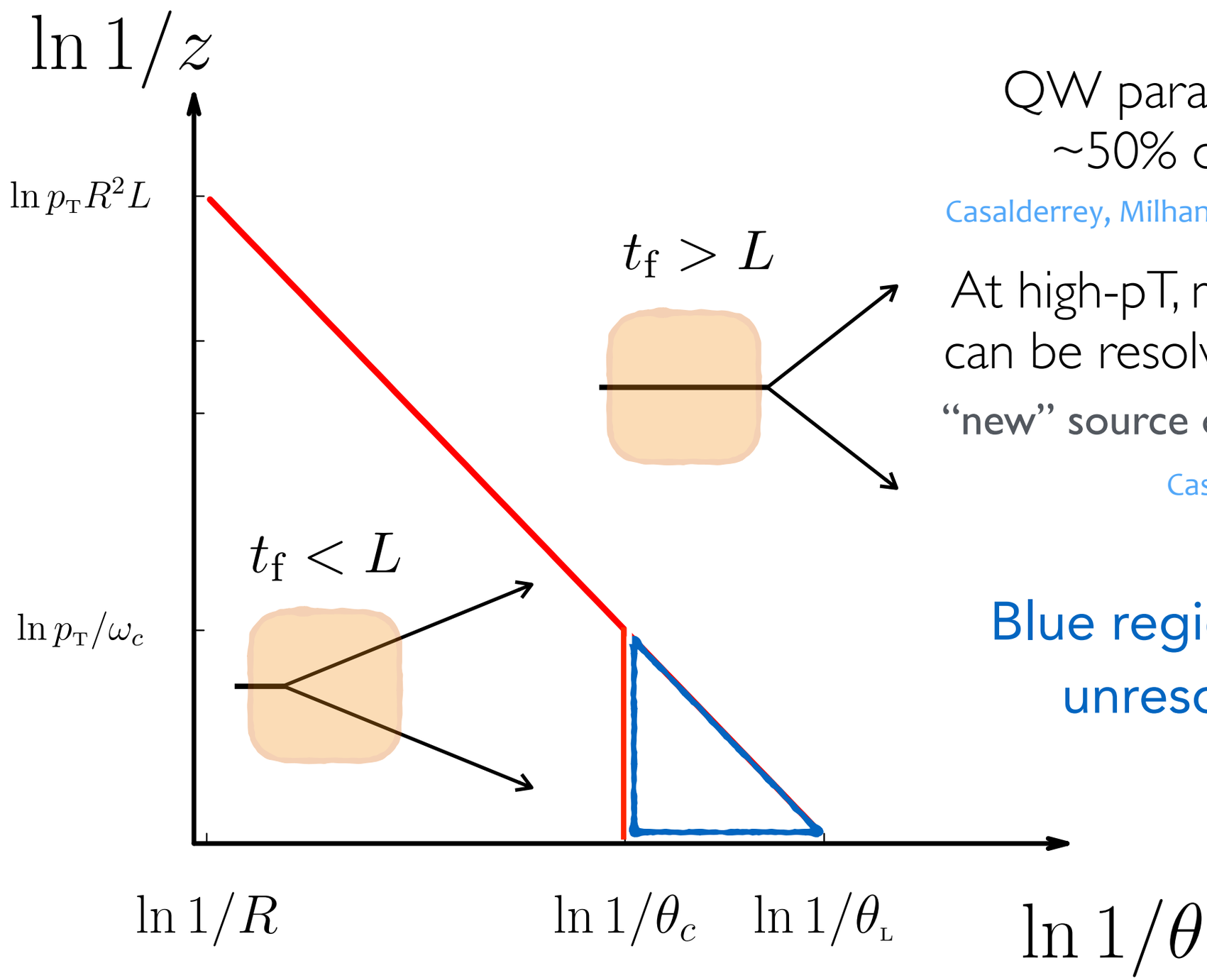

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Blue region corresponds to unresolved splittings.

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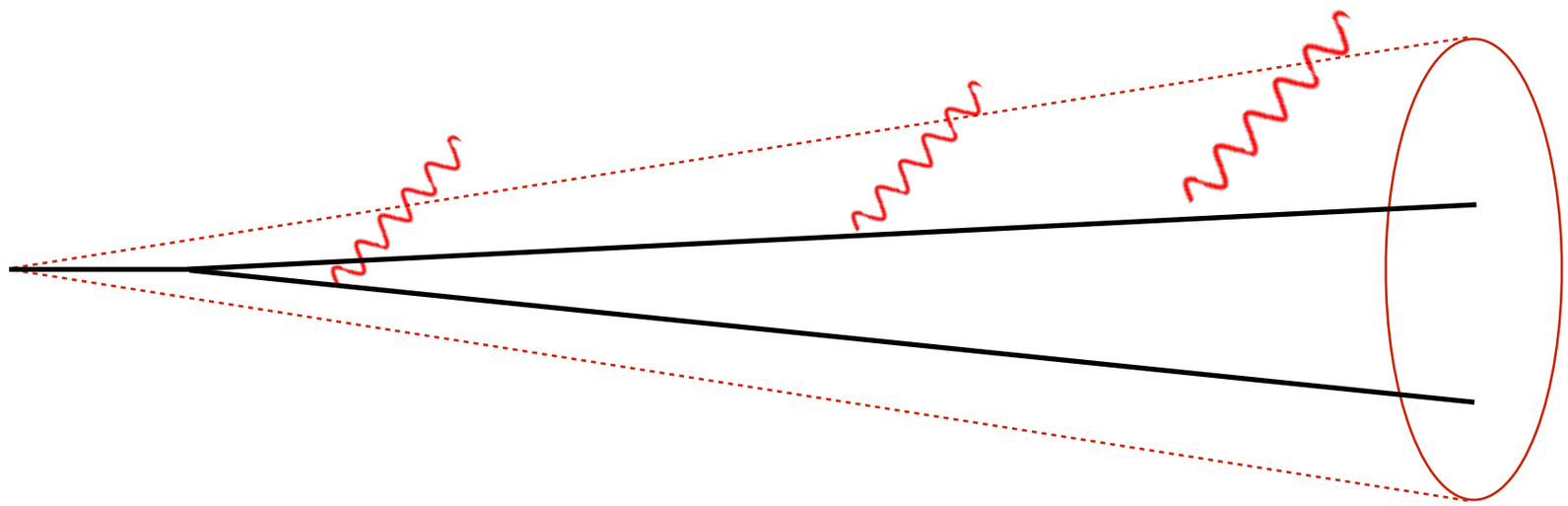
QUENCHING WEIGHTS 2.0

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



$$\mathcal{P}_{qg} = \mathcal{P}_q \otimes \mathcal{P}_{\rm sing}$$

- energy loss off dipole created by collinear splitting
- highlights important role of interferences
- two-prong QW in the large-Nc limit convolution of quenching of total charge & resolved color singlet dipole

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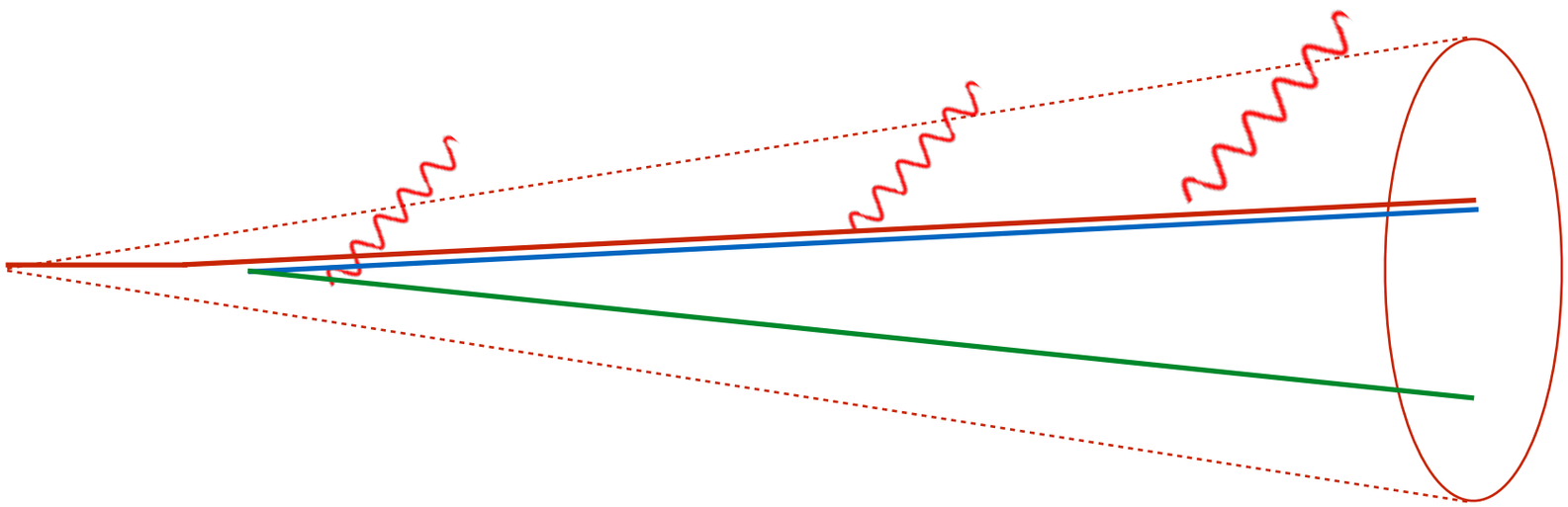

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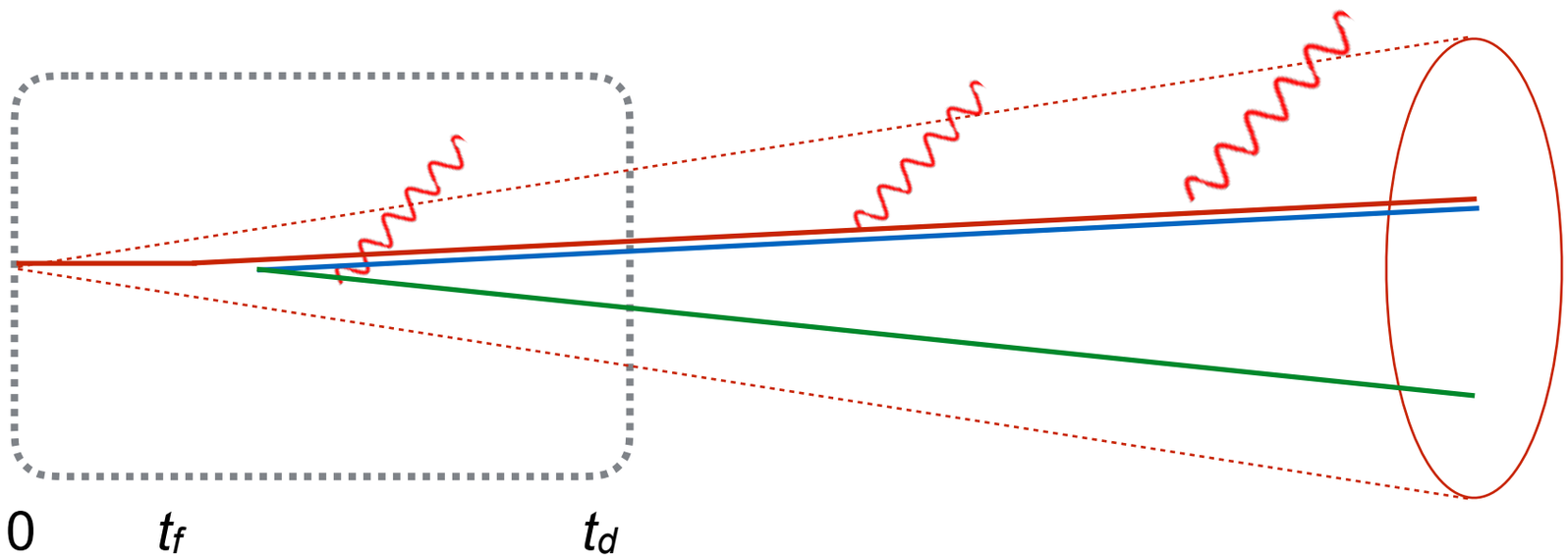

$$t_{\rm d} \sim (\hat{q}\theta_{12})^{-1/3}$$

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Quenching evolution equation

Regularized rates in Laplace space: $\gamma(\nu, t) = \int_0^\infty \mathrm{d}\omega \left(\mathrm{e}^{-\nu\omega} - 1\right) \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}t}$

Rate equation for one charge

$$\frac{\partial}{\partial t}\mathcal{P}(\nu, t) = \gamma_{\mathrm{dir}}(\nu, t)\mathcal{P}(\nu, t)$$

Rate equation for two charges

$$\frac{\partial}{\partial t}\mathcal{P}_{\mathrm{sing}}(\nu, t) = \gamma_{\mathrm{dir}}(\nu, t)\mathcal{P}_{\mathrm{sing}}(\nu, t) + \gamma_{\mathrm{int}}(\nu, t)\mathcal{S}_2(t)$$

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

decoherence parameter

JET SPECTRUM IN HEAVY-ION COLLISIONS

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

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

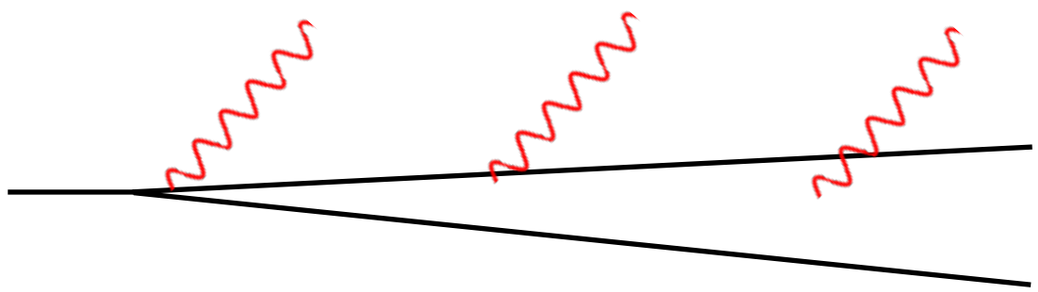
$$\Downarrow$$

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

- product of probabilities (Laplace space)
  - quenching of substructure fluctuations

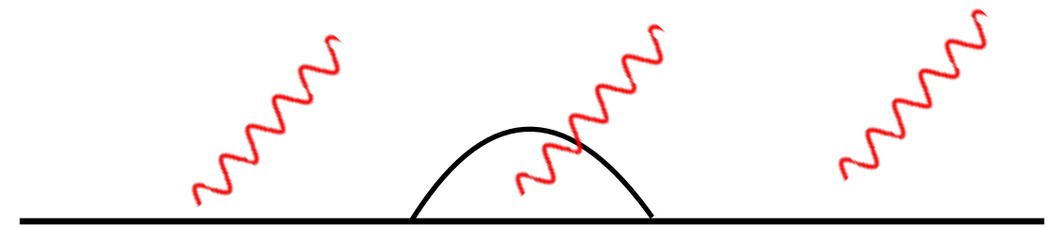
$$\mathcal{Q}_q(p_{\mathrm{T}}) = \mathrm{e}^{-2\sqrt{n\pi\omega_s/p_{\mathrm{T}}}}$$

Higher-order contributions



sensitive to two prongs

+



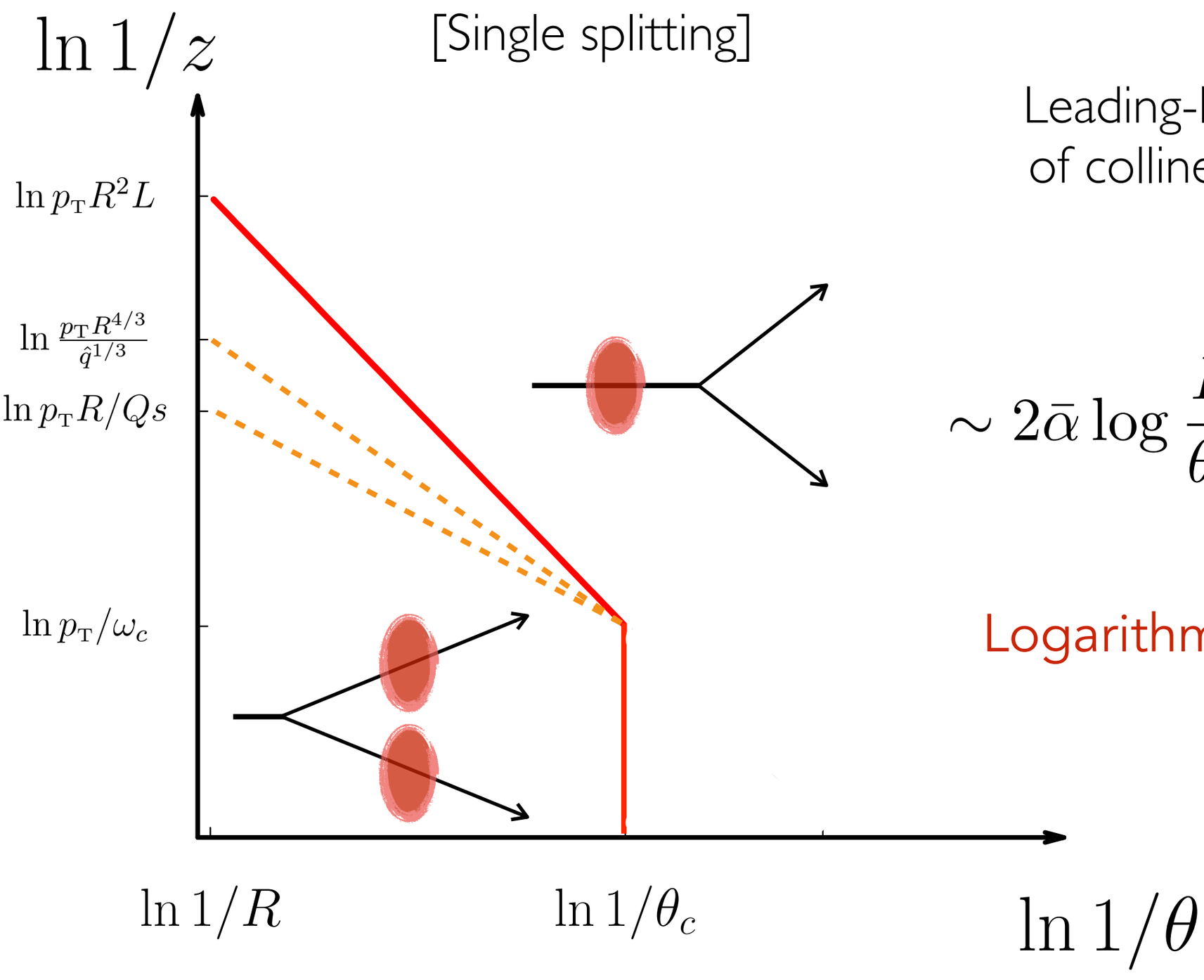
sensitive to one prong

$$R_{\rm jet} = \mathcal{Q}^{(0)}(p_{\rm T}) + \mathcal{Q}^{(1)}(p_{\rm T}) + \mathcal{O}(\alpha_s^2)$$

$$\mathcal{Q}^{(1)}(p_T) = \frac{\alpha_s}{\pi}\int_0^1 \mathrm{d}z P_{gq}(z) \int_0^R \frac{\mathrm{d}\theta}{\theta}\Big[\mathcal{Q}_{qg}(p_T) - \mathcal{Q}_q(p_T)\Big]$$

- LO corresponds to quenching of the total charge
  → common factor at all α_s (large-N_c)
- NLO enhanced by large logarithms!
  - the mismatch is largest at short formation times

Redrawing phase space



Leading-logs count the number of collinear modes resolved by the medium

$$\sim 2\bar{\alpha} \log \frac{R}{\theta_c} \log \frac{p_{\mathrm{T}}}{\omega_c} \left[\mathrm{Q}_q^2(p_{\mathrm{T}}) - 1 \right]$$

Logarithmic enhancement with jet scales!

SUDAKOV SUPPRESSION FACTOR

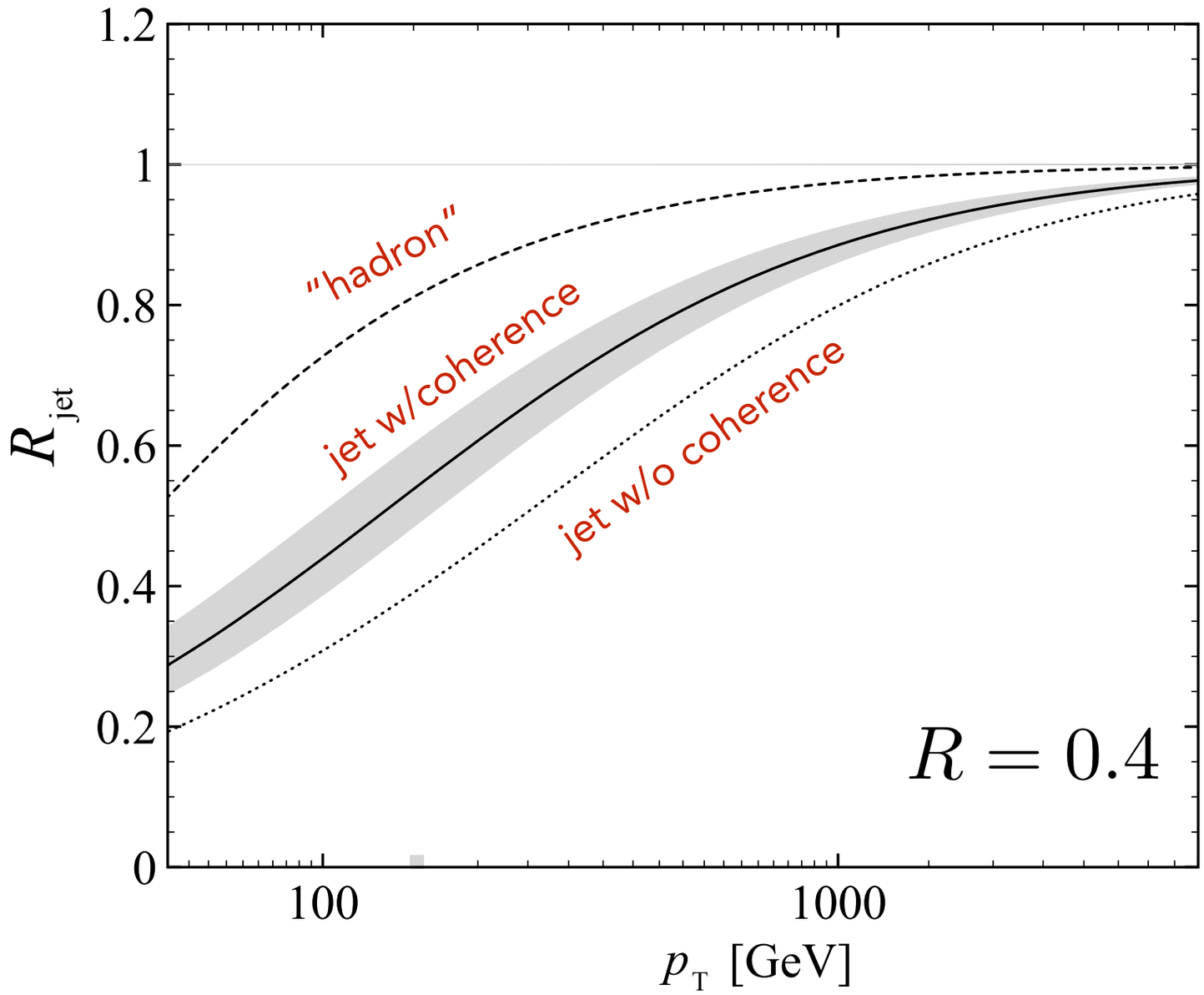
Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

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

- jet loses energy through total charge & resolved substructure fluctuations
  - qualitatively different quenching mechanism compared to leading hadrons
- Sudakov resummation of medium logs via non-linear equation

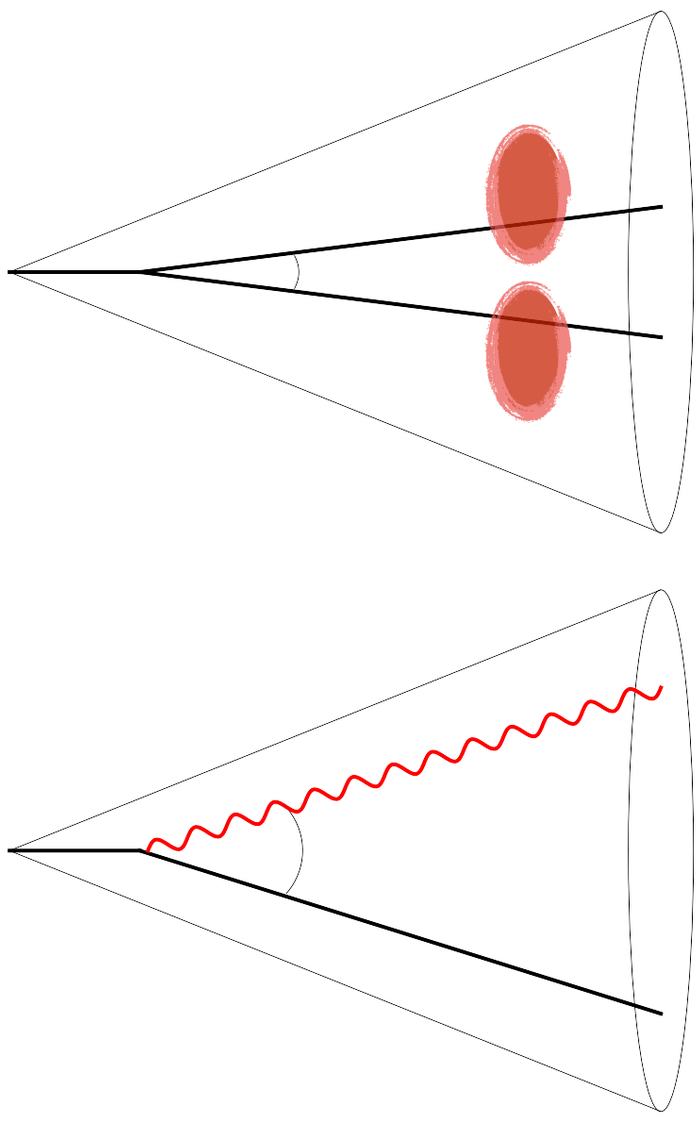
$$\mathcal{C}(1, p_{\rm T}, R) = 1 + \int_0^1 {\rm d}z \int_{\theta_c}^R \frac{{\rm d}\theta}{\theta} \frac{\alpha_s(k_\perp)}{\pi} P_{gq}(z) \Theta(t_{\rm f} < t_{\rm d}) \times \left[\mathcal{C}(z, p_{\rm T}, \theta)\mathcal{C}(1-z, p_{\rm T}, \theta)\mathcal{Q}_q^2(p_{\rm T}) - \mathcal{C}(1, p_{\rm T}, \theta)\right]$$

JET SUPPRESSION: NUMERICS



Quantitative difference for incoherent scenario: $\log \mathcal{C}_{\rm incoh} \sim \alpha_s \log^2 p_{\rm T}$

GUIDANCE FOR SUBSTRUCTURE



- overall suppression of the jet yield
- energy loss affects collinear modes at short formation times
- in addition, medium interactions can give rise to the excitation of new modes
- fragmentation with modified AO

Mehtar-Tani, KT PLB744 (2015) 284
Caucal, Iancu, Mueller, Soyez arXiv:1801.09703 [hep-ph]

Mapping out regions of resummations and higher-order corrections

Conclusions

- jet quenching at high-pT
  - sensitivity to jet evolution
  - novel Sudakov suppression factor (collimator)
- relating quenching to jet scales
  - analytic understanding
  - sensitivity to opening angle (parton mass…)
  - parametric estimates for observables & MC's
- substructure
  - energy loss affects collinear structure of jets