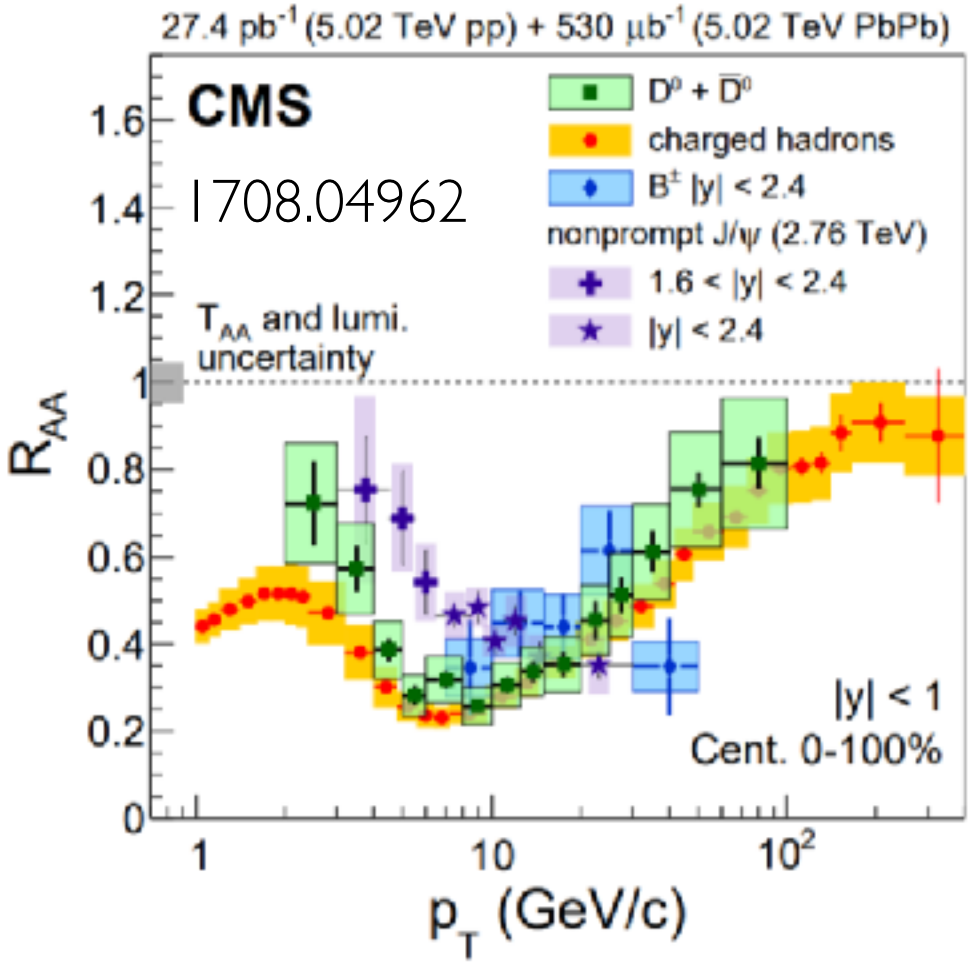
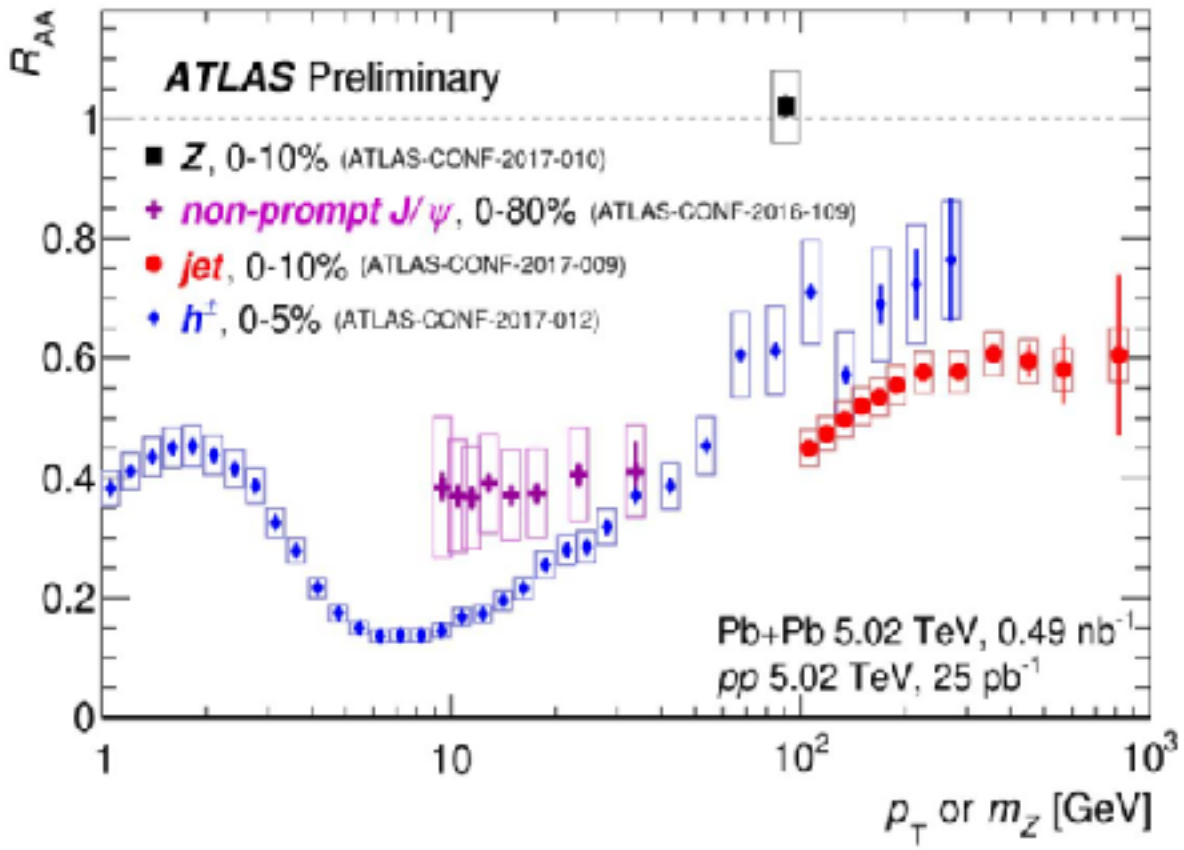
NOVEL CONTRIBUTIONS TO JET QUENCHING AT HIGH-P_T

Konrad Tywoniuk

Probing quark-gluon matter with jets, BNL 23-27 July 2018

JET QUENCHING 101





- jet quenching effects manifest as strong reduction of yields of hadrons & jets over a large range in p_T
- substructure modifications: broadening & softening
  - enhancement of soft & large-angle particles

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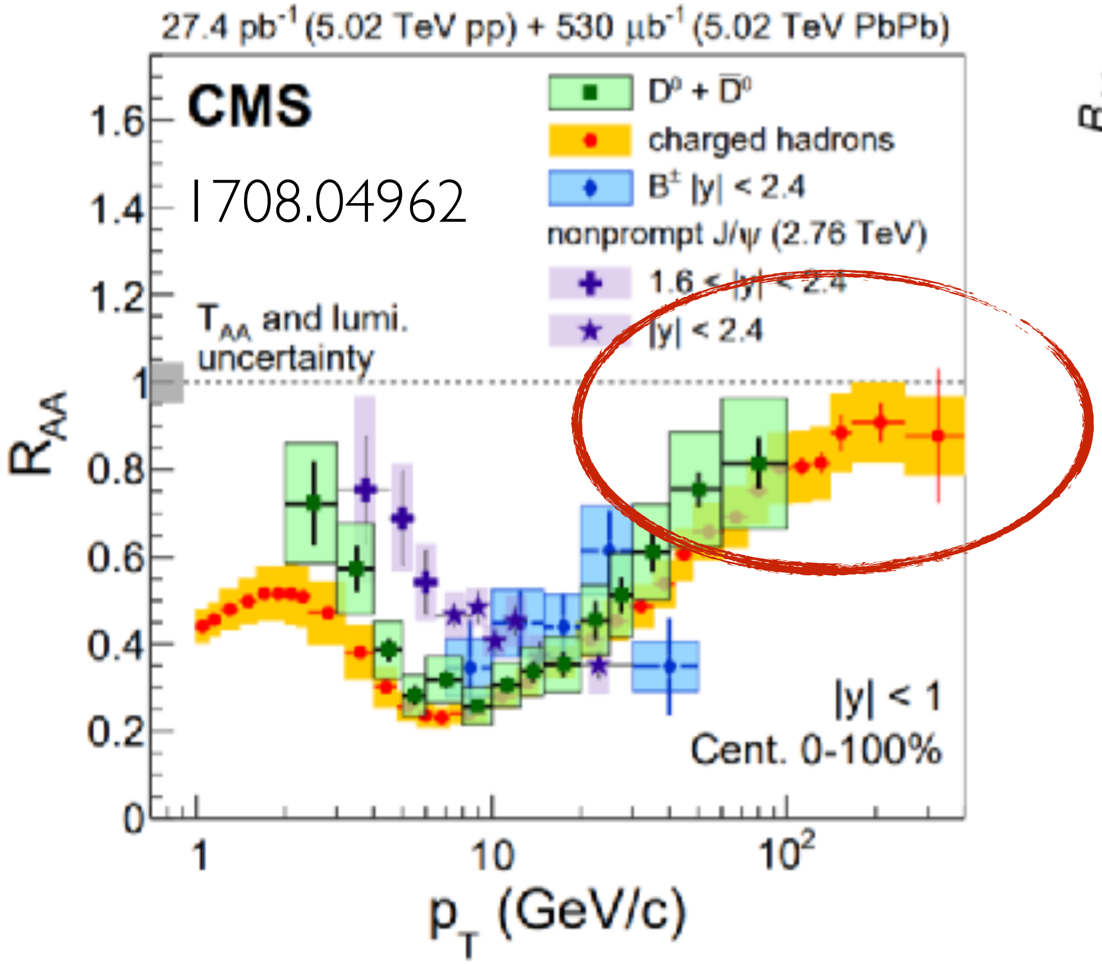

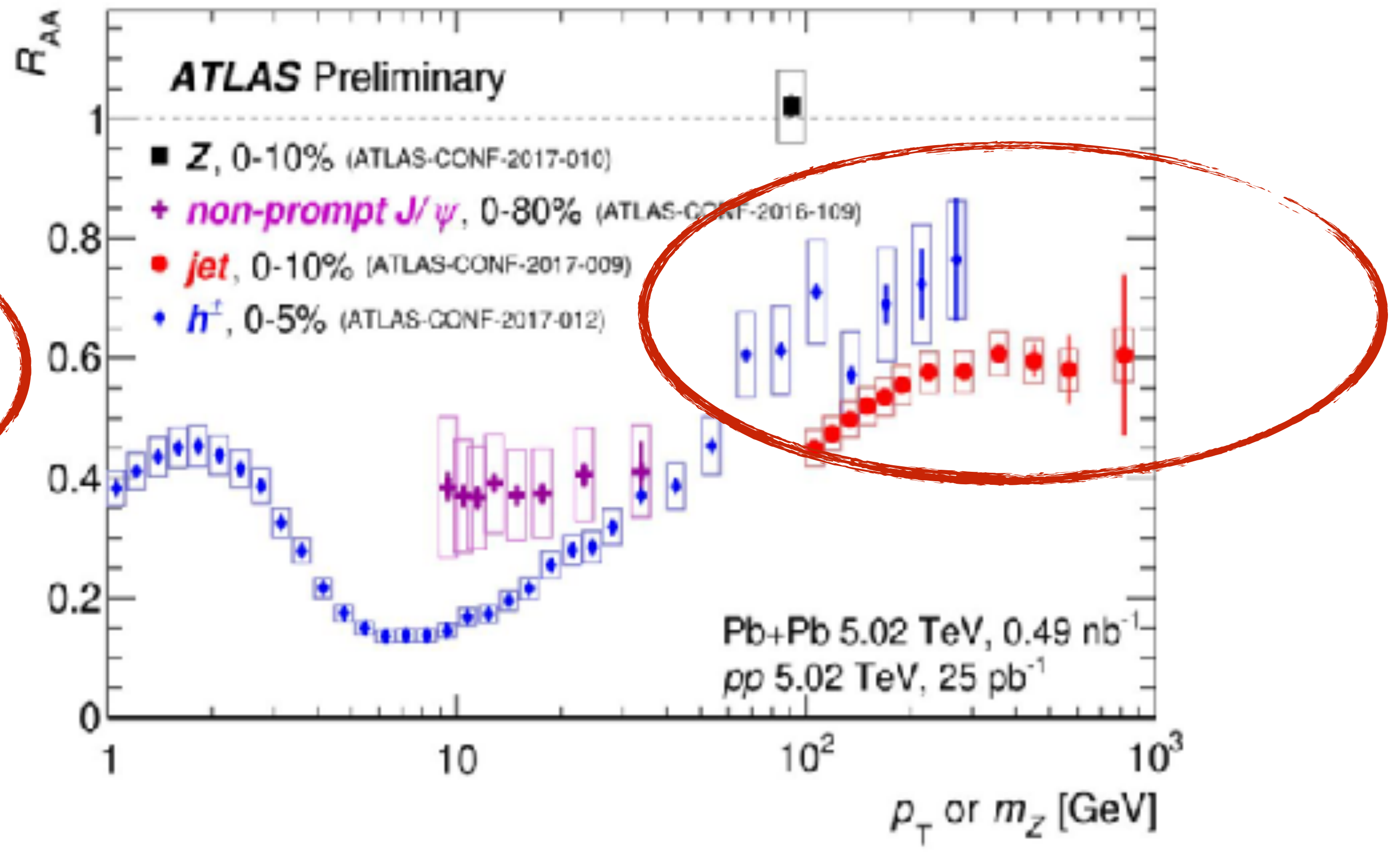

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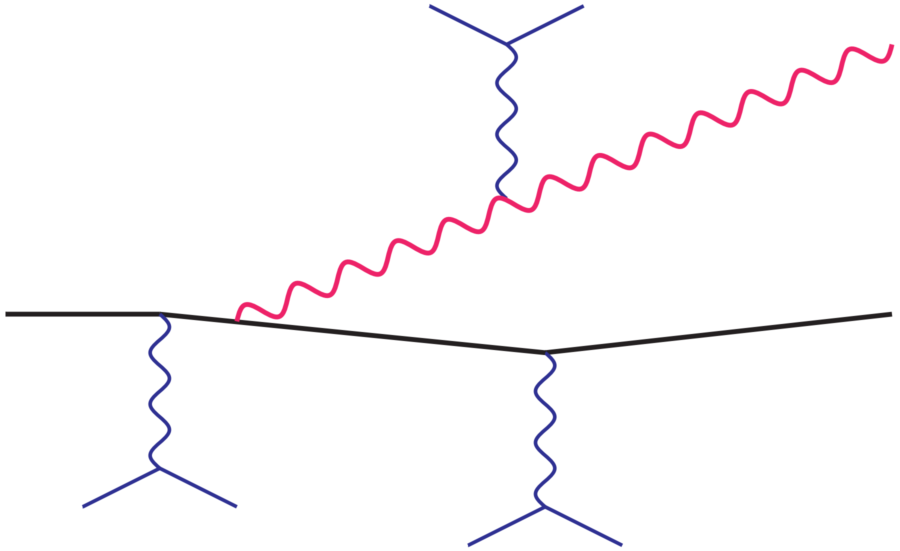
MOTIVATION

- many experimental results & successful model implementations
  - modeling jet quenching phenomena realistically involves "multi-stage" Monte Carlo approach
  - competing effects in the soft sector (medium back-reaction, color decoherence…)

- theoretical guidance at high-p_T?
  - what drives quenching & substructure modifications?
  - developing a probabilistic picture from first principles (including interferences)

RADIATION IN THE MEDIUM

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



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

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

lack of collinear singularity!

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

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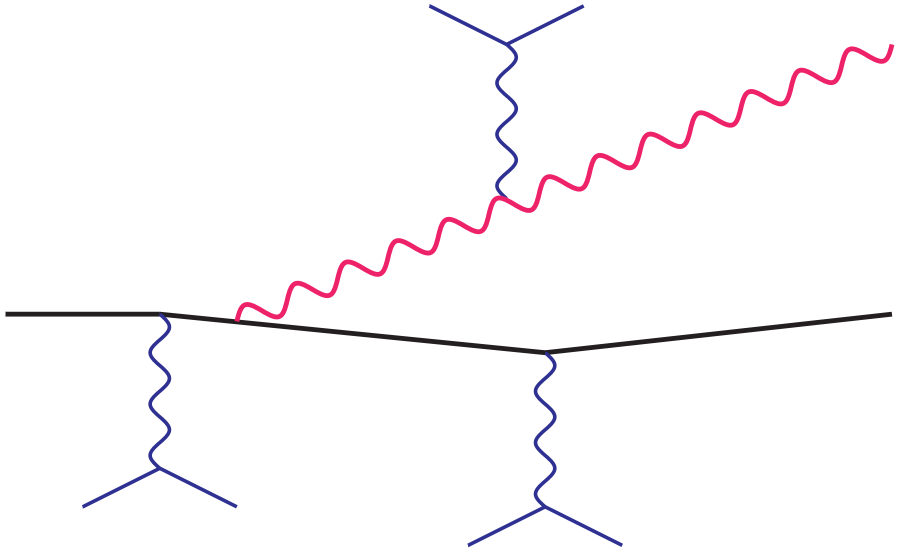

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rare, small-angle emission $\omega_c = \hat{q} L^2$

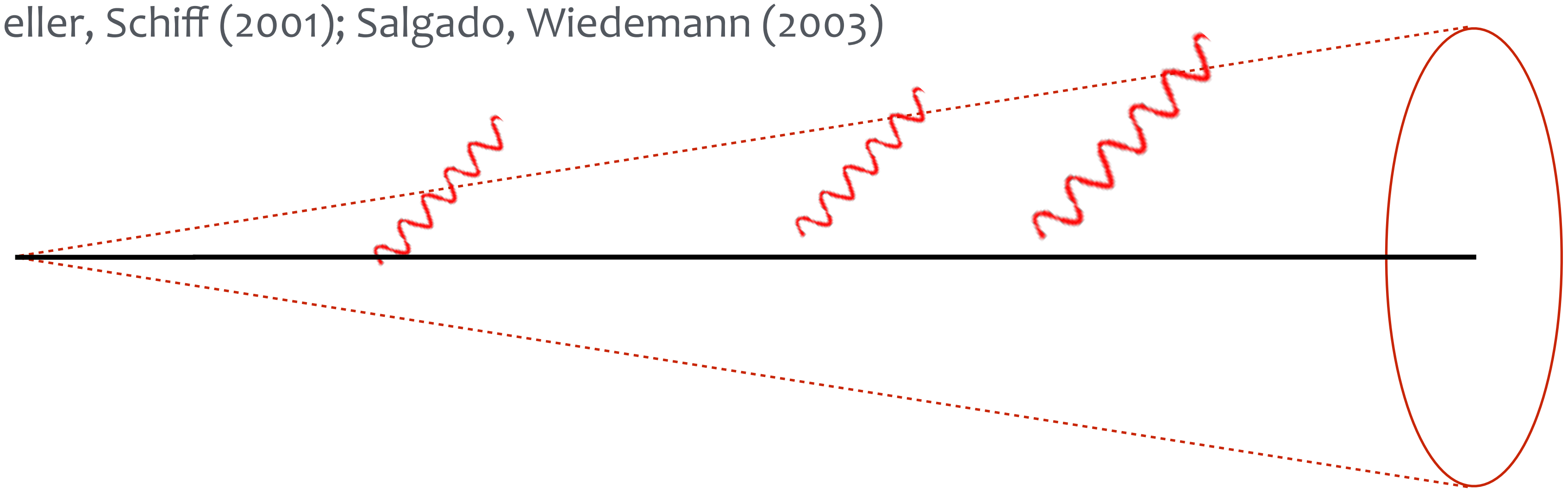
$$\theta_\mathrm{br}(\omega_c) \sim \sqrt{\frac{1}{\hat{q} L^3}} \equiv \theta_c$$

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

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

QUENCHING WEIGHTS PARADIGM

Baier, Dokshitzer, Mueller, Schiff (2001); Salgado, Wiedemann (2003)



- number of radiated gluons become large: resummation
  - energy loss probability (quenching weight)
  - energy carried to large angles & thermalized rapidly
- generically: QW for *any* energy loss
- no *a priori* dependence on jet scales

Strong quenching: energy loss dominated by *typical* emitted energy

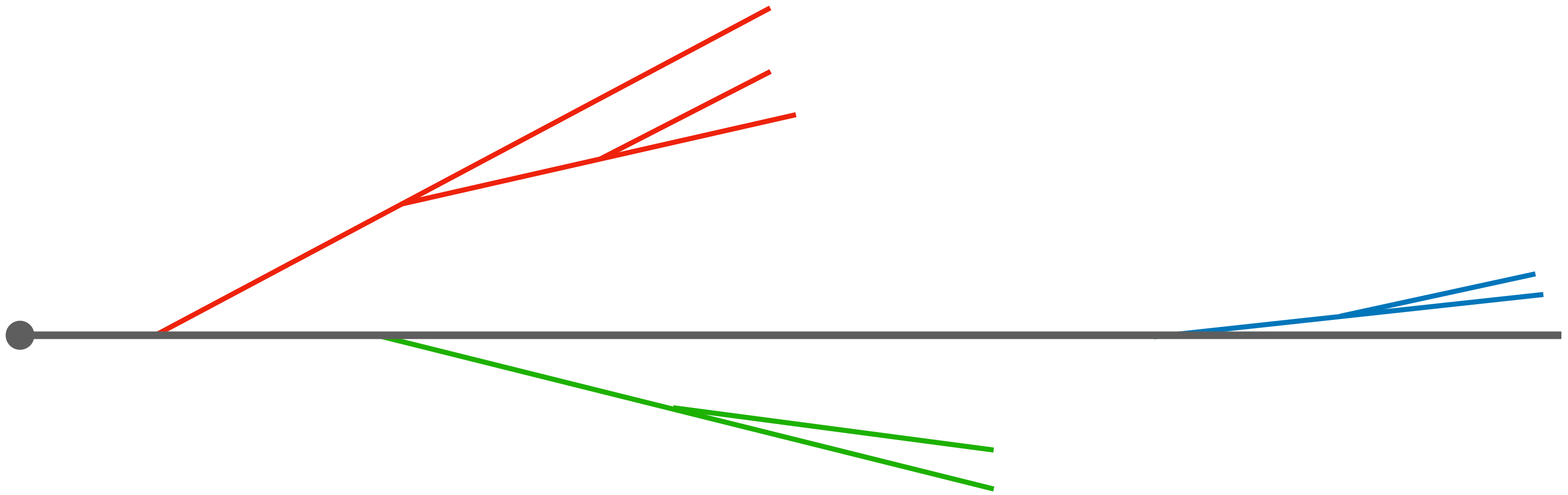
$$\mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}}\,\mathrm{e}^{-\frac{\pi\omega_s}{\epsilon}} \qquad \omega_s \sim \alpha_s^2 C_R^2 \hat{q} L^2$$

QW PARADIGM ASSUMES ONE HARD PARTON PROPAGATING THROUGH THE MEDIUM

When does this approximation break down?

JET SPACE-TIME EVOLUTION

Bassetto, Ciafaloni, Marchesini (1983); Dokshitzer, Troyan, Khoze, Mueller (1991)



- jets are multi-particle objects with interesting space-time pattern
- double-logarithmic regime
  - strong energy ordering
  - ***strong angular ordering***
  - formation time

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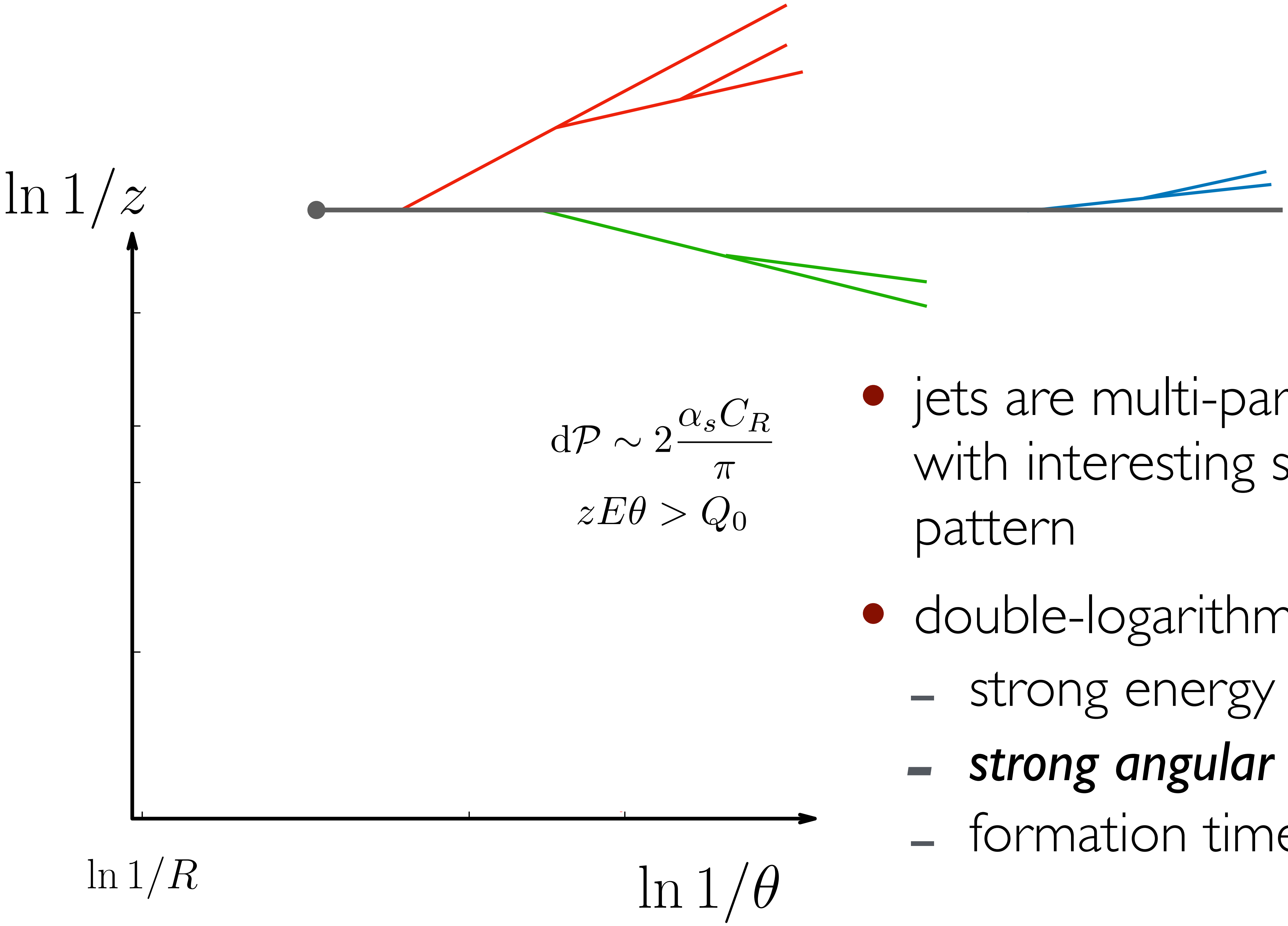

$$\mathrm{d}\mathcal{P} \sim 2\frac{\alpha_s C_R}{\pi}$$

$$zE\theta > Q_0$$

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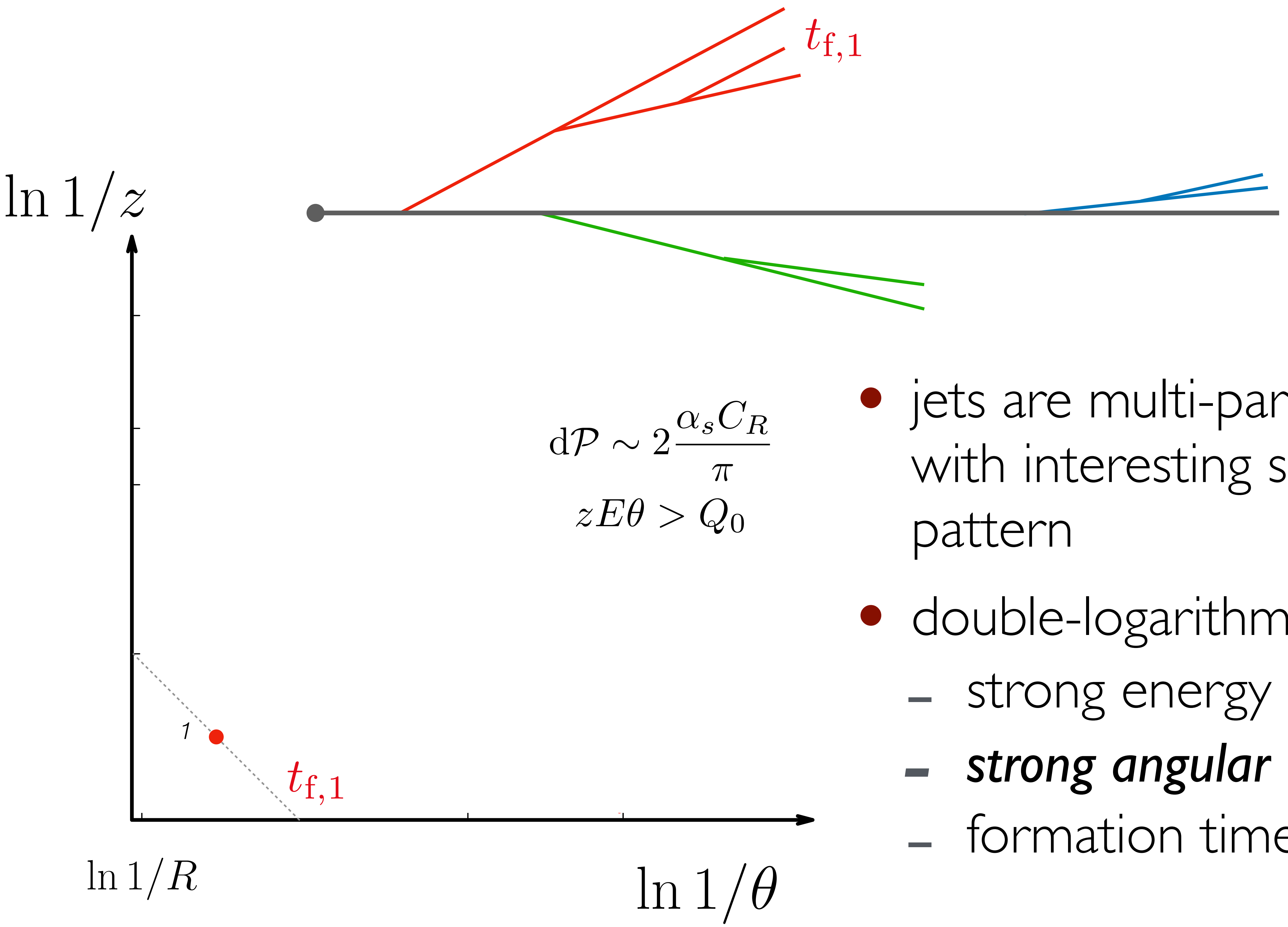

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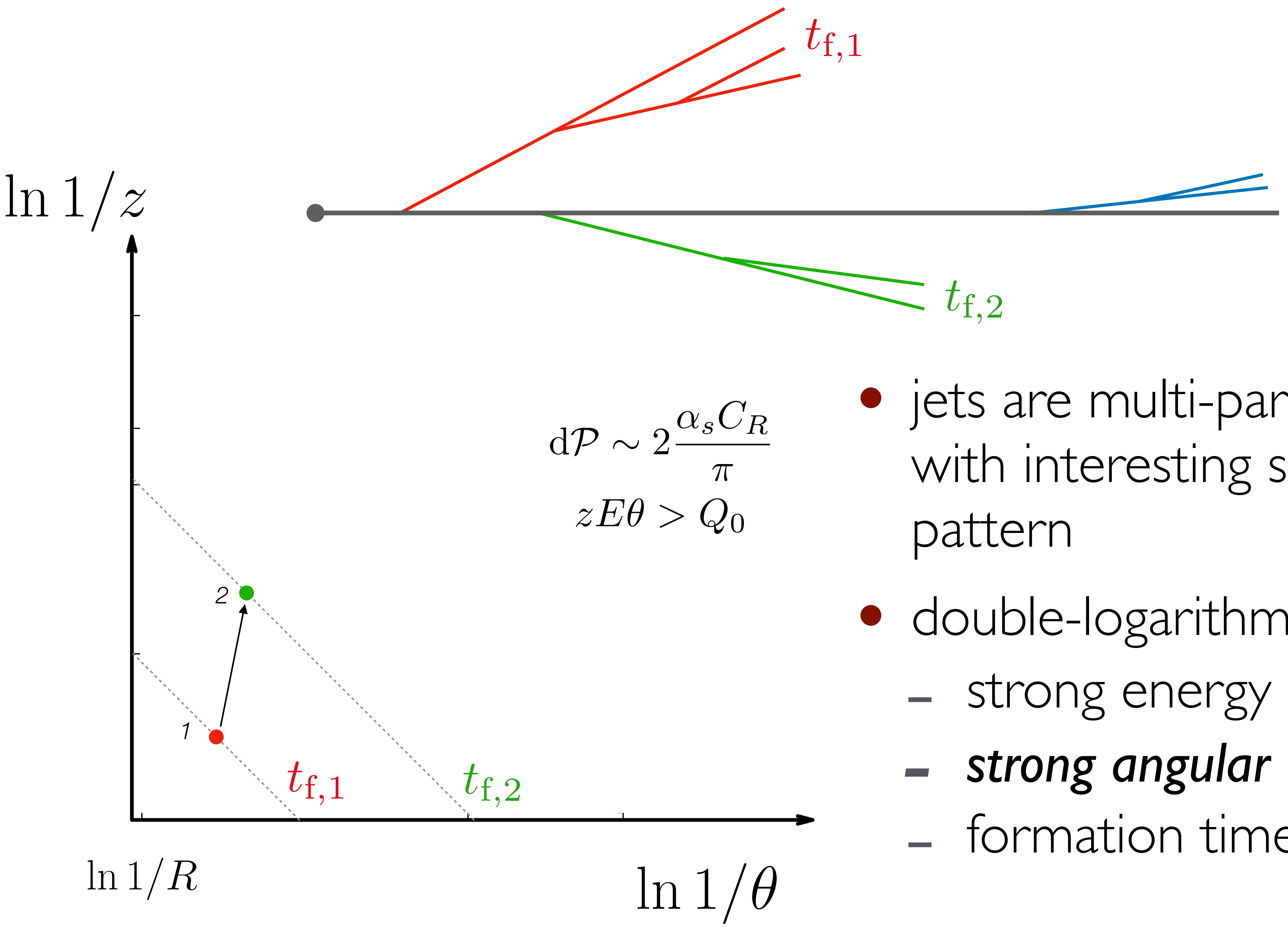

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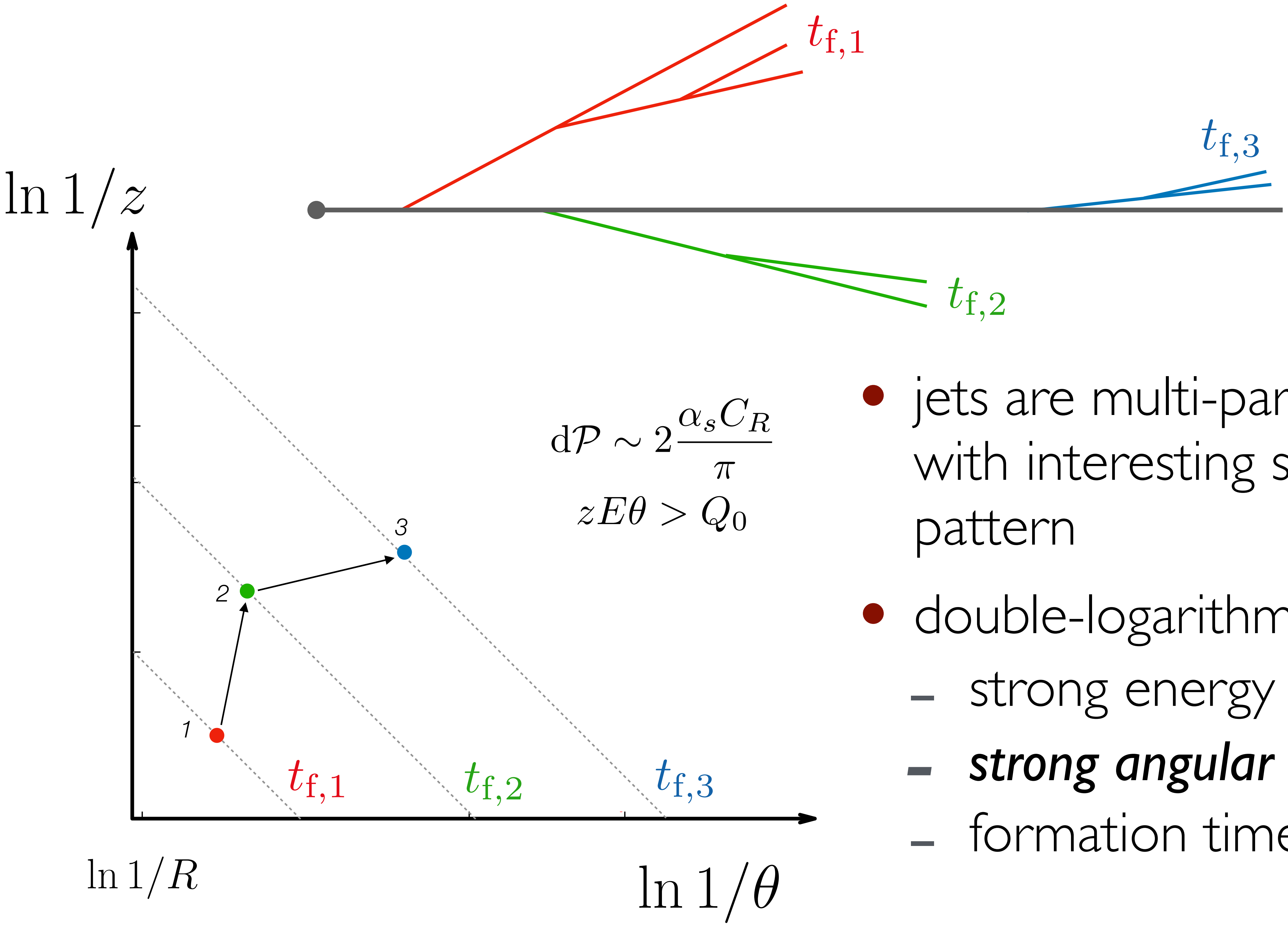

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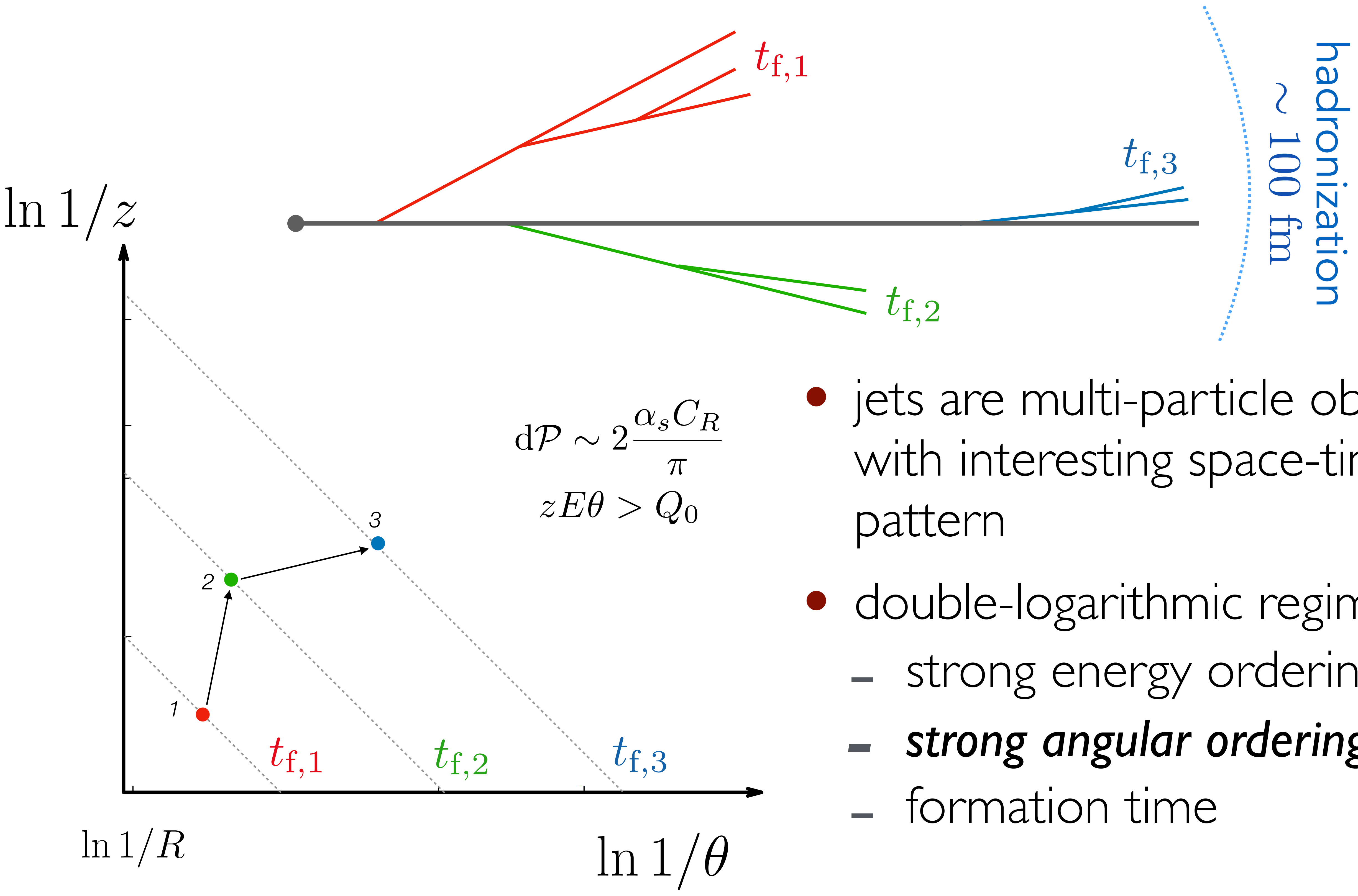

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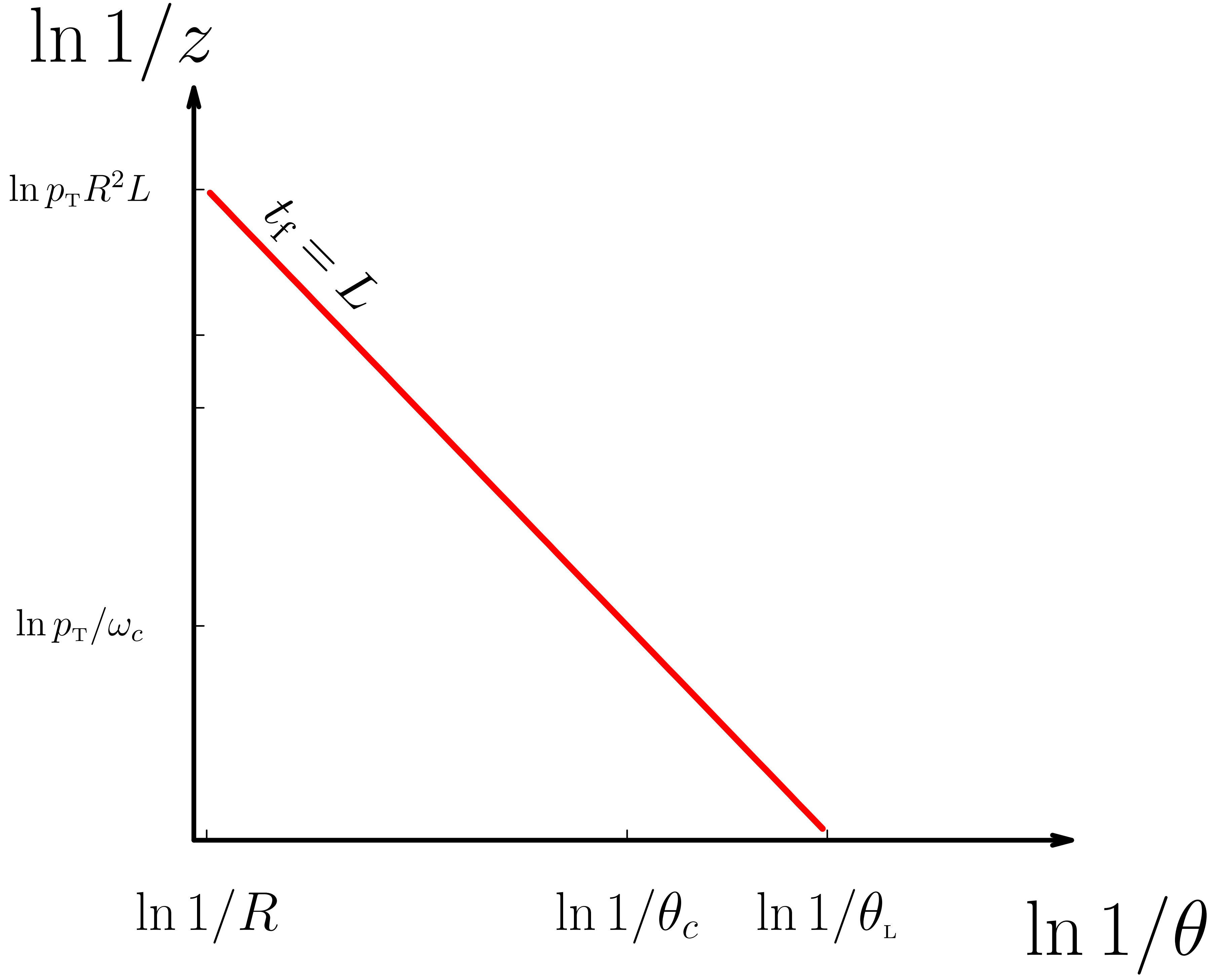
PHASE SPACE FOR MEDIUM EFFECTS

Essential length scale: size of the medium…



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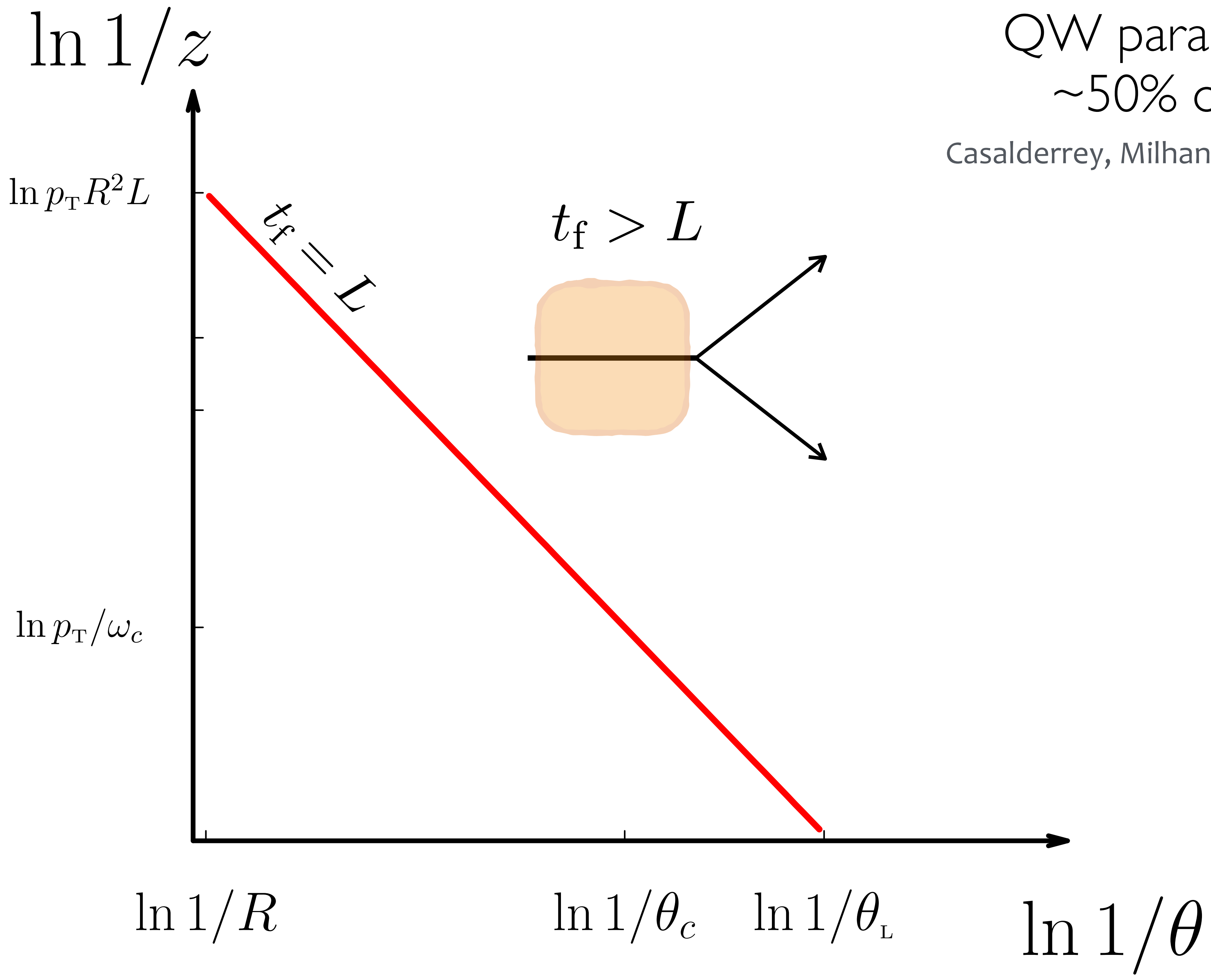

QW paradigm applies only to ~50% of the full diagram!

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

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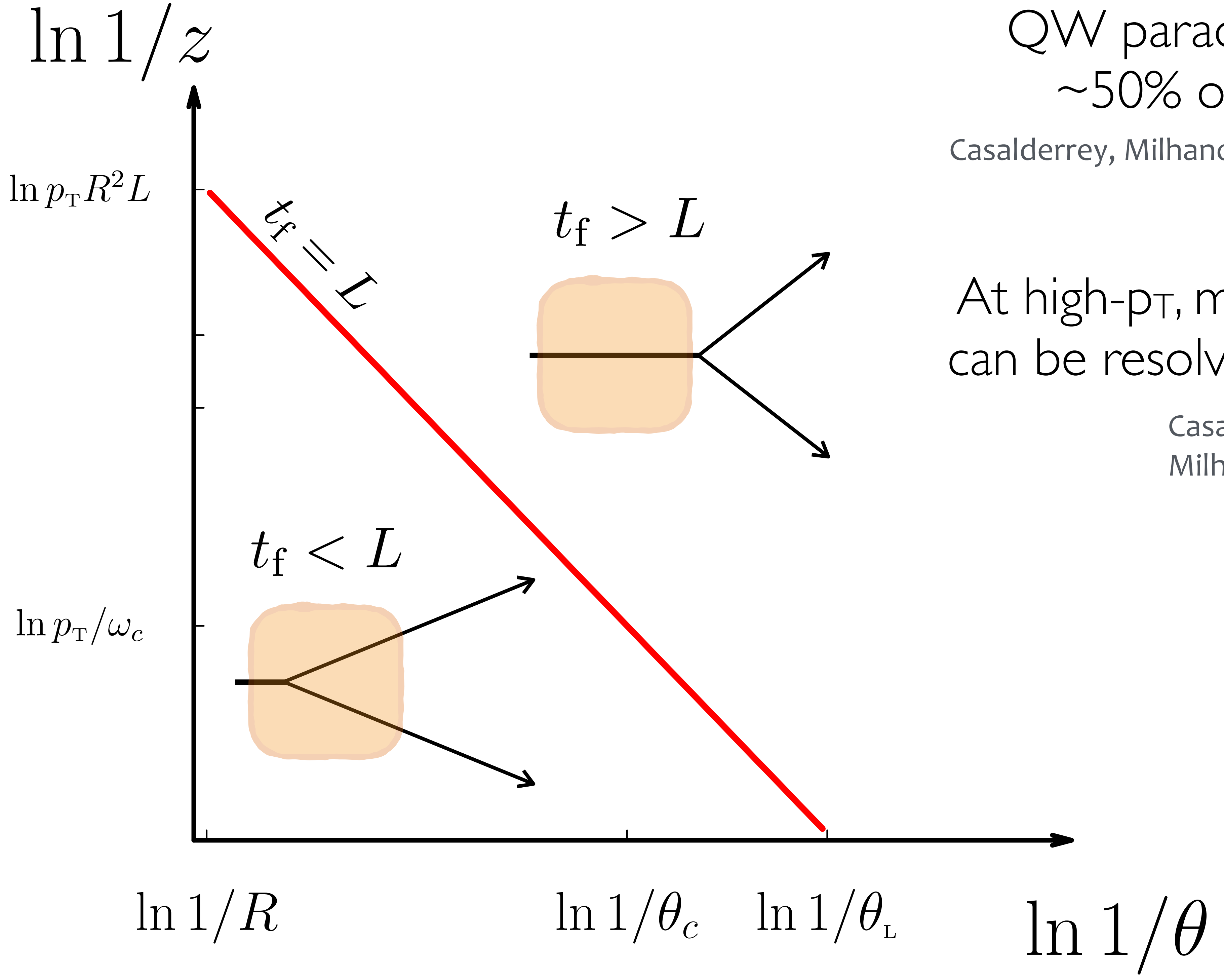

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At high-p_T, many collinear particles can be resolved inside the medium.

Casalderrey et al. JHEP 1703 (2017) 135
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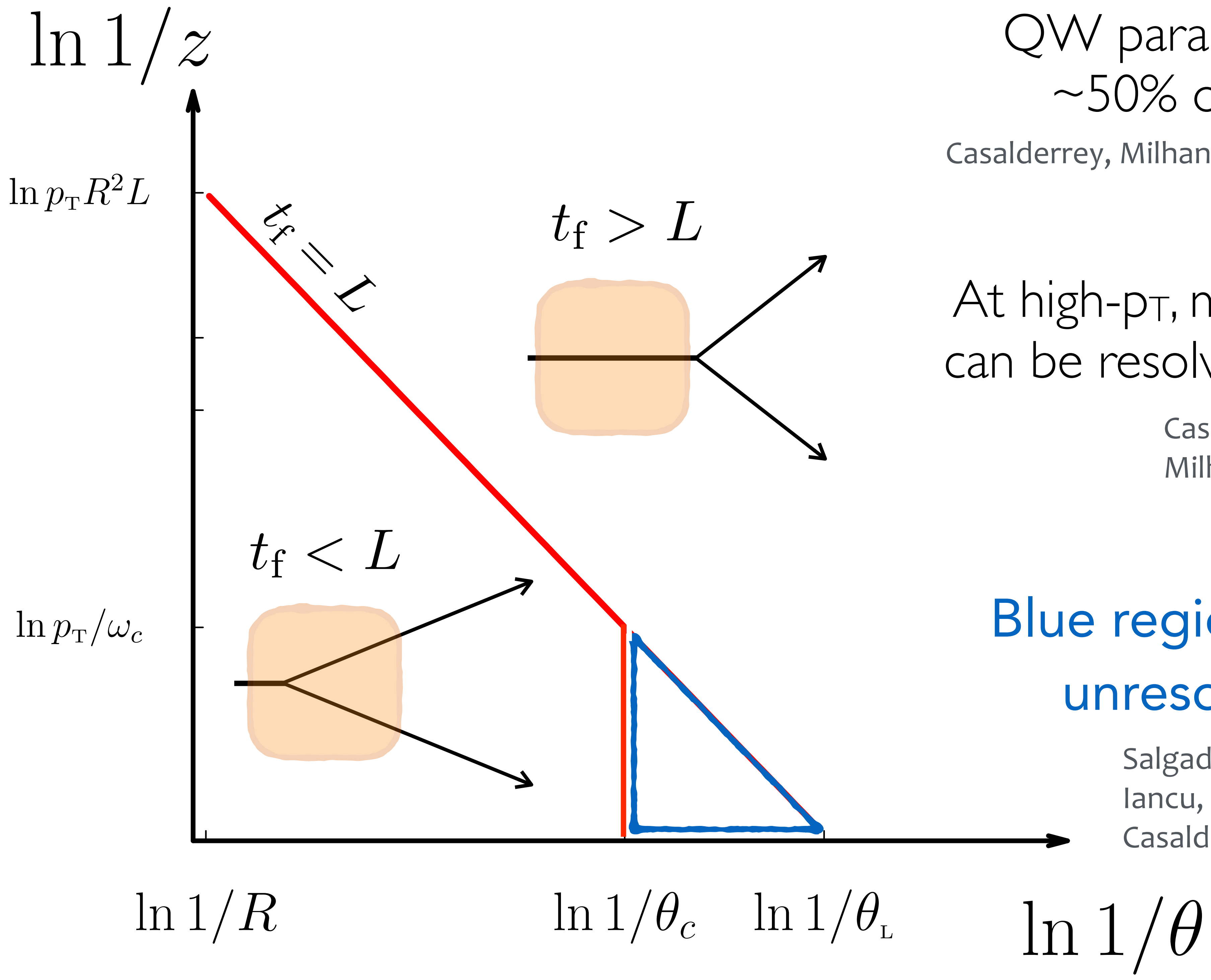

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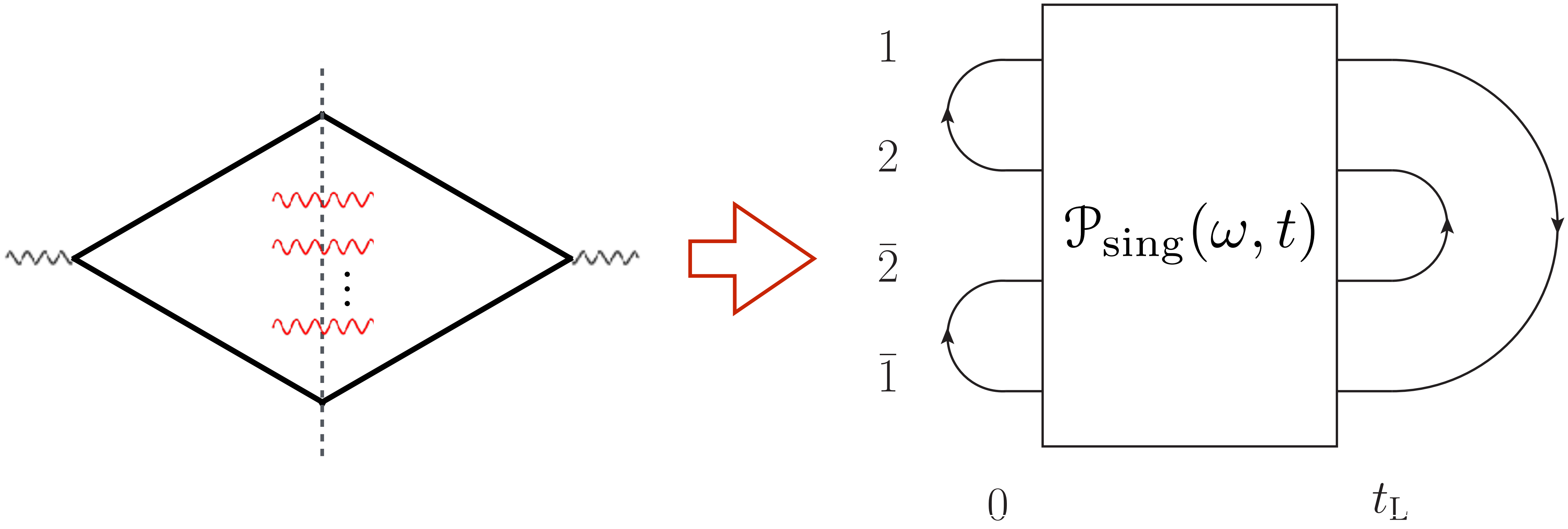
Blue region corresponds to unresolved splittings.

Salgado, Mehtar-Tani, KT (2010-2012)
Iancu, Casalderrey (2011)
Casalderrey, Salgado, Mehtar-Tani, KT (2013)

ENERGY LOSS OF TWO PARTICLES

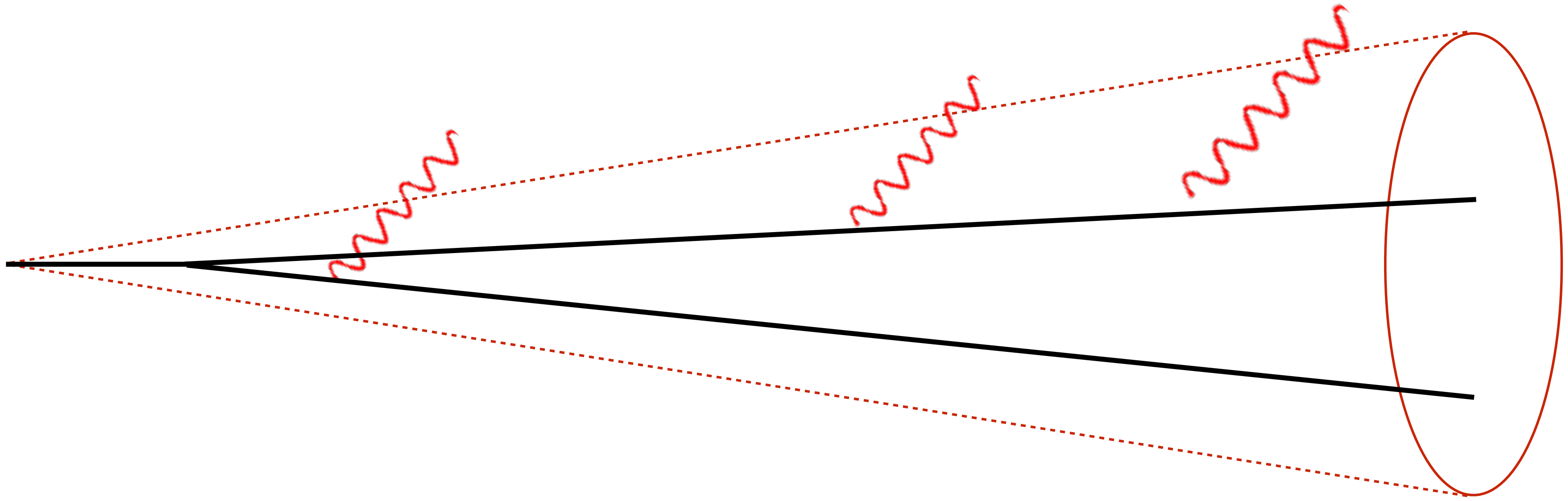
Y. Mehtar-Tani, KT arXiv:1706.06047 [hep-ph]



- consider a color singlet dipole propagating through the medium
  - assume initial splitting is hard (short formation time)
- resum multiple, soft emissions at large angles
  - two-prong quenching weight $\mathcal{P}_{\rm sing}(\omega, t)$

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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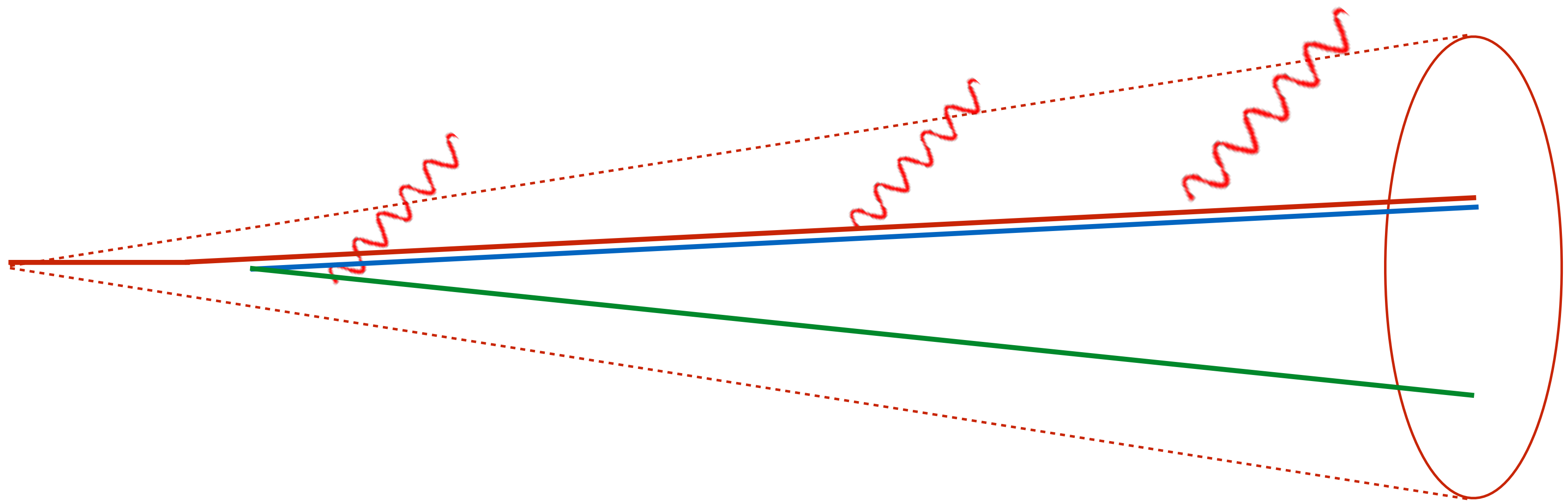

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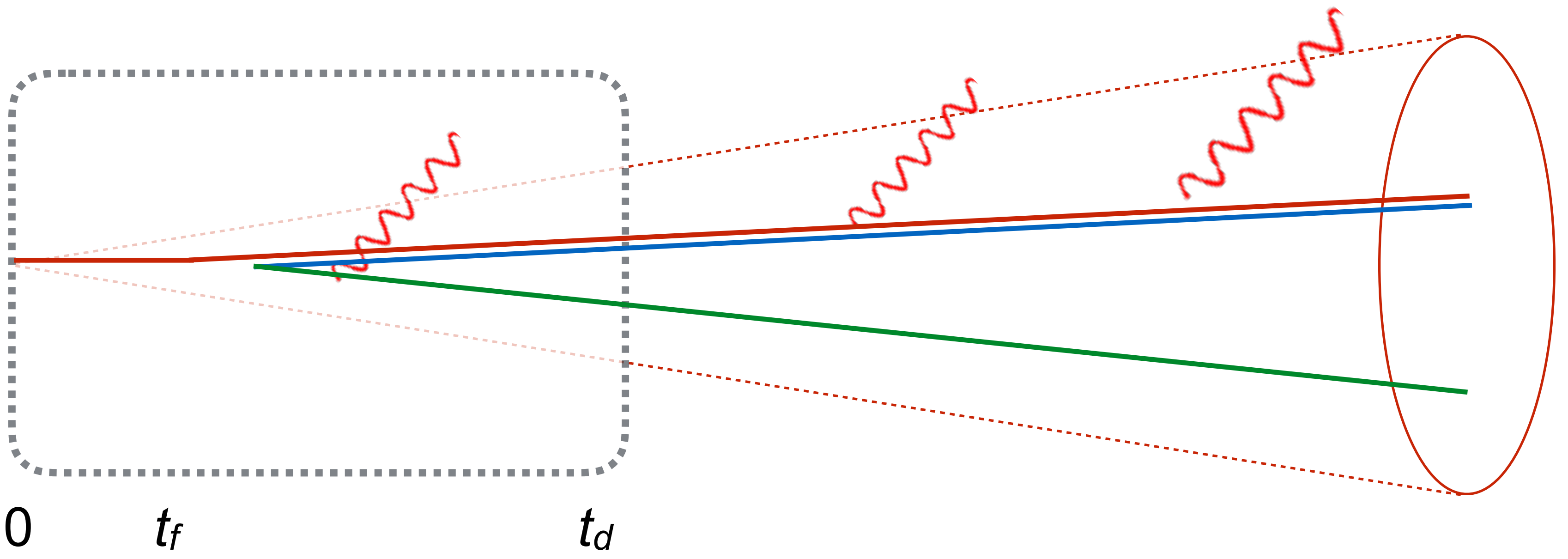

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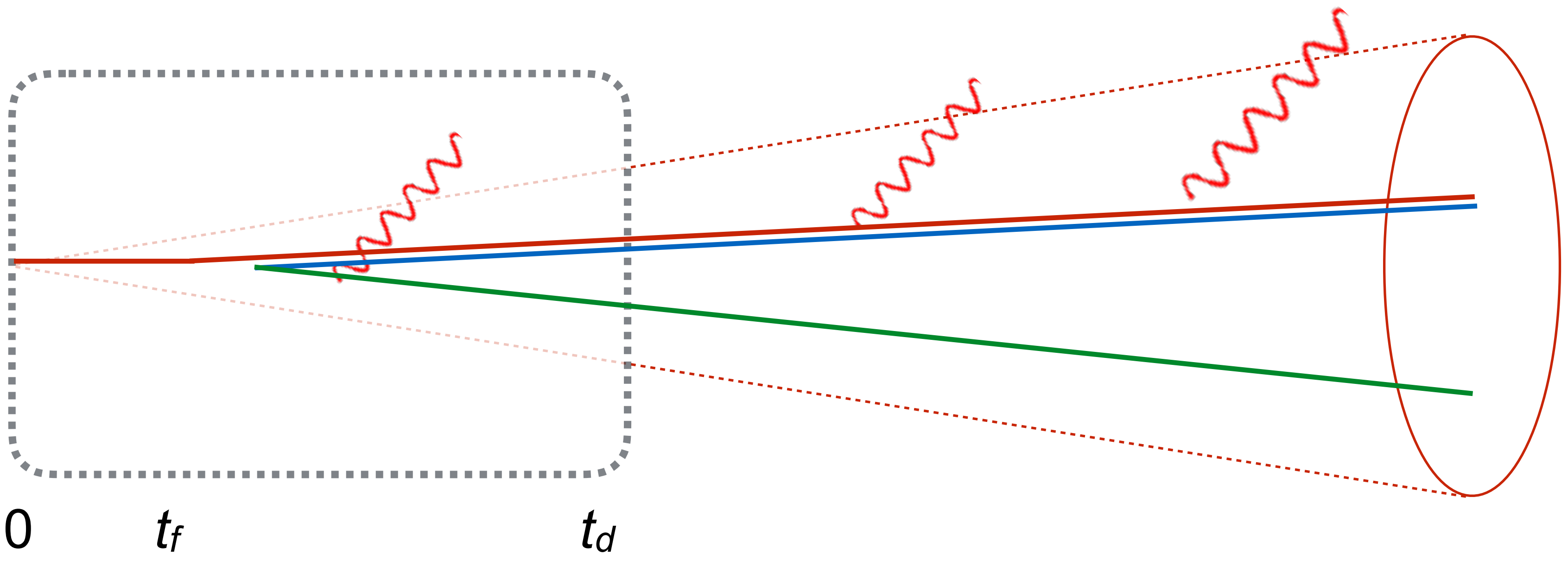

$$t_{\rm d} \sim (\hat{q}\theta_{12}^2)^{-1/3}$$

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

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

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

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HOW DOES THIS AFFECT OBSERVABLES?

Application: single-inclusive jet spectrum

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

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

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$$\Downarrow \quad \longleftarrow\!\!-\!\!-\!\!-\!\!\longrightarrow \quad \frac{p_{\mathrm{T}}^n}{(p_{\mathrm{T}}+\epsilon)^n} \approx \exp\left(-n\frac{\epsilon}{p_{\mathrm{T}}}\right)$$

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

product of probabilities (Laplace space) from quenching of **resolved color density**

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quark quenching $\quad \mathcal{Q}_q(p_{\mathrm{T}}) = \mathrm{e}^{-2\alpha C_F L\sqrt{n\hat{q}/(\pi p_{\mathrm{T}})}}$

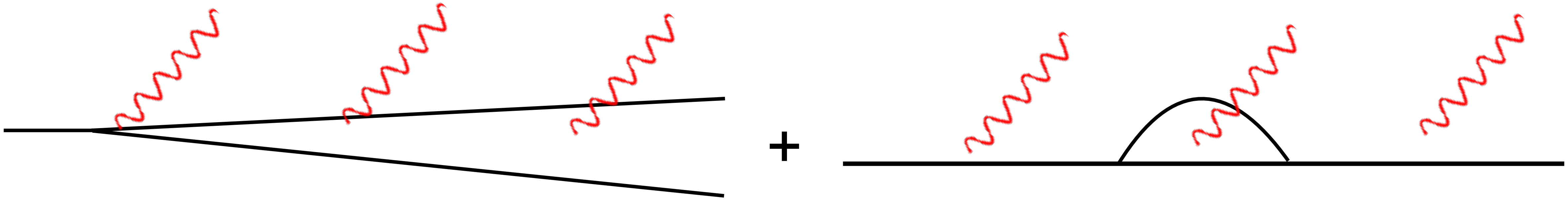
GENERALIZED QUENCHING

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

$$= \mathcal{Q}_q(p_{\rm T})\big(1 + \text{quenching of resolved dipoles}\big)$$

- expanding jet suppression factor in α_s
  - corresponds to accounting for the quenching of higher-order emissions (substructure fluctuations)
- product of probabilities
  - leading term corresponds to quenching of the total charge; common factor at all α_s (large-N_c)

HIGHER-ORDER CONTRIBUTIONS



sensitive to two prongs

sensitive to one prong

$$\mathcal{Q}^{(1)}(p_\mathrm{T}) = \int_0^1 \mathrm{d}z\, P_{gq}(z) \int_0^R \frac{\mathrm{d}\theta}{\theta} \frac{\alpha_s(k_\perp)}{\pi} \left[\mathcal{Q}_{gq}(p_\mathrm{T}) - \mathcal{Q}_q(p_\mathrm{T})\right]$$

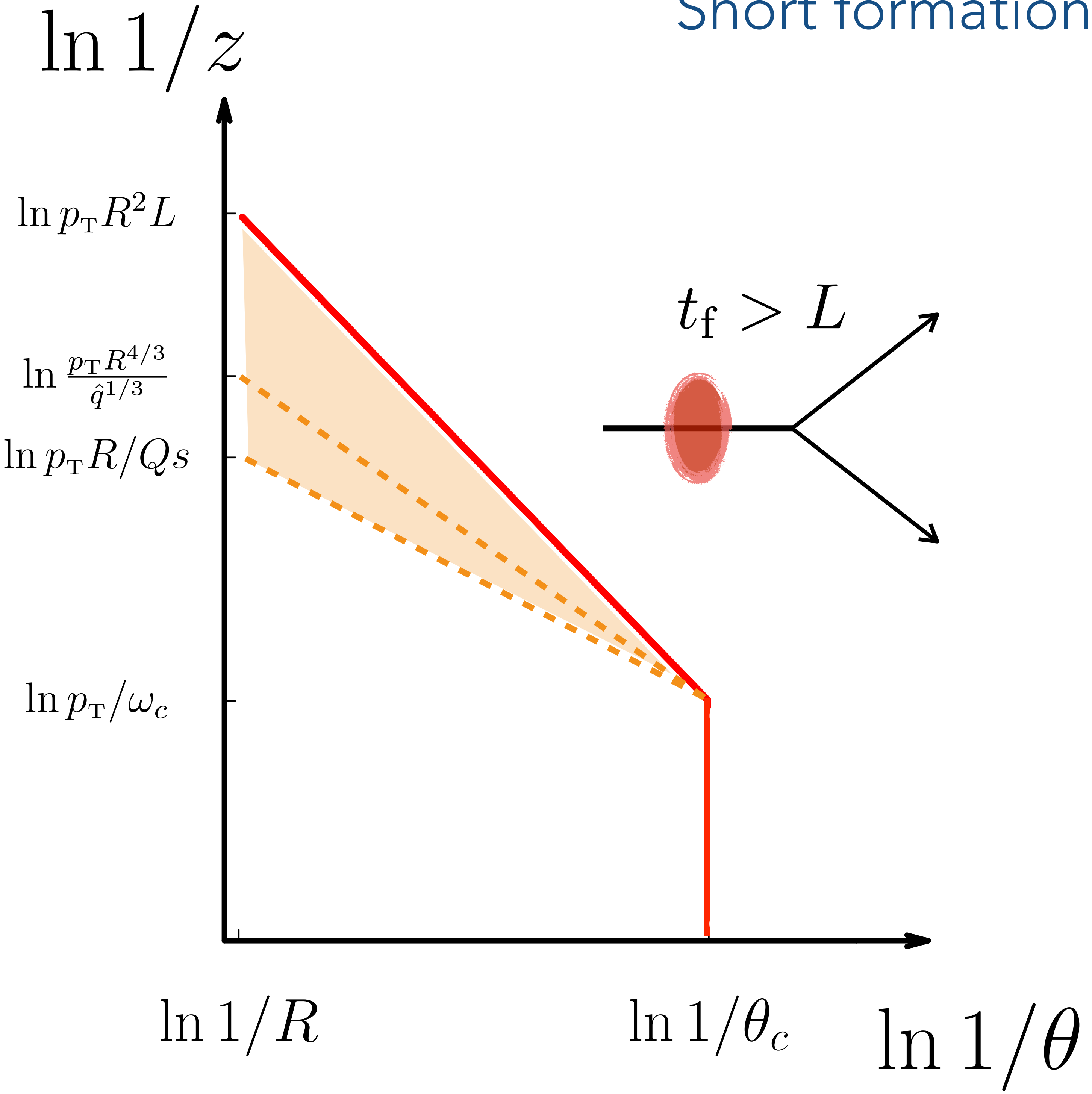
$$\mathcal{Q}_{gq}(p_\mathrm{T}) = \mathcal{Q}_q(p_\mathrm{T})\mathcal{Q}_\mathrm{sing}(p_\mathrm{T})$$

- sensitive to the difference of quenching of real and virtual term
- cancellation a large range kinematical regime
- the mismatch is largest at short formation times
  - *enhances a subset of higher-order corrections*

REDRAWING PHASE SPACE

When is the mismatch between 2 vs 1 QW arising?

Short formation times!



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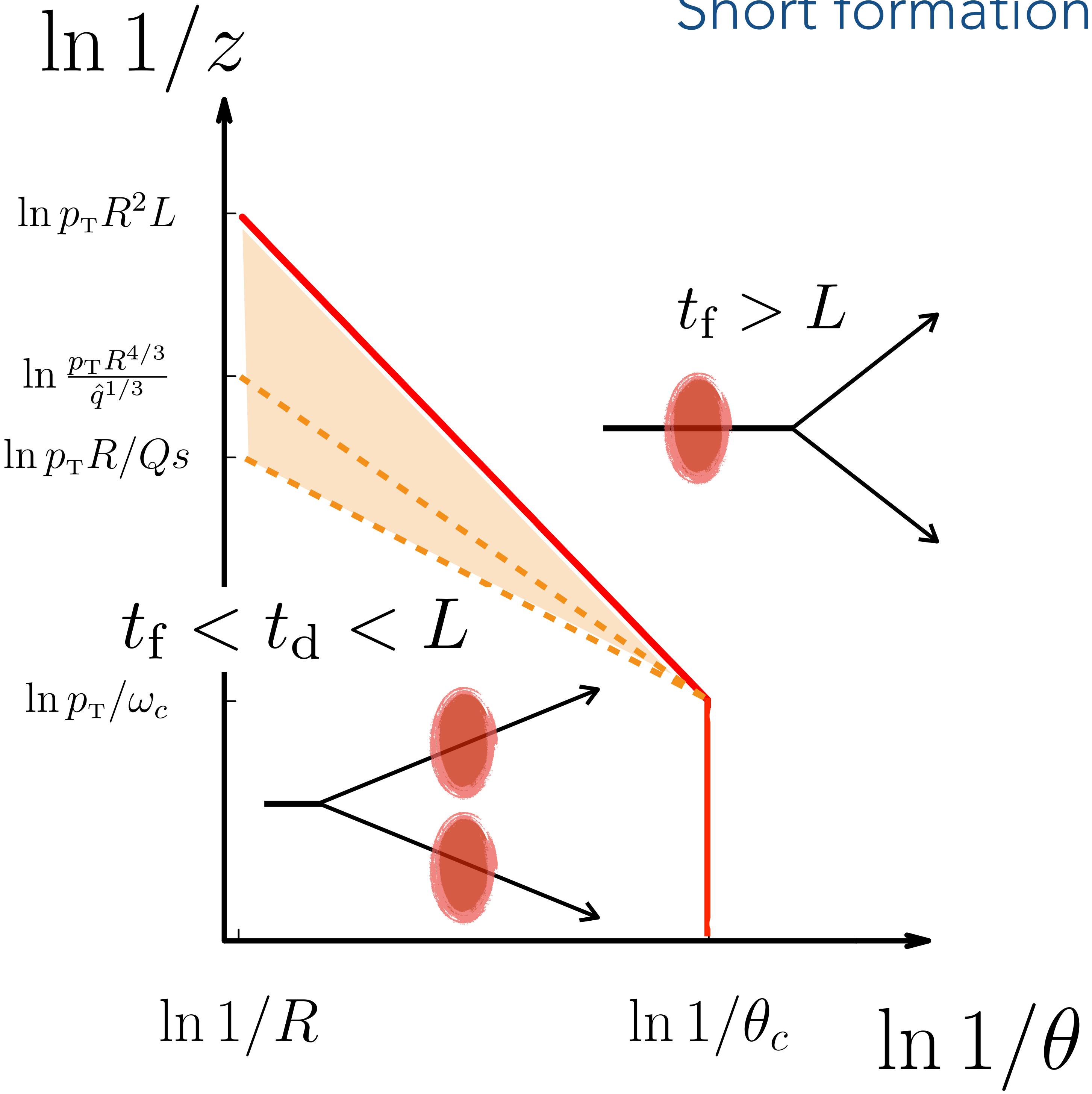

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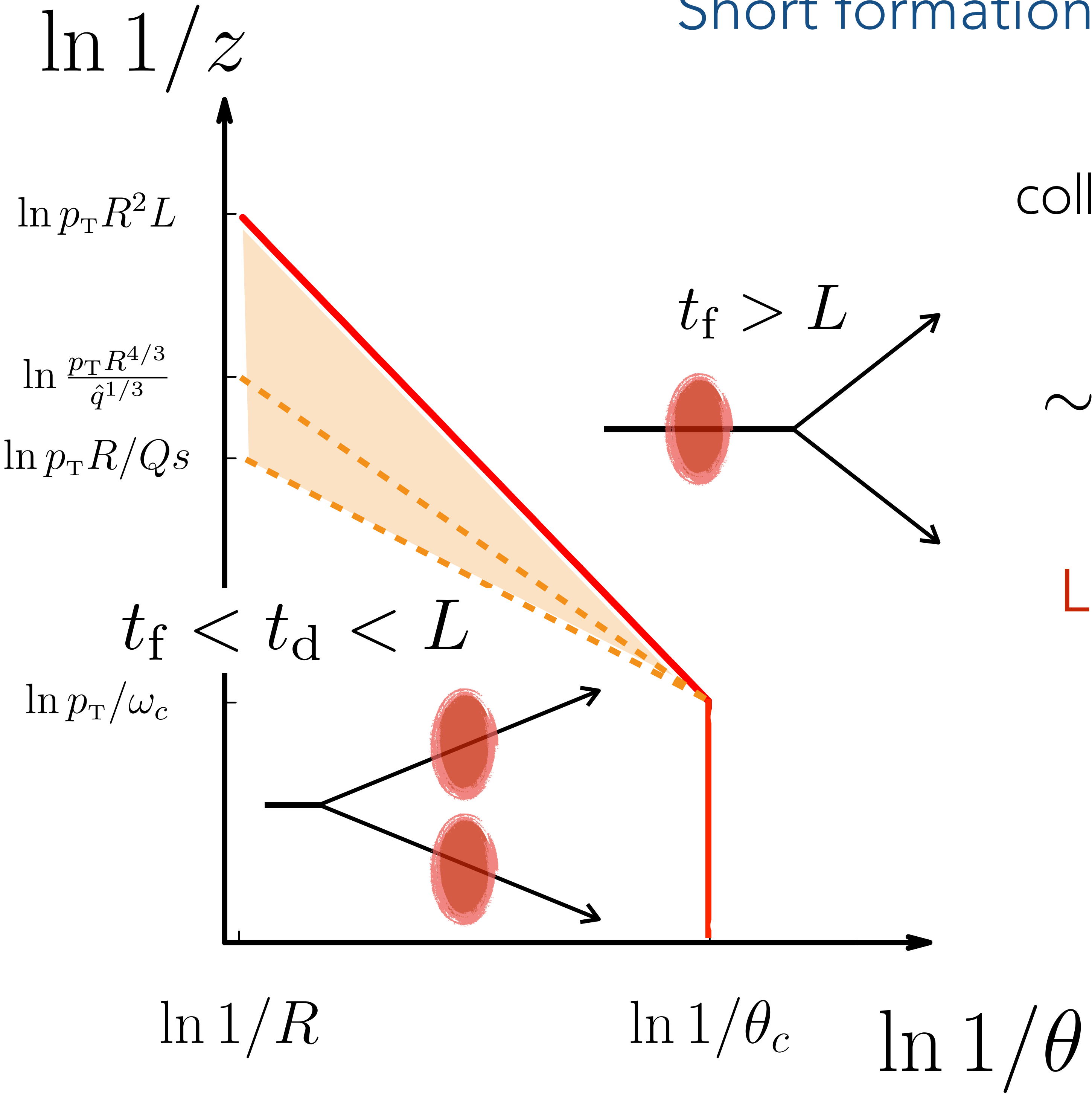

Leading-logs count the number of collinear modes resolved by the medium

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

Log enhancement with jet scales

⇒ resummation

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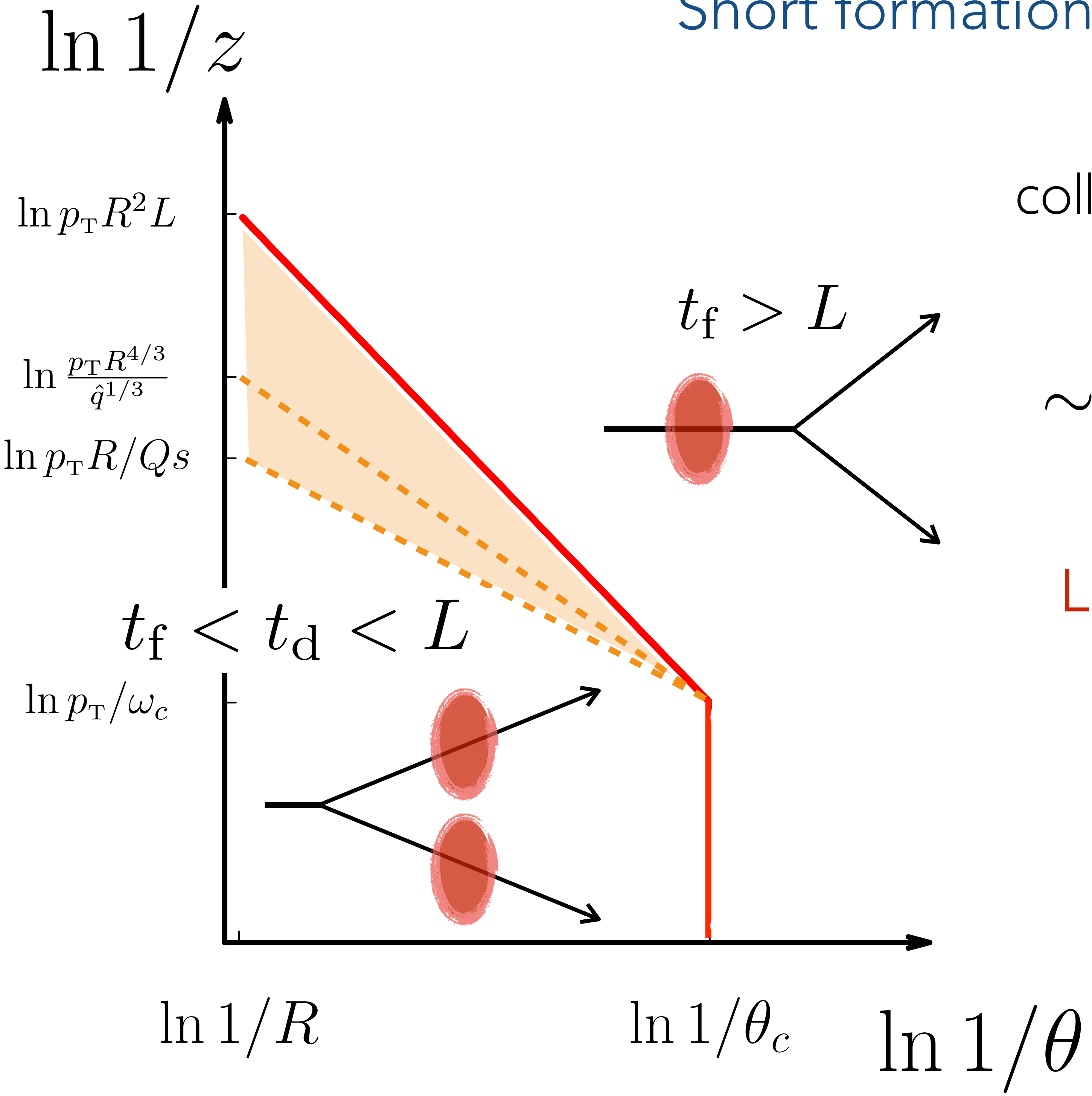

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Log enhancement with jet scales

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Dominance of virtual term (strong quenching approximation $\mathcal{Q}_q(p_{\mathrm{T}}) \ll 1$)

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

SUDAKOV JET SUPPRESSION

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

recall $\mathcal{Q}_q(p_{\rm T}) = {\rm e}^{-2\bar\alpha L\sqrt{n\hat q/(\pi p_{\rm T})}}$

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Resummation of logs leads to exponentiation of NLO result

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

$$\mathcal{C}_g(p_{\rm T}, R) = \left[\mathcal{C}_q(p_{\rm T}, R)\right]^{N_c/C_F}$$

GOING BEYOND STRONG QUENCHING

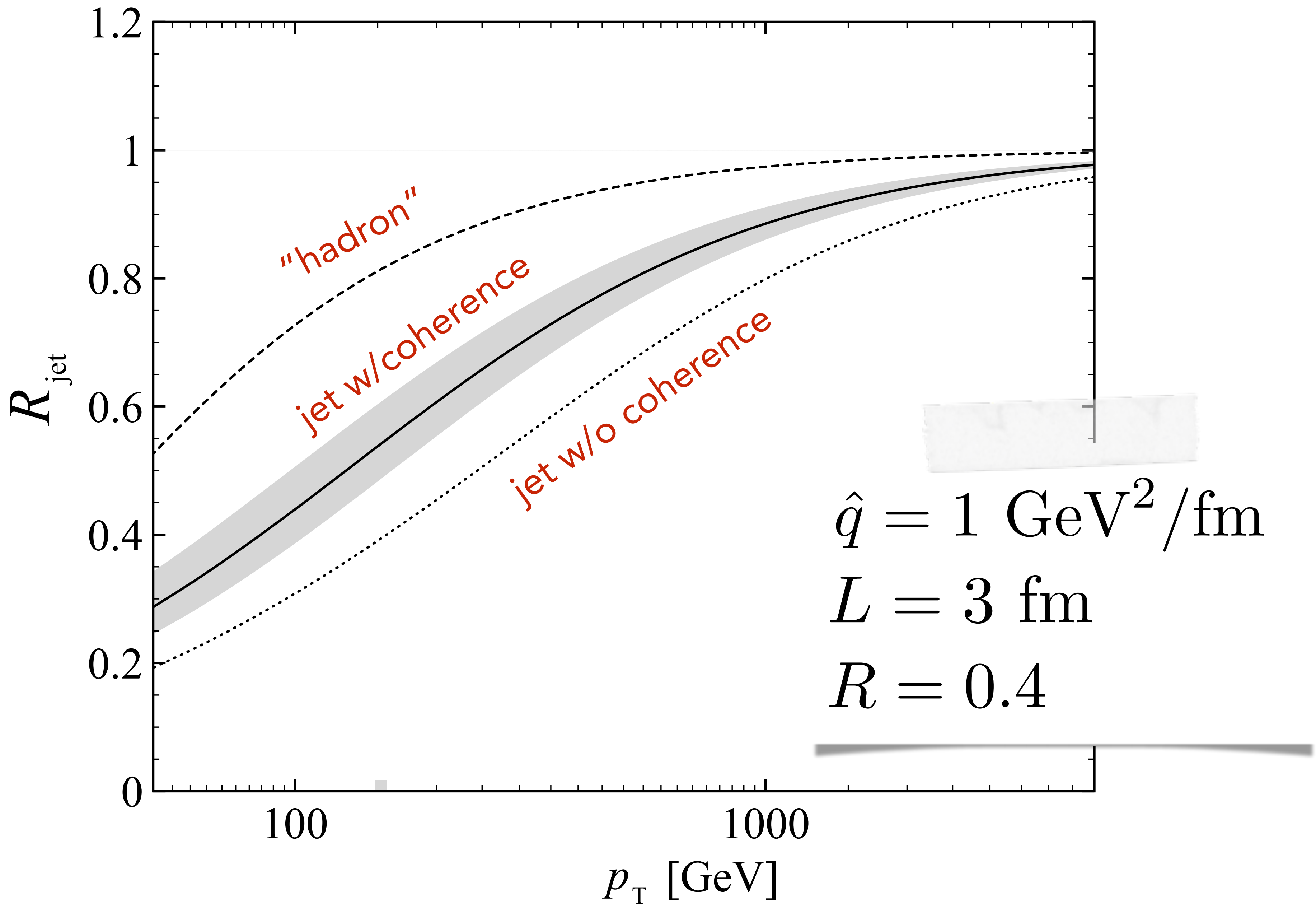
Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

- at finite quenching resummation of medium logs via set of non-linear equations
- running coupling

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

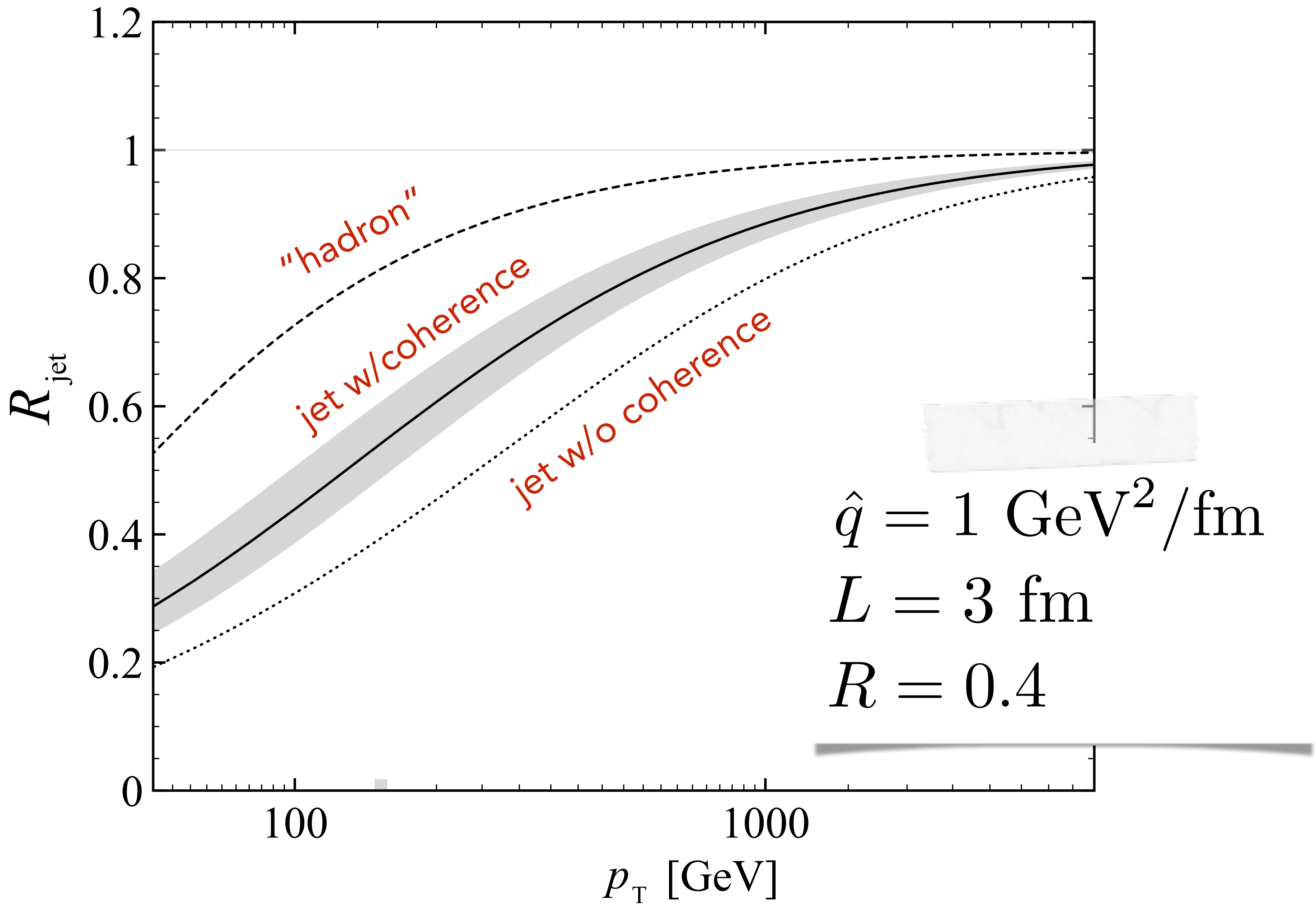
- can easily be generalized to other models of how jets are affected in medium
  - e.g. incoherent scenario = all jets inside the medium lose energy independently

JET SUPPRESSION: NUMERICS



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

JET SUPPRESSION: NUMERICS



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

Several improvements in the pipeline for phenomenological analysis!

CONCLUSIONS

- generalized energy loss probability
  - quenching of total charge (+mass effects)
  - novel Sudakov suppression factor (collimator)
- relating quenching to jet scales
  - analytic understanding
  - sensitivity to opening angle
- general features from hard scale analysis
  - assumptions about medium modifications leads to redrawing of phase space
  - guidance for (a large class of) MC modeling
  - importance of data scanning p_T & R

THANK YOU!