Jet quenching in HIC: Higher order corrections

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Jets and Heavy Flavor Workshop
@ Santa Fe, NM, January 29-31, 2018

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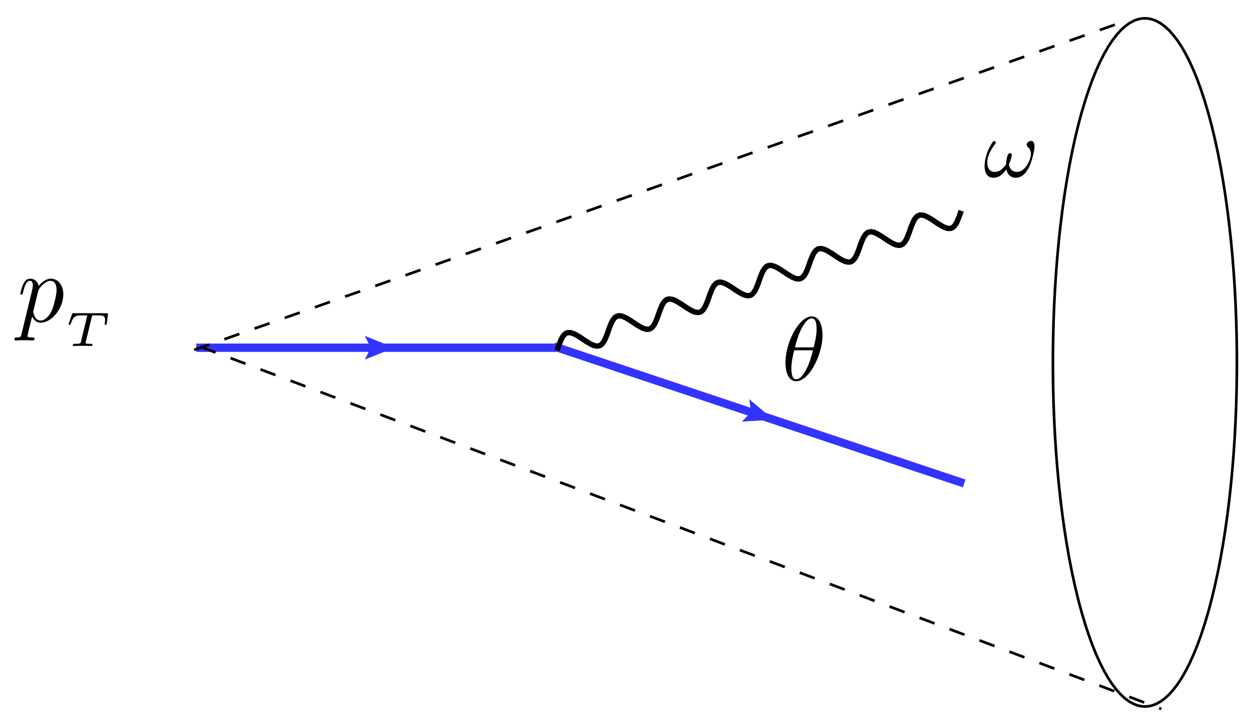
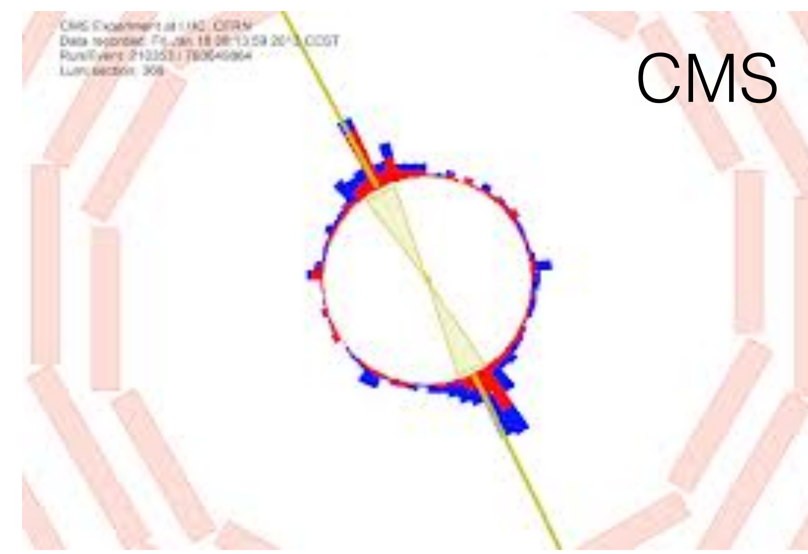
arXiv:1706.06047 [hep-ph], arXiv:1707.07361 [hep-ph]

QCD jets

Building block probability for parton cascades in vacuum





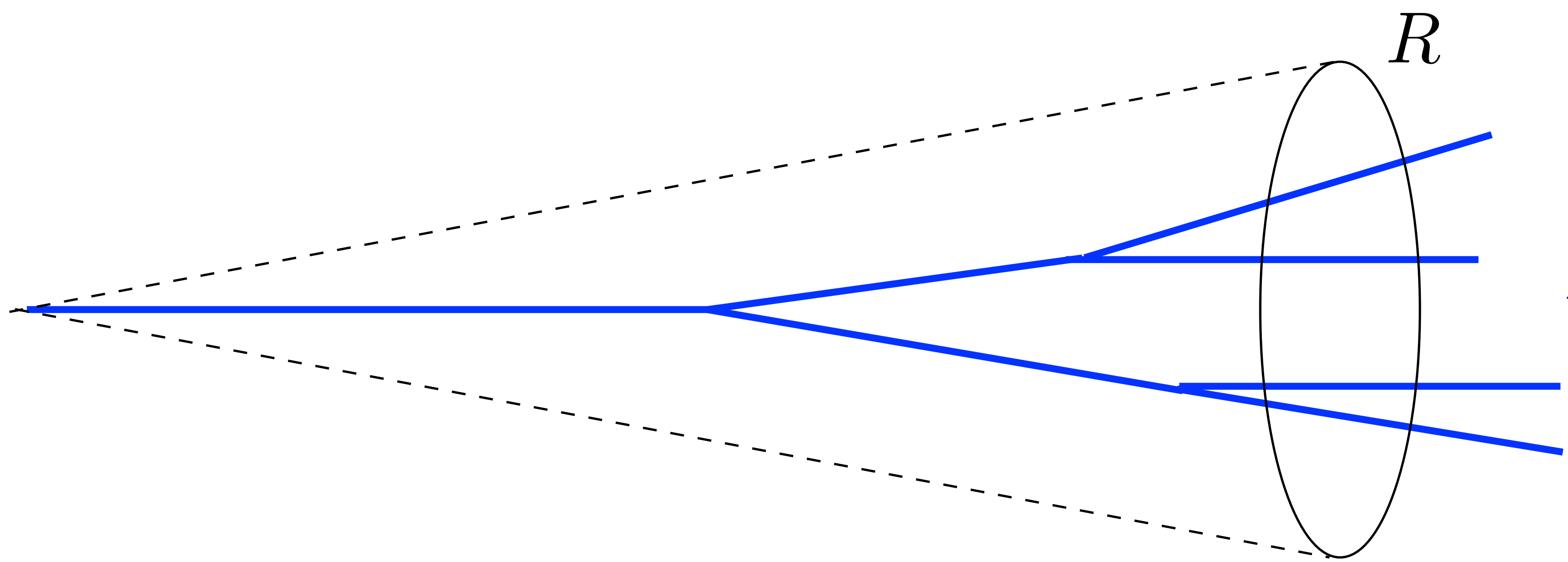
$$\mathrm{d}P \sim \alpha_s C_R \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega}$$

$\Longrightarrow$ collimation of jets

Large phase-space for multiple branching: many particles produced (implemented in Event Generators such as PYTHIA, HERWIG, SHERPA, etc.)

QCD jets

- Soft & Collinear divergences (resummation)
- **Color coherence:** angular ordered shower, interjet activity
- Not uniquely defined: cone size **R**, reconst. algo, …



$$p_T = \sum_i p_{T\,i}$$

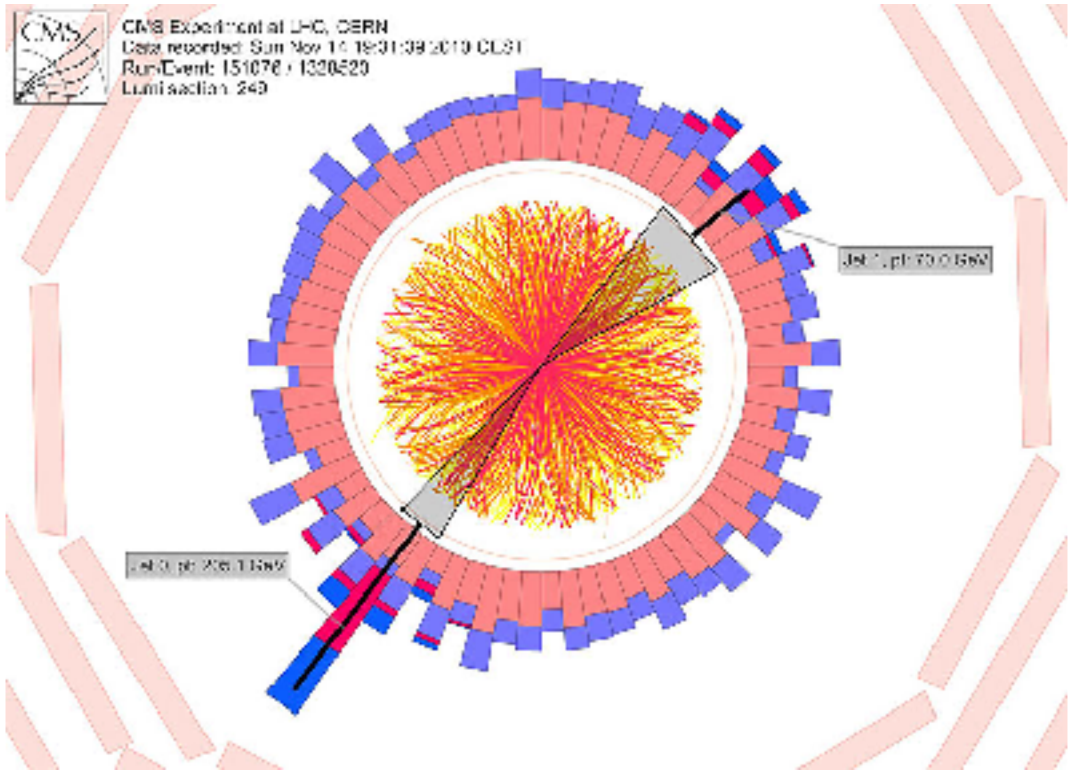
$$\frac{1}{E} \quad \ll \quad t_{\rm form} \sim \frac{k_{||}}{k_\perp^2} \quad \ll \quad \frac{E}{\Lambda_{\rm QCD}} \qquad\qquad p_T \equiv E$$

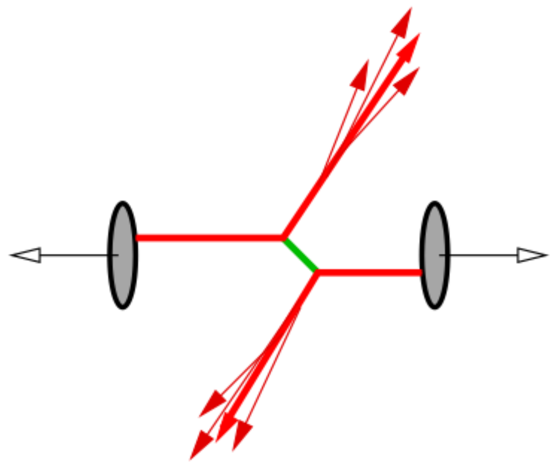
Large separation of time scales

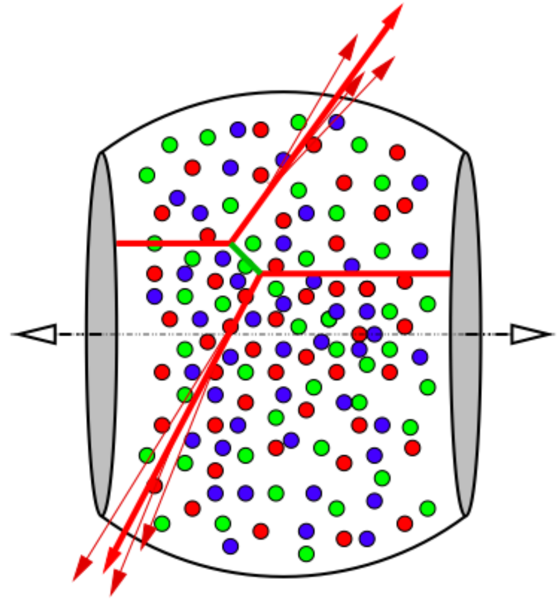
Jet observables of two types

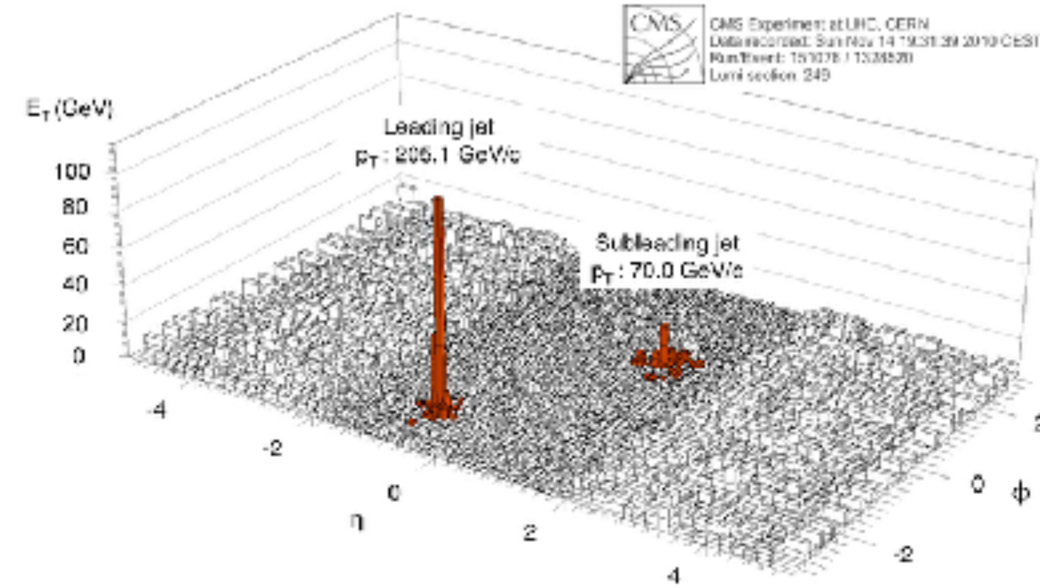
- Infrared-Collinear (IRC) safe observables: sum over final state hadrons $\longrightarrow$ cancellations of divergences. Ex: jet spectra, event shape: thrust, jet mass, etc. Resummation of large logs, e.g. log R, log Q/M, can be necessary
- Collinear sensitive observables: pQCD still predictive (factorization theorems). Ex: Fragmentation Functions

Jets in Heavy Ion Collisions







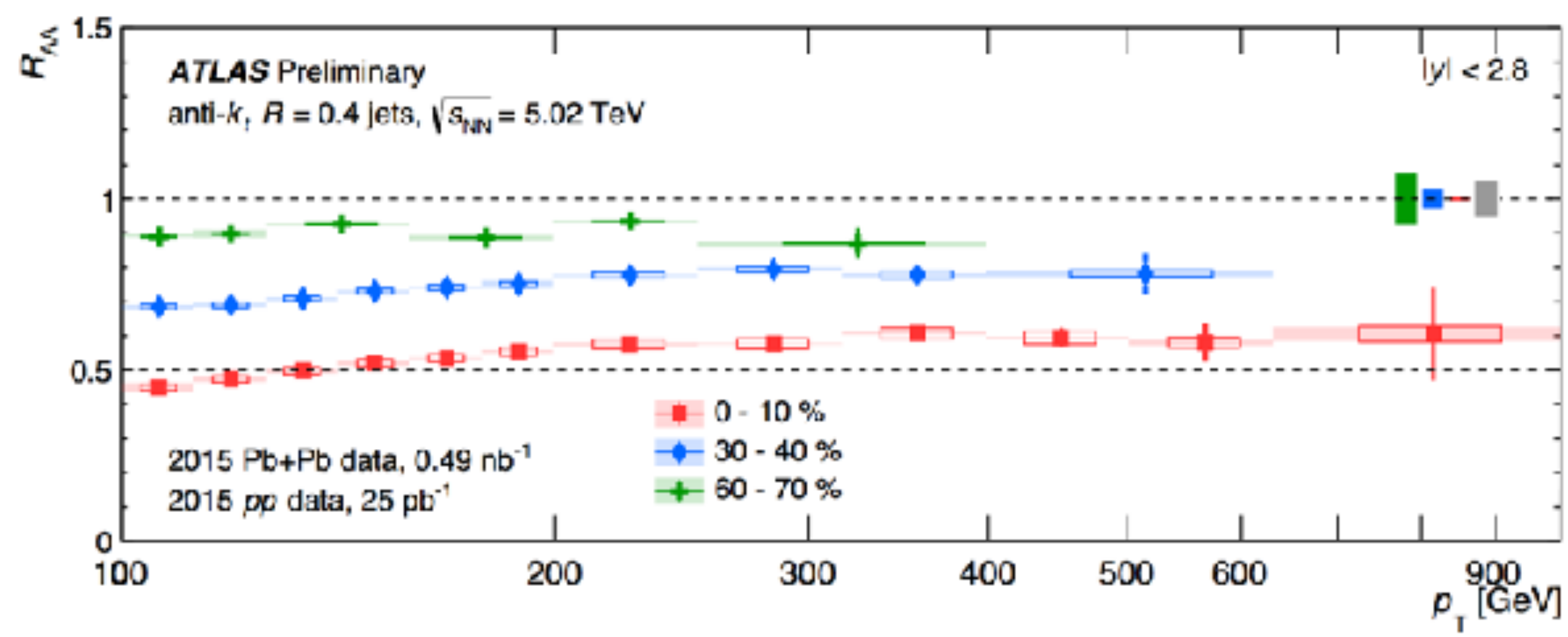


quark-gluon plasma

Strong jet suppression (**up to 1 TeV!**) observed in ultra-relativistic heavy ion collisions at LHC

Inclusive jet spectra ratio

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}^2p_T}{N_{\mathrm{coll}} \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}^2p_T}$$



How much energy is lost?

- **A rough estimate:** consider a constant energy loss ϵ
- using a power spectrum $$\frac{\mathrm{d}N}{\mathrm{d}^2 p_T} \sim p_T^{-n}$$

we have

$$R_{\mathrm{AA}} \sim \frac{p_T^n}{(p_T + \epsilon)^n} \simeq 1 - \frac{n\epsilon}{p_T}$$

Hence, for **$R_{AA} \sim 0.5$** and **$n=6$**, one finds that jets with **$p_T \sim 300$ GeV** lose typically about **$\epsilon \sim 25$ GeV**

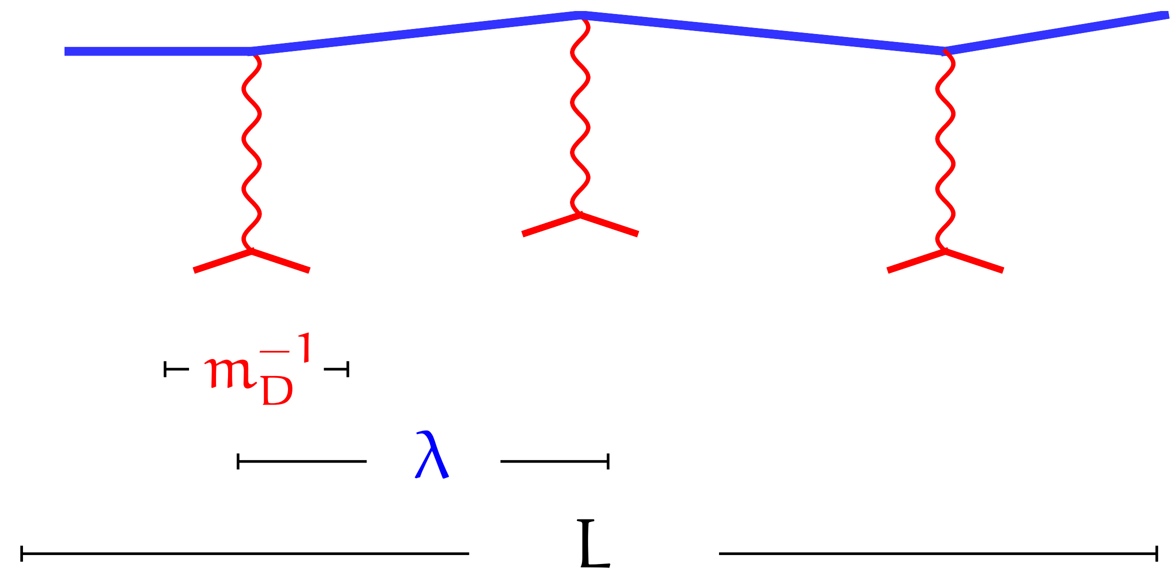
Parton radiative energy energy loss

The jet-quenching parameter

correlation length ≪ mean-free-path ≪ L

Momentum broadening (diffusion in transverse momentum space):

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



- the jet-quenching $\hat{q}$ parameter encodes **medium properties** (LO: 2 to 2 elastic scattering):

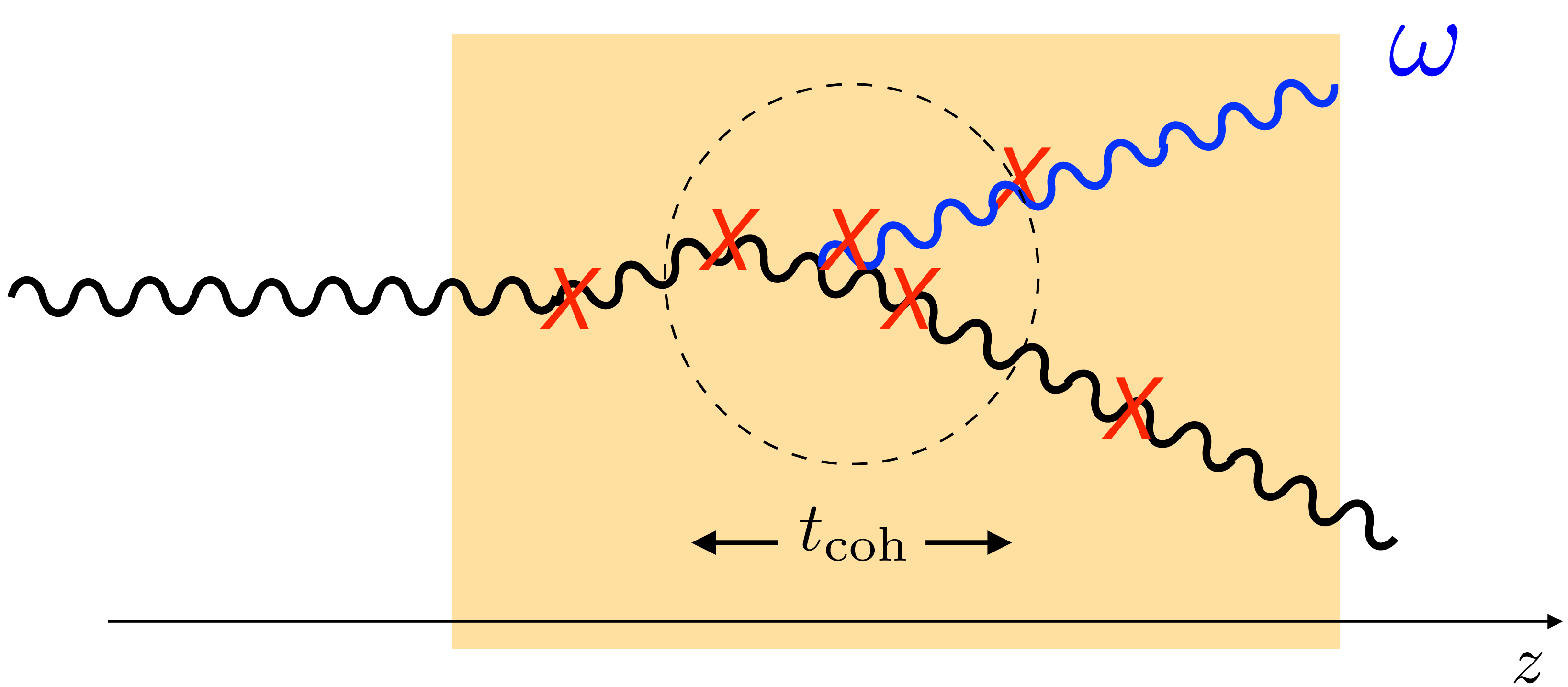
$$\hat{q} \equiv n \int_{q_\perp} q_\perp^2 \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}q_\perp} \sim \alpha_s^2 \, C_R \, n \, \ln \frac{Q^2}{m_D^2}$$

estimate: $Q^2 \sim \hat{q} L \sim 10 \,\mathrm{GeV}^2$

Medium-induced splittings

- Multiple scattering can trigger gluon radiation
- **Laudau-Pomeranchuk-Migdal effect:** during the splitting time many scattering centers act coherently as a single one and thus, suppressing the radiation rate ($k_\perp^2 \sim \hat{q}\, t$)

$$t_{\rm coh} = \frac{\omega}{k_\perp^2} \sim \frac{\omega}{\hat{q}\, t_{\rm coh}} \quad \Rightarrow \quad t_{\rm coh} \sim \sqrt{\frac{\omega}{\hat{q}}}$$



Radiative spectrum

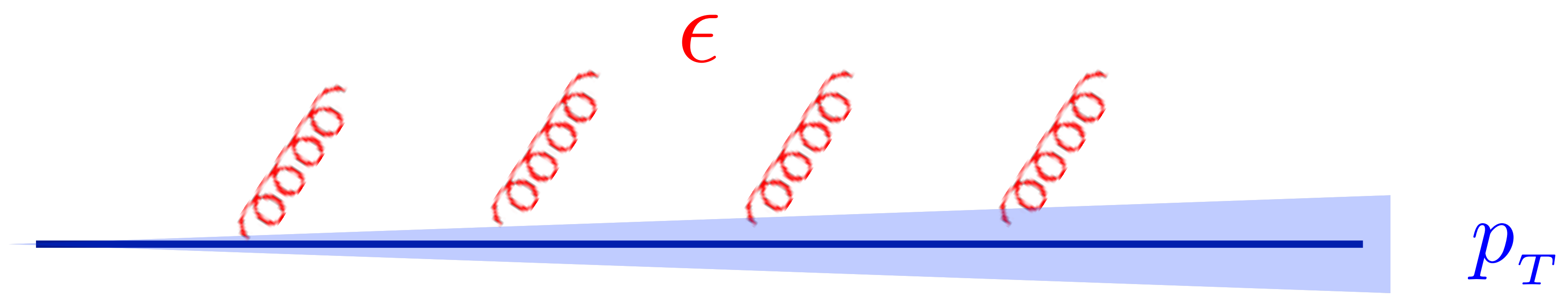
$$\omega \frac{{\rm d}I}{{\rm d}\omega} \sim \bar{\alpha} \sqrt{\frac{\hat{q} L^2}{\omega}}$$

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

[Dilute medium limit. N=1 opacity expansion: Gyulassy, Levai, Vitev (2000) Guo, Wang (2000)]

Single quark energy loss

- **Standard energy loss picture:** medium-induced radiation off a single parton [Baier, Dokshitzer, Mueller, Schiff, JHEP (2001)]



- **Jet spectrum:** convolution of the energy loss probability with the spectrum in vacuum

$$\frac{\mathrm{d}\sigma(p_T)}{\mathrm{d}^2p_T\mathrm{d}y} = \int_0^\infty \mathrm{d}\epsilon\,\mathcal{P}(\epsilon)\,\frac{\mathrm{d}\sigma^{\mathrm{vac}}(p_T+\epsilon)}{\mathrm{d}^2p_T\mathrm{d}y}$$

Single quark energy loss

Because the **jet spectrum** is **steeply falling (n >> 1),** one can make the following approximation

$$\frac{\mathrm{d}\sigma^{\mathrm{vac}}(p_T+\epsilon)}{\mathrm{d}^2 p_T \mathrm{d}y} \sim \frac{1}{(p_T+\epsilon)^n} \simeq \frac{\mathrm{e}^{-\frac{n\epsilon}{p_T}}}{{p_T}^n}$$

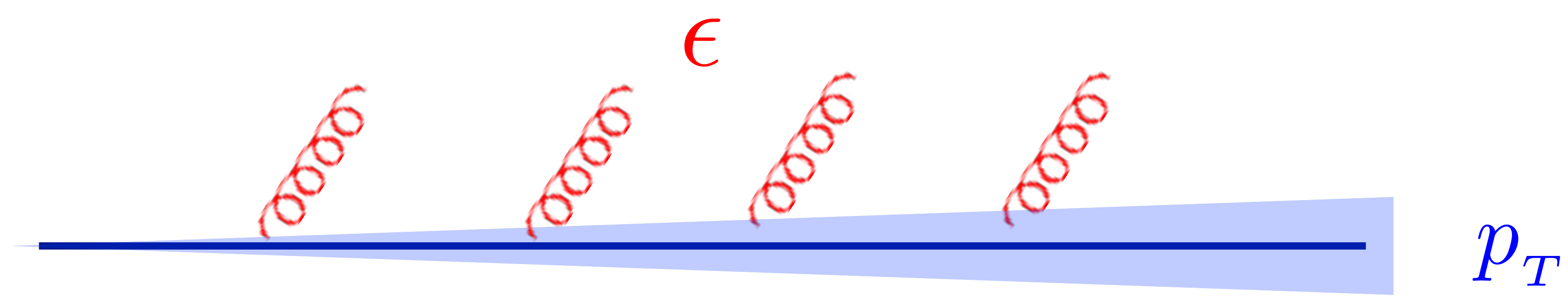
This allows to relate the **jet spectrum** to the **Laplace Transform** of the quenching probability

$$R_{\mathrm{AA}} \sim Q(p_T) \equiv \tilde{\mathcal{P}}(\nu = n/p_T)$$

where

$$\tilde{\mathcal{P}}(\nu) = \int \mathrm{d}\epsilon\, \mathcal{P}(\epsilon)\; \mathrm{e}^{-\nu\epsilon}$$

Single quark energy loss



In the **short formation time** approximation soft radiations can be treaded as independent and exponentiate in Laplace space

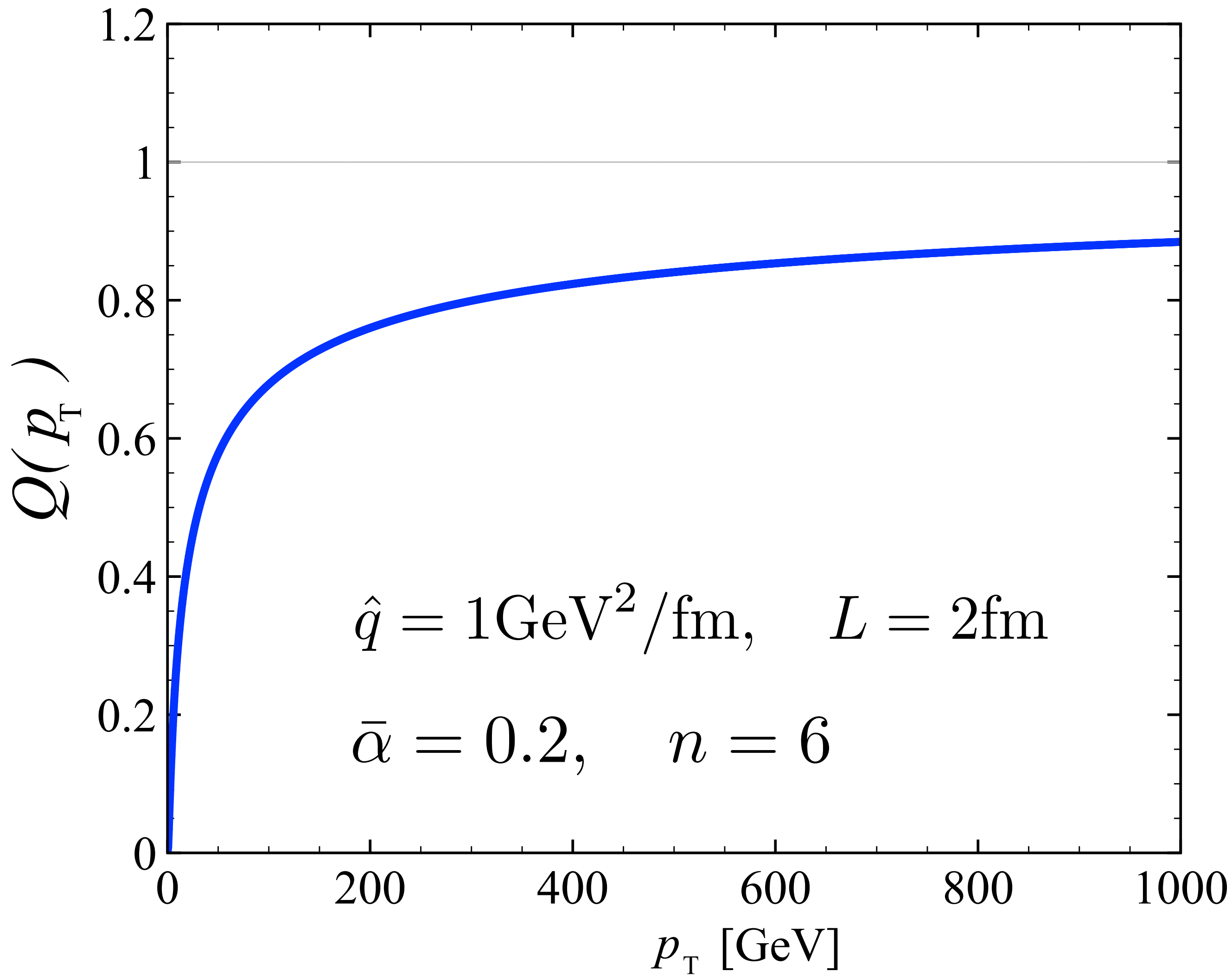
$$\tilde{\mathcal{P}}(\nu) = \exp\left[-\int \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\left(1 - \mathrm{e}^{-\nu\omega}\right)\right]$$

NB: resummation of length enhanced contributions: $\mathrm{d}I \sim \bar{\alpha}\, L$

Single quark energy loss

- Neglecting **finite size effect** one obtains a simple analytic formula for the quenching factor

$$\mathcal{Q}(p_T) \simeq \exp\left(-\bar{\alpha}\, L \sqrt{\frac{\pi \hat{q}\, n}{p_T}}\right)$$



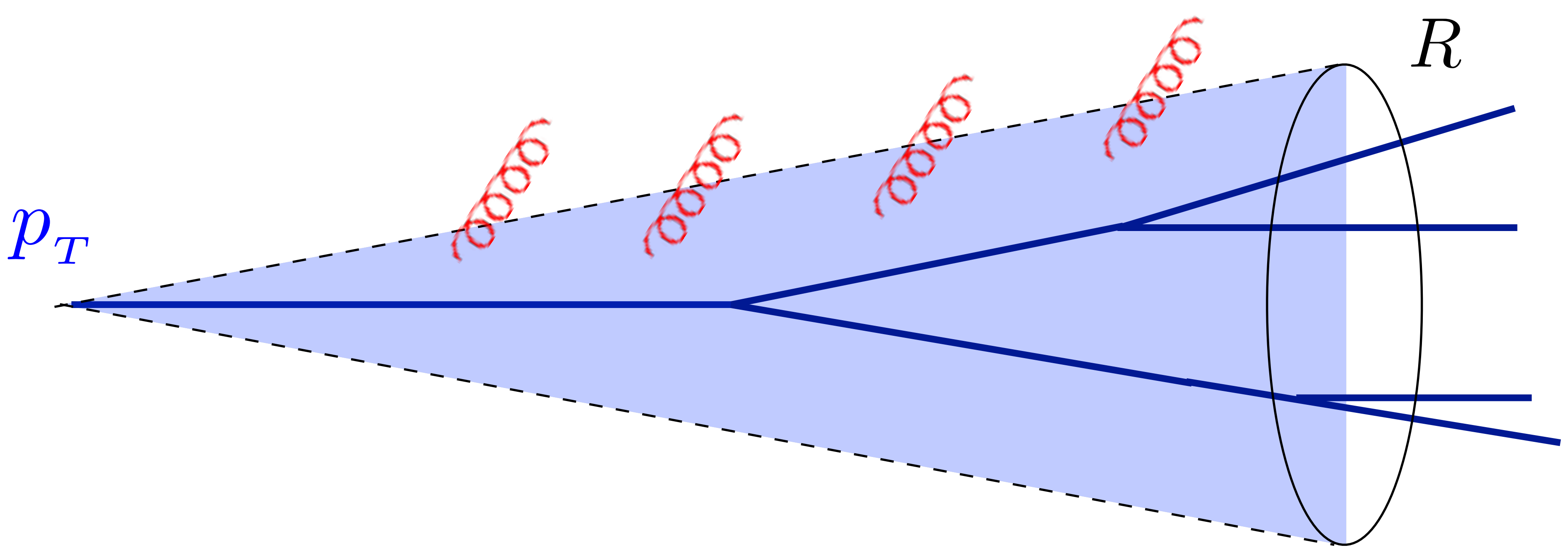
Strong quenching

$$p_T \ll \pi\, n\, \bar{\alpha}^2 \hat{q} L^2$$

$$Q(p_T) \ll 1$$

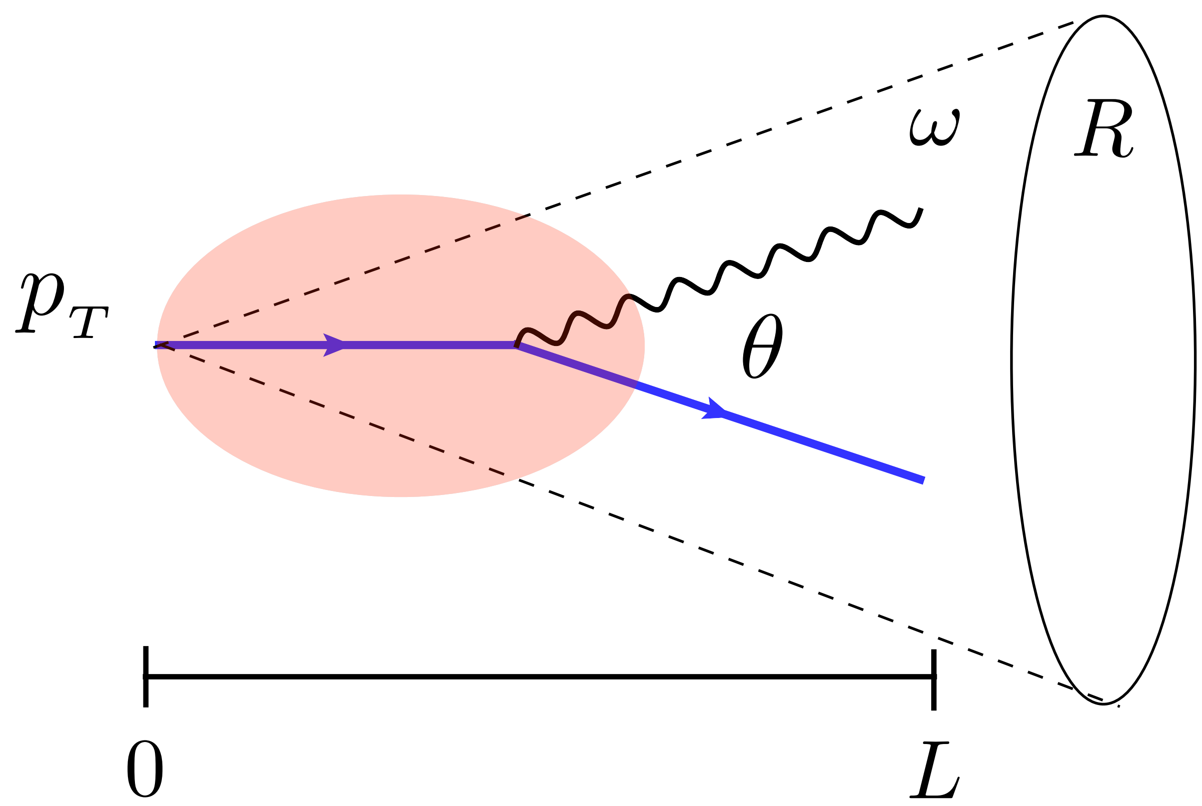
Jet quenching and fluctuations

- Energy is lost mainly via radiation **but how does a jet as a muti-parton system lose energy to the medium?**
- Does one need to account for fluctuations of energy loss due to **fluctuations of the jet substructure**?



Phase-space analysis

- How large are next-to-leading order contributions?



$$t_{\mathrm{f}} = \frac{1}{\omega\theta^2}$$

- Probability for a virtual quark to split inside the medium:

$$\mathrm{PS} = \bar{\alpha} \int_0^{p_T} \frac{\mathrm{d}\omega}{\omega} \int_0^{R} \frac{\mathrm{d}\theta}{\theta} \;\Theta(t_{\mathrm{f}} < L) = \frac{\bar{\alpha}}{4} \log^2\left(p_T R^2 L\right)$$

Phase-space analysis

- Large double-logarithmic phase-space at high pT:

$$\frac{1}{p_T R^2} \quad \ll \quad t_\mathrm{f} \quad \ll \quad L$$

- When $\bar{\alpha} \log^2(p_T R^2 L) \gtrsim 1$ higher-orders are not negligible

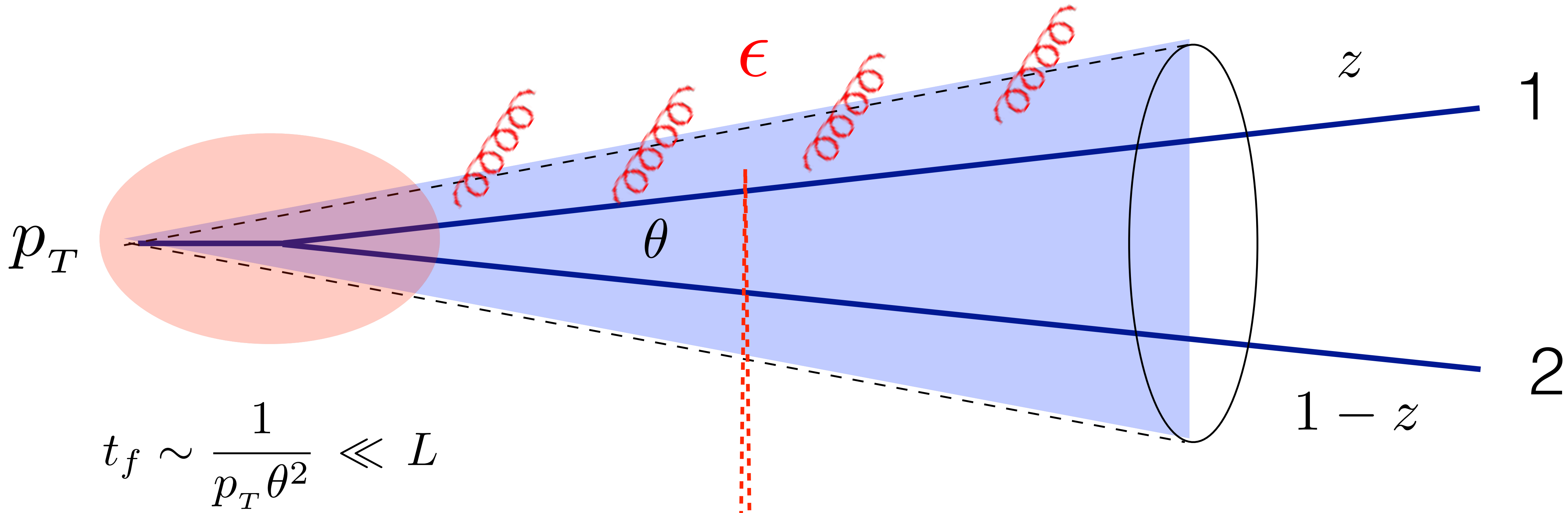
$\Rightarrow$ **double-logs (DL) need to be resummed**

- **Estimate:** for R=0.3, L=2 fm and pT=500 GeV,
  one finds **$\mathrm{Log}^2 \sim 40$**

Two-prong energy loss

Two-prong energy loss

- Consider a high energy parton that splits rapidly into two hard subjects within the jet cone
- At high p_T the branching time is shorter than the length of the medium ⇒ factorization

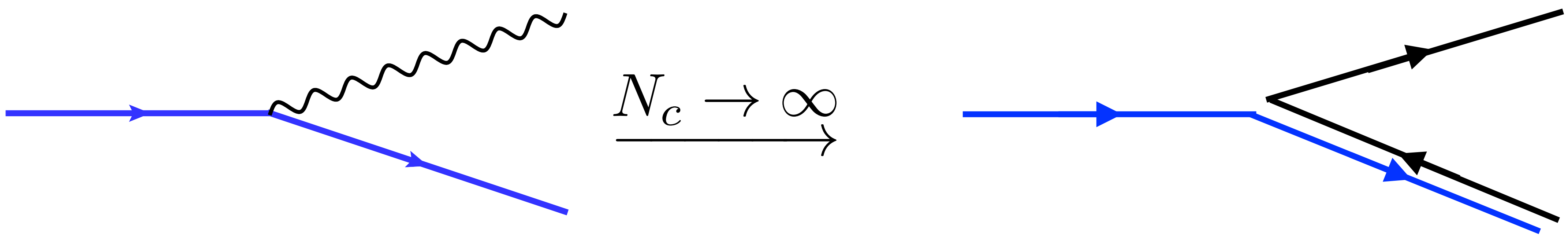


- Two prong inclusive spectrum:

$$\theta \frac{\mathrm{d}N}{\mathrm{d}\theta \mathrm{d}z \mathrm{d}p_T} = \int_0^\infty \mathrm{d}\epsilon \, \boxed{P_2(\epsilon)} \, \bar{\alpha} \, P(z) \, \frac{\mathrm{d}N^{\mathrm{vac}}(p_T + \epsilon)}{\mathrm{d}p_T}$$

Two-prong energy loss

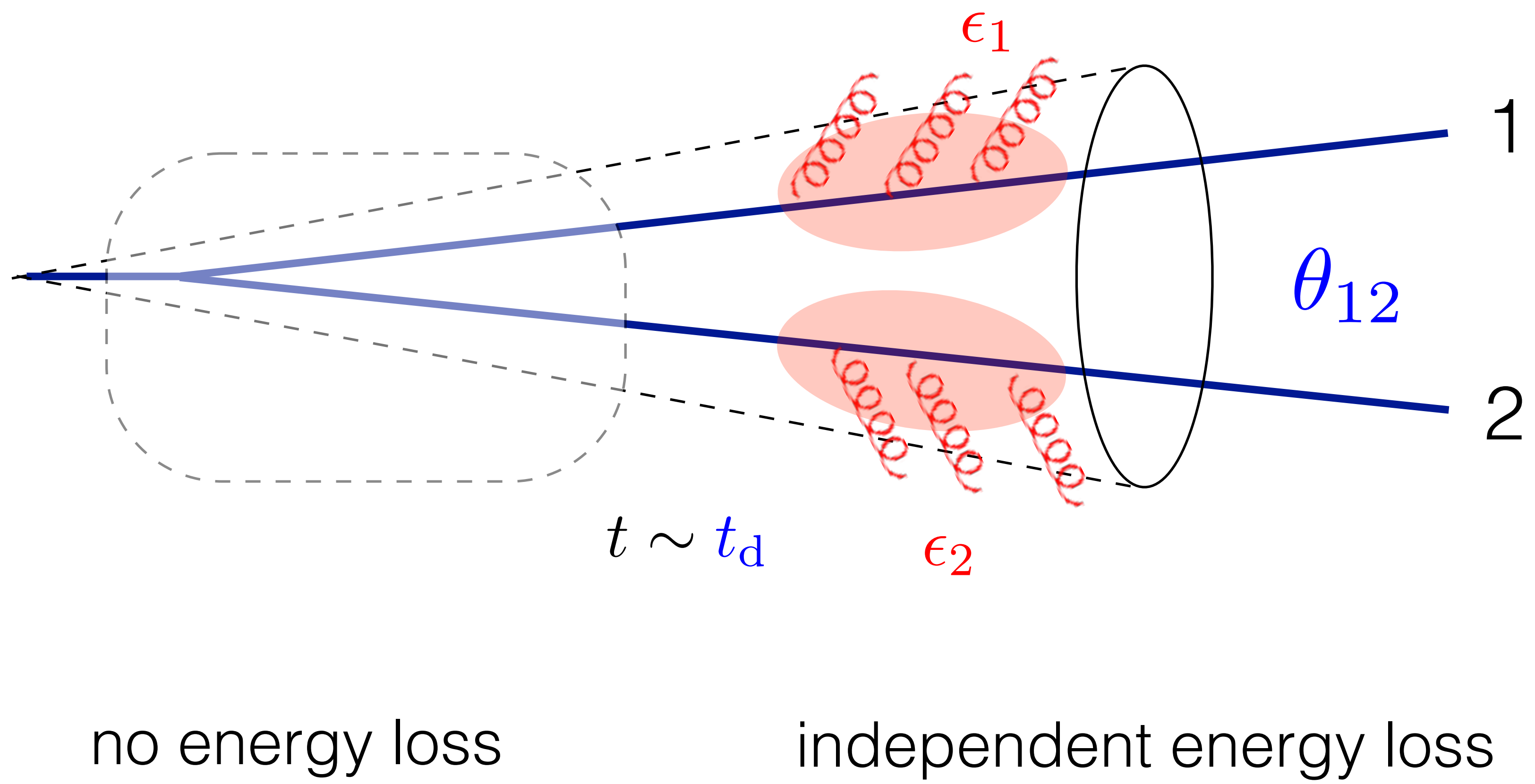
- In the large-Nc approximation



- The two-prong energy loss probability factorizes into the total charge probability convoluted with the color singlet antenna probability distribution

$$\mathcal{P}(\epsilon) = \int_{\epsilon_1,\epsilon_2} \mathcal{P}_{\rm tot}(\epsilon_1)\,\mathcal{P}_{\rm sing}(\epsilon_2)\;\delta(\epsilon - \epsilon_1 - \epsilon_2)$$

Two-prong energy loss



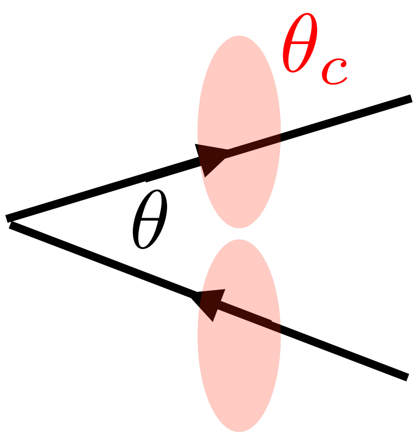
- Propagation of two color charges at fixed angle
- Up to the decoherence time $t_d \sim (\hat{q}\,\theta_{12}^2)^{-1/3}$ radiation off the total charge
- At large angle: suppression of neighboring jets

Two-prong energy loss

Two limiting cases:

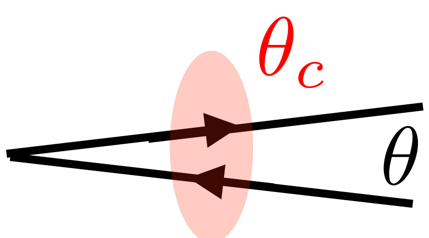
I - the medium resolves the antenna: $t_{\rm d} \ll L \quad (\theta \gg \theta_c \equiv 1/\sqrt{\hat{q}L^3})$

$$\mathcal{P}_{\rm sing}(\epsilon) \to \int_1 \mathcal{P}_q(\epsilon_1)\mathcal{P}_q(\epsilon-\epsilon_1)$$



II - the medium does not resolve the antenna: $t_{\rm d} \gg L \quad (\theta \ll \theta_c)$

$$\mathcal{P}_{\rm sing}(\epsilon) \to \delta(\epsilon)$$



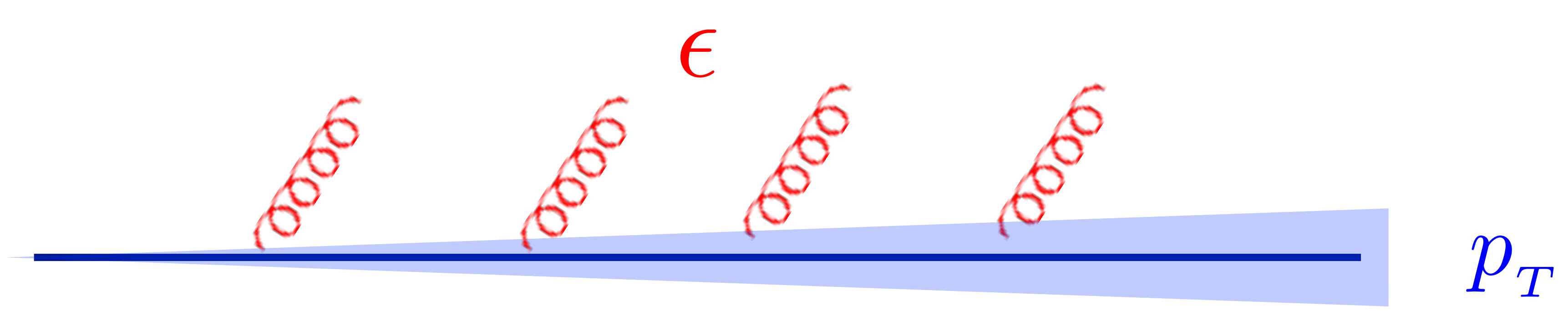
MT, Salgado, Tywoniuk PRL (2011), PLB (2012), JHEP (2011-2012)
Casalderrey-Solana, Iancu JHEP (2012)
Casalderrey-Solana, MT, Salgado, Tywoniuk PLB (2013)

Jet spectrum

First correction to the jet spectrum

- To LO the quenching factor is that of the total charge (primary quark)

$$Q^{(0)}(p_T) = Q_{\rm tot}(p_T) \equiv Q_{\rm q}(p_T)$$

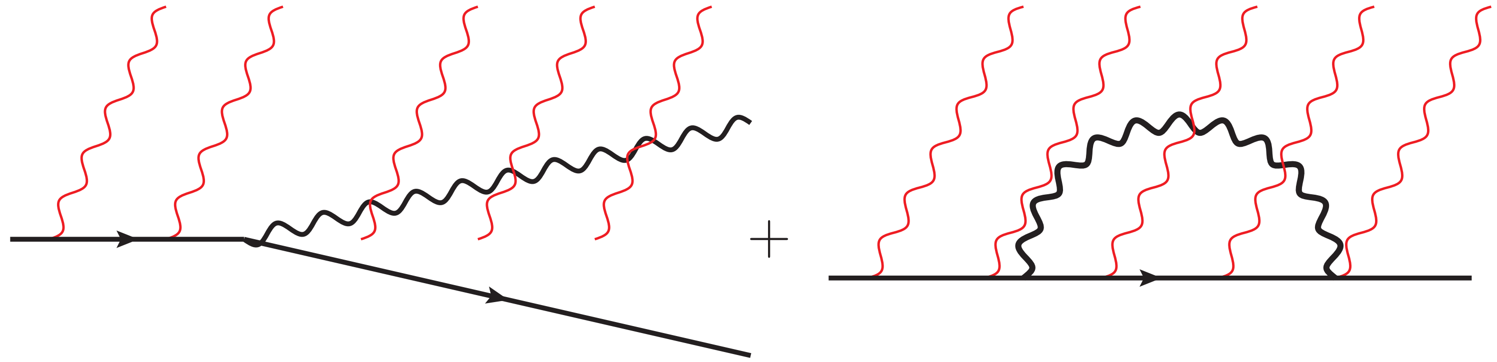


First correction to the jet spectrum

- To leading logarithmic (LL) accuracy there are exact cancellations between real an virtual corrections as in vacuum except when: $t_{\rm f} \ll t_{\rm d} \ll L$

$$Q^{(1)}(p_T) = \bar{\alpha} \int_{\theta_c}^{R} \frac{d\theta}{\theta} \int_{(\hat{q}/\theta^4)^{1/3}}^{p_T} \frac{d\omega}{\omega} \left[Q_q^2(p_T) - 1 \right] Q_{\rm tot}(p_T)$$

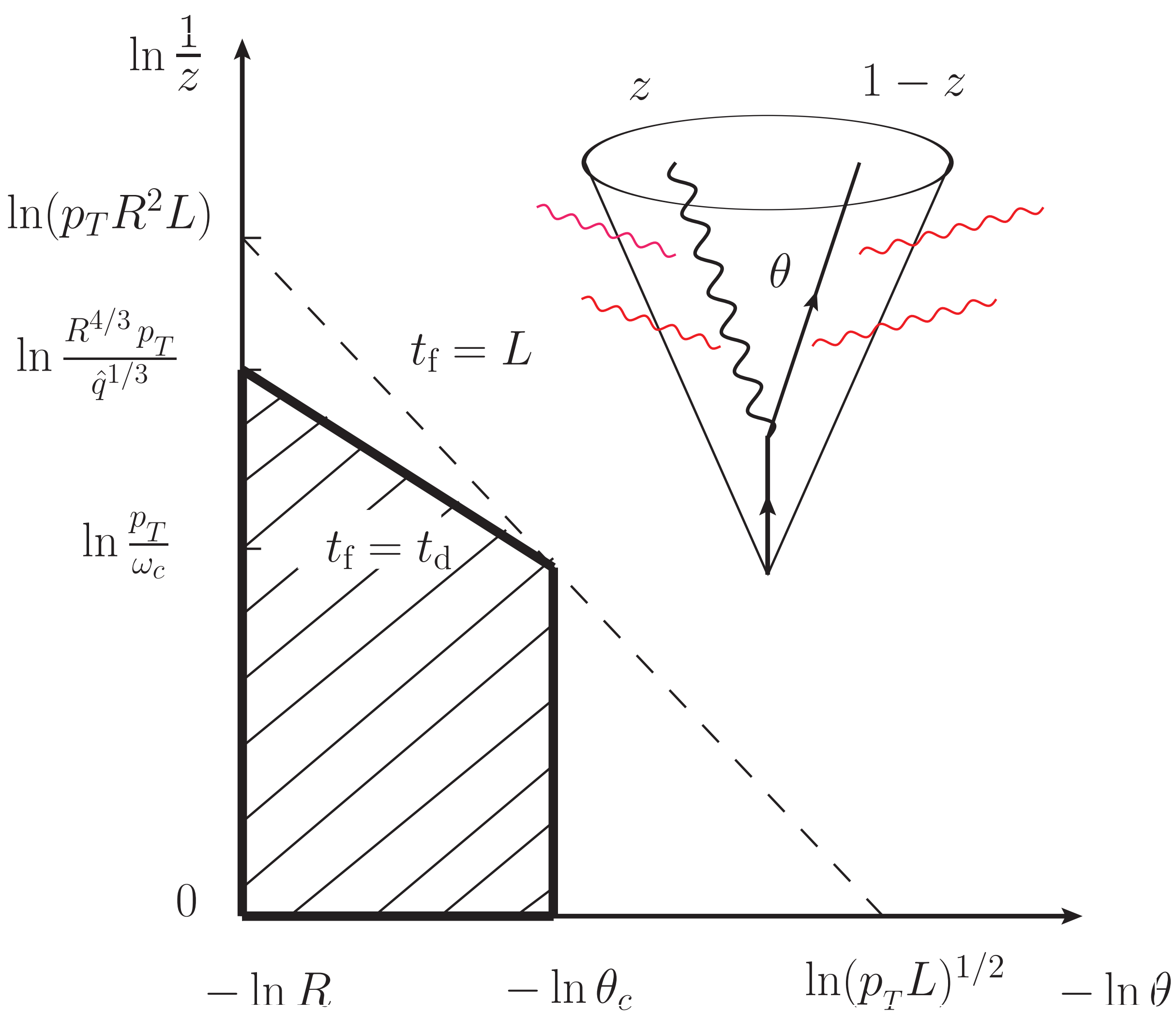
Mismatch between real and virtual



gluon+quark energy loss $\ll$ quark energy loss

First correction to the jet spectrum

- To leading logarithmic (LL) accuracy there are exact cancellations between real an virtual corrections as in vacuum except when: $t_\mathrm{f} \ll t_\mathrm{d} \ll L$



formation time

$$t_\mathrm{f} \sim \frac{1}{z p_T \theta^2}$$

decoherence time

$$t_\mathrm{d} \sim \frac{1}{(\hat{q}\theta^2)^{1/3}}$$

$$\propto \ln \frac{R}{\theta_c} \left[\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right]$$

Exponentiation of the Double-Logs

- Instructive limit: **strong quenching** $Q_{\text{tot}}(p_T) \ll 1$
- It can be shown that the leading logarithms exponentiate into a **Sudakov Form Factor**

$$Q(p_T) = Q_{\text{tot}}(p_T) \times C(p_T)$$

- where

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

$\Rightarrow$ **Fluctuations of the jet substructure yield additional suppression to the jet spectrum**

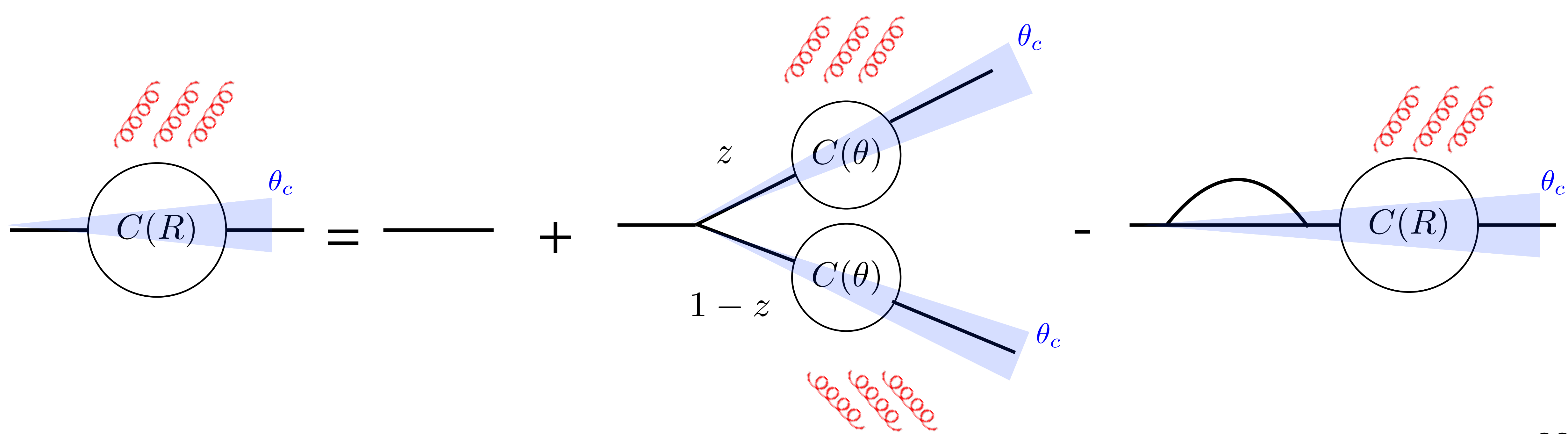
- **Coherent limit:** note that when $R \ll \theta_c$ the medium "sees" only the total charge, in this case

$$C(p_T) \to 1 \qquad \text{and} \qquad Q(p_T) \to Q_{\text{tot}}(p_T)$$

Non-linear evolution equation

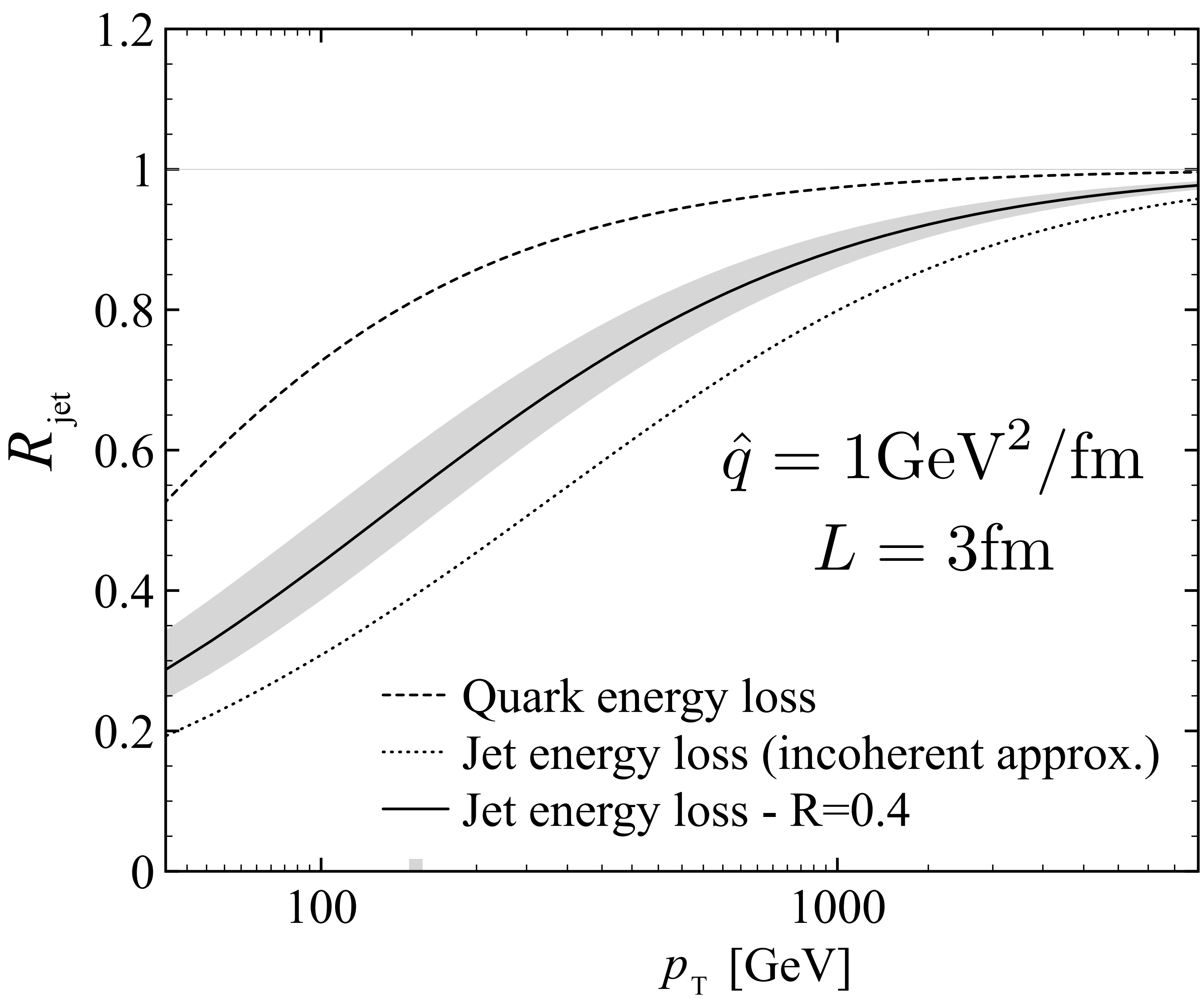
- The function C(p) obeys a **non-linear evolution equation** that resums the leading logarithms: arXiv:1707.07361 [hep-ph]

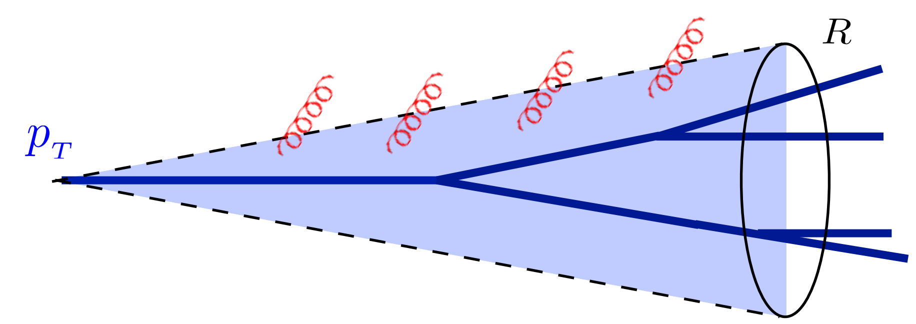
$$C_q(p_T, R) = 1 + \int_0^1 \mathrm{d}z \int_0^R \frac{\mathrm{d}\theta}{\theta} \frac{\alpha_s(k_\perp)}{\pi} P_{qg}(z)\; \Theta(t_\mathrm{f} < t_\mathrm{d} < L)$$
$$\times \left[\; C_q(zp_T, \theta)\; C_g(zp_T, \theta)\; \mathcal{Q}_q^2(p_T) - \; C_q(zp_T, \theta)\; \right]$$



Nuclear modification factor

$$R_{\rm jet} = Q_{\rm tot}(p_T) \times C(p_T)$$





Large contribution from fluctuating jet substructure

Summary

- Due to the large logarithmic phase-space for jets to branch inside a large medium higher-order corrections are found to be important ⇒ relevant for probing medium properties
- These corrections can be resumed to all orders to leading logarithmic accuracy by a non-linear evolution equation
- The effect of color coherence mitigates the importance of higher order corrections to the jet spectrum for narrow jets

Backup

In-medium gluon cascade

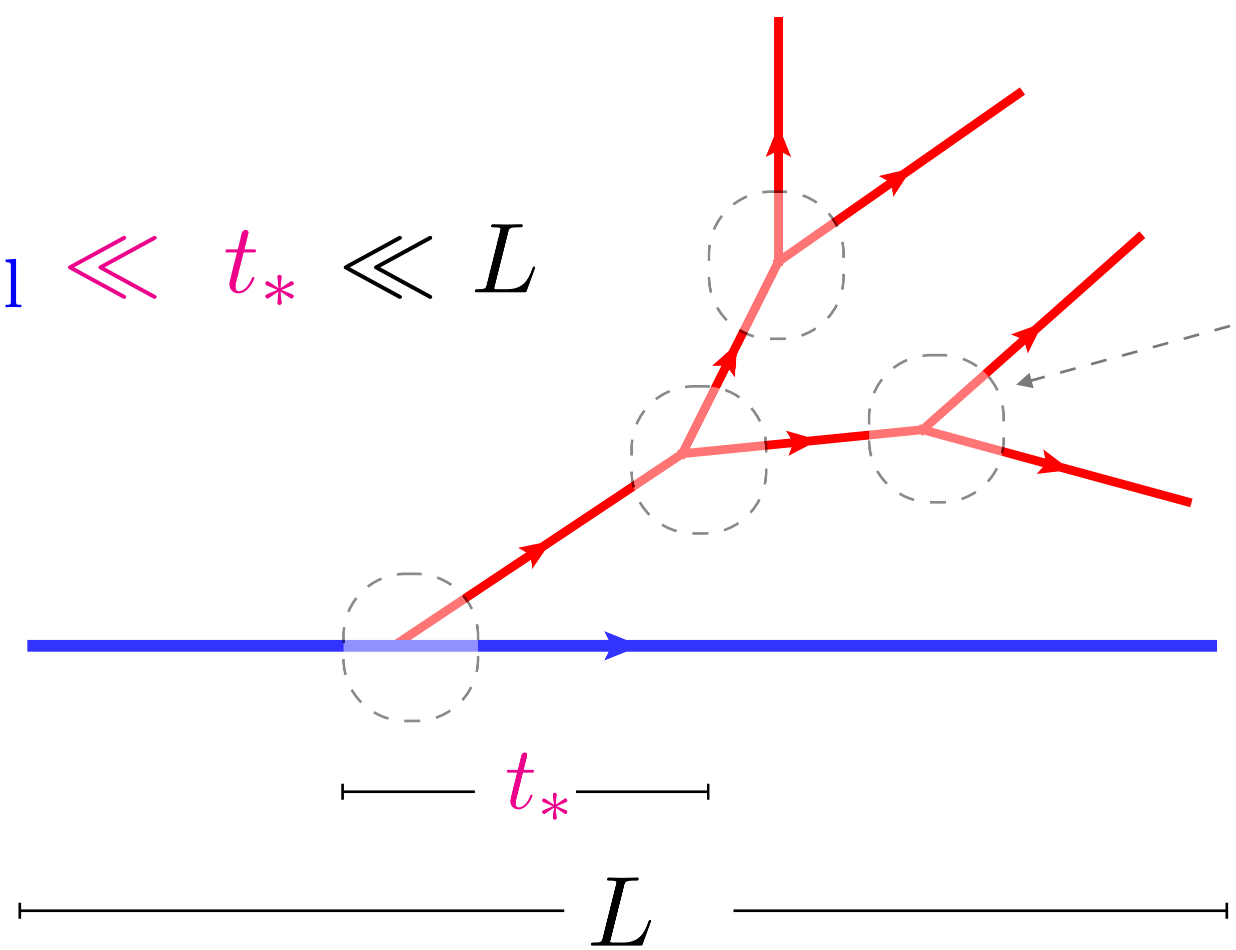
- **Probabilistic picture:** large probability for **soft, rapid and independent multiple gluon branching**

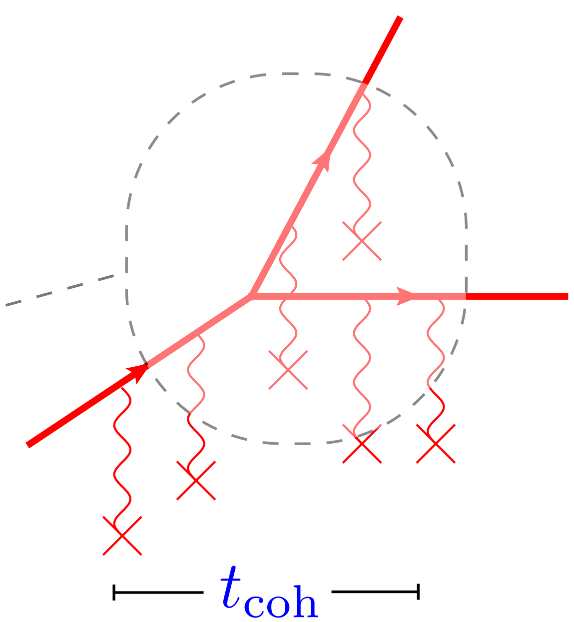
$$\omega \frac{\mathrm{d}P}{\mathrm{d}\omega \mathrm{d}t} \equiv \frac{\alpha_s}{t_{\rm coh}} \equiv \frac{1}{t_*}$$

branching time:

$$t_*(\omega) = \frac{1}{\alpha_s}\sqrt{\frac{\omega}{\hat{q}}}$$

$$t_{\rm col} \ll t_* \ll L$$





[Baier, Dokshitzer, Schiff, Mueller (2001)
Jeon, Moore (2003)
Blaizot, Dominguez, Iancu, MT (2013-2014)]

Energy flow at large angle

[Blaizot, Iancu, Fister, Torres, MT (2013-2014) Kurkela, Wiedemann (2014)]

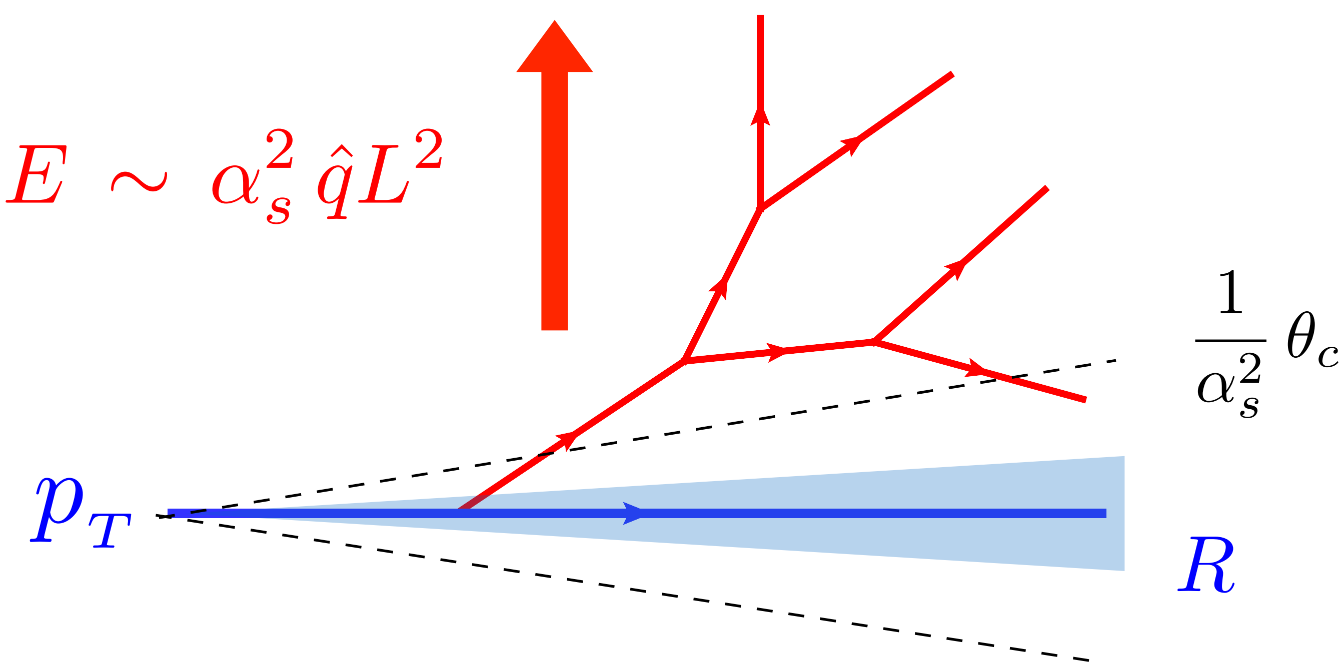
- Multiple branchings at parametrically large angle

$$\theta_{\rm br} \gg \frac{1}{\alpha_s^2}\theta_c \gg R$$

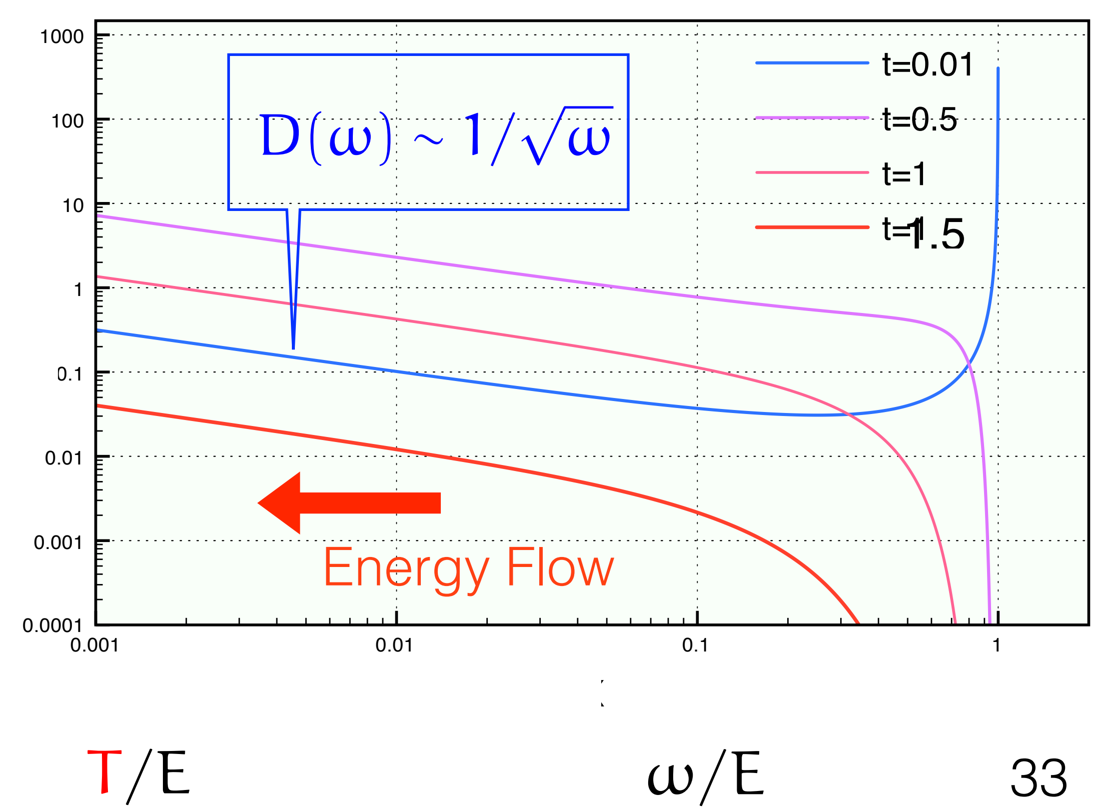
- Constant energy flow from jet energy scale p_T energy down to the medium temperature scale $\omega \sim T$ [Iancu, Wu (2015)]

Energy lost to the medium:

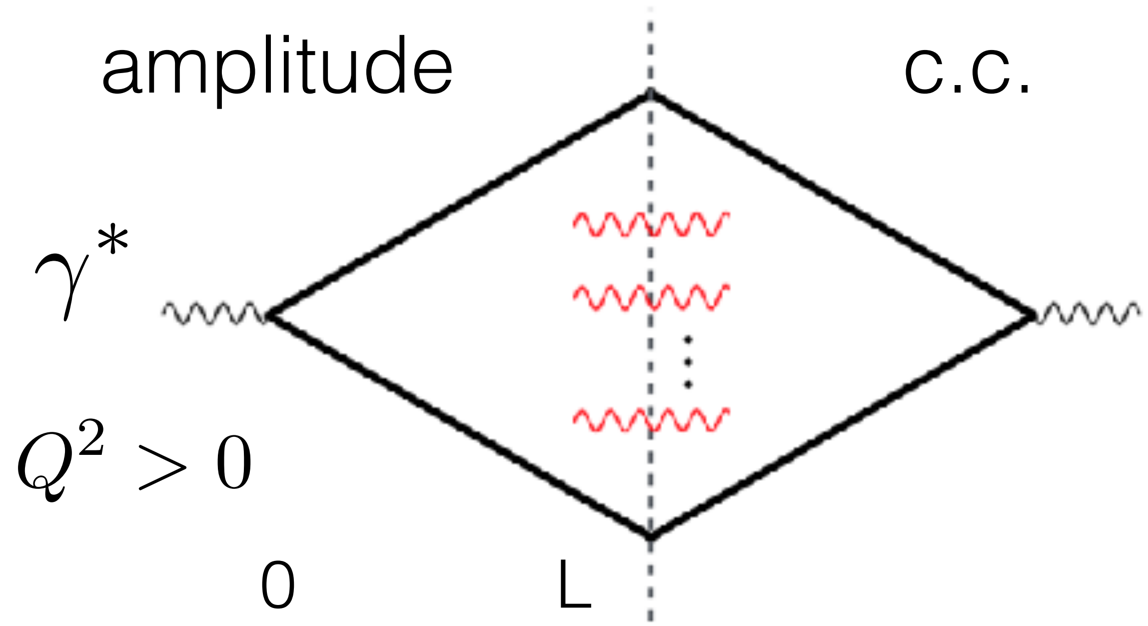
$$\Delta E \sim \alpha_s^2\, \hat{q} L^2$$

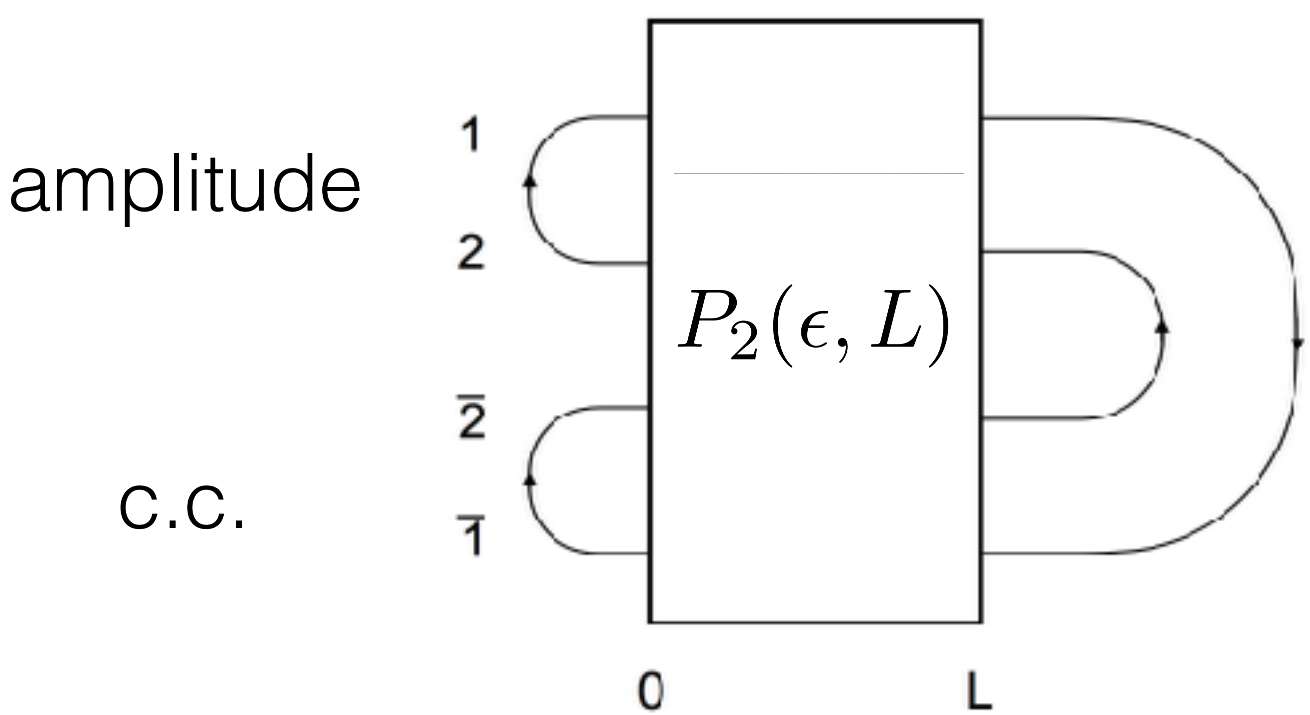


Energy distribution as function of time



Two-prong energy loss



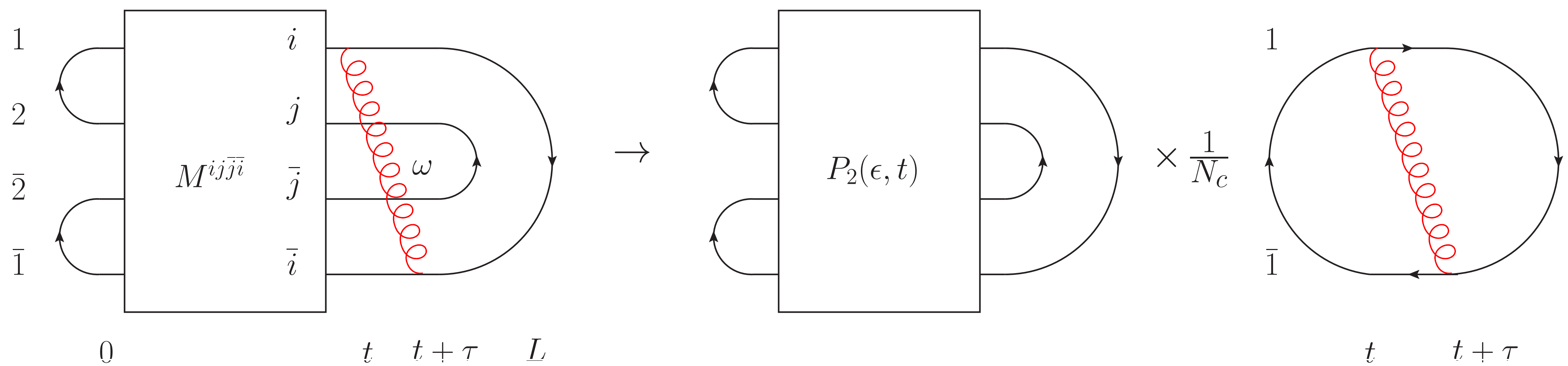


Caveats:

- large N_c
- resum medium-induced soft emissions
- short formation times
- color singlet: straightforward generalization to triplet and octet configurations

Two-prong energy loss

- Direct emission term (diagonal contribution)



$$\Delta P_2(\epsilon, L) = \int_0^L \mathrm{d}t \int_0^\infty \mathrm{d}\omega\, \Gamma_{11}(\omega, t)\, P_2(\epsilon - \omega, t)$$

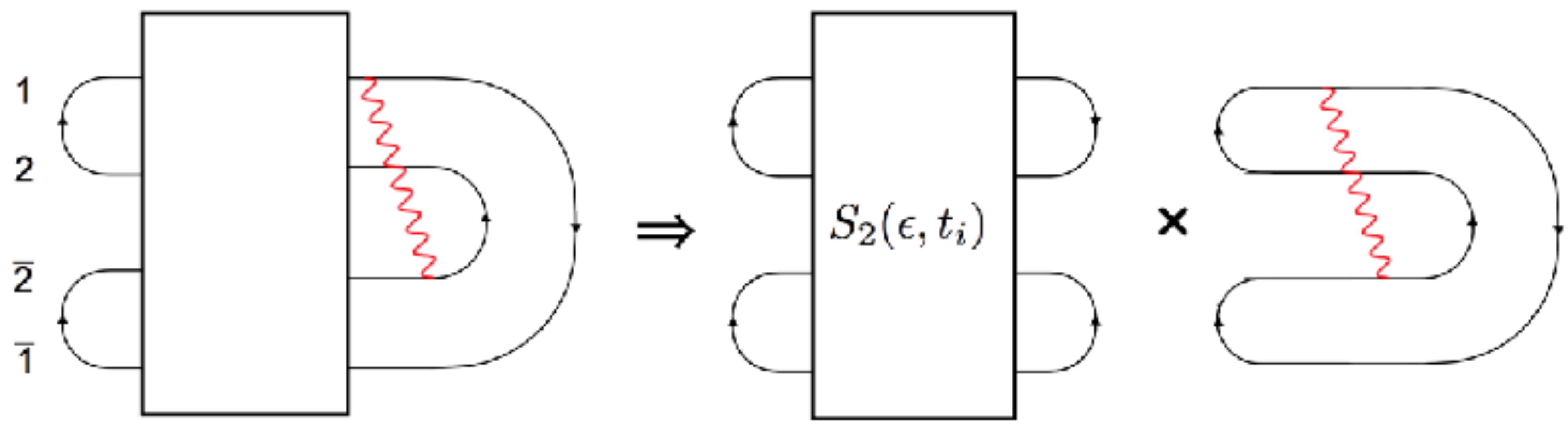
- Correction identical to single particle case:

$$\Gamma_{11}(\omega, t) \equiv \frac{\mathrm{d}I_{11}}{\mathrm{d}\omega \mathrm{d}t} - \delta(\omega) \int_0^\infty \mathrm{d}\omega' \frac{\mathrm{d}I_{11}}{\mathrm{d}\omega' \mathrm{d}t}$$

real virtual

Two-prong energy loss

- Interferences and color flip (recall that all propagators are evaluated in the medium background field)



$$\Delta P_2(\epsilon, L) = \int_0^L \mathrm{d}t \int_0^\infty \mathrm{d}\omega \, \Gamma_{12}(\omega, t) \; S_2(\epsilon - \omega, t)$$

- Involves new color structure

$$S_2 \sim \langle \mathrm{tr}(V_2^\dagger V_1) \, \mathrm{tr}(V_1^\dagger V_2) \rangle$$

Two-prong energy loss

arXiv:1706.06047 [hep-ph]

- The **color singlet antenna** probability distribution reads:

$$\mathcal{P}_{\rm sing}(\epsilon, L) = \int_{\epsilon_1,\epsilon_2} \mathcal{P}_q(\epsilon_1, L)\, \mathcal{P}_q(\epsilon_2, L)\ \delta(\epsilon - \epsilon_1 - \epsilon_2)$$

$$+\, 2\int_0^L {\rm d}t \int_{\epsilon_1,\epsilon_2,\omega} \mathcal{P}_q(\epsilon_1, L-t)\mathcal{P}_q(\epsilon_2, L-t)\, \Gamma(\omega)\, S(t)\delta(\epsilon - \epsilon_1 - \epsilon_2 - \omega)$$

- with $\Gamma(\omega) = \frac{{\rm d}I}{{\rm d}\omega{\rm d}t} - \delta(\omega)\int_0^\infty {\rm d}\omega' \frac{{\rm d}I}{{\rm d}\omega'{\rm d}t}$

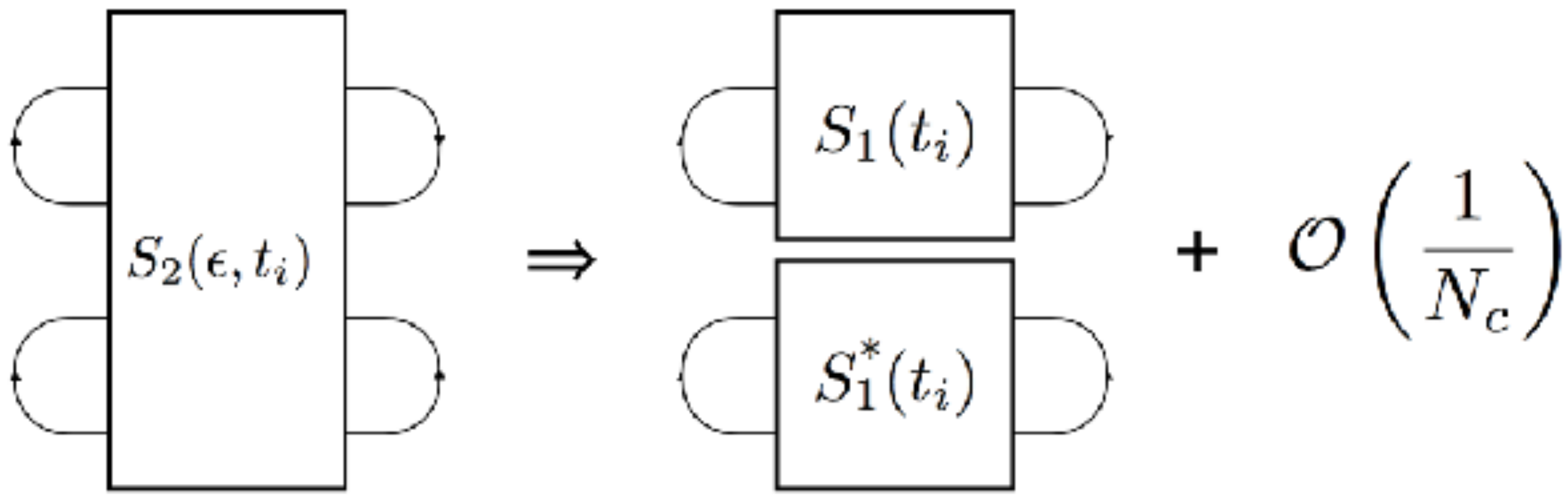
- **Decoherence** time scale

$$t_{\rm d} \equiv (\hat{q}\,\theta^2)^{1/3}$$

- Two terms: **independent energy loss** + **interferences**

Two-prong energy loss

- In the Large N$_c$ approximation



- Amplitude and c.c. are disconnected $\Rightarrow$ only virtual emissions contribute

- In the absence of radiation we recover the decoherence parameter: $\Delta_{\rm med} \equiv 1 - S_1^2$

antenna transverse size

$$S_1(t) \equiv \langle {\rm tr} V_2^\dagger V_1 \rangle_{\rm med} \sim \exp\left[-\frac{1}{4}\,\hat{q}\int_0^t {\rm d}t'\, \boldsymbol{x}_{12}^2(t')\right]$$

[MT, Salgado, Tywoniuk, arXiv:1105.1346, MT, Salgado, Tywoniuk arXiv:1205.5739, Casalderrey-Solana, Iancu arXiv:1105:1760]