Radiative Corrections to Jet Quenching in Dense and Dilute Media

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Jet quenching in the LHC era

Pre LHC

- Evidence: disappearance of away peak in two-particle correlation
- Theory: medium-induced energy loss from leading parton

Today

- Evidence: suppression of fully reconstructed jets, large dijet asymmetries,…
- Theory: medium-modified parton showers (?), flow of energy away from the jet cone (?)

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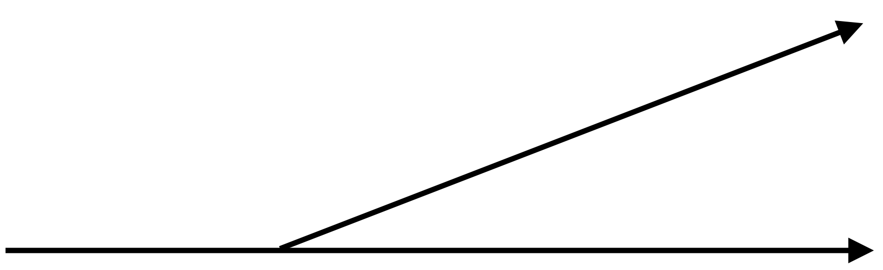

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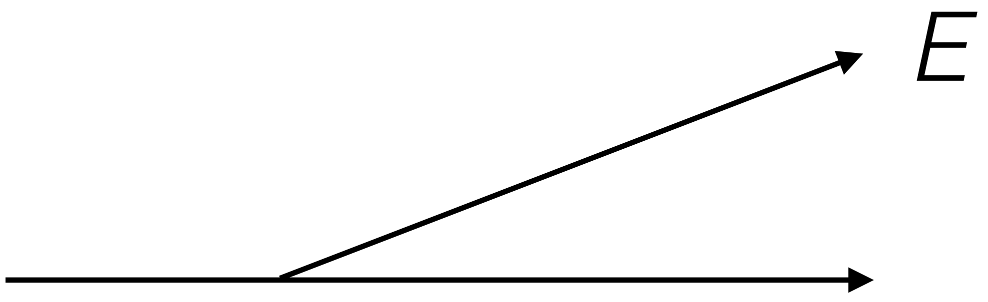

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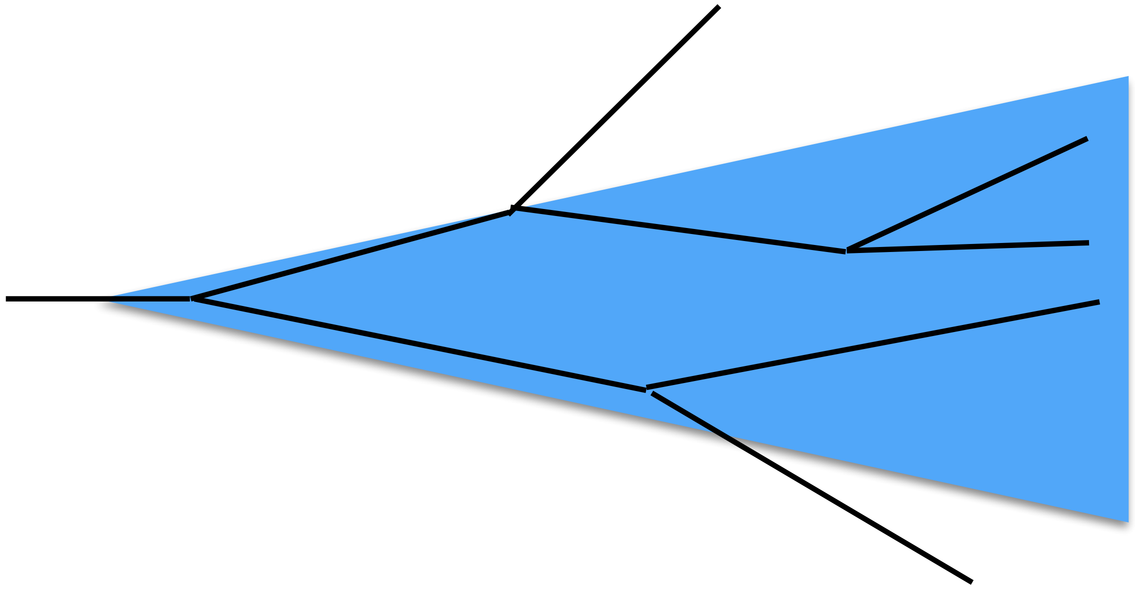
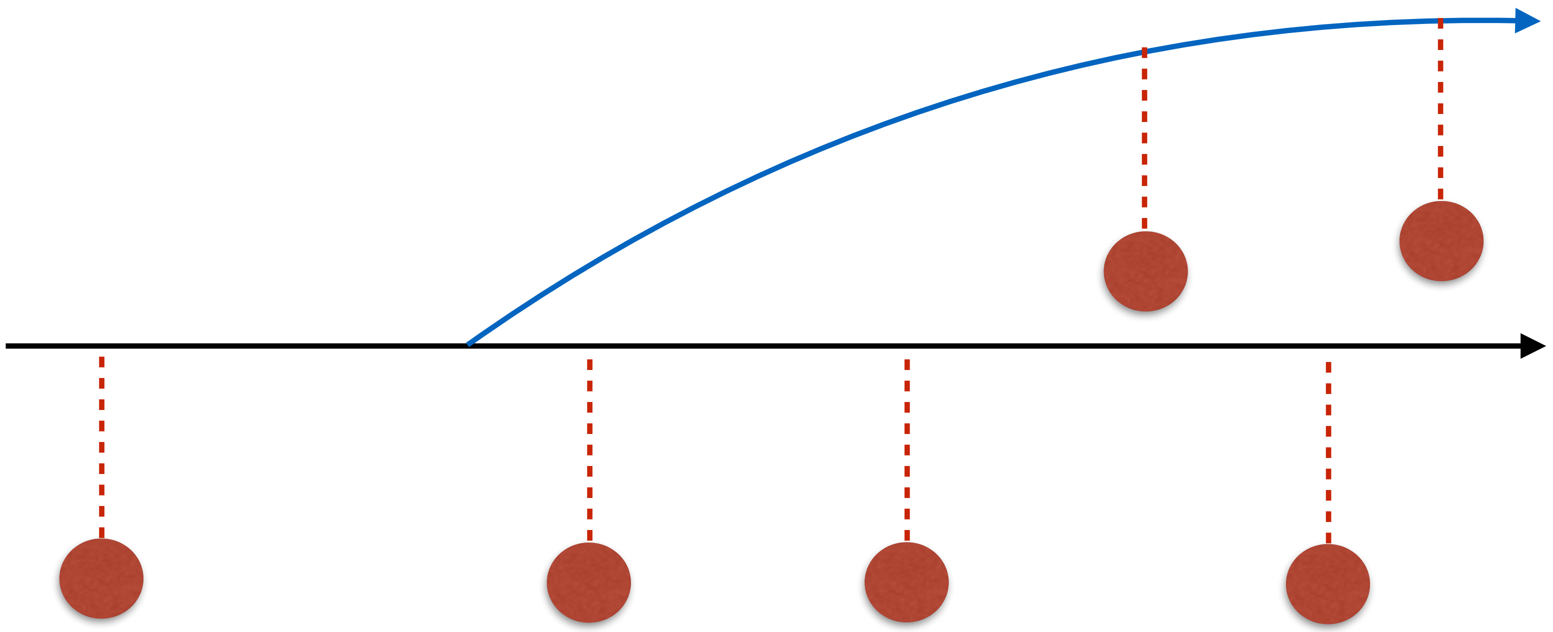


Medium-induced radiation

Hard parton undergoes multiple scatterings and radiates gluons coherently



LPM effect ⟶ BDMPS-Z Formalism

BDMPS-Z

Baier, Dokshitzer, Mueller, Peigné, Schiff; Zakharov

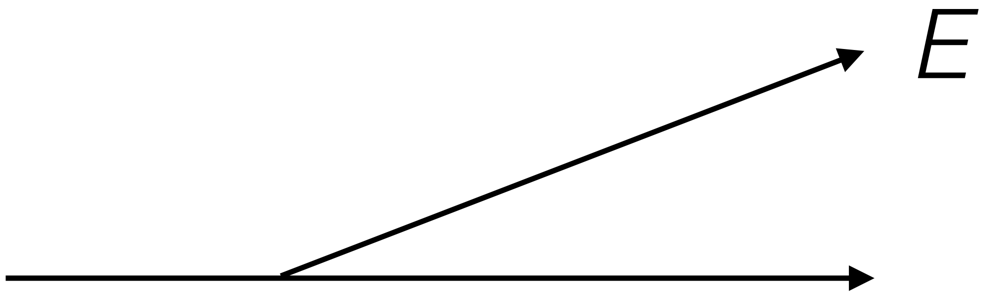
- Established a clear relation between energy loss and transverse momentum broadening

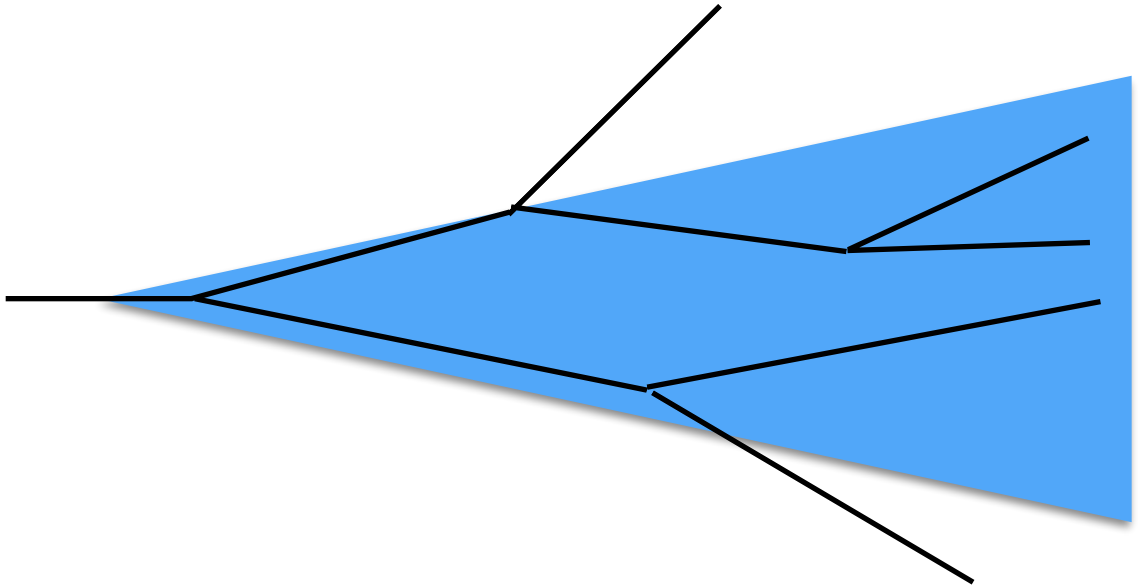
$$-\frac{dE}{dz} \sim \alpha_s N_c \left\langle p_\perp^2 \right\rangle$$

- Focuses in purely medium-induced radiation via subtraction of vacuum component

- For a sufficiently long medium one could consider the initial hard parton as being on-shell

From leading parton energy loss to jets



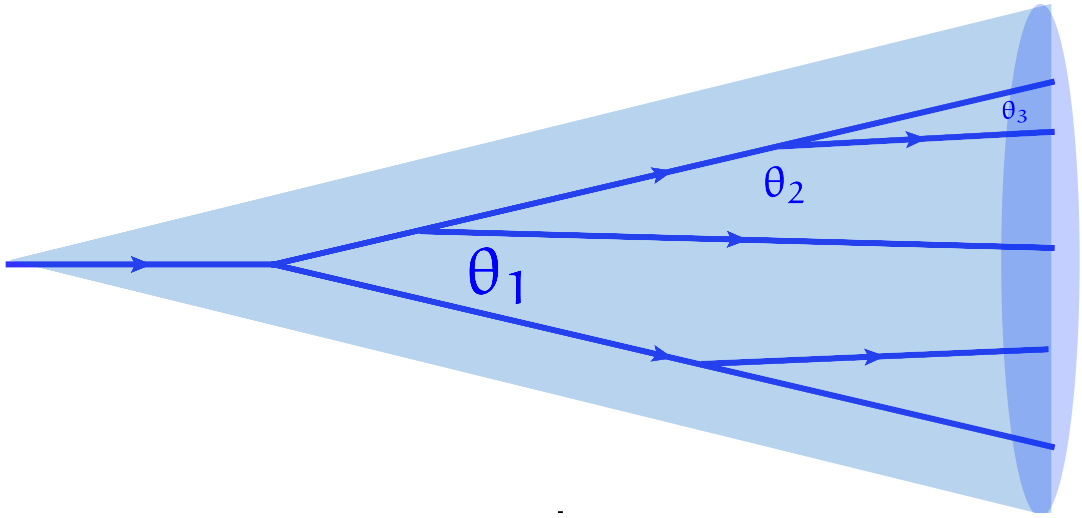


- Multiple branchings instead of single gluon emission. Parton showers
- Where does the energy go?
- No vacuum subtraction
- What is the role of interferences?

Color coherence

Mehtar-Tani, Salgado, Tywoniuk

- In vacuum, color coherence implies angular ordering in the parton shower
- Interaction with the medium can destroy color coherence (antenna calculation)
- Soft emissions at large angles are enhanced



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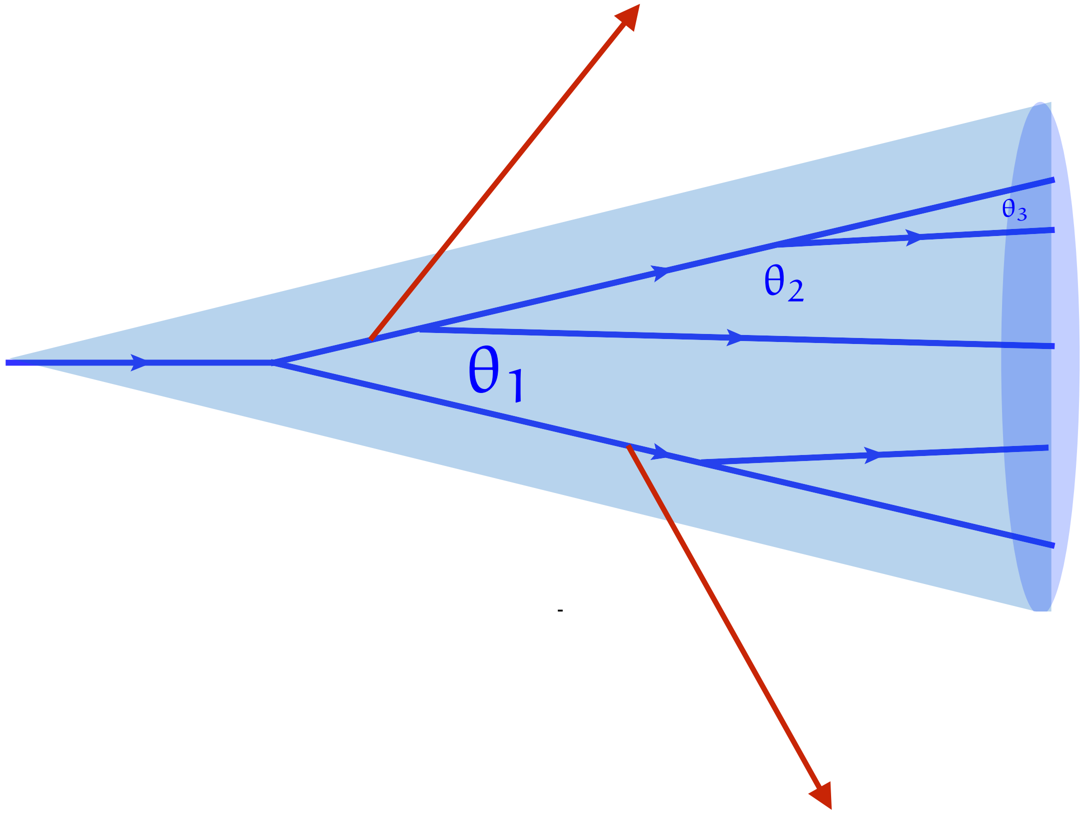
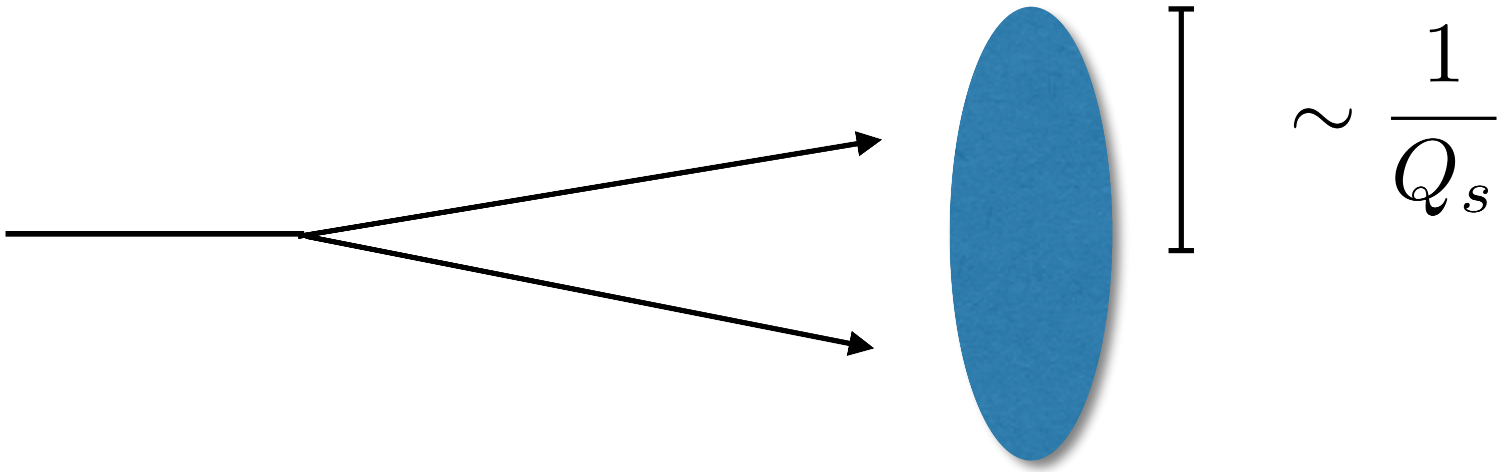


Medium resolution

There is a transverse scale which determines if the medium can resolve the inner structure of a given shower

Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk



$\sim \frac{1}{Q_s}$

$$Q_s \sim \hat{q}L$$

If the medium can't resolve the inner structure then it evolves in an angular-ordered shower while emitting as a single particle (coherent limit)

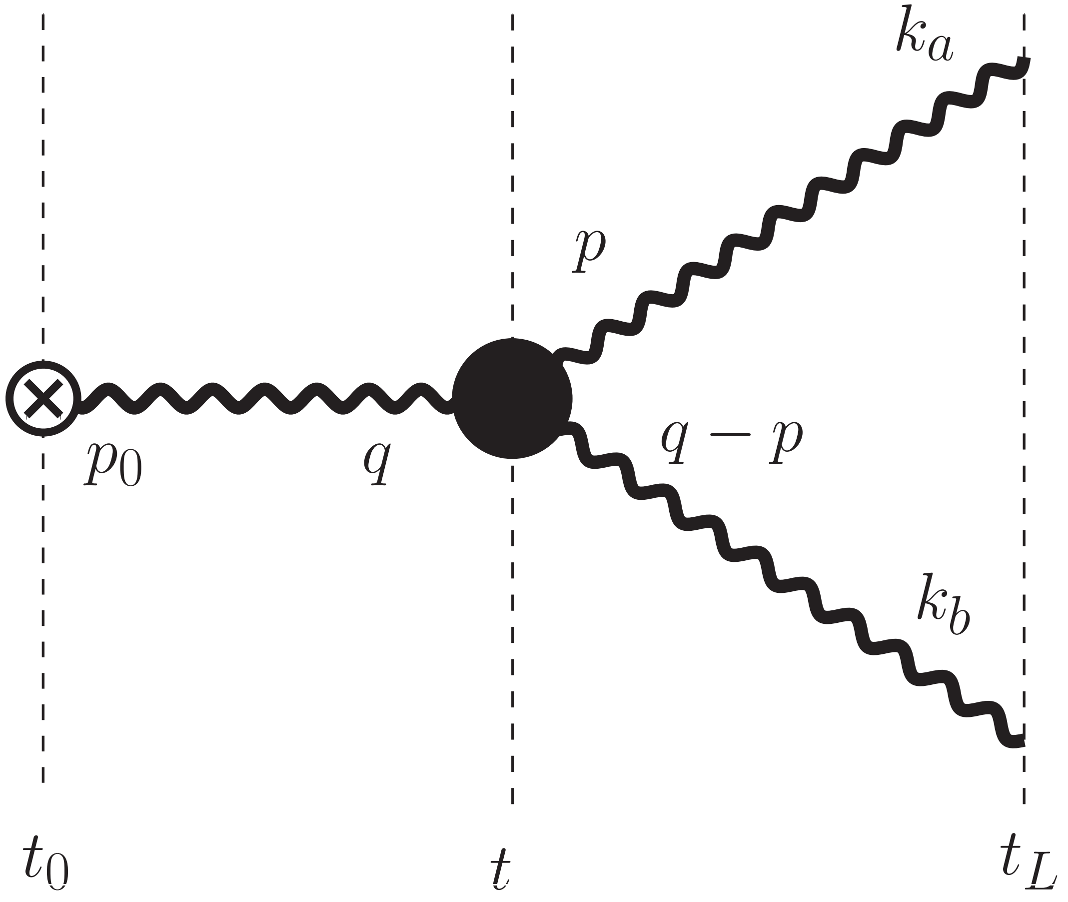
Main Features of Jet Modification

- Suppression by a factor of 2-3 of single jet spectrum in central collisions
- Large dijet and photon-jet asymmetries
- Azimuthal correlations not (largely) modified
- Missing momentum is found in tracks of soft particles at large angles
- Fragmentation functions not modified at large energy fractions but an excess of soft particles inside the jet is observed

Multiple emissions

- Antenna calculation as guidance on how to deal with the interferences
- Branching time = Decoherence time
- In a sufficiently dense and long medium, leading effects come from short formation times and emissions can be considered as local and independent (total decoherence limit)
- Probabilistic picture

In-Medium Gluon Branching



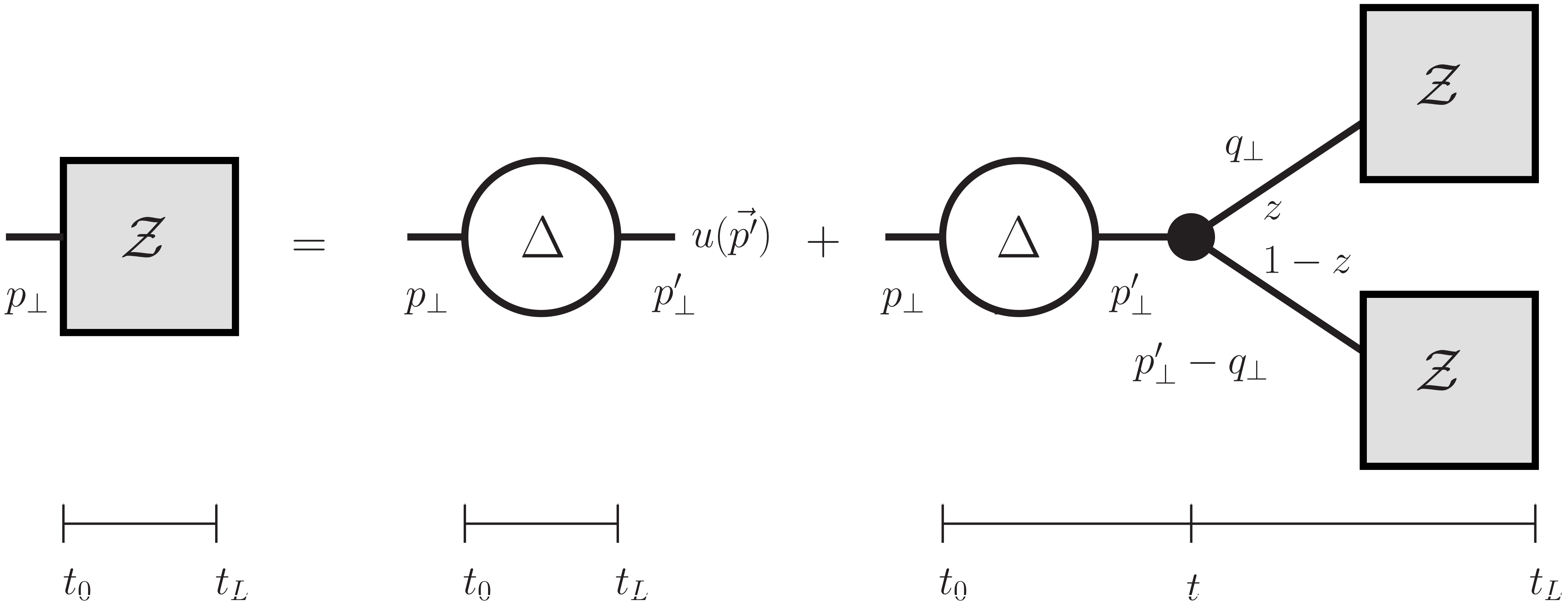
Splitting Kernel

$$\mathcal{P}_2(\boldsymbol{k}_a, \boldsymbol{k}_b, z; t_L, t_0) = 2g^2 z(1-z) \int_{t_0}^{t_L} dt\, \mathcal{K}(z, p_0^+; t)$$
$$\times \int_{\boldsymbol{q}} \mathcal{P}(\boldsymbol{k}_a - z\boldsymbol{q}; t_L, t)\, \mathcal{P}(\boldsymbol{k}_b - (1-z)\boldsymbol{q}; t_L, t) \mathcal{P}(\boldsymbol{q} - \boldsymbol{p}_0; t, t_0)$$

Momentum broadening

Multiple Branchings

- Use a generating functional to resum diagrams



Splittings ordered in time

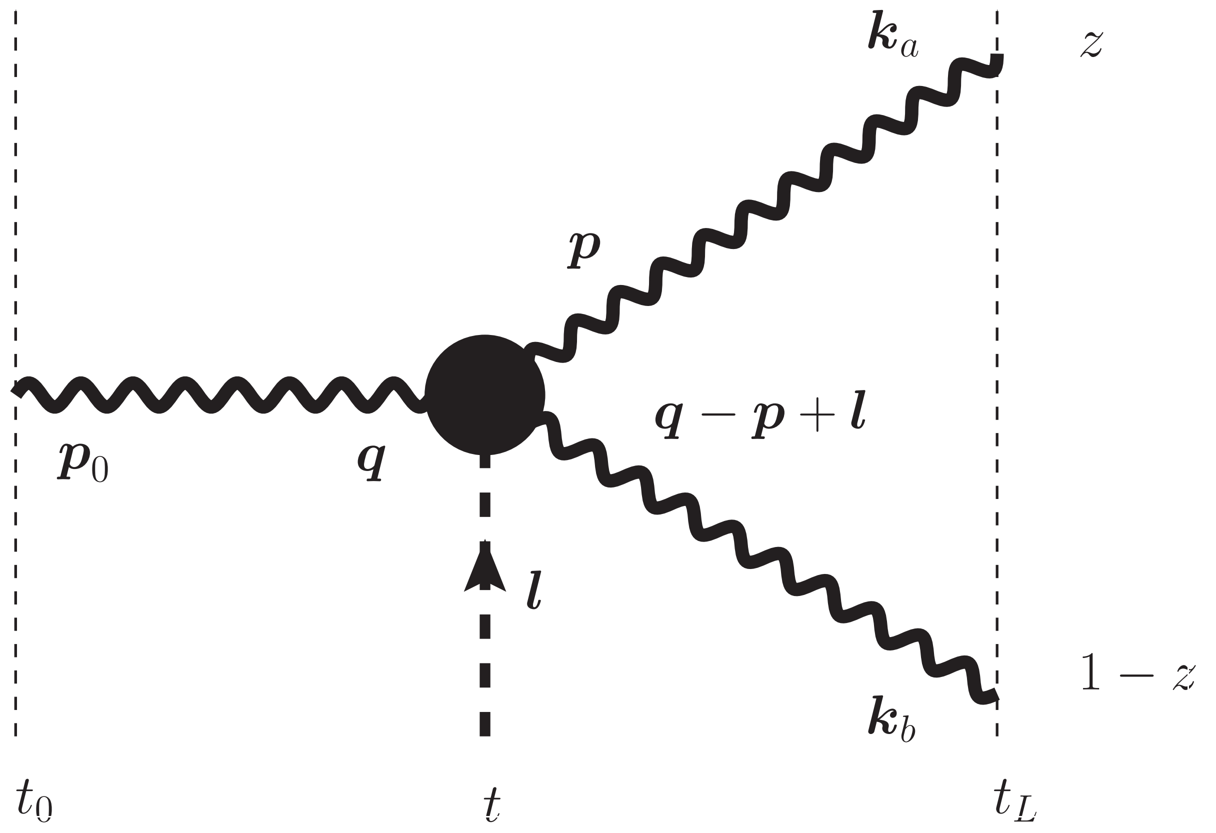
One-Gluon Distribution

$$D(x, \boldsymbol{k}, t) = k^+ \frac{dN}{dk^+ d^2\boldsymbol{k}}$$

Evolution equation:

$$\frac{\partial}{\partial t} D(x, \boldsymbol{k}, t) = \int_l \mathcal{C}(\boldsymbol{l}, t) D\left(x, \boldsymbol{k} - \boldsymbol{l}, t\right)$$
$$+ \alpha_s \int_0^1 dz \left[\frac{2}{z^2} \mathcal{K}\left(z, \frac{x}{z} p_0^+; t\right) D\left(\frac{x}{z}, \frac{\boldsymbol{k}}{z}, t\right) - \mathcal{K}\left(z, x p_0^+; t\right) D\left(x, \boldsymbol{k}, t\right) \right]$$

Radiative Corrections



Kernel depends on transverse momenta

$$\mathcal{P}_2(\boldsymbol{k}_a, \boldsymbol{k}_b, z; t_L, t_0) = 2g^2 z(1-z) \int_{t_0}^{t_L} dt \int_{\boldsymbol{q},\boldsymbol{Q},\boldsymbol{l}} \mathcal{K}(\boldsymbol{Q}, \boldsymbol{l}, z, p_0^+; t)$$
$$\times \mathcal{P}(\boldsymbol{k}_a - \boldsymbol{p}; t_L, t)\, \mathcal{P}(\boldsymbol{k}_b - (\boldsymbol{q} + \boldsymbol{l} - \boldsymbol{p}); t_L, t) \mathcal{P}(\boldsymbol{q}; t, t_0)$$

Liou, Mueller, Wu; Blaizot, Dominguez, Iancu, Mehtar-Tani

Radiative Corrections

One-gluon distribution

$$\frac{\partial}{\partial t_L}D(x,\boldsymbol{k},t_L)=\alpha_s\int_0^1 dz\int_{\boldsymbol{Q},\boldsymbol{l}}\left[\frac{2}{z^2}\mathcal{K}\left(\boldsymbol{Q},\boldsymbol{l},z,\frac{x}{z}p_0^+\right)D\left(\frac{x}{z},(\boldsymbol{k}-\boldsymbol{Q}-z\boldsymbol{l})/z,t_L\right)\right.$$
$$\left.-\mathcal{K}\left(\boldsymbol{Q},\boldsymbol{l},z,xp_0^+\right)D\left(x,\boldsymbol{k}-\boldsymbol{l},t_L\right)\right]-\int_{\boldsymbol{l}}\mathcal{C}(l)D\left(x,\boldsymbol{k}-\boldsymbol{l},t_L\right)$$

Richer momentum structure

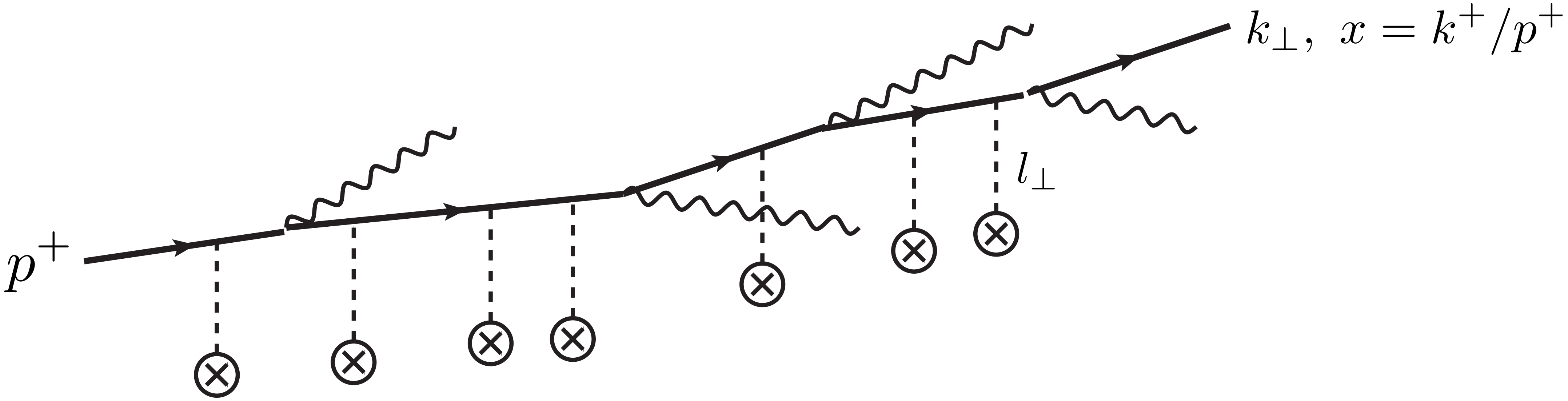
Radiative Corrections

Expand Kernel momenta

Take $z \to 1$

$$\frac{\partial}{\partial t_L} D(x,\boldsymbol{k},t_L) = \alpha_s \int_0^1 dz \left[\frac{2}{z^2}\mathcal{K}\left(z,\frac{x}{z}p_0^+\right) D\left(\frac{x}{z},\frac{\boldsymbol{k}}{z},t_L\right) - \mathcal{K}\left(z,xp_0^+\right) D\left(x,\boldsymbol{k},t_L\right)\right]$$

$$+ \frac{1}{4}\left(\frac{\partial}{\partial \boldsymbol{k}}\right)^2 \left[\left(\hat{q}(\boldsymbol{k}^2)+\delta\hat{q}(\boldsymbol{k}^2)\right) D\left(x,\boldsymbol{k},t_L\right)\right]$$

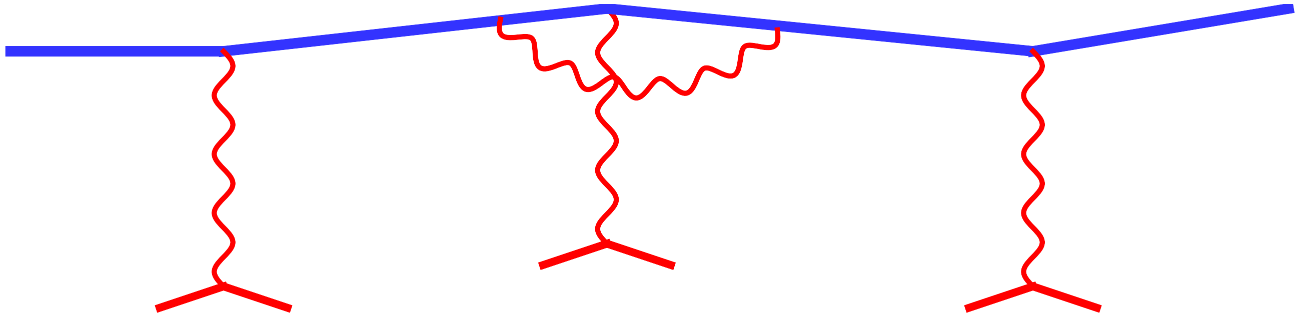


$$\delta\hat{q}(x,\boldsymbol{k}^2) = 2\alpha_s \int_x^1 dz \int_{\boldsymbol{Q},\boldsymbol{l}} \left[(\boldsymbol{Q}+\boldsymbol{l})^2 - \boldsymbol{l}^2\right] \mathcal{K}\left(\boldsymbol{Q},\boldsymbol{l},z,xp_0^+\right)$$

Why it looks like a local correction?

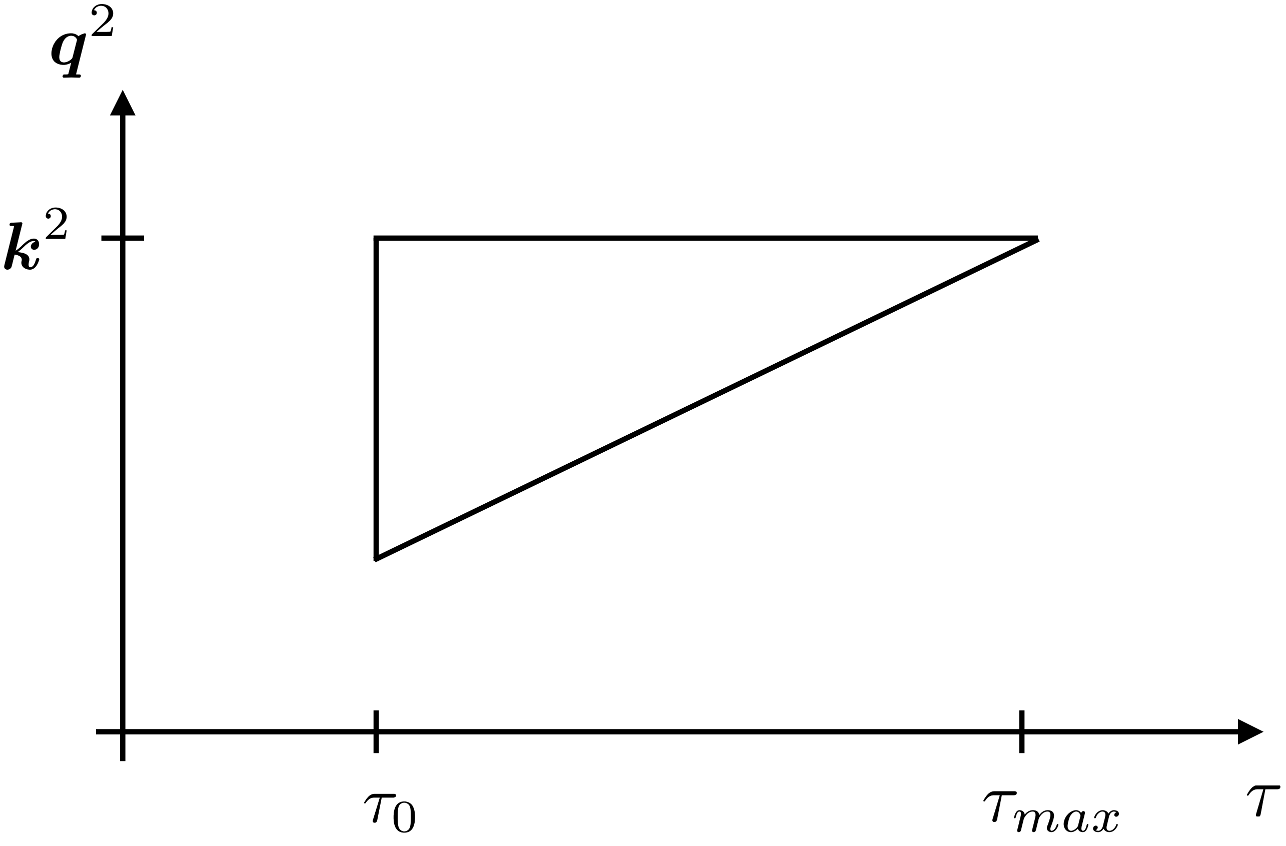
- Singularity at z=1 means main contribution comes from emissions with very short branching times

- Correction comes from interactions with the medium during the short lifetime of the fluctuation



Double log

- Main contribution comes form region of single scattering
- Double log phase space determined by multiple scattering condition



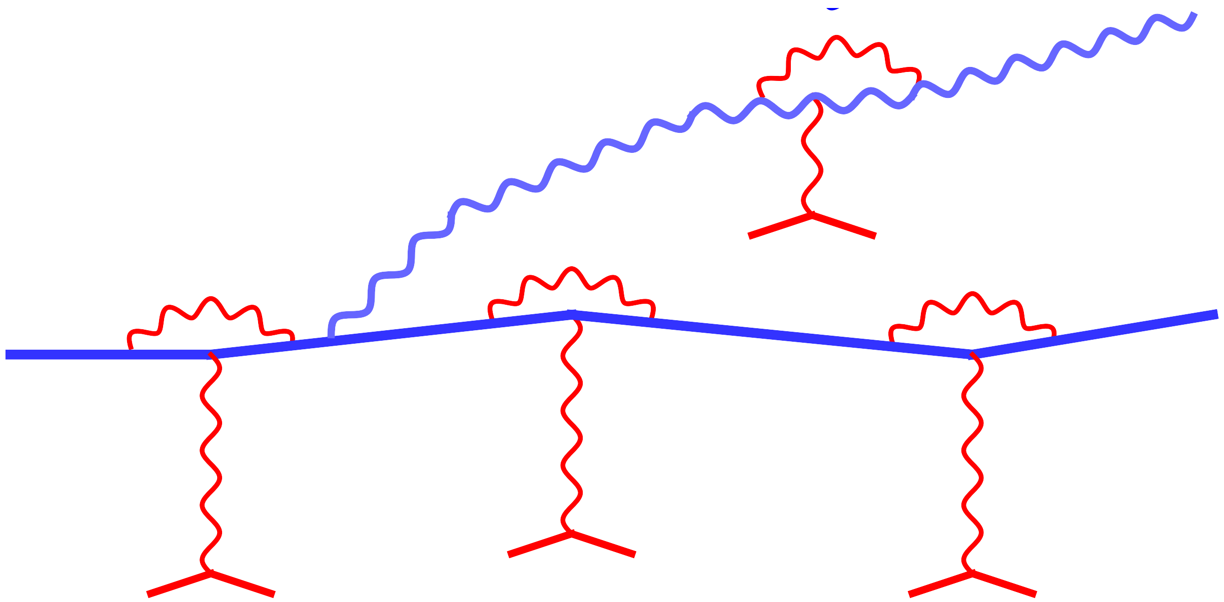
$$\delta\hat{q}(x,\boldsymbol{k}^2) = \frac{\alpha_s N_c}{\pi}\int_{\tau_0}^{\tau_{max}}\frac{d\tau}{\tau}\int_{\hat{q}\tau}^{\boldsymbol{k}^2}\frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2}\hat{q}$$

$$\simeq \frac{\alpha_s N_c}{2\pi}\hat{q}\ln^2\left(\frac{\boldsymbol{k}^2}{\hat{q}\tau_0}\right)$$

Double logarithm

Energy loss

- Same can be done for energy loss, though the calculation is trickier.
- Relationship between transverse momentum broadening and energy loss is preserved at leading log accuracy
- Suggests this radiative correction can be considered as evolution of the jet quenching parameter



Dilute limit

- Once the multiple scattering barrier has been lifted, one can no longer ignore the log dependence in the momentum scale in the jet quenching parameter
- Similar to high transverse momentum tails in saturation formalism
- Branching times no longer constrained and modifications are non-local

Dilute limit - Radiative corrections

$$\delta \left\langle \Delta \boldsymbol{p}^2 \right\rangle = \frac{\alpha_s N_c}{\pi} L \int_{\tau_0}^{\tau_{max}} \frac{d\tau}{\tau} \int^{\boldsymbol{k}^2} \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \hat{q}(\boldsymbol{q}^2)$$

Lower limit in momentum integration given by Debye mass

Some comments

- Even though a potentially big contribution is found, strictly speaking can not be interpreted as a correction to the jet quenching parameter
- As in the dense case, such large contributions come from very soft gluons characteristic of medium-induce radiation

Summary

- New advances in the theory of jet quenching, but still more to be done
- Radiative corrections provide sizable contributions and can be considered as a renormalization of the jet quenching parameter
- Extra care must be taken when extending these ideas to dilute case and early shower dynamics