Jet quenching

2018 Workshop on Probing Quark-Gluon Matter with Jets

BNL, July 24, 2018

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'Jet quenching' refers generically to the modifications of a jet as it propagates through matter

If one is able to control the interaction between jet and matter, one can learn about the properties of the matter traversed by the jet: the jet as a 'test particle'

- produced in a hard collisions very early on
- well understood in pp

Jet quenching is observed at RHIC and LHC

- suppression of yields
- back to back correlations, di-jet asymmetry
- modification of jet internal structure

Jets are complex objects, with an intricate structure

Much of this structure results from **radiation cascades**, which may differ greatly when these develop in vacuum or in matter

Useful (theoretical) **idealisation**: dynamics of an energetic parton in matter. This allows the study of the basic physics, the identification of robust features (focus of the present talk)

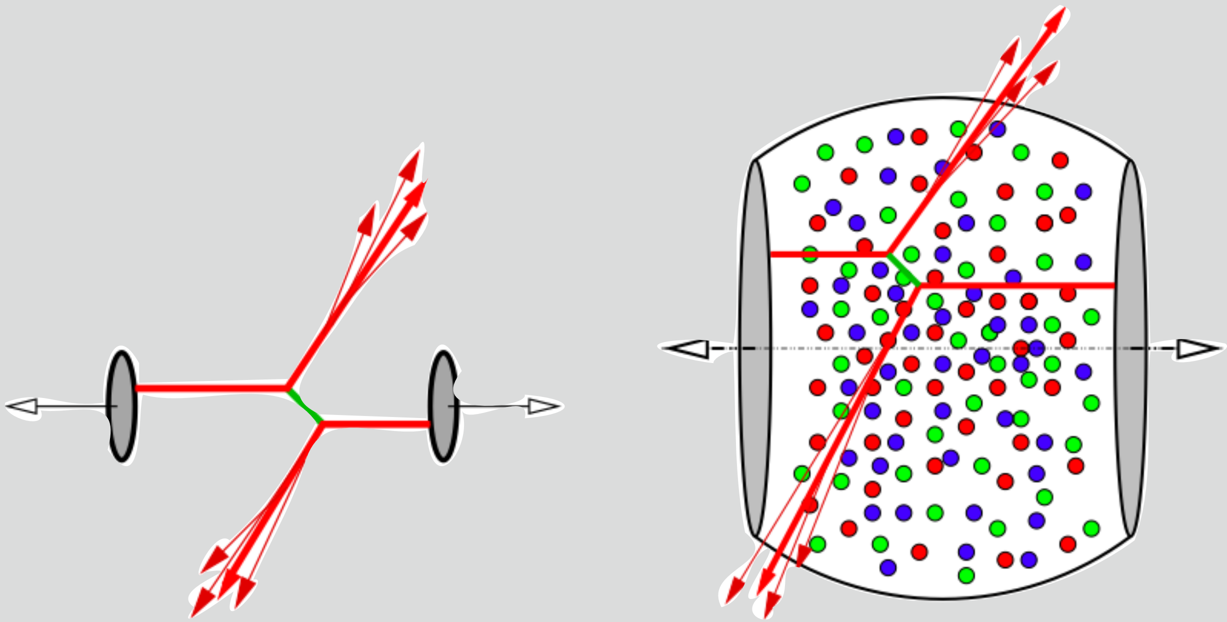
Confrontation of data has to go through complex simulations (Monte Carlo)

Prejudices about the matter probed by jets in heavy ion collisions

- strongly coupled liquid without well defined quasiparticles
- weakly coupled quark-gluon plasma

In fact, most descriptions rely mainly on the assumption that the interaction between the plasma and the jet is weak and can be treated (semi) perturbatively

Jets in a quark-gluon plasma



'Jet quenching' results from the interactions of the jet with the QGP

Theorist's idealization

- Hard parton (gluon or quark) propagating in a QGP
- Medium is uniform and non expanding
- Ignore vacuum radiation and its interference with medium induced radiation

Outline

- Basics of BDMPS-Z (slightly extended)
- What is qhat ?
- Radiative corrections to qhat
- Medium induced QCD cascade
- Recent progress and open challenges

Basics of BDMPS-Z

[Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (1996)]

(slightly extended)

Basics of BDMPS-Z

- An energetic parton propagating through matter undergoes multiple **collisions** with matter constituents and **radiate** gluons

- The dominant collisions are soft (involve small momentum transfers). Their effect can be viewed as diffusion in momentum space

$$\Delta k_\perp^2 \simeq \hat{q}\, \Delta t$$

jet quenching parameter

- The emitted radiation is affected by destructive interferences (LPM effect)

Formation time of a radiated gluon

$$\tau_f = \frac{2\omega}{k_\perp^2}$$

The collisions that occur during this time do not produce additional radiation (LPM). The condition

$$k_\perp^2 \sim \hat{q}\tau_f$$

defines a new time scale

$$\tau_{\rm br} \sim \sqrt{\frac{2\omega}{\hat{q}}}$$

which characterises the branching of a parton in presence of multiple collisions.

Bounds on branching time

$$\ell < \tau_{\rm br} < L$$

(mean free path) (length of the medium)

$$\tau_{\rm br} < L \Rightarrow \omega < \omega_c \qquad \omega_c = \frac{1}{2}\hat{q}L^2$$

$$\tau_{\rm br} \gtrsim \ell \Rightarrow \omega \gtrsim \omega_{\rm BH}$$ (incoherent mult. scat.)

Typical transverse momentum at branching

$$k_{\rm br}^2 = \hat{q}\tau_{\rm br}$$

Corresponding typical angle

$$\theta_{\rm br} \sim \frac{k_{\rm br}}{\omega} \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

Soft emissions occur at large angle

BDMPS-Z spectrum

$$\omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \simeq \alpha_s \frac{N_c}{\pi} \sqrt{\frac{\omega_c}{\omega}} = \bar{\alpha} \frac{L}{\tau_{\mathrm{br}}(\omega)}$$

(LPM suppession)

(Effective number of scatt.)

Energy loss (=radiated energy) is dominated by 'hard' gluons

$$\Delta E = \int_{\omega_0}^{\omega_c} \mathrm{d}\omega \, \omega \frac{\mathrm{d}N}{\mathrm{d}\omega} \sim \bar{\alpha}\omega_c \sim \bar{\alpha}\hat{q}L^2$$

Summary

Main physics involved: radiation of soft gluons (dominant contribution to energy loss) and (soft) collisions with matter constituents:

- ✓ the coupling between parton and medium is eikonal
- ✓ duration of collisions is small compared to the formation times
- ✓ small angles dominate
- ✓ the coupling is weak

Other 'competing' approaches differ mostly in "details" (at least in their leading orders), some of which not necessarily under control, e.g. GLV, ASW, AMY, Twist expansion, SCET, etc. [see Armesto et al 1106.1106 for a detailed comparison of typical predictions of various formalisms]

Techniques based on holography are somewhat apart (see later)

What is $\hat{q}$?

Momentum broadening

Momentum broadening arises from elastic collisions with matter constituents. These collisions are dominated by small momentum transfers (Coulomb like) with cross section

$$\frac{d^2\sigma_{el}}{dq^2} \sim \frac{\alpha_s^2}{q^4}$$

Then $$\hat{q} = \int_q q^2 \, \frac{nN_c g^4}{q^4}$$

Divergent integral

$$\hat{q}(p^2) = 4\pi\alpha_s^2 N_c n \ln \frac{p^2}{m_D^2}$$

At small momentum, the interaction is screened (Debye mass)

p^2 is the typical momentum squared, it fixes the scale at which the jet quenching parameter is evaluated

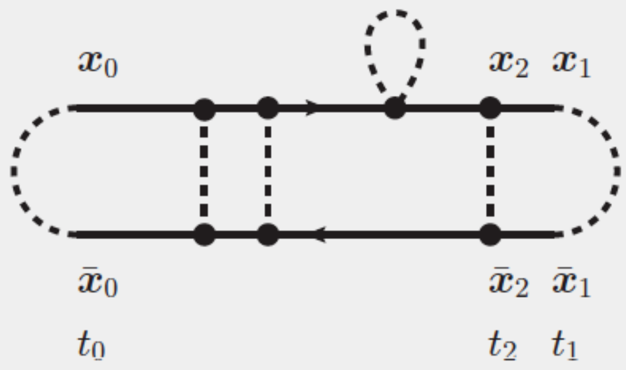
Momentum broadening

Relating momentum distribution and dipole forward amplitude

$$\frac{\mathrm{d}N}{\mathrm{d}^2 p_\perp} = \int \frac{\mathrm{d}^2 r_\perp}{(2\pi)^2} \mathrm{e}^{-ip_\perp \cdot r_\perp} S(r_\perp) \qquad S(r_\perp) = \frac{1}{N_c} \left\langle \mathrm{Tr} U_x U_y^\dagger \right\rangle$$

Wilson line

$$U_x = \mathrm{T} \exp \left[ig \int^{x^+} \mathrm{d}z^+ A^-(z^+, x_\perp) \right]$$



- (Almost) eikonal propagation
- The interaction with the medium (collisions) is treated as the interaction with a random color field with correlation function

$$\left\langle A_a^-(x^+, x_\perp) A_b^-(y^+, y_\perp) \right\rangle = \delta_{ab} n \delta(x^+ - y^+) \gamma(x_\perp - y_\perp)$$

$$\gamma(\boldsymbol{x}) = g^2 \int_q \frac{e^{i\boldsymbol{q}\cdot\boldsymbol{x}}}{\boldsymbol{q}^4}$$

$$x^\pm = \frac{1}{\sqrt{2}}(x^0 \pm x^3)$$

The relation between the transverse momentum distribution and the average of Wilson lines provides a convenient way to estimate momentum broadening, both at weak coupling and at strong coupling.

It also provides a link with more conventional QCD concepts, like dipole cross section, gluon distribution, saturation momentum, etc.

For instance, in leading order

$$S(\boldsymbol{b}, \boldsymbol{r}_\perp) \approx 1 - \frac{g^2}{8N_c}\boldsymbol{r}_\perp^2 \sum_{i,a} \int \mathrm{d}x_1^+ \mathrm{d}x_2^+ \langle N | F_a^{i-}(x_1^+, \boldsymbol{b}) F_a^{i-}(x_2^+, \boldsymbol{b}) | N \rangle.$$

$$\approx 1 - \frac{\alpha \pi^2}{2N_c}\boldsymbol{r}_\perp^2 \, \frac{xG_N(x, 1/r_\perp^2)}{\pi R^2}$$

$$\sigma_{\rm dip} = \frac{\alpha_s \pi^2}{N_c} r_\perp^2 xG(x, Q^2) \qquad \left(Q^2 \sim \frac{1}{r_\perp^2}\right)$$

(dipole cross section)

$$xG(x, Q^2) = \int^{Q^2} \frac{\mathrm{d}k_\perp^2}{4\pi^2} \langle F_a^{i-} k^-, \boldsymbol{k}) F_b^{i-}(-k^-, -\boldsymbol{k}) \rangle.$$

(gluon distribution function)

More on the dipole cross section

$$\sigma(\boldsymbol{u}) = 2g^2 \left[\gamma(0) - \gamma(\boldsymbol{u})\right] \qquad \gamma(\boldsymbol{u}) = g^2 \int_{\boldsymbol{k}} \frac{\mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{u}}}{\boldsymbol{k}_\perp^4}$$

$$\sigma(\boldsymbol{u}) = 2g^4 \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2} \frac{1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{u}}}{\boldsymbol{q}^4} \approx g^4 \frac{\boldsymbol{u}^2}{2} \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2} \frac{1}{\boldsymbol{q}^2} \approx \frac{g^4 \boldsymbol{u}^2}{8\pi} \ln \frac{r_0^2}{u^2}$$

(the log is important to recover the 'perturbative tail')

Multiple scattering (exponentiation of the lowest order result)

$$P(p_\perp) = \int_r \mathrm{e}^{-ip\cdot r}\, \mathrm{e}^{\frac{-L\rho}{2}\sigma(r)} \simeq \frac{4\pi}{Q_s^2}\, \mathrm{e}^{-p^2/Q_s^2}$$

$$Q_s^2 = \frac{2\pi^2 \alpha_s}{N_c} \frac{A x G_N(x, 1/r_\perp^2)}{\pi R^2}$$

relates jet quenching parameter and saturation momentum

$$Q_s^2 = \hat{q} L$$

Summary

The jet quenching parameter is a multifaceted object

- It plays the role of a (momentum dependent) diffusion constant in momentum space, reflecting the effects of multiple soft collisions
- It controls both momentum broadening and energy loss
- It is related (in lowest orders) to the total cross section for a dipole propagating through matter
- It is related to the gluon distribution
- It is related to the saturation momentum

Radiative corrections to $\hat{q}$

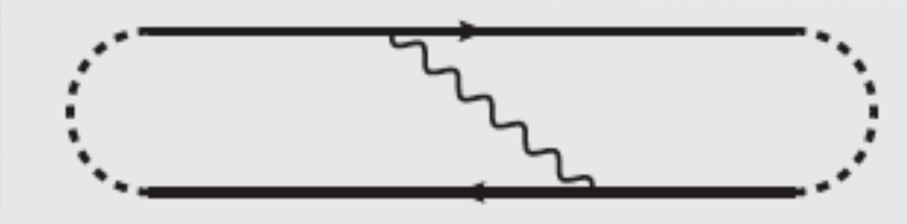
Corrections to the jet quenching parameter

- Perturbative corrections (Arnold, Xiao, 2008)
- Non Perturbative effects (Liao, Shuryak, 2009)
- Euclidean correlators near the light cone (Caron-Huot, 2009)
- Lattice calculations (Majumder, Panero, Rummukainen, Schaëfer, 2013)

- **Radiative corrections**

  (Liou, Mueller, Wu, 2013
  Mehtar-Tani, 2013
  JPB, Mehtar-Tani, 2014
  Iancu, 2014)

Radiative corrections to momentum broadening



Emission of soft gluons may contribute to momentum broadening

In principle this is a correction of order α_s, but it is amplified by a large double logarithm

$$\Delta\hat{q}(\tau_{\max}, \boldsymbol{p}^2) \equiv \frac{\alpha_s N_c}{\pi} \int_{\tau_0}^{\tau_{\max}} \frac{\mathrm{d}\tau}{\tau} \int_{\hat{q}\tau}^{\boldsymbol{p}^2} \frac{\mathrm{d}\boldsymbol{q}^2}{\boldsymbol{q}^2}\, \hat{q}(\boldsymbol{q}^2)$$

dominated by single scattering with the medium

One obtains the same correction for momentum broadening

$$\langle k_\perp^2 \rangle_{\rm typ} \simeq \hat{q} L \left(1 + \frac{\bar{\alpha}}{2} \ln^2 \frac{L}{\tau_0}\right)$$

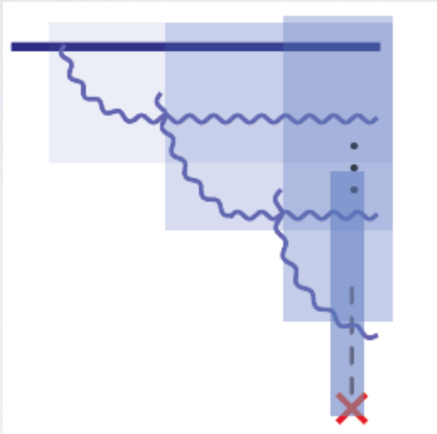
and for the energy loss

$$\langle \omega \rangle \sim \hat{q} L^2 \left(1 + \frac{\bar{\alpha}}{2} \ln^2 \frac{L}{\tau_0}\right)$$

The radiative correction can be interpreted as a renormalization of the jet quenching parameter

$$\hat{q} \longrightarrow \hat{q} \left(1 + \frac{\bar{\alpha}}{2} \ln^2 \frac{L}{\tau_0}\right)$$

The double log corrections cane be resummed assuming strong ordering in formation times and transverse momenta



This yields new power laws (anomalous dimension)

$$\hat{q}(L) \sim L^{\gamma} \qquad \gamma = 2\sqrt{\bar{\alpha}}$$

so that

$$\left\langle \Delta p_{\perp}^{2} \right\rangle \sim L^{1+\gamma} \qquad \langle \Delta E \rangle \sim L^{2+\gamma}$$

Radiative correction and single scattering

(JPB, F. Dominguez, 2018)

- A puzzle: most approaches to jet quenching ignore the double log corrections... including those which treat more fully the single scattering (e.g. within the opacity expansion).

- A thorough treatment of the single scattering yields

$$\langle \Delta p_\perp^2 \rangle = 2\alpha_s N_c n \int \frac{d\omega}{\omega} \int_{\boldsymbol{k}'\boldsymbol{k}} \sigma(\boldsymbol{k}' - \boldsymbol{k}) \frac{2(\boldsymbol{k}' \cdot \boldsymbol{k})^2}{\boldsymbol{k}'^2 \boldsymbol{k}^2} \left\{ L - \frac{2\omega}{\boldsymbol{k}'^2} \sin\left[\frac{\boldsymbol{k}'^2}{2\omega} L \right] \right\}$$

- Small L and large L limits $\left(\tau' \equiv \frac{2\omega}{k'} \right)$

$$L - \tau' \sin \frac{L}{\tau'} \qquad \frac{L}{\tau'} \ll 1 : \left\langle \Delta p_\perp^2 \right\rangle \to 0, \qquad \frac{L}{\tau'} \gg 1 : \left\langle \Delta p_\perp^2 \right\rangle \sim L$$

Finite size effects versus multiple scattering

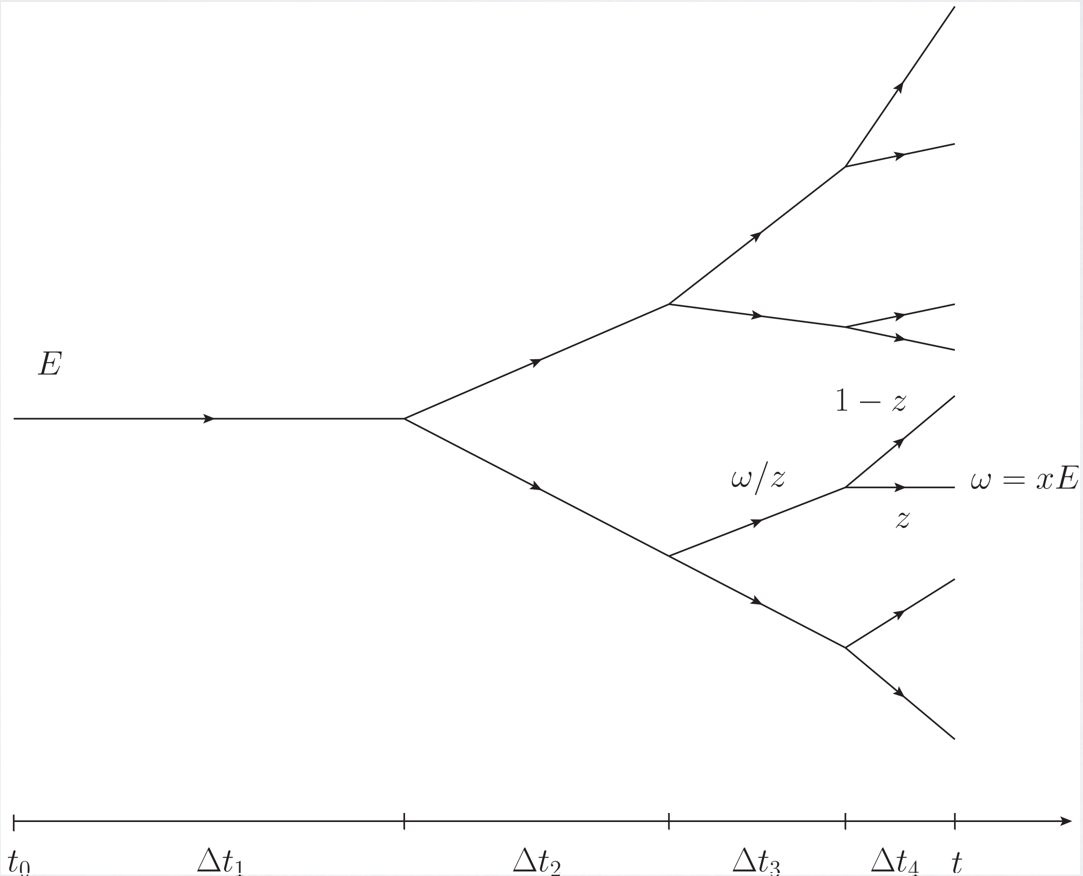
$$p^2 > \hat{q}L$$

- Large logarithm requires large medium size L
- But in a large medium the probability to have more than one scattering is large....

$$\int_{\hat{q}\tau_{\min}}^{\hat{q}L} \frac{d\boldsymbol{k}^2}{\boldsymbol{k}^2} \int_{\boldsymbol{k}^2\tau_{\min}}^{\boldsymbol{k}^4/\hat{q}} \frac{d\omega}{\omega} + \int_{\hat{q}L}^{\boldsymbol{p}^2} \frac{d\boldsymbol{k}^2}{\boldsymbol{k}^2} \int_{\boldsymbol{k}^2\tau_{\min}}^{\boldsymbol{k}^2 L} \frac{d\omega}{\omega}$$

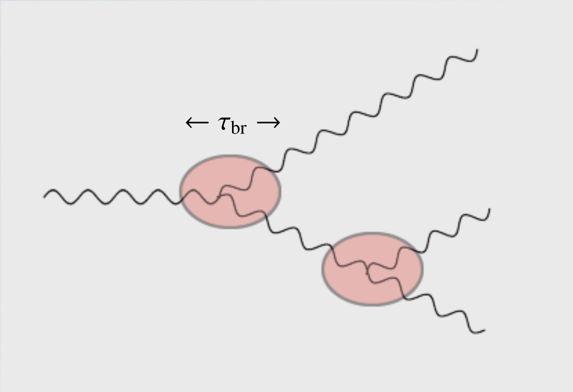
$$= \frac{1}{2} \ln^2 \frac{L}{\tau_{\min}} + \ln \frac{L}{\tau_{\min}} \ln \frac{\boldsymbol{p}^2}{\hat{q}L}.$$

The in-medium cascade

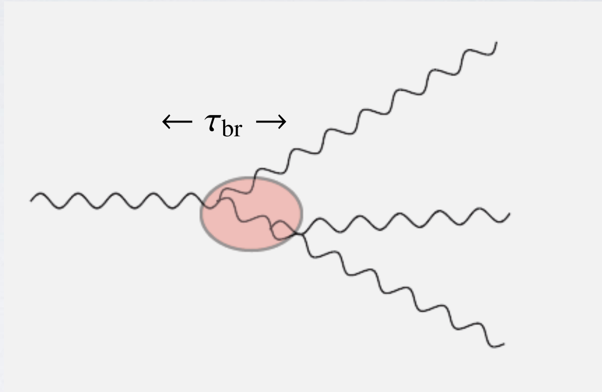


Multiple emissions

In medium, for large L, independent emissions are enhanced by a factor $L/\tau_{\rm br}$



$$\sim \left(\alpha_s \frac{L}{\tau_{\rm br}}\right)^2$$



$$\sim \alpha_s^2 \frac{L}{\tau_{\rm br}}$$

When $\bar{\alpha} L/\tau_{br} \sim 1$ all powers of $\bar{\alpha} L/\tau_{br} \sim 1$ need to be resummed.

The leading order resummation is equivalent to a probabilistic cascade, with nearly local branchings

→ A QCD cascade of a new type

Exhibits wave turbulence

Comparing the two cascades

Equation for the inclusive energy distribution

$$\frac{\partial}{\partial t}D(x,t) = \int_x^1 \mathrm{d}z\,\mathcal{K}(z)\,\frac{D\left(x/z,t\right)}{t_*(x/z)} - \frac{D\left(x,t\right)}{t_*(x)}\int_0^1 \mathrm{d}z\; z\mathcal{K}(z) = \mathcal{I}[D]$$

BDMPS

$$\mathcal{K}(z) \approx \frac{1}{z^{3/2}(1-z)^{3/2}}$$

$$t_*(x) \sim \sqrt{x}$$

$$D_{\rm sc}(x) \sim \frac{1}{\sqrt{x}}$$

$$\int_{x_0\to 0} D_{\rm sc}(x) \qquad \text{finite}$$

DGLAP

$$\mathcal{K}(z) = \frac{1}{z(1-z)}$$

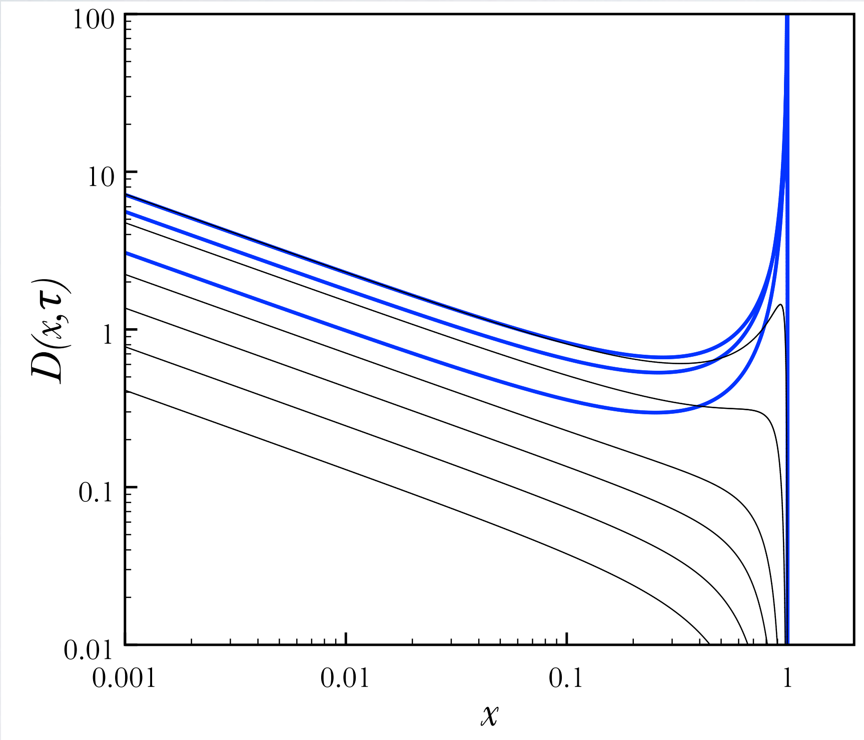
$$t_*(x) \sim \text{cst}$$

$$D_{\rm sc}(x) \sim \frac{1}{x}$$

$$\int_{x_0\to 0} D_{\rm sc}(x) \qquad \text{infinite}$$

(JPB, Y. Mehtar-Tani, arXiv:1501.03443)

BDMPS


100
10
1
0.1
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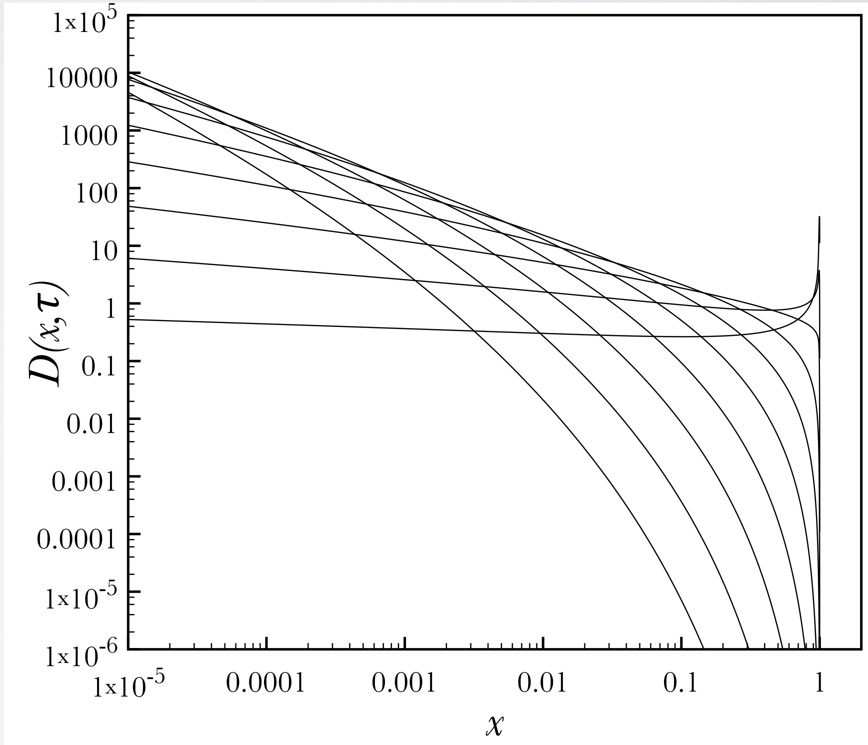
0.1
1
$D(x,\tau)$
x

DGLAP


1x10^5
10000
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1
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0.01
0.001
0.0001
1x10^-5
1x10^-6
1x10^-5
0.0001
0.001
0.01
0.1
1
$D(x,\tau)$
x

Summary

In a medium of large size, the successive branchings can be treated as independent, giving rise to a cascade that is very different from the vacuum cascade (no angular ordering, turbulent flow)

This cascade provides a simple and efficient mechanism for the transfer of jet energy towards very large angles. The mechanism is intrinsic, not related to a specific coupling between the jet and the medium (only qhat enters)

The angular structure is qualitatively compatible with the data

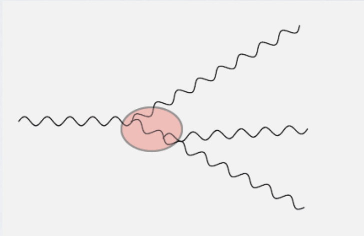
This turbulent cascade may play a role in the latest stages of the thermalization of the quark-gluon plasma produced in ultra-relativistic heavy ion collisions

The mixing of vacuum like and medium induced radiation may change the picture in major ways (see talks by E. Iancu, and K. Tywonyuk)

Ongoing progress/major challenges

Improving probabilistic picture: coherence effects, better treatment of overlapping formation times, etc

(P. Arnold, Iqbal 2015,2016)



Development of new theoretical tools like SCET

Combining both vacuum and medium induced radiation presents new challenges (interferences, color coherence, angular ordering, etc)

Interaction of the jet with the medium (talk by X-N. Wang)

Major developments in understanding jet (sub)structure (in pp, and in AA)