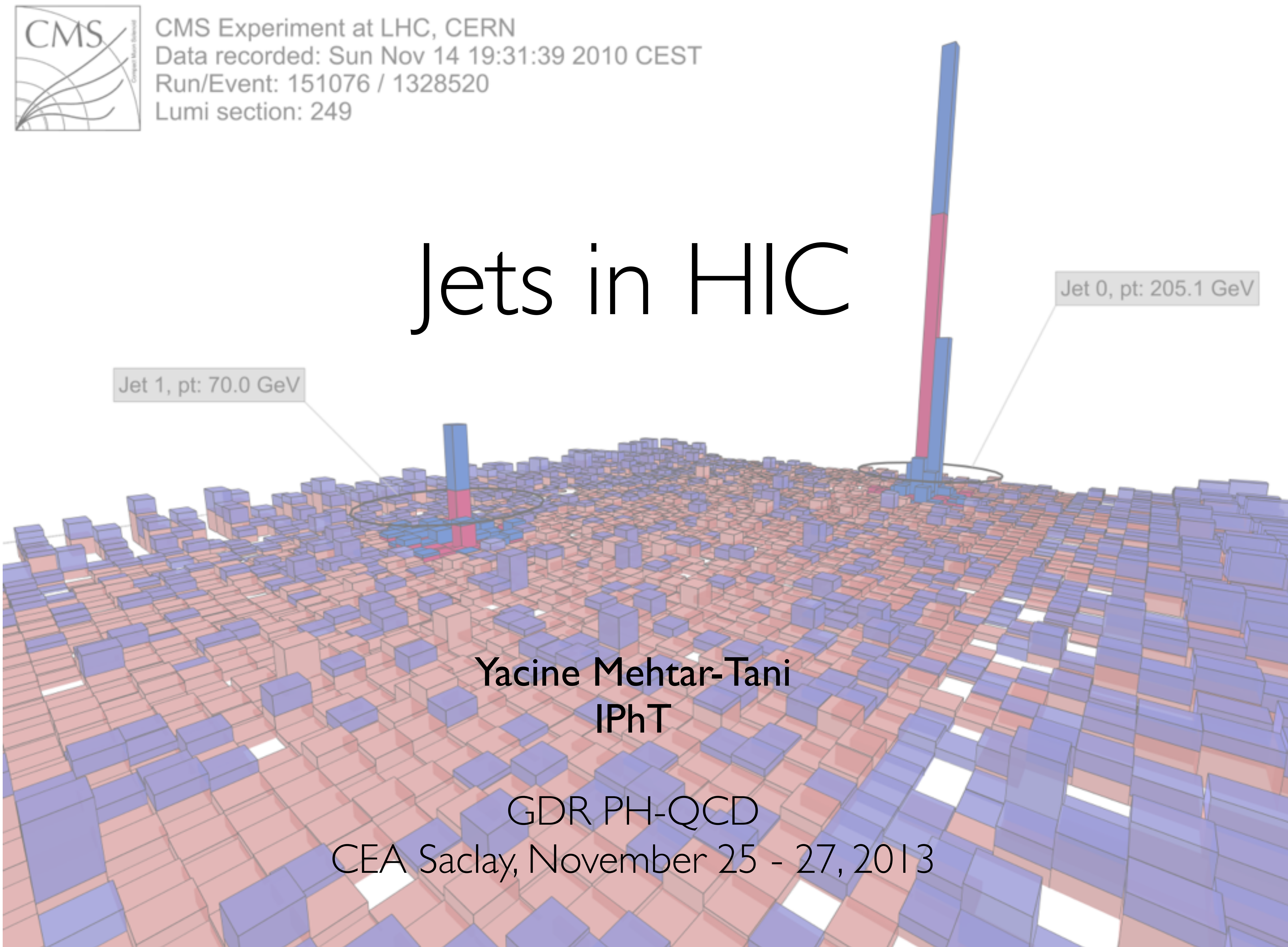


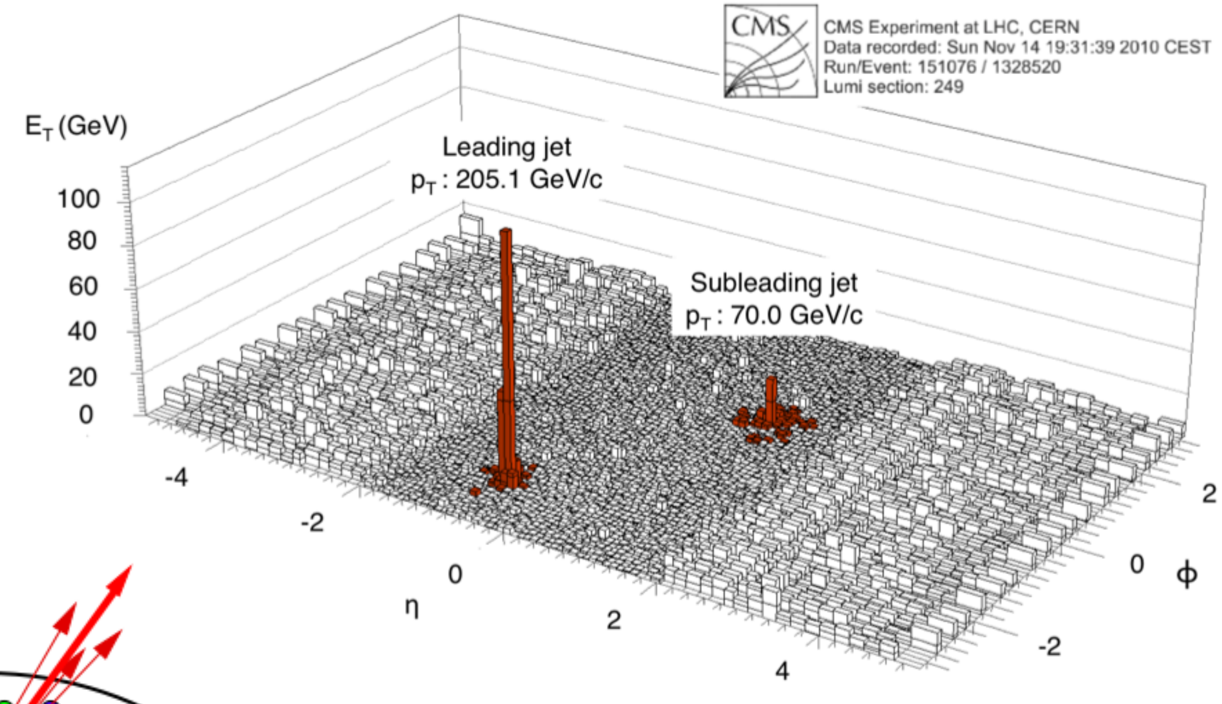
Jets in HIC

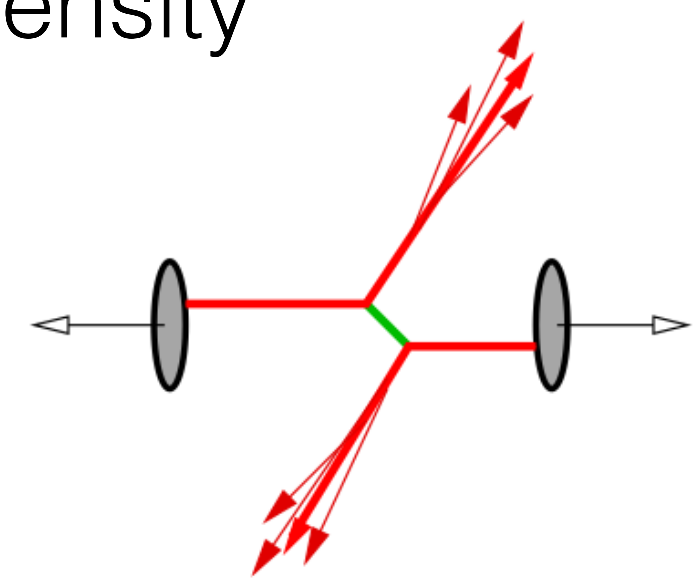
Yacine Mehtar-Tani
IPhT

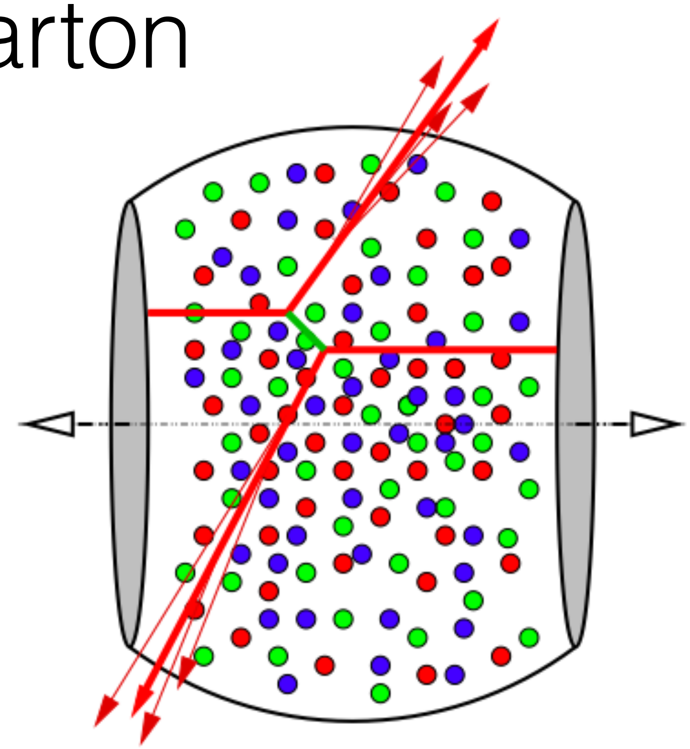
GDR PH-QCD
CEA Saclay, November 25 - 27, 2013

Jets in QCD

- JET QUENCHING : a tool to probe the Quark-Gluon-Plasma and QCD dynamics at high parton density







in-medium jet modification: departures from p-p baseline

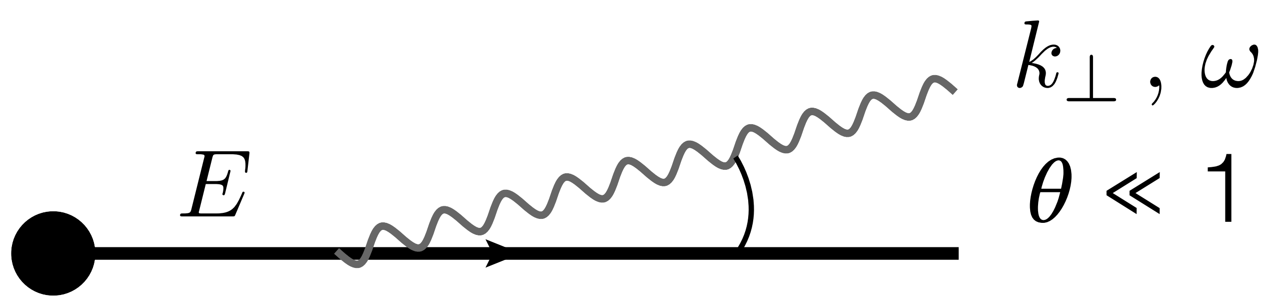
Jets in QCD

- a Jet is an energetic and collimated bunch of particles produced in high energy collisions
- Partons to Hadrons: at high energy large separation between short and large distance physics (QCD-factorization). Hard scale: $Q \gg \Lambda_{QCD}$
- Jets are originated from highly virtual partons that degrade their virtuality by successive branchings

Jets in QCD

Elementary branching process is enhanced in the collinear region

$$dP \sim \alpha_s \, C_R \, \frac{d\omega}{\omega} \, \frac{d^2 k_\perp}{k_\perp^2}$$



$$k_\perp^2 \ll Q^2$$

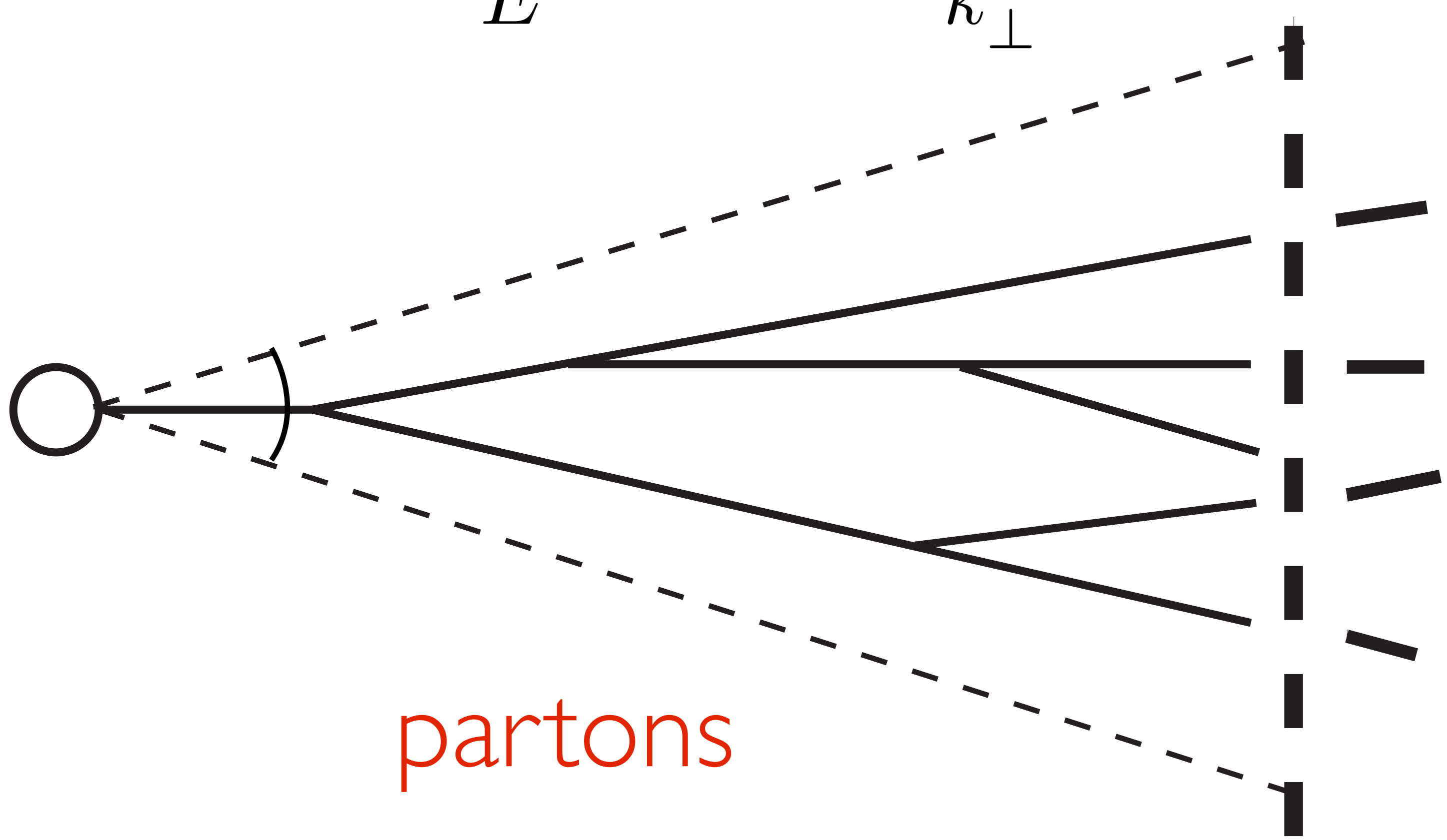
$\Longrightarrow$ Collimated jets

Jets in QCD

The jet is a coherent object, at each step of the cascade the total color charge is conserved: successive branchings are ordered in angles

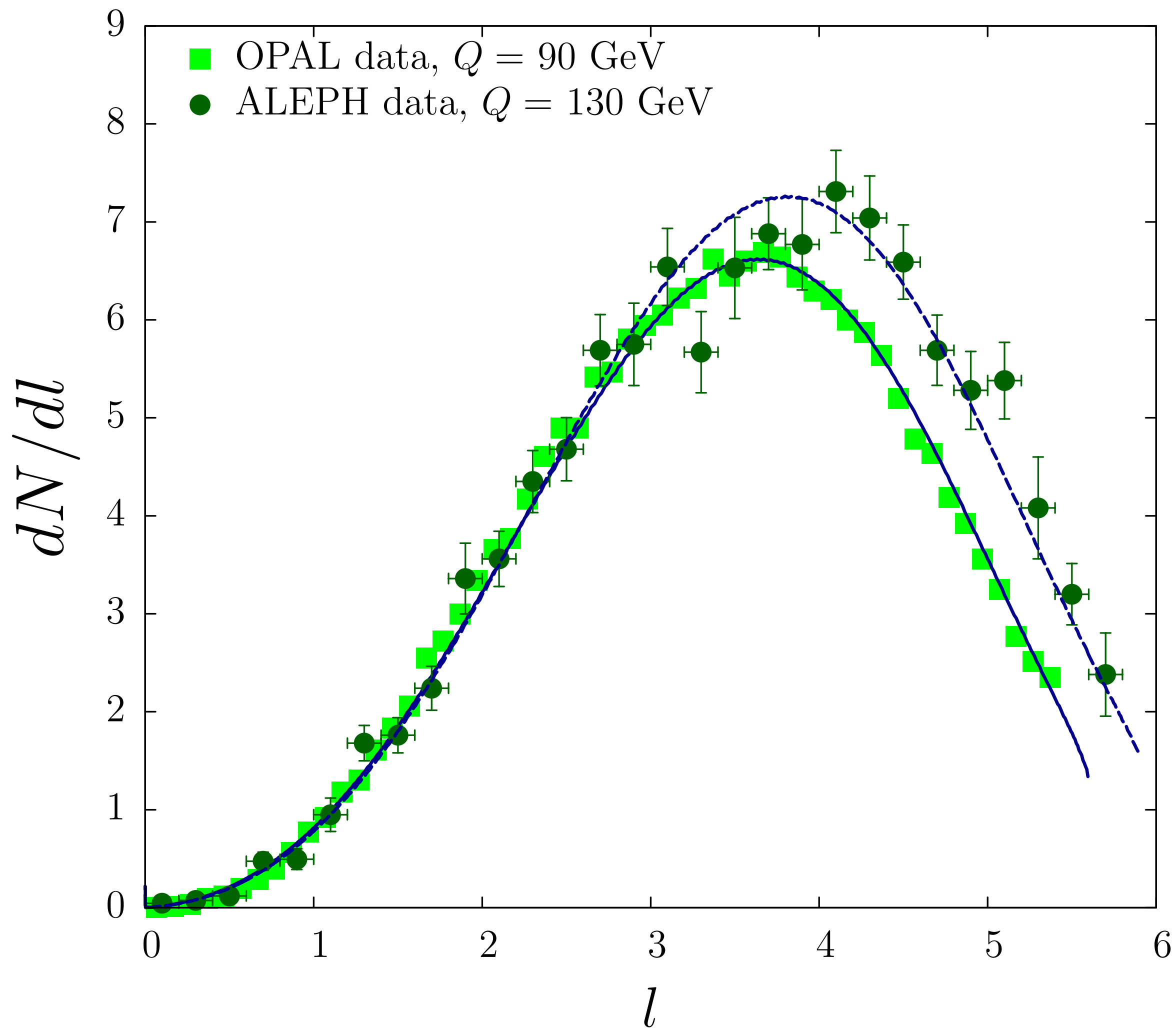
$$\frac{1}{E} < t_{\mathrm{form}} \sim \frac{\omega}{k_\perp^2} \qquad t_{\mathrm{hadr}} \sim \frac{E}{Q_0^2}$$

$$Q \equiv E\,R$$



$$Q_0 \sim \Lambda_{\mathrm{QCD}}$$

Jets in QCD



- MLLA + LPHD (limiting spectrum $Q_0 = \Lambda_{QCD}$)
- perturbative jet scale Q= E R
- color coherence ⇒ angular ordering (AO)

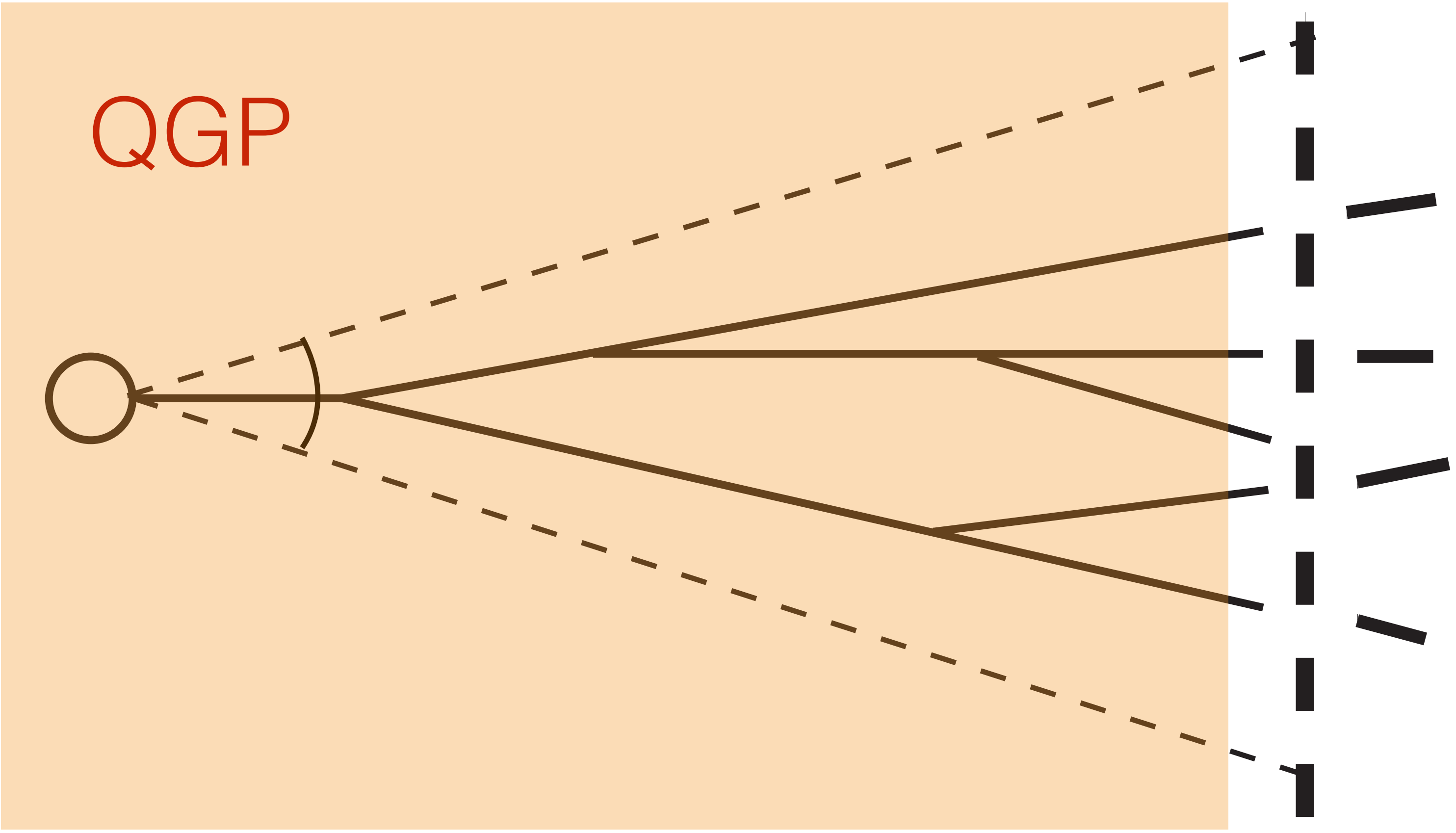
l=ln(1/x)

[Dokshitzer, Khoze, Mueller, Troyan, Kuraev, Fong, Webber...]

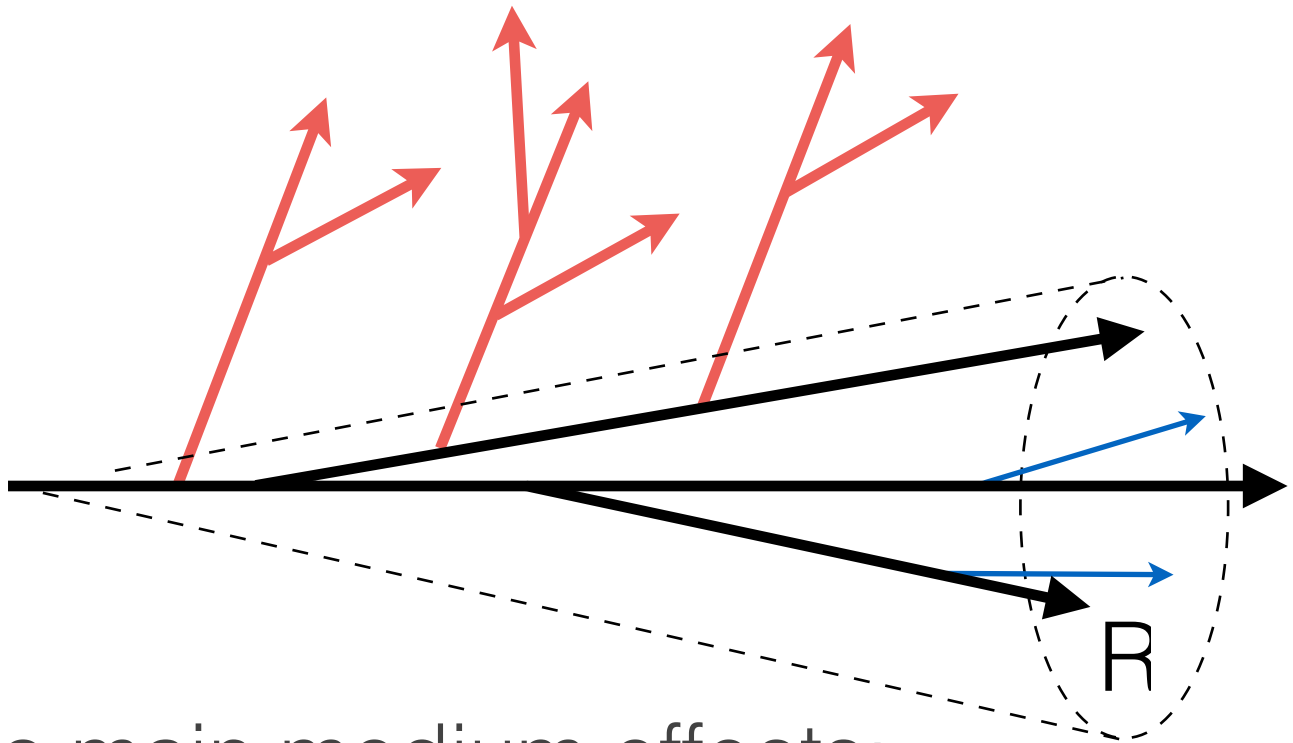
Jets in the QGP

- How does the medium interact with a jet?

  Color coherence will be altered inside a colored medium (quantum disentanglement)



General Picture



- jets at sufficiently high-p_T are collimated
- the medium resolves only the total charge $\langle C_{jet} \rangle \neq 0$

two main medium effects:

- C_{jet} induces BDMPS radiation: onset of rapid branching & broadening (multiple-scatterings)

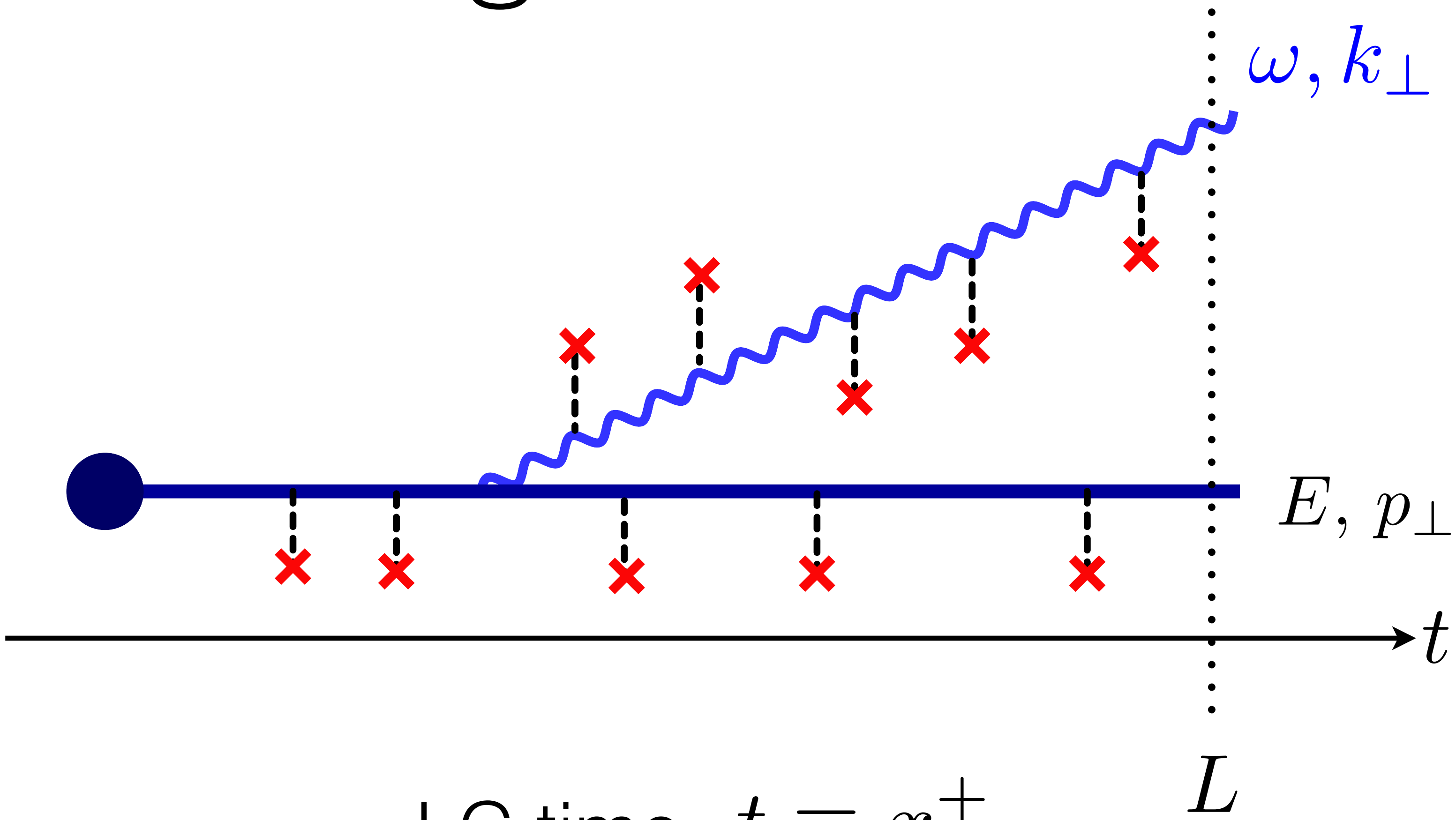
J. -P. Blaizot, F. Dominguez, E. Iancu, Y. M. -T. (2013)

- coherent structure (AO) is weakened :: antiangular radiation (quasi-collinear & long form times)

Y. M.-T, K. Tywoniuk, C. A. Salgado, PRL (2011)

BDMPS: induced g-radiation

- Scatterings with the medium can induce gluon radiation
- The radiation mechanism is closely related to transverse momentum broadening



LC time $t \equiv x^+$

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

where the quenching parameter $\hat{q} \equiv \frac{\Delta k_\perp^2}{\Delta t} \simeq \frac{m_D^2}{\lambda} = \frac{(\text{Debye mass})^2}{\text{mean free path}}$

is related to the collision rate in a thermal bath

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

BDMPS: induced g-radiation

How does it happen? After a certain number of scatterings coherence between the parent quark and gluon fluctuation is broken and the gluon is formed (decoherence is faster for soft gluons)

$$t_f \equiv \frac{\omega}{\langle q_\perp^2 \rangle} \simeq \frac{\omega}{\hat{q}\, t_f} \quad \Rightarrow \quad t_f = t_{\rm br} \equiv \sqrt{\frac{\omega}{\hat{q}}}$$

maximum frequency for this mechanism $\omega_c = \frac{1}{2}\hat{q}\, L^2$

BDMPS: induced g-radiation

$$\omega \frac{dN}{d\omega} = \frac{\alpha_s C_R}{\pi} \sqrt{\frac{2\omega_c}{\omega}} \propto \alpha_s \frac{L}{t_{\rm br}}$$

- mean energy loss dominated by «hard» emissions $\omega \sim \omega_c$
- soft gluon emissions $\omega \ll \omega_c$

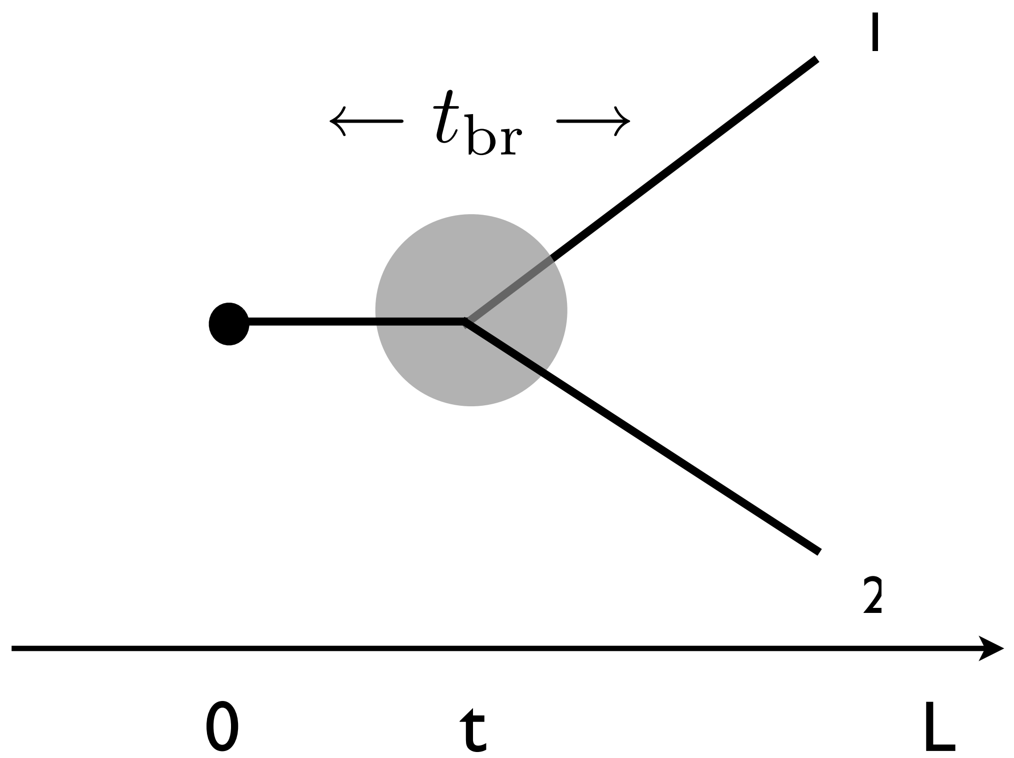
➡ Short branching times $t_{\rm br} \ll L$ and large phase-space

when $\alpha_s \frac{L}{t_{\rm br}} \gtrsim 1$ Multiple branchings are no longer negligible

➡ High gluon multiplicity regime:

Dominant in jet shapes and differential energy loss

Decoherence of multi-g branching

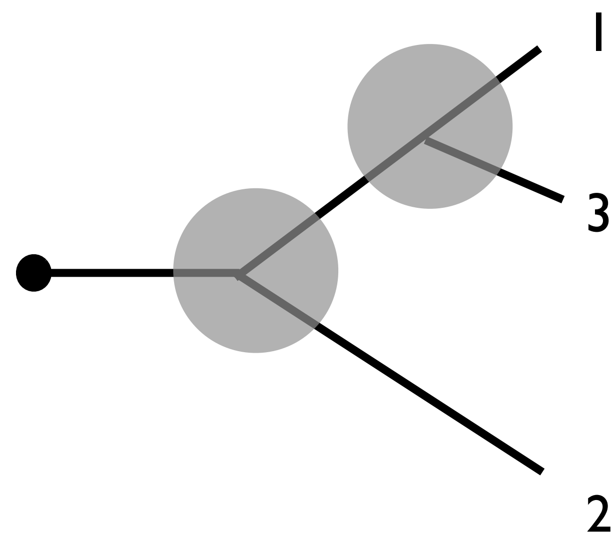


Color randomization: re-scatterings with color charges in the medium quickly destroy color coherence of partons in the jet

Decoherence of multi-g branching

incoherent emissions

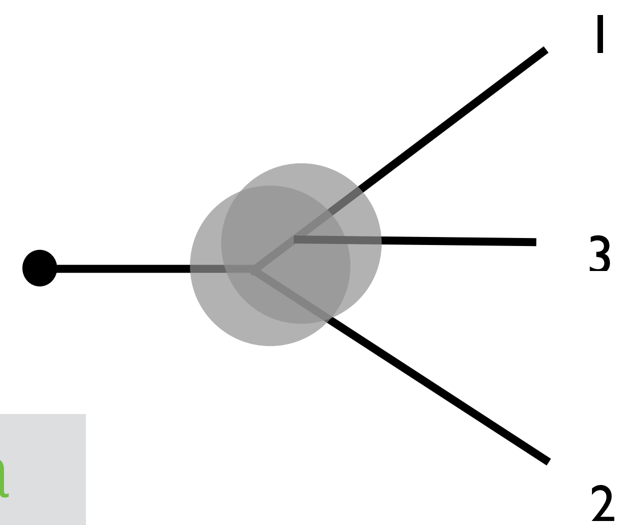
- For large media two subsequent emissions are independent and therefore factorize



$$\propto \left(\alpha_s \frac{L}{t_{\rm br}}\right)^2$$

coherent emissions (suppressed!)

- Interferences are suppressed by a factor $t_{\rm br}/L \ll 1$

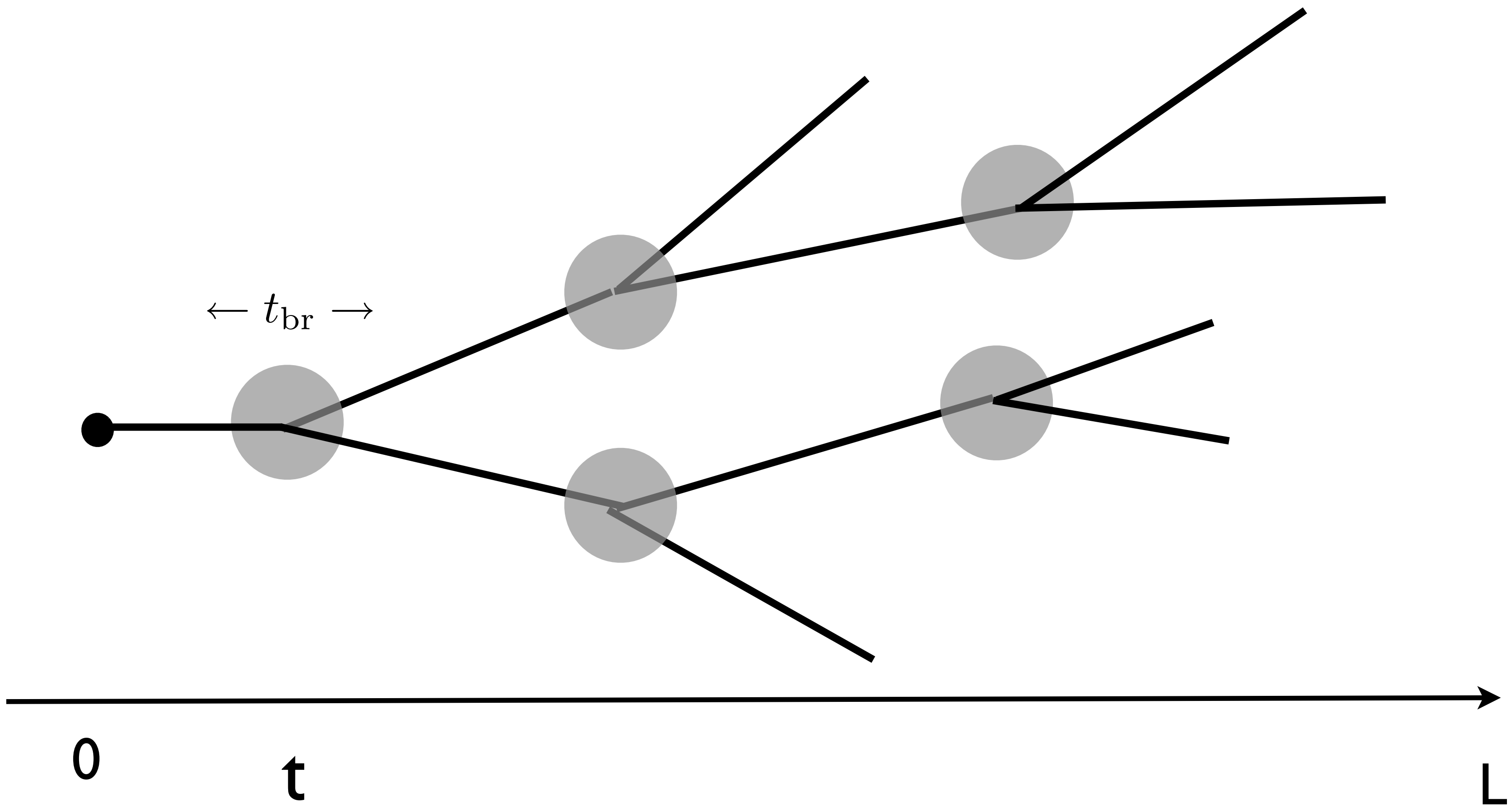


$$\propto \alpha_s \left(\alpha_s \frac{L}{t_{\rm br}}\right)$$

Note that this is not the case in a vacuum shower where color coherence is responsible for Angular-Ordering

Y. M.-T, K. Tywoniuk, C. A. Salgado (2010)
J. Casalderray-Solana, E. Iancu (2011)

Decoherence of multi-g branching



Successive branchings are then independent and quasi-local.

Time-scale separation: $t_{\mathrm{br}} \ll t \sim L$

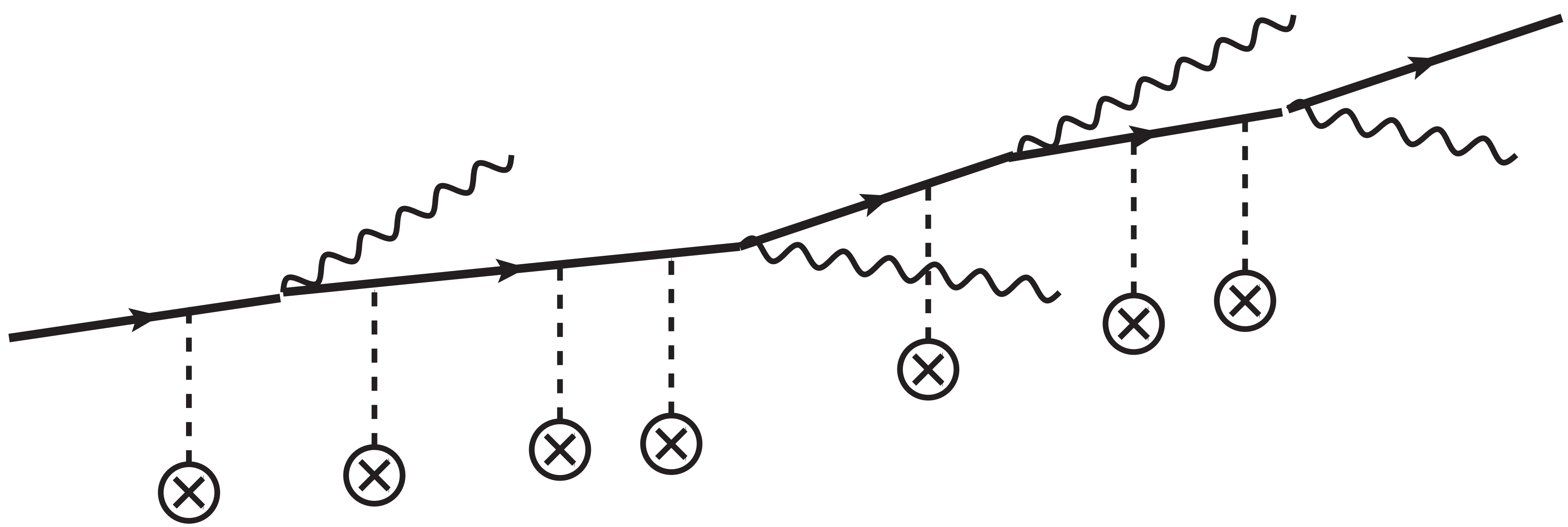
Inclusive Gluon Distribution

J. -P. Blaizot, F. Dominguez, E. Iancu, Y. M. -T. arXiv:1311.5823

The inclusive distribution of gluons with momentum k inside a parton with momentum p is defined as :

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

$k_\perp, \; x = k^+/p^+$

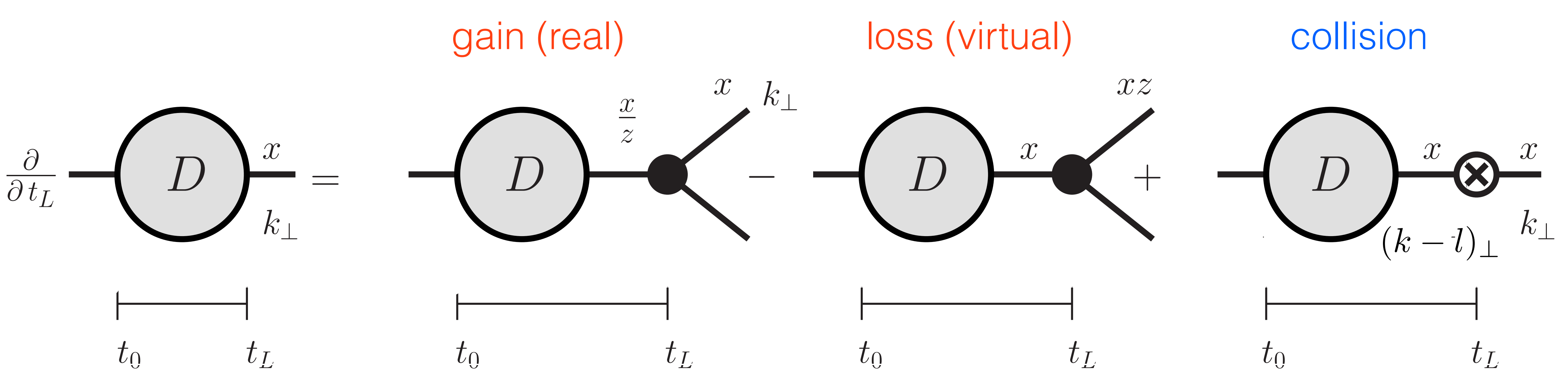


Inclusive Gluon Distribution

J. -P. Blaizot, F. Dominguez, E. Iancu, Y. M. -T. arXiv:1311.5823

- we assume no pt-broadening during the branching
- broadening is accounted for classically in a diffusion term

$$\frac{\partial}{\partial t} D(x,\boldsymbol{k},t) = \alpha_s \int_0^1 dz \left[2\mathcal{K}(z)\, D\left(x/z, \boldsymbol{k}/z, t\right) - \mathcal{K}(z)\, D\left(x, \boldsymbol{k}, t\right)\right] - \frac{1}{4}\left(\frac{\partial}{\partial \boldsymbol{k}}\right)^2 \hat{q}(\boldsymbol{k}^2)\, D\left(x, \boldsymbol{k}, t\right)$$

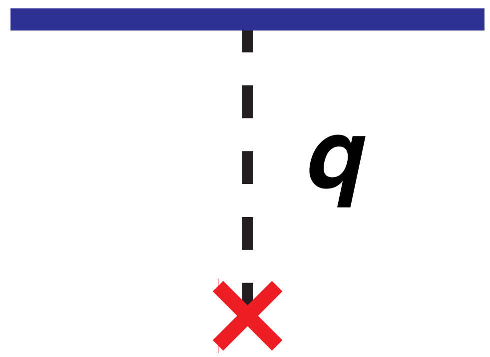


Radiative corrections to the quenching parameter

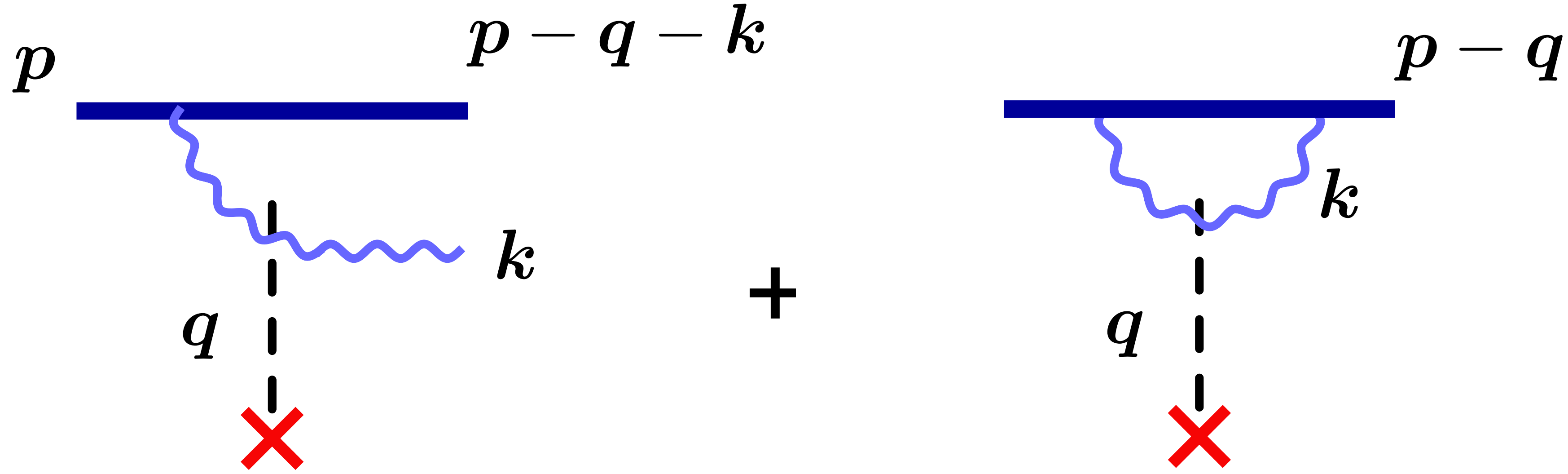
The quenching parameter as a (local) transport coefficient is defined as

$$\hat{q} \equiv \frac{\langle p_\perp^2 \rangle}{L} = \rho \int_{\boldsymbol{q}} \boldsymbol{q}^2 \, \frac{d\sigma_{\rm el}}{d^2\boldsymbol{q}} \propto \alpha_s^2 \, C_R \, \rho \, \log(Q^2/m_D^2)$$

The hard scale Q depends on the process and is related to the typical transverse momentum in the problem: $Q^2 \sim \hat{q} L$



Radiative corrections to the quenching parameter



correction to pt-broadening due to single-gluon radiation

correction due to the prob. of no emission (unitarity)

$$\hat{q}_1 = \int_{\boldsymbol{q},\boldsymbol{k}} [(\boldsymbol{q}+\boldsymbol{k})^2 - \boldsymbol{q}^2] \int_\omega \frac{d\sigma_{\text{inel}(1)}}{d^2\boldsymbol{q}\, d^2\boldsymbol{k}\, d\omega}$$

Radiative corrections to the quenching parameter

1- Single scattering requires the time scale of the fluctuation to be smaller than the BDMPS formation time at which multiple scatterings become important, i.e.,

$$\Delta t \ll \sqrt{\omega/\hat{q}_0} \sim t_{\rm br} \qquad \text{or} \qquad \sqrt{\omega\,\hat{q}_0} \ll \boldsymbol{k}^2 \ll \boldsymbol{p}^2$$

2- We define now an initial transport coeff. $\hat{q} \to \hat{q}_0(\Delta t_0)$ measured at a initial time

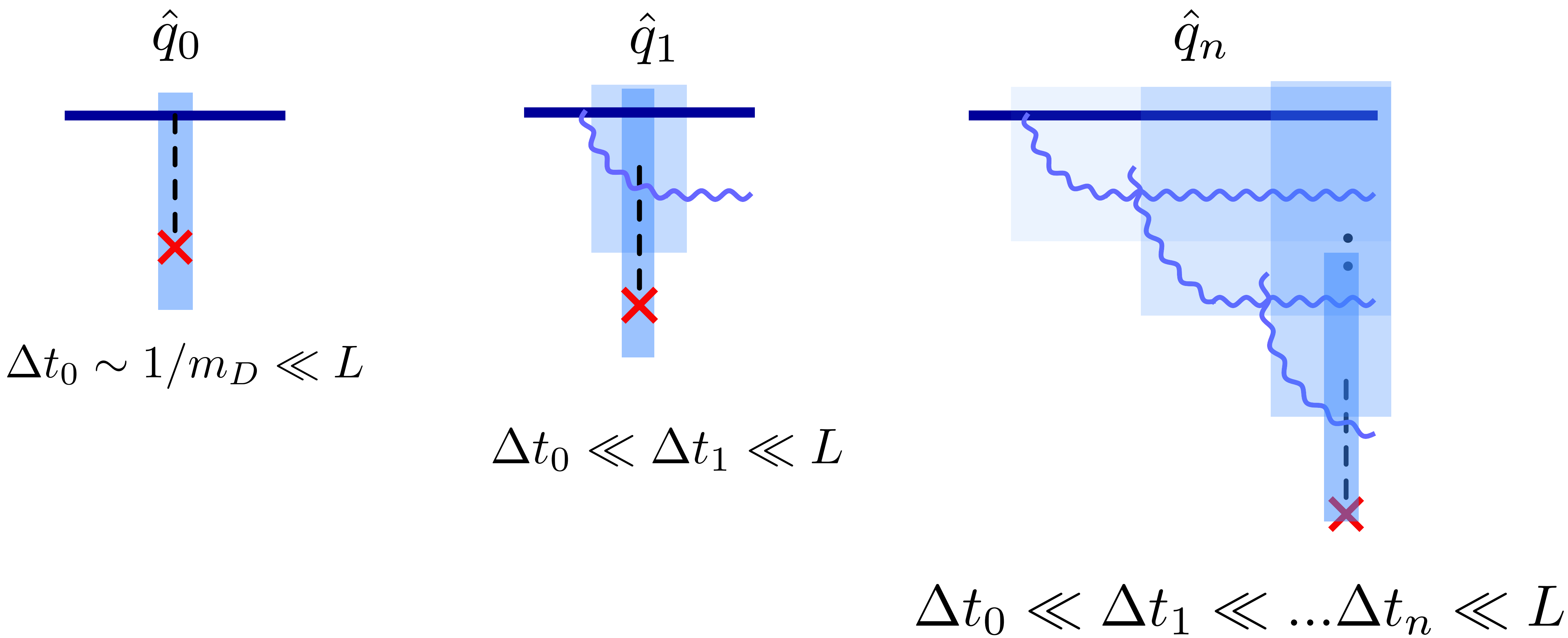
$$\hat{q}_1 \simeq \frac{\alpha_s C_A}{\pi} \int_{\Delta t_0}^{L} \frac{d\Delta t}{\Delta t} \int_{\hat{q}_0 \Delta t}^{\boldsymbol{p}^2} \frac{d\boldsymbol{k}^2}{\boldsymbol{k}^2}\, \hat{q}_0(\Delta t_0) \simeq \frac{\alpha_s C_A}{2\pi} \hat{q}_0 \log^2\left(\frac{\boldsymbol{p}^2}{\hat{q}_0 \Delta t_0}\right)$$

[A. H. Mueller, B. Wu, T. Liou arXiv: 1304.7677]

The double logs correspond to gluons that are formed before the medium resolves the system «gluon-emitter» (no LPM suppression)

Radiative corrections to the quenching parameter

The DL's are resummed assuming strong ordering in formation time (or energy) and transverse mom. of overlapping successive gluon emissions (*a la* BFKL or DGLAP)



Gluon distribution II

We end-up with 2 coupled equations

1 - Distribution of gluons as a function of time

$$\frac{d}{dt} D(x, \boldsymbol{k}, t) = \alpha_s \int dz\, \mathcal{K}(z, \hat{q}) \, [2D(x/z, \boldsymbol{k}/z, t) - D(x, \boldsymbol{k}, t)] - \frac{1}{4} \left(\frac{\partial}{\partial \boldsymbol{k}} \right)^2 \hat{q}\, D(x, \boldsymbol{k}, t)$$

II- The quenching parameter

$$\frac{\partial \hat{q}(\Delta t, \boldsymbol{k}^2)}{\partial \log(\Delta t / \Delta t_0)} = \alpha_s \int_{\hat{q}\Delta t}^{\boldsymbol{k}^2} \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \, \hat{q}(\Delta t, \boldsymbol{q}^2)$$

J. -P. Blaizot, Y. M. -T. (in preparation)

the transport coefficient runs up to the typical (local) scale $\boldsymbol{k}^2 \sim \hat{q} \Delta t_{\rm f}$

Radiative energy loss revisited

As a consequence, the DL's not only enhance the pt-broadening but also the radiative energy loss expectation:

$$\Delta E \equiv \int d\omega\, \omega\, dN/d\omega$$

When the logs become large (asymptotic behavior)

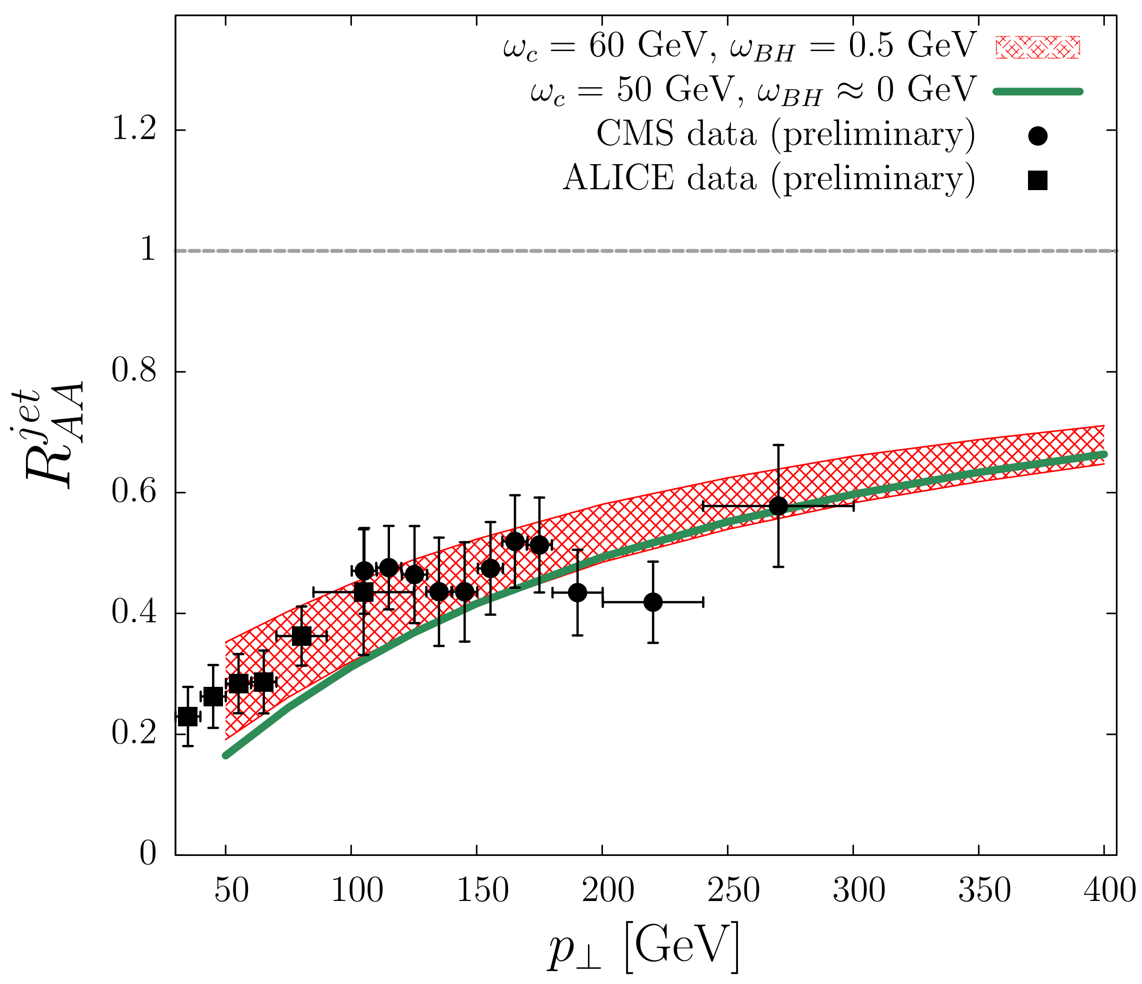
$$\Delta E \sim \alpha_s \hat{q}_0 L^2 \left(\frac{\hat{q}L}{m_D^2}\right)^{\sqrt{\frac{4\alpha_s N_c}{\pi}}}$$

To be compared to the ADS/CFT (strong coupling) estimate $\Delta E \sim L^3$

[F. Dominguez et al (2008) C. Marquet (2009)]

Understanding jet modifications at LHC

Nuclear modification factor $R_{AA} = dN_{AA} / (dN_{pp} \times N_{coll})$



Solving the evolution equation for D convoluted with an initial power low spectrum $p_\perp^{-n}$

L = 2-3 fm
$\hat{q}$ = 6-2.5 GeV^2/fm

K. Tywoniuk, Y. M. -T. (in preparation)

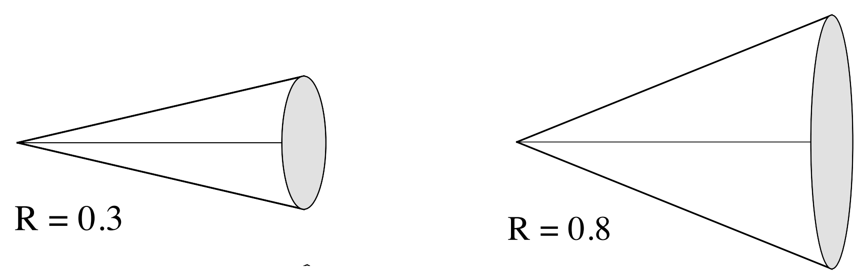
Understanding jet modifications at LHC

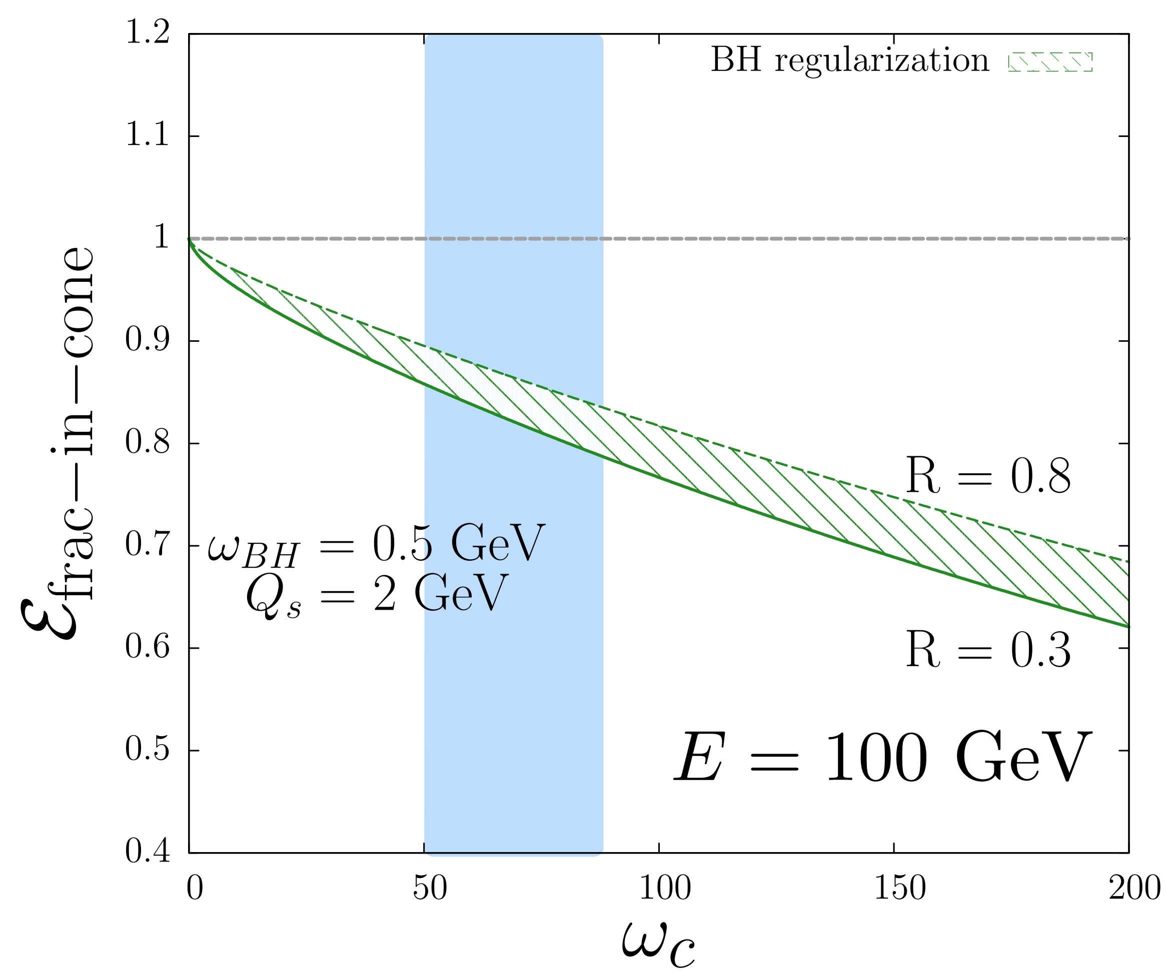
Dijet asymmetry

integrating D and excluding out-cone gluons

$$\theta_{\rm med} \sim \frac{\sqrt{\hat{q}L}}{\omega} > R$$

- little energy is recovered up to large cone angles, R~0.8
- striking effect due to multiple branching + broadening
- Possible explanation for energy transfer to large angles and soft modes in asymmetric dijet events observed by CMS (2012)



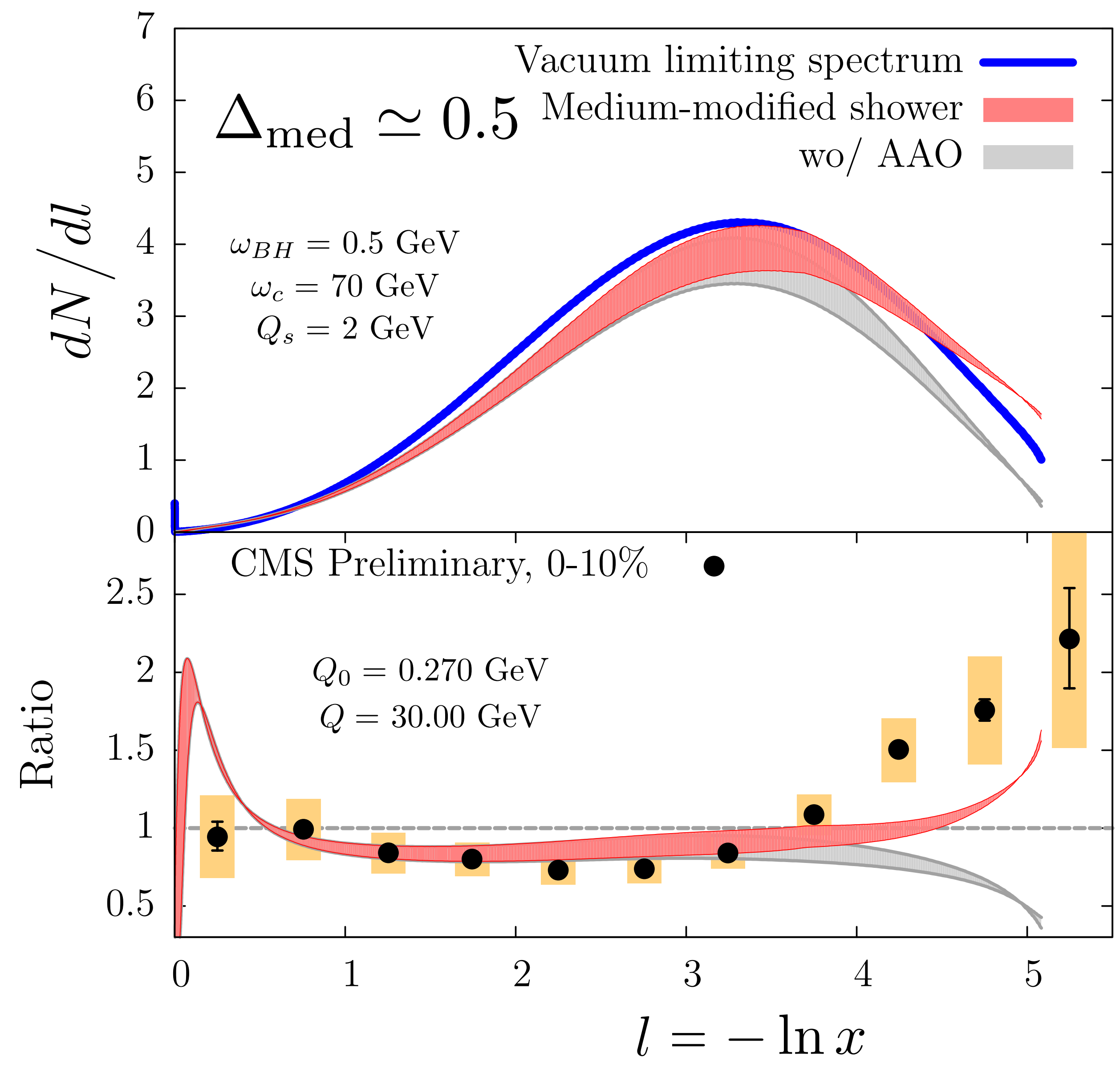


K. Tywoniuk, Y. M. -T. (in preparation)

Understanding jet modifications at LHC

Fragmentation functions

- MLLA distribution for pp vacuum
- medium-induced energy loss & broadening depletes energy inside the cone
  - responsible for dip in the ratio
- small angle radiation due to AAO/decoherence: novel ingredient
  - soft gluons, produced with large formation time :: not affected by broadening
  - responsible for enhancement at large l = shift of humpbacked plateau!



K. Tywoniuk, Y. M. -T. (in preparation)

Summary and outlook

- For large media: in-medium gluon branchings are independent: Probabilistic picture
- Radiative corrections to this picture are important and can be absorbed in a renormalization of the quenching parameter without spoiling the probabilistic picture.
- Phenomenology: agreement with observed nuclear modify. factor, FF’s and dijet asymmetry ; need for more detailed analysis and implementation in an event generator

Thank you !