New picture of jet quenching (from coherence)

Konrad Tywoniuk

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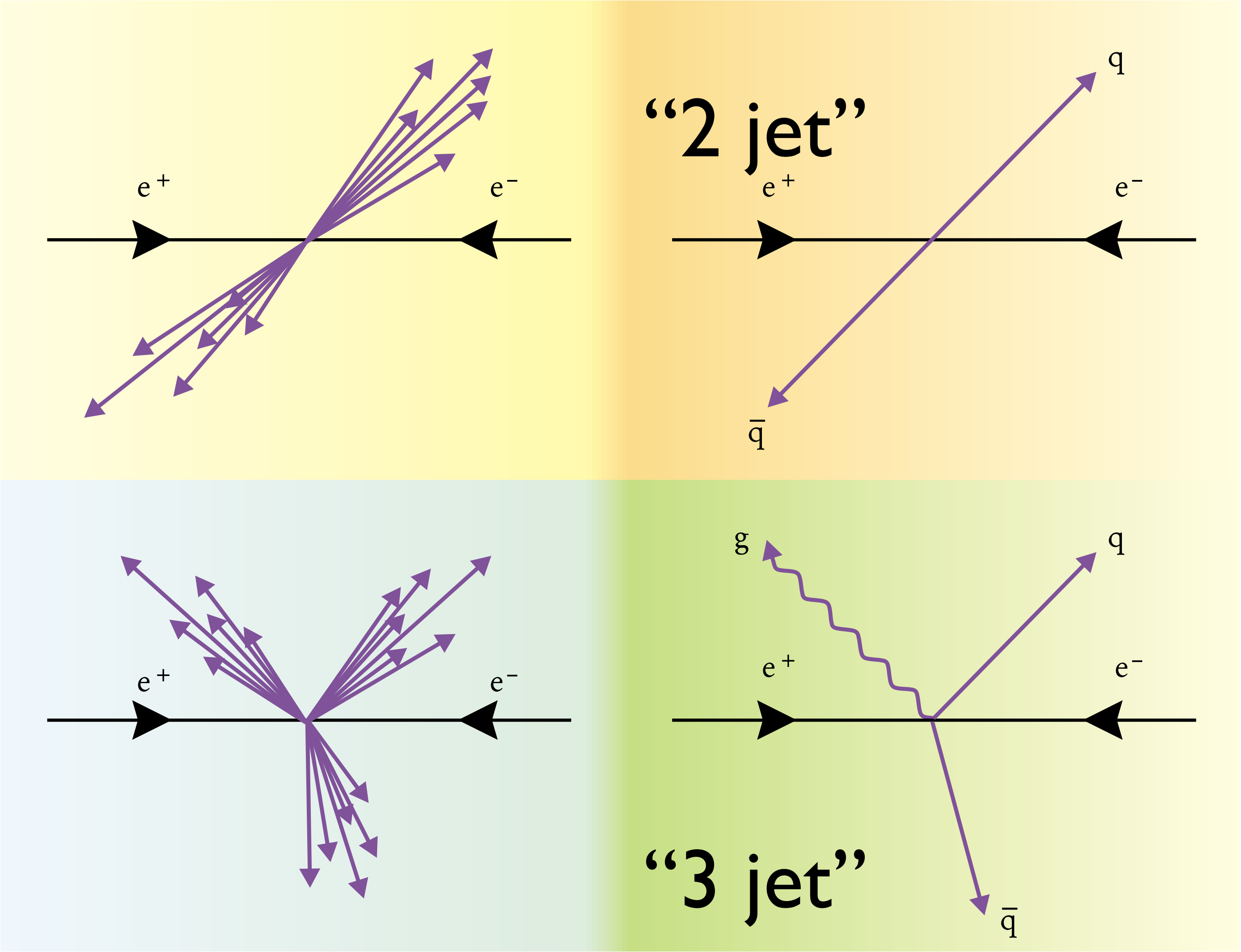
UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

Jets



- physically: sprays of particles in the detector — probing partonic degrees of freedom
- well defined objects in perturbation theory*
- ideal hard probes for extracting properties of the medium!

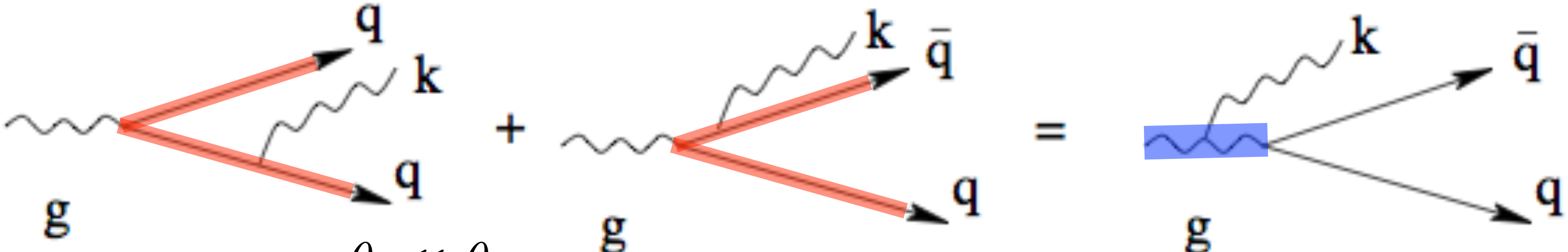
* *free from problems related to hadronic fragmentation functions…*

Two main features

Resummation of double logarithms + single log corrections

$$\frac{1}{p\cdot k}=\frac{1}{E\omega(1-\cos\theta)}\Rightarrow\alpha_s\int_{Q_0}^{E}\frac{d\omega}{\omega}\int_{\omega/Q_0}^{1}\frac{d\theta}{\theta}\sim\alpha_s\log^2\frac{E}{Q_0}$$

Color coherence = angular ordering



large-angle emissions are restored with the total charge!

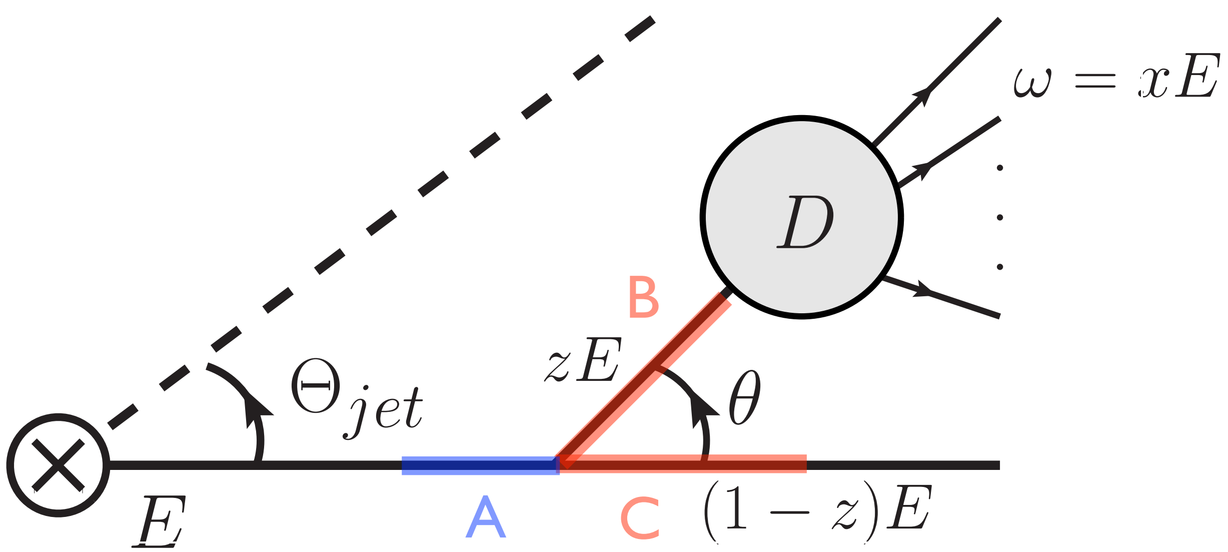
$\theta \ll \theta_{q\bar{q}}$

$$\omega\frac{dN_g}{d\omega d^2k_\perp}\propto\frac{\alpha_s C_F}{k_\perp^2}+(q\to\bar{q})$$

$$\omega\frac{dN_g}{d\omega d^2k_\perp}\propto\frac{\alpha_s C_A}{k_\perp^2}\qquad\theta\gg\theta_{q\bar{q}}$$

MLLA evolution equation

$$\frac{d}{d\log Q} x D_A^D(x,Q) = \int_0^1 dz \frac{\alpha(k_\perp)}{2\pi} \hat{P}_A^{BC}(z) \frac{x}{z} D_B^D\left(\frac{x}{z}, zQ\right)$$

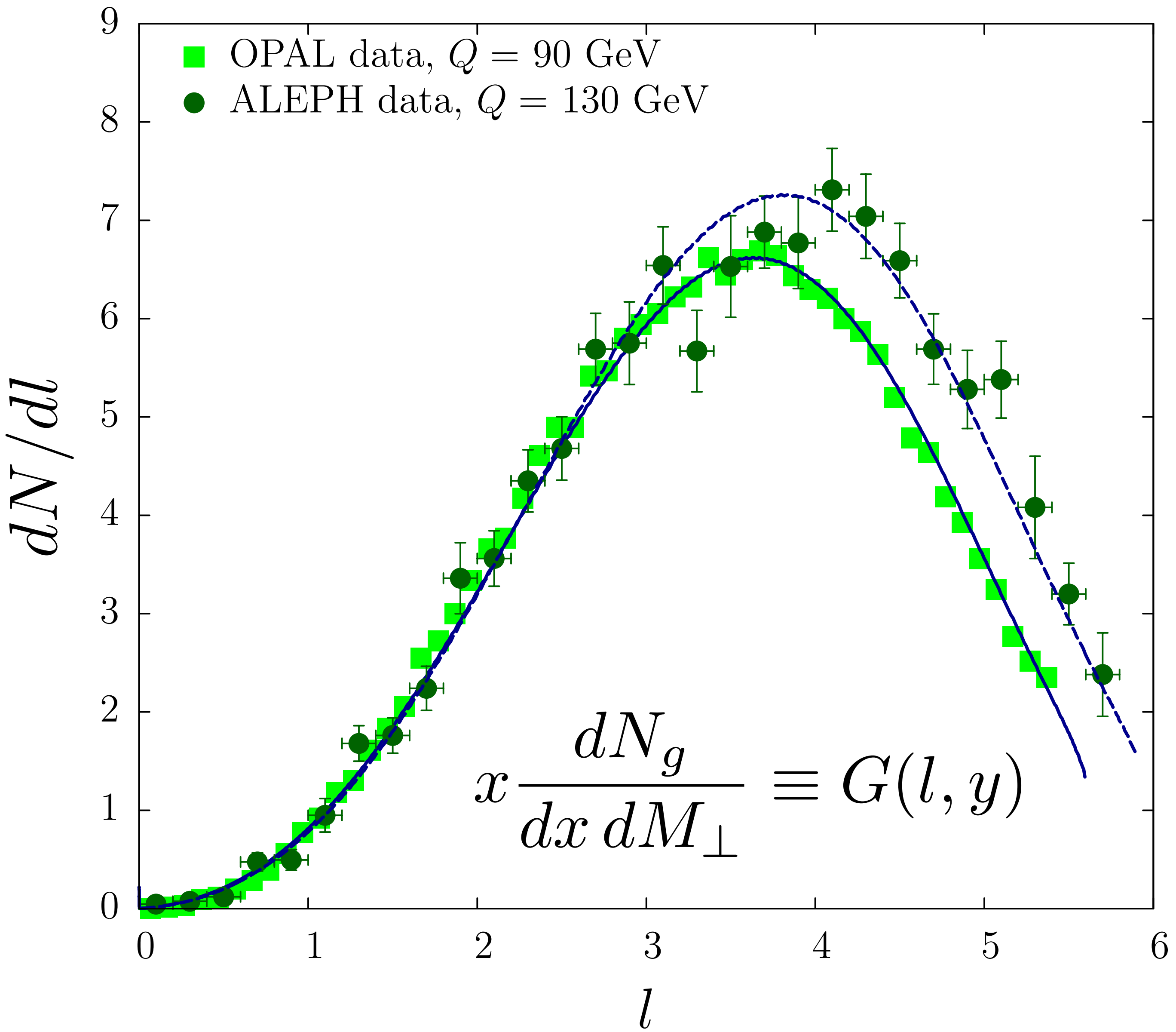


$$P_g^{gg} \simeq N_c \left[\frac{1}{z(1-z)} - \frac{11}{6}\right]$$

- probabilistic picture, factorization
- jet scales — perturbative evolution
- angular ordering — essential for small x
- MLLA + Local-Parton-Hadron-Duality
  - K factor

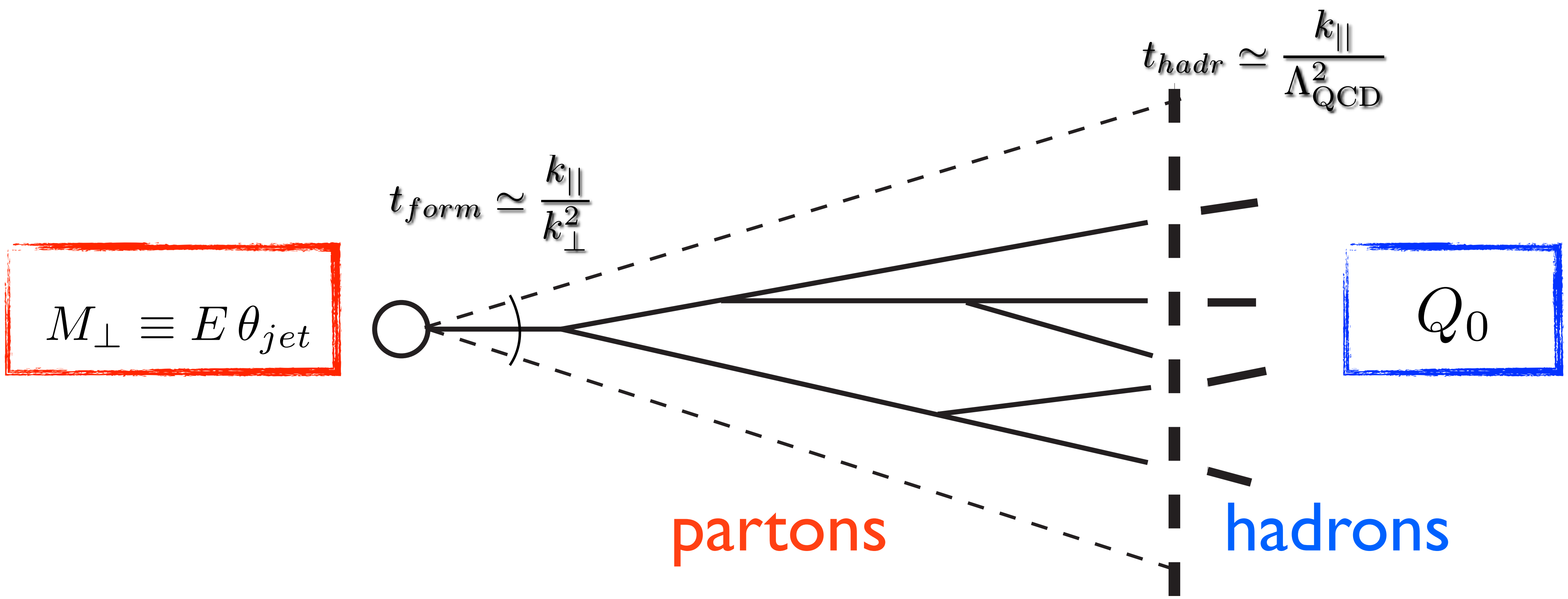
Bassetto, Ciafaloni, Marchesini, Mueller, Dokshitzer,
Khoze, Troyan, Fadin, Lipatov (80's)

Distribution of gluons in a jet

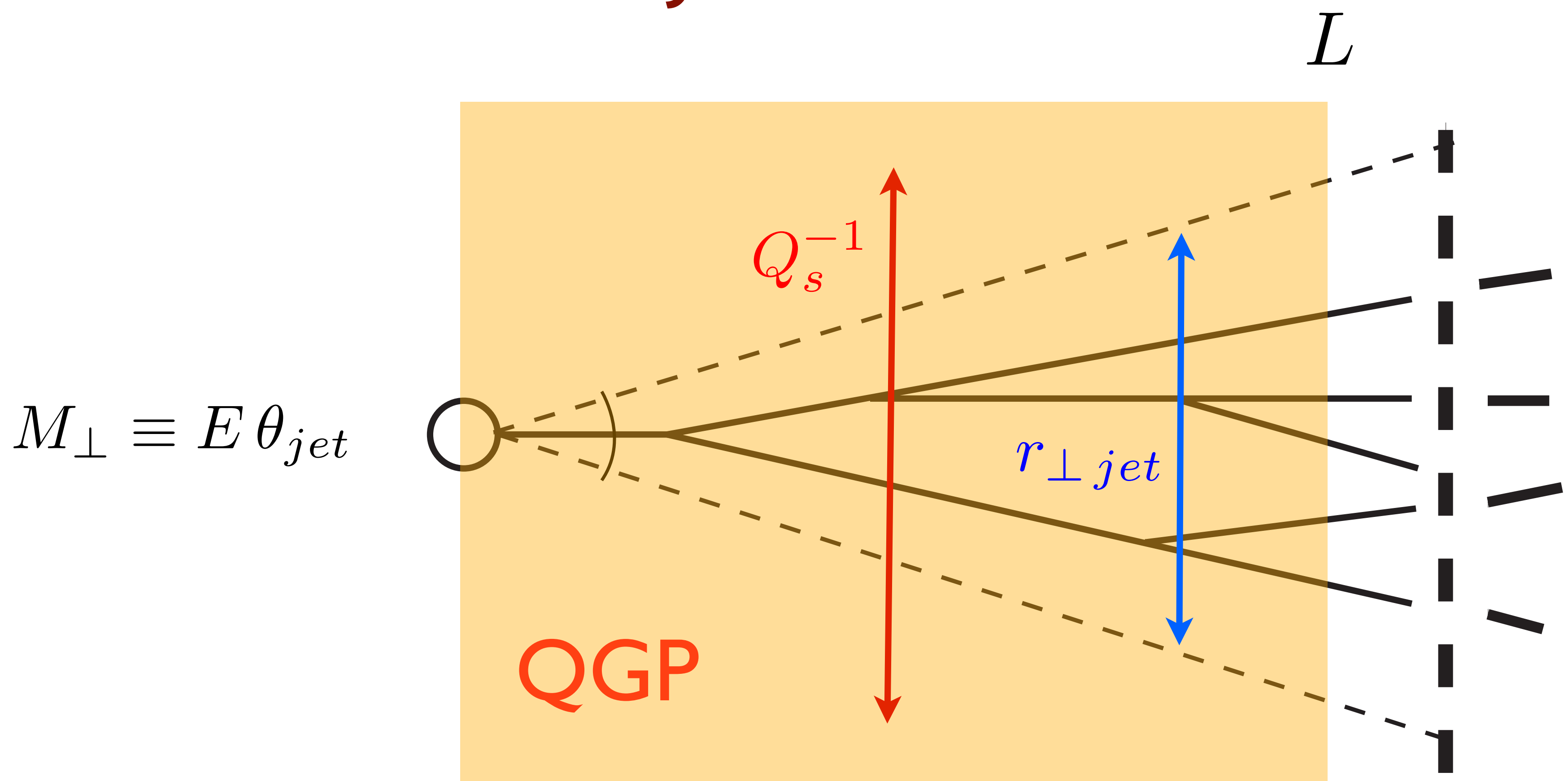


$$l = \ln\left(1/x\right)$$

QCD jet in vacuum



QCD jet in medium



New scales:

$$M_\perp \equiv E\,\theta_{jet}$$
$$Q_0 \sim \Lambda_{\rm QCD}$$

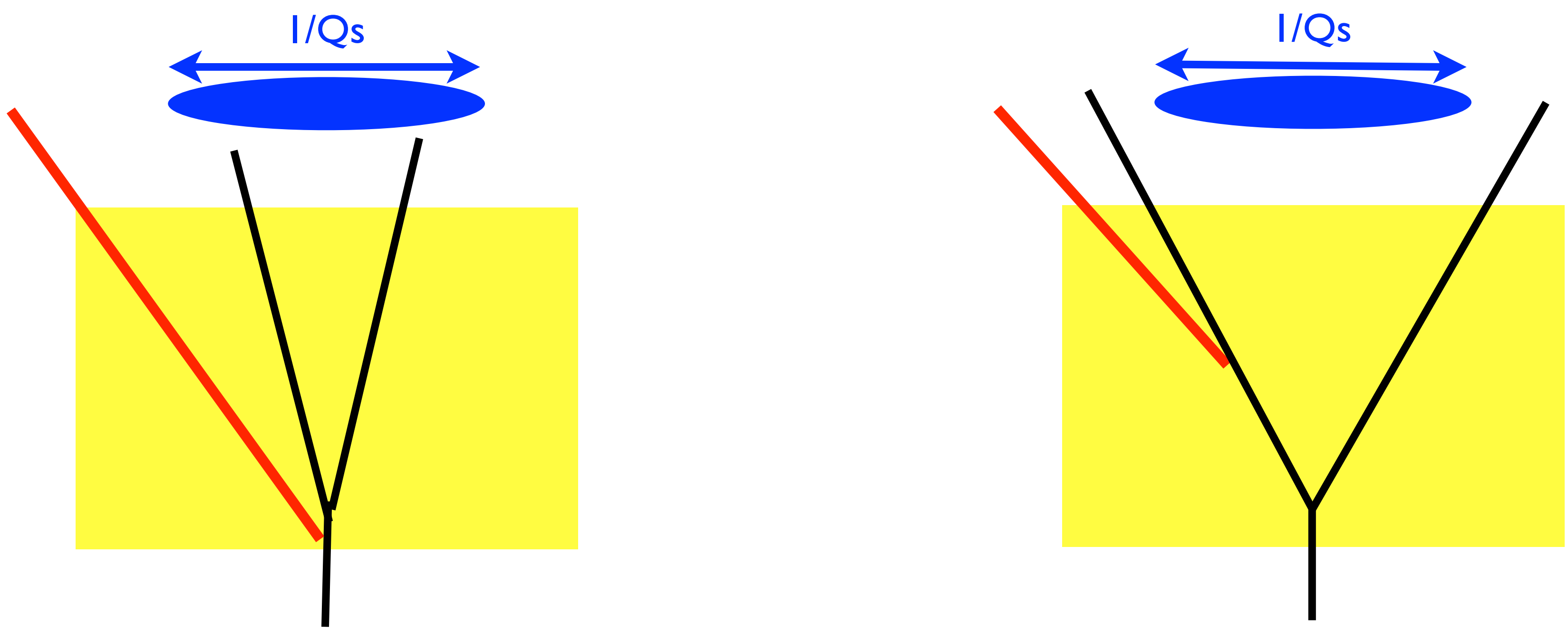
+

$$Q_s \equiv \sqrt{\hat{q}L} \equiv m_D \sqrt{N_{\rm scat}}$$
$$r_{\perp\,jet}^{-1} \equiv (\theta_{jet} L)^{-1}$$

Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765

Counting sources

One emitter | **Two emitters**



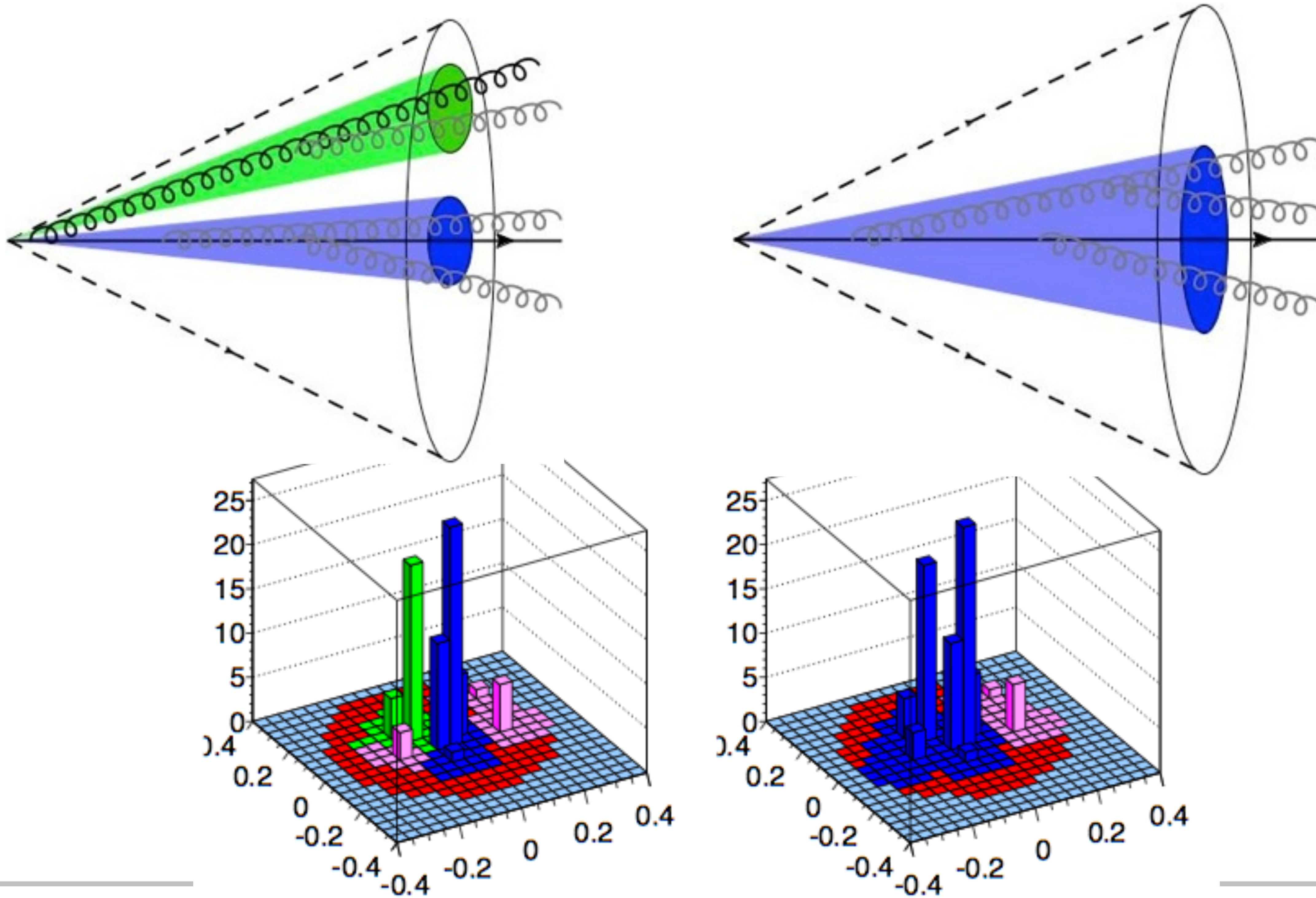
jet remains coherent | subjets decohere

The scale Q_s^{-1} determines the number of independent color sources that can are resolved by the medium.

—— :: medium induced radiation (BDMPS,… spectrum)

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397; Casalderrrey-Solana, Iancu 1105.1760

Resolved effective charges



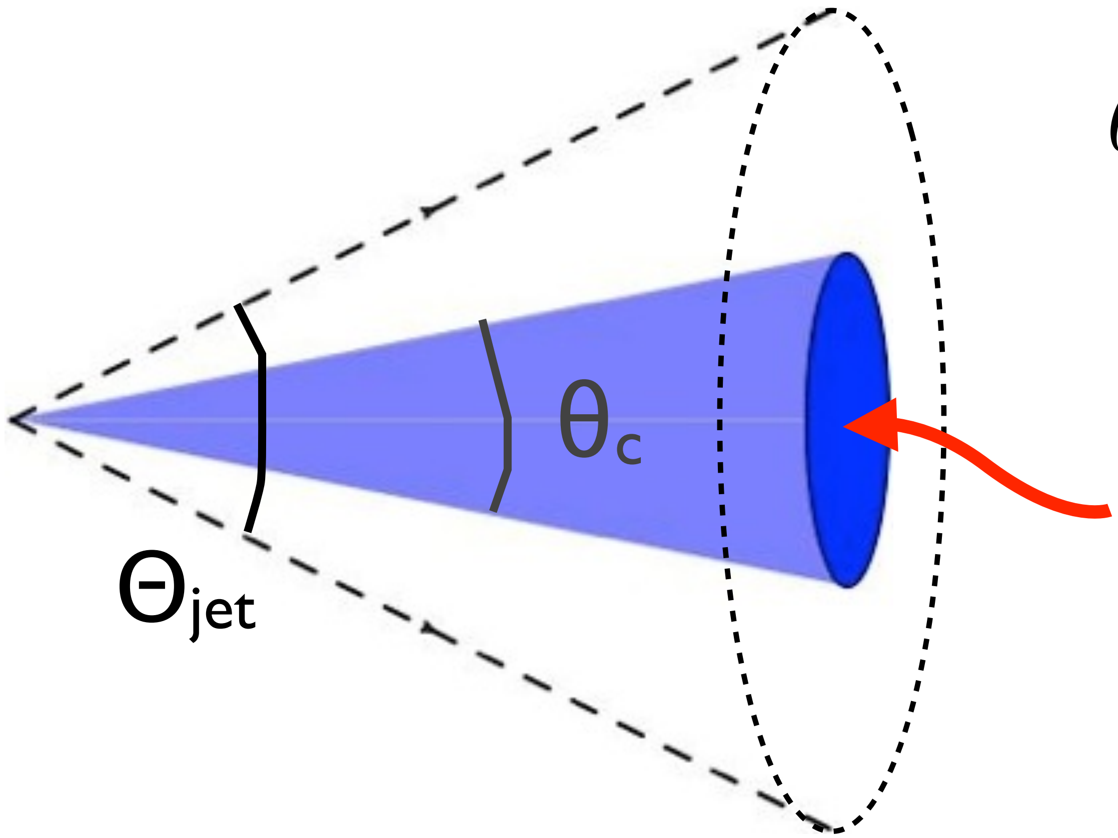
Resolving jet substructure

Coherence survival prob.

$$\Delta_{\mathrm{med}} = 1 - e^{-\Theta_{\mathrm{jet}}^2/\theta_c^2}$$

$$\theta_c = 1/\sqrt{\hat{q}L^3}$$

jet definition (Θ_{jet}=R)!



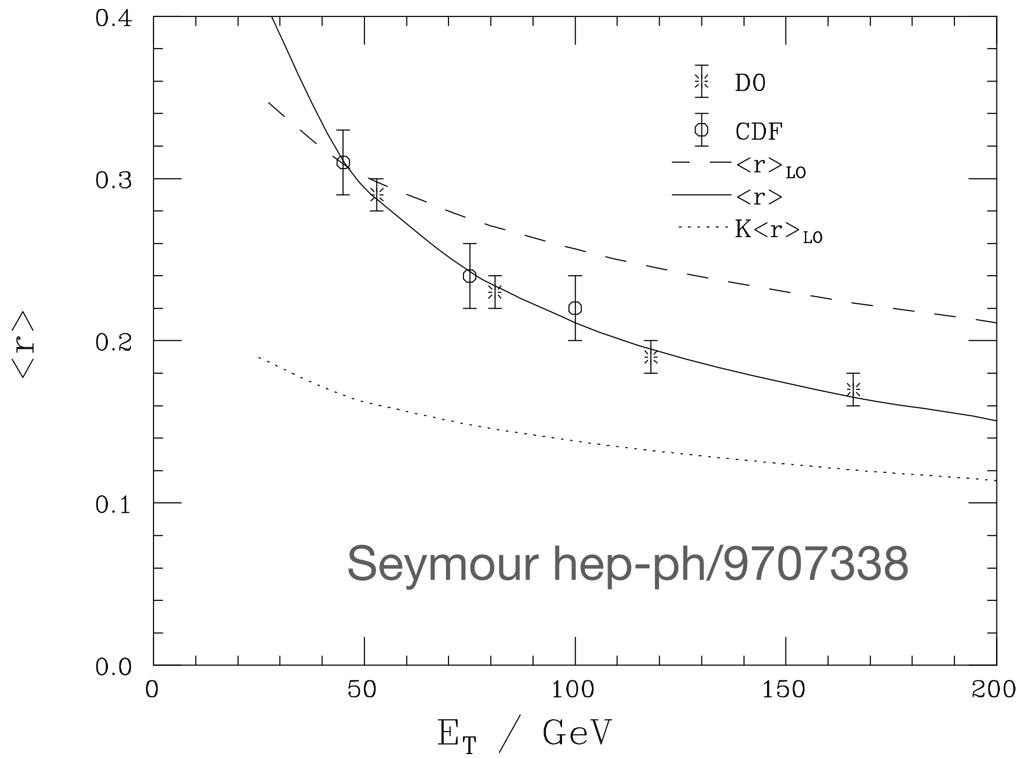
Coherent inner 'core'

- branchings occurring inside the medium with $\theta < \theta_c$ — hard modes
- the core interacts w/ medium coherently
- induces radiation — loses energy

A large fraction of the jets contain 90% of their energy within Θ~0.1

Casalderrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765
Perez-Ramos, Mathieu PLB 718 (2013) 1421 [arXiv:1207.2854]; Perez-Ramos, Renk arXiv:1401.5283

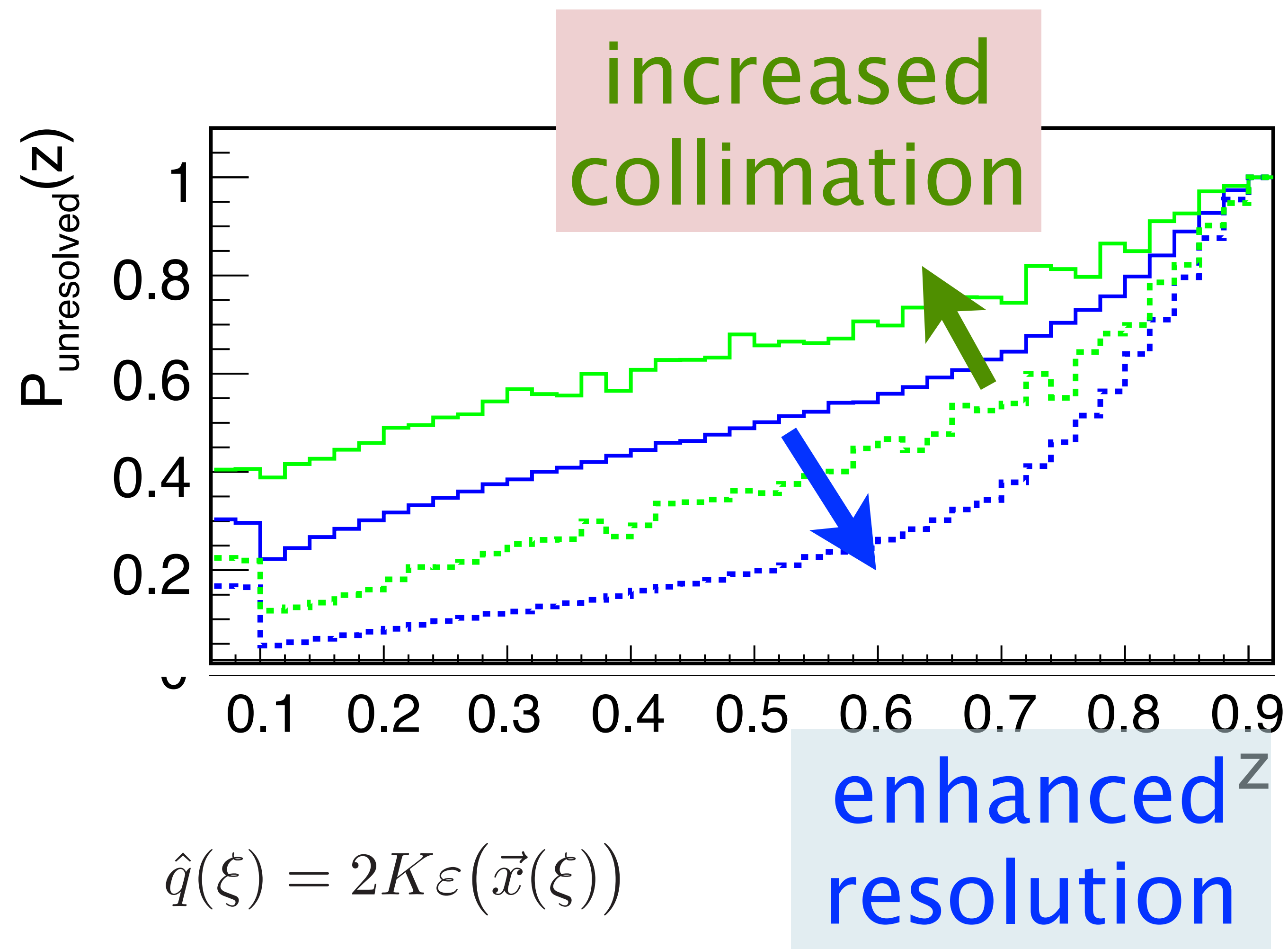
Motivation



$$\psi(r;R) = \frac{\int dE_T\; E_T \frac{d\sigma}{dE_T\, dr}}{\int_0^R dr \int dE_T\; E_T \frac{d\sigma}{dE_T\, dr}}$$

Bias in HIC: jets are filtered by energy loss mechanisms

probability of only finding one leading subjet in the presence of a fragment with mom frac z



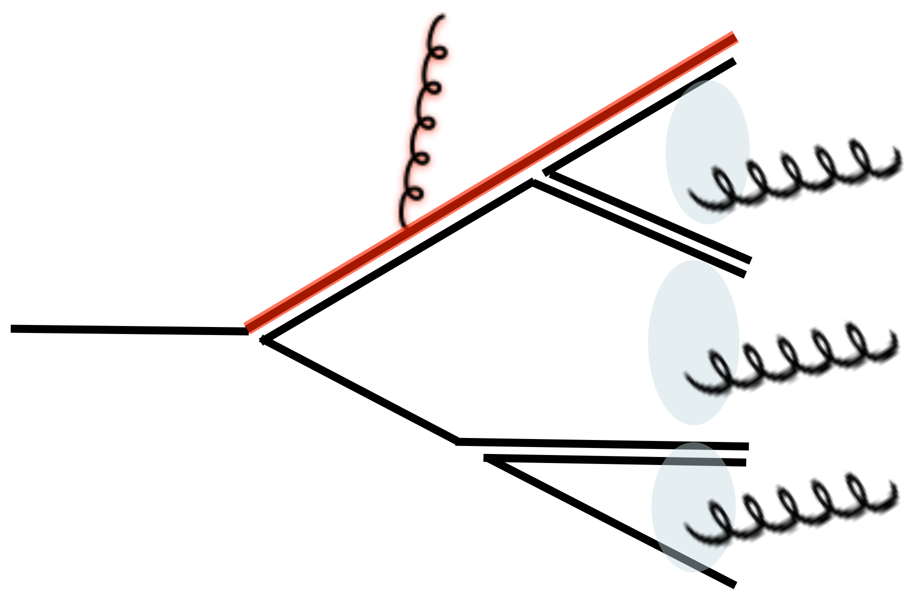
$$\hat{q}(\xi) = 2K\varepsilon\big(\vec{x}(\xi)\big)$$

blue/green curves :: p_T = 100, 200 GeV

solid/dashed curves :: K = 1, 10

Let's stick to the theoretically cleanest situation taking into account small deviations and look for a consistent picture…

Factorization of radiation



- assume collimated jets and coherence — leading contribution to inclusive spectra at high energies
- separation in angles — only the total charge radiates — jet calculus

$$D^{\rm coh}_{\rm med}(x;Q,L) = \int_x^1 \frac{{\rm d}z}{z} D^{\rm vac}\left(\frac{x}{z};Q\right) D^{\rm med}_q(z,p_\perp,L)$$

small angle, vacuum-like evolution

medium induced, large angle radiation

Mehtar-Tani, KT 1401.8293

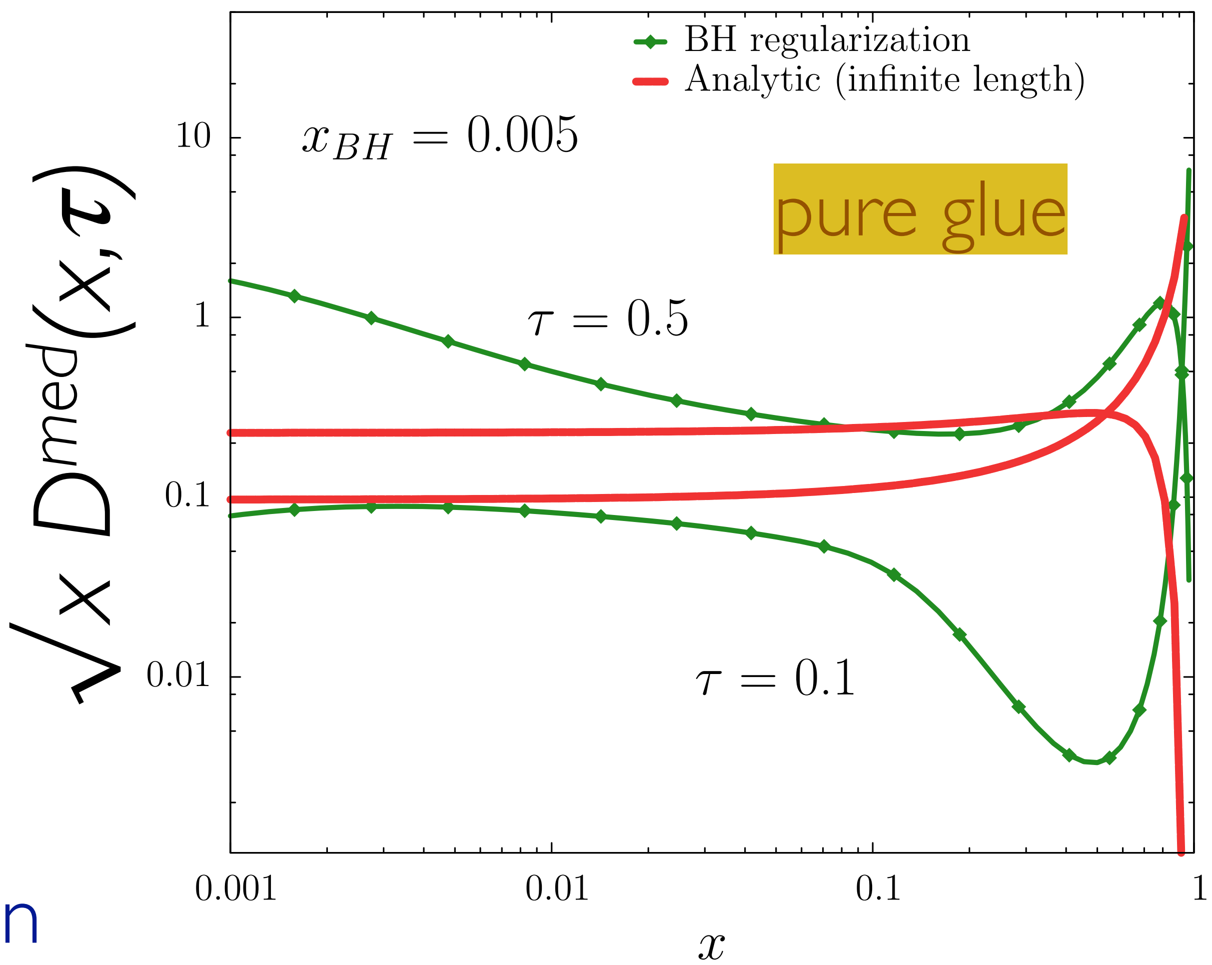
Jeon, Moore hep-ph/0309332; Baier, Mueller, Schiff, Son hep-ph/0009237; Blaizot, Iancu, Mehtar-Tani 1301.6102

Induced radiation

Distribution of particles after passing a medium of "length"

$$\tau = \frac{\alpha_s N_c}{\pi}\sqrt{\frac{\hat{q}L^2}{E}}$$

$$D(x,\tau=0) = \delta(1-x)$$

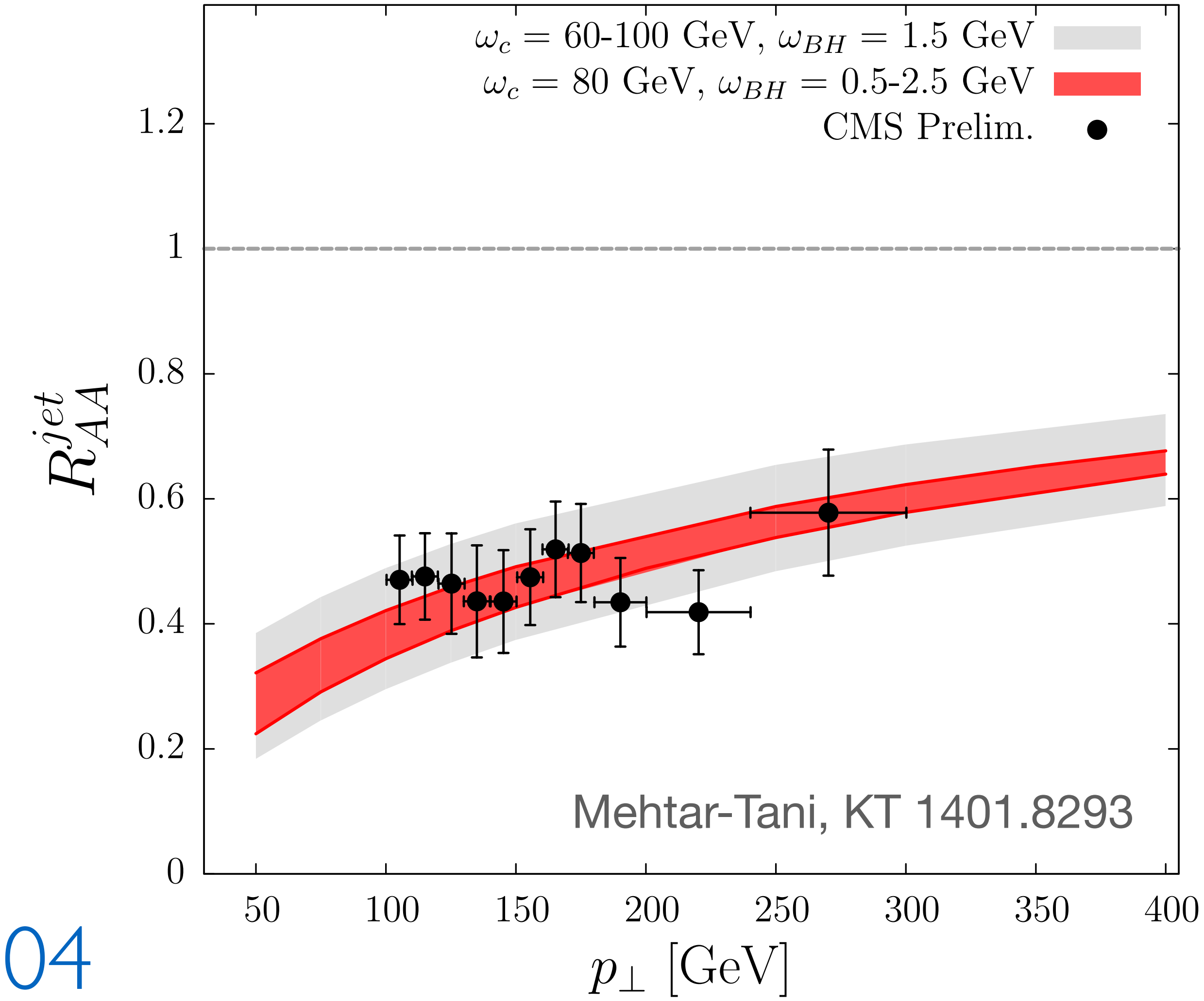


- probabilistic interpretation
- turbulent flow: no intrinsic accumulation of energy
- effective in transporting sizable energy to large angles
- x_{BH}: regularization at short formation times ~ λ_{mfp}

Jeon, Moore hep-ph/0309332; Baier, Mueller, Schiff, Son hep-ph/0009237; Blaizot, Iancu, Mehtar-Tani 1301.6102

Nuclear modification factor

- assuming quark jets (n=5.6)
- allows to fix medium scales (fixing L = 2.5 fm)
- high-$p_\perp$ jets are the most reliable probe of $\hat{q}$



$Q_s = 3.6$ GeV

Jet deflection :: $\Delta\Theta \sim Q_s/E \sim 0.04$

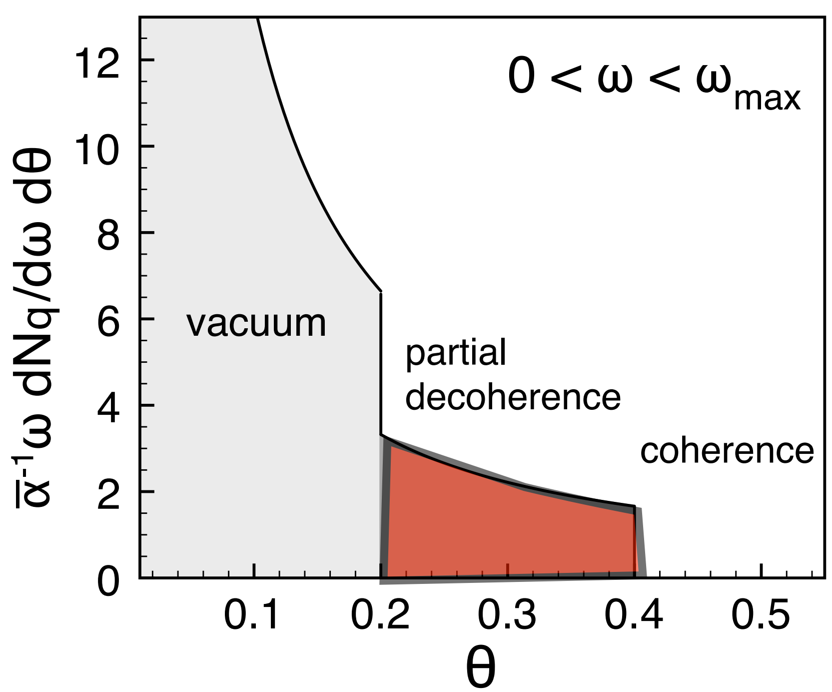
Missing pt in dijet events	Θ	Θ
missing energy at θ<Θ	14 - 19 %	9 - 15 %

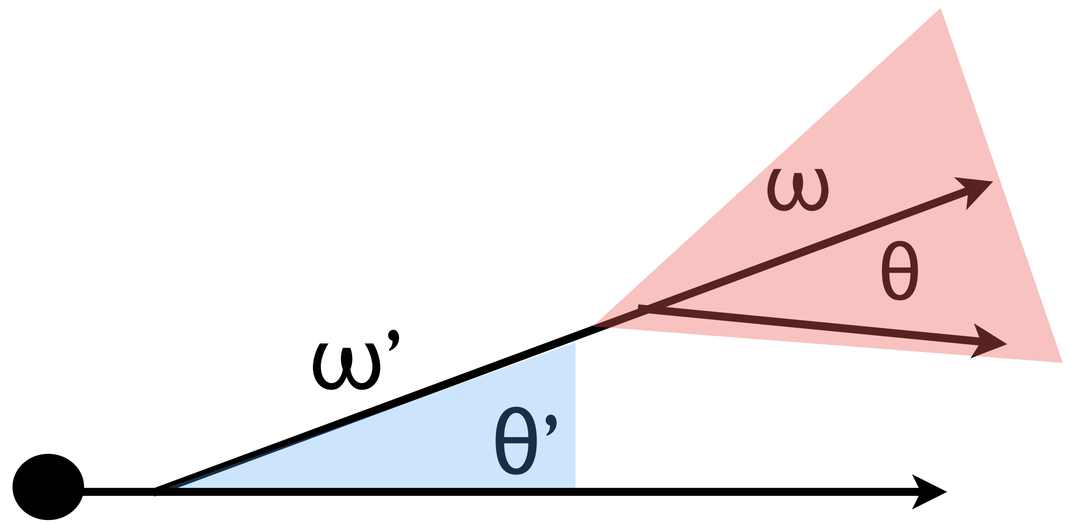
Soft gluons in the cone

Going beyond the inclusive jet spectrum, the assumption of fully coherent jets marginal

$\Theta_{\rm jet} = 0.3$

$\Theta_c = 0.08$





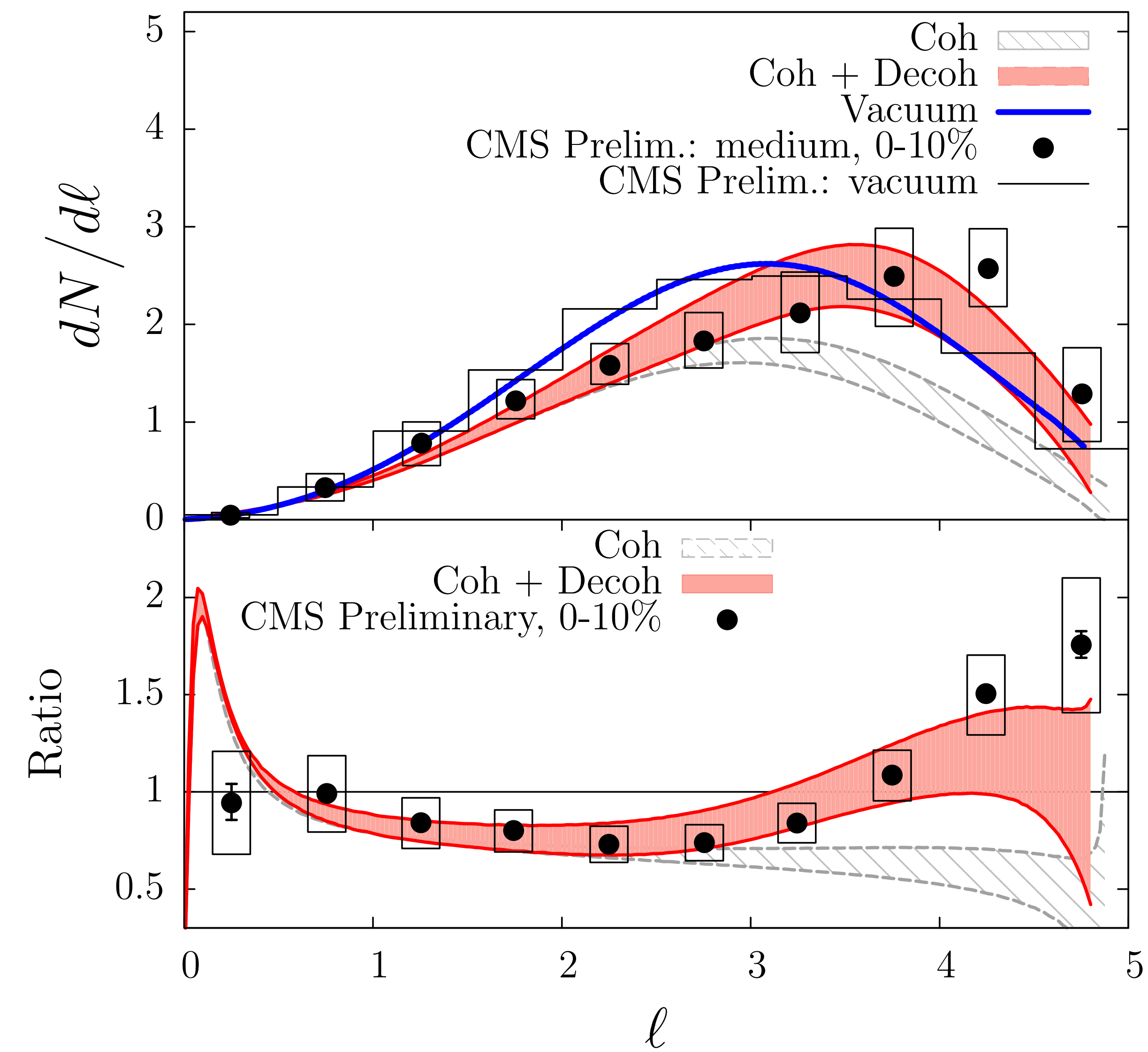
Contribution from 2nd emission in DLA w/ running coupling.

$$D^{\rm jet}_{\rm med}(x;Q,L) = D^{\rm coh}_{\rm med}(x;Q,L) + \Delta D^{\rm decoh}_{\rm med}(x;Q,L)$$

Mehtar-Tani, Salgado, KT 1009.2965; Mehtar-Tani, KT 1401.8293

Fragmentation function

- vacuum baseline reproduced by MLLA :: valid close to the humpbacked plateau
- allow the jet energy to vary (due to energy loss)
- coherent jet quenching important for intermediate ℓ
- decoherence plays main role at large ℓ (small x)



Uncertainties: varying jet energy scale (~20 %), varying non-perturbative contribution in Q_{med}/Q_0

Mehtar-Tani, KT 1401.8293

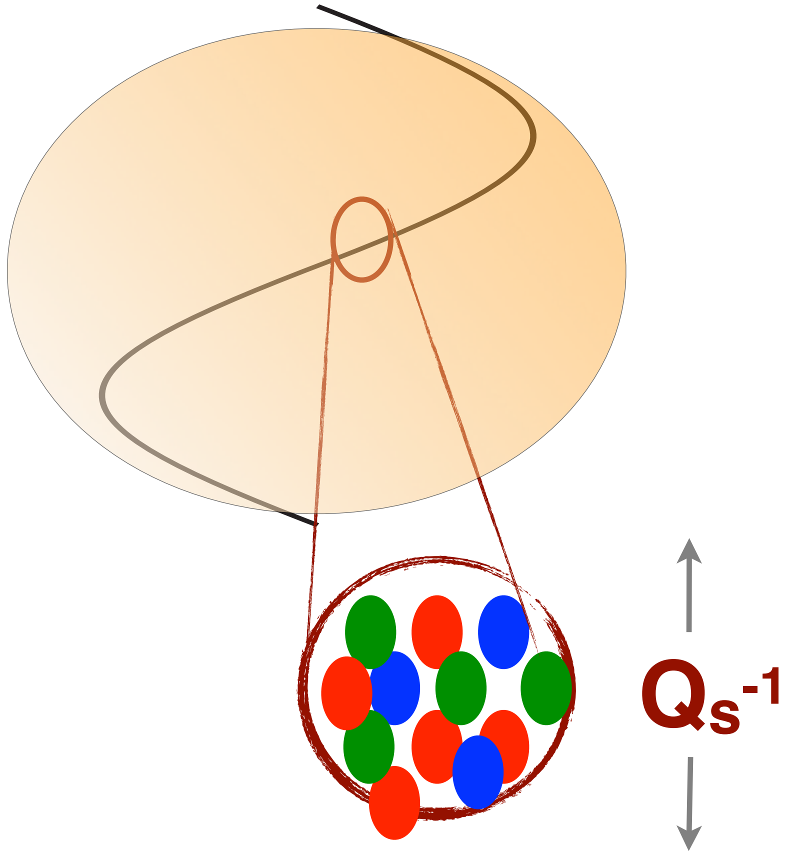
Summary

- jet quenching is a powerful tool to access properties (e.g. $\hat{q}$) of the hot and dense QGP
  - resolved sub-jets are a consequence of color transparency (perturbative QCD)
  - good description with a consistent set of parameters
- Outlook
  - need further refinements (nuclear geometry, pQCD jet cross sections, hydro, improved observables) and systematic approach to pin down medium parameters

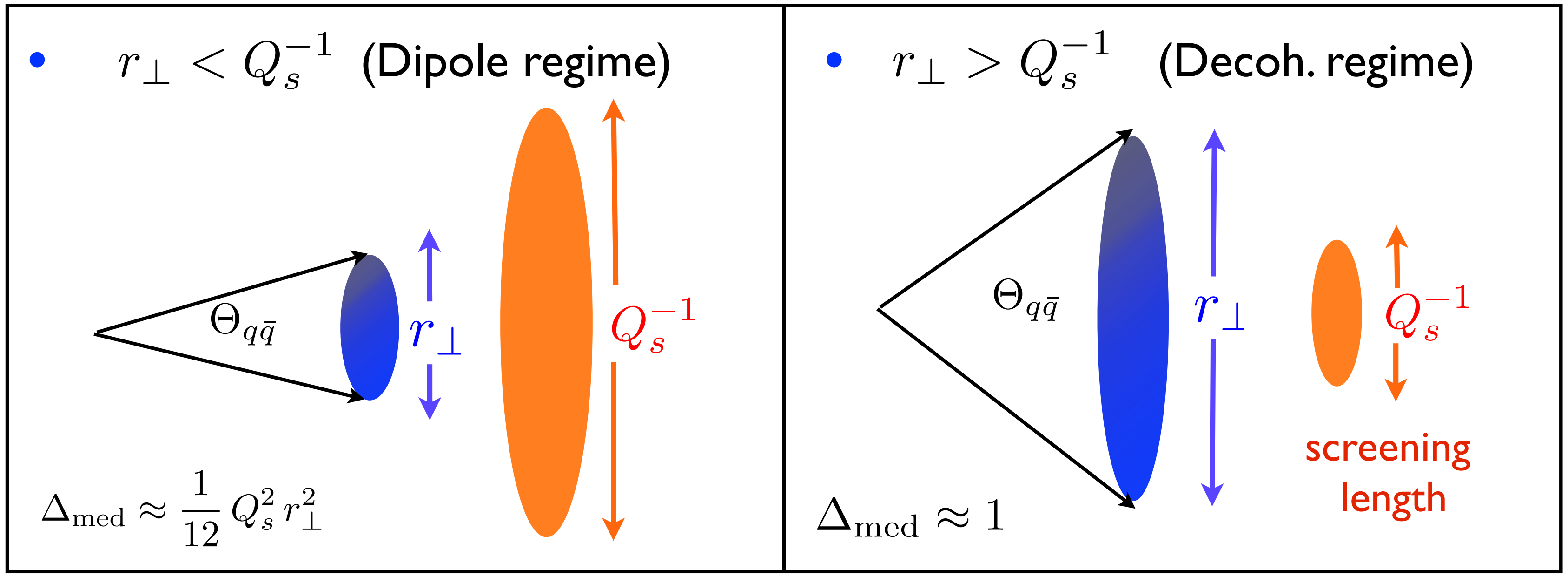
backup

Transparency vs decoherence

a snapshot of the medium:



a simple case — the antenna



$$\Delta_{\rm med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$$

decoherence parameter

$$k_\perp < Q_{\rm hard}$$

hardest scale determines phase space for radiation

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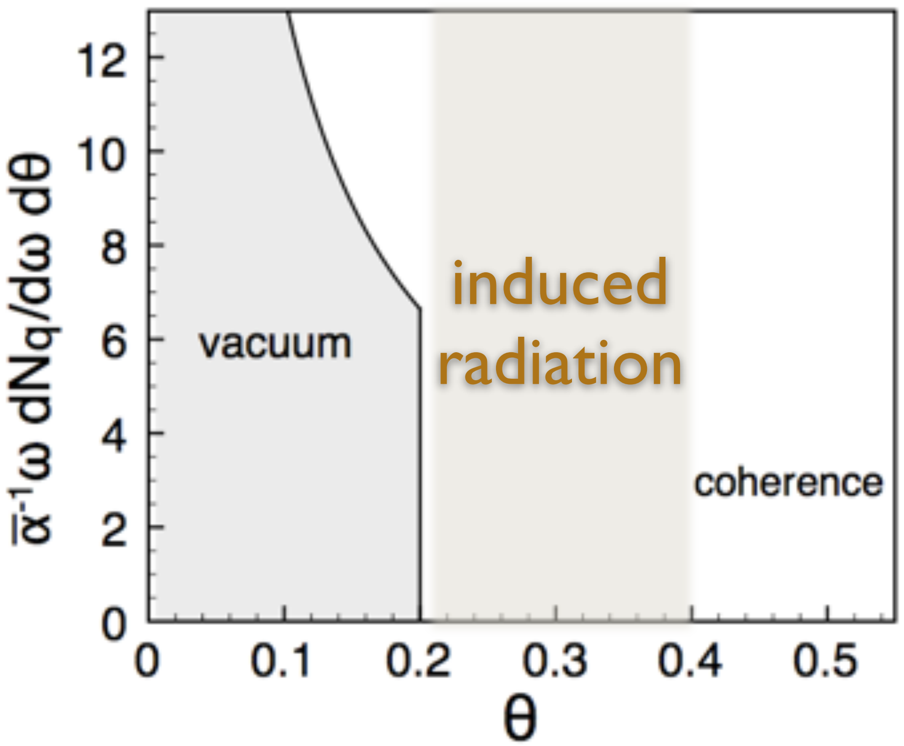
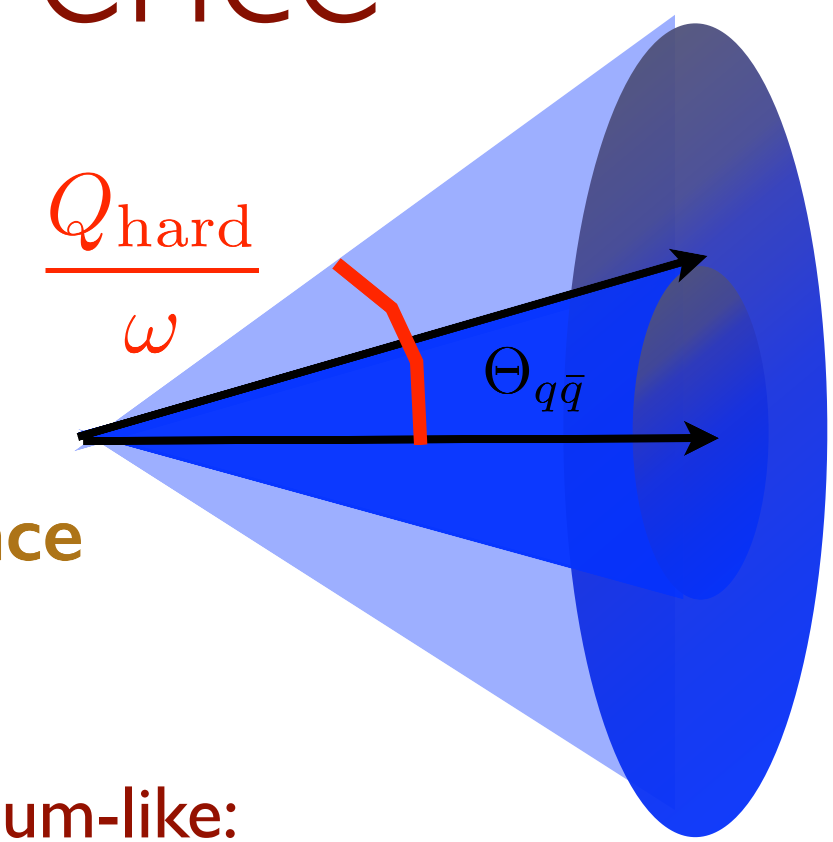
Onset of decoherence



$\Delta_{\rm med} \to 0$ **Coherence**

$\Delta_{\rm med} \to 1$ **Decoherence**



In ω→0 limit, only vacuum-like:

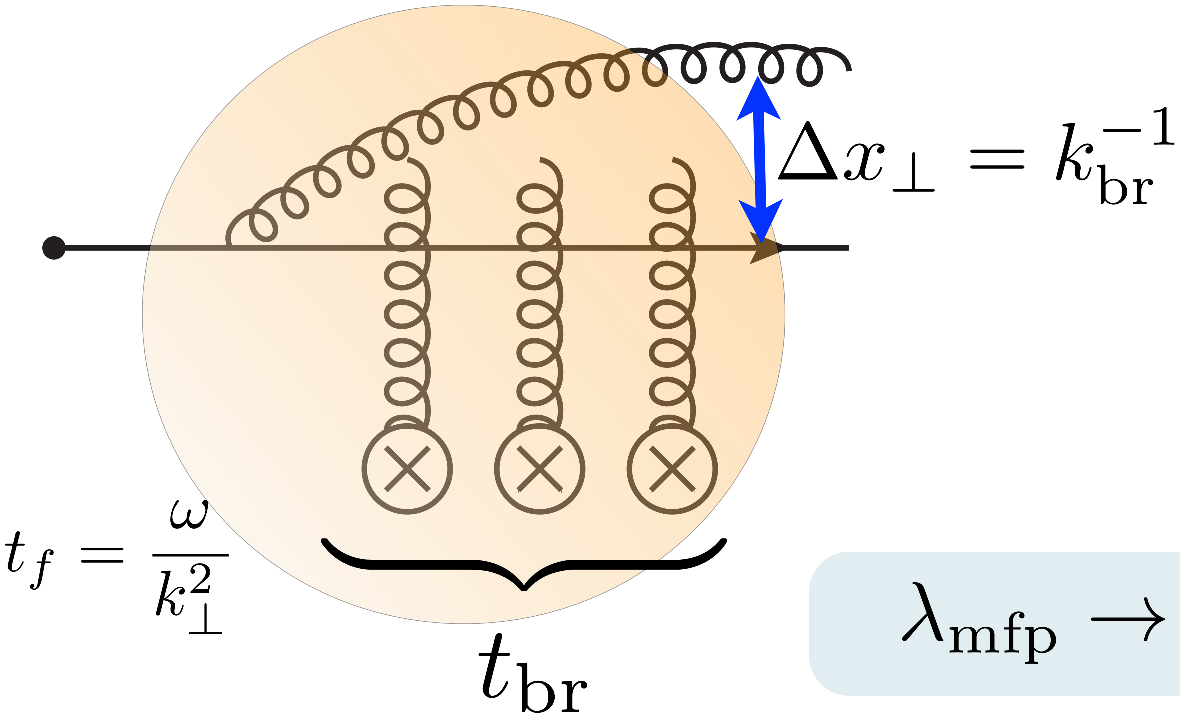
$$dN_q^{\rm tot} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin\theta \; d\theta}{1-\cos\theta} \left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\, \Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right] \; .$$

$$Q_{\rm hard} = \max\left(r_\perp^{-1}, Q_s\right)$$

$$k_\perp < Q_{\rm hard}$$

- decoherence opens phase space at large angles $\theta_{max}=Q_{hard}/\omega$
- modification of angular ordering

Induced radiation



Multiple scattering in the medium:

$$\left.\begin{aligned} t_{br} &= \lambda_{mfp} N_{coh} \\ k_{br}^2 &= \mu^2 N_{coh} \end{aligned}\right\} \quad \begin{aligned} t_{br} &= \sqrt{\omega/\hat{q}} \\ k_{br}^2 &= \sqrt{\hat{q}\omega} \end{aligned}$$

$\lambda_{mfp} \to t_{br}$ :: Landau-Pomeranchuk-Migdal effect

Bethe-Heitler regime

$$t_{br} \sim \lambda_{mfp}$$

$$\omega_{BH} = \lambda^2 \hat{q} \sim \lambda m_D^2$$

Factorization regime

$$t_{br} \sim L$$

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

LPM regime

$$\omega_{BH} \ll \omega \ll \omega_c$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)