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Understanding jet modifications at the LHC

Konrad Tywoniuk

h3QCD, ECT* Trento, 17-21 June 2013

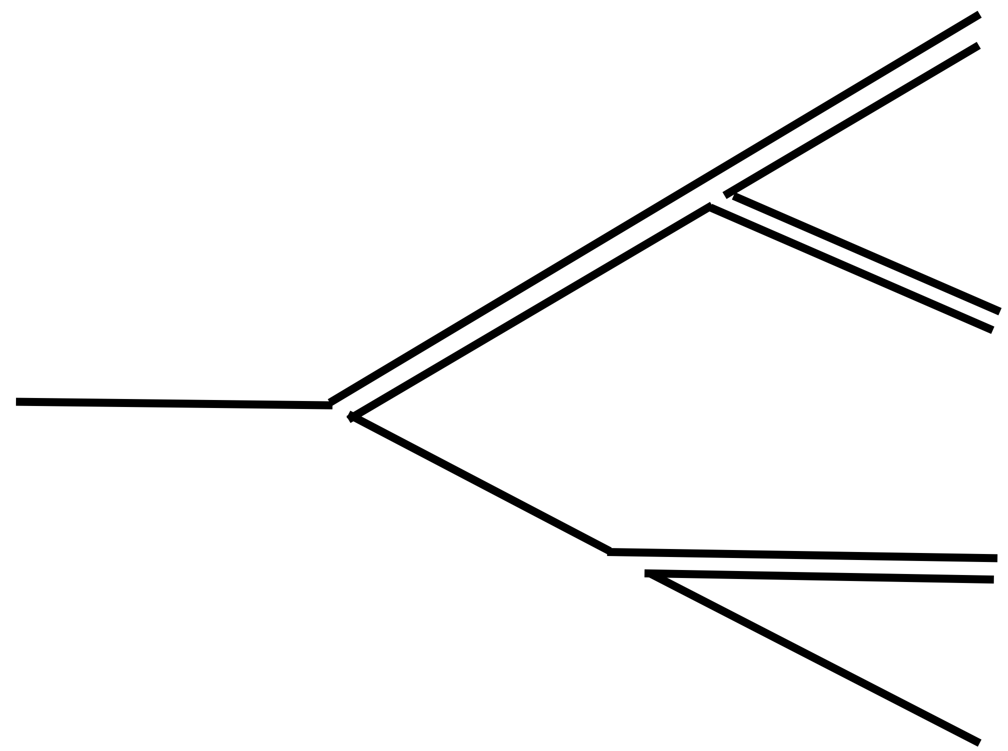
Overview

- PART I: Coherence effects & resolution
  - what interacts with the medium: color transparency
  - the simplest case: space-time picture
- PART II: Phenomenological analysis

  [...work in progress]
  - jet energy loss in medium
  - intra-jet modifications
  - out-of-cone energy flow

In collaboration with: C.A. Salgado, J. Casalderrey-Solana, Y. Mehtar-Tani

Jet "quenching" in HIC



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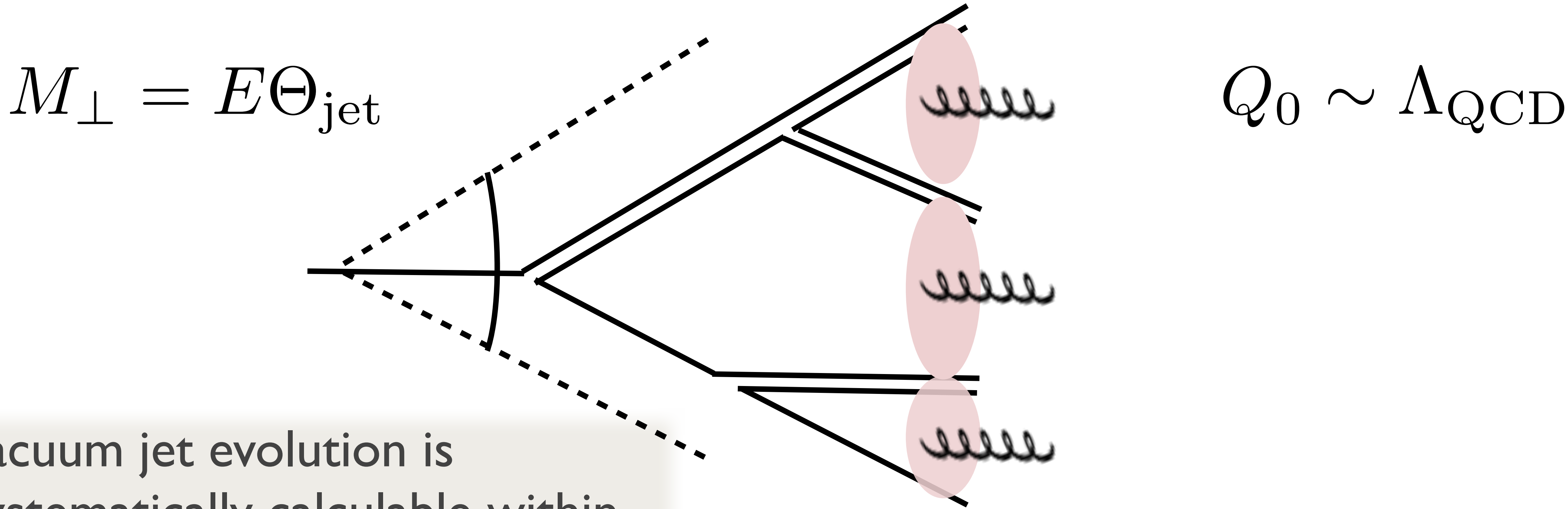
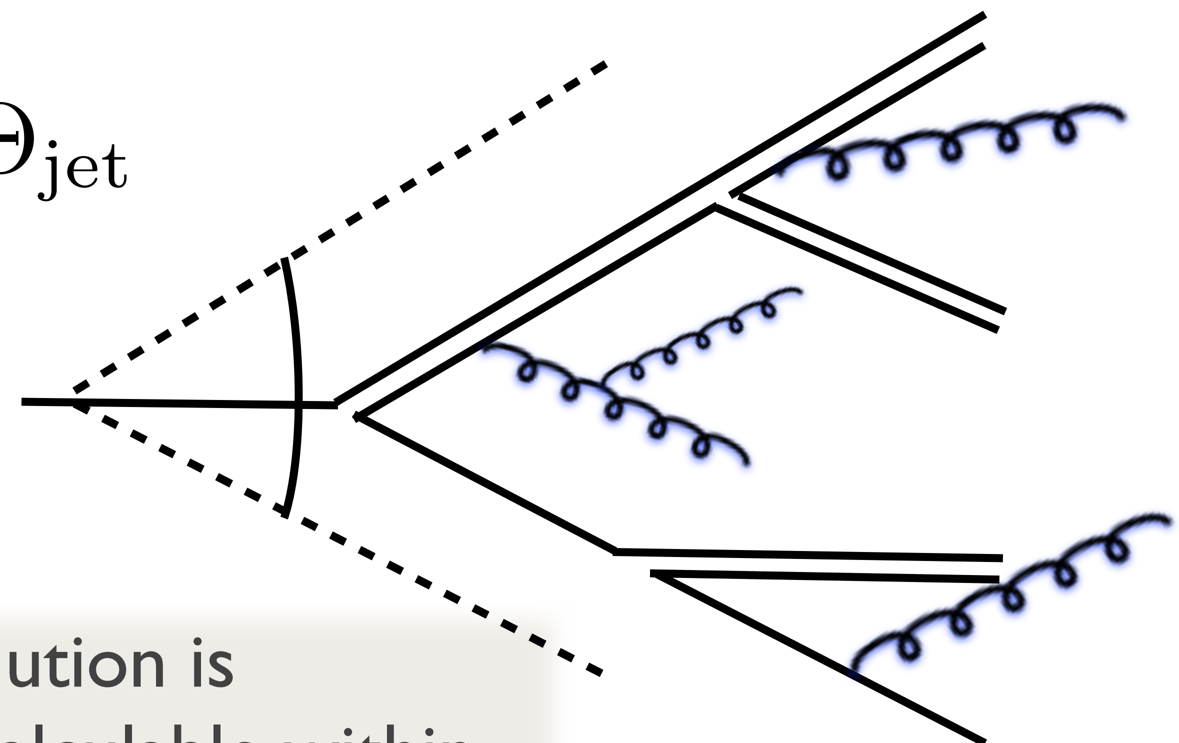


- vacuum jet evolution is systematically calculable within pQCD (large-N_c)
- resummation of soft and collinear divergences
- time-like evolution: angular ordering

Jet "quenching" in HIC

$$M_\perp = E\Theta_{\text{jet}}$$

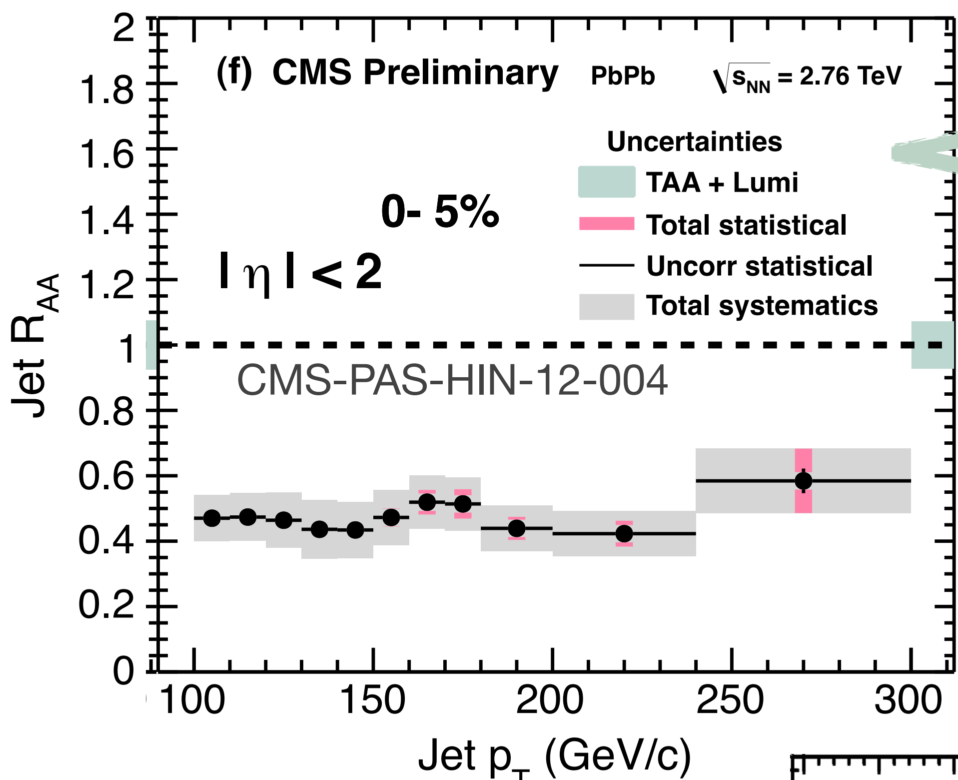


$$Q_0 \sim \Lambda_{\text{QCD}}$$

- vacuum jet evolution is systematically calculable within pQCD (large-N_c)
- resummation of soft and collinear divergences
- time-like evolution: angular ordering

- transverse mom broadening
- induced energy-loss
- resolution power of the medium
- space-time picture

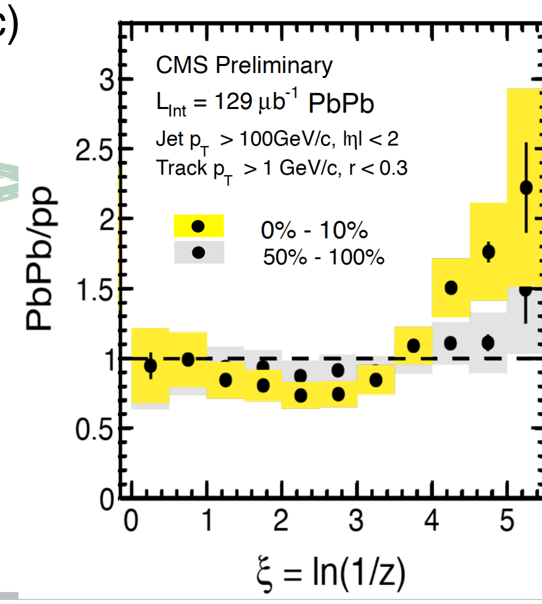
Experimental signatures

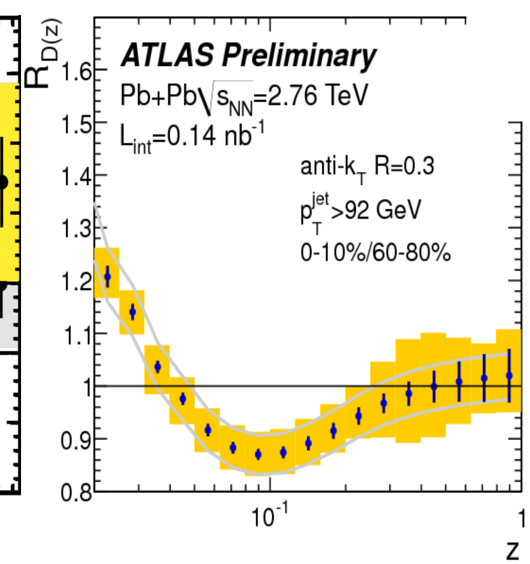


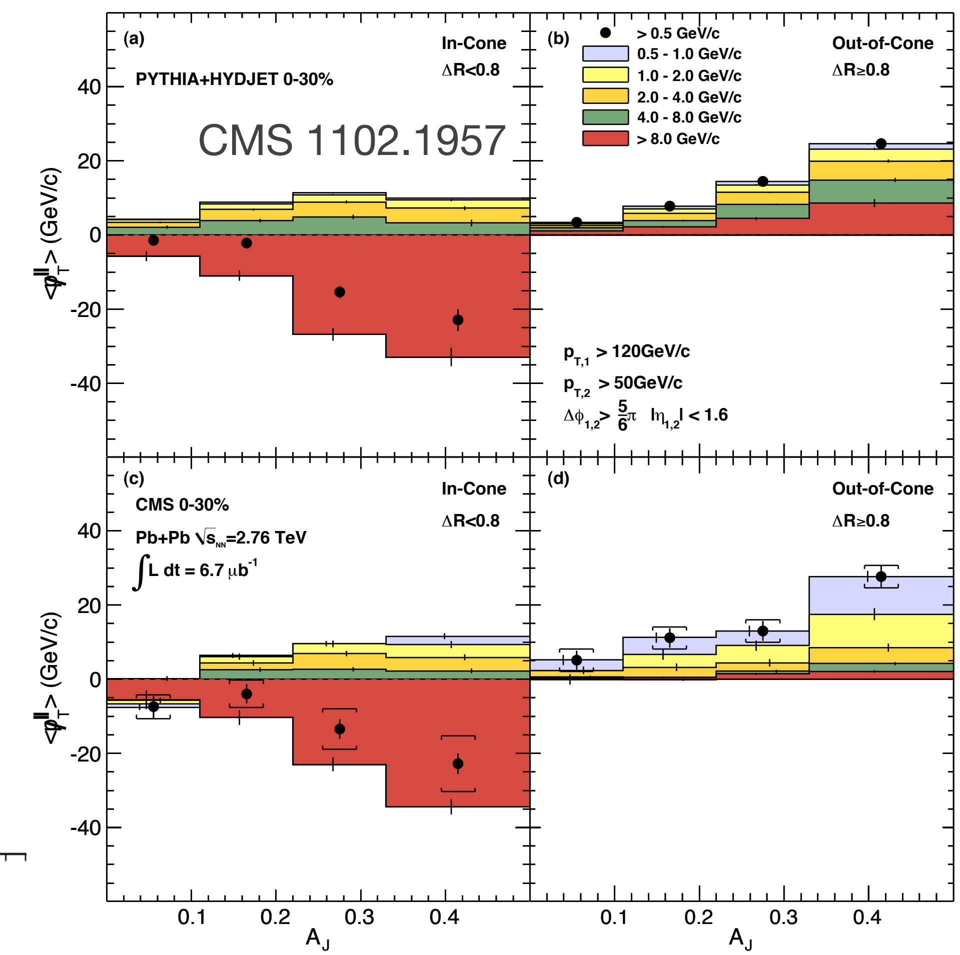
jet rate is suppressed

dip & softening of the jet long fragmentation function

CMS-PAS-HIN-12-013
ATLAS-CONF-2012-115







a significant fraction of the jet energy is found at large angles

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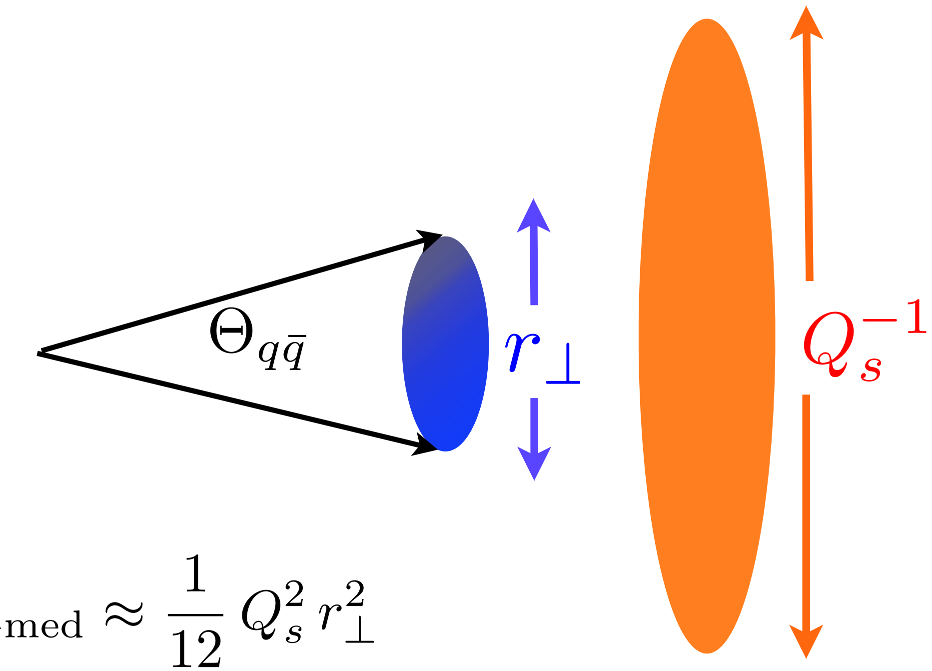
The antenna in medium

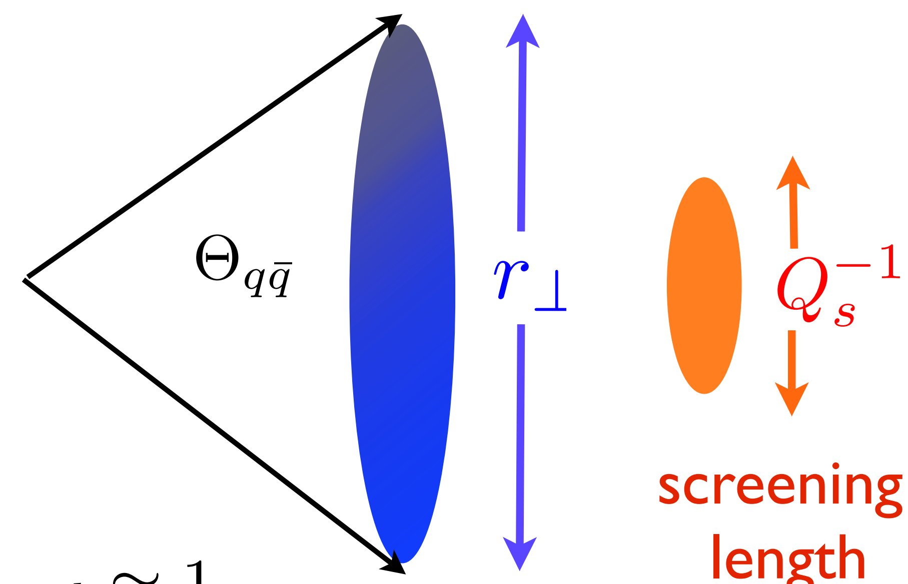
HARD SCALES FROM THE MEDIUM:

- $r_\perp < Q_s^{-1}$ (Dipole regime)



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

- $r_\perp > Q_s^{-1}$ (Decoh. regime)



$\Delta_{\rm med} \approx 1$

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

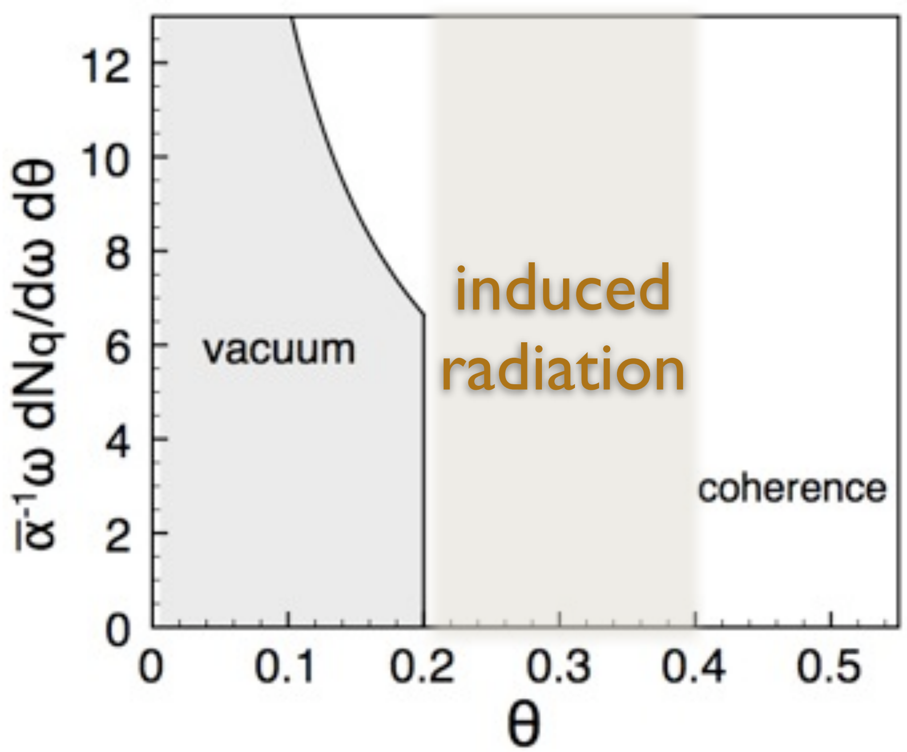
the decoherence parameter

$r_\perp = \theta_{q\bar{q}} L$

Qs: characteristic momentum scale of the medium

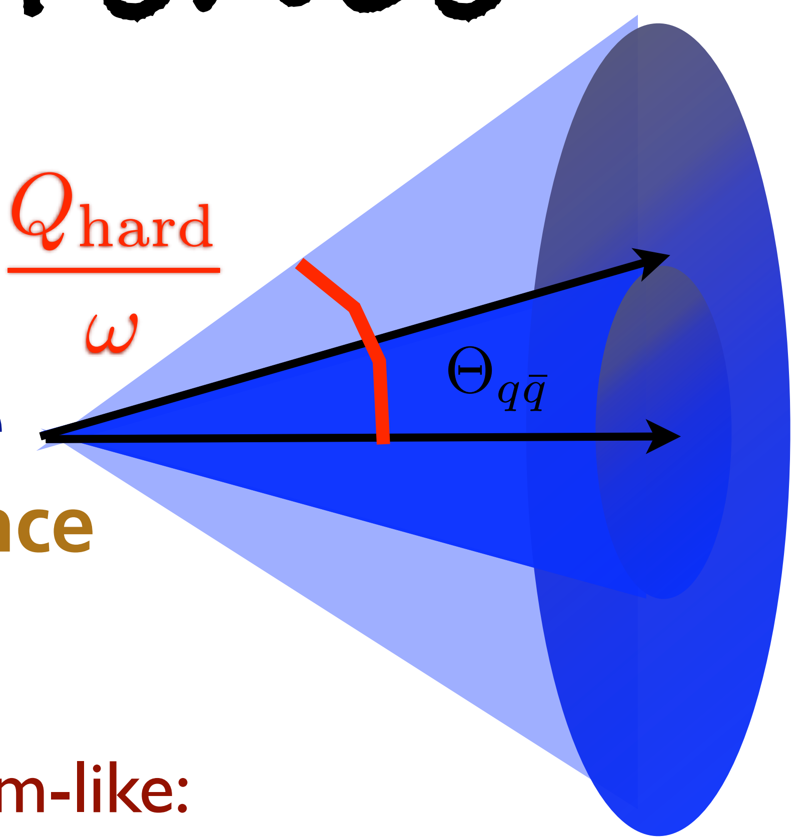
Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397
Casalderrrey-Solana, Iancu 1105.1760

Onset of decoherence



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

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



In ω→0 limit, only vacuum-like:

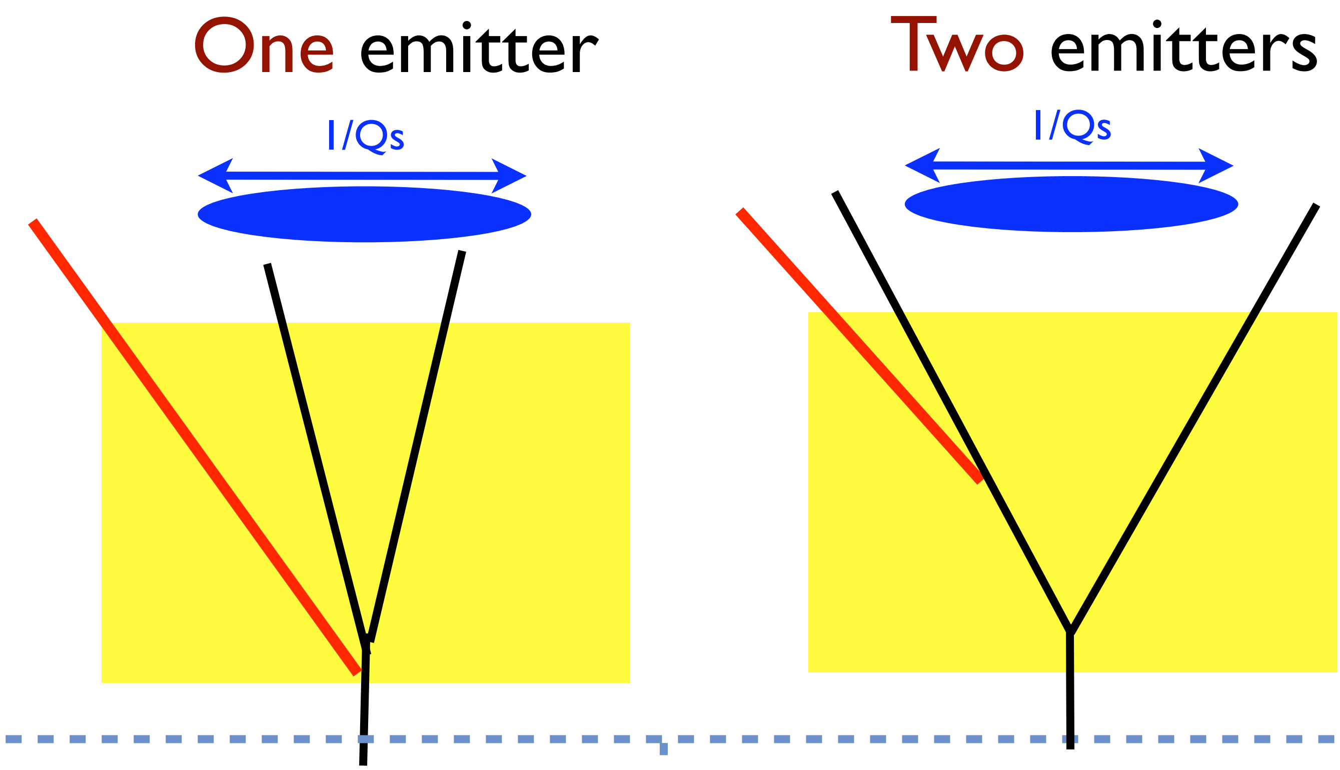
$$dN_q^{\rm tot} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\ d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right] .$$

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

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

- decoherence opens phase space at large angles $\theta_{max}=Q_{hard}/\omega$
- jet spectrum unmodified at small angles

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



vacuum coherence (at large angles)	weak AAO, $\propto \Delta_{med} < 1$	AO completely broken, radiation up to $k_\perp \sim Q_s$
"medium-induced"	radiation as total charge	radiation as independent charges

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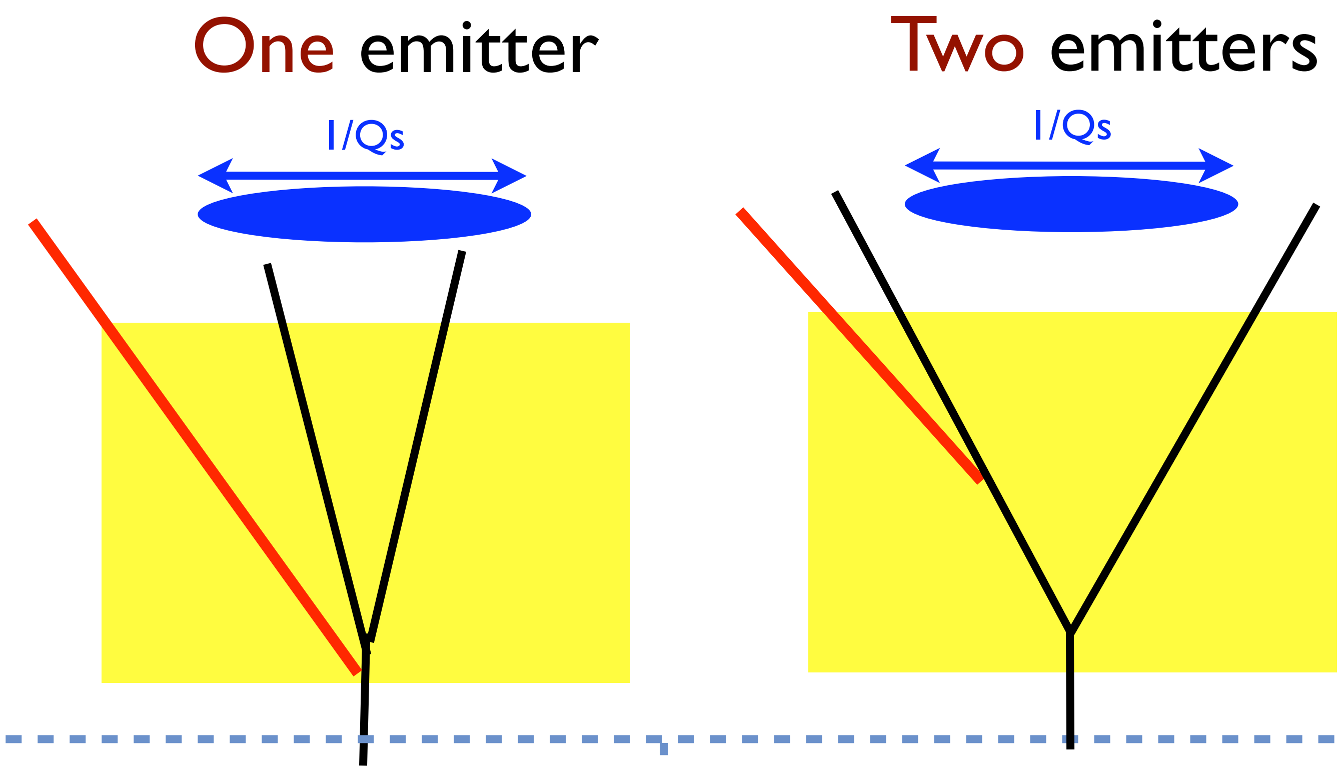


	One emitter	Two emitters
vacuum coherence (at large angles)	weak AAO, $\propto \Delta_{med} < 1$	AO completely broken, radiation up to $k_\perp \sim Q_s$
"medium-induced"	radiation as total charge	radiation as independent charges

→ importance of medium-resolved sub-jets!

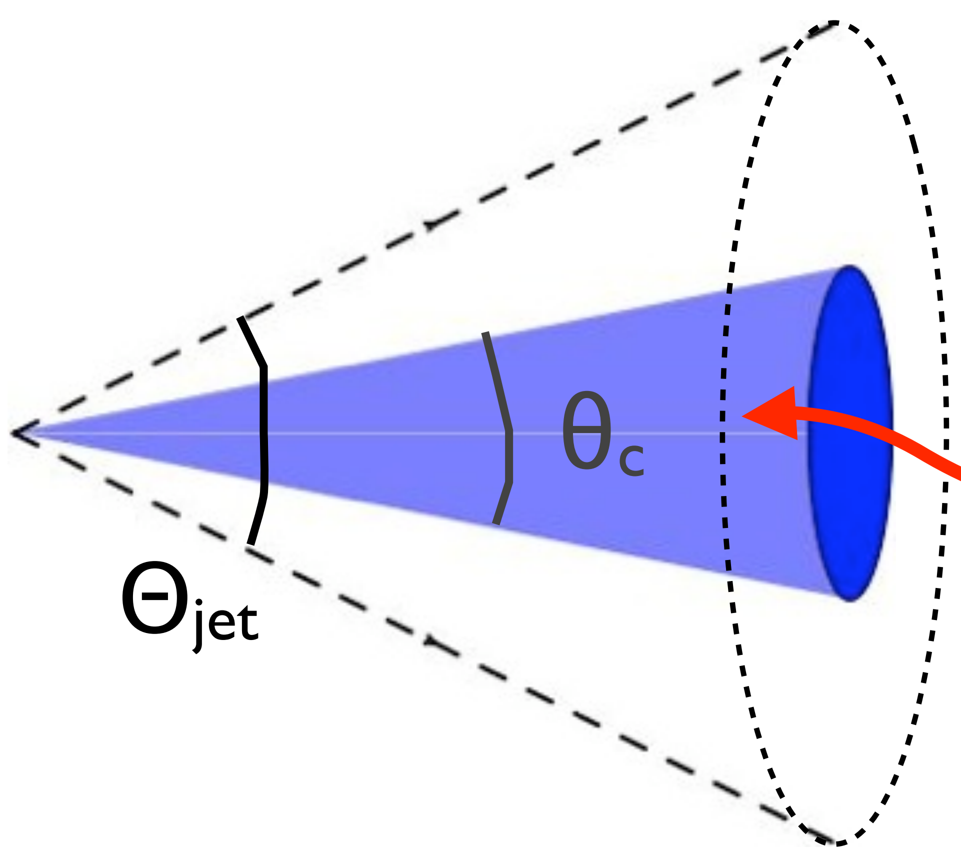
Resolving jet substructure

Generic scaling will involve the medium length L.

In terms of angles: $$\Delta_{\rm med} = 1 - e^{-\Theta_{\rm jet}^2/\theta_c^2}$$

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

jet definition (Θ_{jet}=R)!



Coherent inner 'core'

- branchings occurring inside the medium with $\theta < \theta_c$
- modes with $\lambda_\perp < Q_s^{-1}$ ($k_\perp > Q_s$)
- $t_f < L \rightarrow Q_s^2 L < \omega < E$
- the core loses energy coherently

In central collisions: $\Theta_{jet} > \theta_c$

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

Resolved effective charges

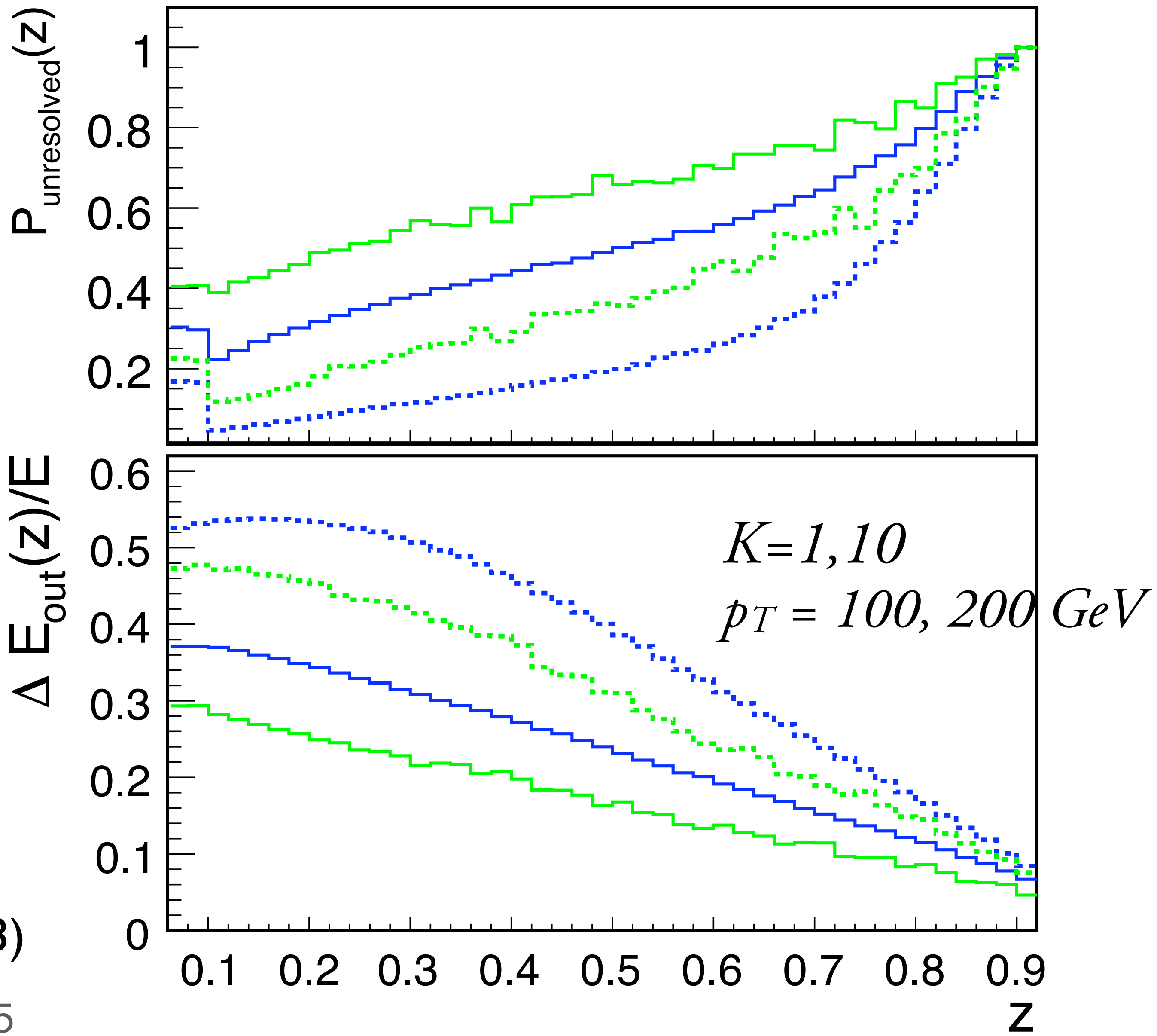
- study the magnitude of the medium resolution @ LHC
- substructure analysis with θ_c
- often we only have one effective fragment within R!
- contains most of the jet energy (jet core)

$$\hat{q}(\tau) = 2K\varepsilon^{3/4}(\tau)$$

PYTHIA 8.150 + 3D hydro + FastJet (anti-kt, R = 0.3)

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

Hydro from: T. Hirano, P. Huovinen, and Y. Nara, Phys.Rev. C84, 011901; Phys.Rev. C83, 021902



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

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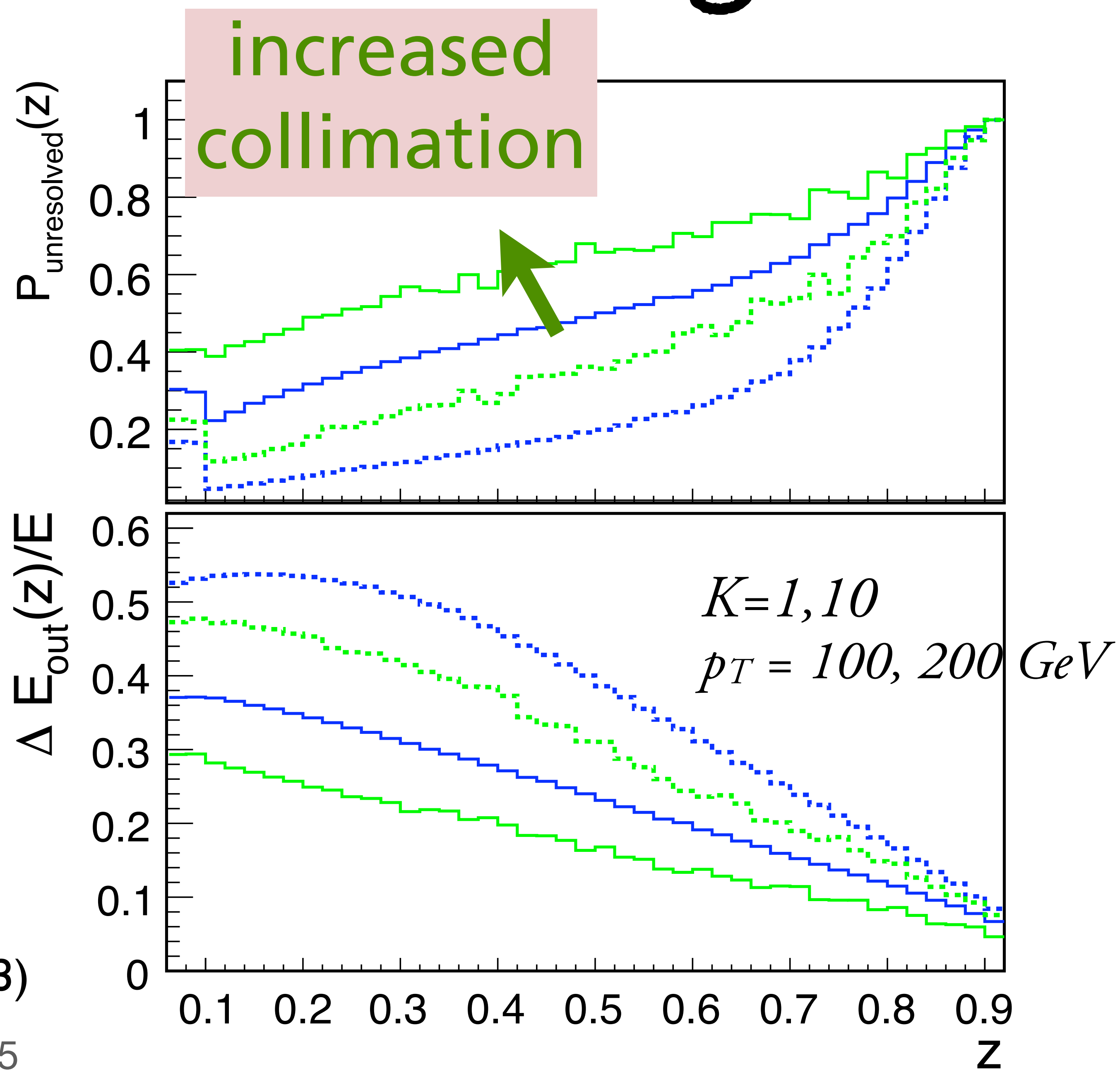

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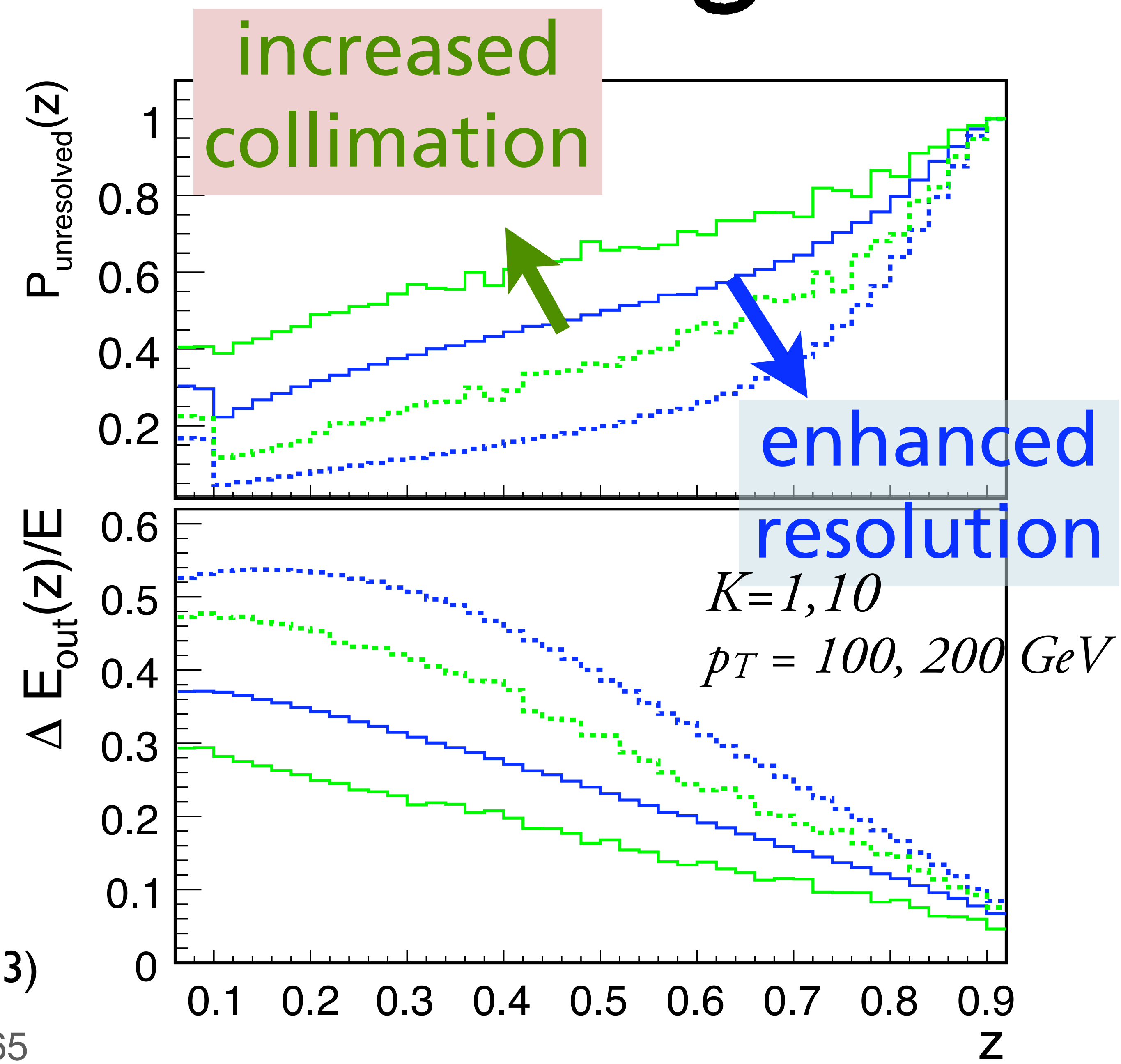

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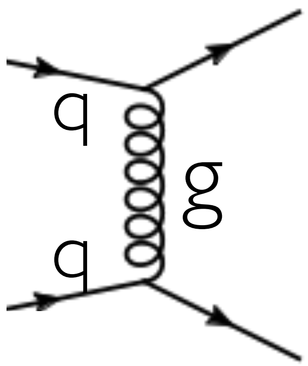
:: probability of only finding one leading subjet in the presence of a fragment with mom frac z

$\longrightarrow$ the objects interacting and radiating in the medium are really resolved subjets (multiparticle states) and not single partons...

Factorization of energy loss

Very often we have only a leading (unresolved) subjet that carries most of the momentum of the full jet :: color transparency.

A “factorization” for leading medium-resolved subjet:



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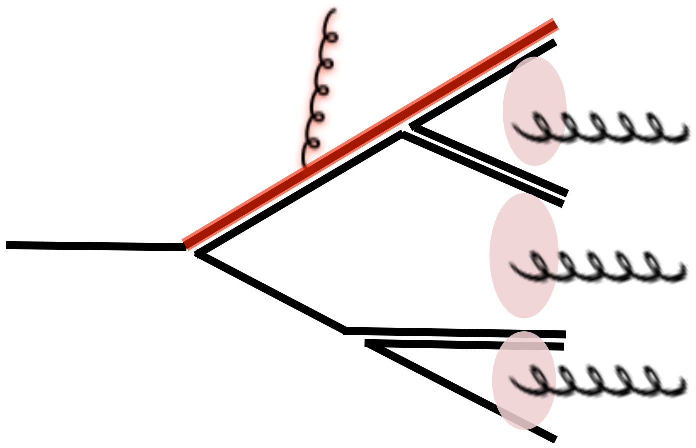

- separation in angles & separation in time :: only the total charge radiates
- allows to separate the treatment of the two different processes

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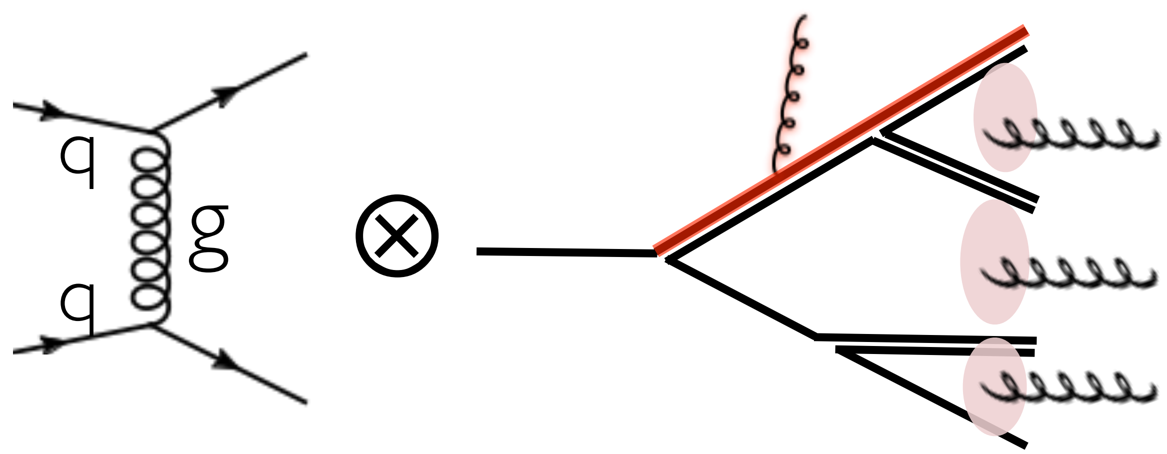


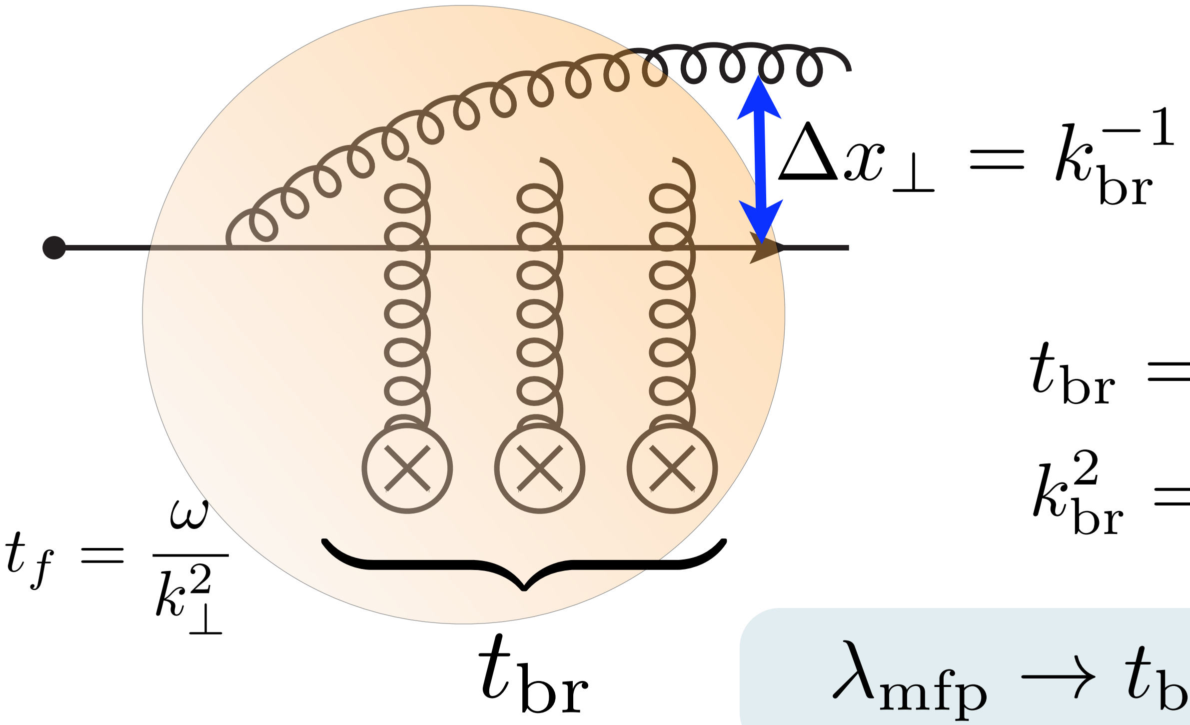
- separation in angles & separation in time :: only the total charge radiates
- allows to separate the treatment of the two different processes

jet produced with given p_T, $D_0(x) = \delta(1-x)$ $\Rightarrow$ *total charge/ancestor particle lose energy* $\Rightarrow$ vacuum showering (with reduced energy) starts

The 'quenching factor' for jets:

$$Q(p_\perp)^{\rm jet} = \int_0^1 dz\, D(z,\tau) \frac{d\sigma^{\rm jet,vac}(p_\perp/z)}{dp_\perp} \Bigg/ \frac{d\sigma^{\rm jet,vac}(p_\perp)}{dp_\perp}$$

Induced radiation



Decoherence :: the virtual gluon fluctuates until it reaches the size $\Delta x_\perp^2 \sim (\tilde{q}\Delta t)^{-1}$ where it can be resolved by the medium.

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

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

Bethe-Heitler regime

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

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

Factorization regime

$$t_{\rm br} \sim L$$

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

LPM regime

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

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

The rate-equation

Multiple emission regime

- independent emission
- possible in large media
- very soft radiation at large angles!

$$\omega_{\rm BH} \ll \omega \ll \bar{\alpha}^2 \omega_c$$

$$\theta \gg \theta_{\rm br} \equiv \left(\hat{q}/\omega^3\right)^{1/4}$$

Blaizot, Dominguez, Iancu, Mehtar-Tani 1209.4585

$$\frac{\partial}{\partial \tau} D(x,\tau) = \int_{\mathcal{C}} dz\, \mathcal{F}(z,x;\tau) \left[\sqrt{\frac{z}{x}} D\left(\frac{z}{x},\tau\right) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

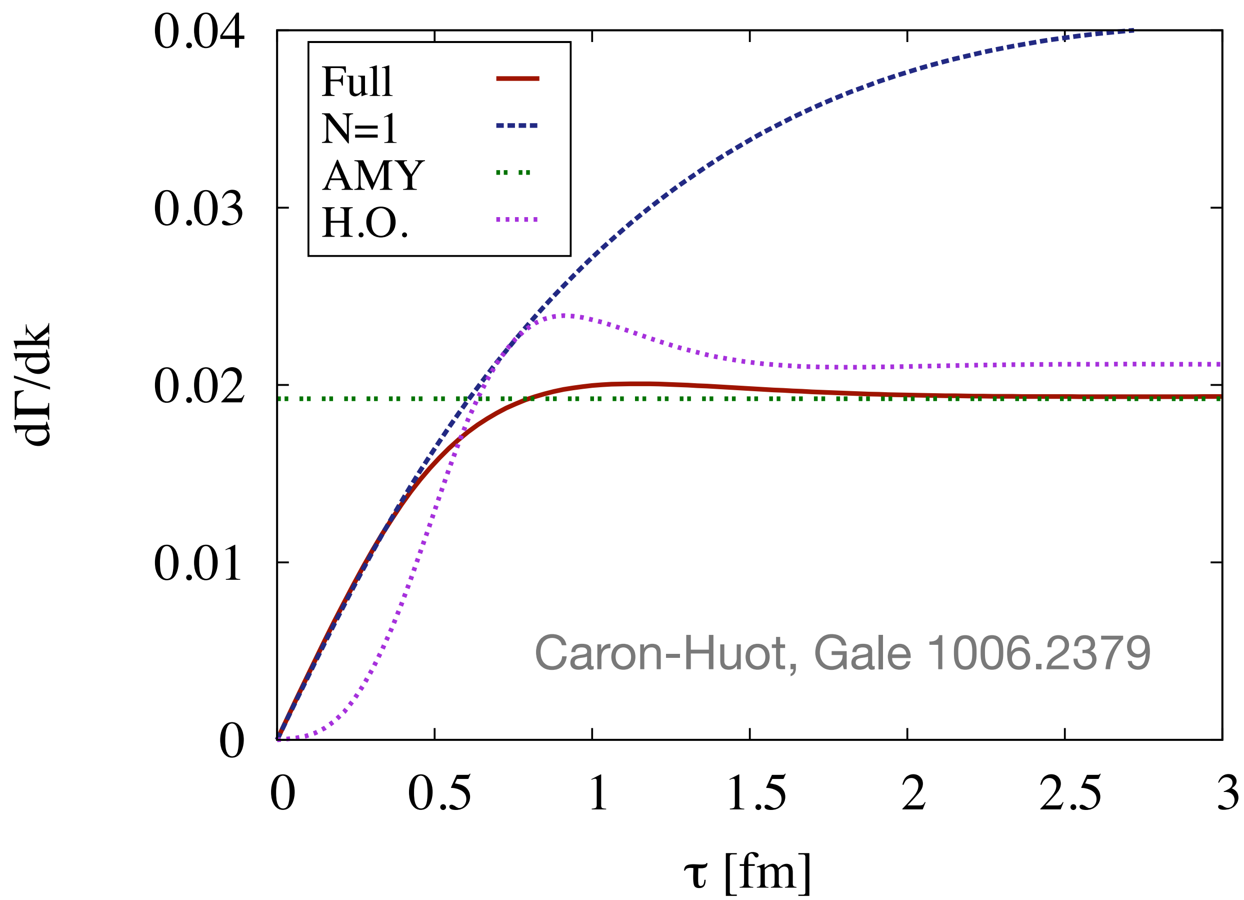
Jeon, Moore hep-ph/0309332
Baier, Mueller, Schiff, Son hep-ph/0009237
Blaizot, Iancu, Mehtar-Tani 1301.6102

$$\tau = \bar{\alpha} \sqrt{\frac{\omega_c}{E}}$$

- keeps track of the leading + all the fragments
- probabilistic interpretation
- turbulent flow: no intrinsic accumulation of energy
- spectrum is self-replicating :: scaling

Analytical solution (infinite length): $$D_0(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} e^{-\pi \frac{\tau^2}{1-x}}$$

Finite-size effects



- including finite-size effects in the 'harmonic oscillator' approximation
- could be improved by including the full rate or interpolate between N=1 and HO

$$z\frac{dI^{\rm ind}}{dz} = \frac{\alpha_s}{2\pi} z P_{gg}(z) \,\ln \left| \cos(1+i)\sqrt{\frac{\hat{q}_{\rm eff}L^2}{z(1-z)p^+}} \right| \quad \Rightarrow \quad z\frac{dI^{\rm ind}}{dz\,dL}$$

$$k_{\rm br}^2 = \sqrt{z(1-z)p_0^+\hat{q}_{\rm eff}} \qquad \hat{q}_{\rm eff} = \hat{q}\left[(1-z)N_c - zC_R\right]$$

Regularization

$$\frac{d^2\mathcal{P}}{dz\,d\tau} = \frac{1}{2}\frac{\mathcal{F}(z,x;\tau)}{\sqrt{x}}$$

$$x_c = \omega_c/p_0^+ \qquad \tau \equiv \bar{\alpha}\sqrt{2x_c}$$

$$\mathcal{F}(z,x;\tau) = \tilde{P}_{gg}(z)\mathcal{K}(z)\frac{\sinh\sigma(z,x;\tau) - \sin\sigma(z,x;\tau)}{\cosh\sigma(z,x;\tau) + \cos\sigma(z,x;\tau)}$$

$$\sigma(z,x;\tau) = \frac{\mathcal{K}(z)}{\bar{\alpha}\sqrt{x}}\tau$$

$$\tilde{P}_{gg}(z) = \frac{\left(1 - z(1-z)\right)^2}{[z(1-z)]_{\epsilon_1}}$$

$$\mathcal{K}(z) = \sqrt{\frac{1 - z(1-z)}{[z(1-z)]_{\epsilon_2}}}$$

$$t_{\rm br} \sim \lambda_{\rm mfp} \Rightarrow \omega_{\rm BH} = \lambda_{\rm mfp}^2 \hat{q}$$
$$\sim m_D^2 \lambda_{\rm mfp}$$

$$k_\perp \sim k_{\rm br} < \omega$$
$$\Downarrow$$
$$\omega < \hat{q}^{1/3}$$

$$\lambda_{\rm mfp} > 1/m_D \Rightarrow \omega_{\rm BH} > \hat{q}^{1/3}$$

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$$\Downarrow$$

$$\omega < \hat{q}^{1/3}$$

$$\lambda_{\rm mfp} > 1/m_D \Rightarrow \omega_{\rm BH} > \hat{q}^{1/3}$$

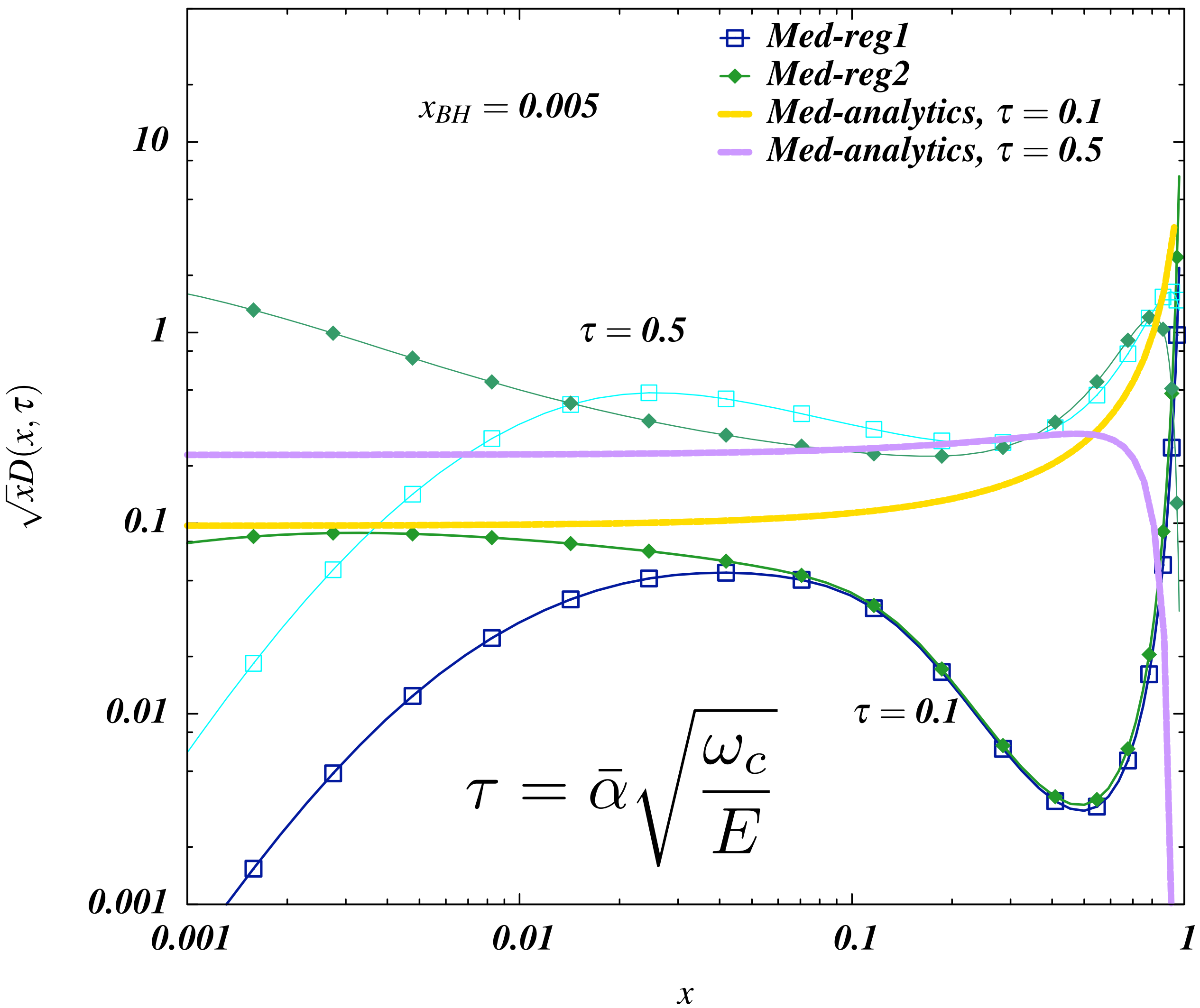
reg1: $$\frac{1}{(1-z)_\epsilon} = \frac{\xi(\xi-x)}{(\xi - x + x_{\rm BH})^2}$$ 'strong'

reg2: $$\frac{1}{(1-z)_\epsilon} = \frac{\xi}{\xi - x + x_{\rm BH}}$$ 'smooth'

$$x_{\rm BH} = \omega_{\rm BH}/E$$
$$\xi = x/z$$

→ apply it only to the medium $\mathcal{K}$

Evolution equation



Blaizot, Iancu, Mehtar-Tani 1301.6102
[...work in progress]

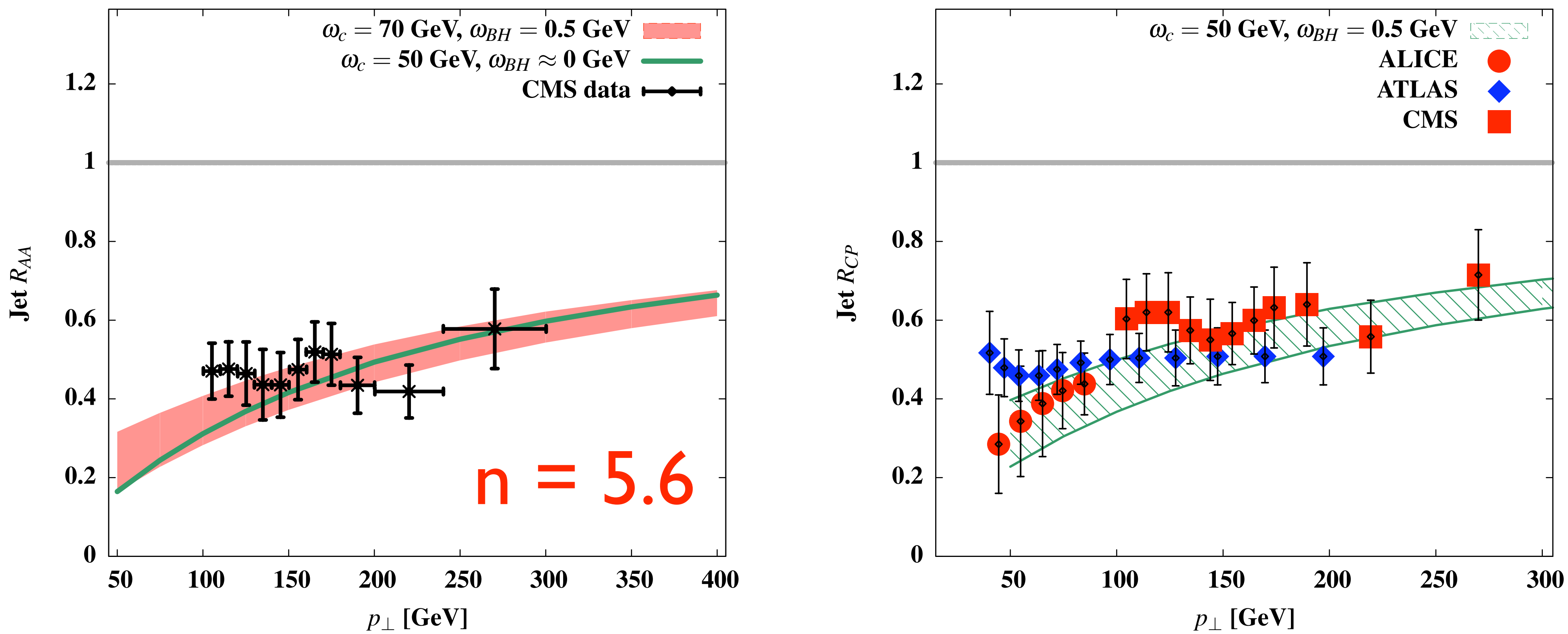
- rapid depletion of leading probe into soft fragments
- finite-size and regularization play a significant role
- slows down the evolution
- important for phenomenological analysis

Analytical solution (infinite length):

$$D_0(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} e^{-\pi \frac{\tau^2}{1-x}}$$

Jet suppression

Calculating quenching factor for "leading sub-jet"



- sensitivity to regularization prescription
- low-p_T sensitive to sub-leading resolved subjets
- baseline: need more realistic collision geometry

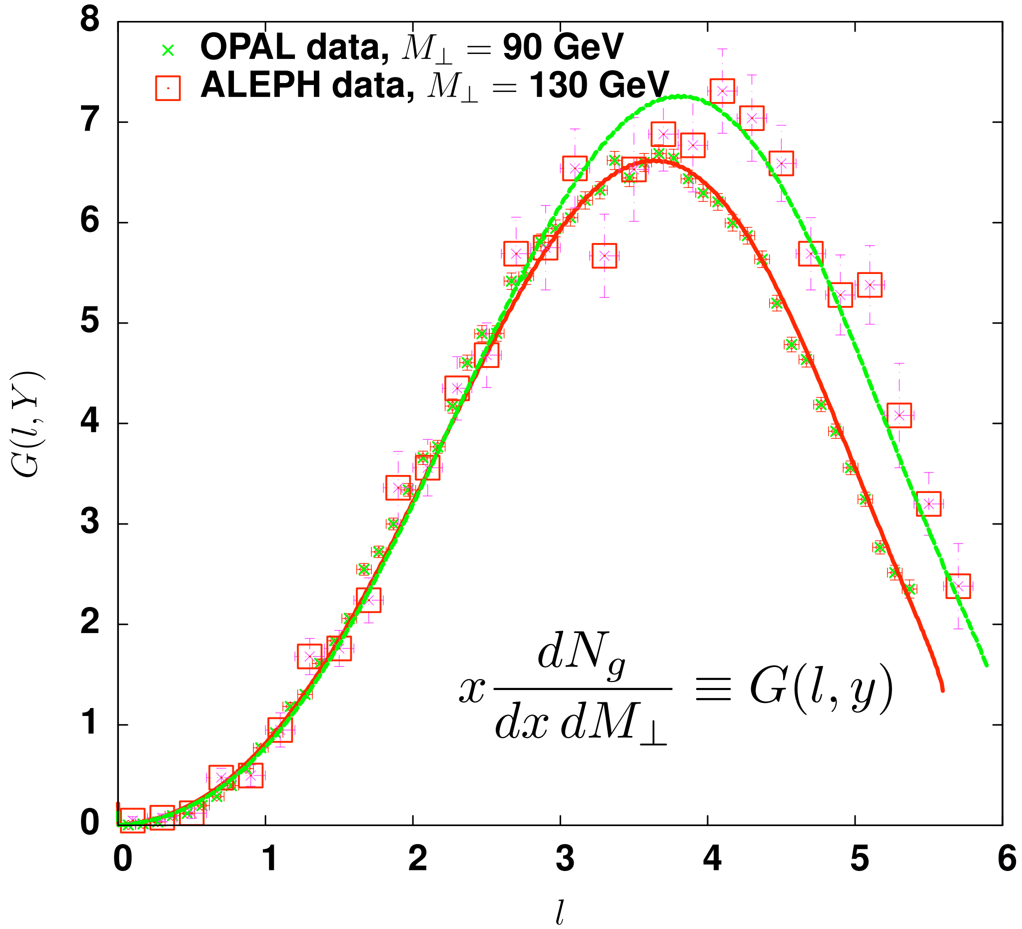
$$\omega_c = 70 \text{ GeV}$$
$$L \sim 4 \text{ fm}$$
$$\hat{q} \sim 1 - 2 \frac{\text{GeV}^2}{\text{fm}}$$

MLLA evolution

$$G(l,y) = \delta(l) + \int_0^l dl' \int_0^y dy' \gamma_0^2(l'+y')\big[1 - a\delta(l-l')\big]G(l',y')$$

$$l = \ln\left(1/x\right) \qquad y = \ln\left(xM_\perp/Q_0\right) \equiv Y - l$$

$$\gamma_0(\alpha_s) = \sqrt{2N_c\alpha_s/\pi}$$



Dokshitzer, Khoze, Mueller, Troyan “Basics of pQCD”
Ramos hep-ph/0605083

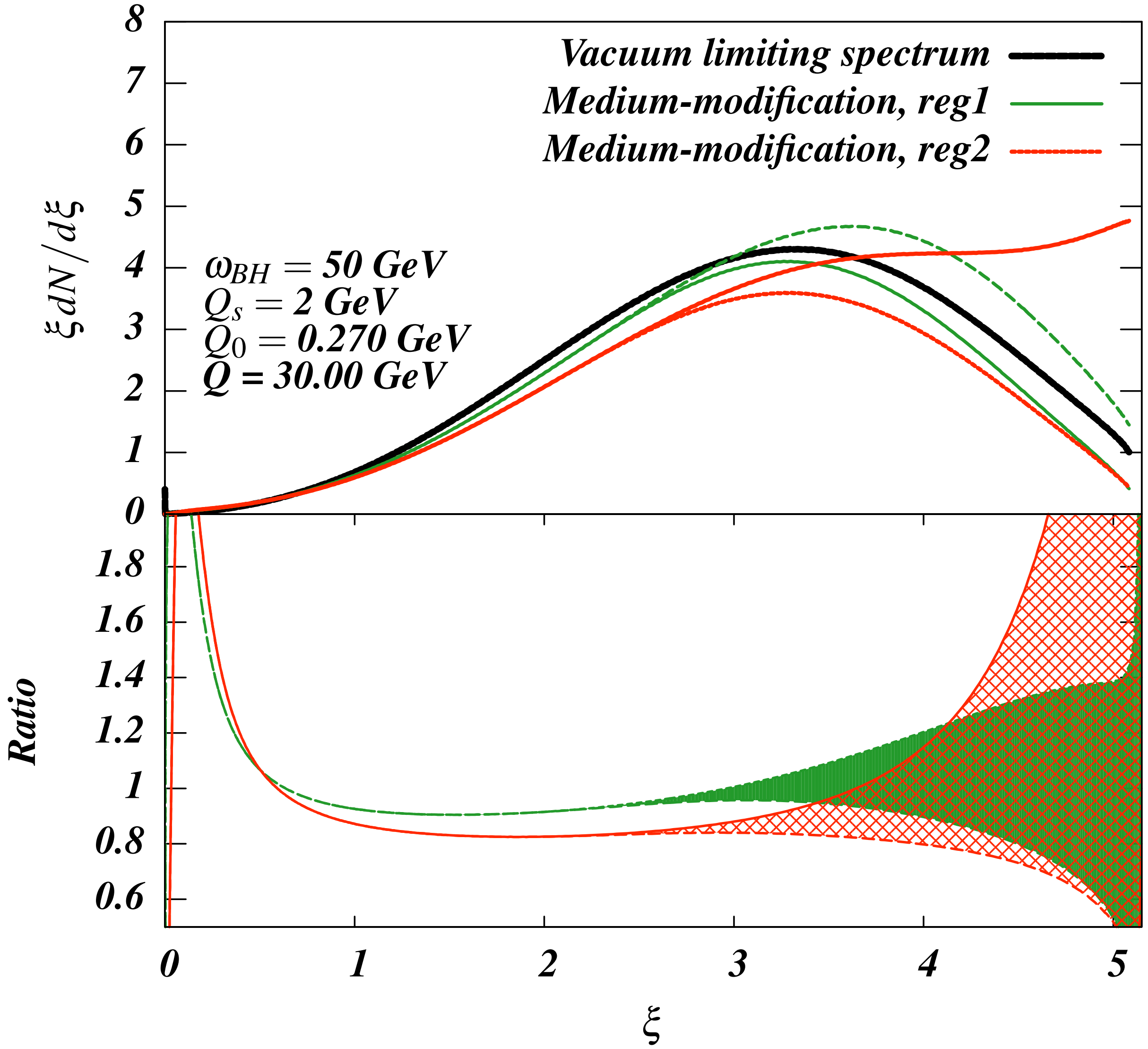
- LPHD (K factor)
- including mass effect: $E_h = \sqrt{p_h^2 + m_h^2}$
- good description of e^+e^- data
- iterative procedure (α_s=const):

$$G^{(0)}(l,y) = \delta(l)$$ :: initial condition

$$G^{(1)}(l,y) = \gamma_0^2 y\left[1 - a\delta(l)\right]$$

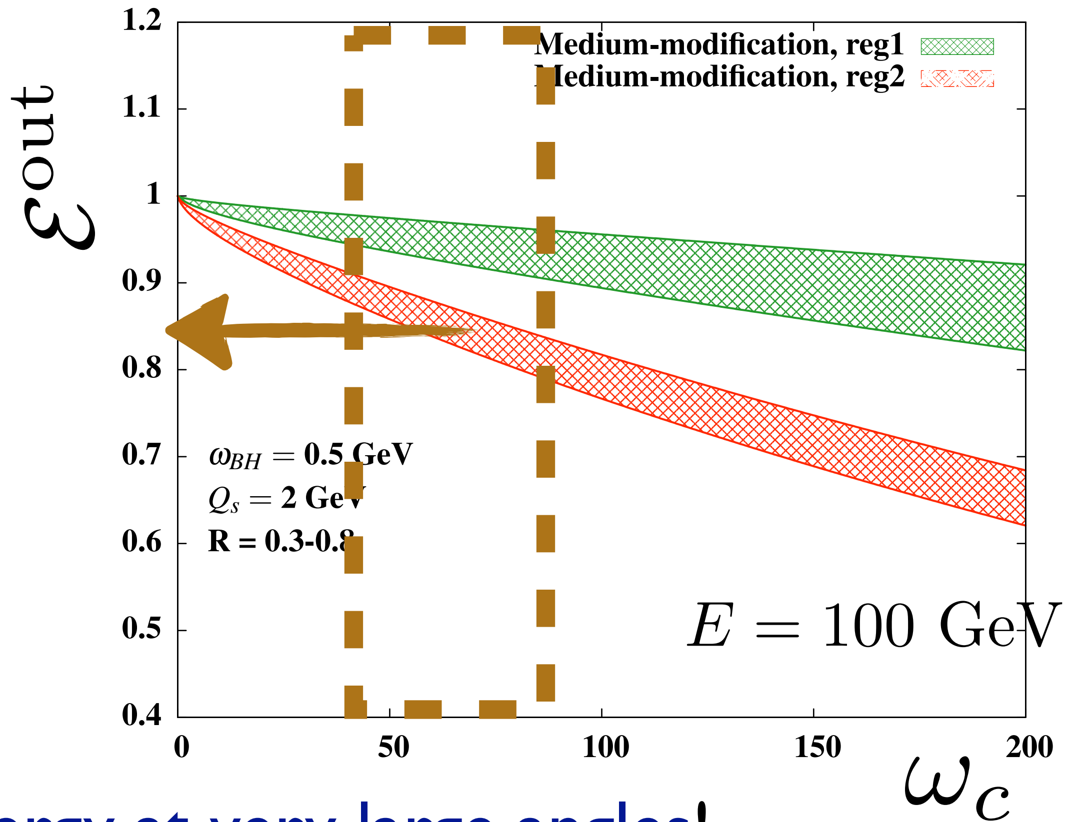
$$G^{(2)}(l,y) = \gamma_0^2 y\left[\frac{1}{2}\gamma_0^2 ly - a\gamma_0^2 y + a^2\delta(l)\right]$$

Broadening effect



$$D(x, \theta < \Theta_{jet}) = \int^{\Theta_{jet}} \frac{d^2\boldsymbol{k}}{(2\pi)^2} \mathcal{P}(\boldsymbol{k})\, D(x)\,,$$

$$\theta \lesssim \theta_c \qquad = \left[1 - \exp\left(-\frac{x^2 M_T^2}{Q_s^2}\right)\right] D(x)$$



- strong sensitivity in the soft sector
- broadening a powerful effect: missing energy at very large angles!

Antiangular component

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

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

DLA accuracy (a=0) :: affects only 2nd emission

Estimating the phase space for AAO emission:

$$\int_{\Gamma_{\rm med}} \frac{dz}{z}\frac{d\theta'}{\theta'} = \int_{\Gamma_{\rm vac}} \frac{dz}{z}\frac{d\theta'}{\theta'} + \Delta_{\rm med}\int_x^{\frac{Q_{\rm hard}}{M_\perp}} \frac{dz}{z}\int_{\Theta_{\rm jet}}^{\frac{Q_{\rm hard}}{xE}} \frac{d\theta'}{\theta'}$$

$$l_{\rm max} = \log\frac{Q_{\rm hard}}{xM_\perp} = \lambda_2 - Y + l$$

$$y_{\rm max} = \log\frac{Q_{\rm hard}}{Q_0} = \lambda_2$$

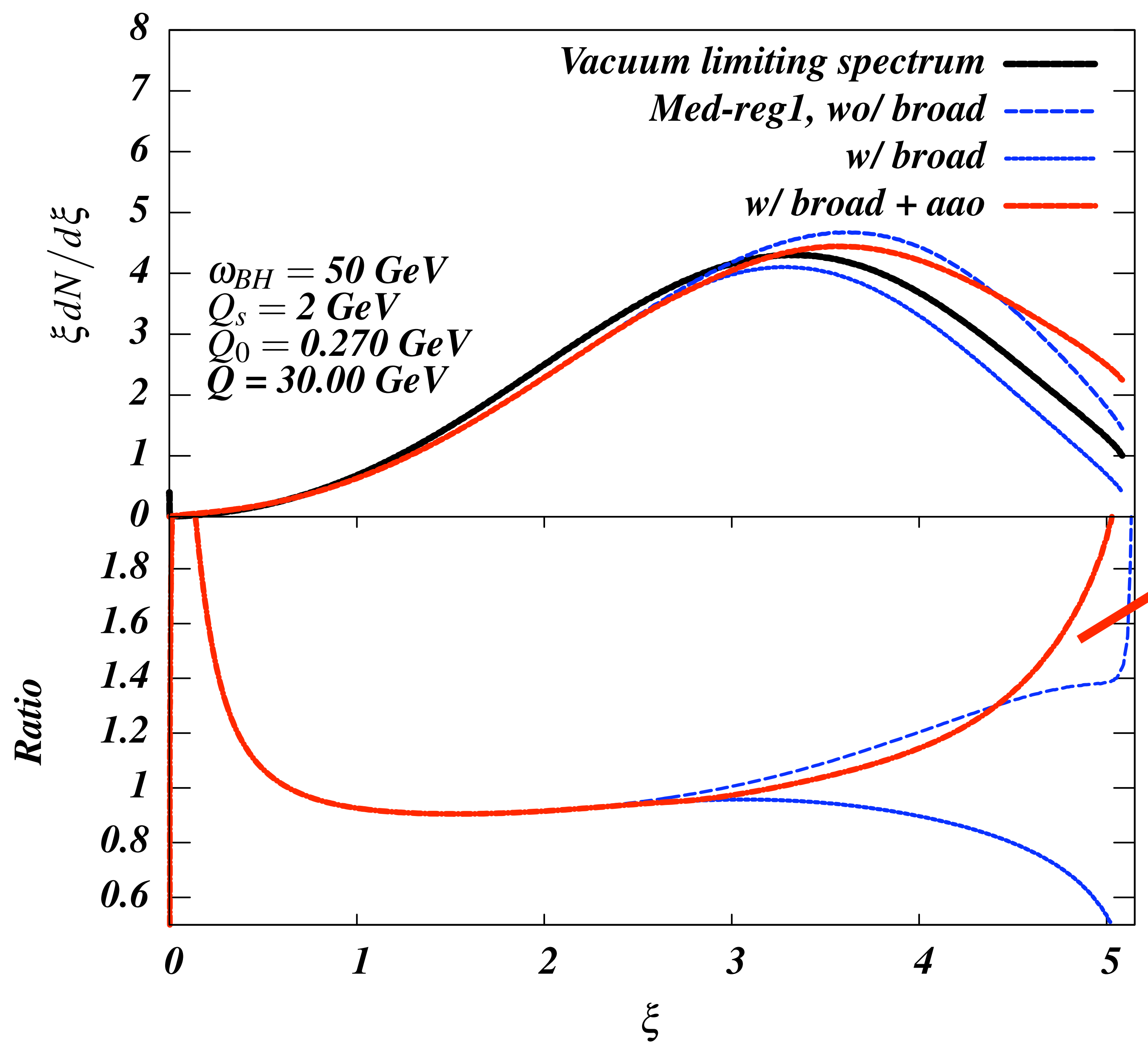
$$y_{\rm min} = \log\frac{xE\theta_0}{Q_0} = Y - l$$

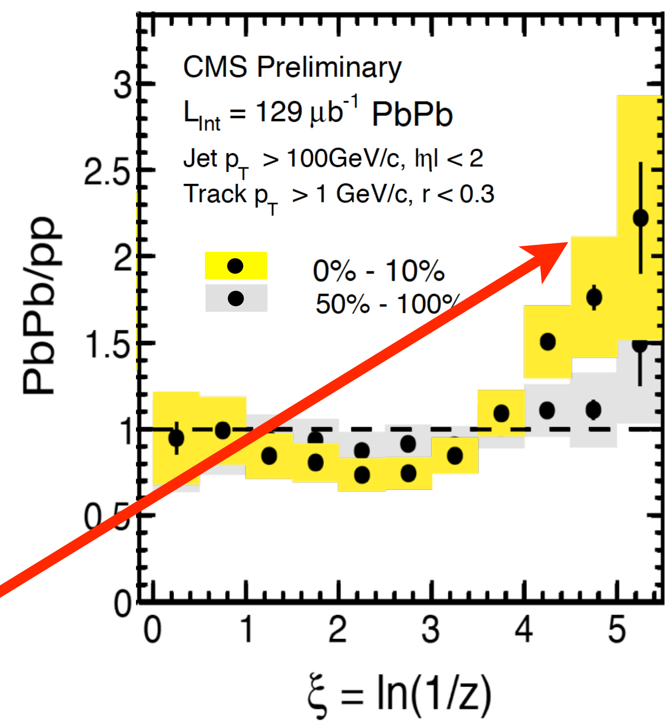
$$G^{(2)}(l,y)\Big|_{a=0} = G^{(2)}_{\rm vac}(l,y)\Big|_{a=0} + \frac{1}{2}\overbrace{\Delta_{\rm med}\gamma_0^4}^{\text{constants}}(l+\lambda_2 - Y)(\lambda_2^2 - (Y-l)^2)\,,$$

↳ allows to continue resumming the vacuum emissions!

Full modification

CMS-PAS-HIN-12-013

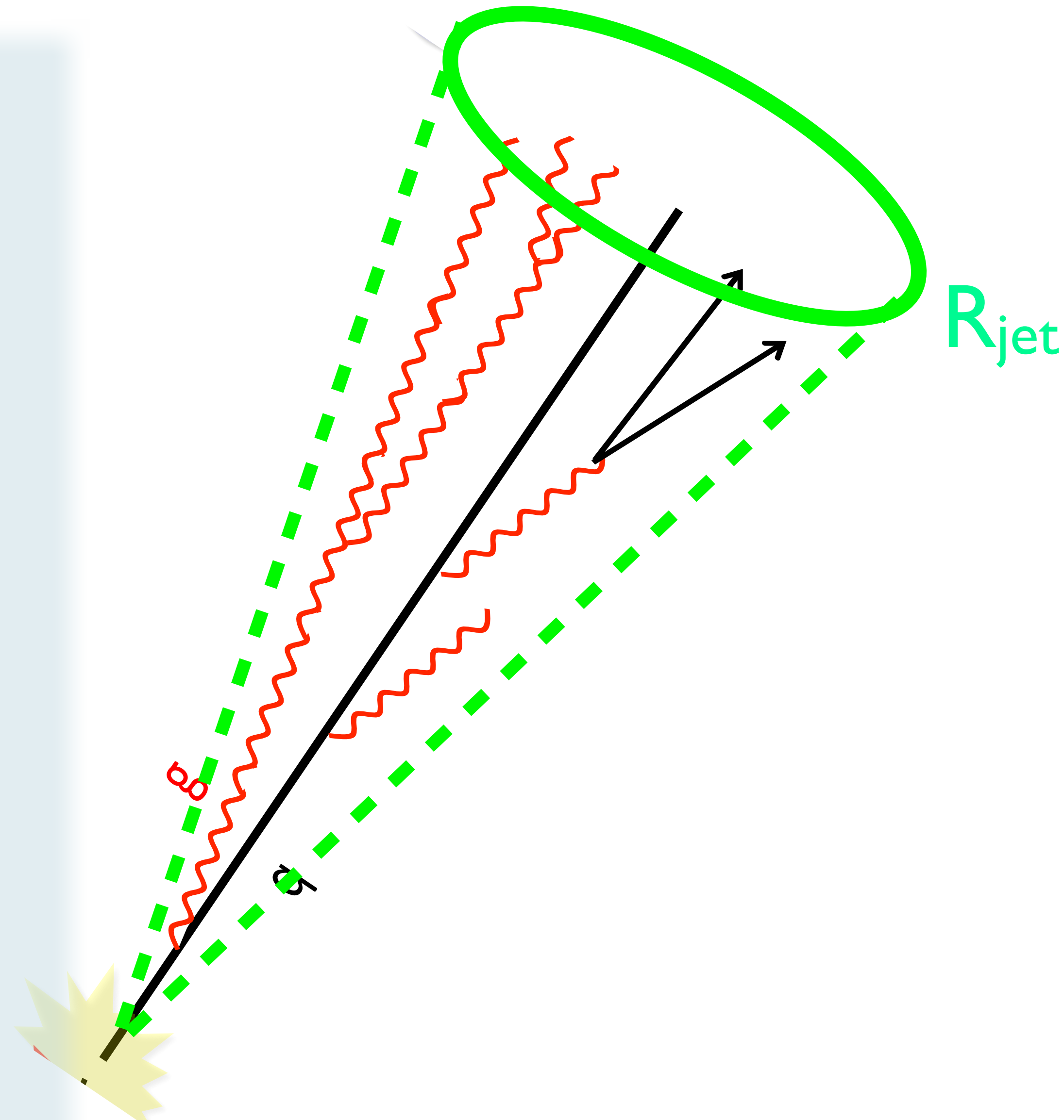




- AAO valid for soft gluons with long formation times → add them on top of modified spectrum
- low-x enhancement inside the cone is delicate :: not sensitive to resolution scales
- sensitive to the decoherence parameter (in reality a dynamic quantity)

Summary

- three observables (inclusive jet suppression, modification of the fragmentation function, out-of-cone energy) constrain mechanisms of "jet quenching"
- color transparency :: resolved subjets
- decoherent radiation inside the jet cone :: a crucial component
- induced large-angle radiation + broadening :: transport out of cone
- good understanding of the data



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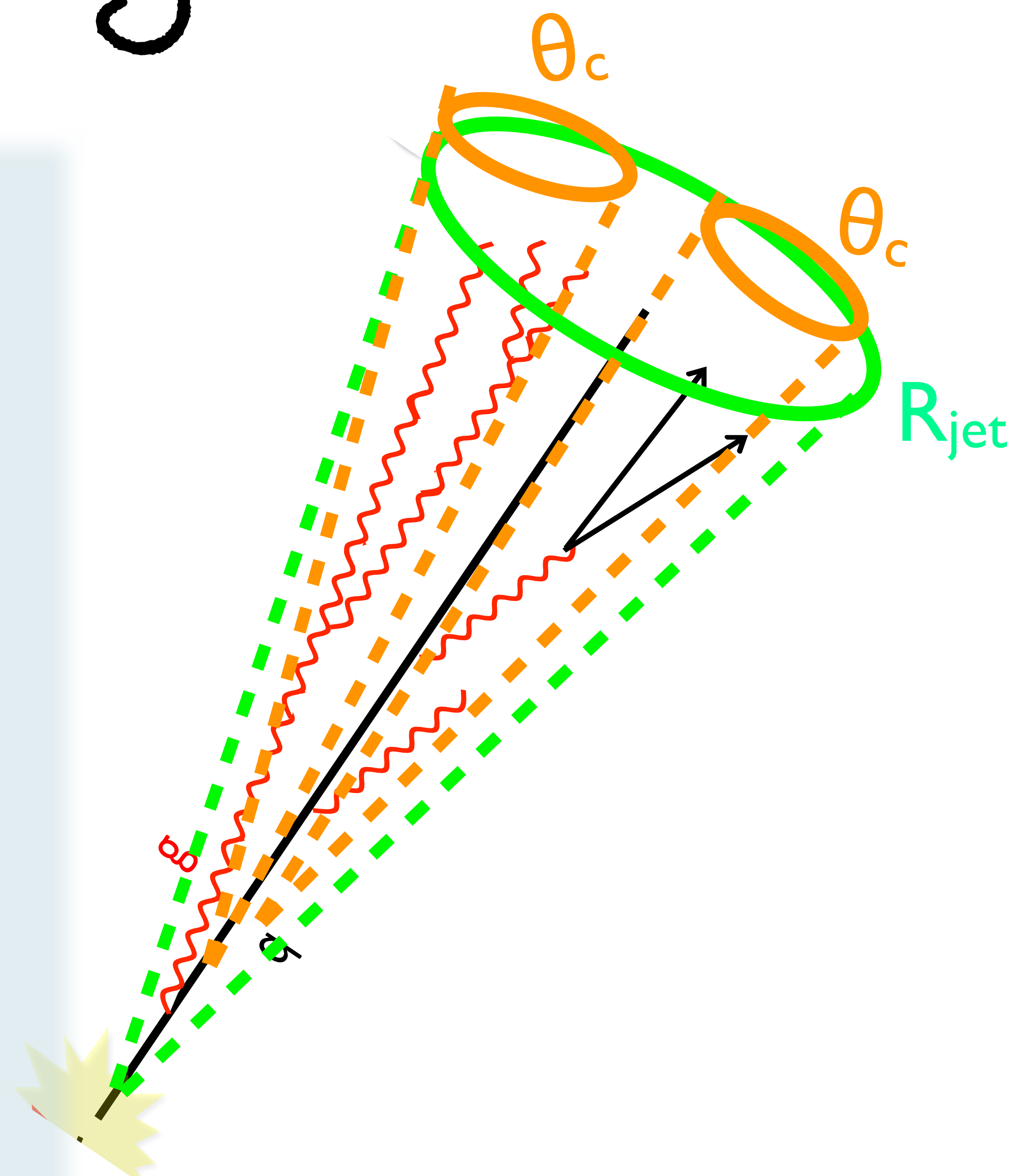

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Resolved effective charges