UNIVERSITAT DE BARCELONA

New picture of jet quenching dictated by color coherence

Konrad Tywoniuk

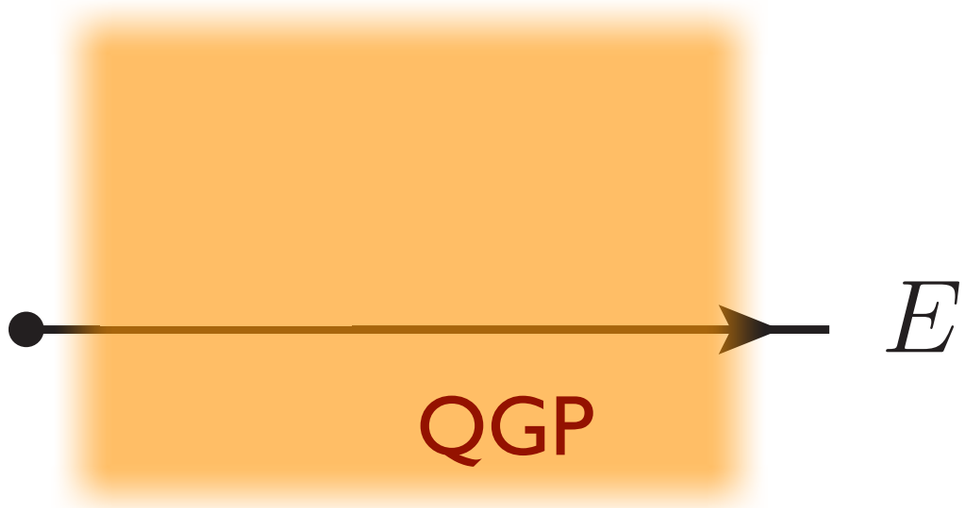
Work done in collaboration with: Y. Mehtar-Tani, C.A. Salgado, J. Casalderrey-Solana

Partikeldagarna 2012, Stockholm 26-27 November 2012

Hard probes in the medium

Induced radiation carry an imprint of the medium characteristics.

Hard probes in the medium



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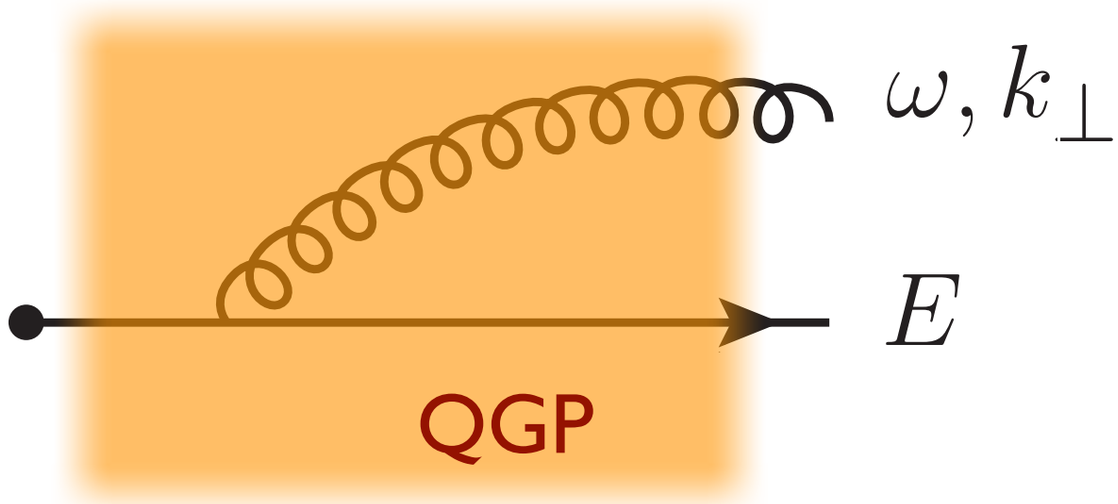

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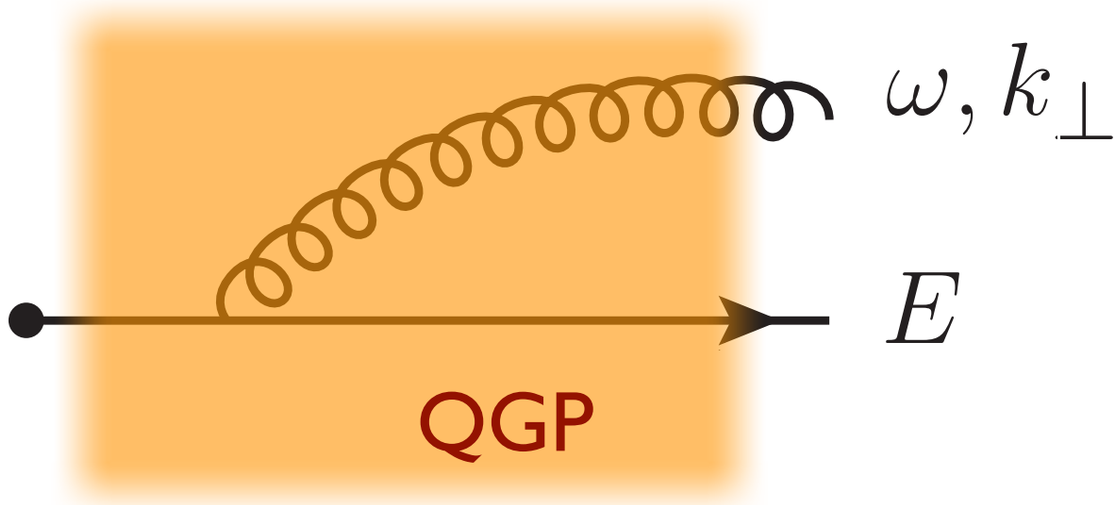

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$\Rightarrow$ one-gluon spectrum (BDMPS-Z, GLV, HT,...)

- inclusive observables
- energy loss of particle

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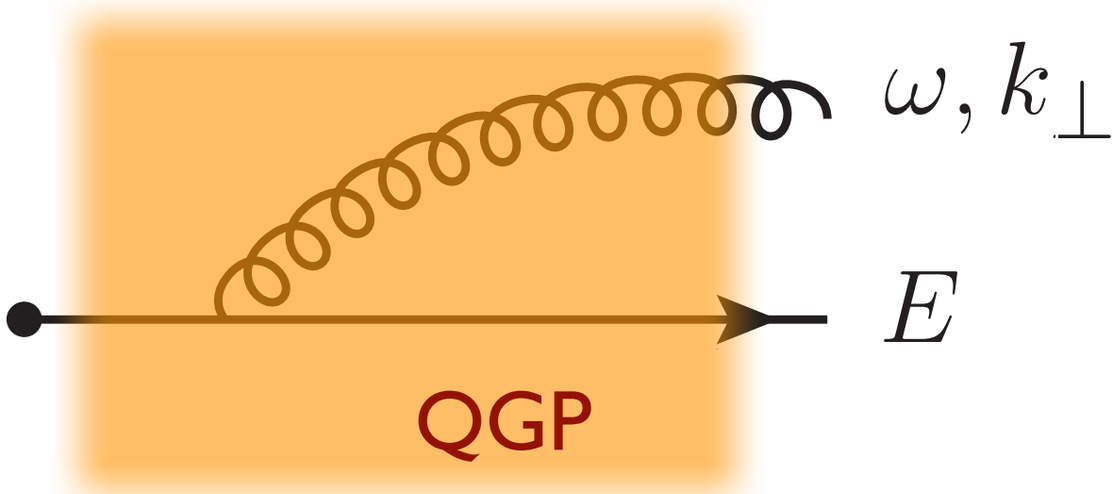

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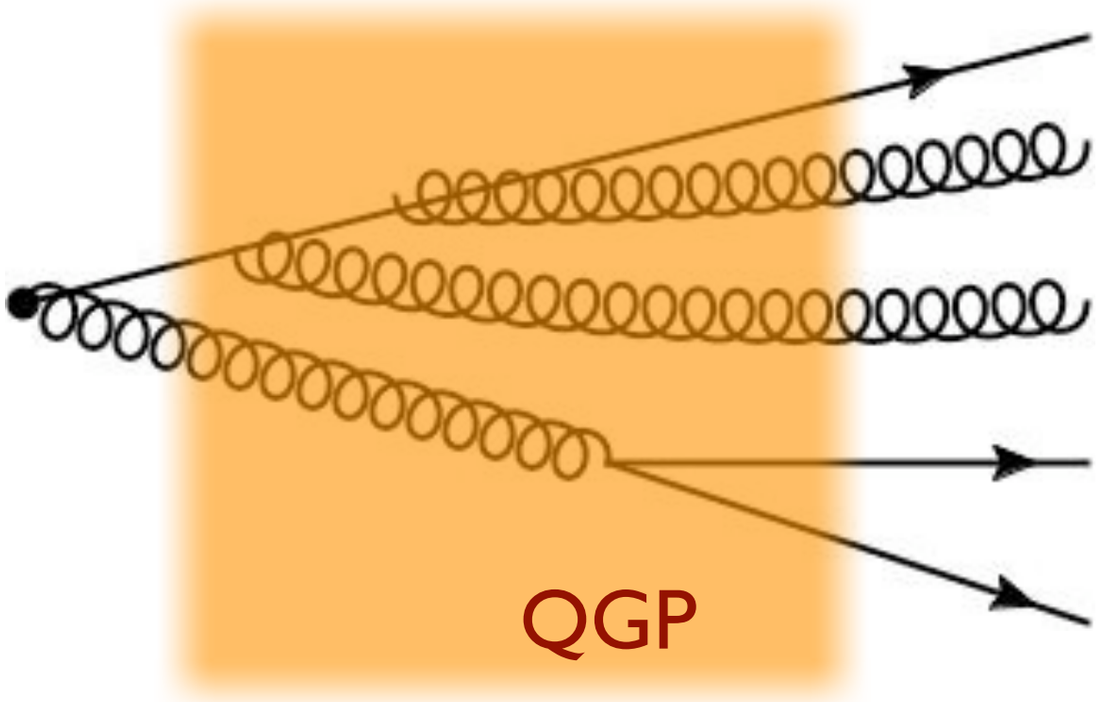
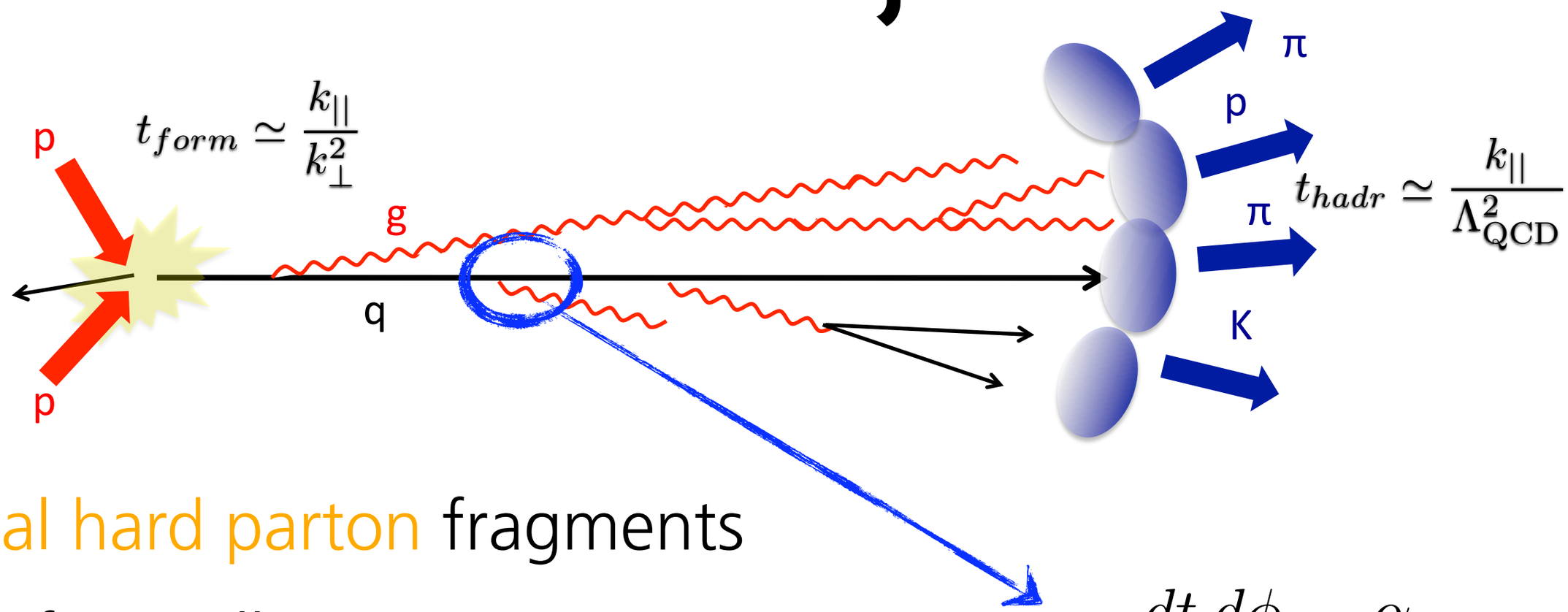


$\Rightarrow$? (working models)

- exclusive observables
- jet substructure

What is a jet?



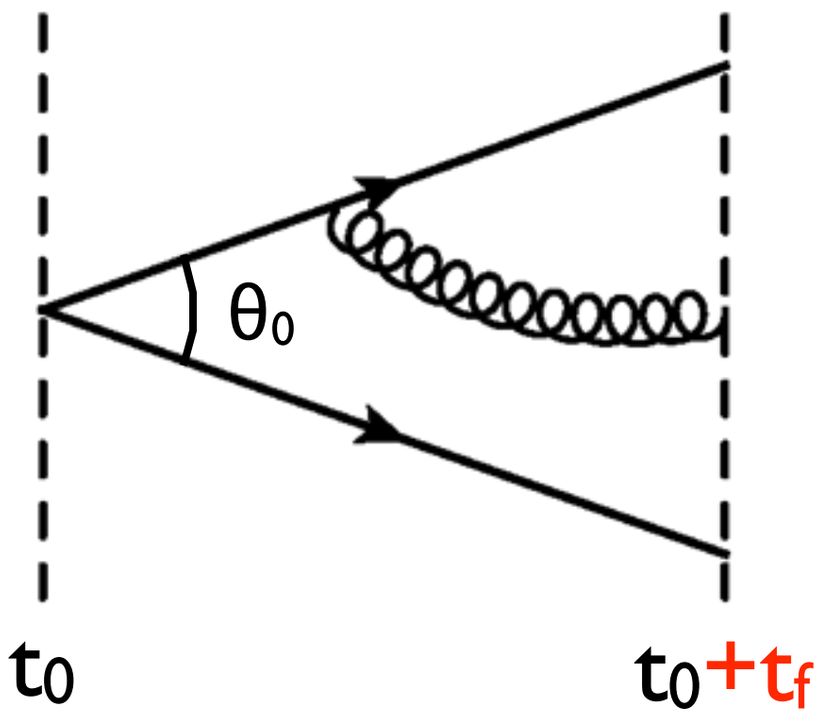
- virtual hard parton fragments
  - soft & collinear
- LPHD: hadronization does not affect inclusive observables

LL: $$d\sigma_{n+1} = d\sigma_n \, \frac{dt}{t} \frac{d\phi}{2\pi} dz \, \frac{\alpha_s}{2\pi} P(z)$$

$$t = z(1-z) E_a^2 \theta^2$$

Large time domain for pQCD: $$\frac{1}{\sqrt{s}} < t < \frac{\sqrt{s}}{\Lambda_{\rm QCD}^2}$$

A step in the evolution



$$\lambda_\perp \sim \frac{1}{k_\perp} = \frac{1}{\omega\theta}$$

$$r_\perp \sim \theta_0 t_f = \frac{\theta_0}{\omega\theta^2}$$

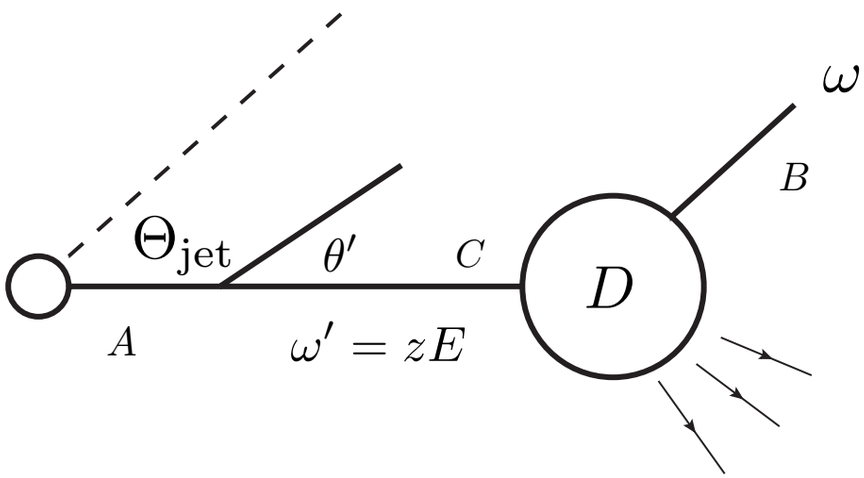
- antenna grows during the formation time of the gluon
- $\lambda_\perp \ll r_\perp$: gluon resolves the charges of antenna legs
- $\lambda_\perp \gg r_\perp$: gluon resolves the total charge (0 if color singlet)

$$\lambda_\perp < r_\perp \rightarrow \theta < \theta_0$$

$$k_\perp < zQ$$

Angular ordering condition!

Coherent parton evolution



Jet scale: $Q = E\Theta_{\rm jet}$

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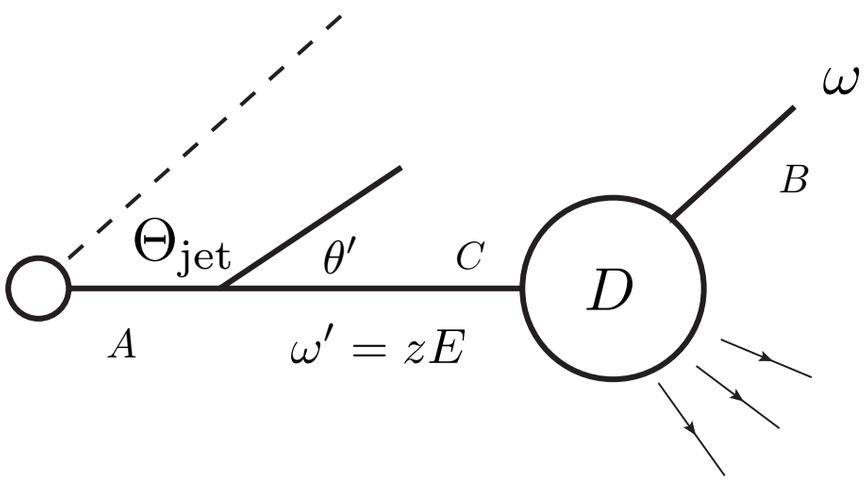

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$$\frac{d}{d\log Q} D_A^B(x,Q) = \frac{\alpha_s}{2\pi}\int_x^1 dz P_{+A}^C(z)\, D_C^B(x/z, zQ)$$

$$Q' = \omega'\theta' \sim \omega'\Theta_{\rm jet} = zQ$$ → effective scale

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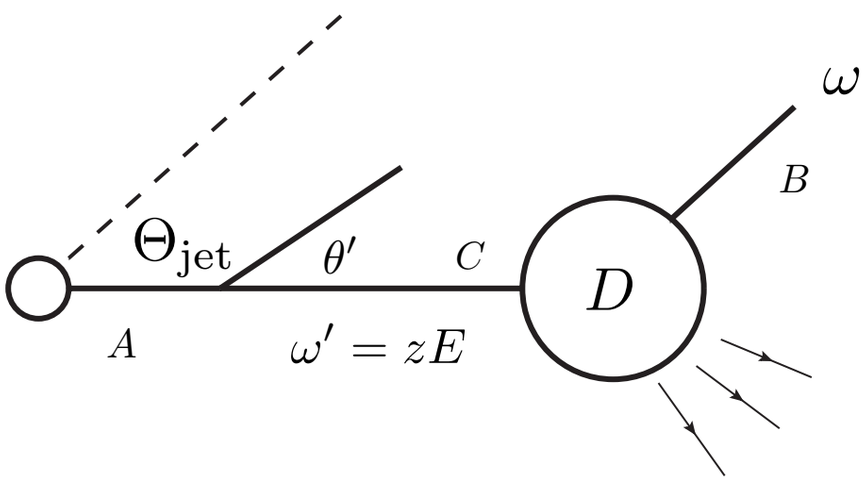

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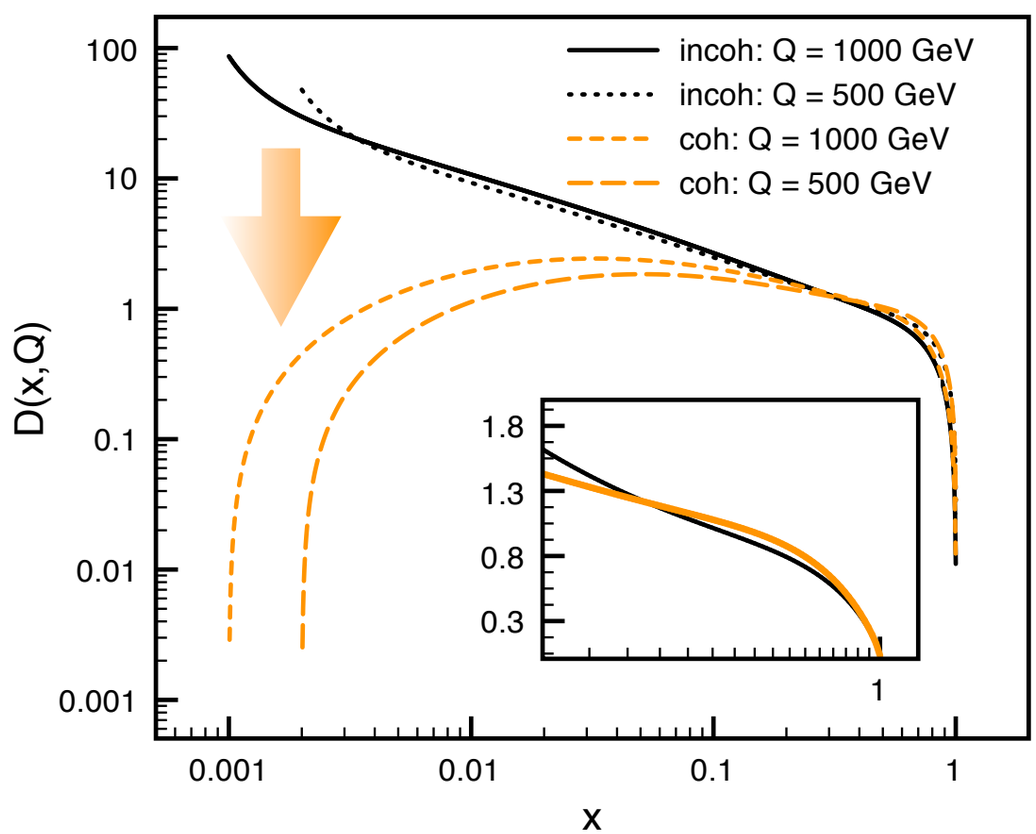
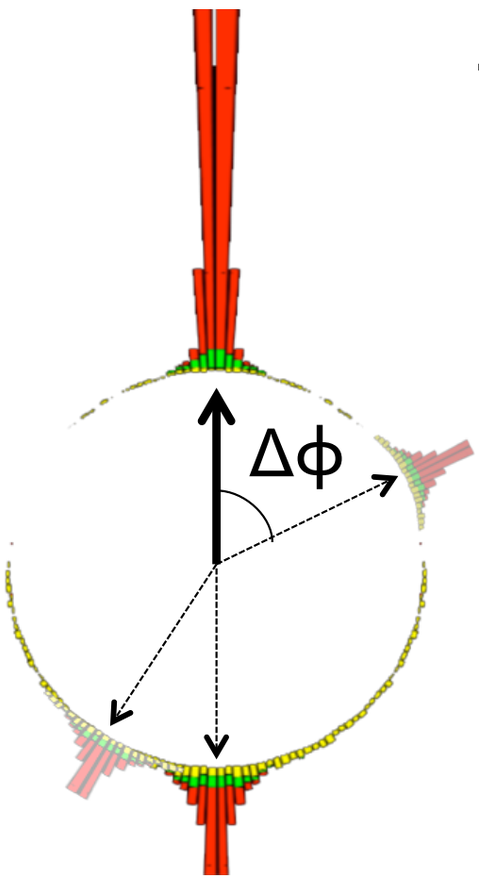
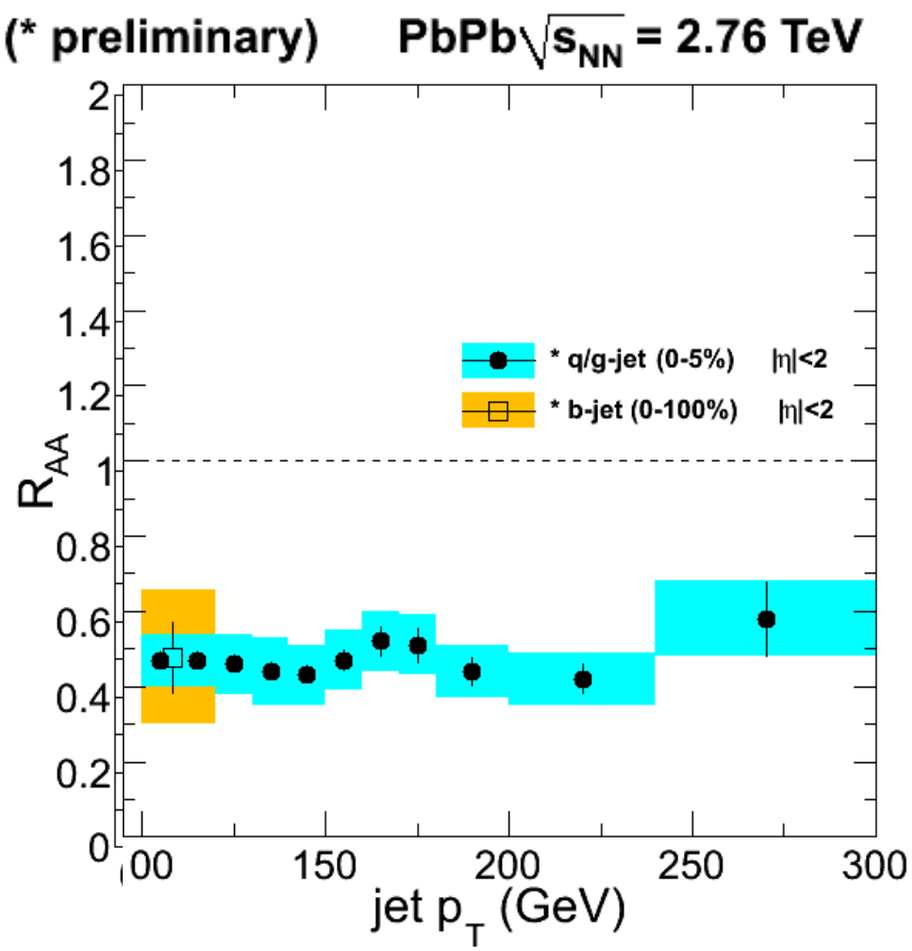


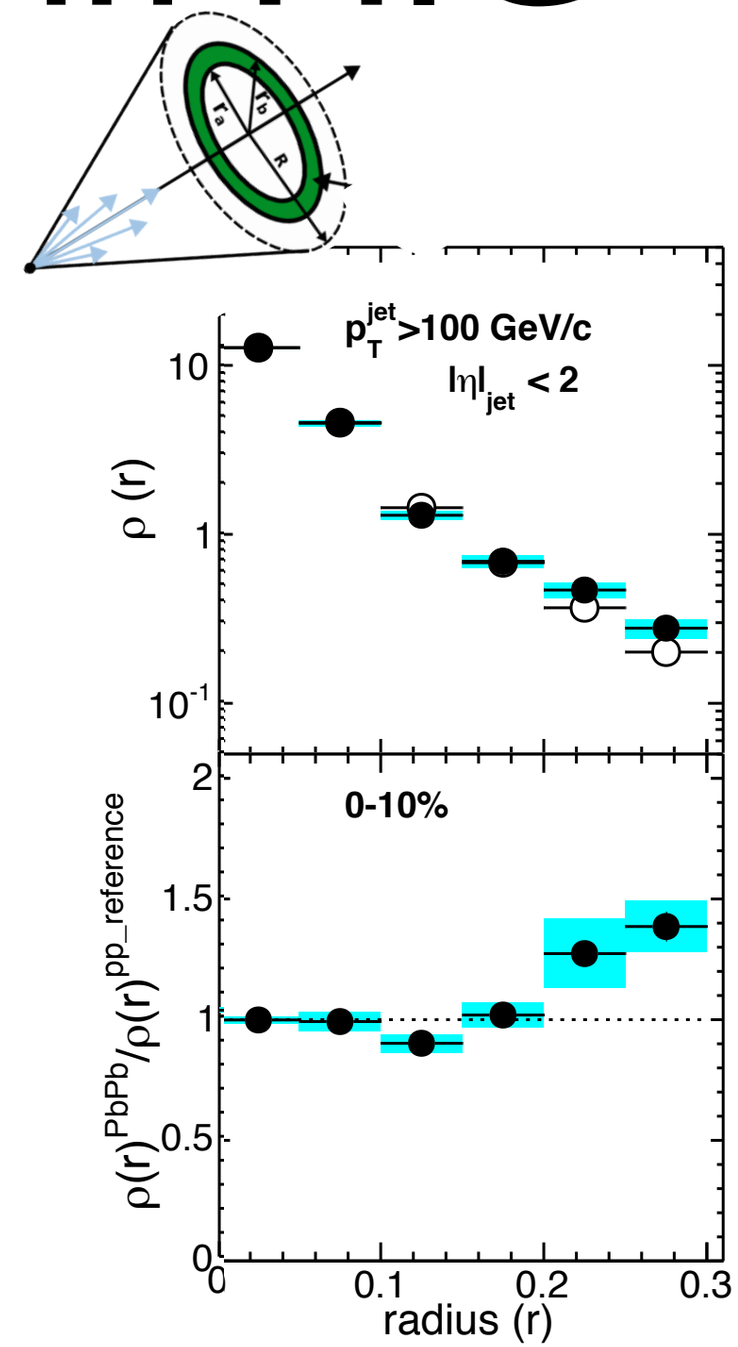
- suppression of soft particles at large angles
- basis for precision pQCD
- jet is a well-calibrated probe!

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

Jet modification in HIC







- significant jet suppression
- back-to-back kinematics
- modifications of intra-jet particle distribution on the edges of the jet

[CMS Coll. arXiv:1202.5022, HIN-12-013]

In the deconfined medium

Radiative processes

- induced radiation
- absorptive reactions

Elastic processes

- momentum broadening
- drag effects

Can we get a handle on each/one separately?

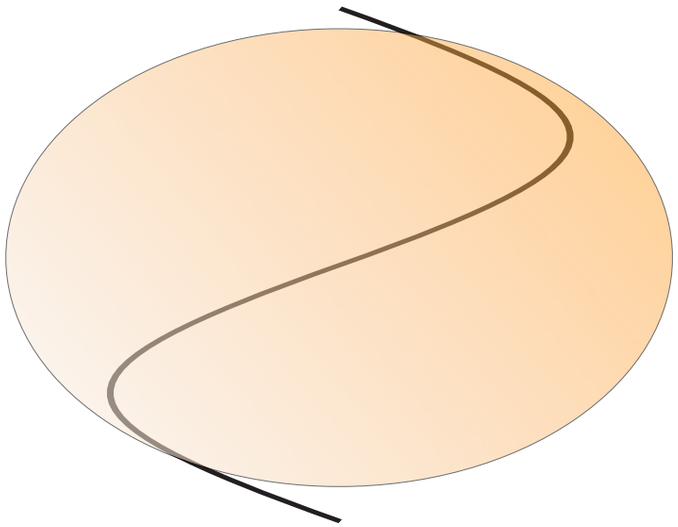
Identify the typical momentum & time scales:

vacuum ⇔ medium

quantum ⇔ classical

[pQCD] [Boltzman eq., ...]

A new scale in medium



How is the medium resolved

- medium fluctuates with typical transverse wave length Q_s^{-1}
- zero color on average, $\lambda > Q_s^{-1}$
- resolved by $\lambda < Q_s^{-1}$

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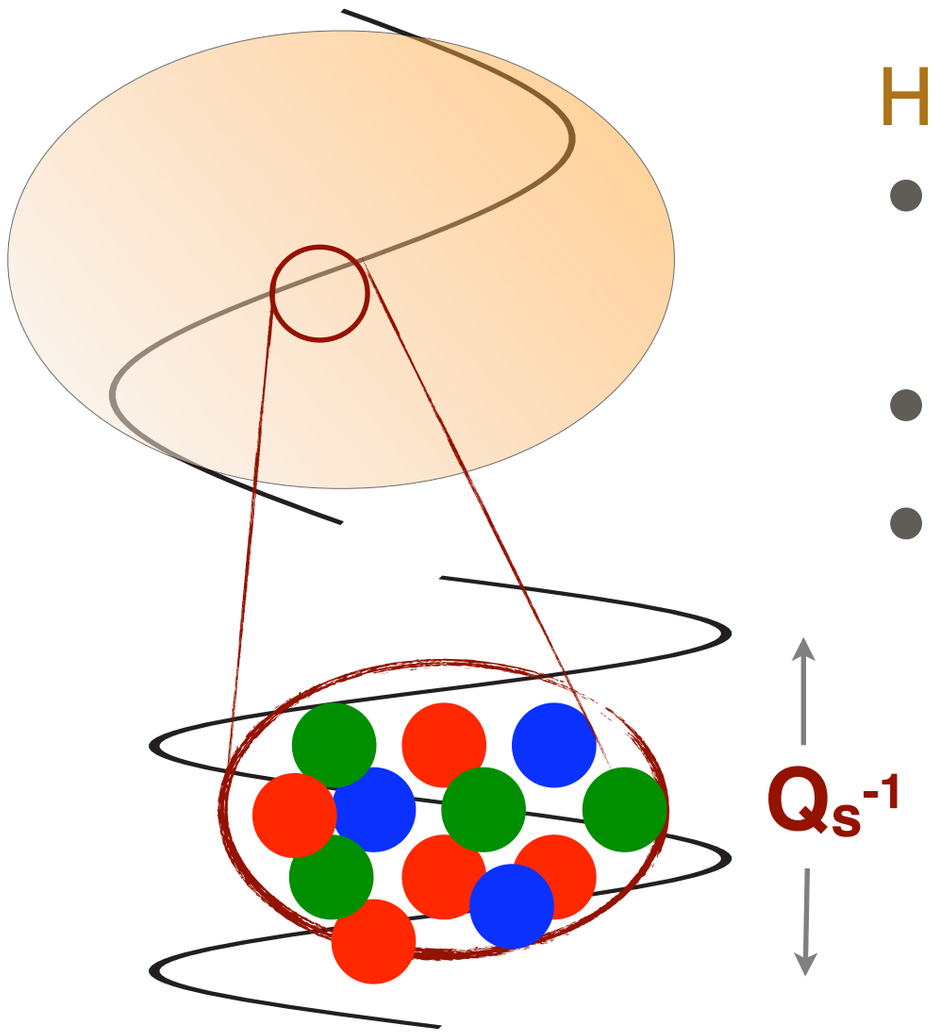

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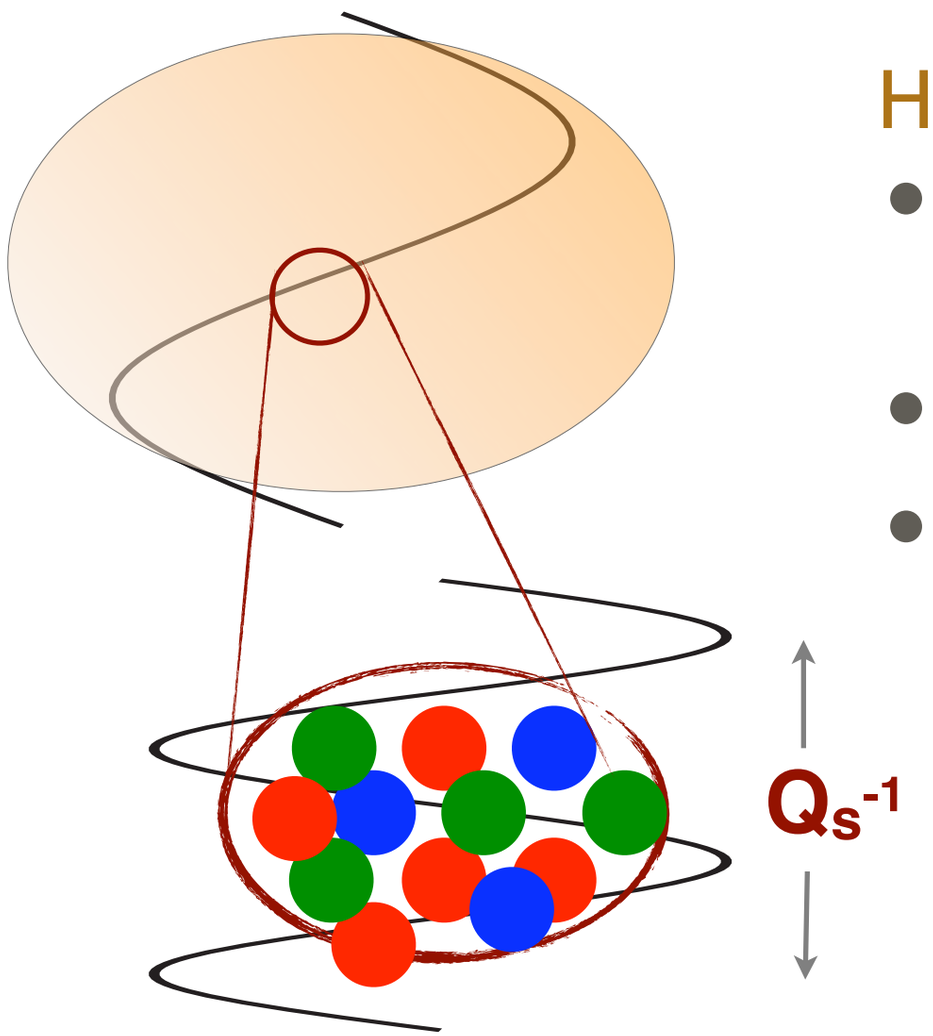

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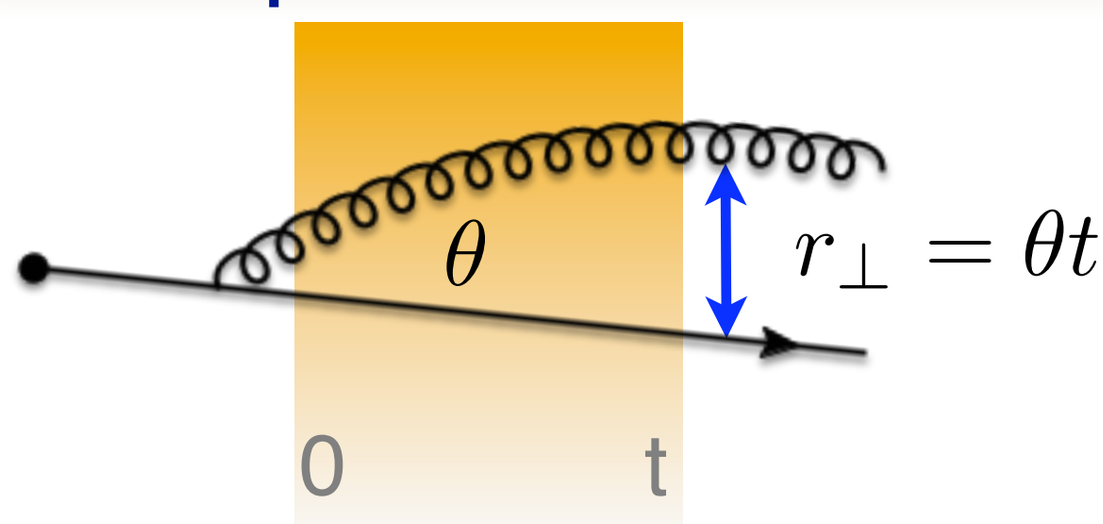

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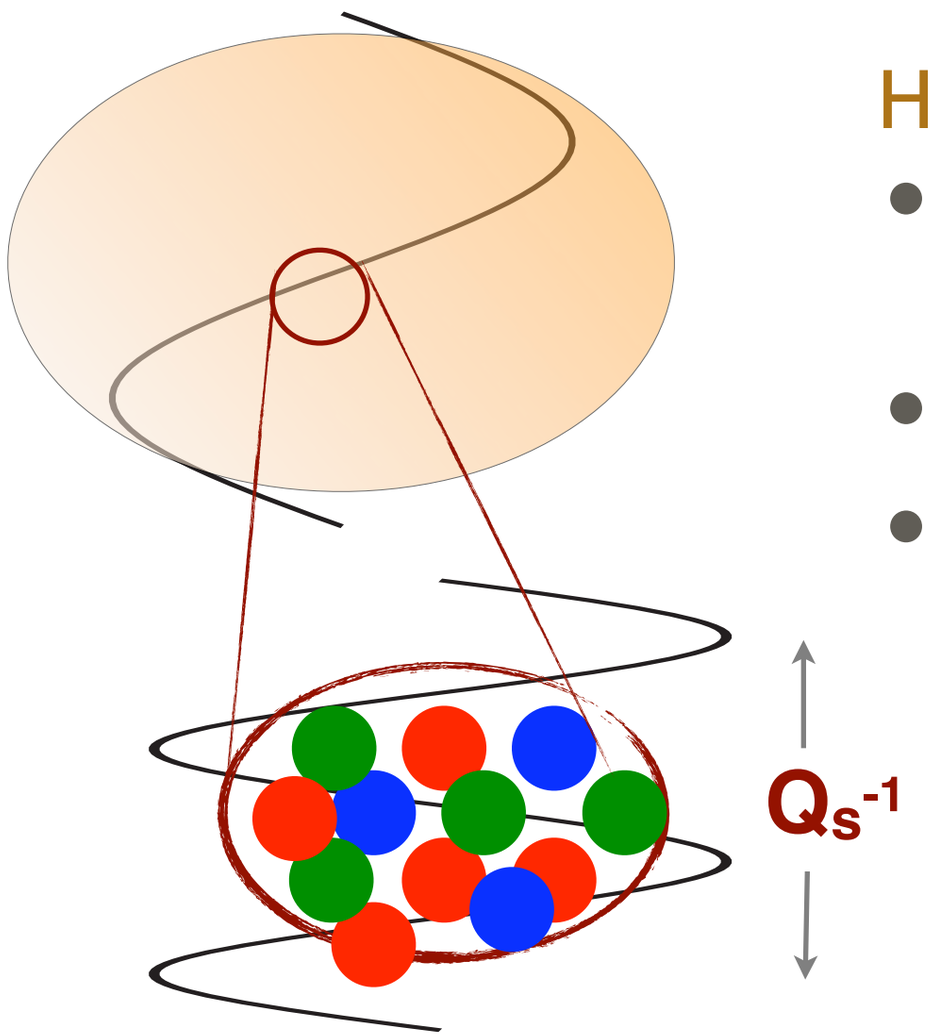

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$$Q_s^2(t) = \hat{q}t$$

→ transverse momentum sq. per unit t x length

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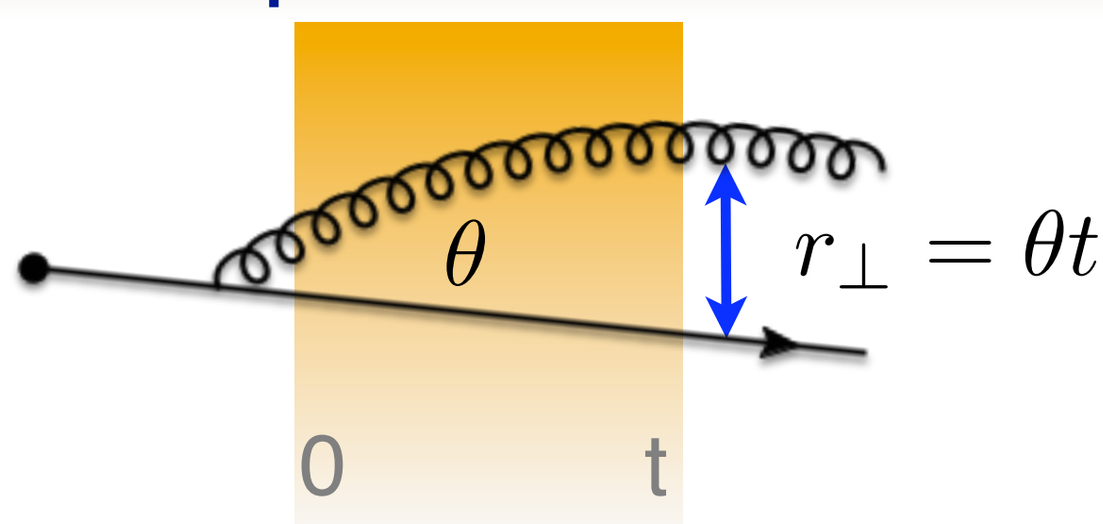
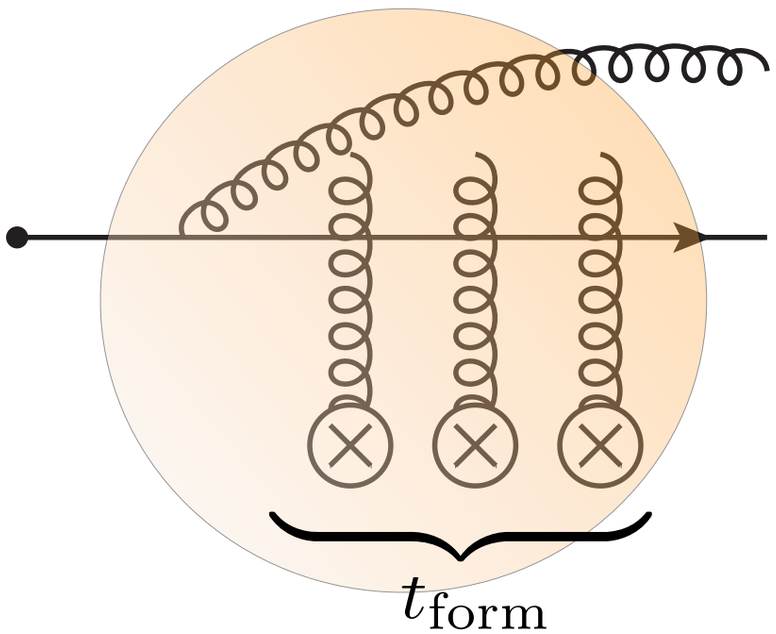


Medium-induced radiation



Mehtar-Tani, Salgado, KT JHEP 1210, 197, Blaizot, Dominguez, Iancu, Mehtar-Tani arXiv:1209.4585

LPM effect in QCD

$$\left.\begin{aligned} t_{\rm form} &= \lambda_{\rm mfp} N_{\rm coh} \\ k^2_{\rm ind} &= \mu^2 N_{\rm coh} \end{aligned}\right\} \qquad \begin{aligned} t_{\rm form} &= \sqrt{\omega/\hat{q}} \\ k^2_{\rm ind} &= \sqrt{\hat{q}\omega} \end{aligned}$$

- soft gluons are formed rapidly!
- in contrast to the vacuum
- induced gluon is de-correlated!

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

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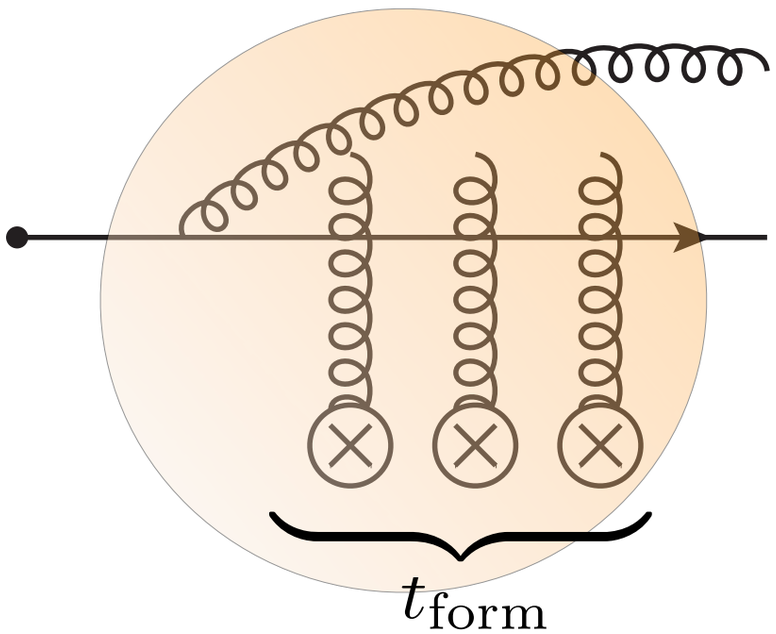

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Coherent spectrum

$$\omega \frac{dN}{d\omega} \propto \alpha_s \frac{L}{t_{\rm form}} = \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}$$

Energy loss: $\Delta E \propto \hat{q} L^2$

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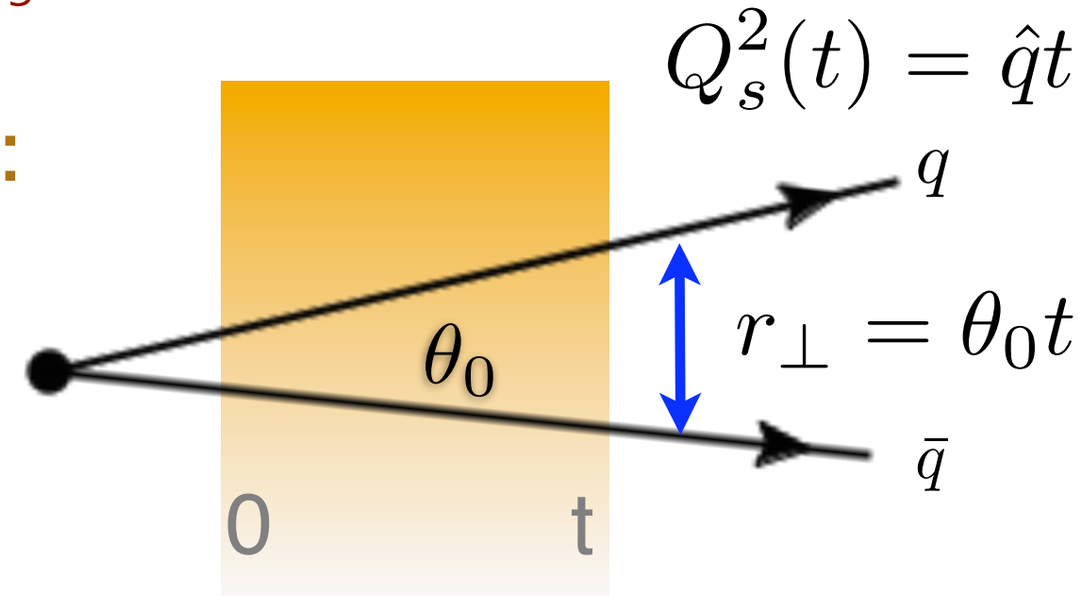
Interferences in the medium

Mehtar-Tani, Salgado, KT PRL106,122002; PLB 707, 156; JHEP 1204, 064; JHEP 1210, 197
Casalderrey-Solana, Iancu JHEP 1108 (2011) 015



Importance of interferences:

- condition: color correlation between emitters
- what is the probability that the pair remains correlated?

$$\Delta_{\rm med}(t) = 1 - \exp\left(-\frac{1}{12} r_\perp^2 Q_s^2(t)\right)$$

decoherence parameter

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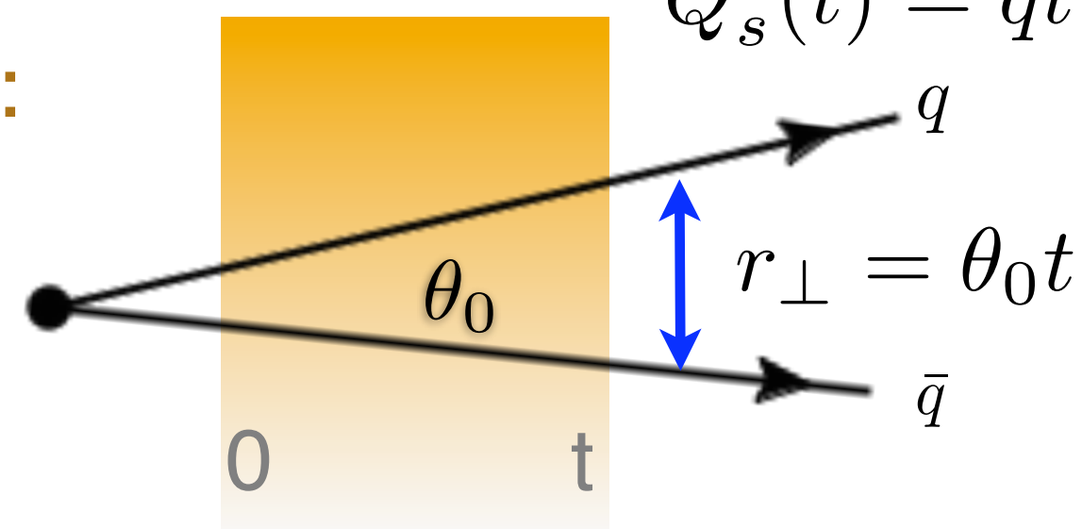

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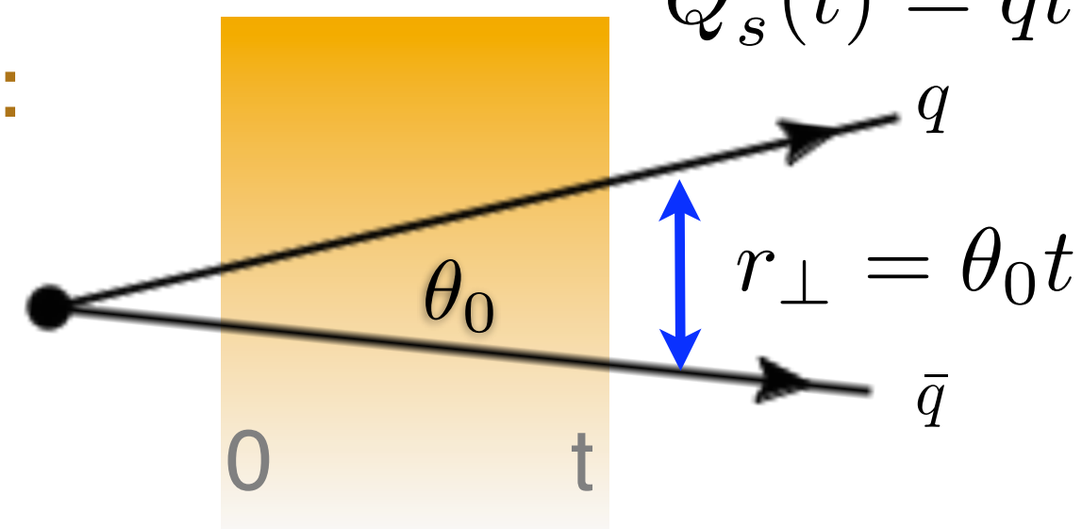

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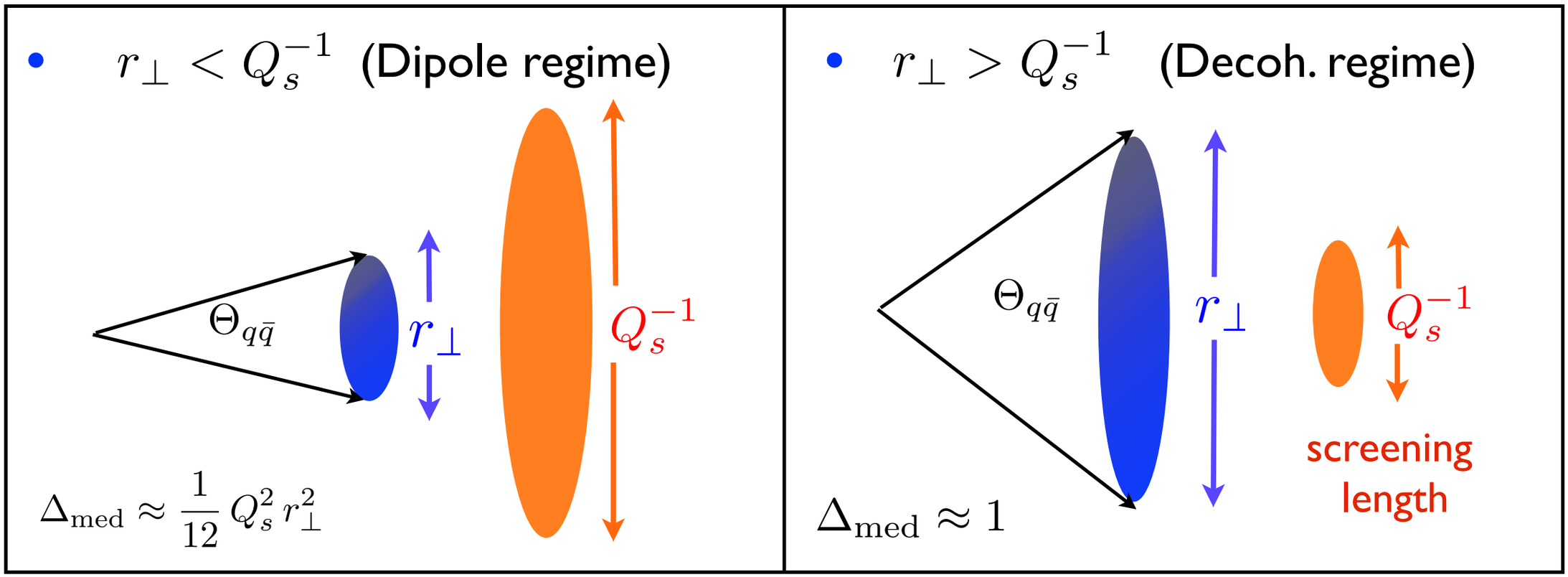
decoherence parameter

characteristic decoherence time

- at $t > t_d$: independent radiation
- at short timescales: sensitive to interferences

Hard scale analysis



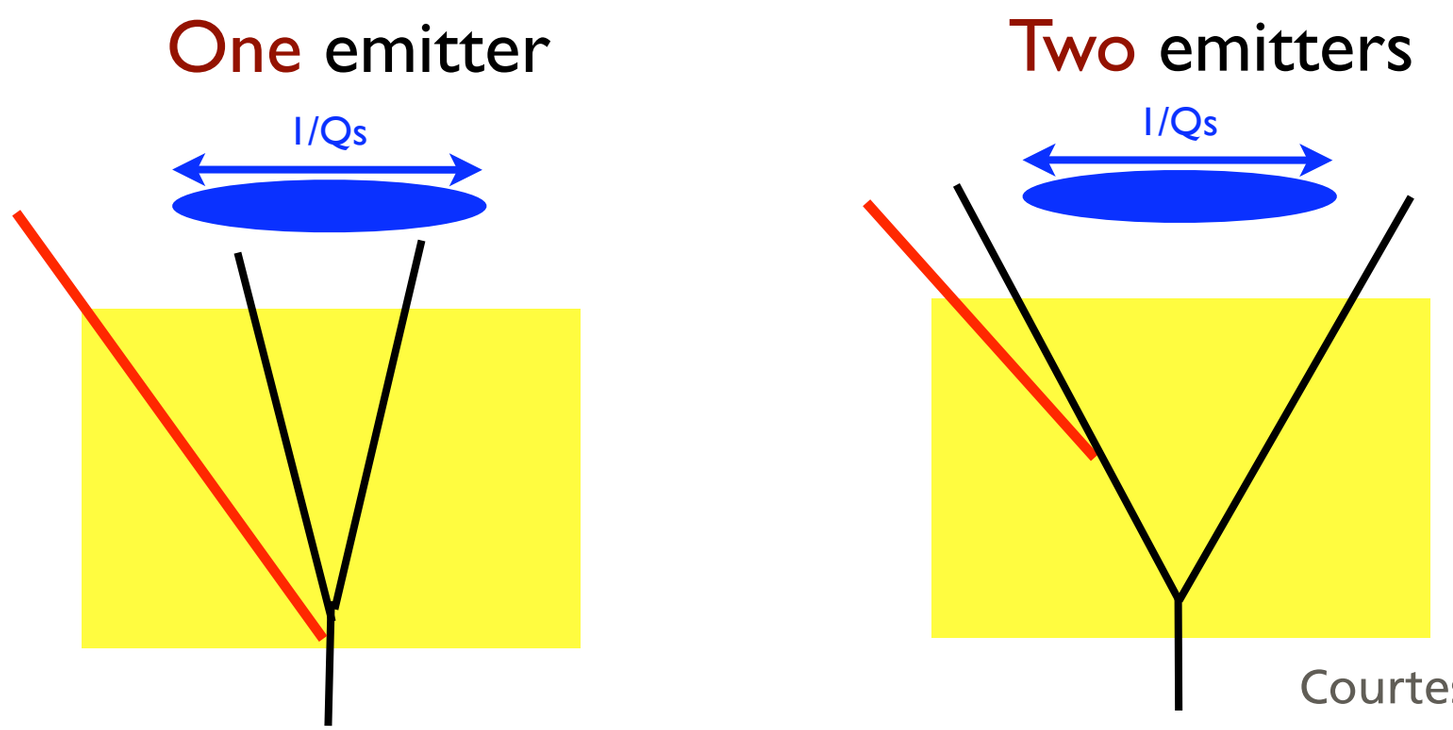
$$\Delta_{\rm med} \approx 1 - \exp[-\frac{1}{12} Q_s^2 r_\perp^2]$$

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

Q_s: characteristic momentum scale of the medium

Mehtar-Tani, Salgado, KT JHEP 1204 (2012) 064; JHEP 1210, 197

A simple conclusion



Courtesy: J. Casalderrey-Solana

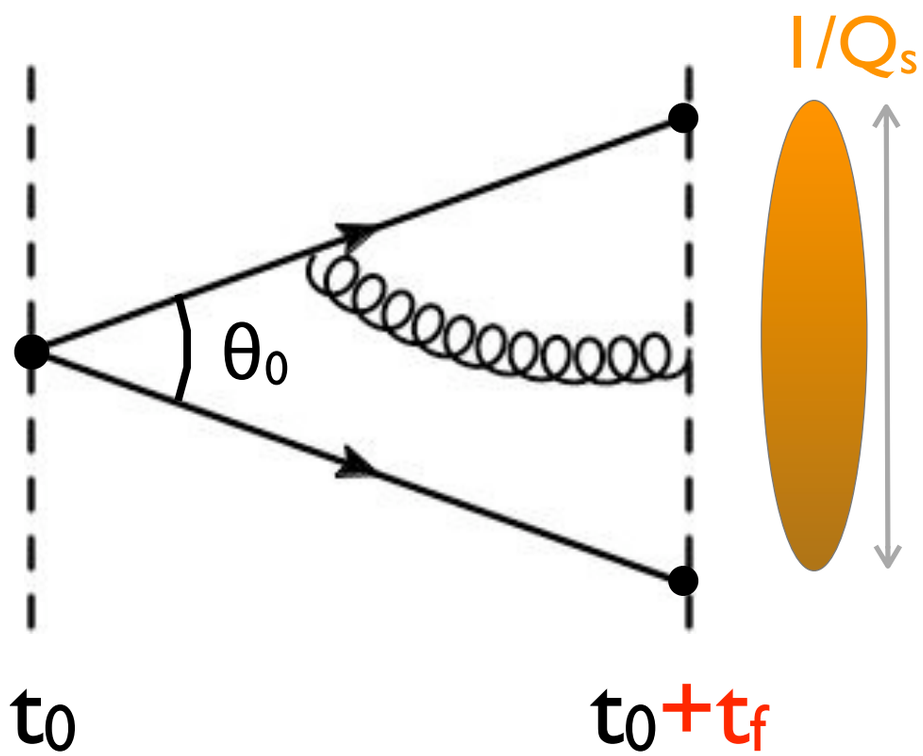
- Shower size < 1/Qs ⇒ rad. as the total charge
- Shower size > 1/Qs ⇒ rad. as a independent partons

Medium acts in a two-fold way:
resolves effective charges & induces radiation

Step in the evolution

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

AO: $\lambda_\perp < r_\perp$



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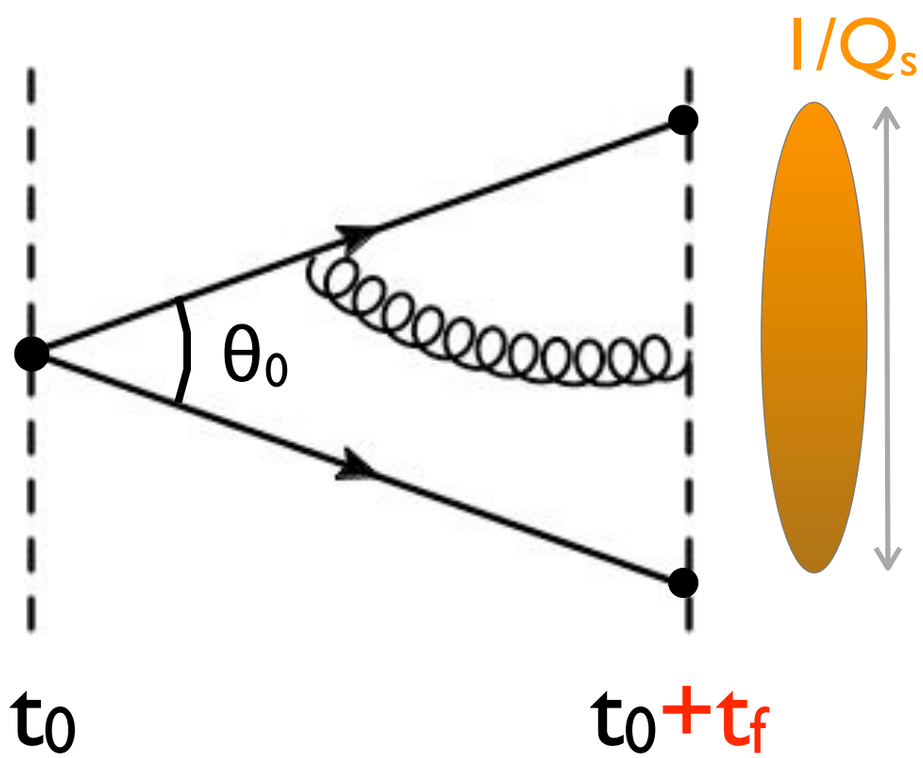

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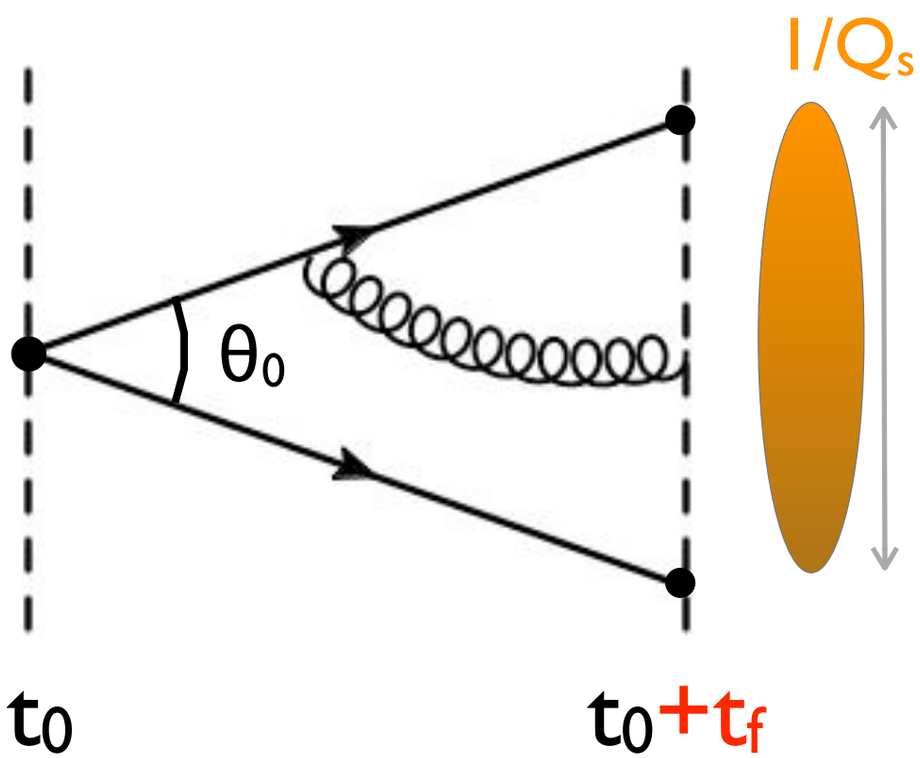

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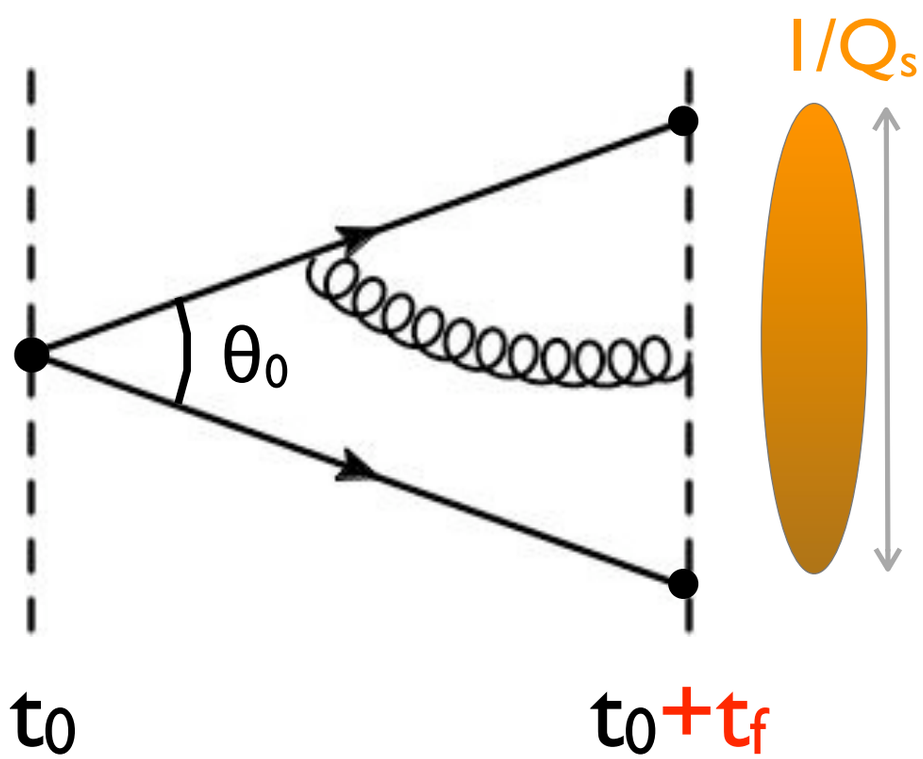

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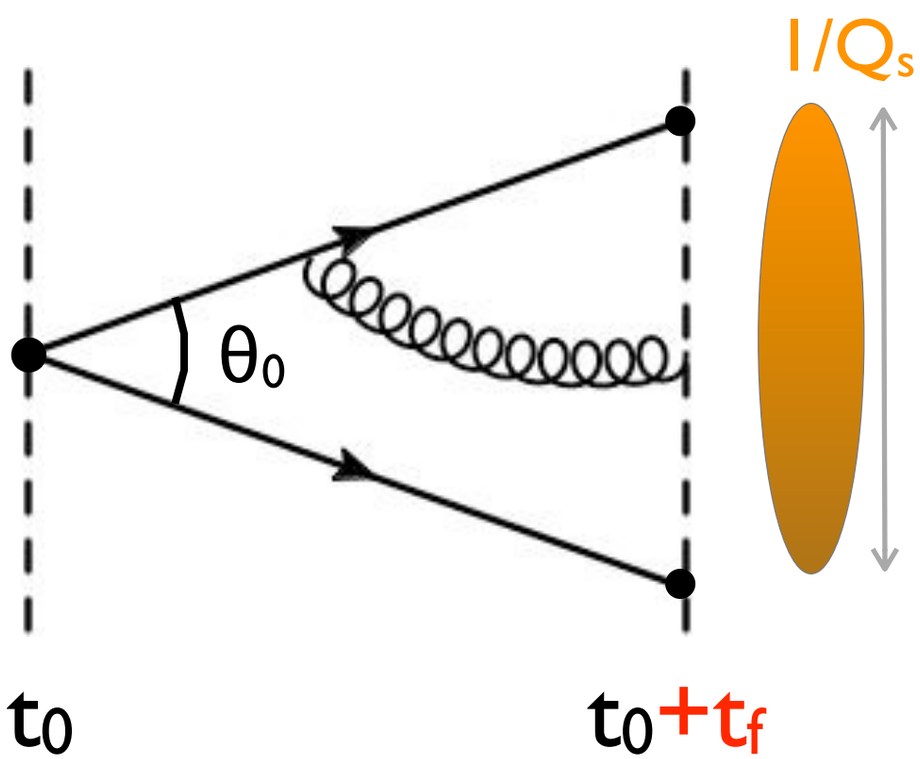

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→ hard modes are never resolved!

Parametric behavior

Generic scaling will involve the medium length L

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

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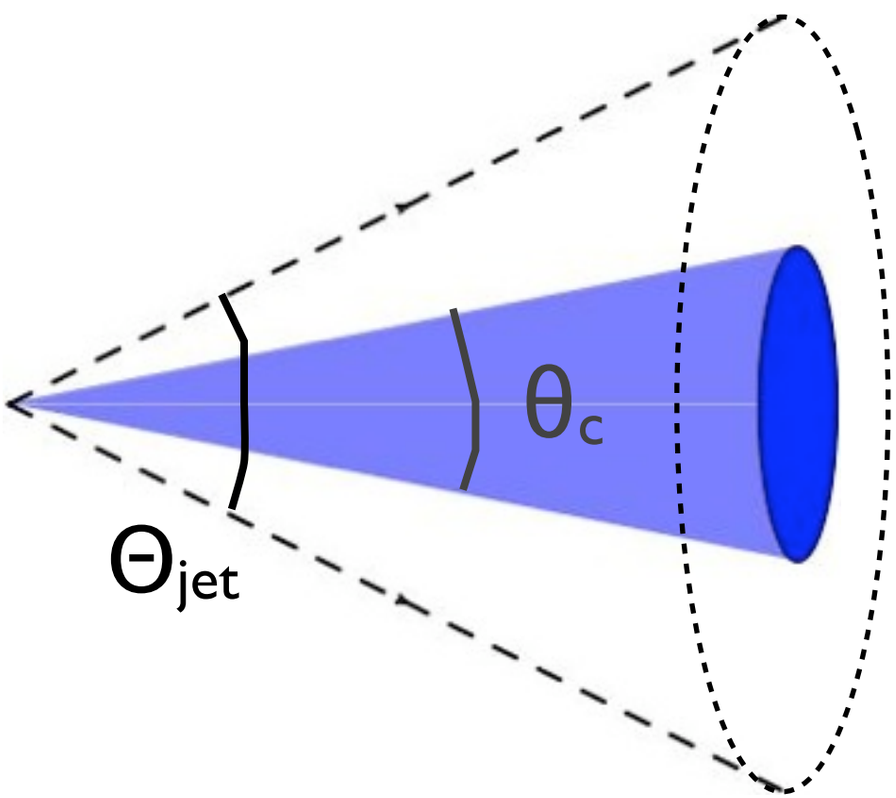

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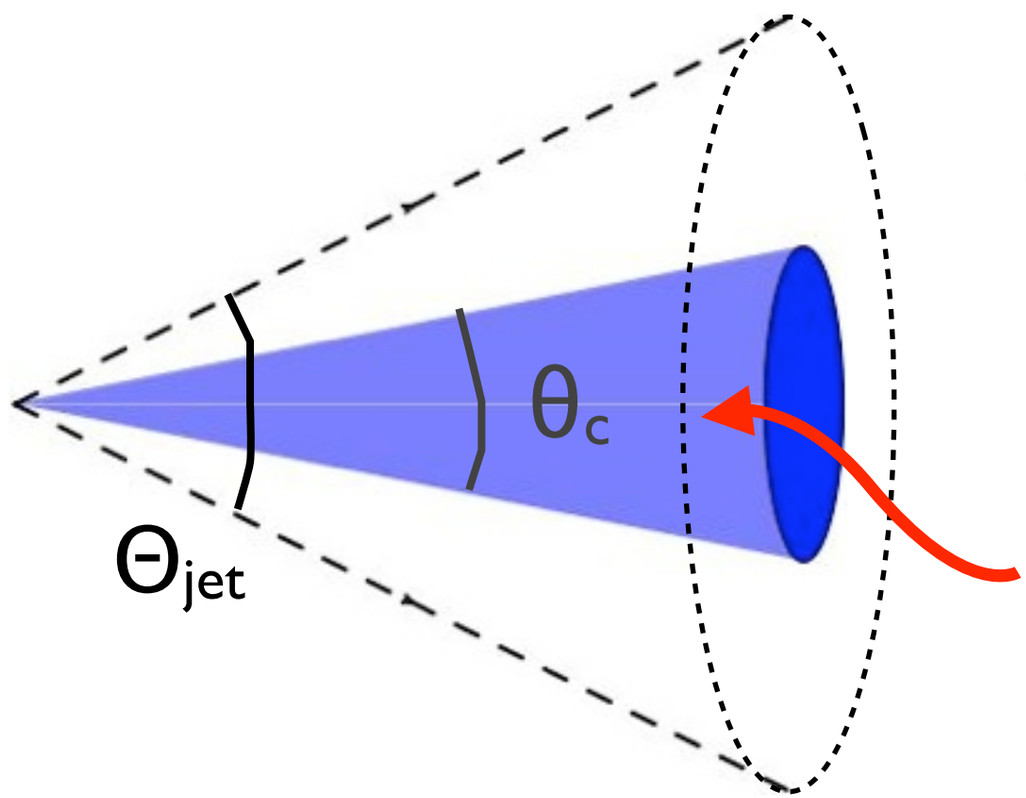
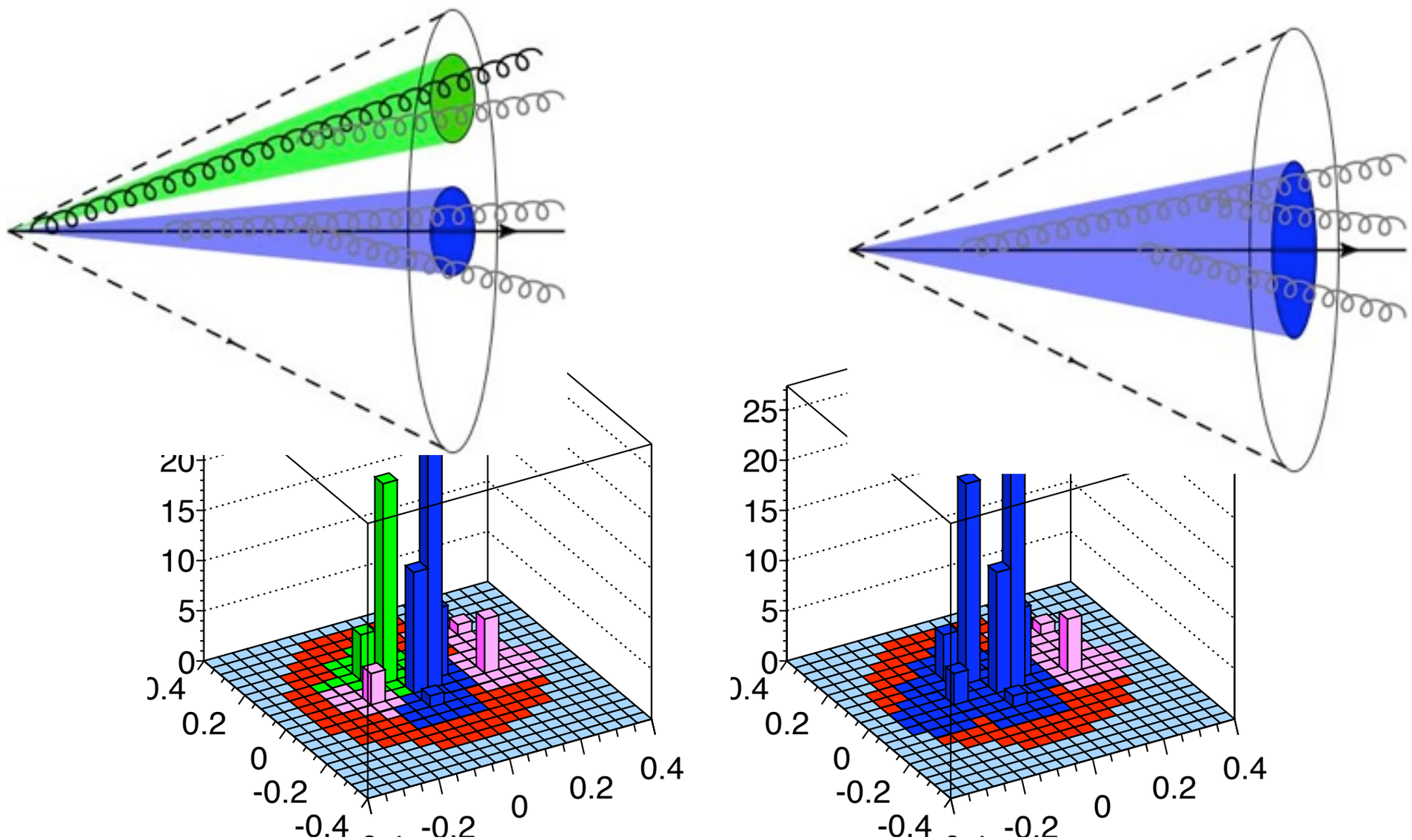


In central collisions: $\Theta_{jet} > \theta_c$

Coherent inner 'core'

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

Resolved effective charges



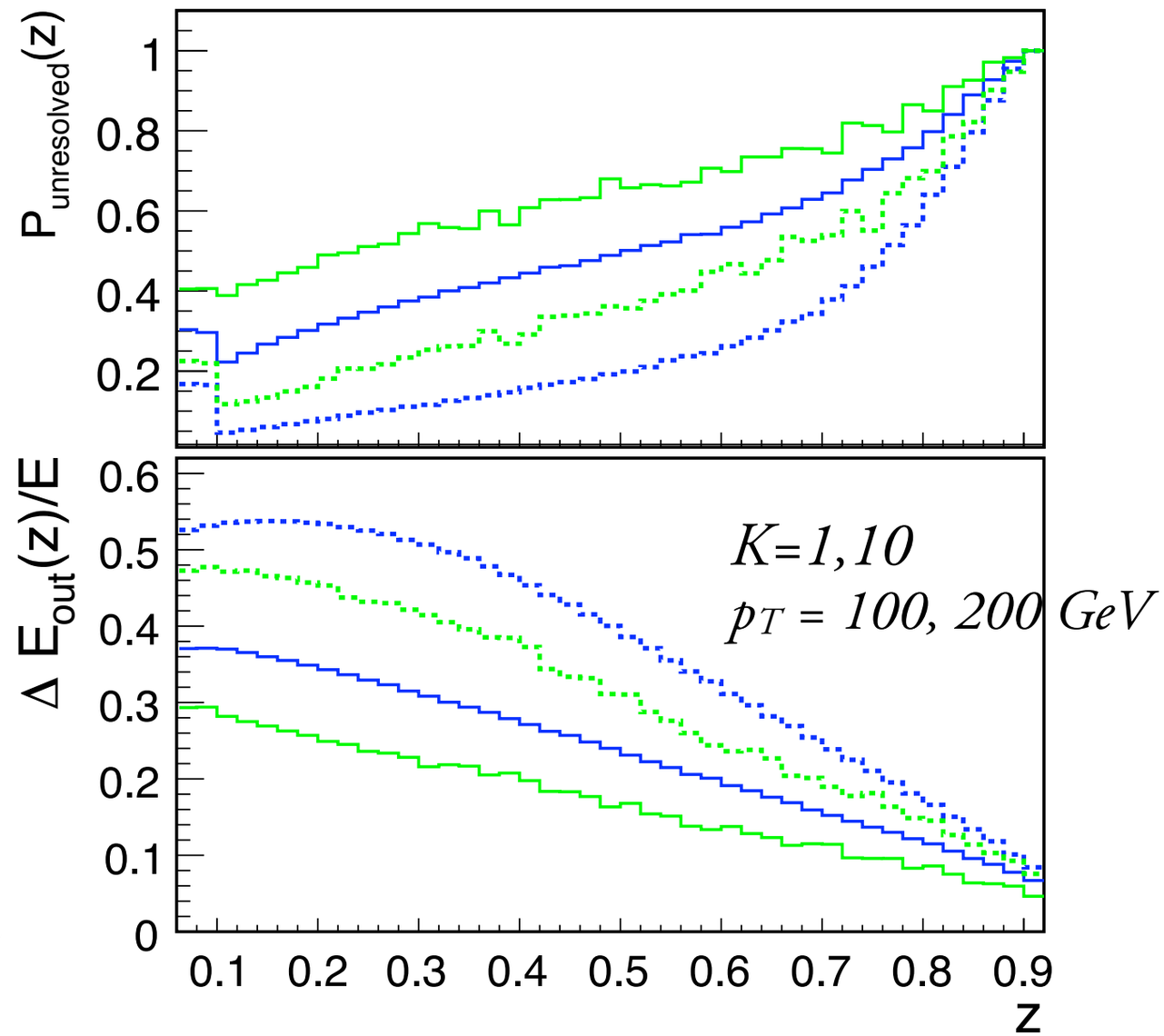
Finite medium resolution power:

medium sees the jet in terms of effective charges

Relevant for LHC

Casalderrey, Mehtar-Tani, Salgado, KT arXiv:1210.7765

- studied the magnitude of the medium resolution @ LHC
- PYTHIA 8.150 + 3D hydro + FastJet (anti-kt, R = 0.3)
- substructure analysis with $R_{med} = \theta_c$
- often we only have one effective fragment within R!
- contains most of the jet energy (jet core)



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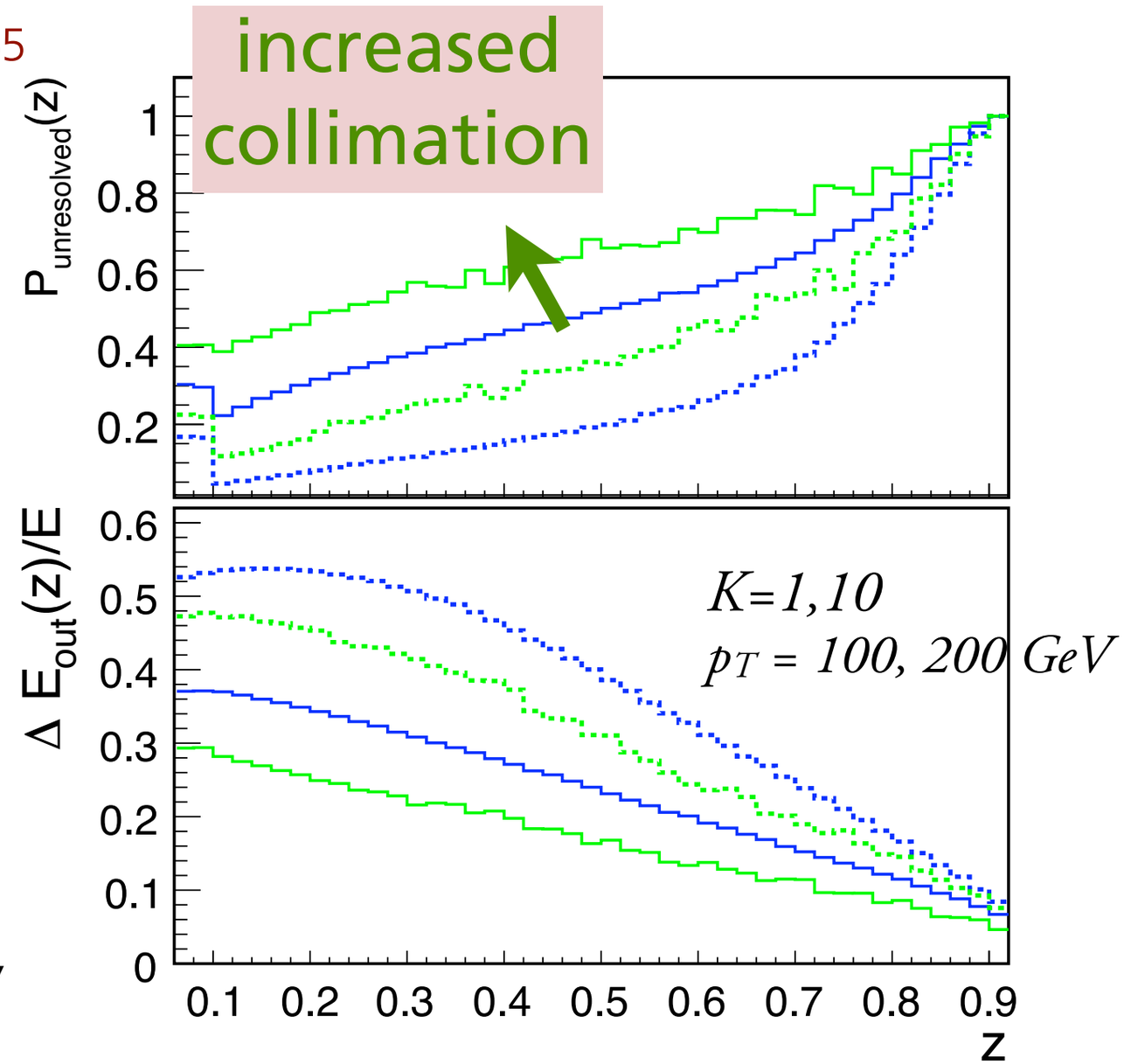

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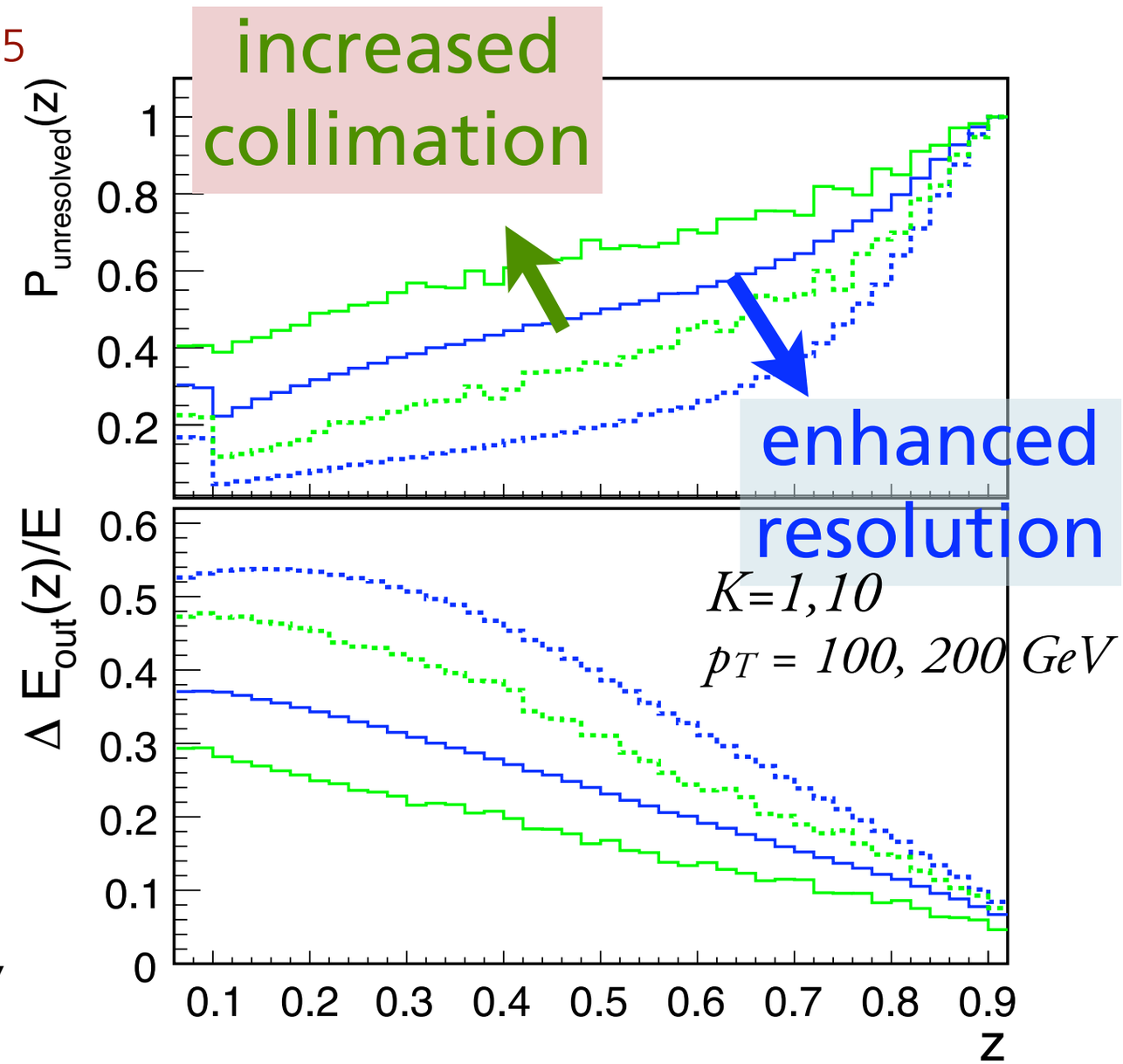

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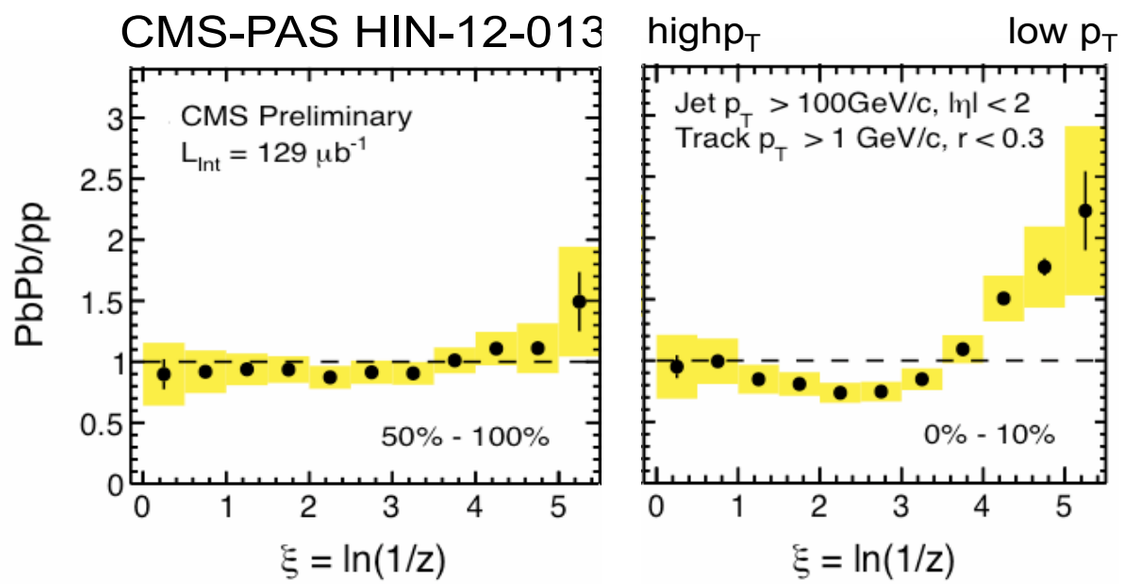
Modifications of the FF



MLLA: collimated modes

$$Q_0 < k_\perp < zE\theta_c$$

$$z > \frac{Q_0}{E\theta_c}$$ → no modification of the fragmentation function!

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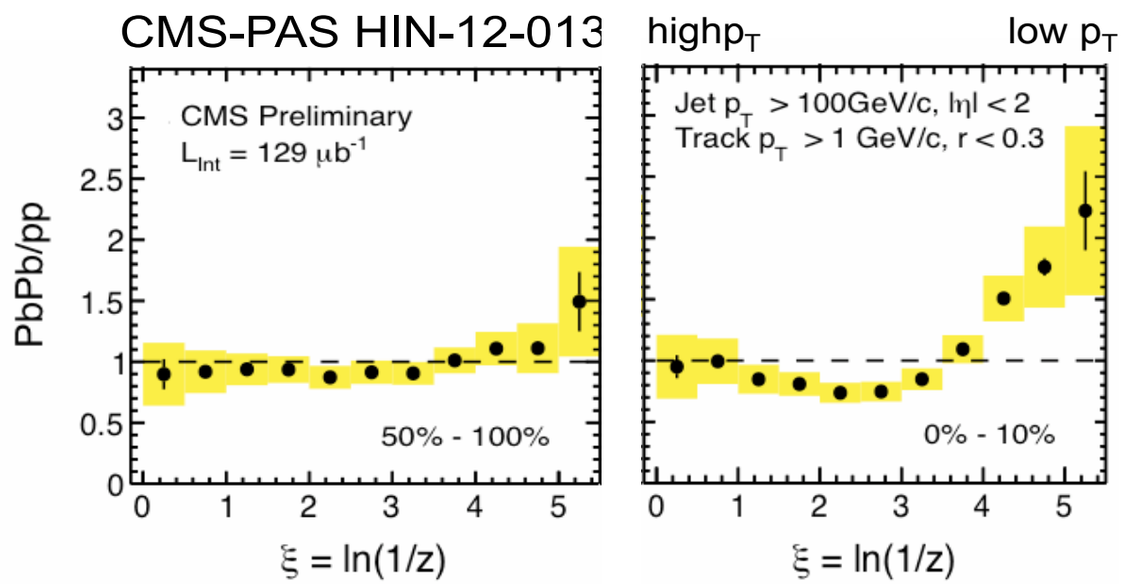

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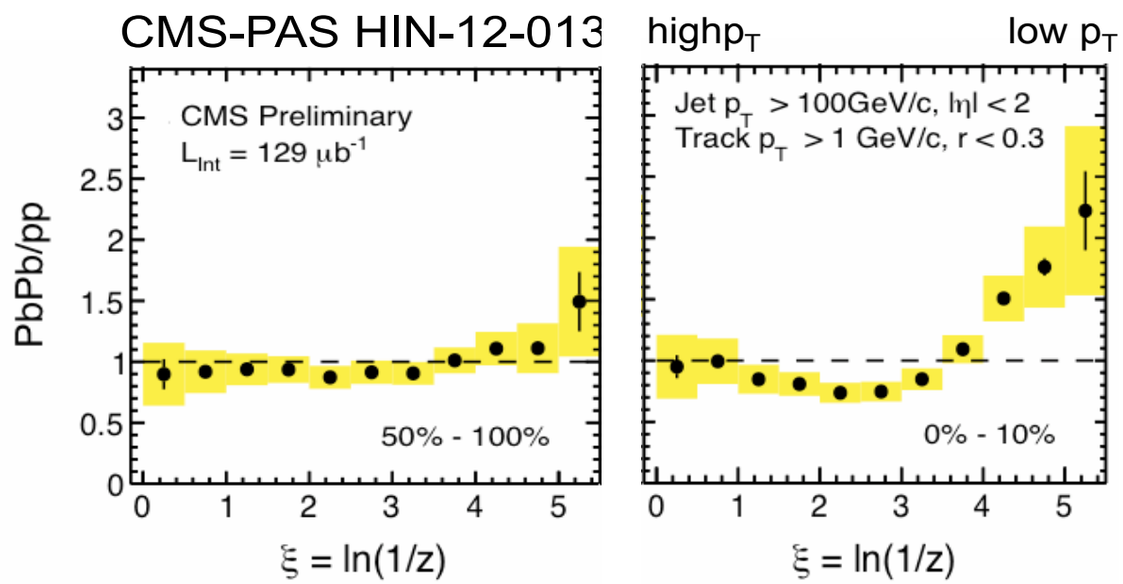

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- no modification of the distribution of collimated hard fragments
  - all constituents inside collimated sub-jet lose energy coherently!
- detailed aspects: need further study

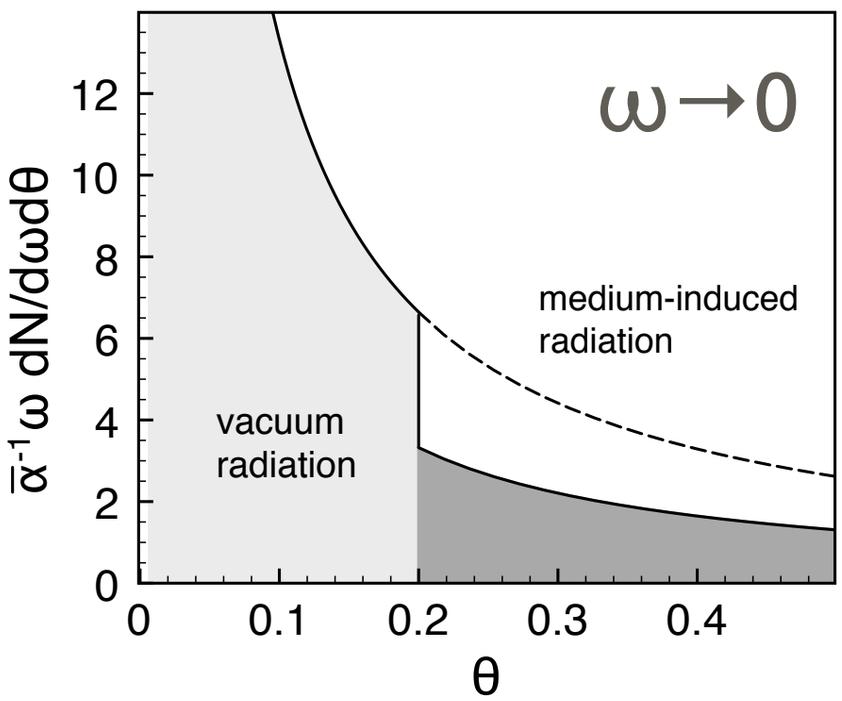
Conclusions

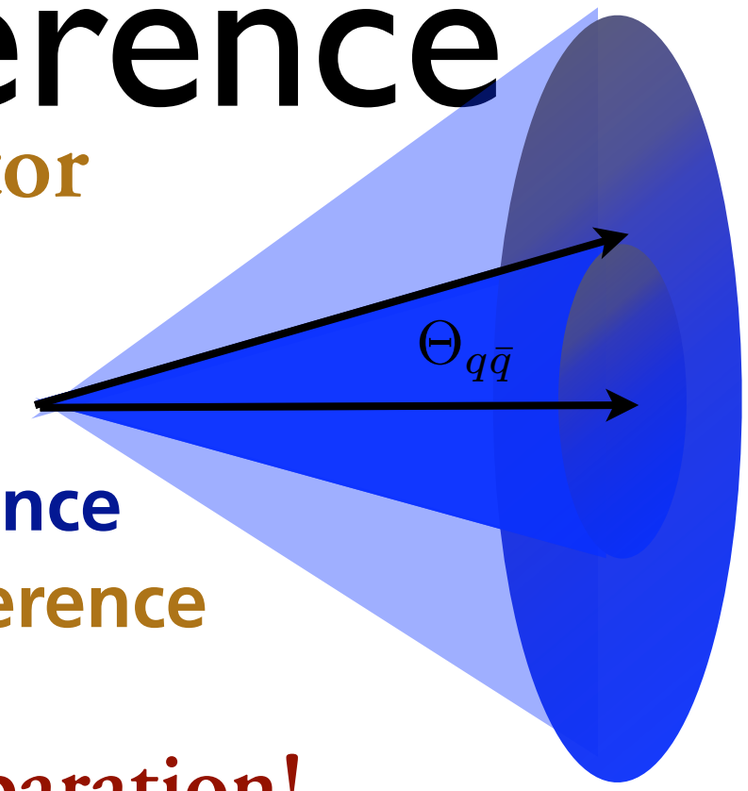
- establishing an understanding of jet dynamics in medium in terms of hard scales
  - common framework for jet fragmentation & medium-induced radiation
- developing a space-time picture of radiation
- new picture of "jet quenching" dictated by color coherence emerges
  - appealing observables: collimated jets
  - precise estimate of medium parameters

Backup

Onset of decoherence

- in the soft sector





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

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

Geometrical separation!

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

Soft gluons with long formation times

- all particles radiate independently
- “memory loss”: no color correlation to parent

Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002; PLB 707 (2011) 156**

Modeling the medium

Medium modeled as a classical background field:

$$A^-_{\rm med}(x^+, x_\perp) = -\frac{1}{\partial_\perp^2}\rho_{\rm med}(x^+, x_\perp) \quad , \quad A^i_{\rm med} = A^+_{\rm med} = 0$$

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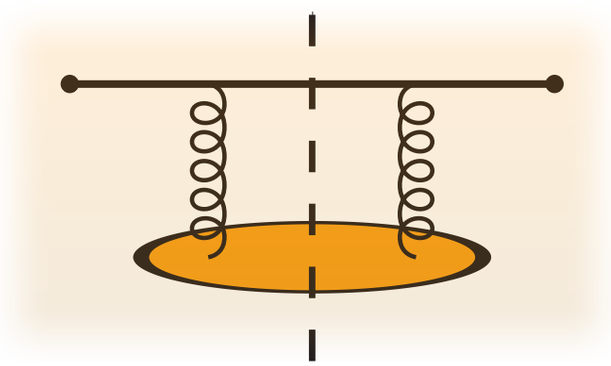

$$V^2(\boldsymbol{q}) = \frac{m_D^2}{(2\pi)^2\left(\boldsymbol{q}^2 + m_D^2\right)^2}$$

static scattering centers

M. Gyulassy, X. Wang
NPB 420 (1994) 583

$\lambda_{\rm mfp} \gg 1/m_D$

$$\langle A^a_{\rm med}(t, \boldsymbol{q}) A^{*\,b}_{\rm med}(t', \boldsymbol{q}')\rangle = \delta^{ab}\delta(t - t')\delta(\boldsymbol{q} - \boldsymbol{q}')V^2(\boldsymbol{q})$$

- standard in analyses of energy loss
- can be improved!
- consistency in treatment of other thermal effects [?]