UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

MC implementation of coherence effects - status and perspectives

Konrad Tywoniuk

CERN / 13 January 2013

In the medium...

Radiative processes
- induced radiation
- absorptive reactions

Elastic processes
- momentum broadening
- drag effects

... reflect characteristics of the underlying medium!

Can we get a handle on each/one separately?

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Identify the typical momentum & time scales:

vacuum ⇔ medium

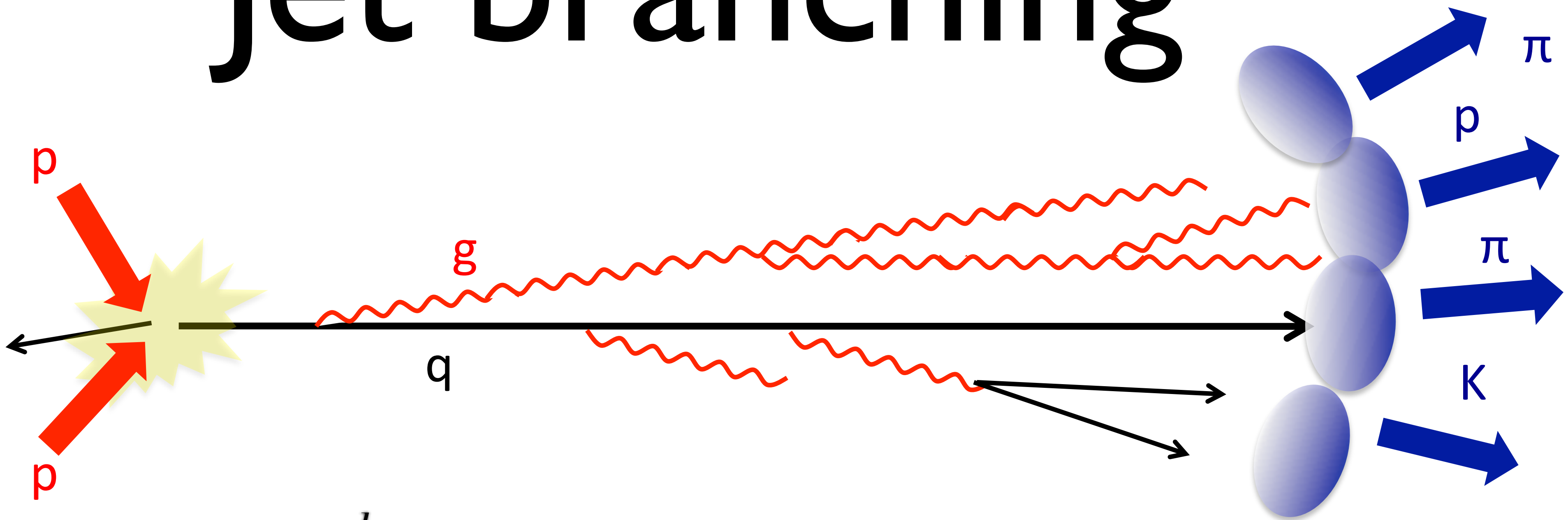
quantum ⇔ classical

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

Outline

- Ordering features & MC implementation
  - Coherence effects: angular ordering (vacuum) & Landau-Pomeranchuk-Migdal (medium)
- Interface: jets in heavy-ion collisions
  - the role of decoherence

Jet branching



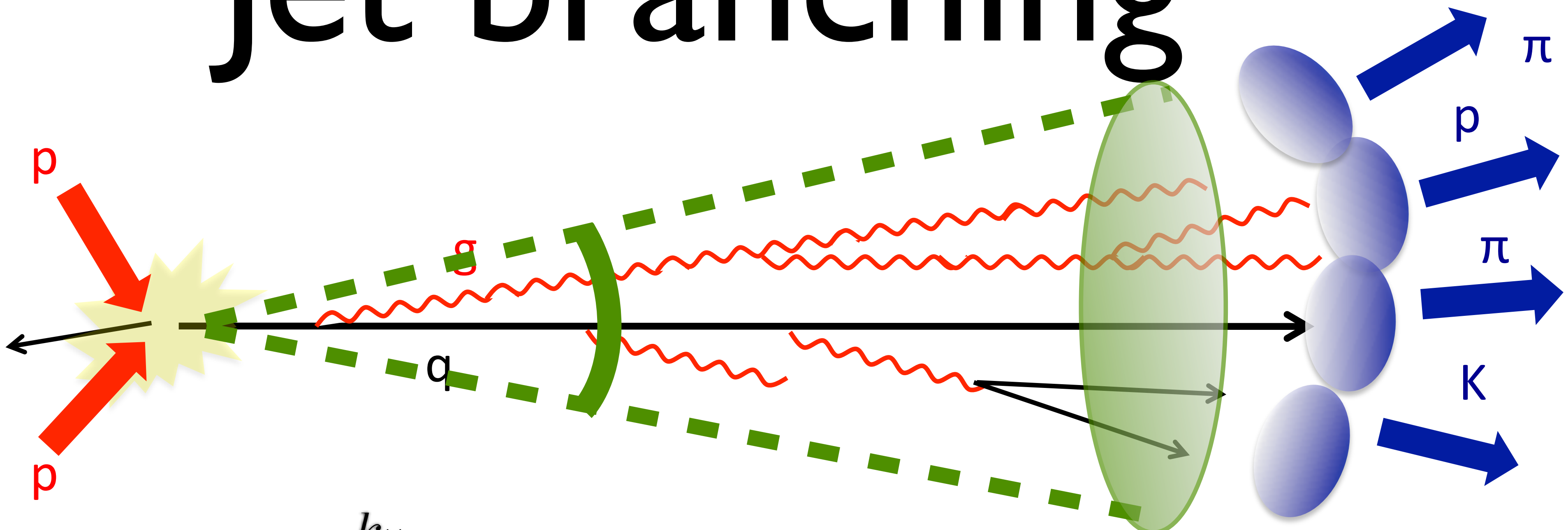
$$t_{form} \simeq \frac{k_{||}}{k_\perp^2}$$

$$t_{hadr} \simeq \frac{k_{||}}{\Lambda^2_{\rm QCD}}$$

- virtual hard parton fragments
- LPHD: hadronization does not affect inclusive observables
- baseline

Large time domain for pQCD: $\frac{1}{E} < t < \frac{E}{\Lambda_{\rm QCD}}$

Jet branching



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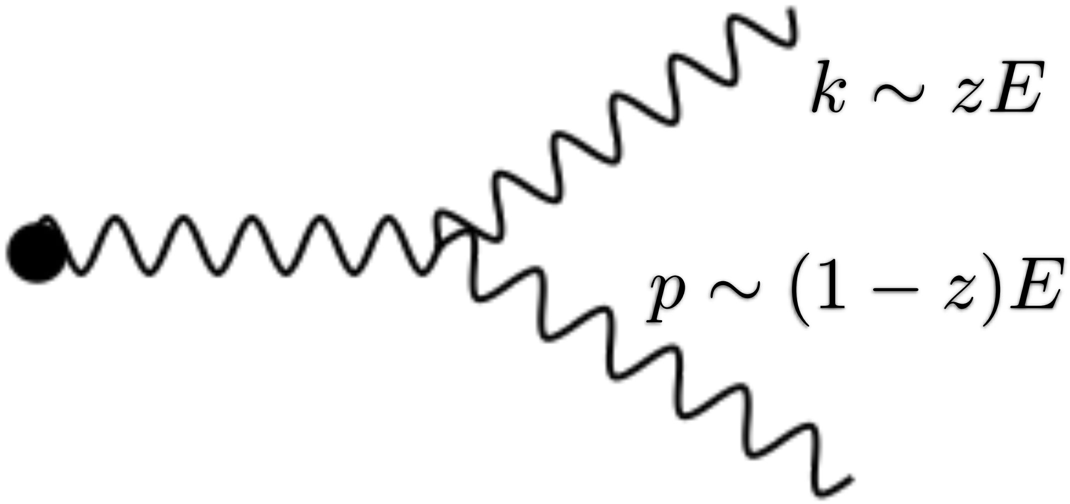
Jet scales:

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

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

Large time domain for pQCD: $\frac{1}{E} < t < \frac{E}{\Lambda_{\rm QCD}}$

Elementary splitting



$$dP = \frac{\alpha_s}{2\pi}\frac{d^2k_\perp}{k_\perp^2}P_{ij}(z)dz$$

$$k_\perp \approx z(1-z)E\theta > Q_0$$

$\Rightarrow$ soft & collinear singularities

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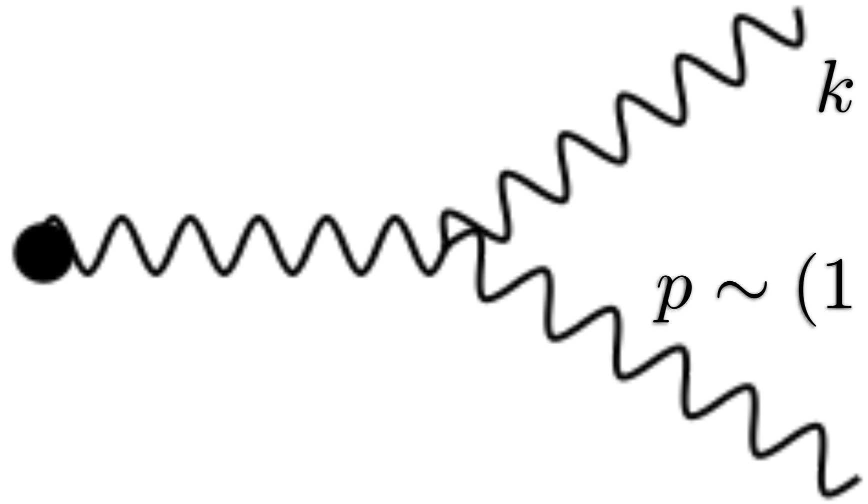

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- factorization
- phase-space enhancement: need for resummation of multiple branchings

$$P = \alpha_s \int_{Q0}^{M_\perp} \frac{d^2 k_\perp}{k_\perp^2} \int_{Q_0/M_\perp}^{1} \frac{dz}{z}$$

$$\sim \alpha_s \log^2 \frac{M_\perp}{Q_0} \gg \alpha_s$$

- characteristic timescale

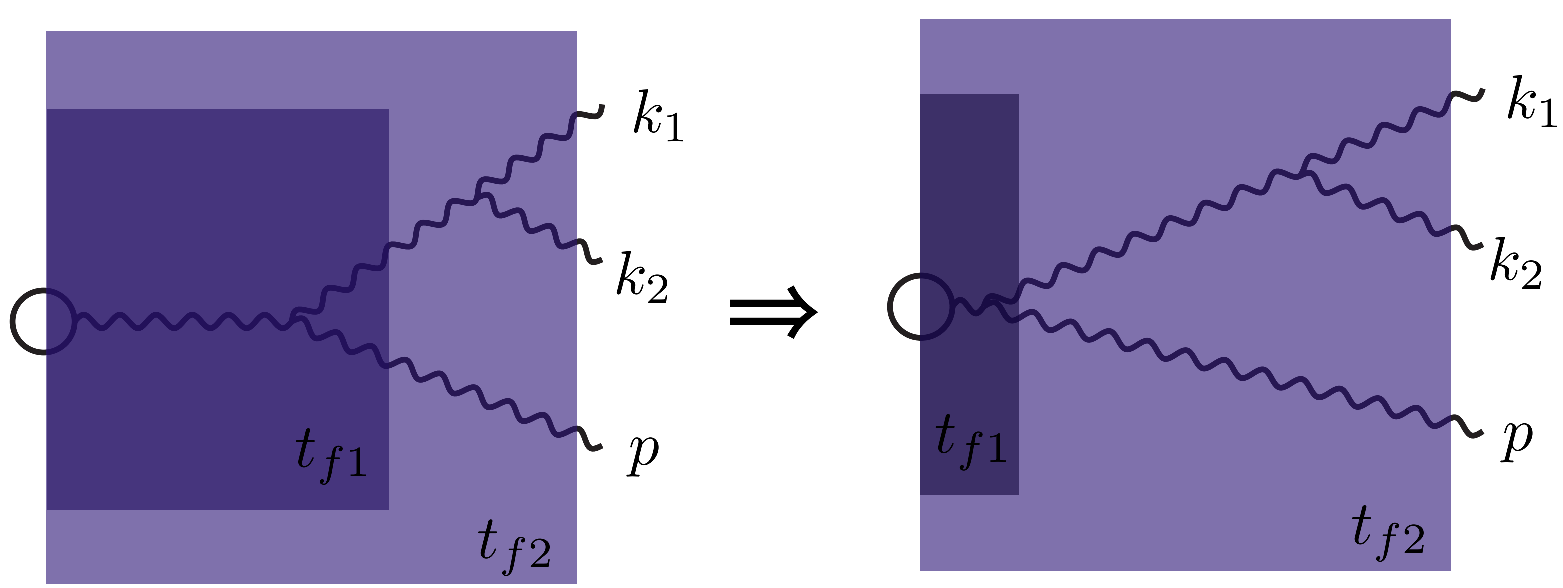
$$t_{\rm form} = \frac{E}{(p+k)^2} \sim \frac{\omega}{k_\perp^2}$$

Leading-log contributions

$$M_\perp \gg k_{1\perp} \gg k_{2\perp} \gg \ldots \gg Q_0$$

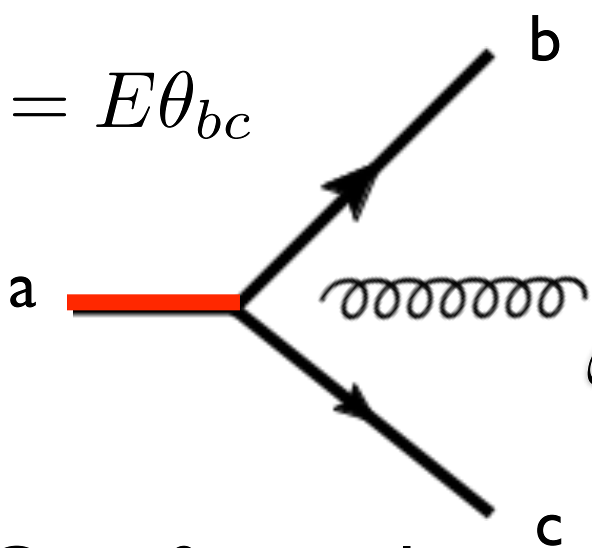
- large contributions if strong ordering in the evolution variable ⇒ **probabilistic**
- implies space-time picture

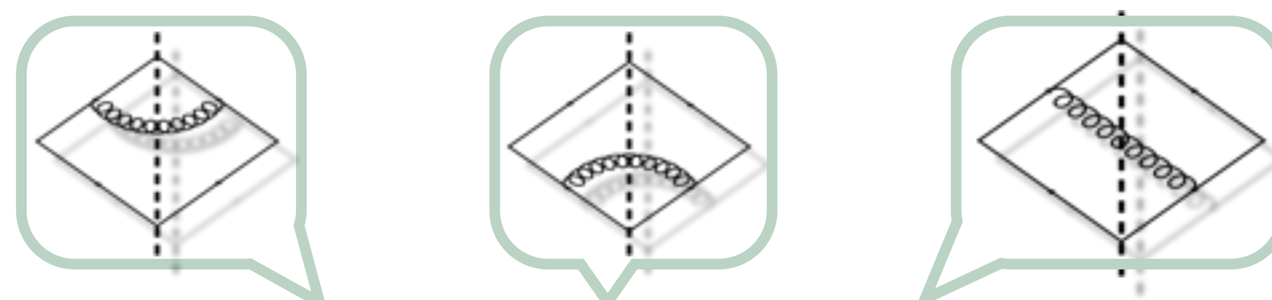
$$t_{\text{form},1} \ll t_{\text{form},2} \ll \ldots$$



Color coherence in vacuum

$Q = E\theta_{bc}$





$$\omega \frac{dN}{d^3k} = \frac{\alpha_s}{(2\pi)^2\omega^2}\left[\boldsymbol{Q}_b^2\mathcal{R}_b + \boldsymbol{Q}_c^2\mathcal{R}_c + 2\boldsymbol{Q}_b \cdot \boldsymbol{Q}_c\mathcal{J}\right]$$

$Q_a = 0$ :: singlet

$Q_a \neq 0$ :: octet

- interference effects
- conservation of color charge

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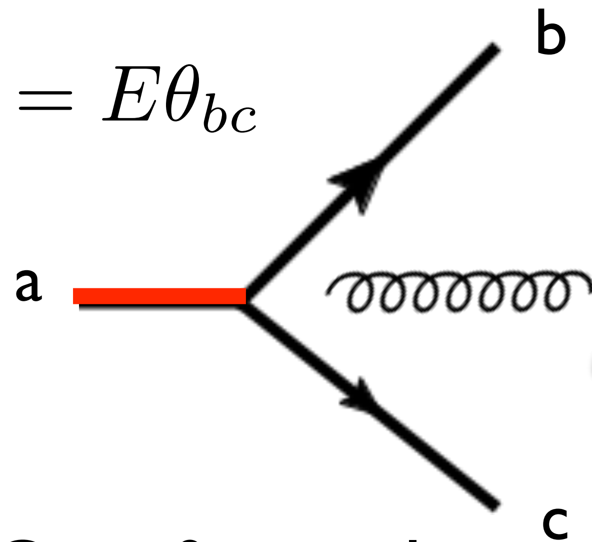

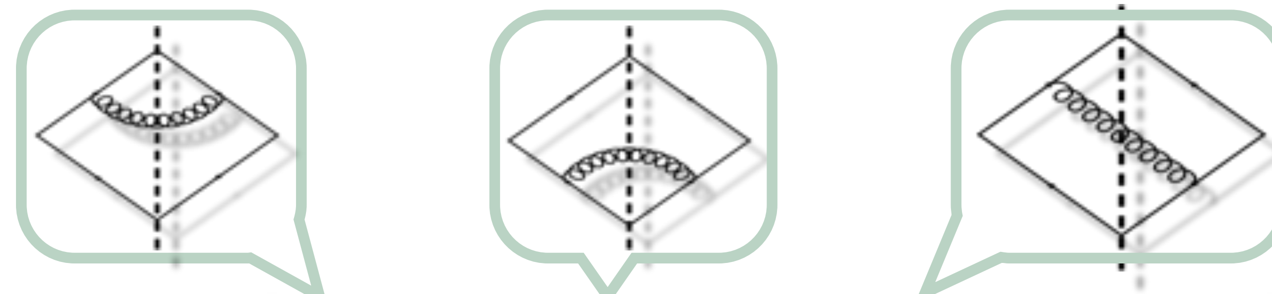

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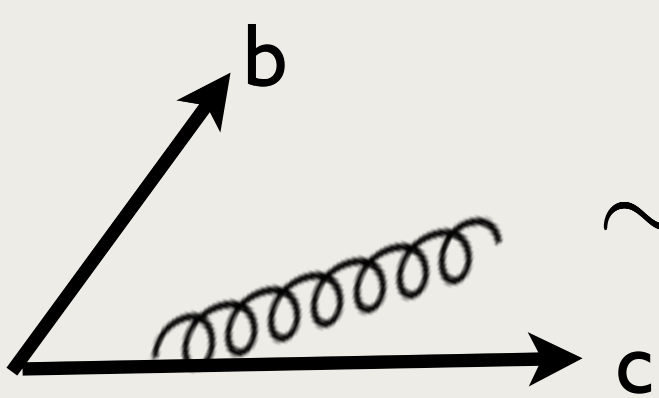
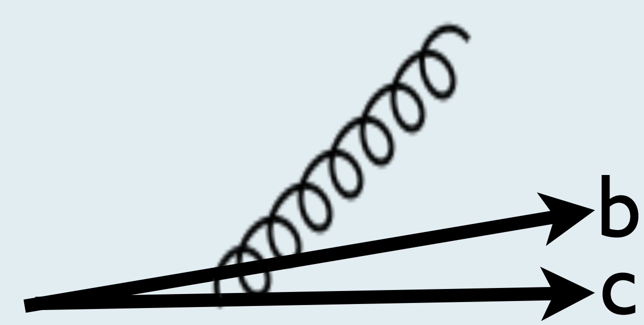


$$\sim \frac{\alpha_s Q_c^2}{k_\perp^2}$$



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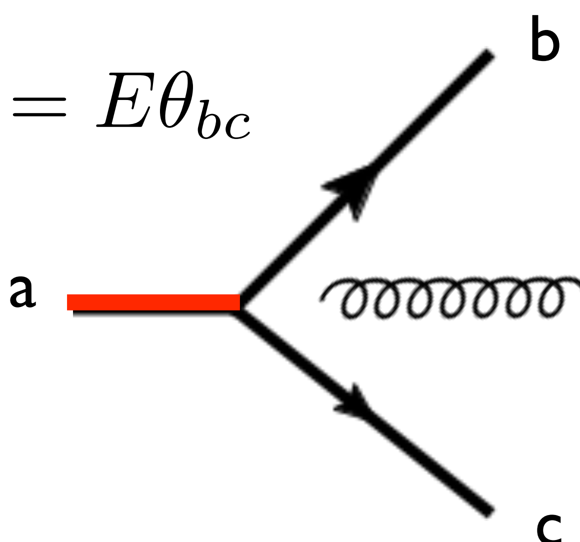

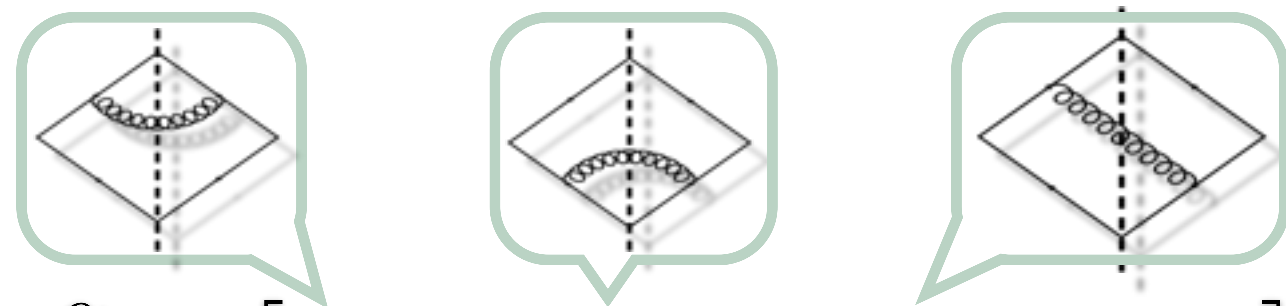

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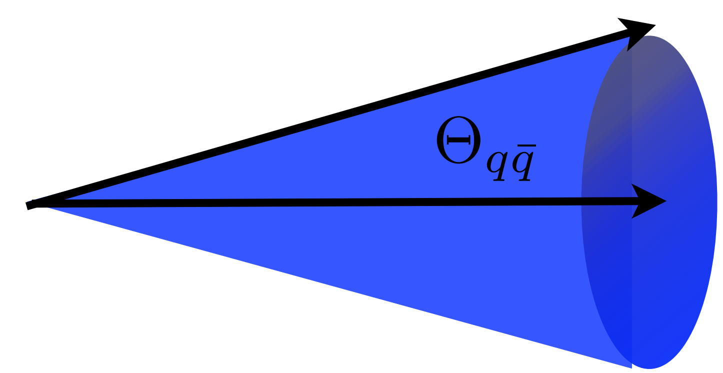
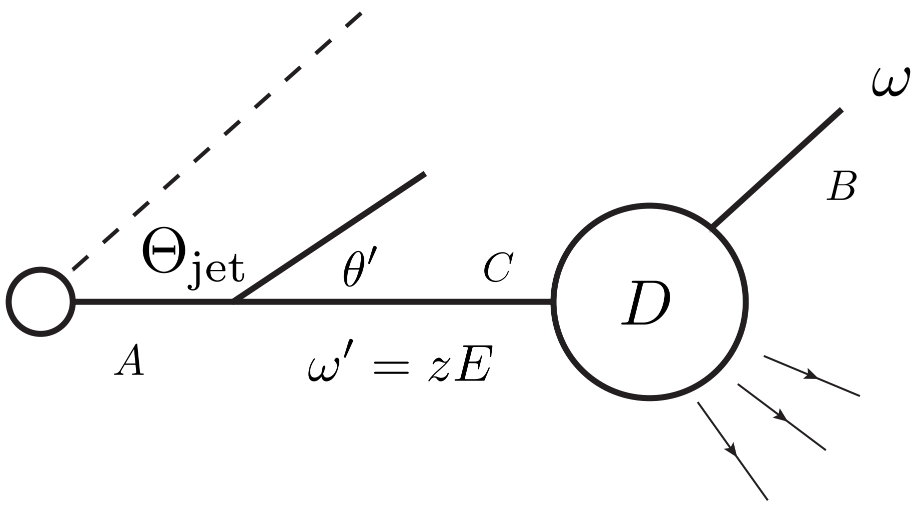
Coherent spectrum:

$$\langle dN_q\rangle_\varphi = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\Theta(\cos\theta - \cos\theta_{q\bar{q}})$$



Coherent parton evolution



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

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

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

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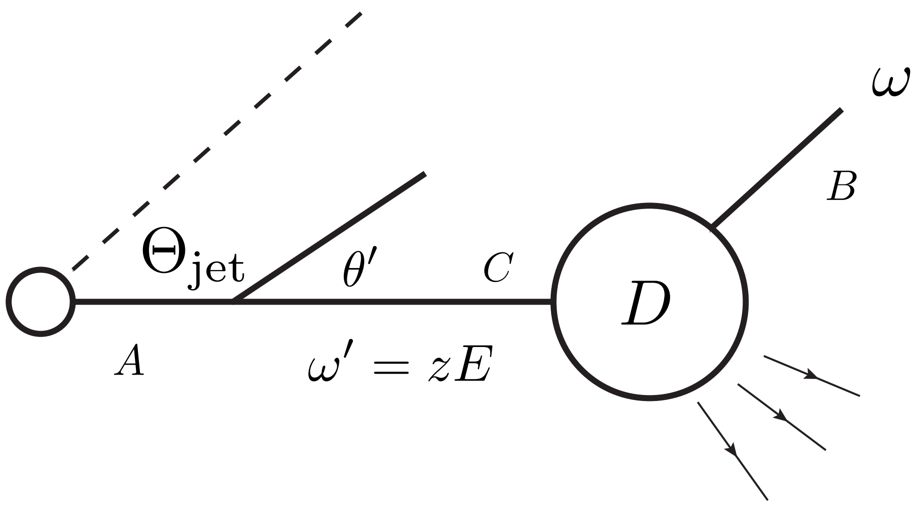

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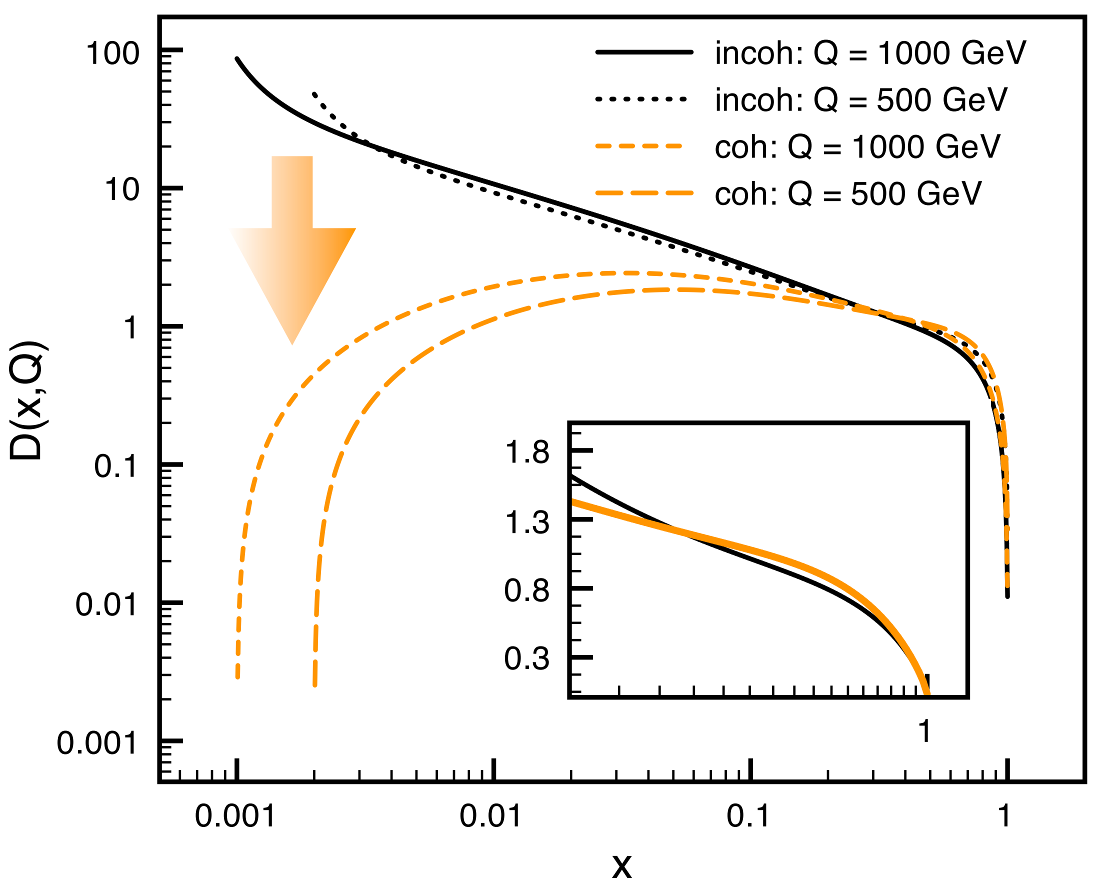
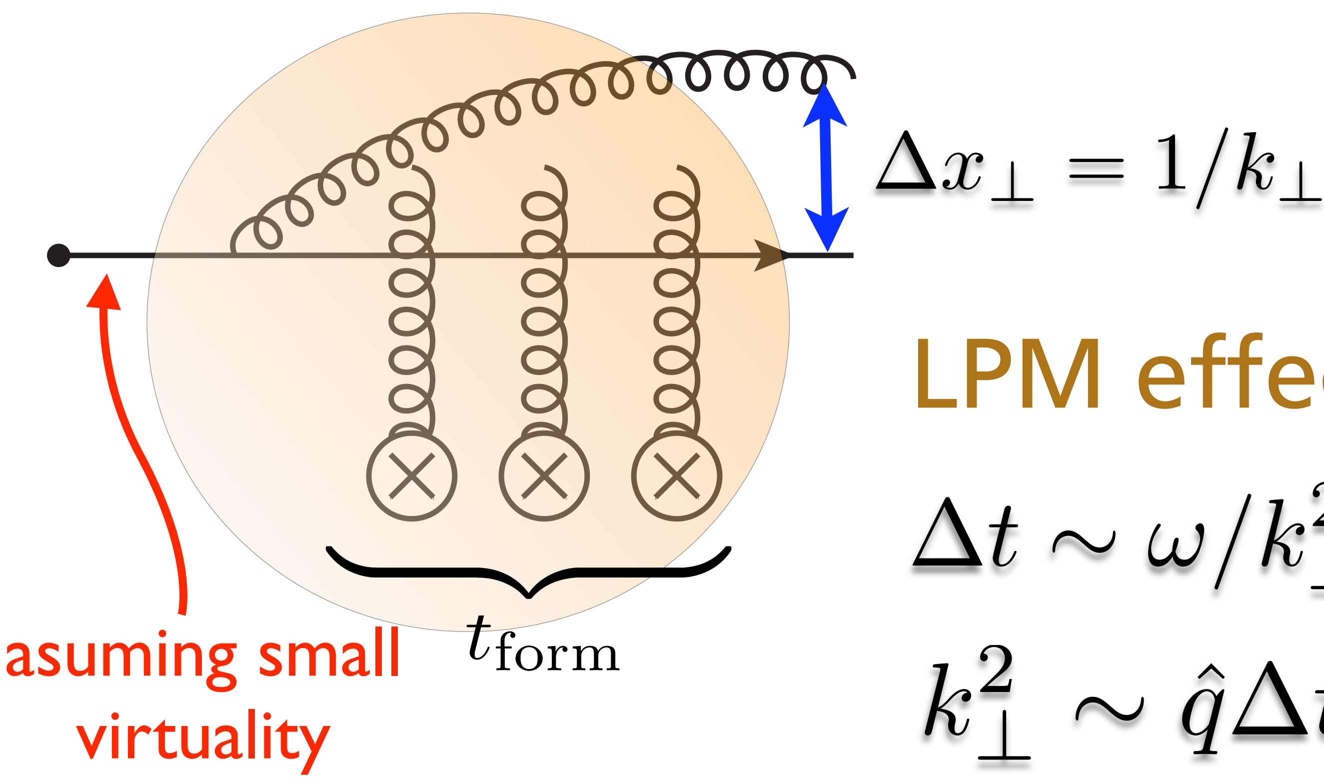


- resummation of branchings
- probabilistic picture
- angular ordering
- basis for precision pQCD & MC

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

Radiation in medium



Naïvely: $\omega \dfrac{dI}{d\omega} \sim \alpha_s N_{\rm scat}$

LPM effect in QCD:

$$\left.\begin{aligned} \Delta t &\sim \omega/k_\perp^2 \\ k_\perp^2 &\sim \hat{q}\Delta t \end{aligned}\right\} \qquad \begin{aligned} t_{\rm br} &= \sqrt{\omega/\hat{q}} \\ k_{\rm br}^2 &= \sqrt{\omega\hat{q}} \end{aligned}$$

soft gluons are formed rapidly!

Coherent spectrum

$$\omega \frac{dI}{d\omega} \sim \alpha_s N_{\rm eff} \sim \alpha_s \frac{L}{t_{\rm br}}$$

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

Multiple radiation

$\Rightarrow$ important when: $\Delta N(\omega) = \alpha_s \frac{L}{t_{\rm br}} \gtrsim 1 \quad \Rightarrow \quad \omega < \alpha_s^2 \hat{q} L^2$

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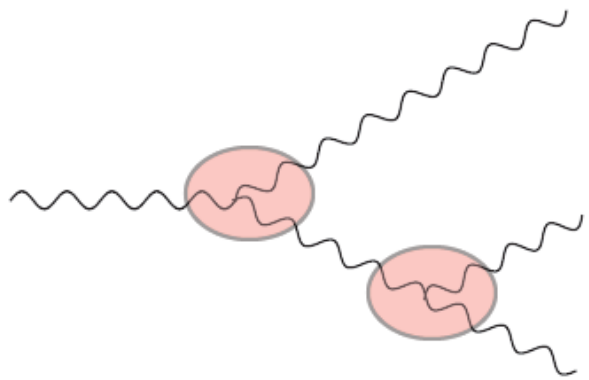
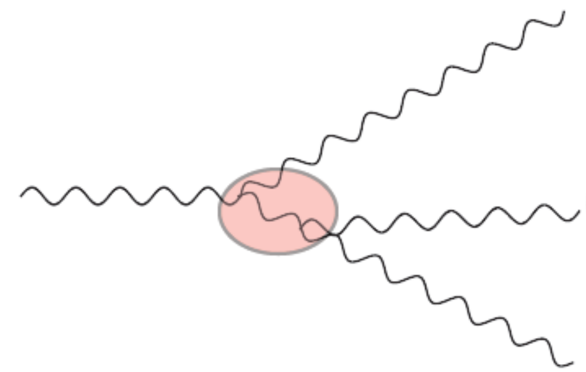


$$\sim \left(\alpha_s \frac{L}{t_{\rm br}}\right)^2$$



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

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; JHEP 1210, 197**, Casalderrey-Solana, Iancu **JHEP 1108 (2011) 015**
Blaizot, Dominguez, Iancu, Mehtar-Tani JHEP 1301, 143

- decoherence in medium!
- interferences are down by factor L
- **probabilistic** picture

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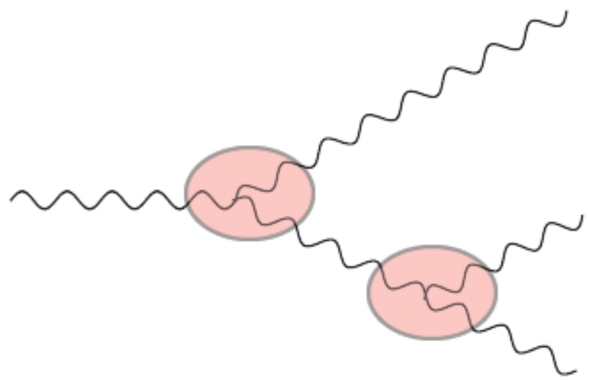

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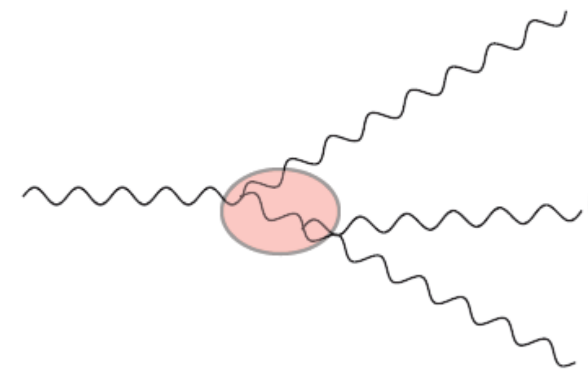

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$$t_{\rm br} = \sqrt{\frac{\hat{q}}{E_a}\frac{1-z(1-z)}{z(1-z)}}$$

Rate of emissions: $dP^{\rm med} = \frac{P(z)}{t_{\rm br}} dz\, dt$

scales with length

Rate equation

$$\frac{d}{d\tau}D(x,\tau) = \int dz\, \frac{\mathcal{K}(z)}{\sqrt{x}}\left[\sqrt{z}D(x/z,\tau) - zD(x,\tau)\right]$$

$$\mathcal{K}(z) = \frac{[1-z(1-z)]^{5/2}}{[z(1-z)]^{3/2}} \sim z^{-3/2}$$

Baier, Dokshitzer, Mueller, Schiff, Son (2001)
Jeon, Moore (2005)
Blaizot, Iancu, Mehtar-Tani (2013)

$\tau = \bar{\alpha}\sqrt{\hat{q}/E}\, t$ :: rescaled time-variable

$$\mathcal{E}_{\text{flow}} \sim \alpha_s^2 \hat{q} L^2$$

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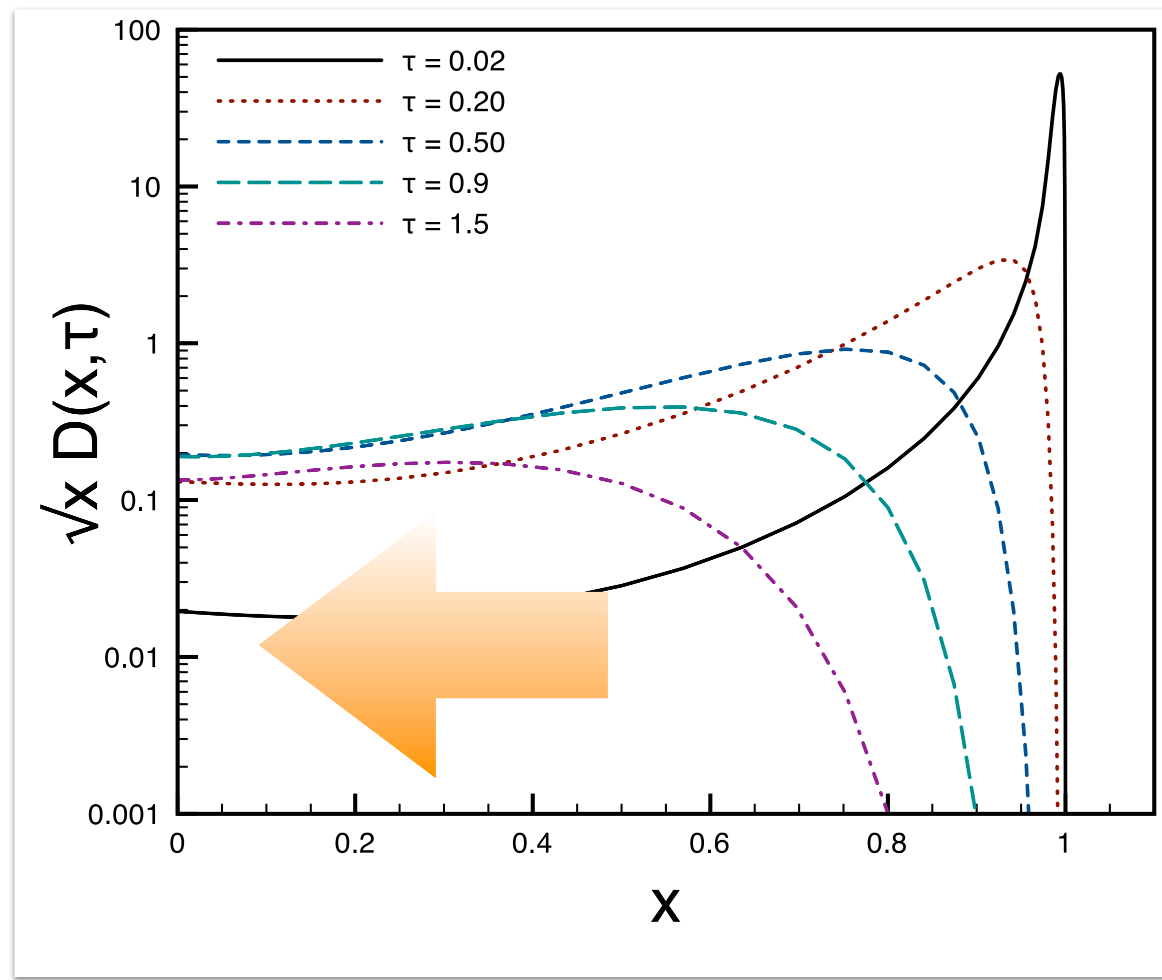
- more: Generating Functional
- $\mathcal{K}$ describes emission
- surprising component: turbulent flow of energy to very soft modes at large angles! $\mathcal{E}_{\text{flow}} \sim \alpha_s^2 \hat{q} L^2$



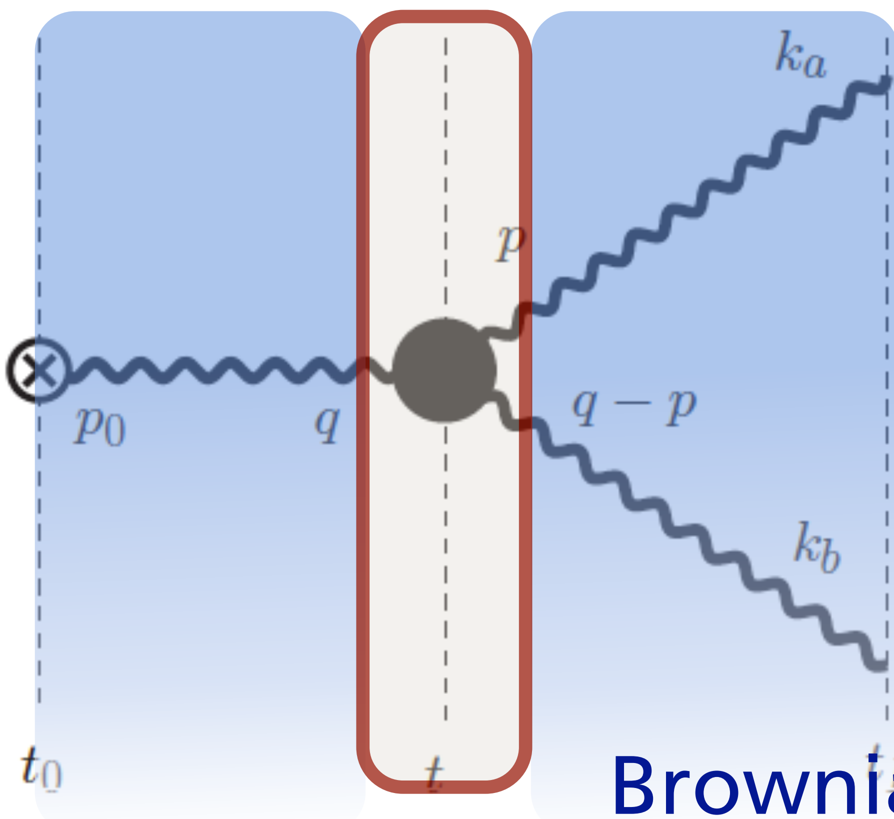
Angular structure

$$\frac{d^2\sigma}{d\Omega_{k_a}\, d\Omega_{k_b}} = 2g^2 z(1-z) \int_{t_0}^{t_L} \mathrm{d}t \int_{\boldsymbol{p}_0,\boldsymbol{q},\boldsymbol{p}} \mathcal{P}(\boldsymbol{k}_a - \boldsymbol{p}, t_L - t)\, \mathcal{P}(\boldsymbol{k}_b - \boldsymbol{q} + \boldsymbol{p}, t_L - t)$$

$$\times\, \mathcal{K}(\boldsymbol{p} - z\boldsymbol{q}, z, p_0^+, t)\, \mathcal{P}(\boldsymbol{q} - \boldsymbol{p}_0, t - t_0)\, \frac{\mathrm{d}\sigma_{hard}}{\mathrm{d}\Omega_{p_0}}\,,$$

emission with mom. **p**

prob. of acquiring momentum in t_L-t



Brownian motion

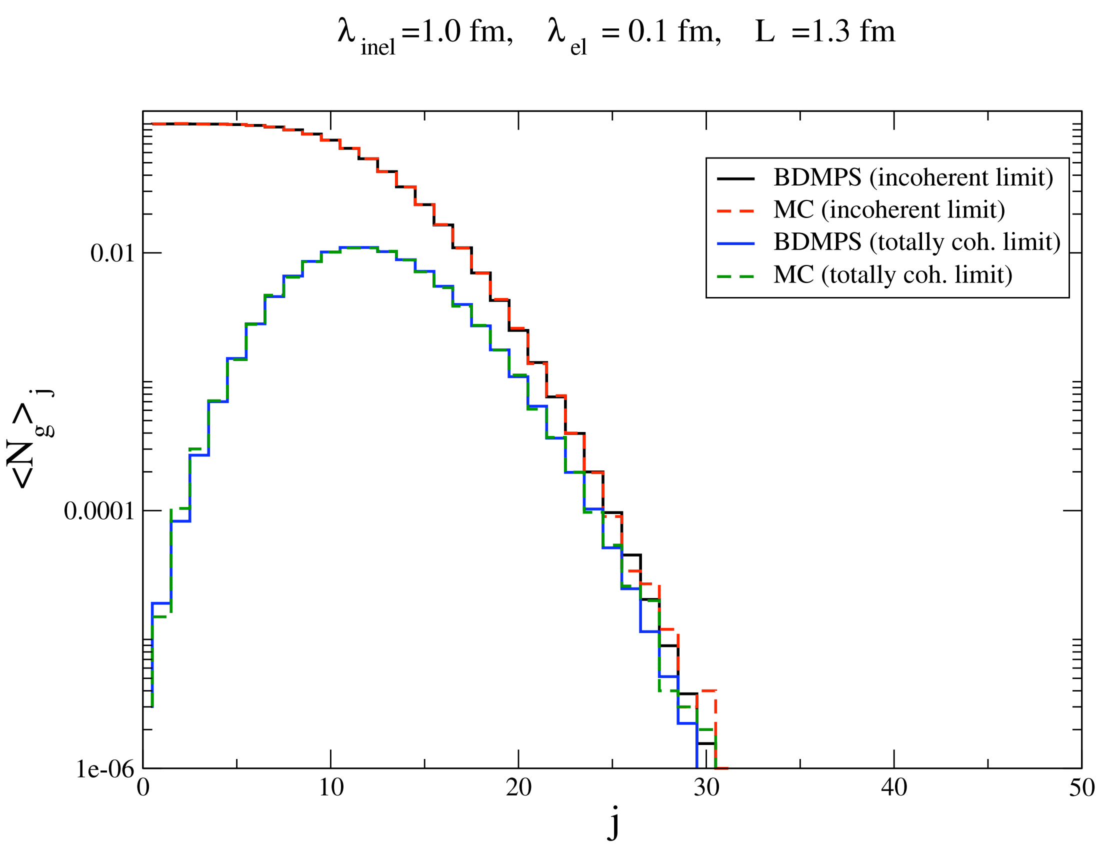
Medium scale: $Q_s^2 = \hat{q}L$

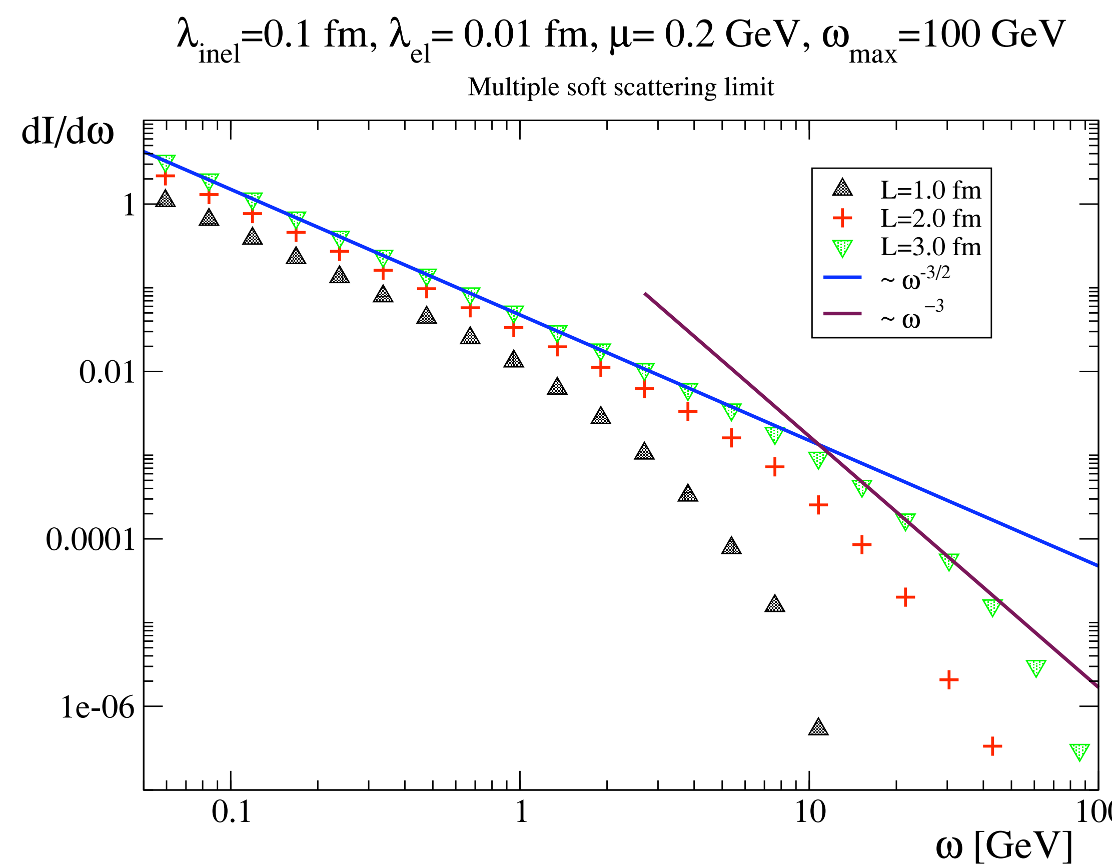
- proof: factorization up to corrections ~ L/t_{br}
- $\mathcal{P}$ describes $k_\perp$-broadening
- $\mathcal{K}$ describes emission

Mehtar-Tani, Salgado, KT JHEP 1210 (2012) 197
Blaizot, Dominguez, Iancu, Mehtar-Tani JHEP 1301, 143

MC implementation of LPM

Stachel, Wiedemann, Zapp PRL 103 (2009) 152302, JHEP 1107 (2011) 118



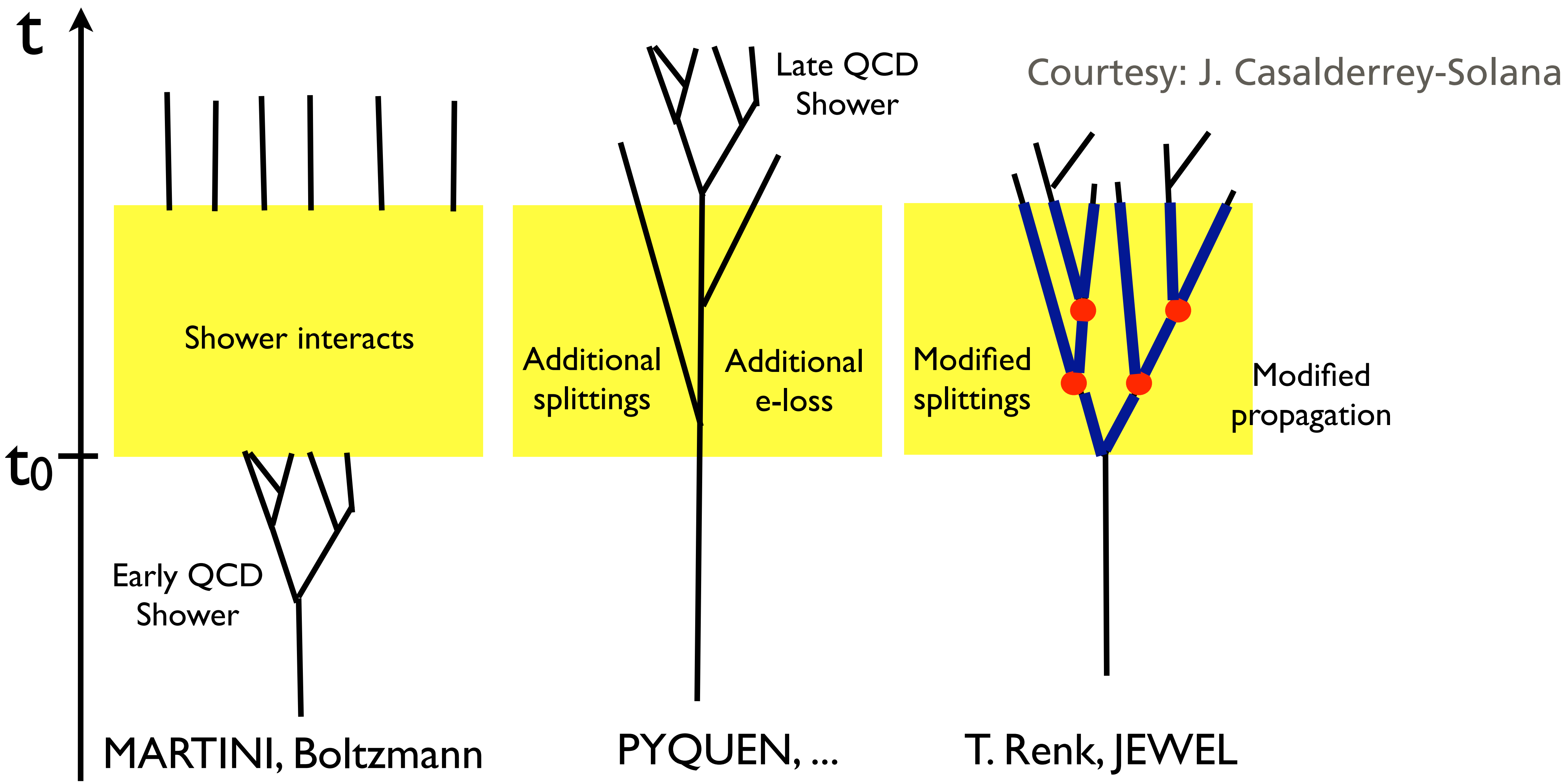


- well-controlled, probabilistic prescription
- allows to go beyond known approximations

$$\lambda_{(in)el} = \frac{1}{n_0 \sigma_{(in)el}}$$

$$S_{\rm no}^{\rm (in)el}(L) = \exp\left(- L/\lambda_{\rm (in)el}\right)$$

Interface: HE jet in medium



Is it reasonable to assume a separation of these processes?

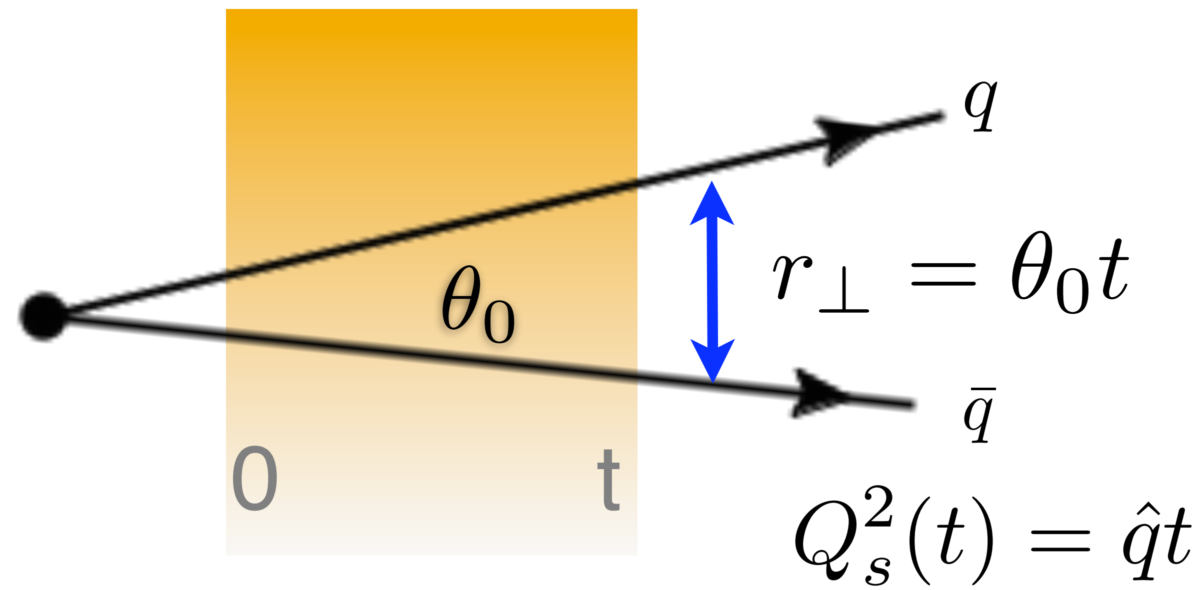
Guidance from theory is needed!

Interferences: analysis

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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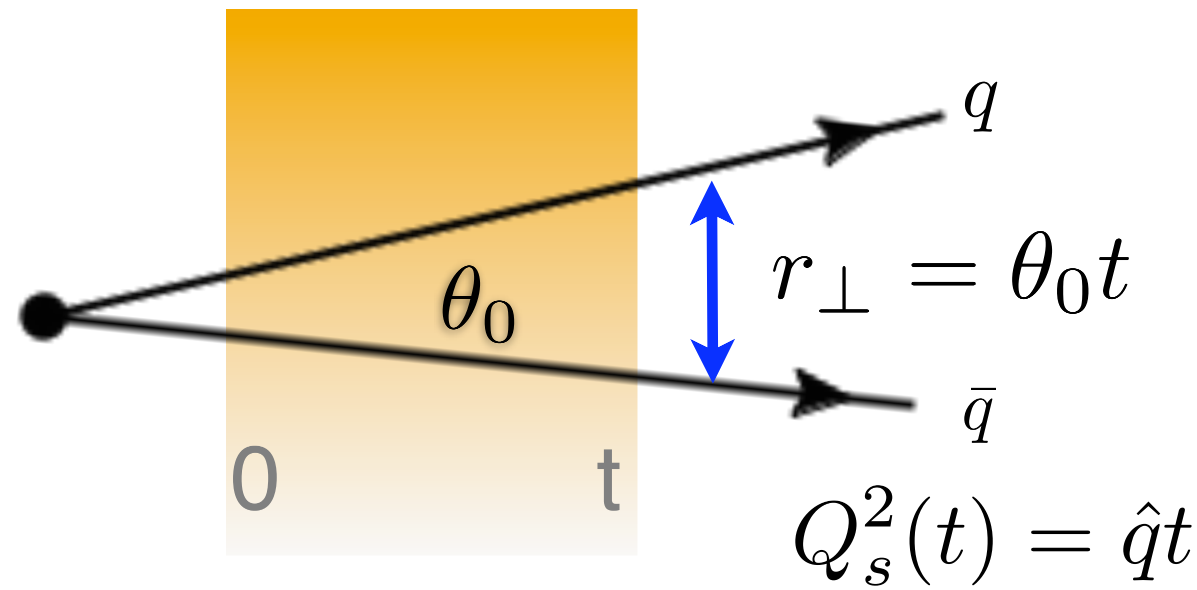

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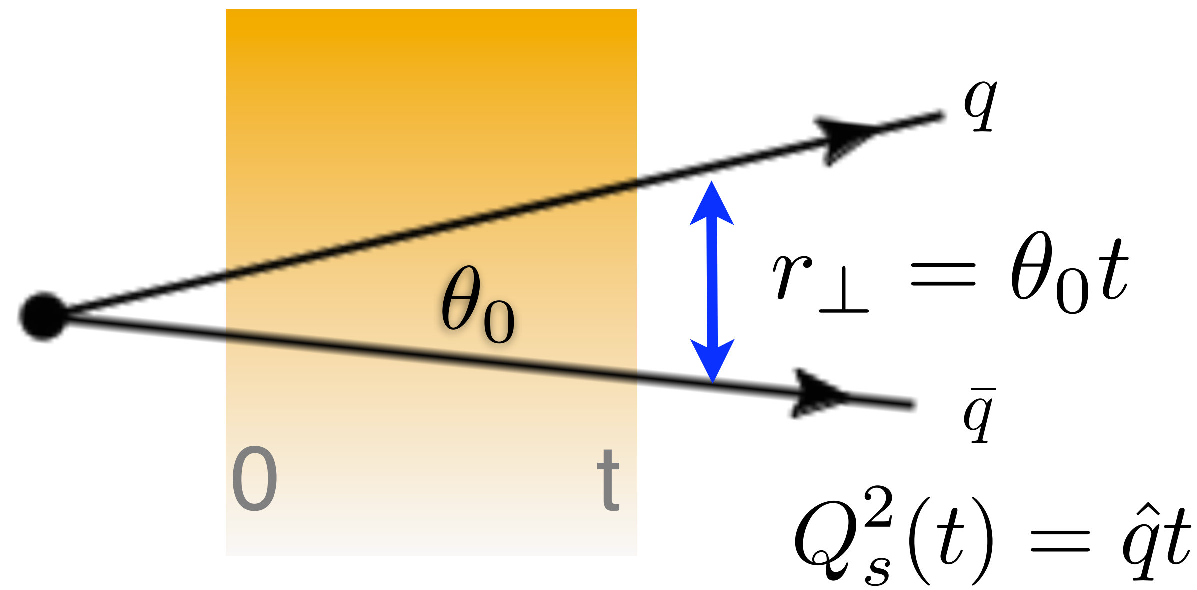

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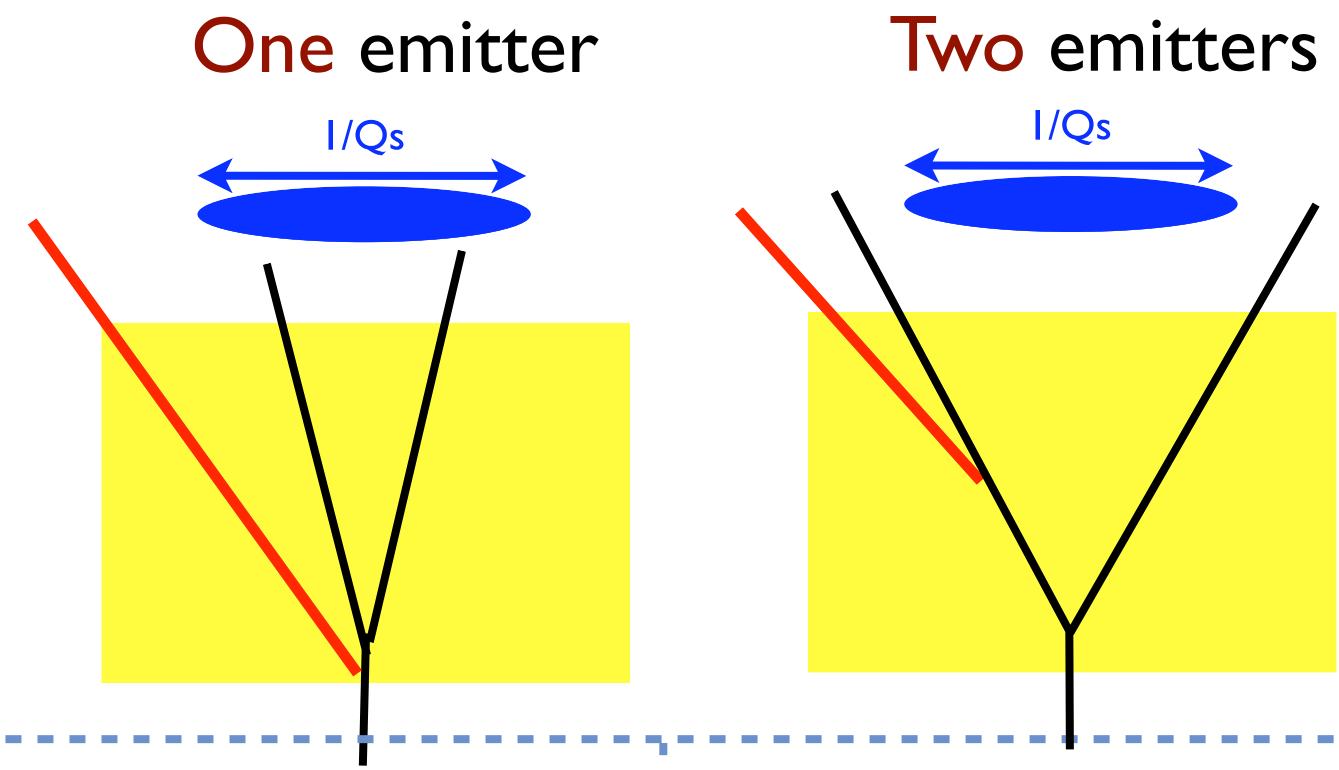
decoherence parameter

characteristic decoherence time

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

Two simple conclusions

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



Courtesy: J. Casalderrey-Solana

vacuum coherence	AO survives, radiation inside dipole	AO broken, radiation up to Q_s
"medium-induced"	radiation as total charge	radiation as independent charges

Revises the usual picture of rad. in medium!

Parametric behavior

Generic scaling will involve the medium length L

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

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jet definition (Θ_{jet}=R)!

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$$\theta_c = 1/\sqrt{\hat{q}L^3}$$ jet definition ($\Theta_{\rm jet}$=R)!

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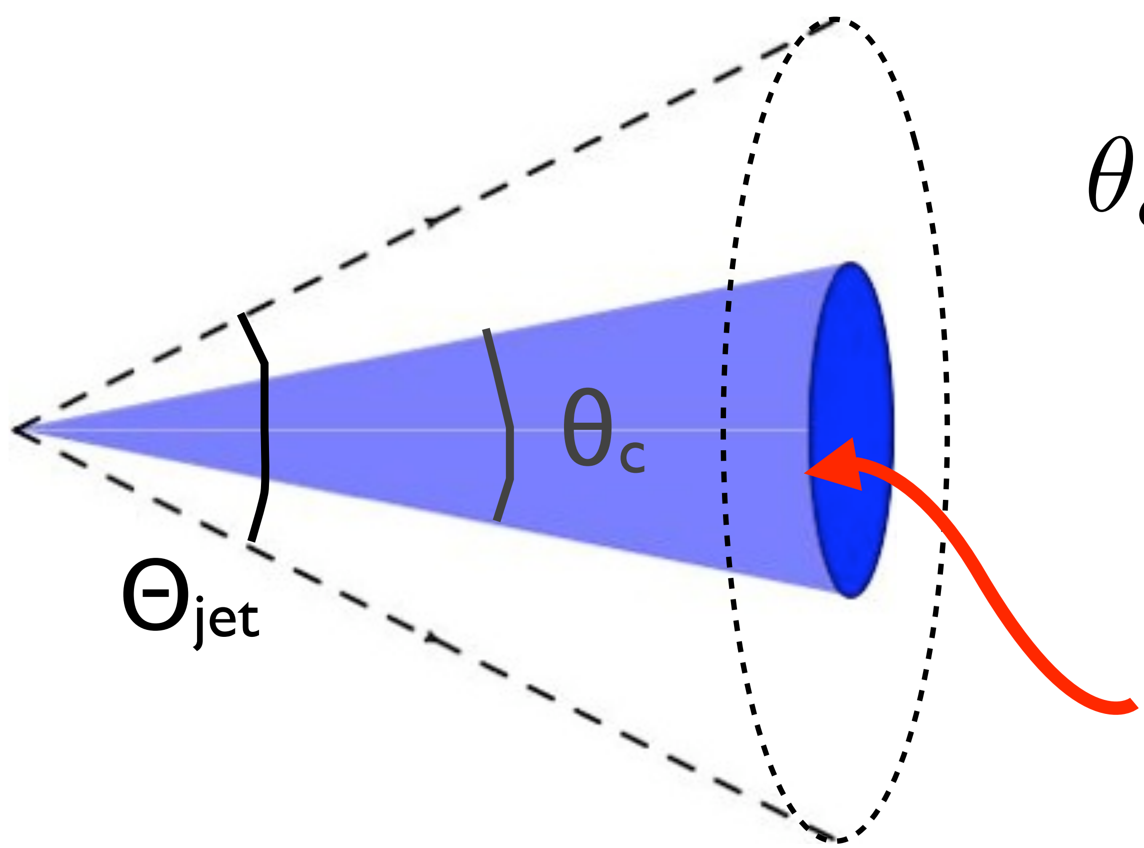


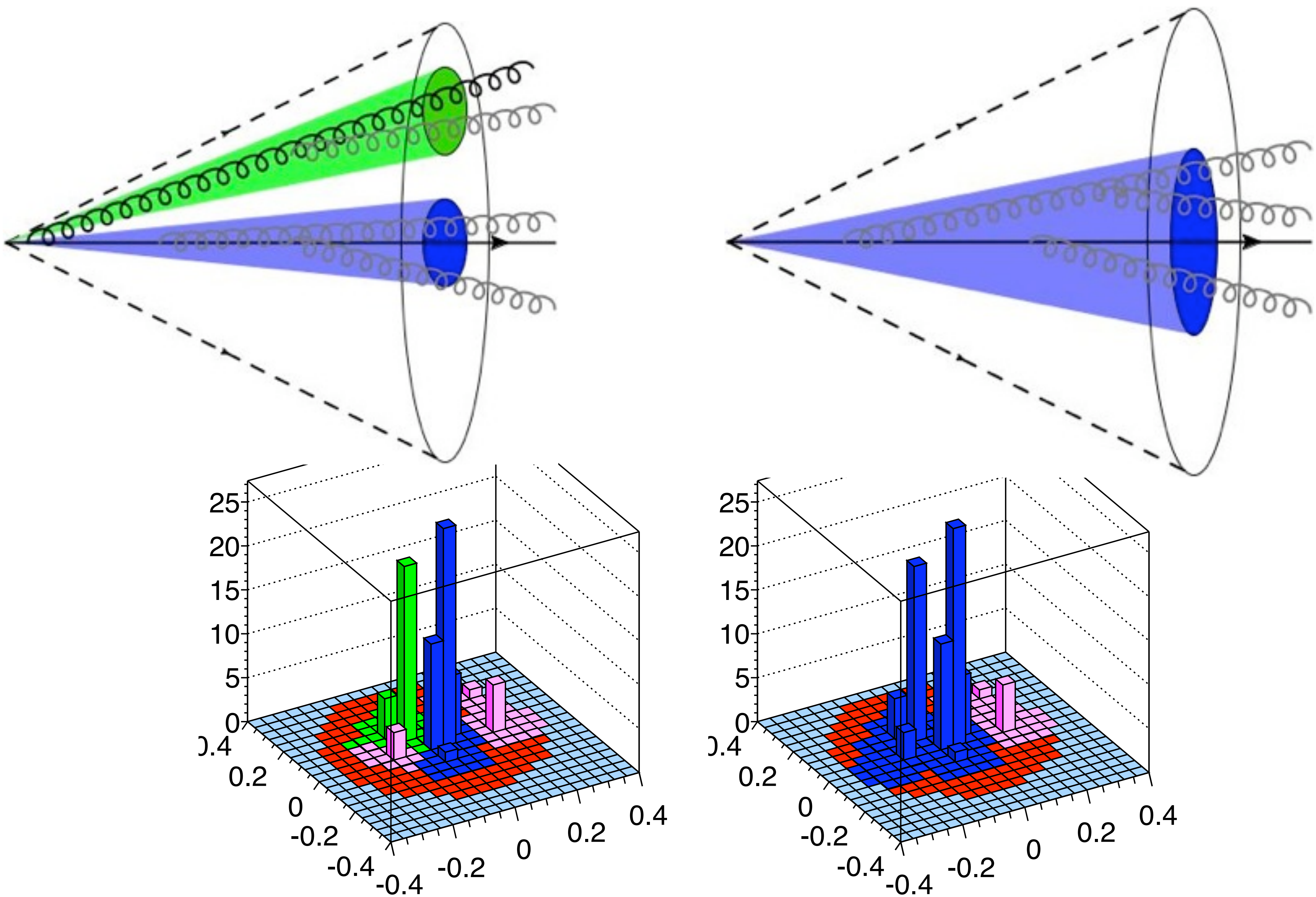
Coherent inner 'core'

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

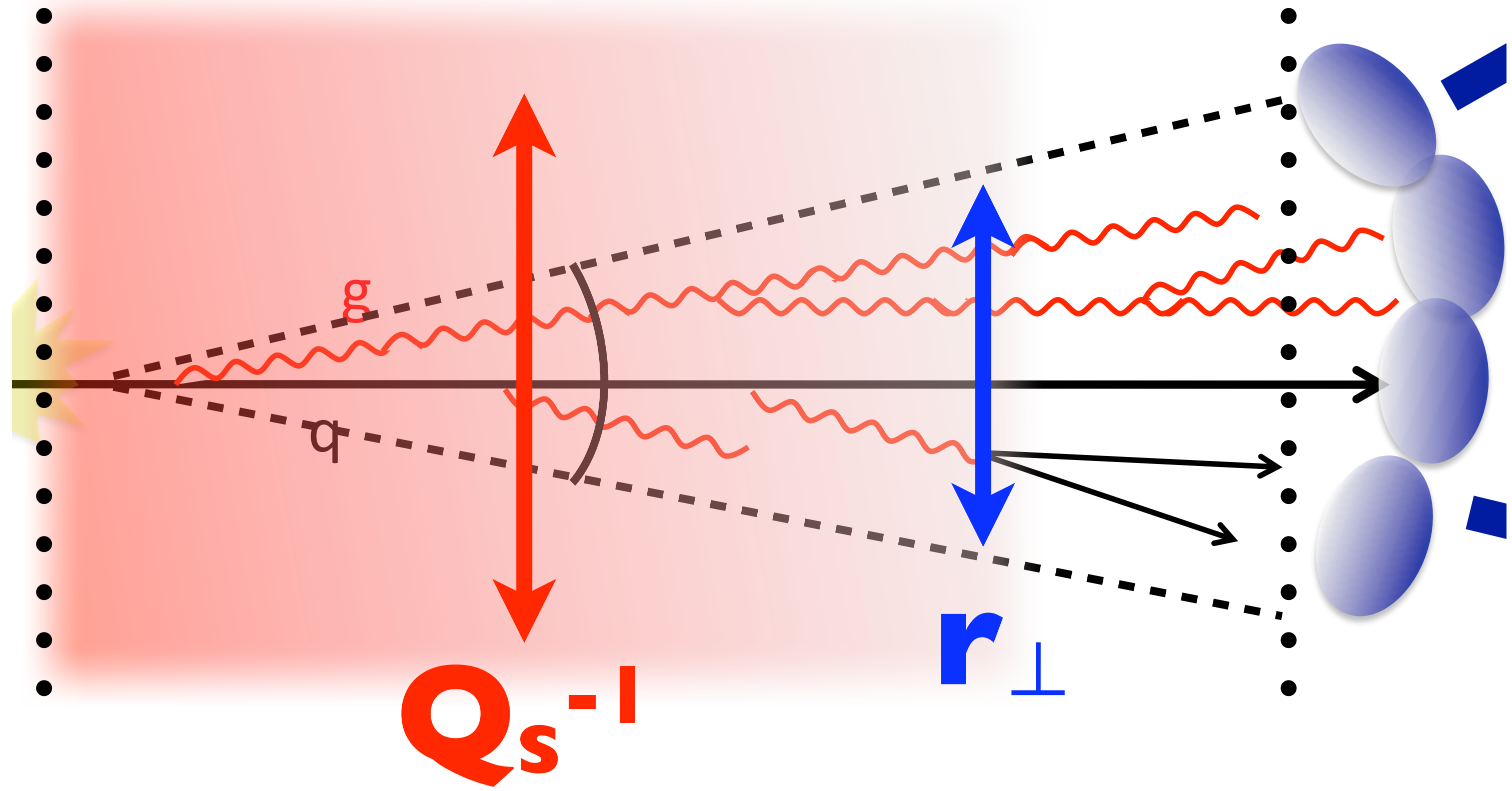
In central collisions: $\Theta_{\text{jet}} > \theta_c$

Casalderrey-Solana, Mehtar-Tani, Salgado, KT (2013)

Resolved effective charges



$M_\perp = E\Theta_{\text{jet}}$ $Q_0 \sim \Lambda_{\text{QCD}}$



- emerging well-controlled picture in limiting cases: separation of scales
- "theoretically motivated" prescriptions:
  - JEWEL: MC-LPM + t_{form} ordering +...
  - QPYTHIA: modified splitting function
  - MARTINI: vac. shower + rate equation
  - PYQUEN: induced gluons + vac. shower