Theory Jet Overview II

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Jet Modification in the RHIC and LHC Era

Detroit

MOTIVATION

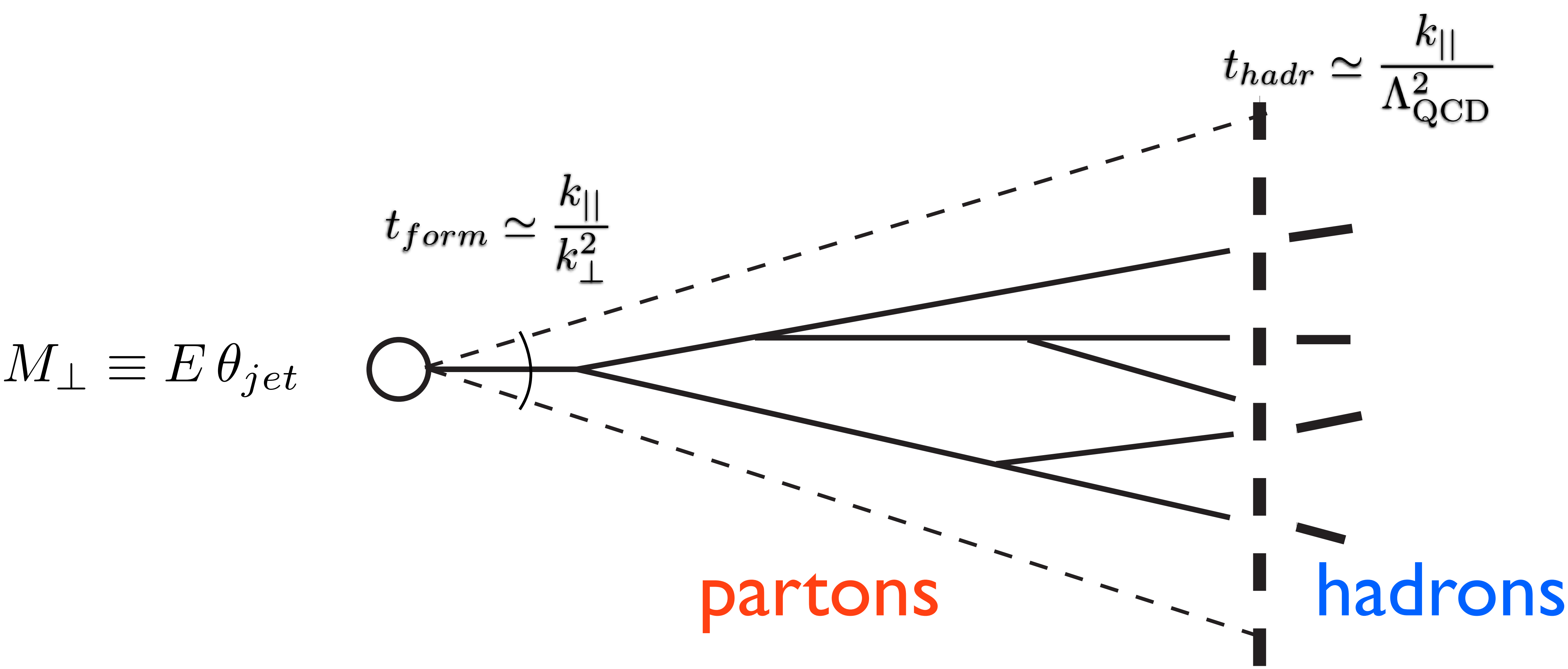
- Fantastic results on jet observables at QM!
- In-medium jets match the vacuum base line (Fragmentation functions)
- Look for deviations of in-medium observables from vacuum ones in pQCD

OUTLINE

- Introduction
- Jets in vacuum (transverse coherence)
- Medium-induced gluon radiation (longitudinal coherence)
- In-medium multiple parton branching:

...toward an understanding of jets in HIC?

- Originally a hard parton (quark/gluon) which fragments into many partons with virtuality down to a non-perturbative scale where it hadronizes
- LPHD: Hadronization does not affect inclusive observables (jet shape, energy distribution etc..)

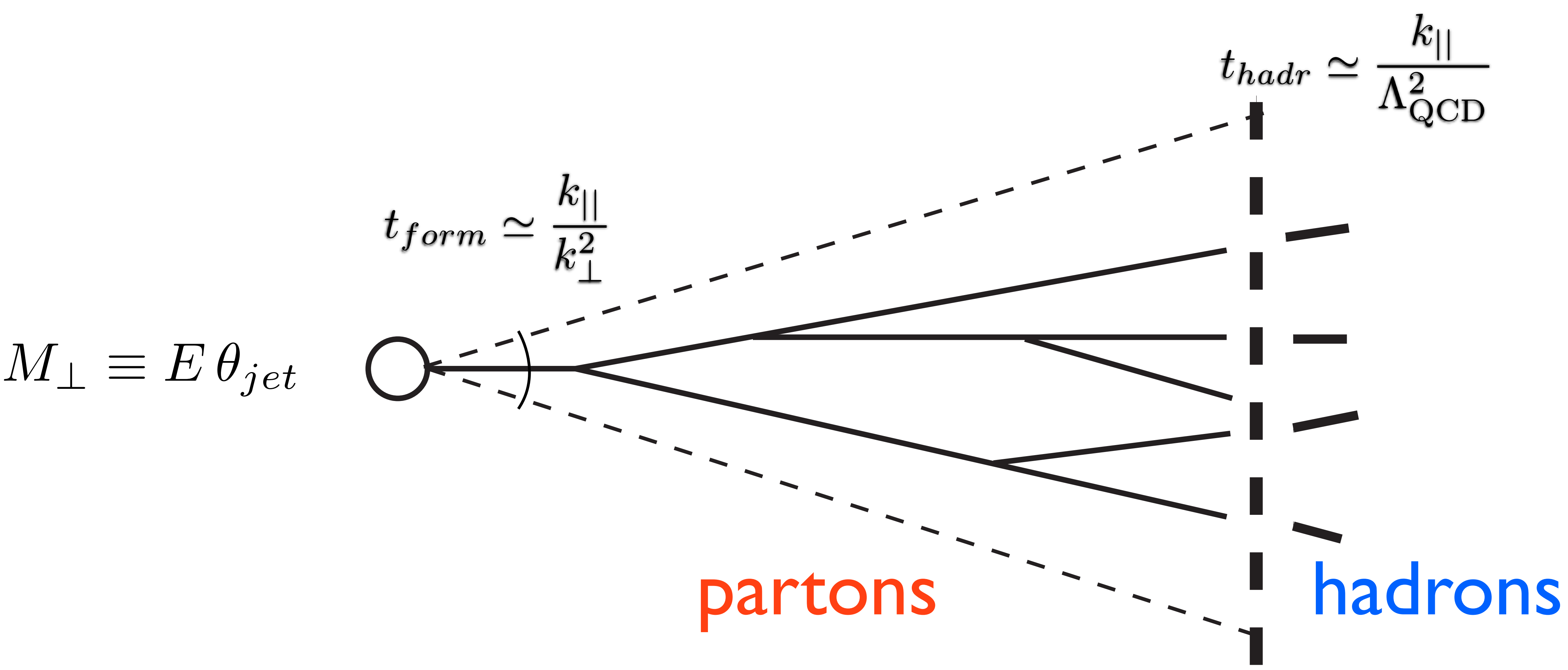


Large time domain for pQCD: $\frac{1}{E} < t < \frac{E}{\Lambda^2_{\rm QCD}}$

- Inclusive jet observables determined by two scales:

the jet transverse mass $M_\perp \equiv E\,\theta_{jet}$

non-perturbative scale $Q_0 \sim \Lambda_{\rm QCD}$



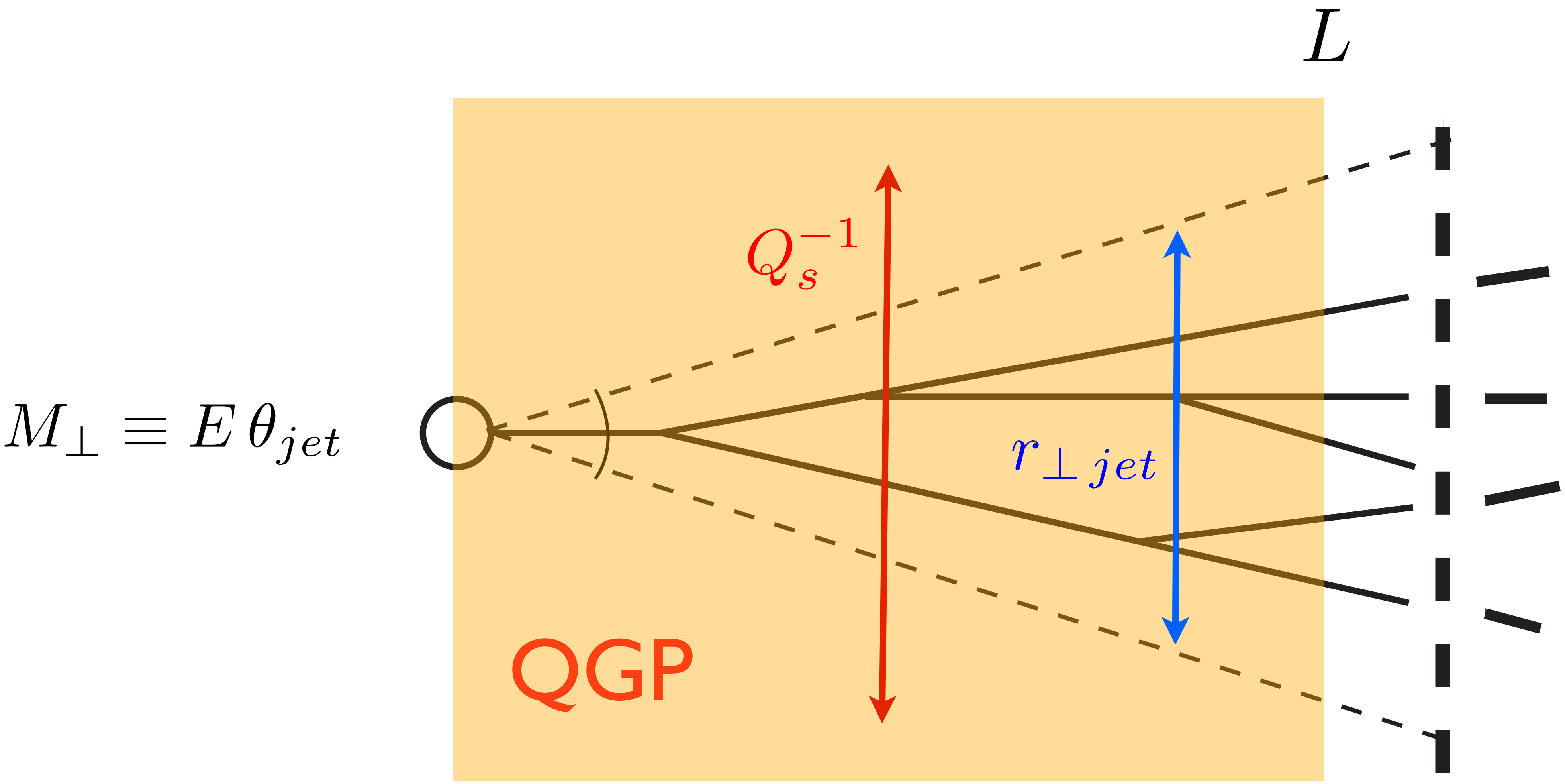
Large time domain for pQCD: $\frac{1}{E} < t < \frac{E}{\Lambda^2_{\rm QCD}}$

- In-medium scales? (before doing the math)

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

+

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



- Hadronization outside the medium for energetic partons: $t_{hadr} \sim \frac{1-100}{(0.2)^2\cdot 5} = 5 - 500\,{\rm fm}$

- In medium scales? (before doing the math)

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

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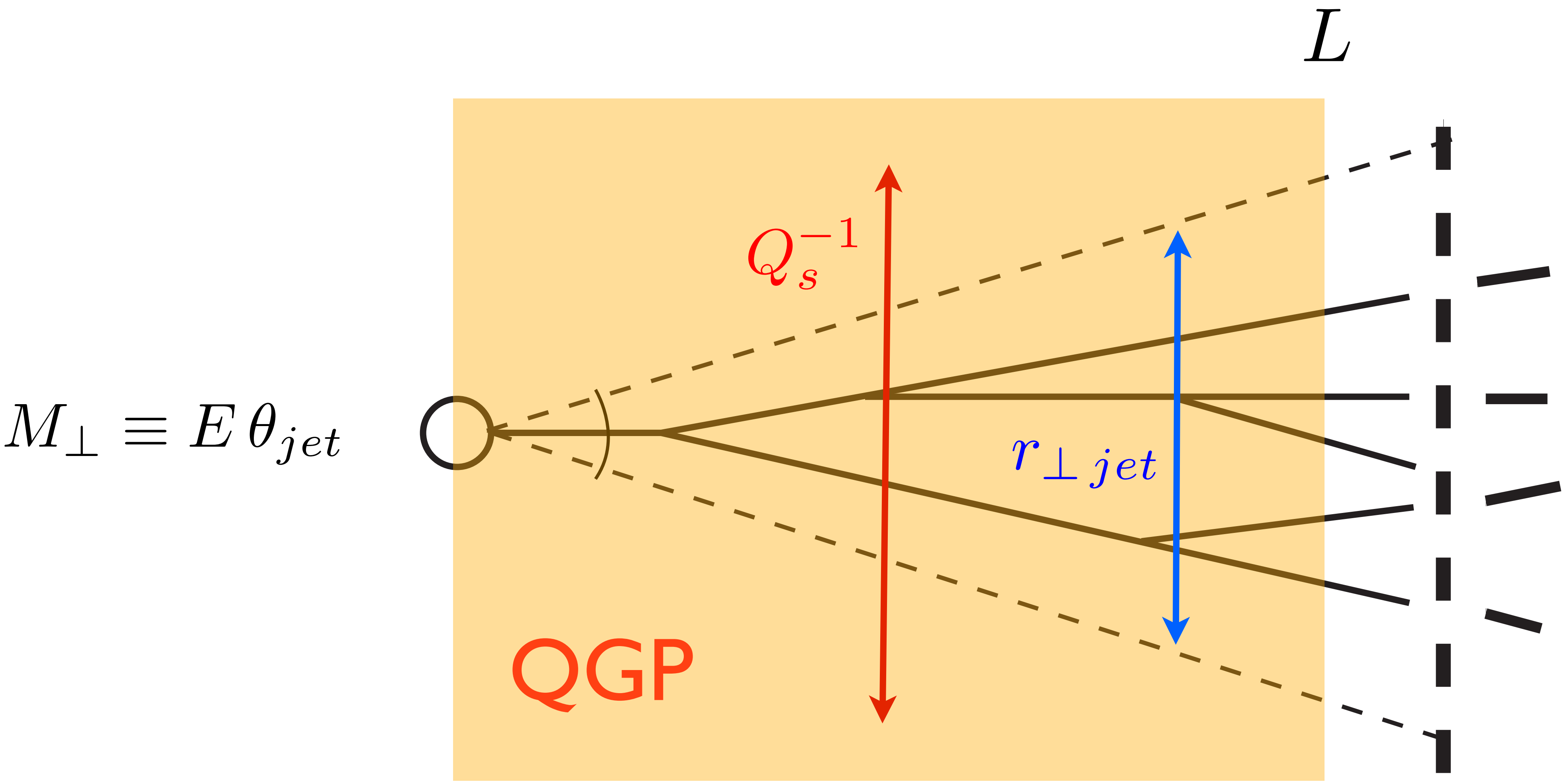
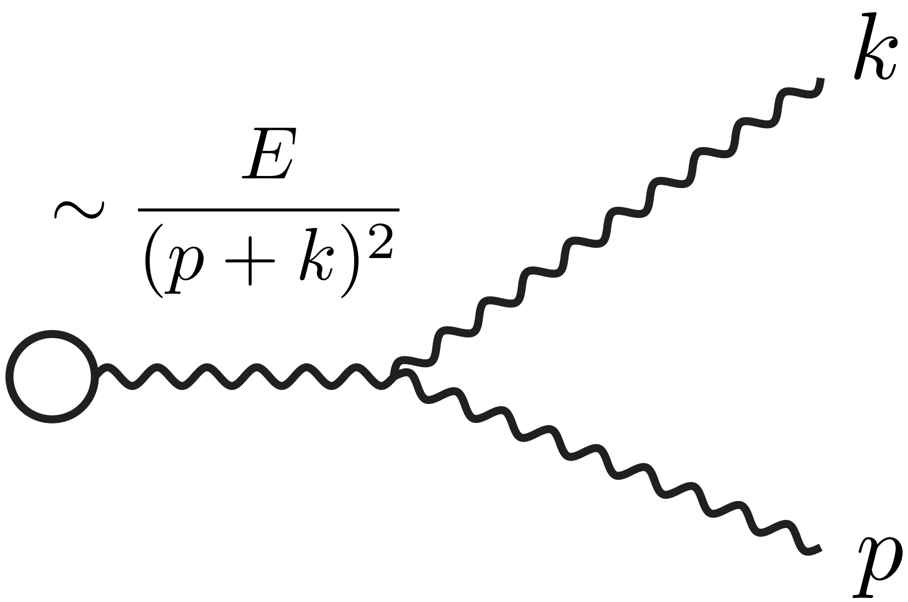


- Multiscale problem!

JETS IN VACUUM
TRANSVERSE COHERENCE

FACTORIZATION OF BRANCHINGS IN VACUUM

$$M_\perp \equiv E\,\theta_{jet}$$



$$k_\perp > Q_0 \qquad z = \omega / E$$

the diff-branching probability

$$dP = \frac{\alpha_s\, C_R}{\pi}\, P(z)\, dz\, \frac{d^2 k_\perp}{k_\perp^2}$$

soft and collinear divergences

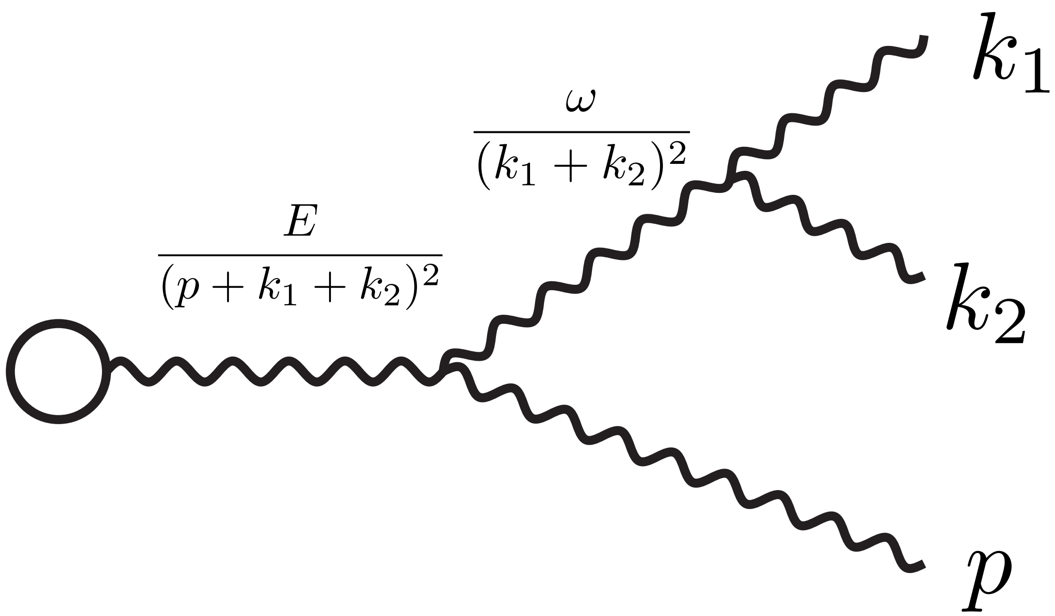
phase-space enhancement

$$\alpha_s \to \alpha_s \ln^2 \frac{M_\perp}{Q_0}$$

formation time of the daughter partons

$$t_f \equiv \frac{E}{(p+k)^2} \sim \frac{E}{2p\cdot k} \sim \frac{\omega}{k_\perp^2}$$

FACTORIZATION OF BRANCHINGS IN VACUUM



$$\omega_2 \ll \omega_1 \ll E$$

$$\frac{E}{(p+k_1+k_2)^2} \sim \frac{E}{2p\cdot k_1} \sim \frac{\omega_1}{k_{1\perp}^2}$$

$$\frac{\omega}{(k_1+k_2)^2} \sim \frac{\omega_1}{2k_1\cdot k_2} \sim \frac{\omega_2}{k_{2\perp}^2}$$

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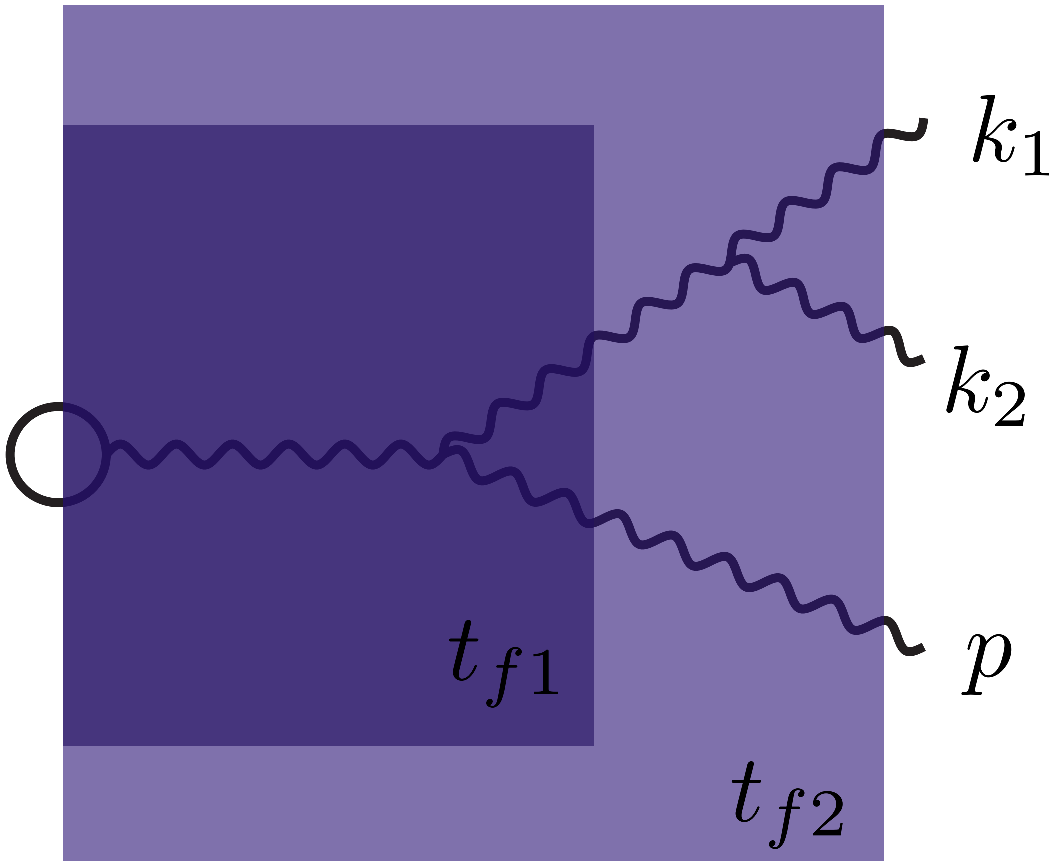

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Logarithmic regions $t_{f2} \gg t_{f1}$

$$P_{12} = \left(\frac{\alpha_s C_A}{\pi}\right)^2 \int^E \frac{d\omega_1}{\omega_1} \int^{\omega_1} \frac{d\omega_2}{\omega_2} \int^{M_\perp} \frac{d^2k_{\perp 1}}{k_{\perp 1}^2} \int^{k_{\perp 1}} \frac{d^2k_{\perp 2}}{k_{\perp 2}^2}$$

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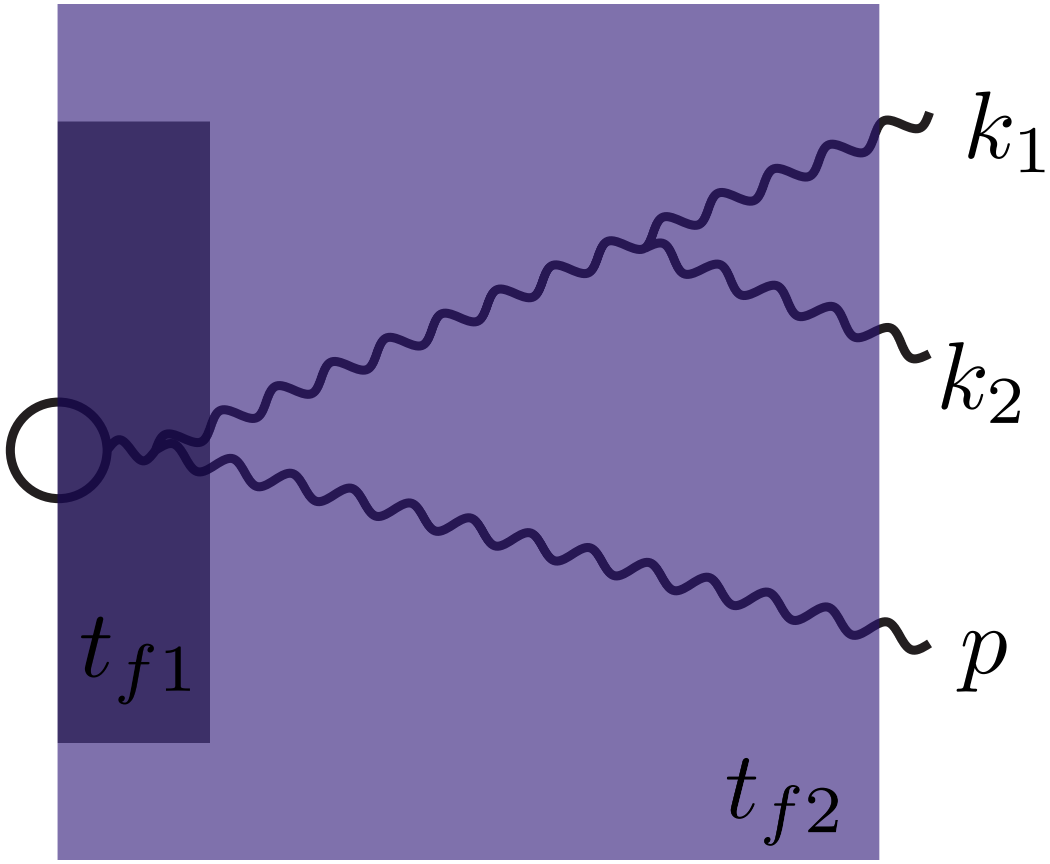

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The softest gluon sees its parent as if they were produced at t=0

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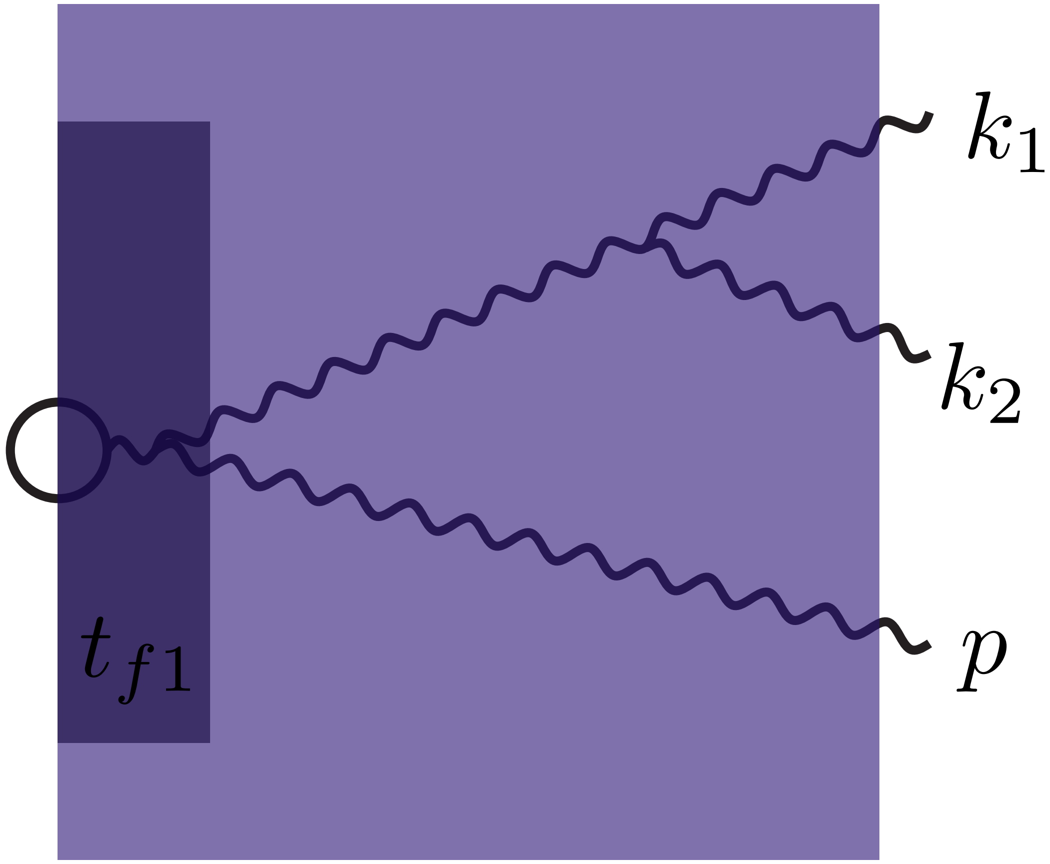

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Logarithmic regions $t_{f2} \gg t_{f1}$

For arbitrary gluon emissions

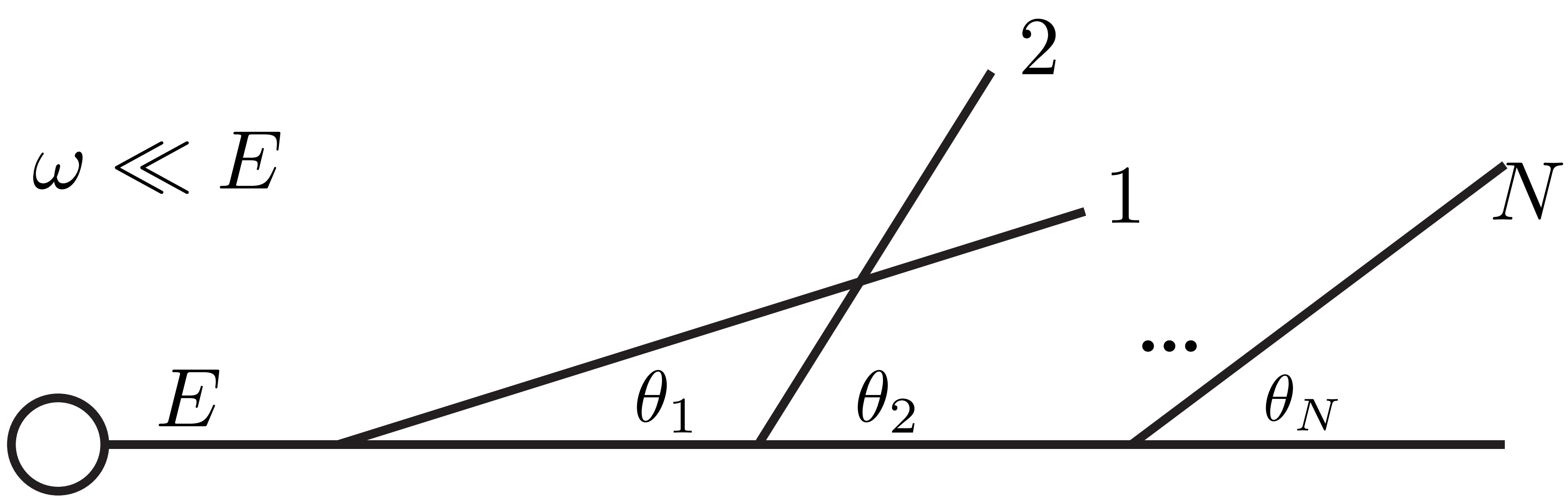
$$t_{fN} \gg \ldots \gg t_{f2} \gg t_{f1}$$

BRANCHING IN VACUUM

Ladder diagrams (no interferences) resum mass singularities:
Strong ordering in k_T (DGLAP)

$$\frac{d}{d\ln M_\perp} D_A^B(x, M_\perp) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P_A^C(z)\, D_c^B(x/z, M_\perp)$$

In the soft regime $\omega \ll E$



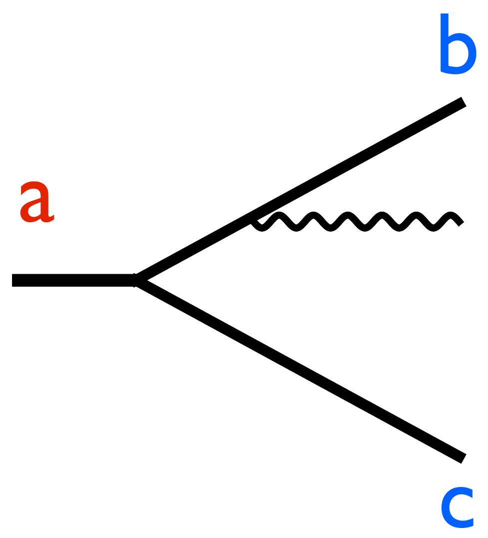
$$M_\perp \gg k_{\perp 1} \gg k_{\perp 2} \gg \ldots \gg k_{\perp N}$$

Radiation suppressed at $\theta_2 > \theta_1$ because of coherence phenomena: Interference of 1 with 2 at large angles

$k_{2\perp} \ll k_{1\perp}$ $\quad\quad$ $\theta_1 < \theta_2 \ll \frac{\omega_1}{\omega_2}\theta_1$ $\quad\quad$ k_T ordering fails!

COLOR COHERENCE
(BUILDING BLOCK OF QCD EVOLUTION)

gluon radiation off a pair of color charges b and c which originates from a (highly virtual) charge a



classical current

$$J^\mu = T_a \frac{p_a^\mu}{p_a \cdot k} + T_b \frac{p_b^\mu}{p_b \cdot k}$$

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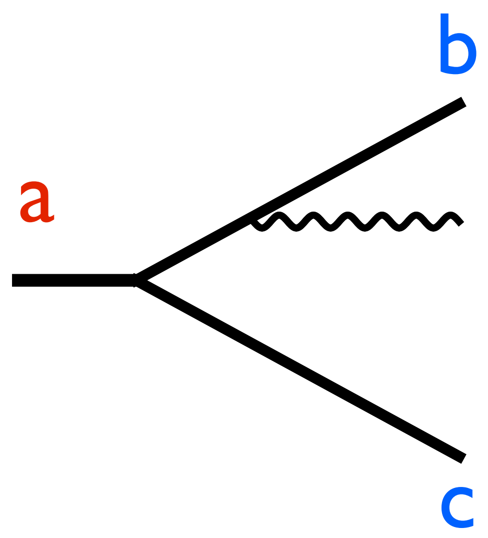

classical current $$J^\mu = T_a \frac{p_a^\mu}{p_a \cdot k} + T_b \frac{p_b^\mu}{p_b \cdot k}$$

$$(2\pi)^2 \, \omega \frac{dN_\mathrm{a}}{d^3k} = \frac{\alpha_s}{\omega^2} \left[C_\mathrm{b} \left(\mathcal{R}_\mathrm{b} - \mathcal{J} \right) + (\mathrm{b} \to \mathrm{c}) + C_\mathrm{a} \, \mathcal{J} \right]$$

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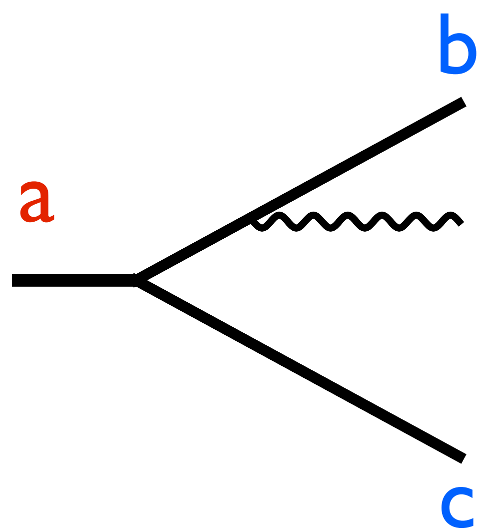

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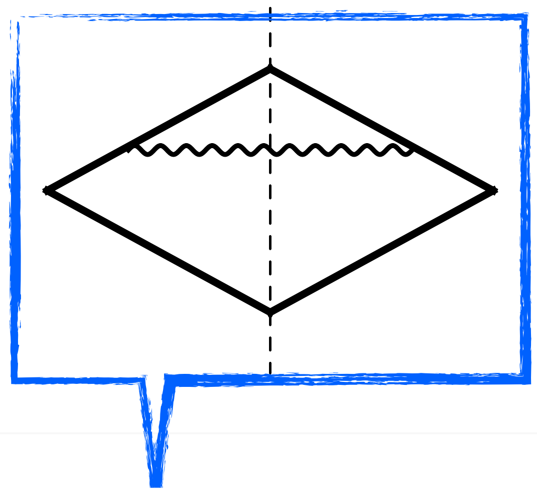
direct emission



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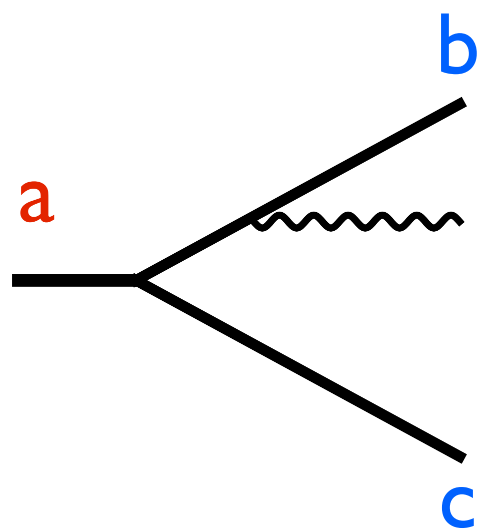

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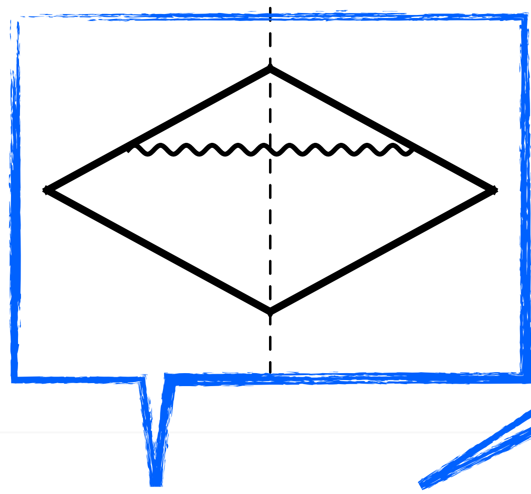
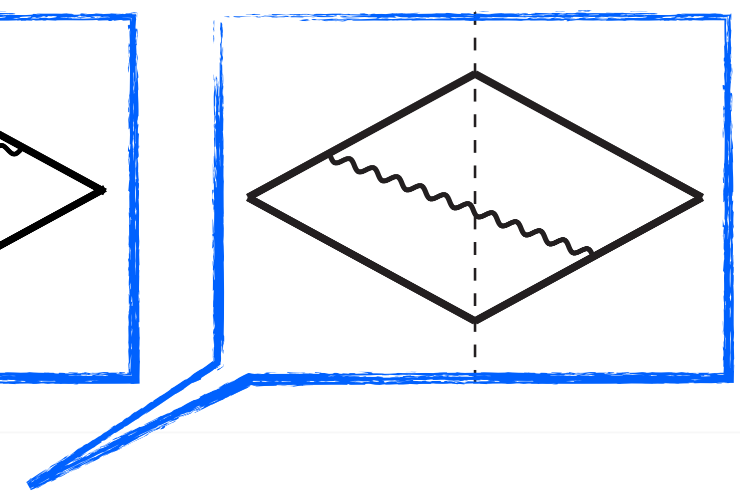


interference



$$(2\pi)^2\, \omega \frac{dN_{\rm a}}{d^3k} = \frac{\alpha_s}{\omega^2} \left[C_{\rm b} \left(\mathcal{R}_{\rm b} - \mathcal{J} \right) + ({\rm b} \to {\rm c}) + C_{\rm a}\, \mathcal{J} \right]$$

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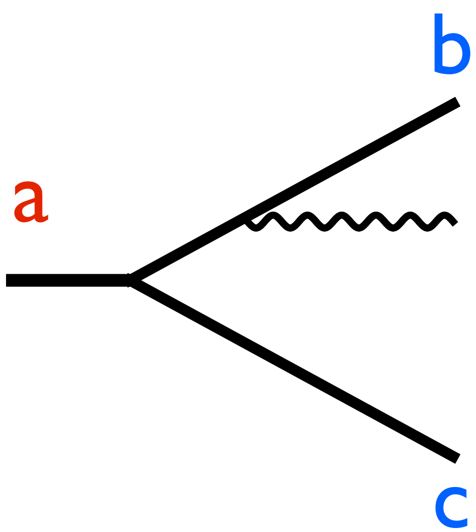

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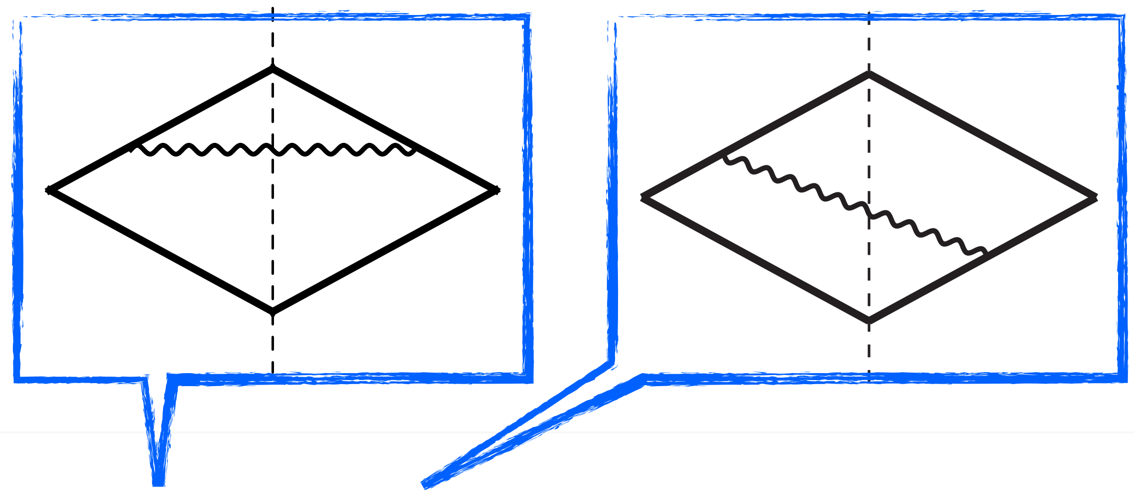
direct emission | interference



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For g→qq $\quad C_{\mathrm{b}} = C_{\mathrm{c}} = C_F$ and $C_{\mathrm{a}} = C_A$

For γ→qq $\quad C_{\mathrm{b}} = C_{\mathrm{c}} = C_F$ and $C_{\mathrm{a}} = 0$

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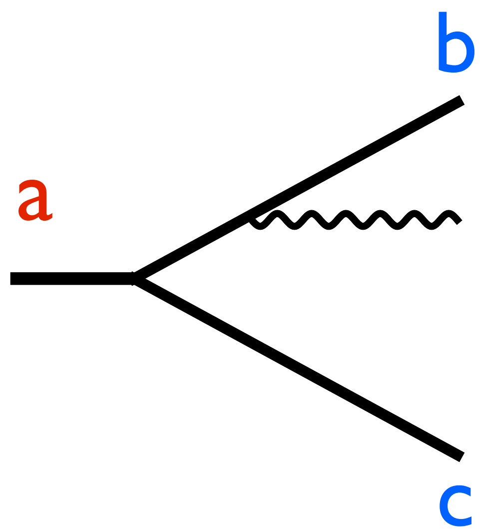
(BUILDING BLOCK OF QCD EVOLUTION)



Incoherent emissions at small angles

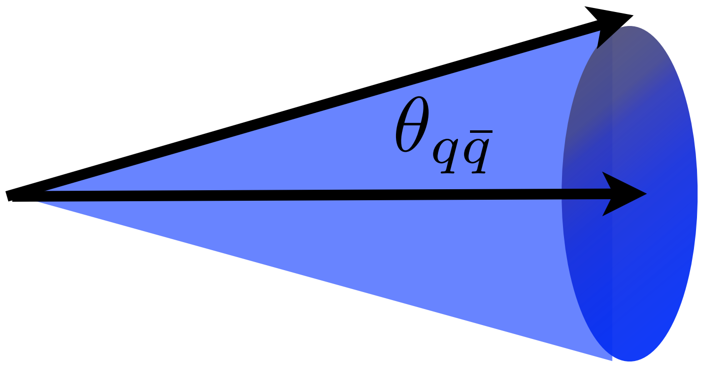
$$\omega \frac{dN_{\rm a}}{d\omega d^2 k_\perp} \propto \frac{\alpha_s C_{\rm b}}{k_\perp^2} + ({\rm b} \to {\rm c}) \qquad \theta \ll \theta_{bc} \quad (k_\perp \ll \omega \theta_{bc})$$

large angle emission by the total charge

$$\omega \frac{dN_{\rm a}}{d\omega d^2 k_\perp} \propto \frac{\alpha_s C_{\rm a}}{k_\perp^2} \qquad \theta \gg \theta_{bc} \quad (k_\perp \gg \omega \theta_{bc})$$

ANTENNA IN VACUUM (BUILDING BLOCK OF QCD EVOLUTION)

$$dN^{\rm vac}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\ d\theta}{1-\cos\theta}\Theta(\cos\theta - \cos\theta_{q\bar{q}}),$$



Angular ordering in vacuum

- Radiation confined inside the cone
- Why?

gluons emitted at angles larger than the pair opening angle cannot resolve its internal structure: Emission by the total charge (suppressed for a white antenna)

gluon transverse wave length

$$\lambda_\perp \sim \frac{1}{k_\perp}$$

antenna size at formation time

$$r_\perp \sim t_f \theta_{q\bar{q}} \sim \frac{\omega}{k_\perp^2}\theta_{q\bar{q}}$$

$$\lambda_\perp > r_\perp \quad \Rightarrow \quad \theta > \theta_{q\bar{q}}$$

[Bassetto, Mueller, Ciafaloni, Marchesini, Dokshitzer, Khoze, Troyan, Fadin, Lipatov, 80's]

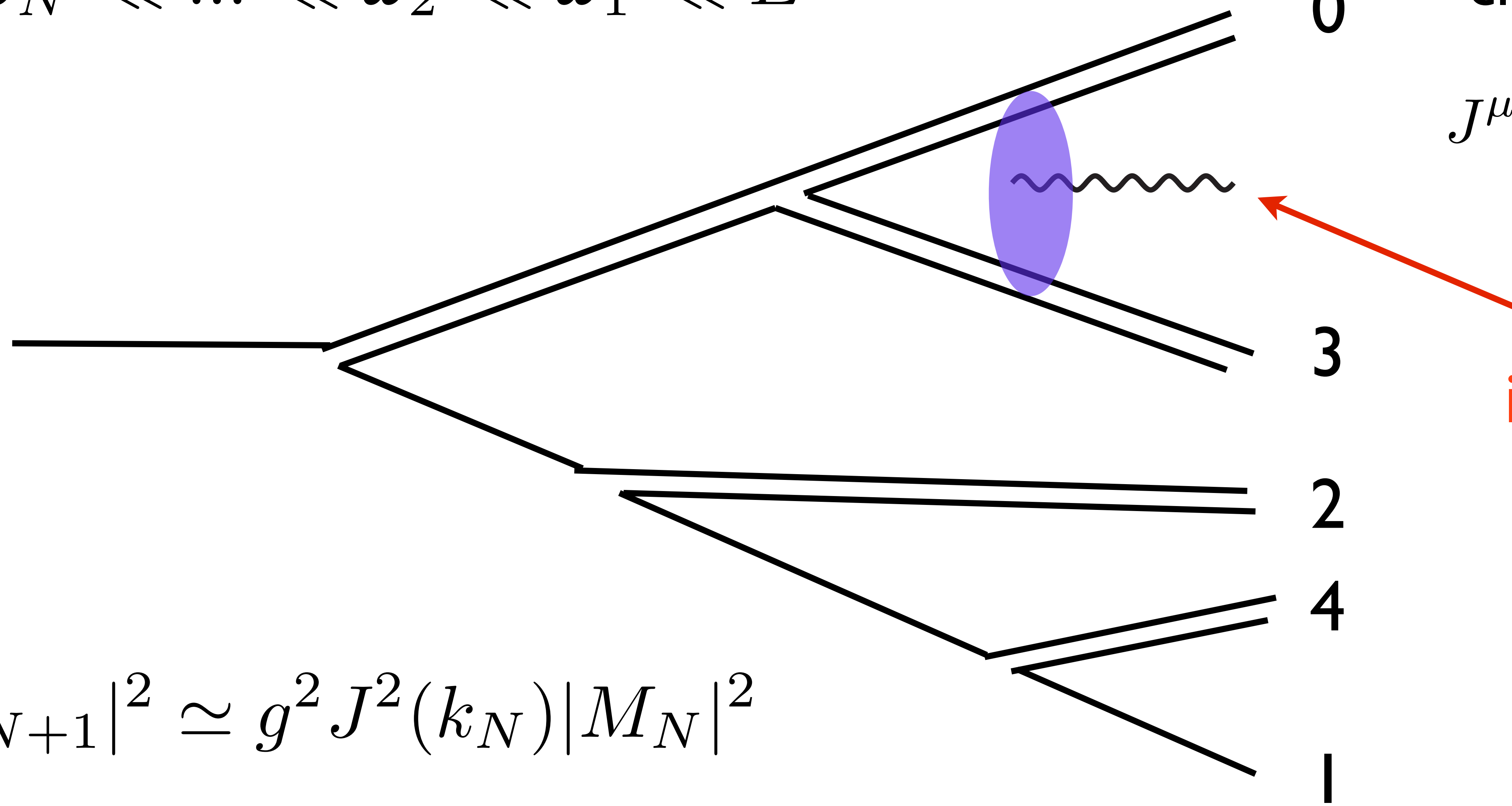
COLOR COHERENCE
(Soft-gluon insertion techniques)

Singlet antenna as a building block of jet evolution: factorization of soft gluon emissions in large Nc (resummation of soft gluon logs)

$\omega_N \ll ... \ll \omega_2 \ll \omega_1 \ll E$

classical current

$$J^\mu = \sum_i T_i \frac{k_i^\mu}{k_i \cdot k}$$



Large angle interferences

$$|M_{N+1}|^2 \simeq g^2 J^2(k_N) |M_N|^2$$

$$J^2(k_N) = C_F \sum_{i,j(c.c)}^{N-1} \frac{(k_i \cdot k_j)}{(k_i \cdot k_N)(k_j \cdot k_N)}$$

(Angular Ordering)

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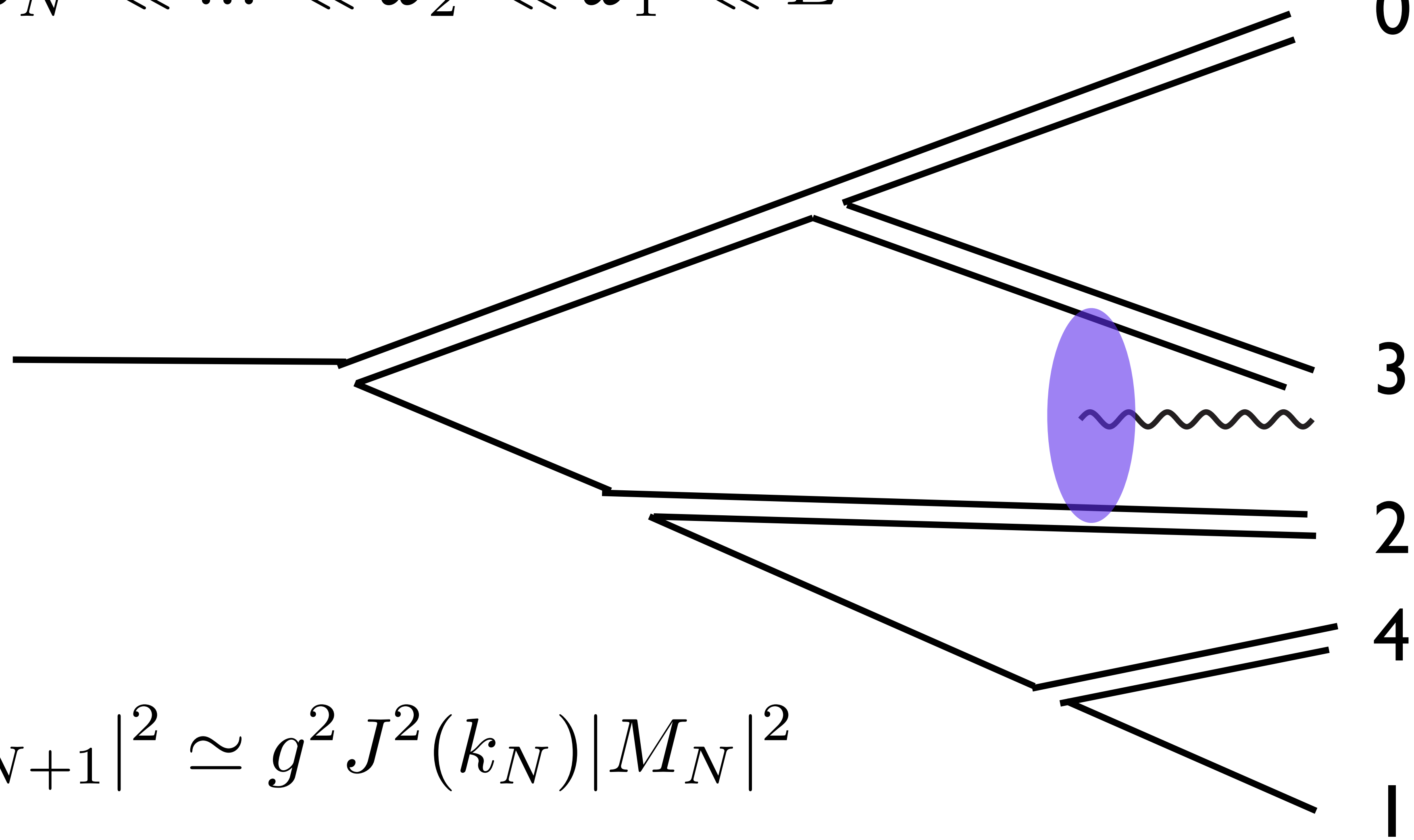

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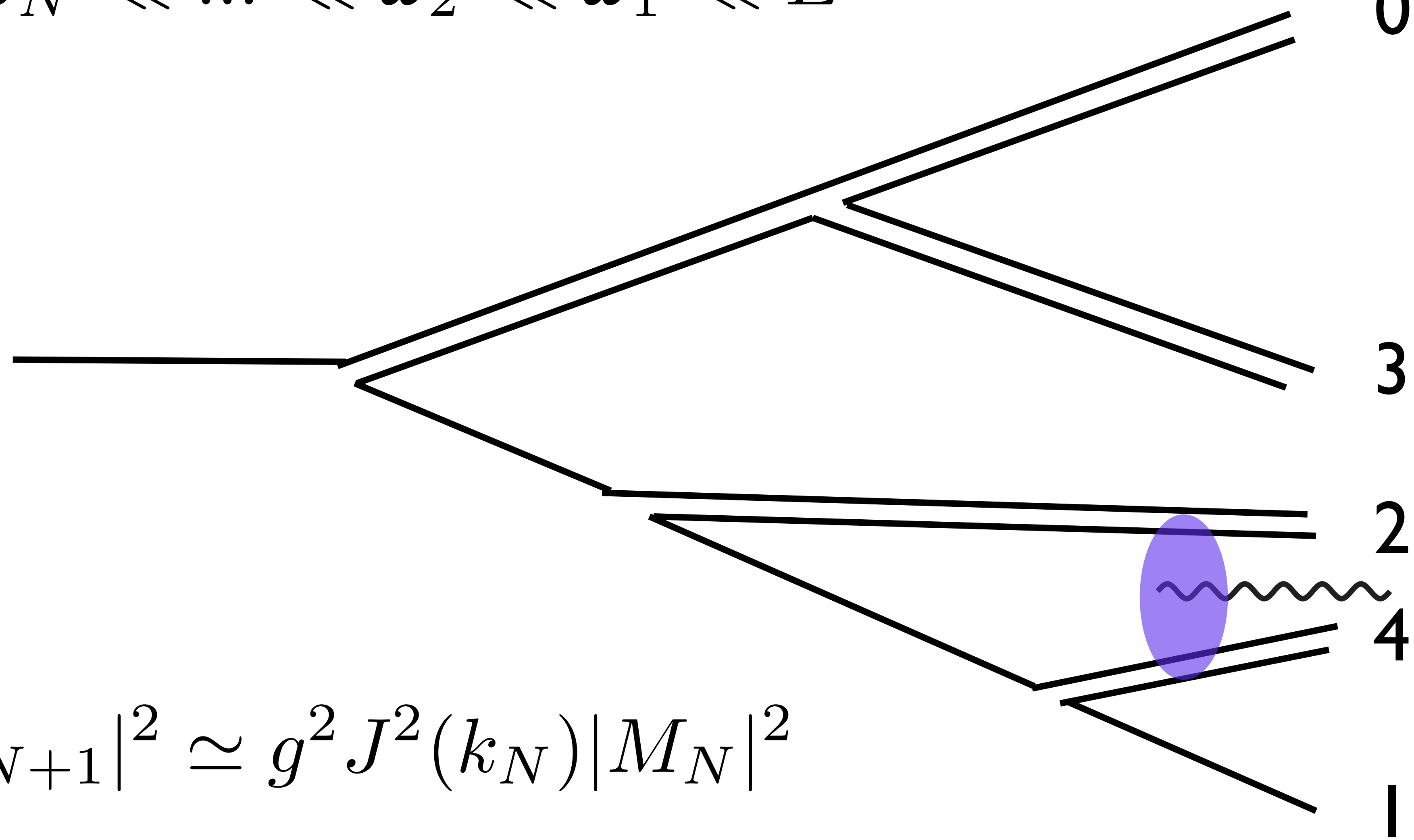

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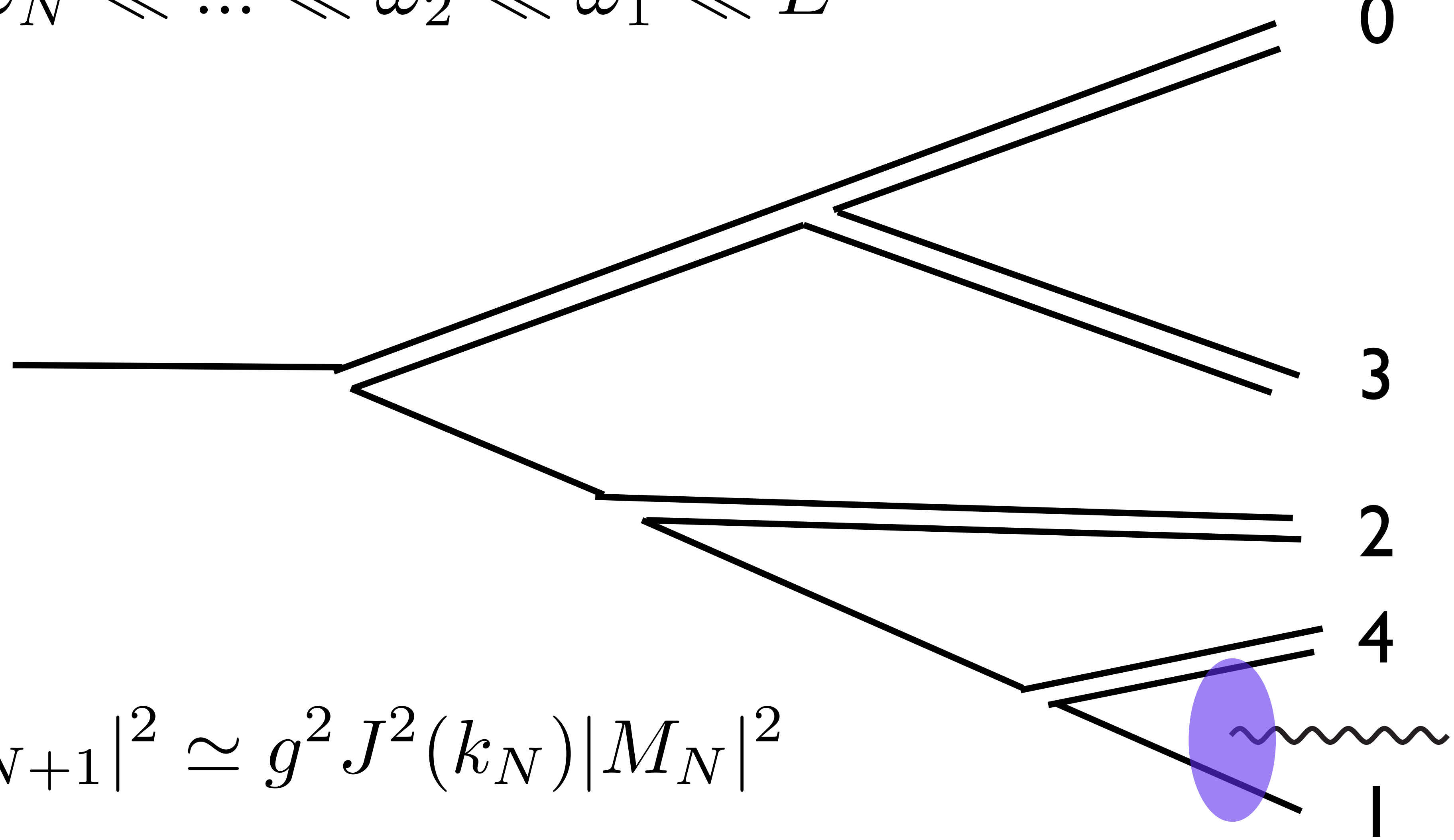

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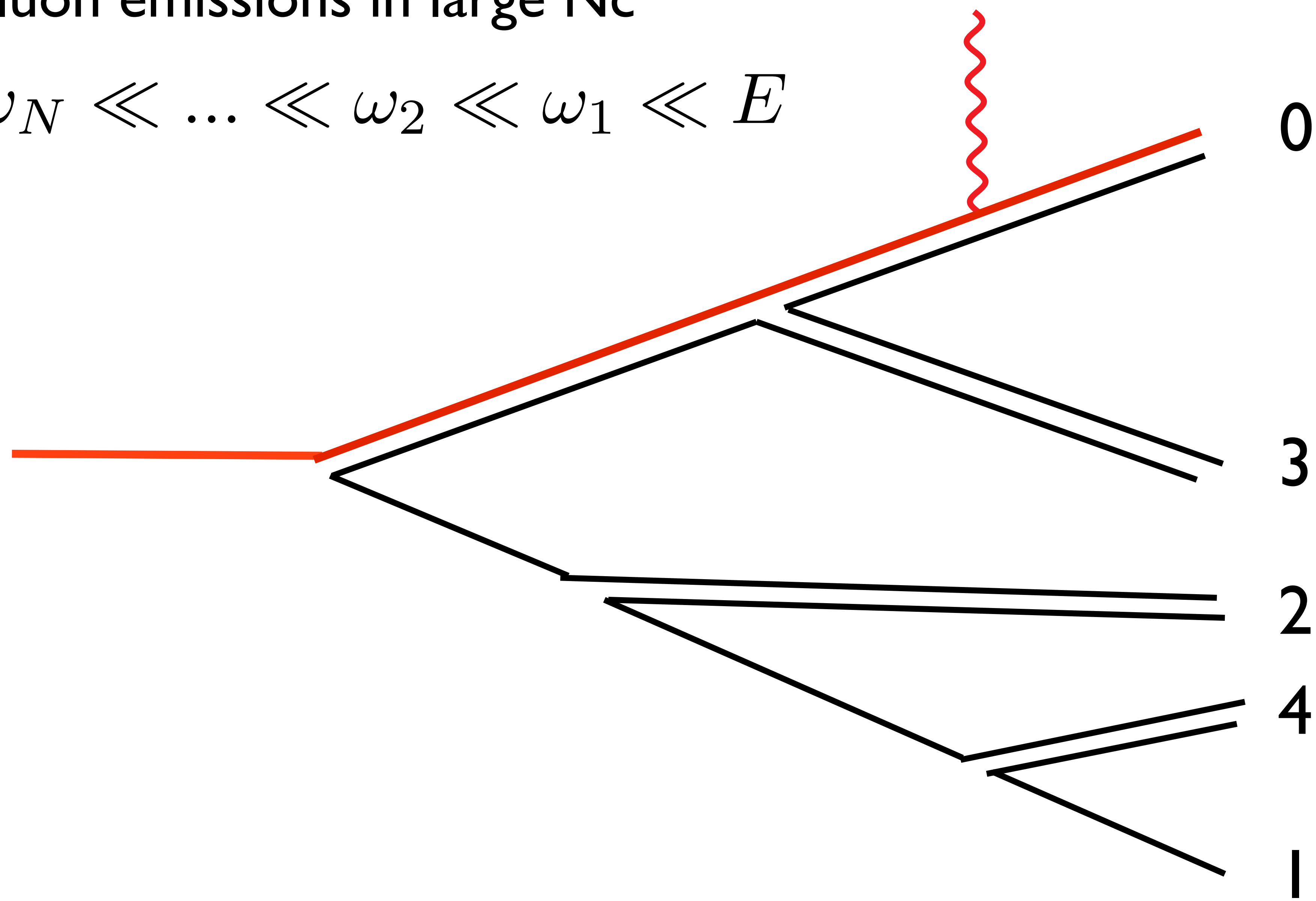


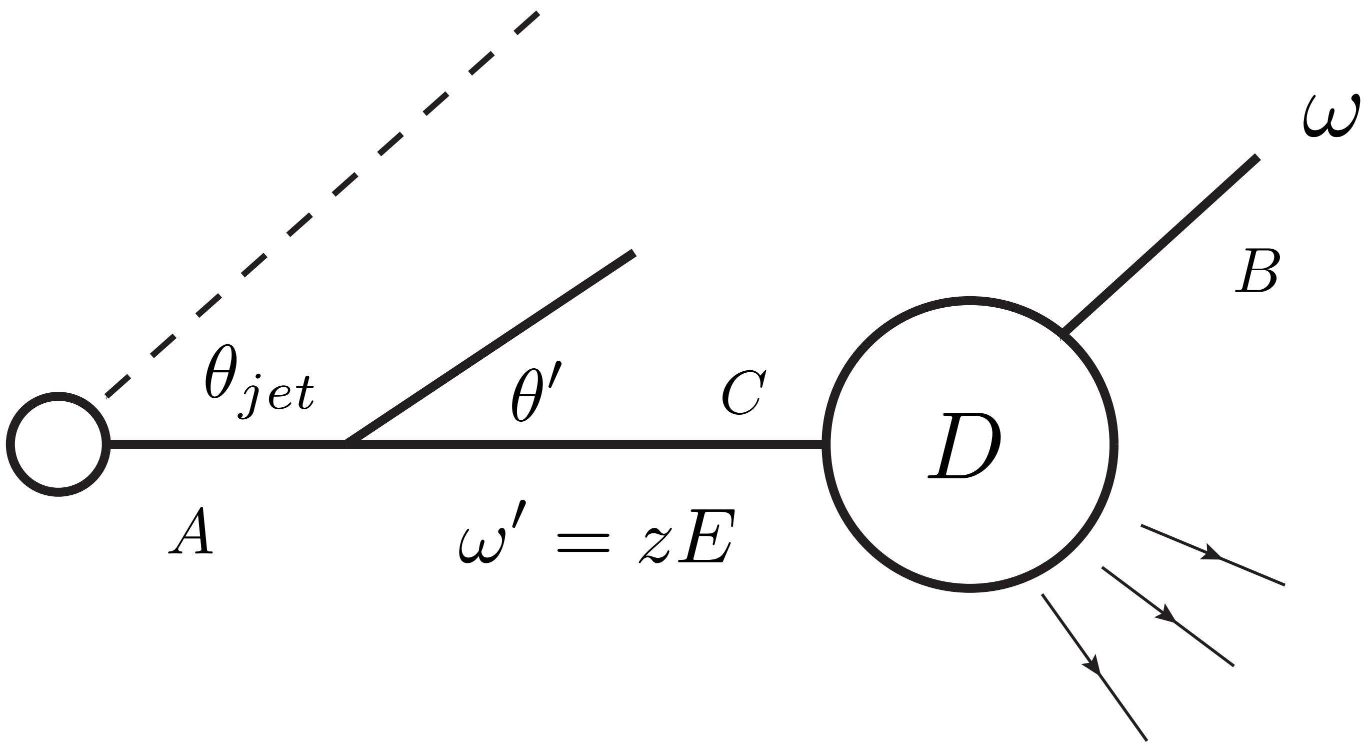
In the soft sector color coherence suppresses large angle gluon emissions.

$$C_0 \ll \sum C_i$$

[Bassetto, Mueller, Ciafaloni, Marchesini, Dokshitzer, Khoze, Troyan, Fadin, Lipatov, 80's]

Modified-Leading-Log-Approximation (MLLA)

Fragmentation function



Recall DGLAP (no-angular ordering)

$$\frac{d}{d\ln M_\perp} D_A^B(x, M_\perp) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P_A^C(z)\, D_C^B(x/z, M_\perp)$$

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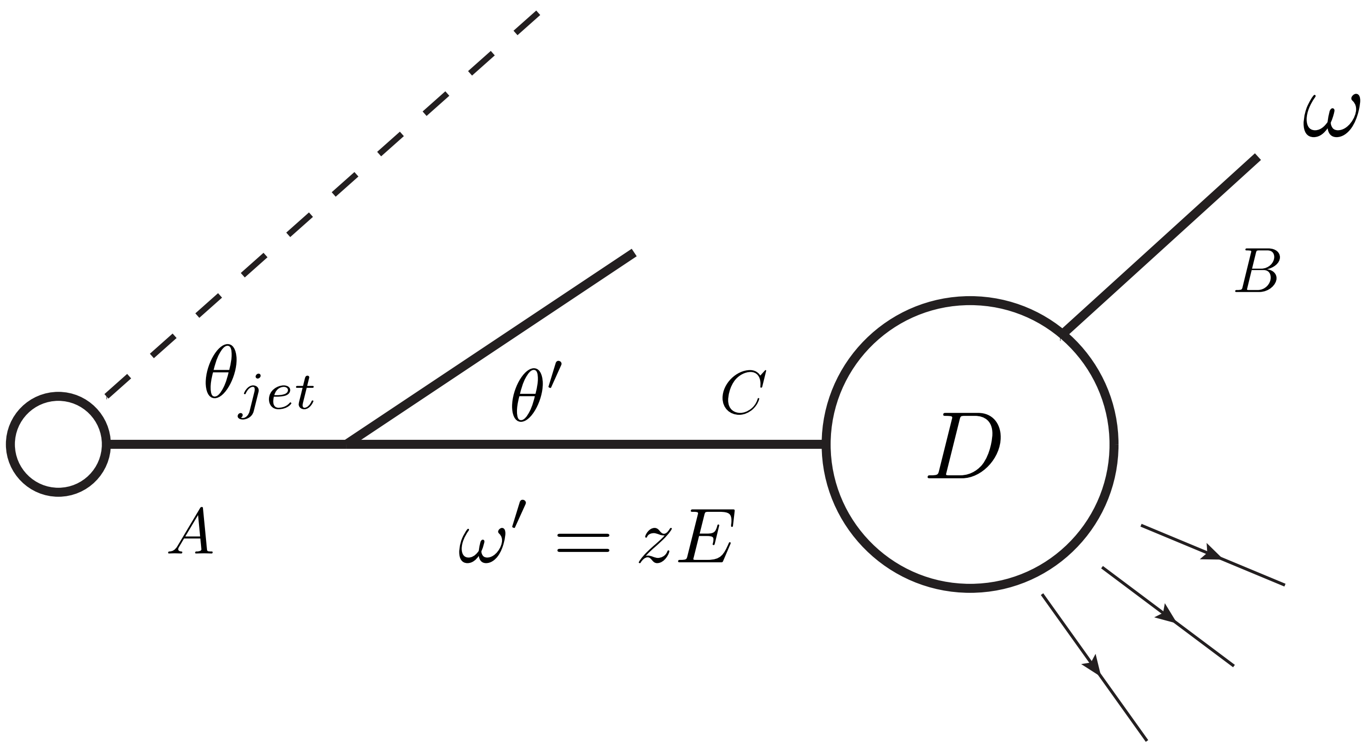

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$$\theta' \sim \theta_{jet} \rightarrow M'_\perp = \omega'\theta' \sim \omega'\theta_{jet} = zM_\perp$$

Modified-Leading-Log-Approximation (MLLA)

Fragmentation function

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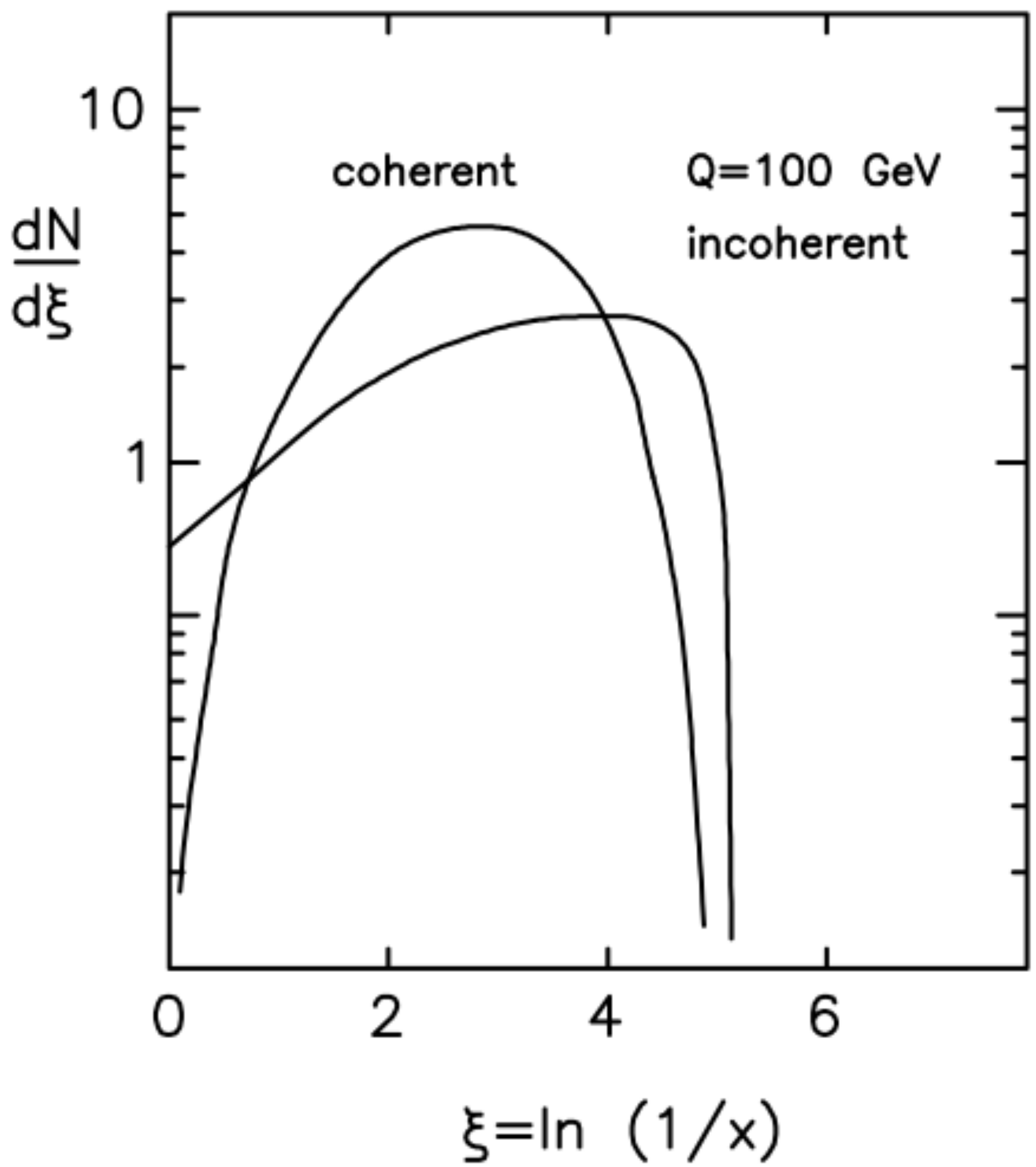
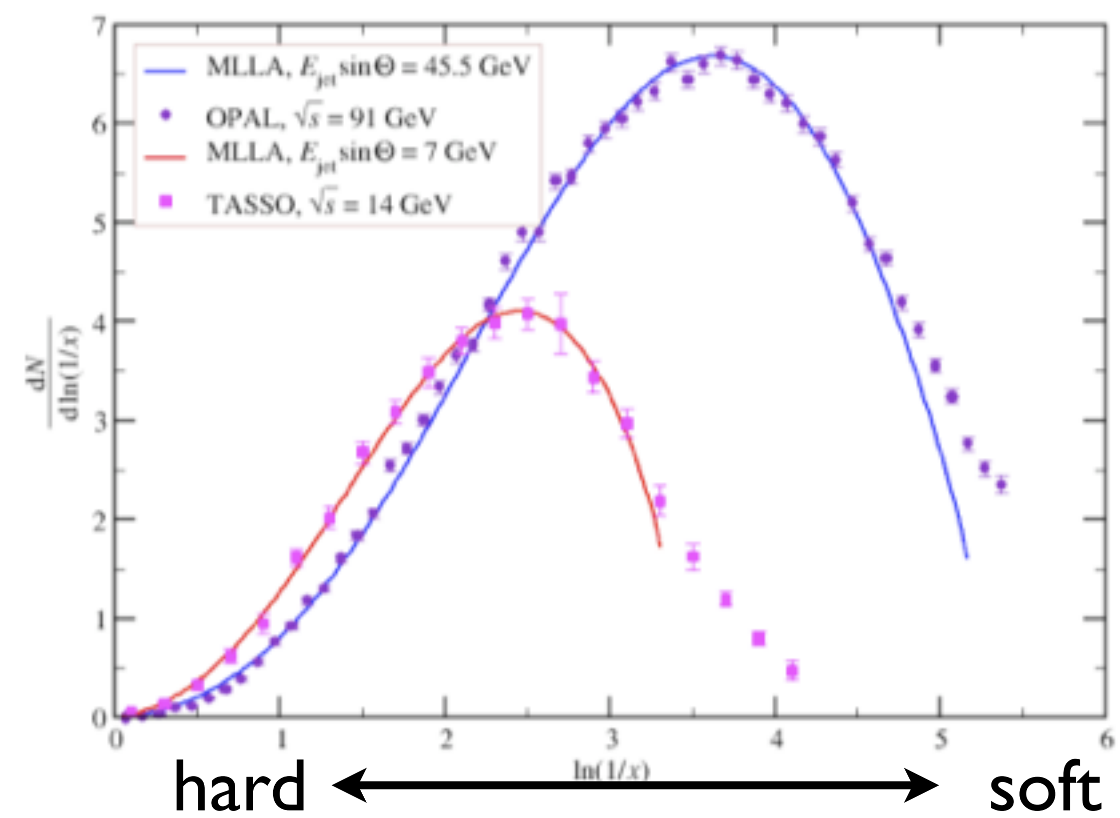




TASSO Collaboration, Z. Phys. C 47 (1990) 187

OPAL Collaboration, Phys. Lett. B 247 (1990) 617

- What is the space-time structure of in-medium jets?

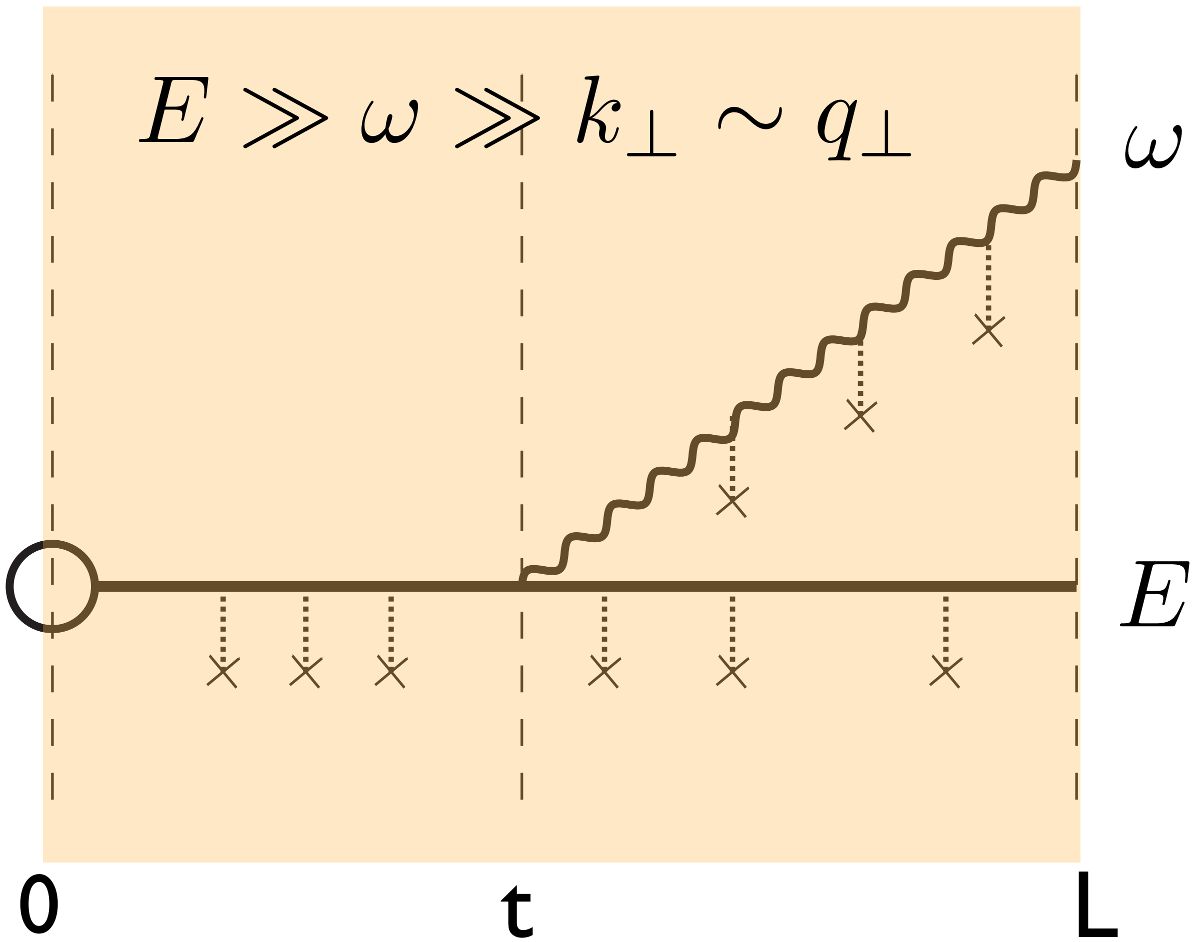
- Resummation scheme?
  ordering variable?
  probabilistic picture?

MEDIUM-INDUCED GLUON RADIATION (LPM)-LONGITUDINAL COHERENCE

Zakharov (1996) Baier, Dokshitzer, Mueller, Peigné, Schiff (1997)
Gyulassy, Levai, Vitev (2000)
Wiedemman (2001)
Arnold, Moore, Yaffe (2002)

MEDIUM-INDUCED GLUON RADIATION

In-medium radiative energy loss of hard partons



Medium described by a static background field

[Gyulassy, Wang (1994)]

$$V^2(q_\perp) = \frac{m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$

[Arnold, Moore, Yaffe (2002)]

$n(t)$: density of scatterers

$$\langle A_a^-(t, q_\perp) A_b^-(t', q'_\perp)\rangle = n(t)\delta_{ab}\,\delta(t-t')\,\delta(q_\perp - q'_\perp)\,V^2(q_\perp)$$

No energy transfer.

Dynamical medium?

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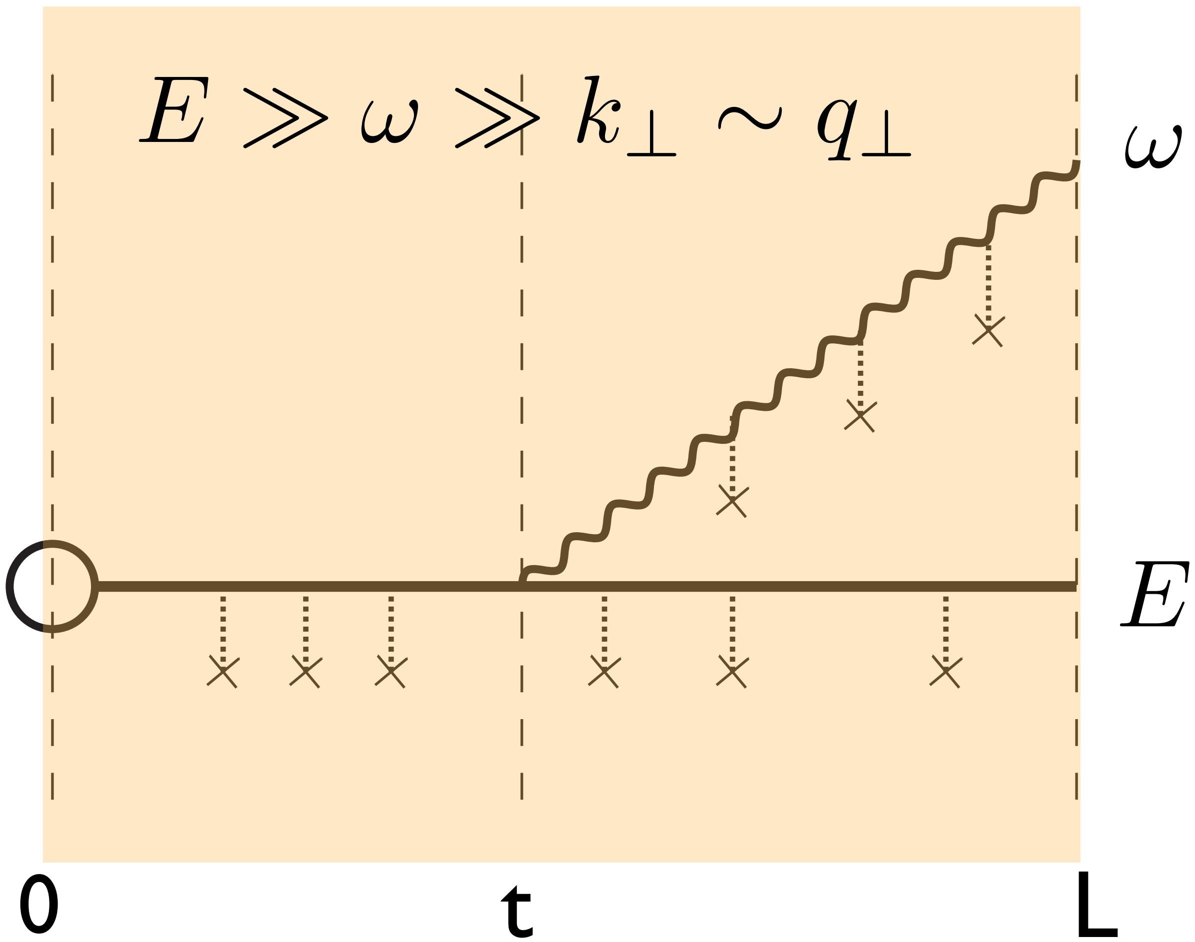

quark eikonal trajectory

$$U(0_\perp, t) = \mathcal{P} \exp\left[ig \int_0^t d\xi\, A^-(\xi, 0_\perp)\right]$$

Gluon prop. : Brownian motion in transverse plane

$$\mathcal{G}\left(x^+, \boldsymbol{x}; y^+, \boldsymbol{y} | k^+\right) = \int \mathcal{D}[\boldsymbol{r}] \exp\left[i\frac{k^+}{2}\int_{y^+}^{x^+} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right] U(x^+, y^+; [\boldsymbol{r}])$$

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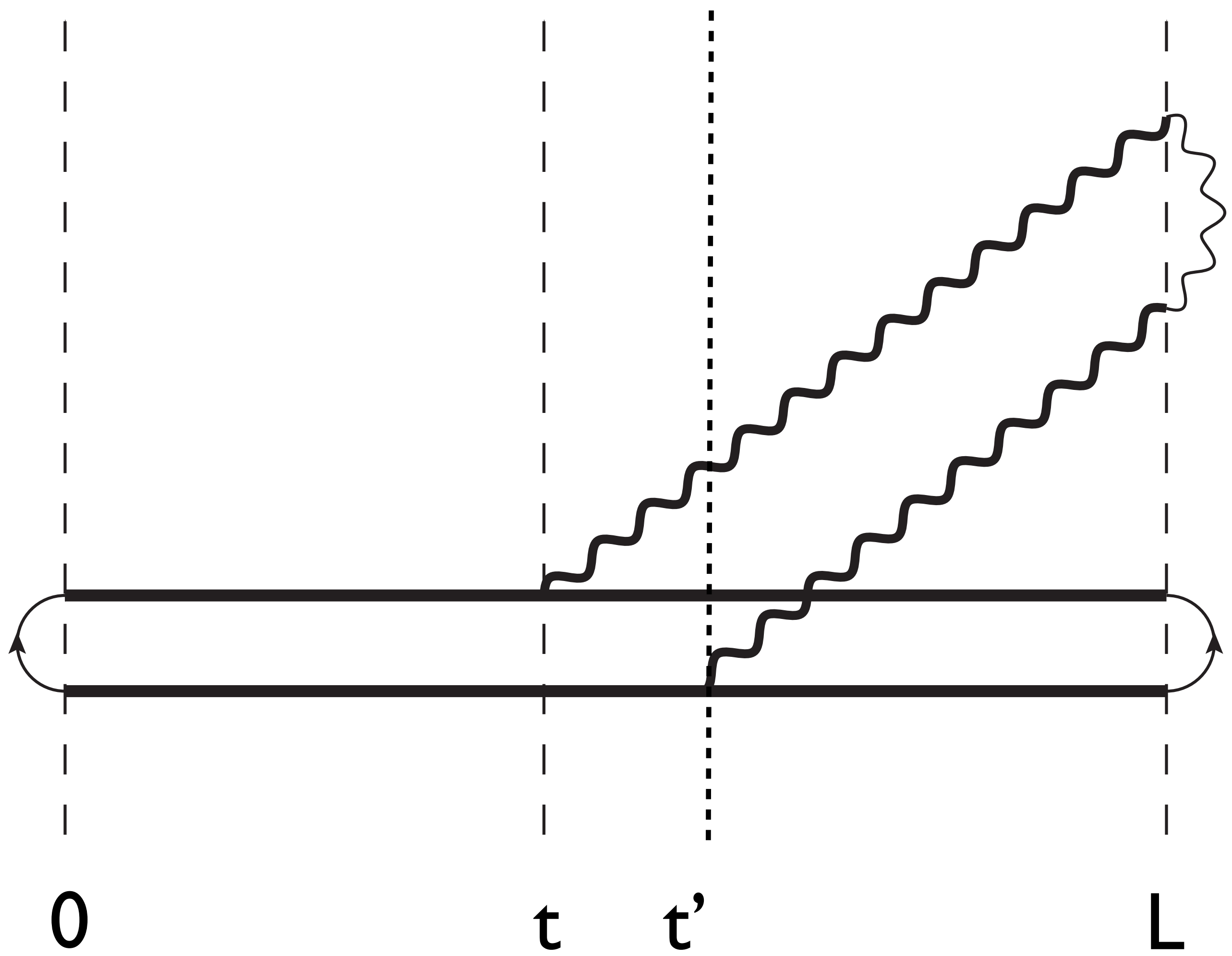
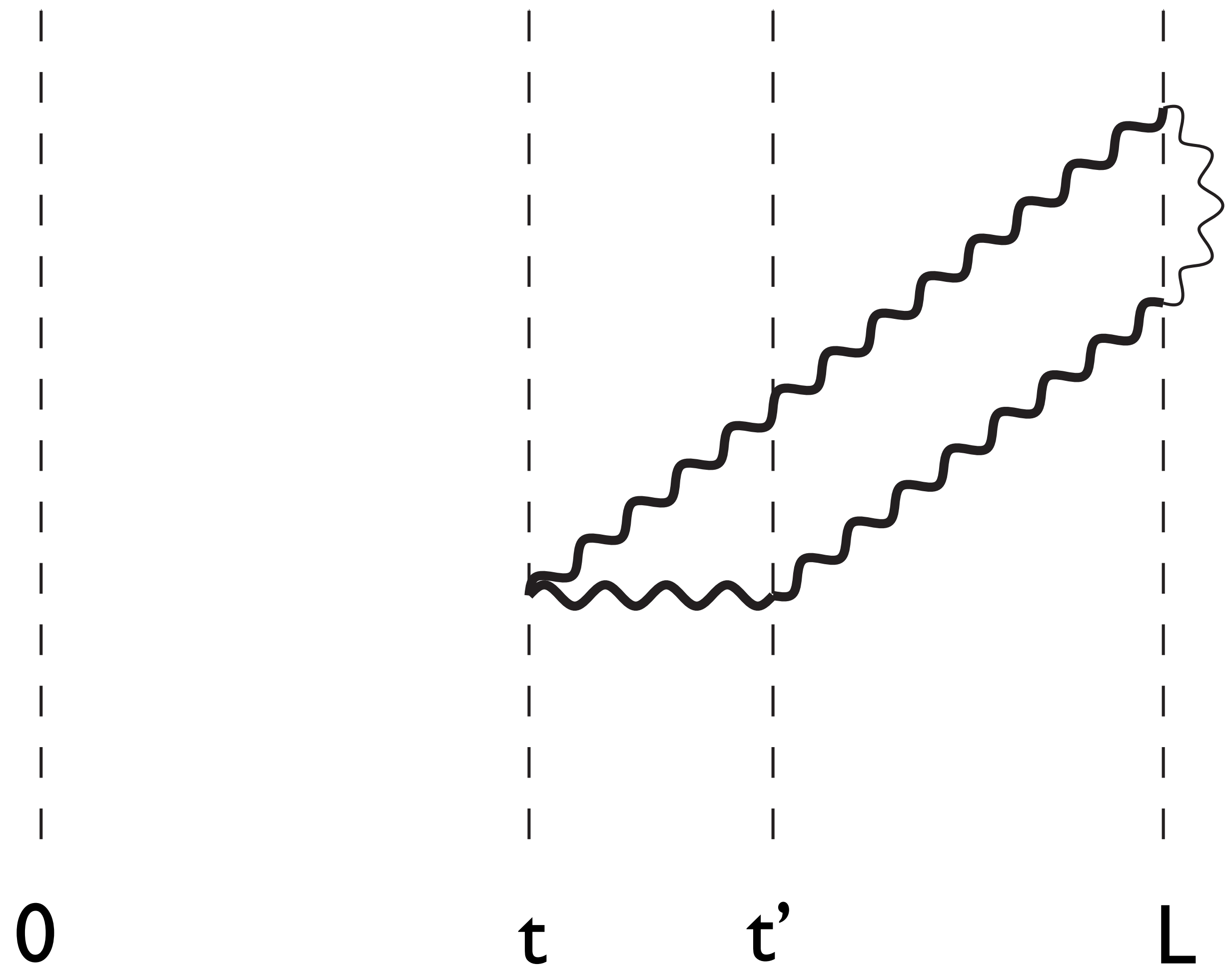


Amplitude
X
(Amplitude)*

MEDIUM-INDUCED GLUON RADIATION



the medium does not resolve the gluon dipole when the transverse size of the pair is smaller than the medium resolution

$$r_\perp^2(\Delta t) < \frac{1}{\hat{q}\,\Delta t}$$

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

This implies that the gluon decoheres from the quark-antiquark octet after a time

$$t_f = \sqrt{\frac{\omega}{\hat{q}}}$$

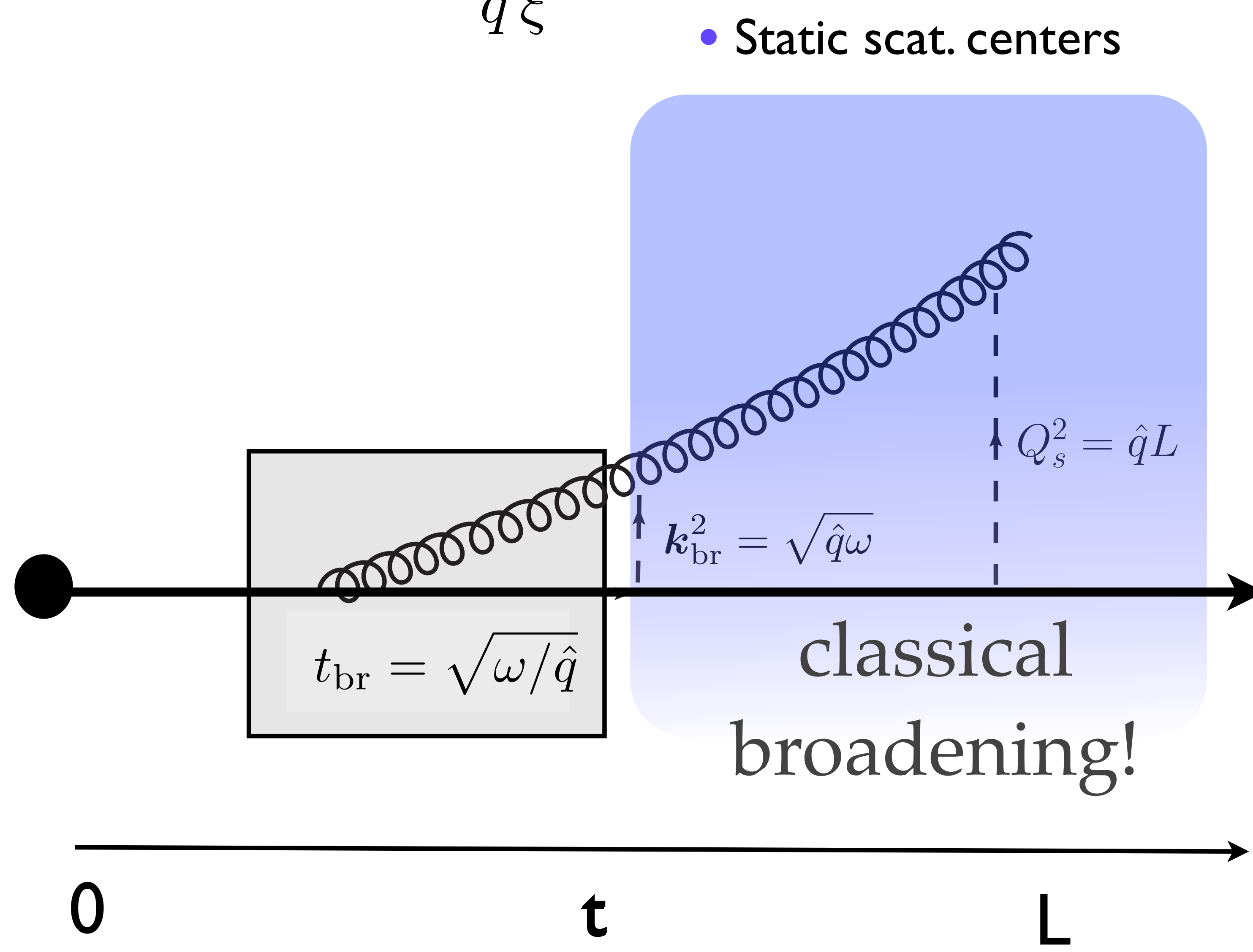
MEDIUM-INDUCED GLUON RADIATION

$$(2\pi)^2\omega\frac{dN}{d\omega d^2\boldsymbol{k}} = \frac{4C_F\alpha_s}{\omega}\int_0^L dt\int\frac{d^2\boldsymbol{q}}{(2\pi)^2}\mathcal{P}(\boldsymbol{k}-\boldsymbol{q},L-t)\,\sin\left(\frac{\boldsymbol{q}^2}{2\boldsymbol{k}_{\rm br}^2}\right)\,\exp\left(-\frac{\boldsymbol{q}^2}{2\boldsymbol{k}_{\rm br}^2}\right)$$

- prob. of acquiring mom. k after ξ $\mathcal{P}(\boldsymbol{k},\xi) = \frac{4\pi}{\hat{q}\,\xi}e^{-\frac{\boldsymbol{k}^2}{\hat{q}\xi}}$
- branching time $t_{\rm br}$

Mean Energy loss

$$\Delta E \sim \alpha_s\,\hat{q}\,L^2$$



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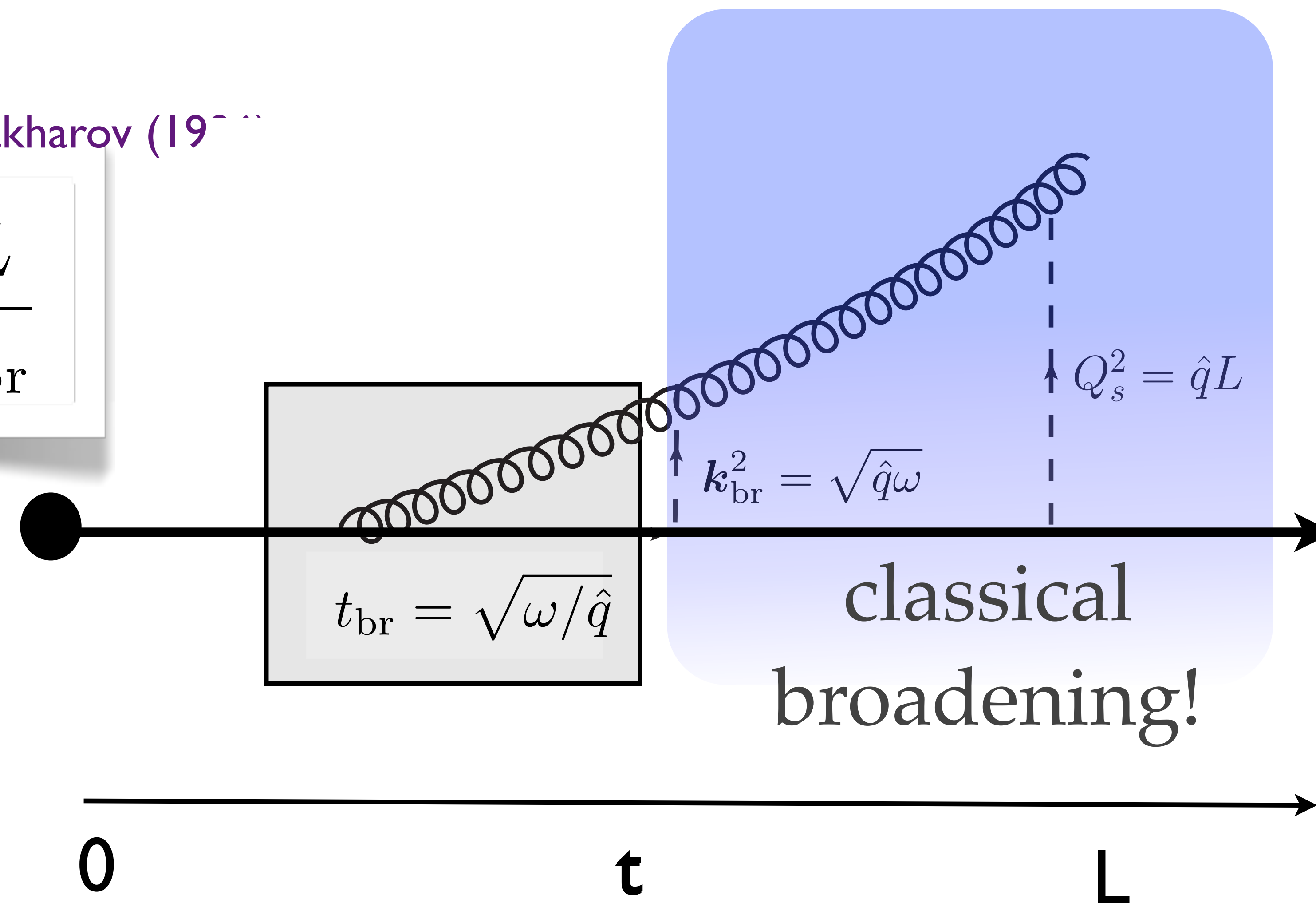
- prob. of acquiring mom. k after ξ $\quad \mathcal{P}(\boldsymbol{k},\xi) = \frac{4\pi}{\hat{q}\,\xi}e^{-\frac{\boldsymbol{k}^2}{\hat{q}\xi}}$
- branching time $\quad t_{\rm br}$

- Static scat. centers

Baier, Dokshitzer, Mueller, Peigné, Schiff (1995-2000) Zakharov (19

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



Mean Energy loss

$$\Delta E \sim \alpha_s\,\hat{q}\,L^2$$

RADIATIVE ENERGY LOSS POISSON DISTRIBUTION

Independent gluon emissions: probability that a hard parton loses a total energy ϵ by radiating an arbitrary number of gluons

$$P(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dN(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right) \exp\left[\int_0^{\infty} d\omega \frac{dN}{d\omega}\right]$$

Better treatment than the mean energy loss

Medium modified FF's

$$x = \epsilon / E$$

$$D_{med}(z, Q^2) = \int dx\, P(x)\, \frac{1}{1-x} D_{vac}\left(\frac{z}{1-x}, Q^2\right)$$

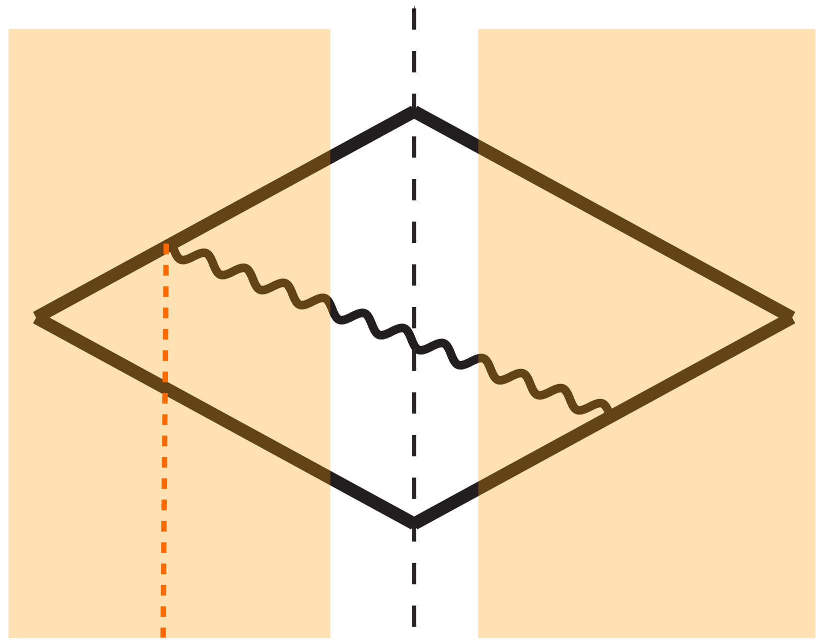
How about coherence phenomena? more exclusive observables?

THE ANTENNA RADIATION PATTERN IN MEDIUM (DE)COHERENCE

SPACE-TIME STRUCTURE OF IN-MEDIUM INTERFERENCES

$\mathcal{R}$: direct emission - BDMPS spectrum - anywhere up to L

$\mathcal{J}$: interferences $\Rightarrow$



interferences depend on the decoherence parameter

$$\Delta_{\rm med} = 1 - \frac{1}{N_c^2 - 1} \langle \mathbf{Tr}\, U_p(t,0) U^\dagger_{\bar{p}}(t,0) \rangle \approx 1 - e^{-\frac{1}{12}\hat{q}\theta^2 t^3}$$

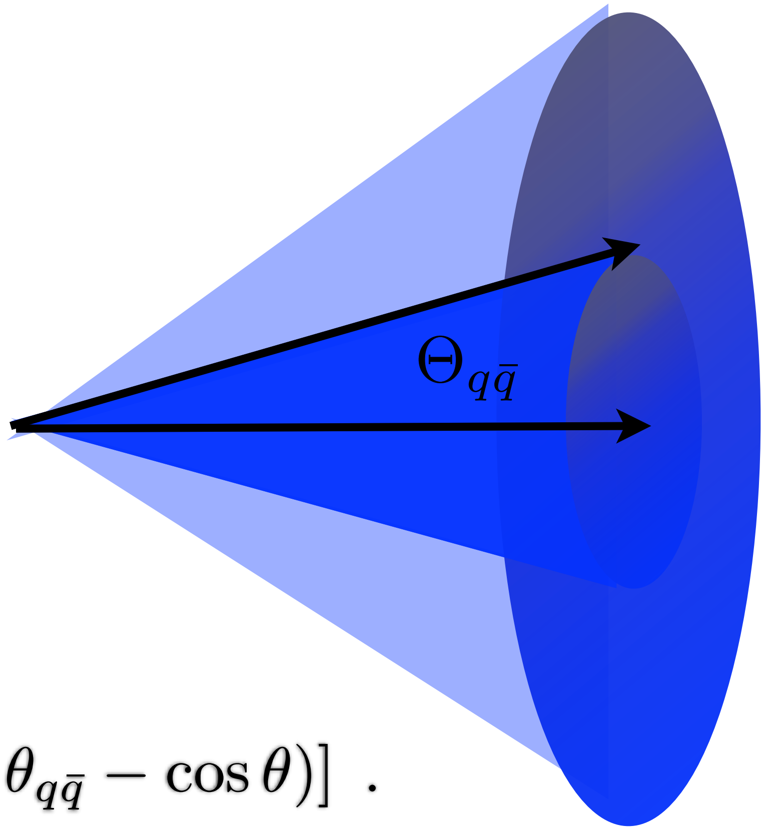
decoherence time

only gluons formed at $t < t_d \equiv (\hat{q}\,\theta^2_{q\bar{q}})^{-1/3}$ interfere

$\Rightarrow$ Suppression of interferences

[Y. M.-T., C.A. Salgado and K. Tywoniuk 2011]
[E. Iancu and J. Casalderray-Solana 2011]

ONSET OF DECOHERENCE - SOFT GLUONS



$$\Delta_{\rm med} \equiv \Delta_{\rm med}(L)$$

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

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

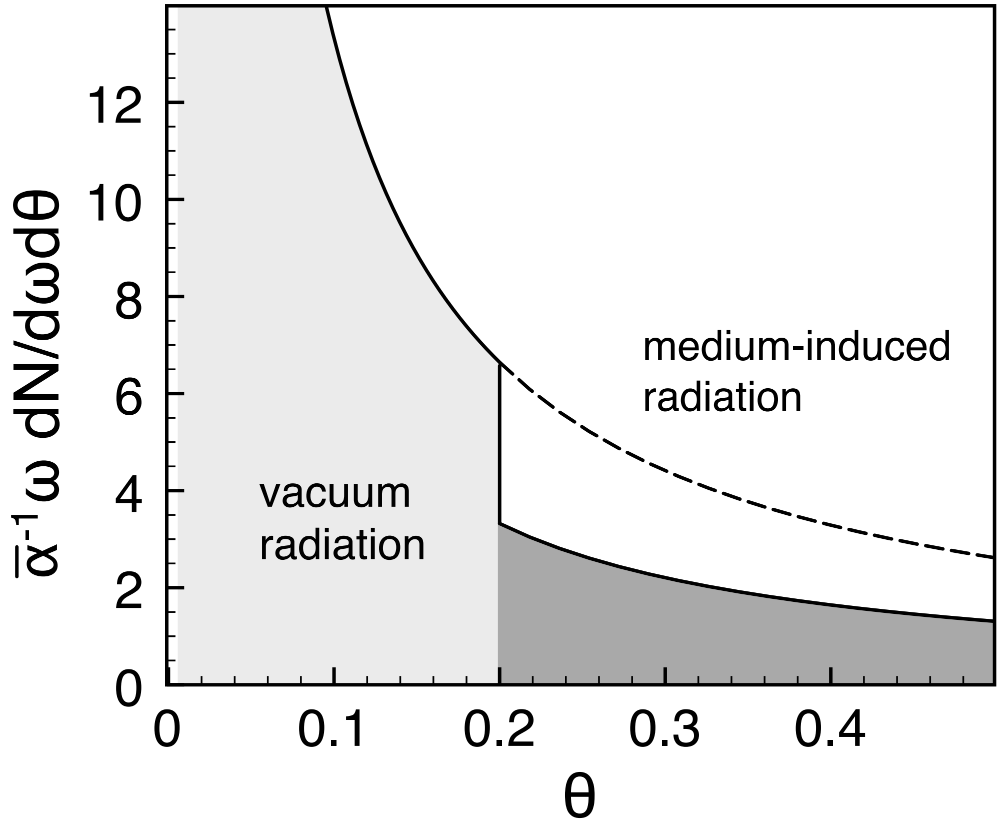
$$dN^{\rm tot}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right]\;.$$

⇒ geometrical separation!

$$dN^{\rm tot}_{q,\gamma^*}\Big|_{\rm opaque} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta}\;.$$

and gluon!

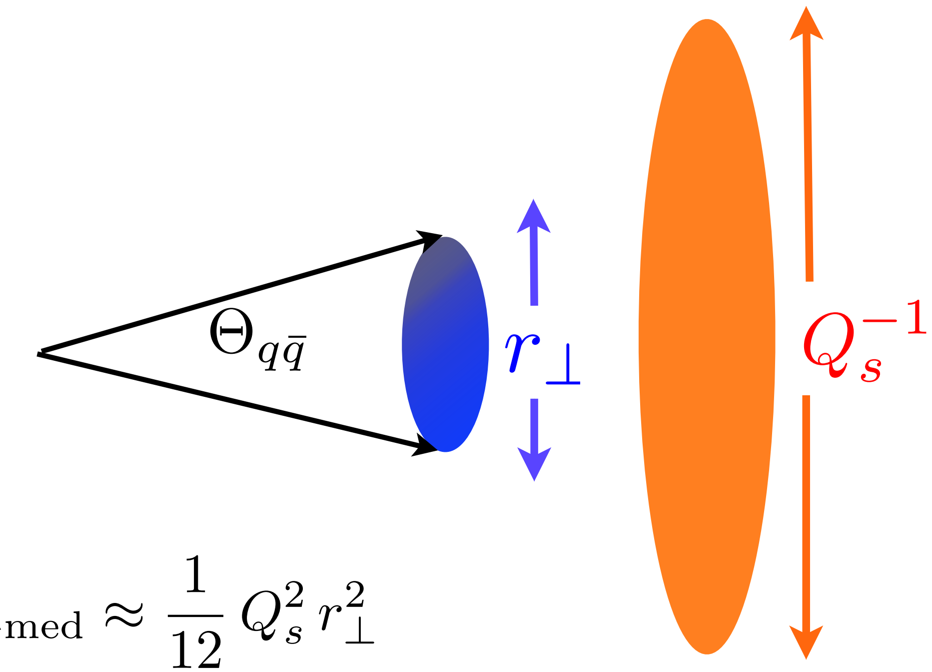
1) Independent emissions!
2) “Memory loss” effect



HARD SCALES IN THE PROBLEM

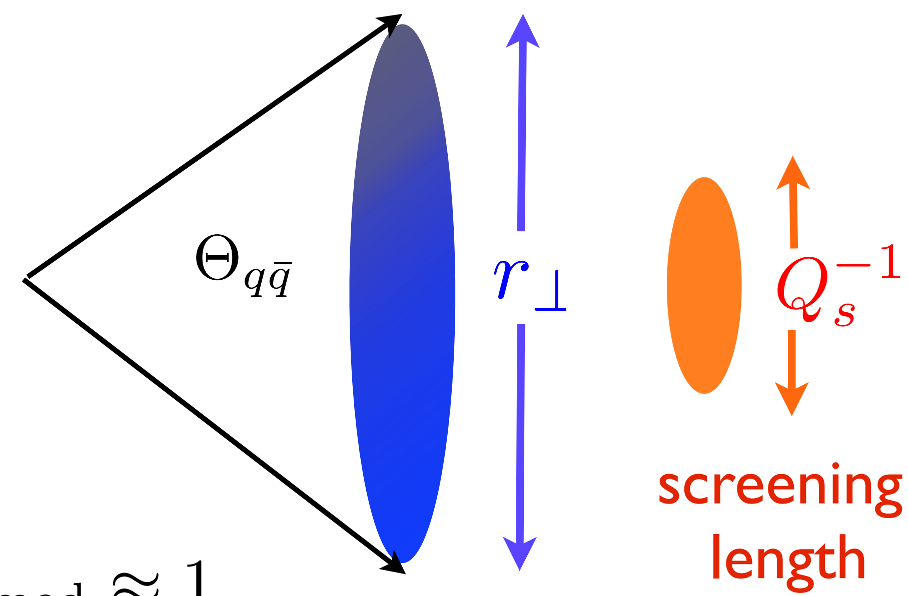
$Q_s^2 = \hat{q}\, L$ $\qquad r_\perp = \theta_{q\bar{q}}\, L$ $\qquad$ - a two scale problem!

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



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

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



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

$\tau_d = \left(\hat{q}\theta_{q\bar{q}}^2\right)^{-1/3}$

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

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

Q_s: characteristic momentum scale of the medium

HARD SCALES IN THE PROBLEM

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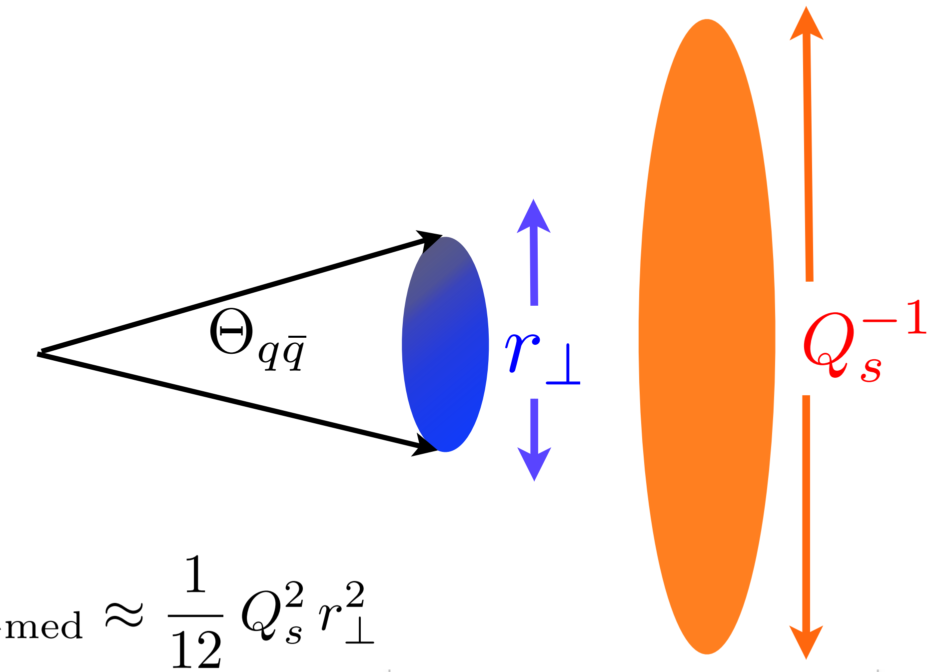

$\Delta_{\text{med}} \approx \frac{1}{12} Q_s^2\, r_\perp^2$

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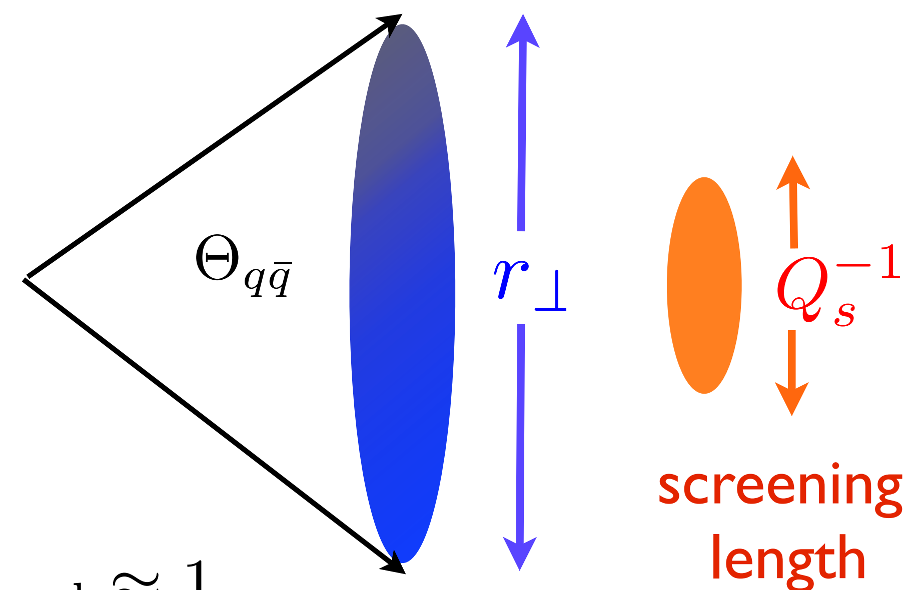


$\Delta_{\text{med}} \approx 1$

$\tau_d \gg L$

$\tau_d \ll L$

$\tau_d = \left(\hat{q}\theta_{q\bar{q}}^2\right)^{-1/3}$

$r_\perp =$

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

Qs: characteristic momentum scale of the medium

HARD SCALES IN THE PROBLEM

Gluon spectrum characterized by the hardest scale in the problem

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

$$Q_s^2 = \hat{q}\, L \qquad\qquad r_\perp = \theta_{q\bar{q}}\, L$$

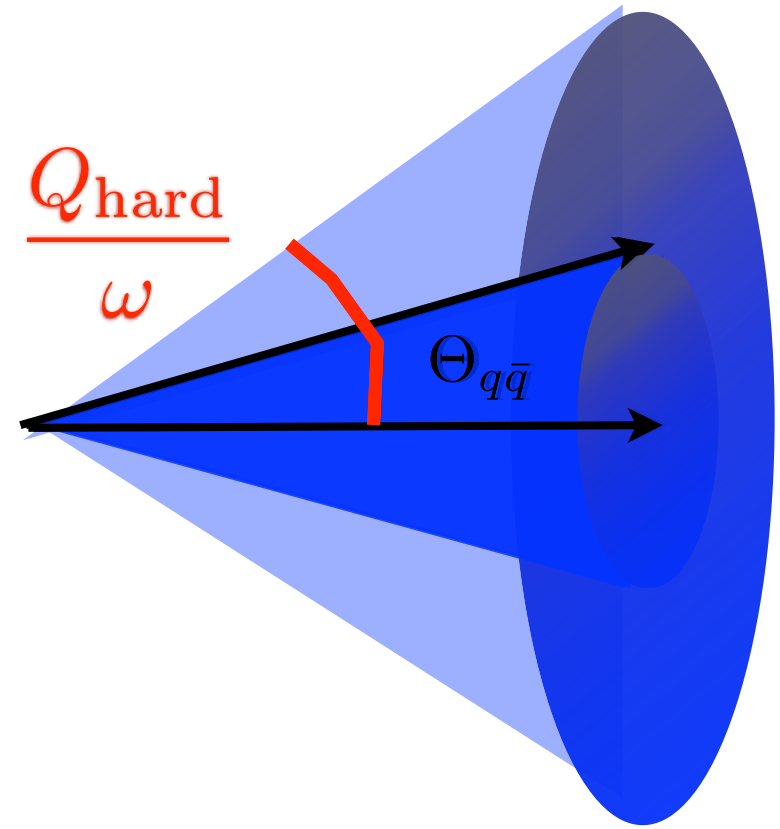
medium-induced color randomization destroys the coherence of the antenna and opens up phase space for gluon radiation at large angles

for gluon momentum $k_\perp > Q_{\rm hard}$ the spectrum is suppressed and coherence is restored

✓ The system cannot induce radiations harder than the intrinsic scales of the problem

ONSET OF DECOHERENCE - FINITE GLUON ENERGIES

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



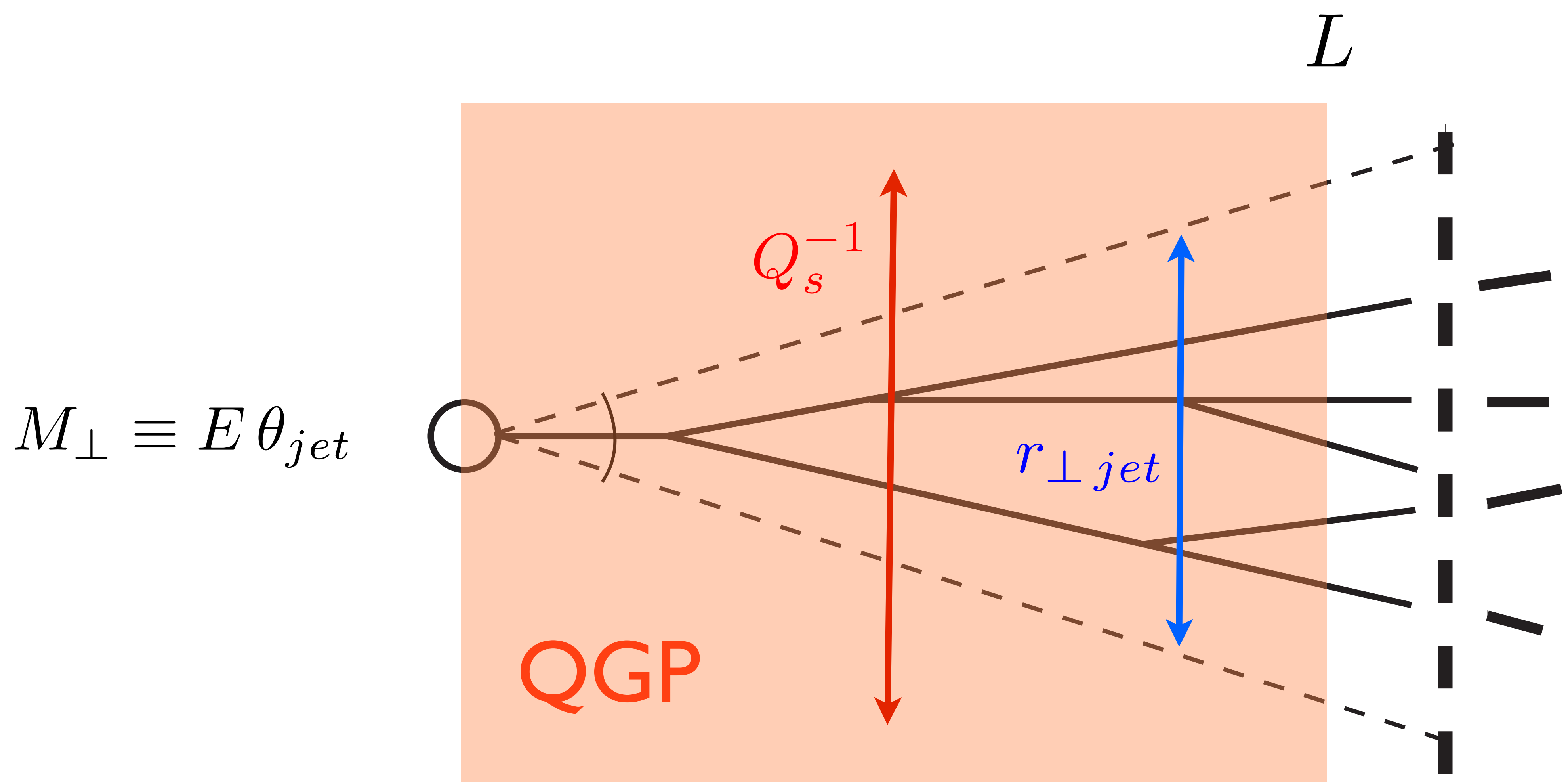
In terms of angular variables:

Vacuum: Independent emissions for $\theta < \theta_{q\bar{q}}$
Emission off the total charge otherwise (coherence)

Full decoherence: Independent emissions for $\theta < \theta_{\rm med} = \frac{Q_s}{\omega}$
Emission off the total charge otherwise (coherence)

⇒ In the opaque limit, simple shift of the angular constraint!

WHAT WE HAVE LEARNED



Color transparency for $r_\perp < Q_s^{-1}$ or $\theta_{jet} < \theta_c \sim \dfrac{1}{\sqrt{\hat{q} L^3}}$

Decoherence $r_\perp > Q_s^{-1}$

WHAT WE HAVE LEARNED

Vacuum-like jets
Color coherence
High virtuality

Medium dynamics

in-medium jet evolution
?

Antenna in medium
Decoherence

Energy loss:
Medium-induced 1-gluon emission
(Collisional EL)

CONCLUSION

- Need improvement of the standard picture of energy loss: medium dynamics, collisional +radiative, large angle soft radiation.
- Developing a complete theory of jets as probes of the medium:

  - Understanding hard scale interplay. (regimes)
  - Space-time picture of jet evolution (multiparton branching): resummation scheme, Factorization, probabilistic picture? (see Fabio's talk)

FACTORIZATION IN THE OPAQUE LIMIT (TOTAL DECOHERENCE)

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

(in preparation)

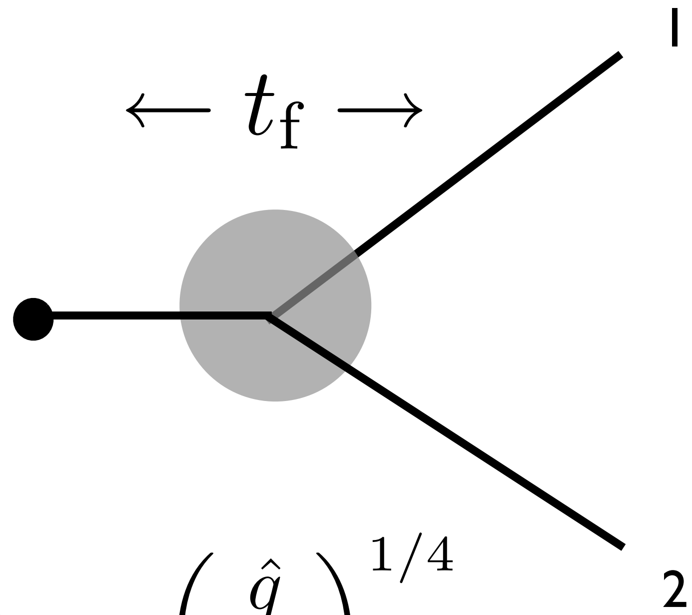
DECOHERENCE OF MULTI-GLUON EMISSIONS

decoherence time

$$t_{\rm d} = (\hat{q}\,\theta_{gg}^2)^{-1/3}$$

formation time

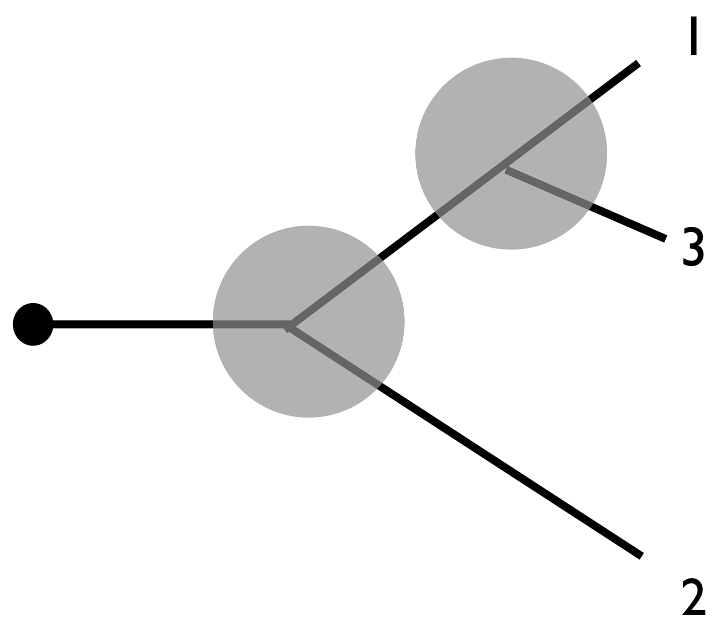
$$t_{\rm f} = \sqrt{\frac{\omega}{\hat{q}}}$$



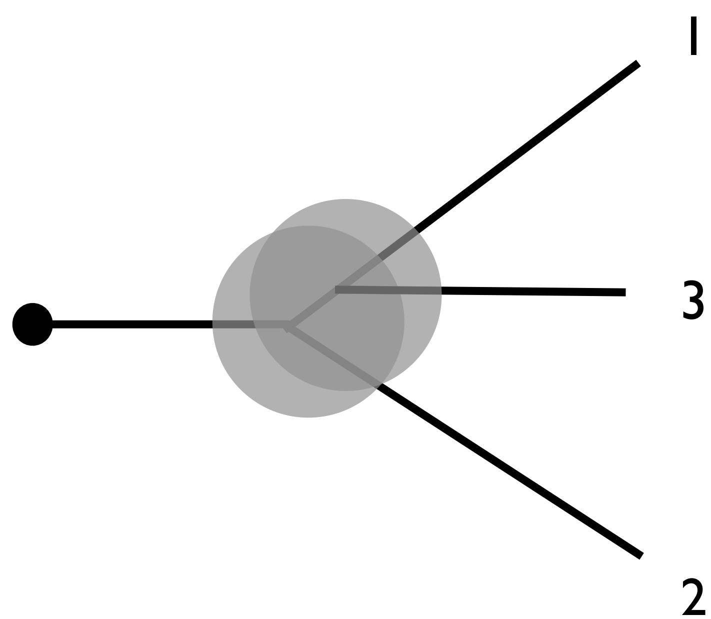
typical angle for medium-induced gluon

$$\theta_{gg} = \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$

$$t_{\rm d} \equiv t_{\rm f}$$



incoherent emissions



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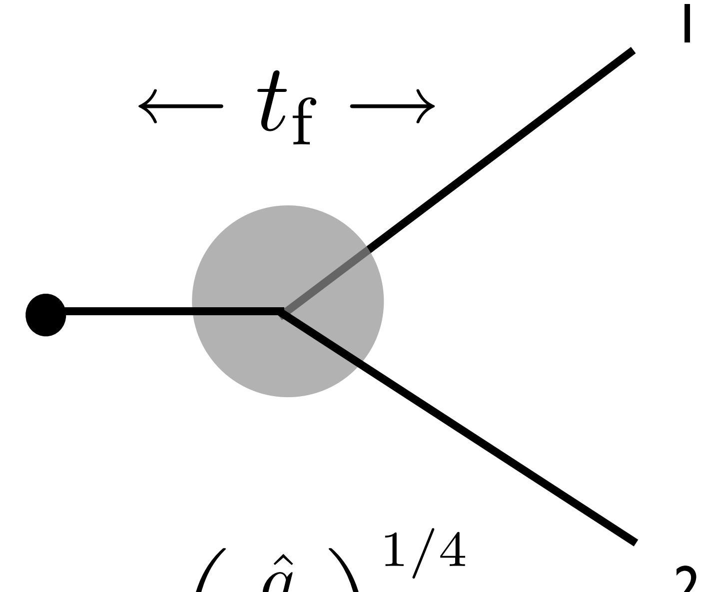

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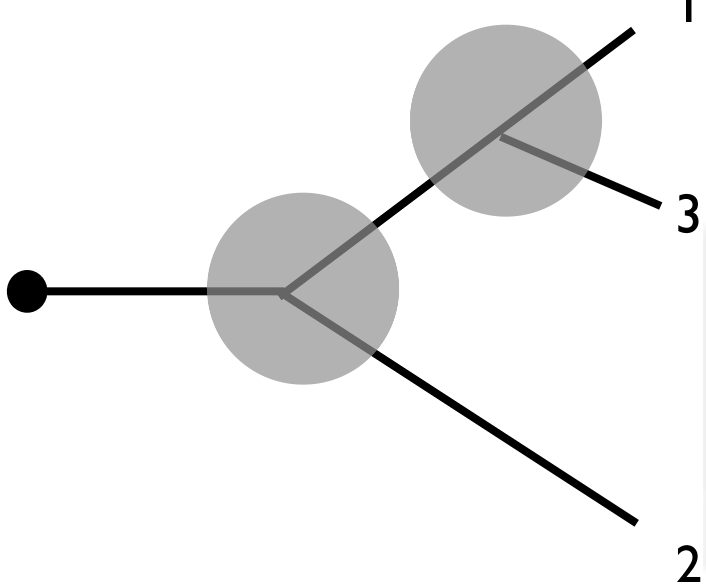
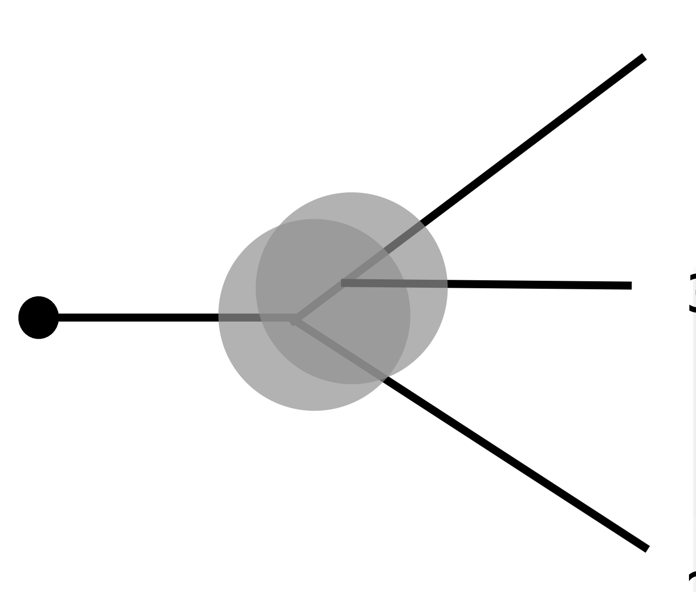


$$\propto \left(\alpha_s \frac{L}{t_{\rm f}}\right)^2$$

incoherent emissions



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

coherent emissions

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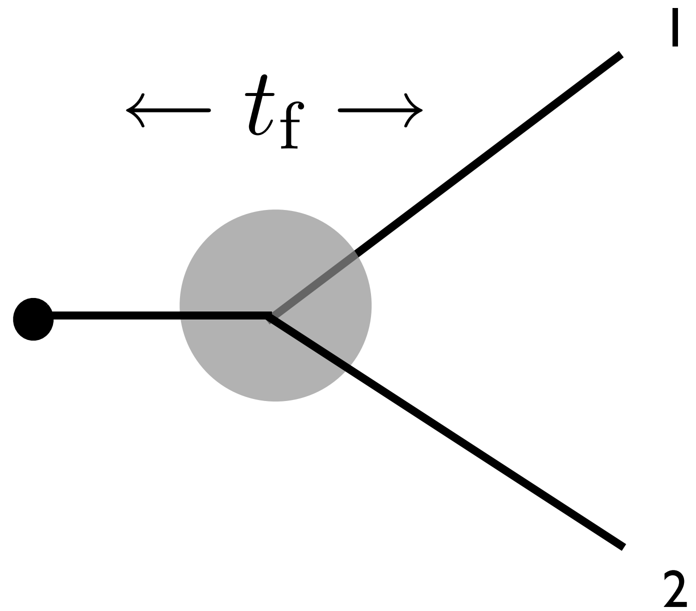
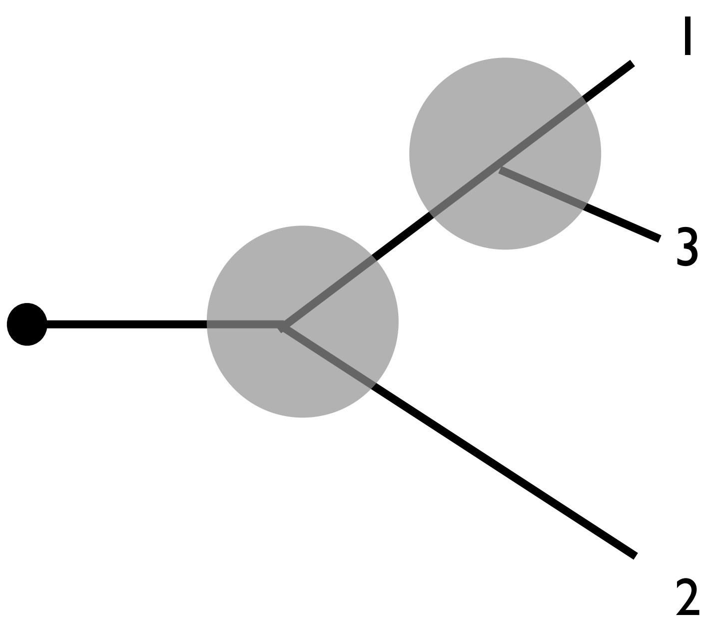
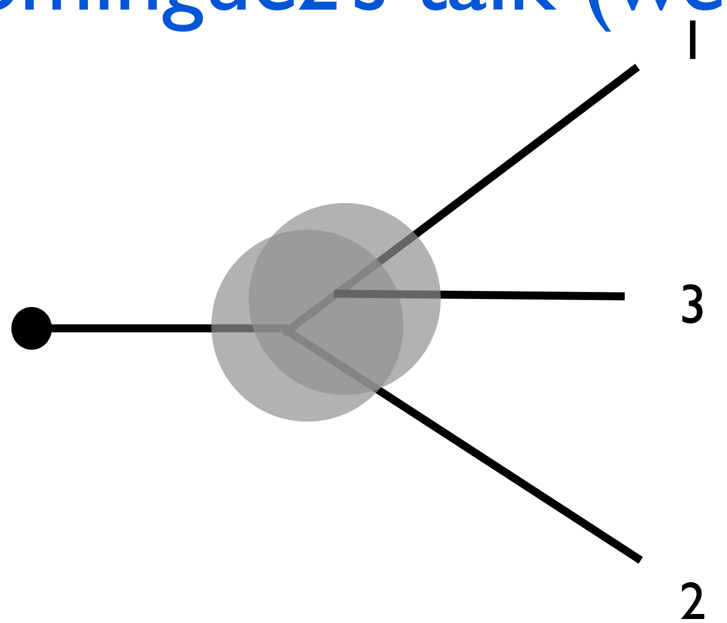




incoherent emissions

See F. Dominguez's talk (wednesday)



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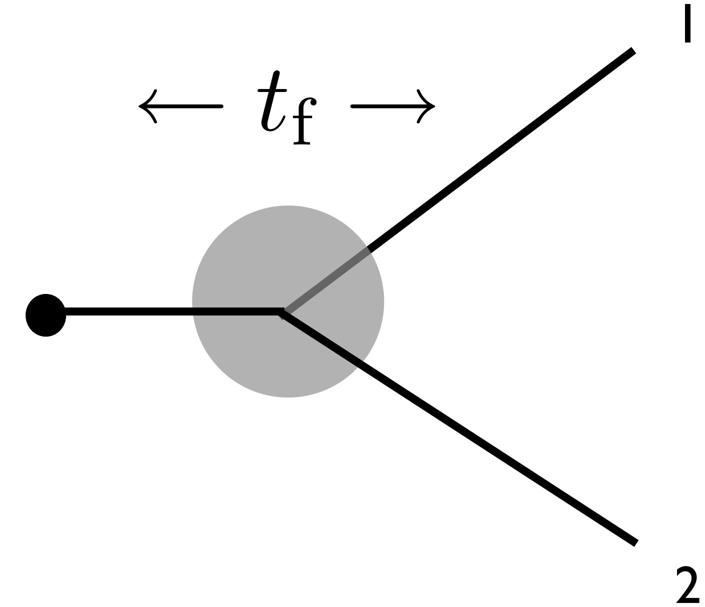

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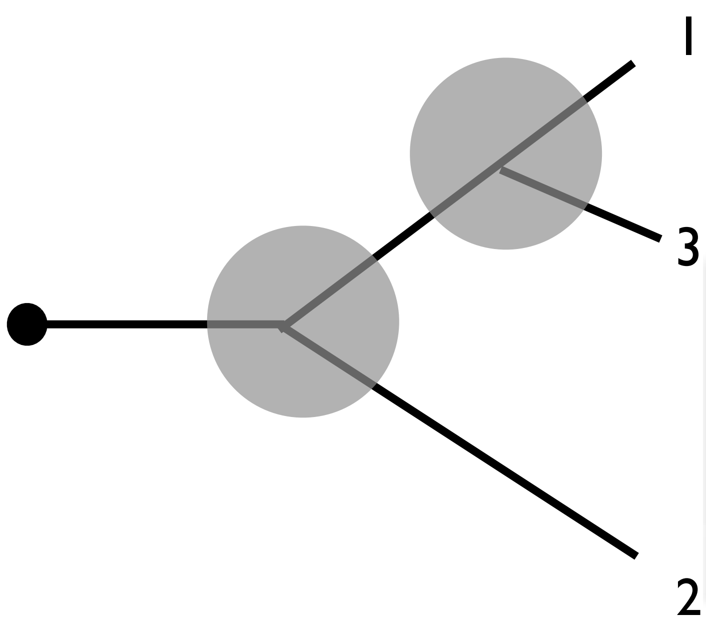
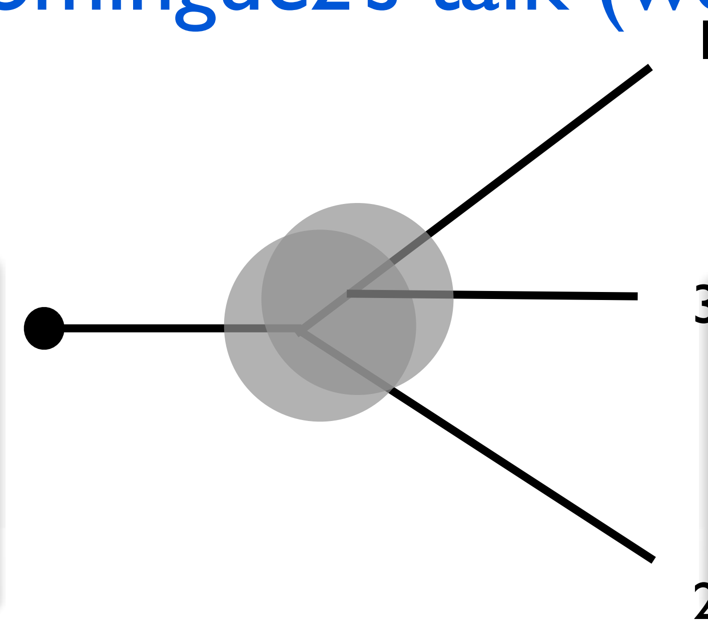


$$\propto \left(\alpha_s \frac{L}{t_{\rm f}}\right)^2$$

incoherent emissions



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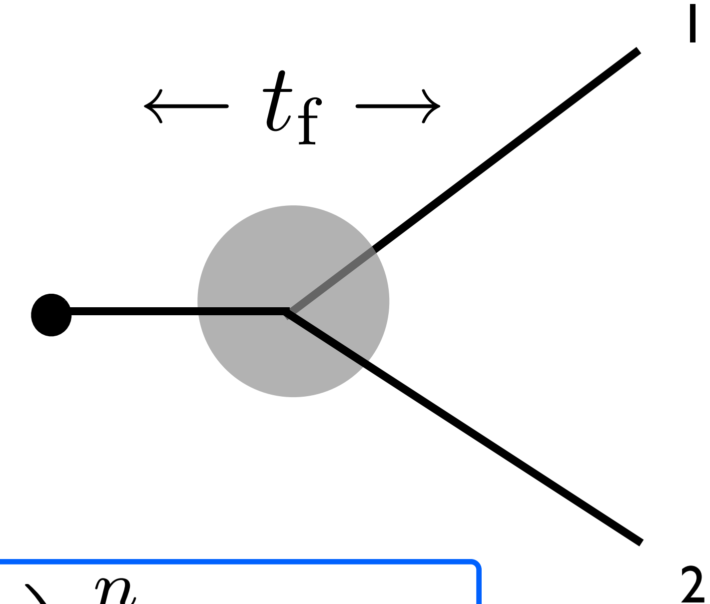
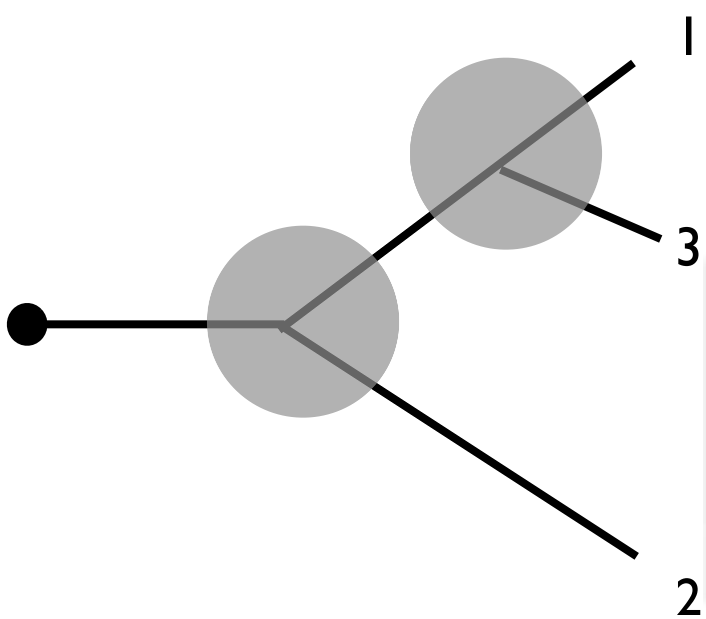


⇒ Probabilistic Scheme

$$\sigma = \sum_n a_n \left(\alpha_s \frac{L}{t_{\mathrm{br}}}\right)^n$$

See F. Dominguez's talk (wednesday)



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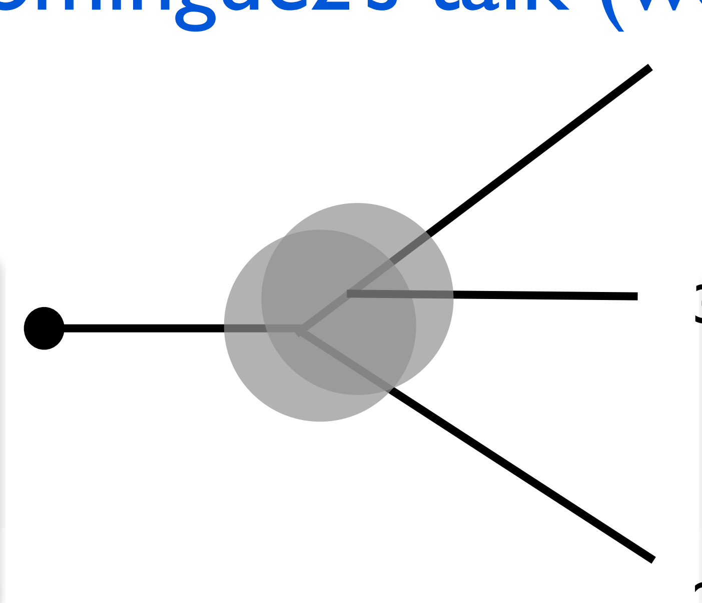
incoherent emissions



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coherent emissions