# Interference Effects for Jets in Medium

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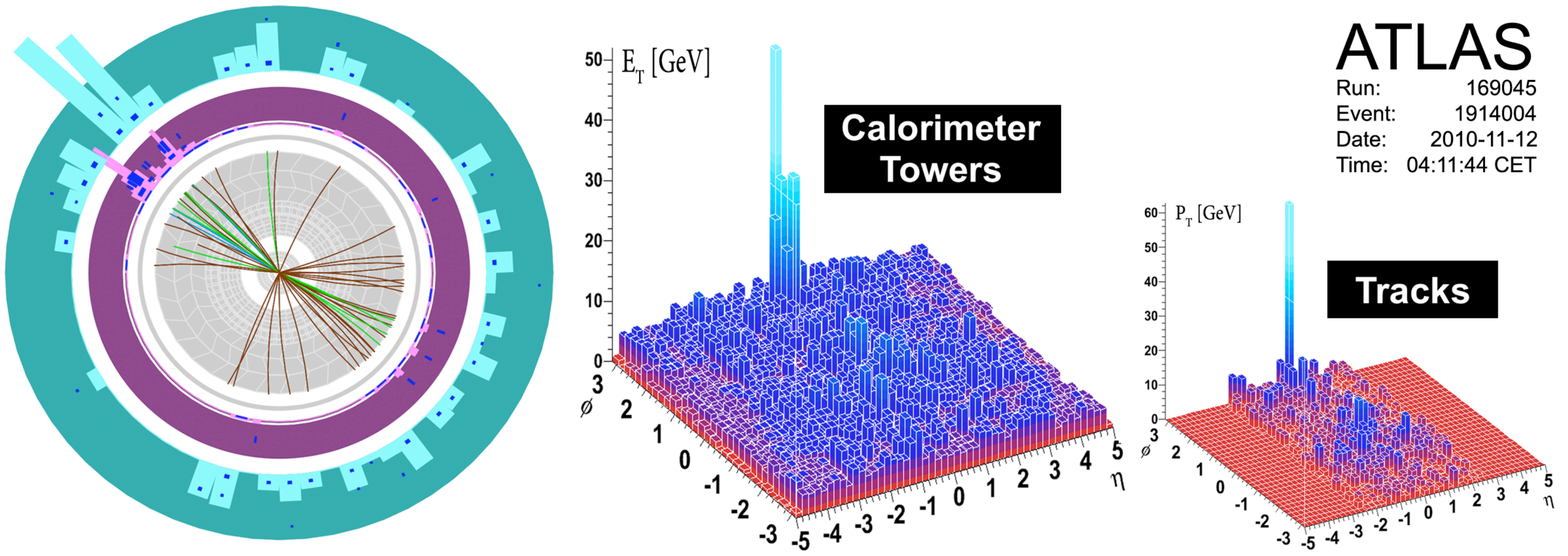
# Jets in Heavy Ion Collisions



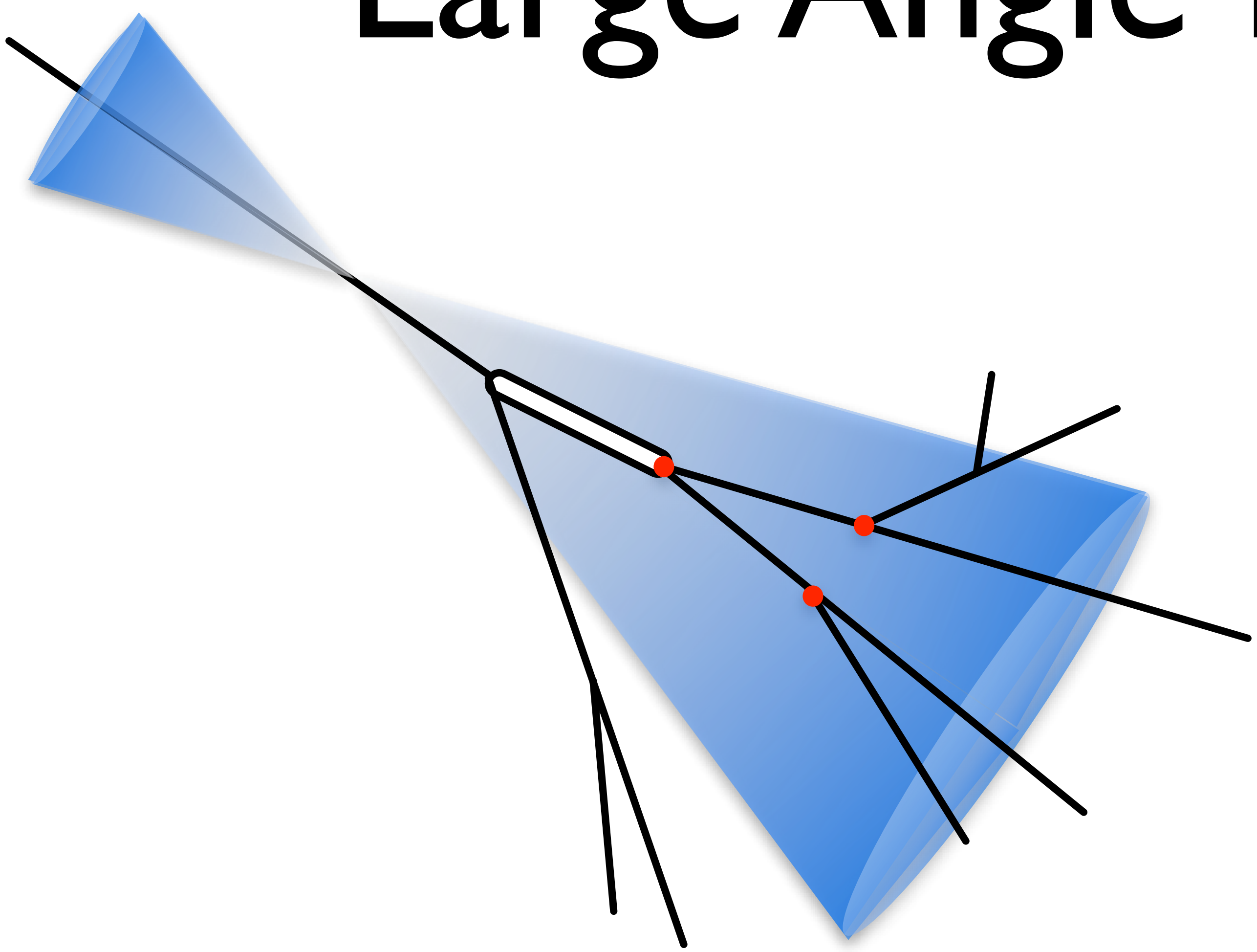

- Jets are strongly modified in a heavy ion environment
- Interactions in the collision lead to a large energy loss

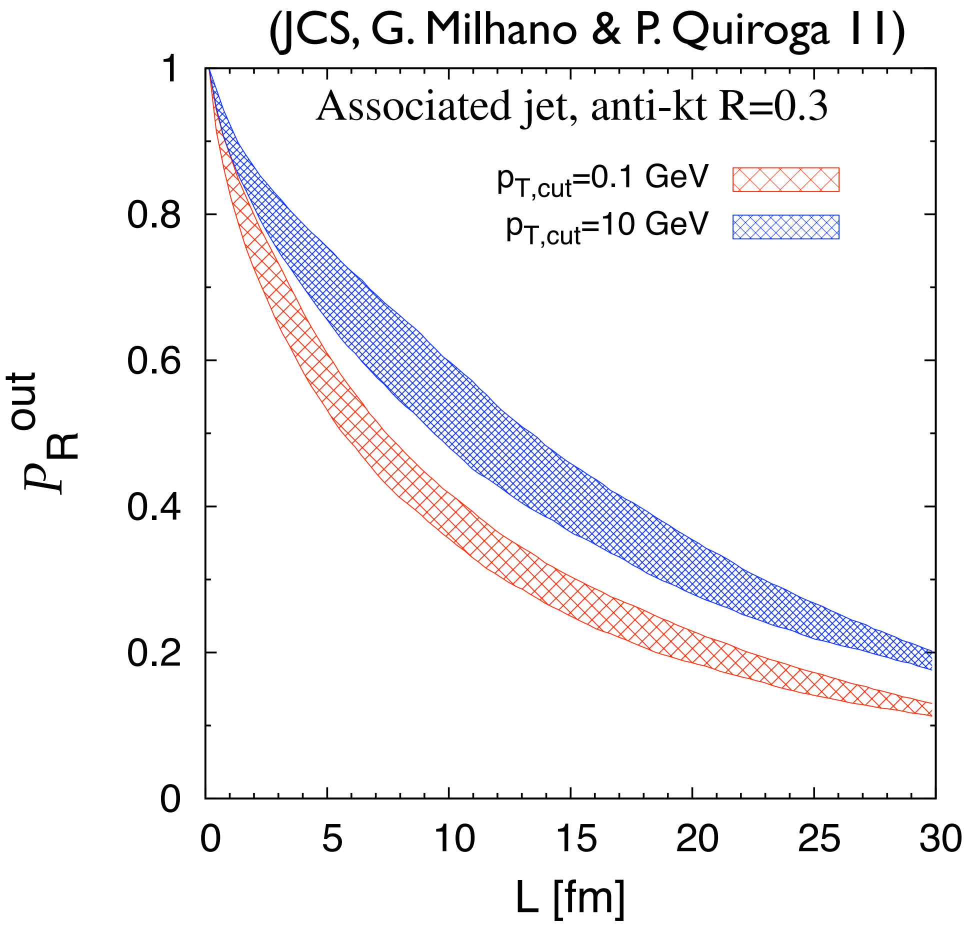
$$\langle \Delta E \rangle \sim 20\,\mathrm{GeV}$$ (JCS, G. Milhano & U. Wiedemann 10)

- However, the fragmentation patter is unmodified.

(at least for relatively narrow jet cones)

# Large Angle Radiation






- In vacuum most of the fragmentation happens at large distances
- Jet energy loss is produced by extra interactions
- These must be emitted at large angles, not to affect the fragmentation pattern.

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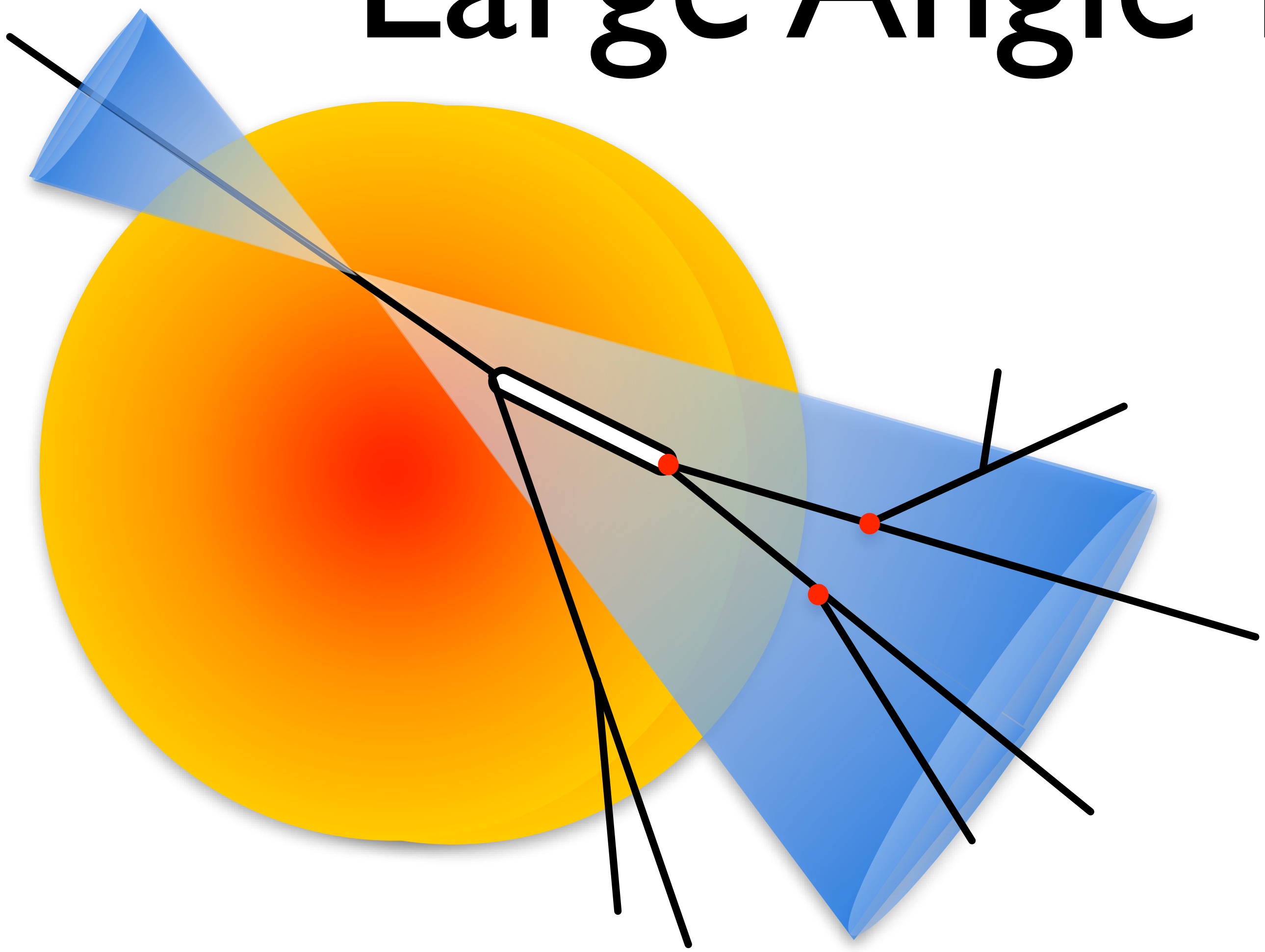

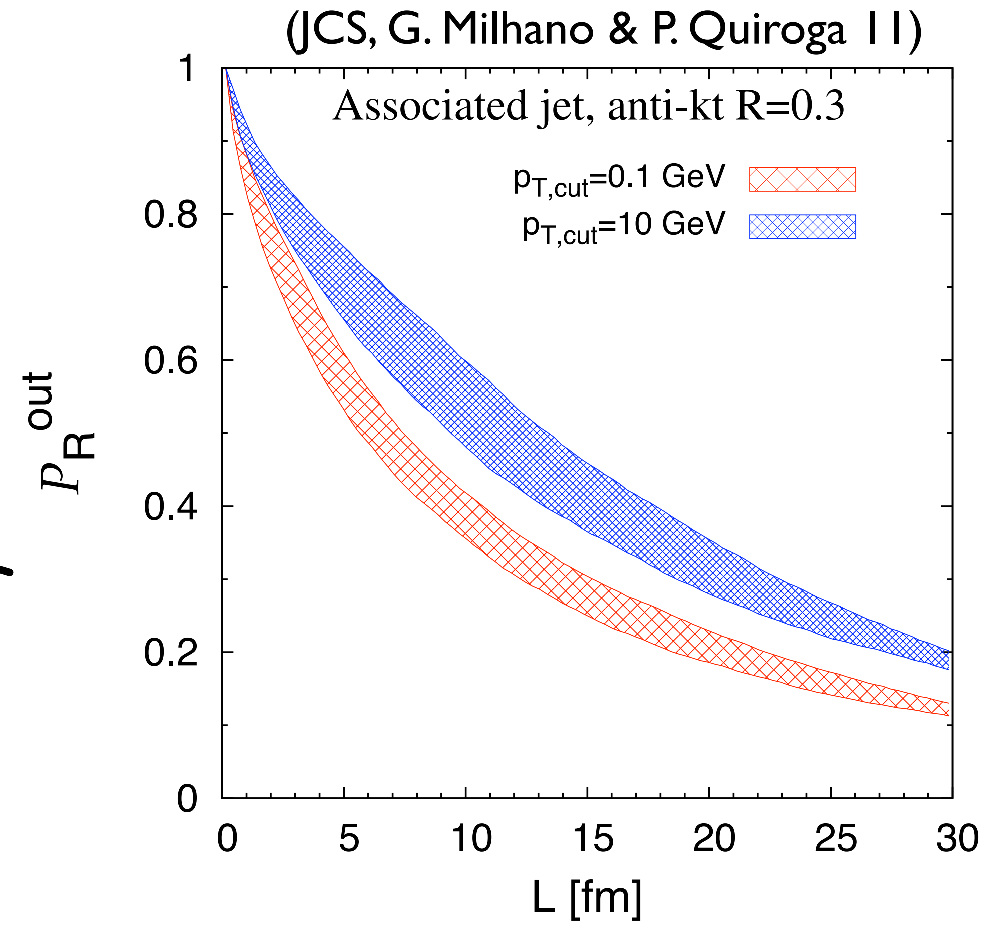


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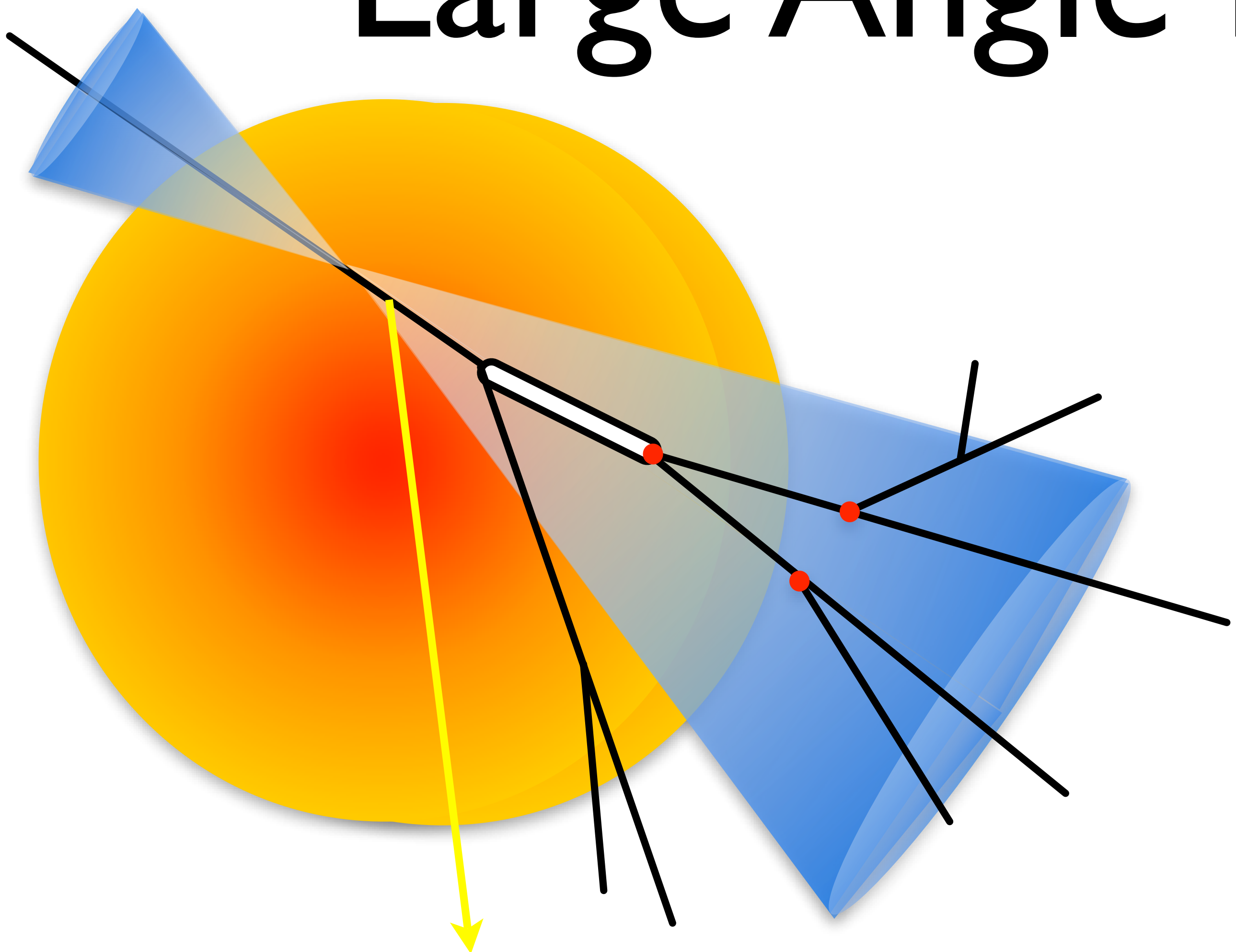
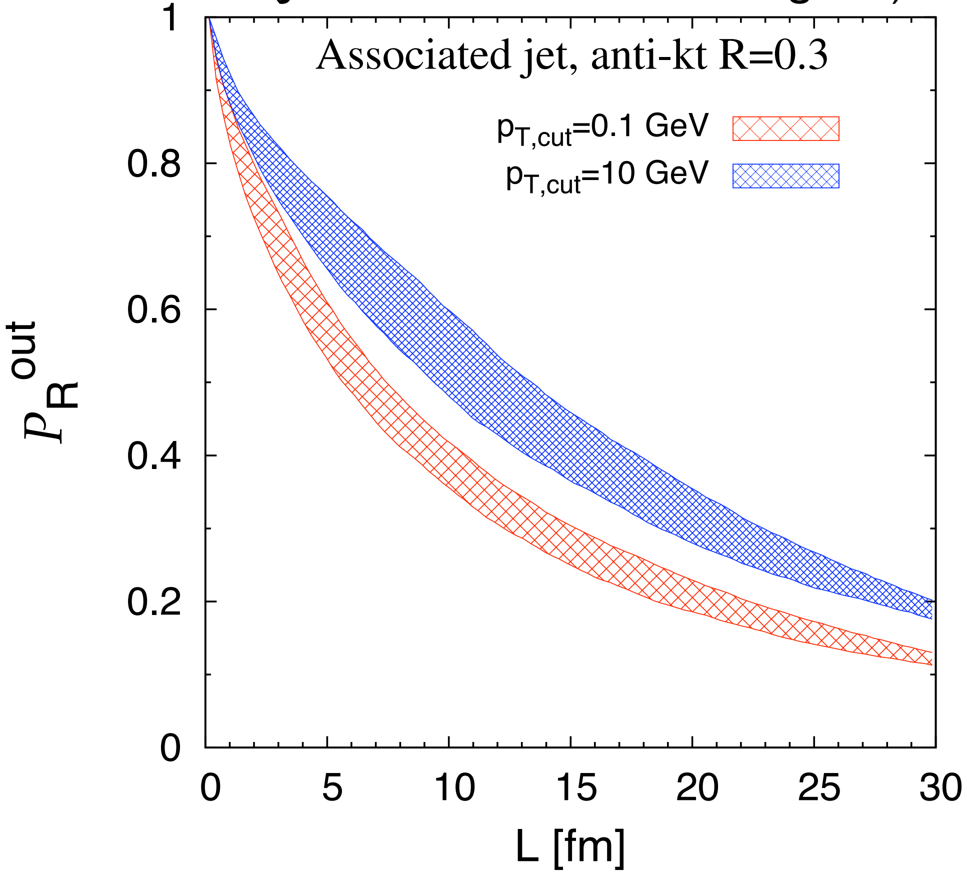


(JCS, G. Milhano & P. Quiroga 11)

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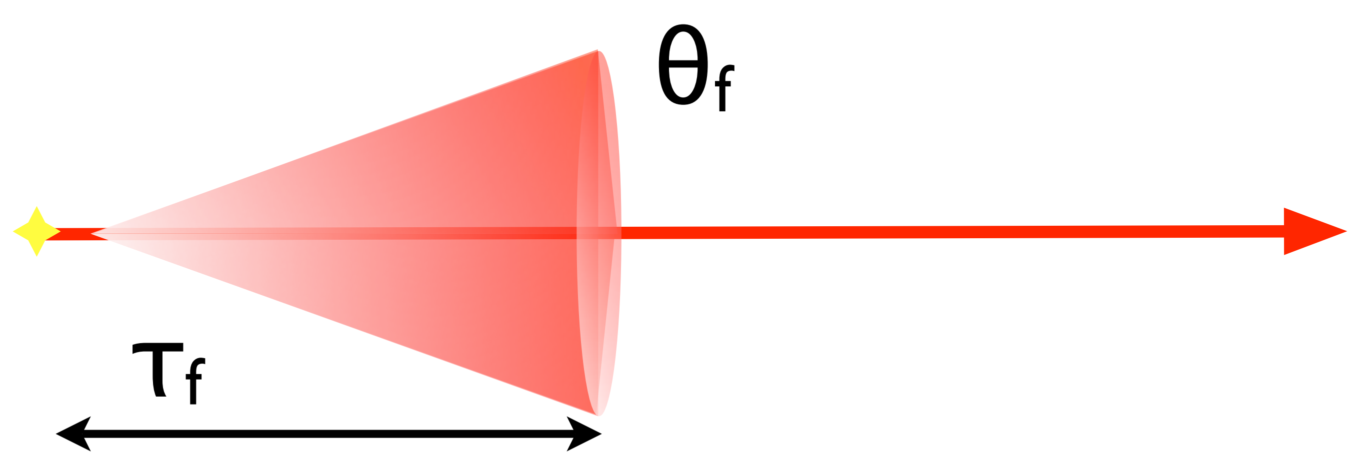
# Single Source in Vacuum



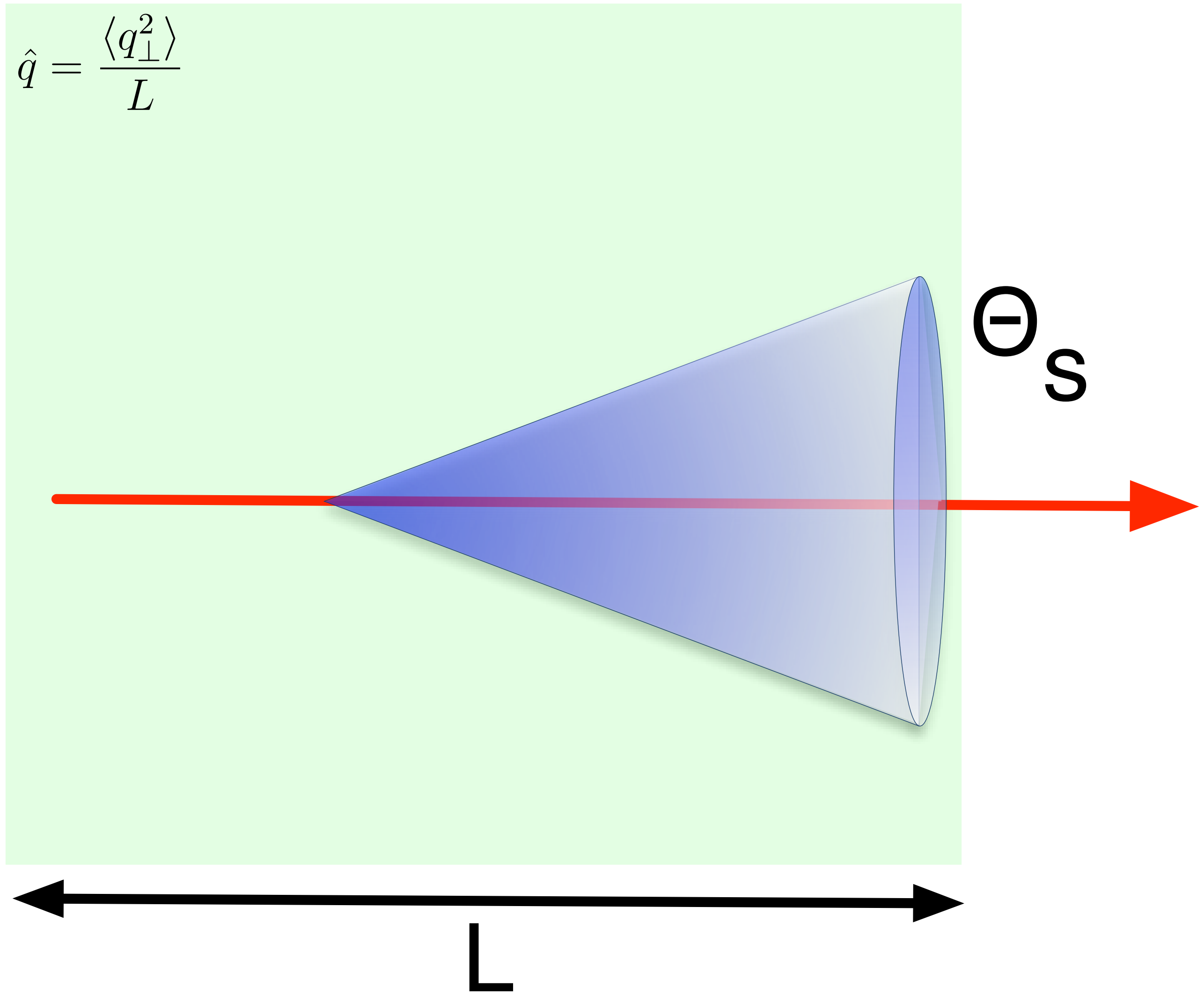

- We focus on soft gluons of frequency ω<<E.
- Gluon emission rate at an angle $\Theta_f$ from the source:

$$dN \propto \theta_f^2 \, \tau_f^2 \qquad\qquad \tau_f \sim \frac{1}{\omega\theta_f^2}$$

- $\tau_f$ is the time scale within which vacuum gluons are formed
- After the quark and gluon decohere and behave as independent objects

- Vacuum radiation is mostly collinear.

# Single Source in Medium




$$\theta_s^2 = \frac{\hat{q}L}{\omega^2}$$

- Gluons are emitted with a typical angle $\Theta_s$

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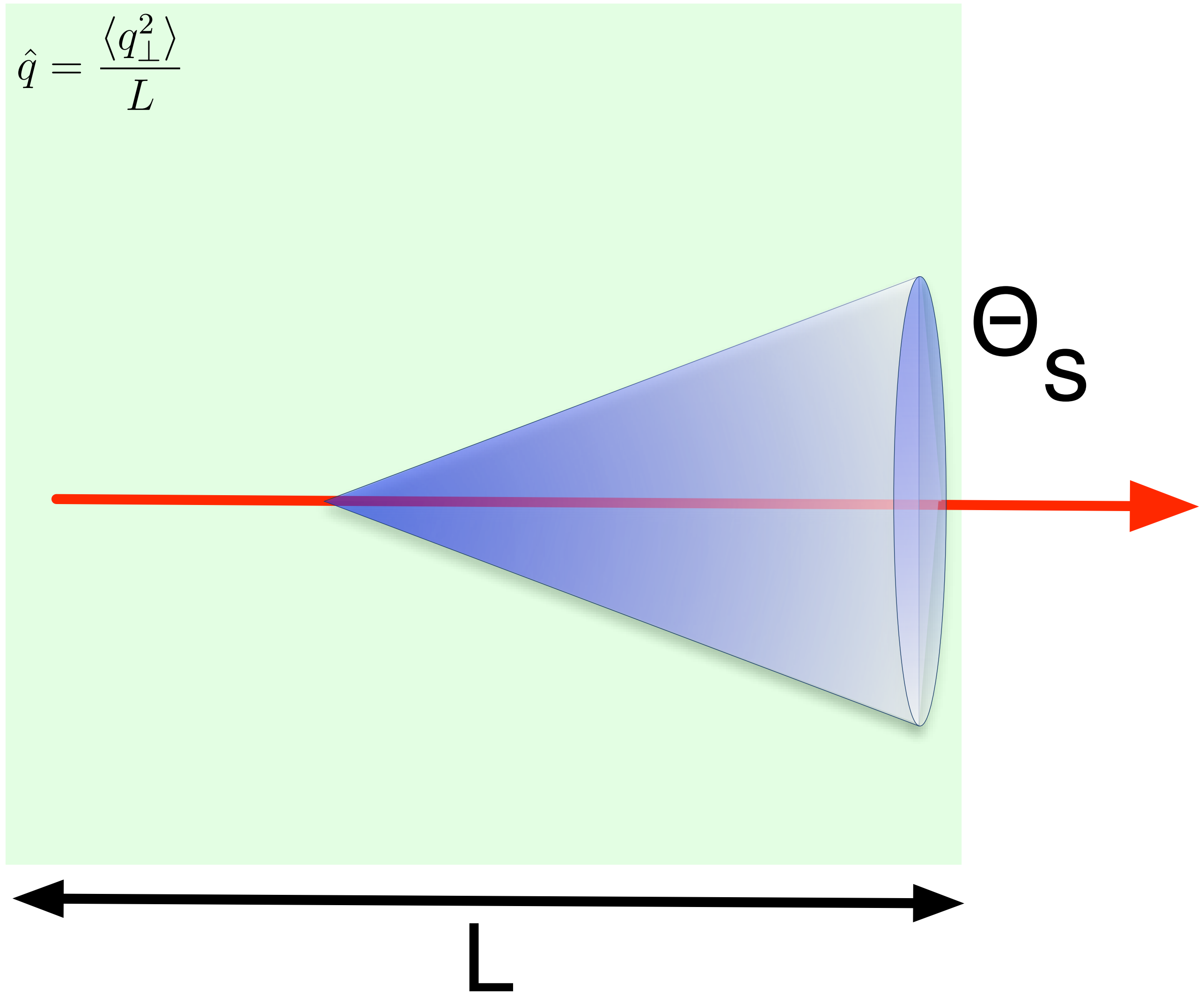


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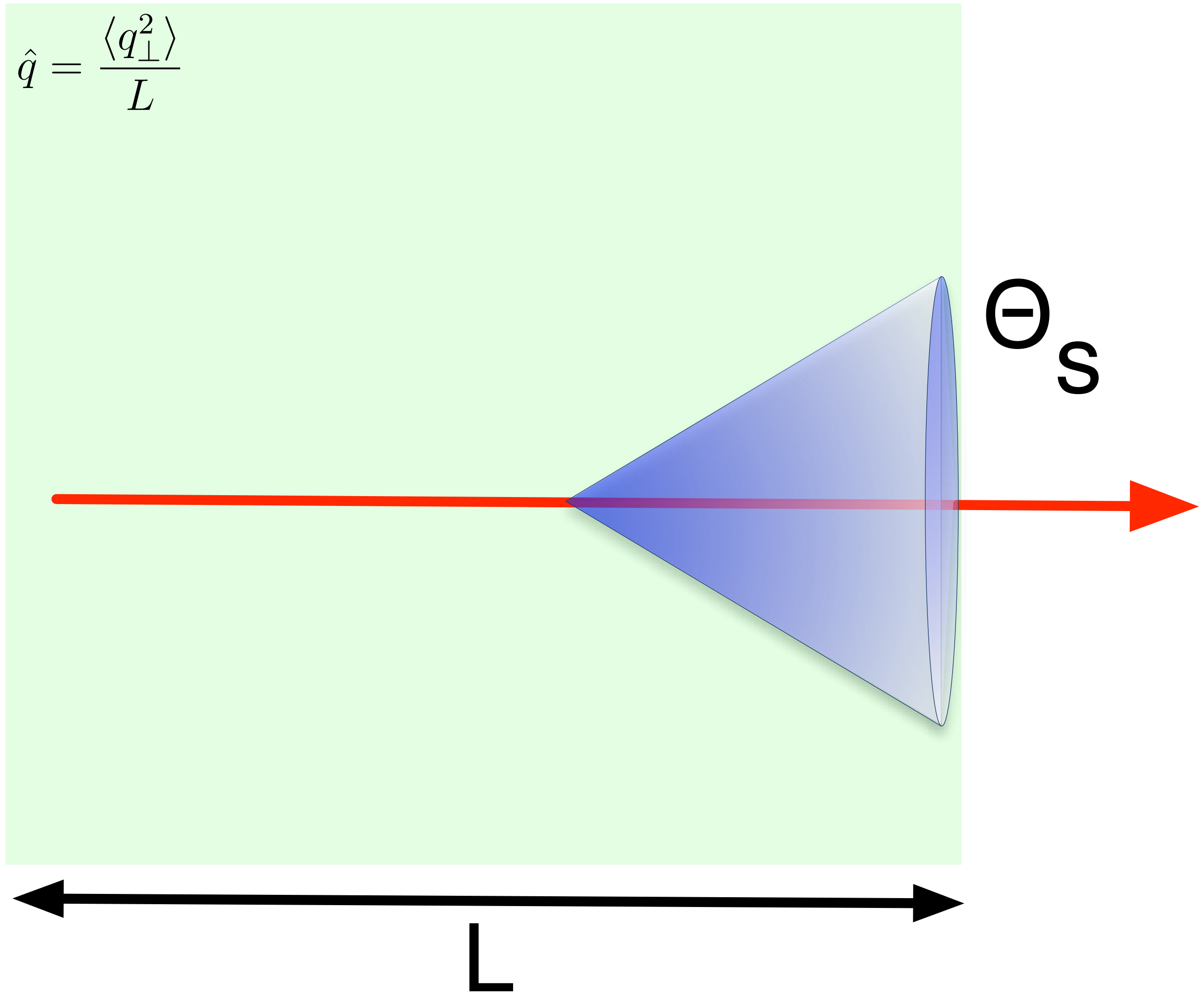


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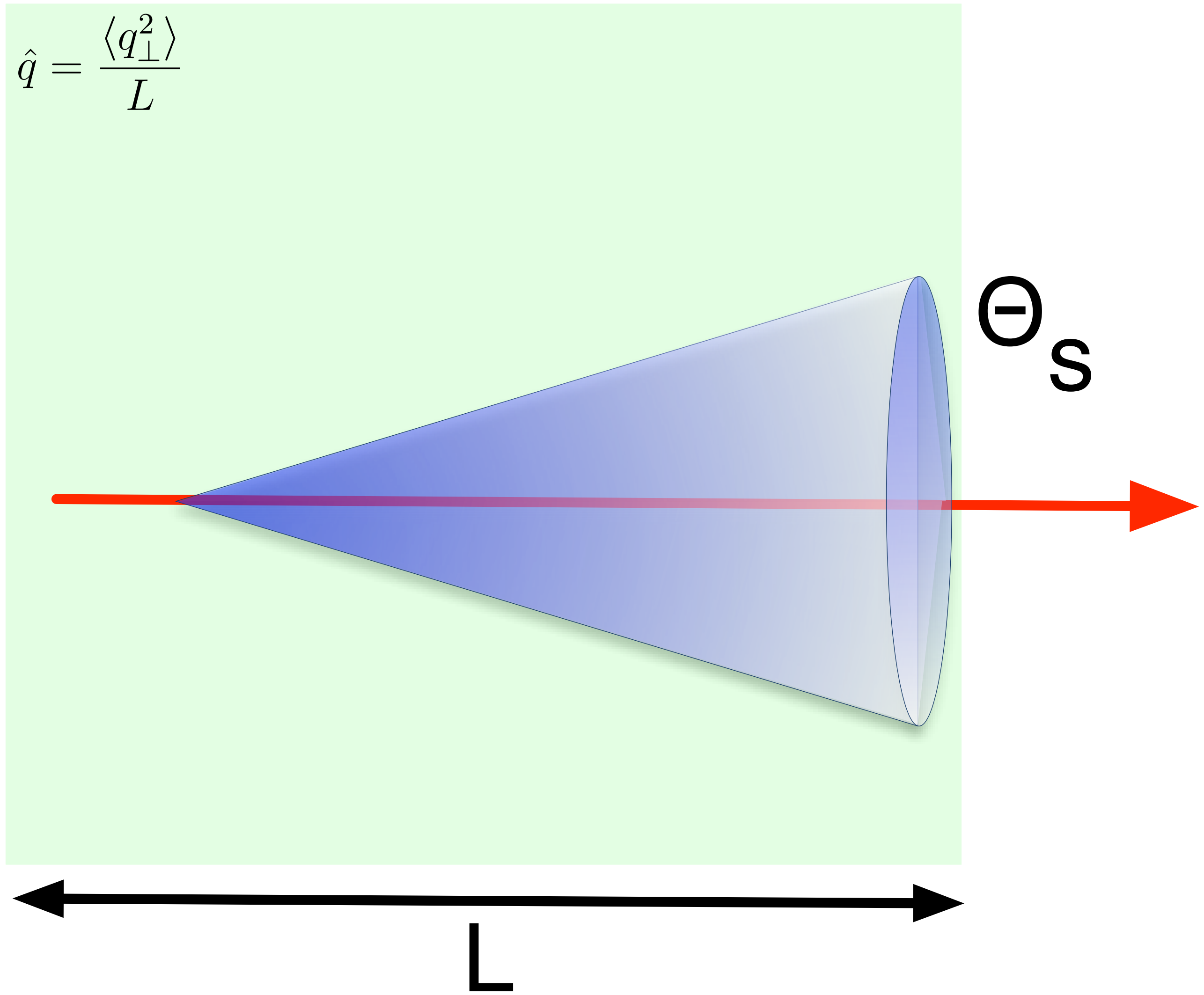


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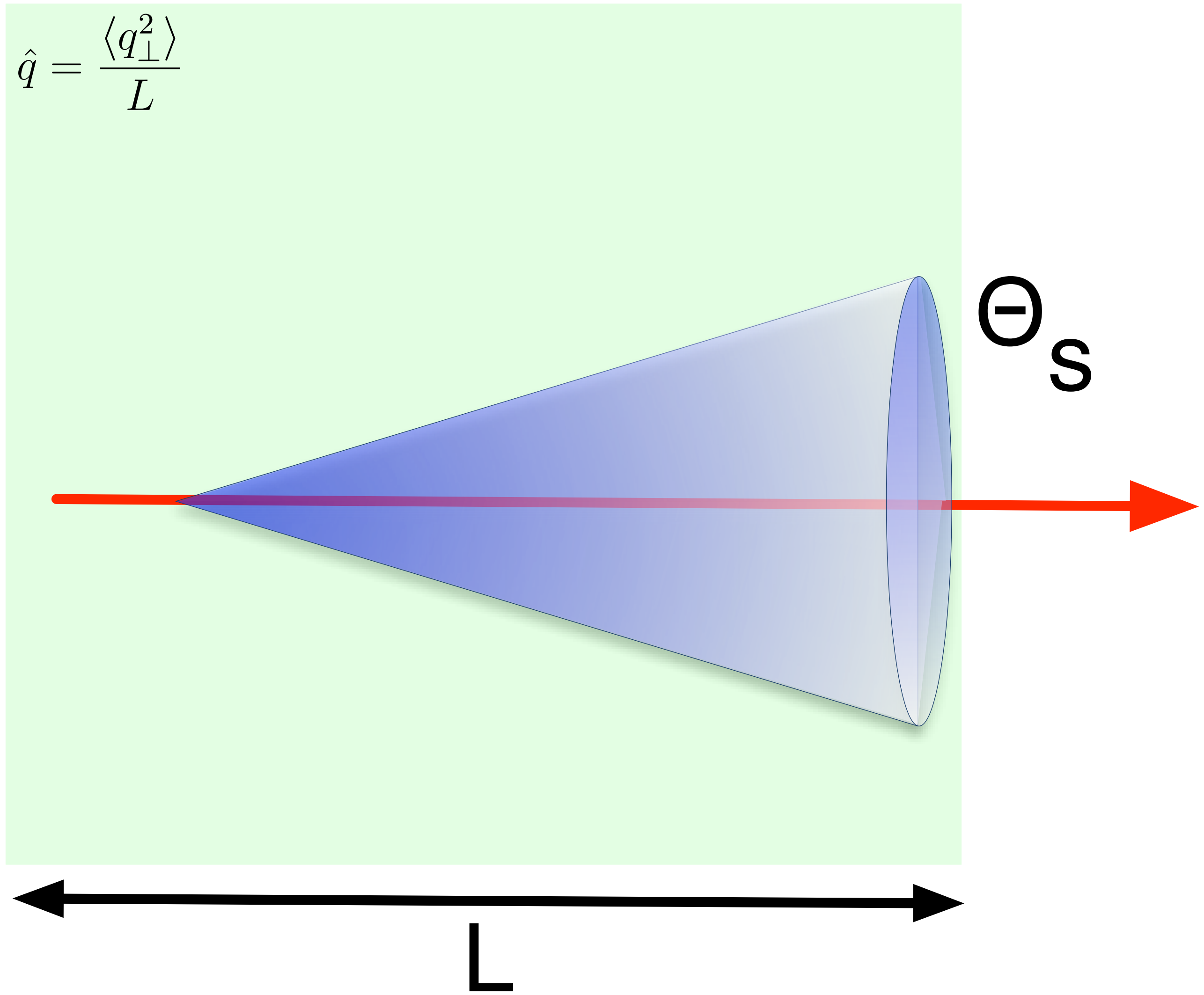


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- Emissions occur all along the medium: $dN \propto L$

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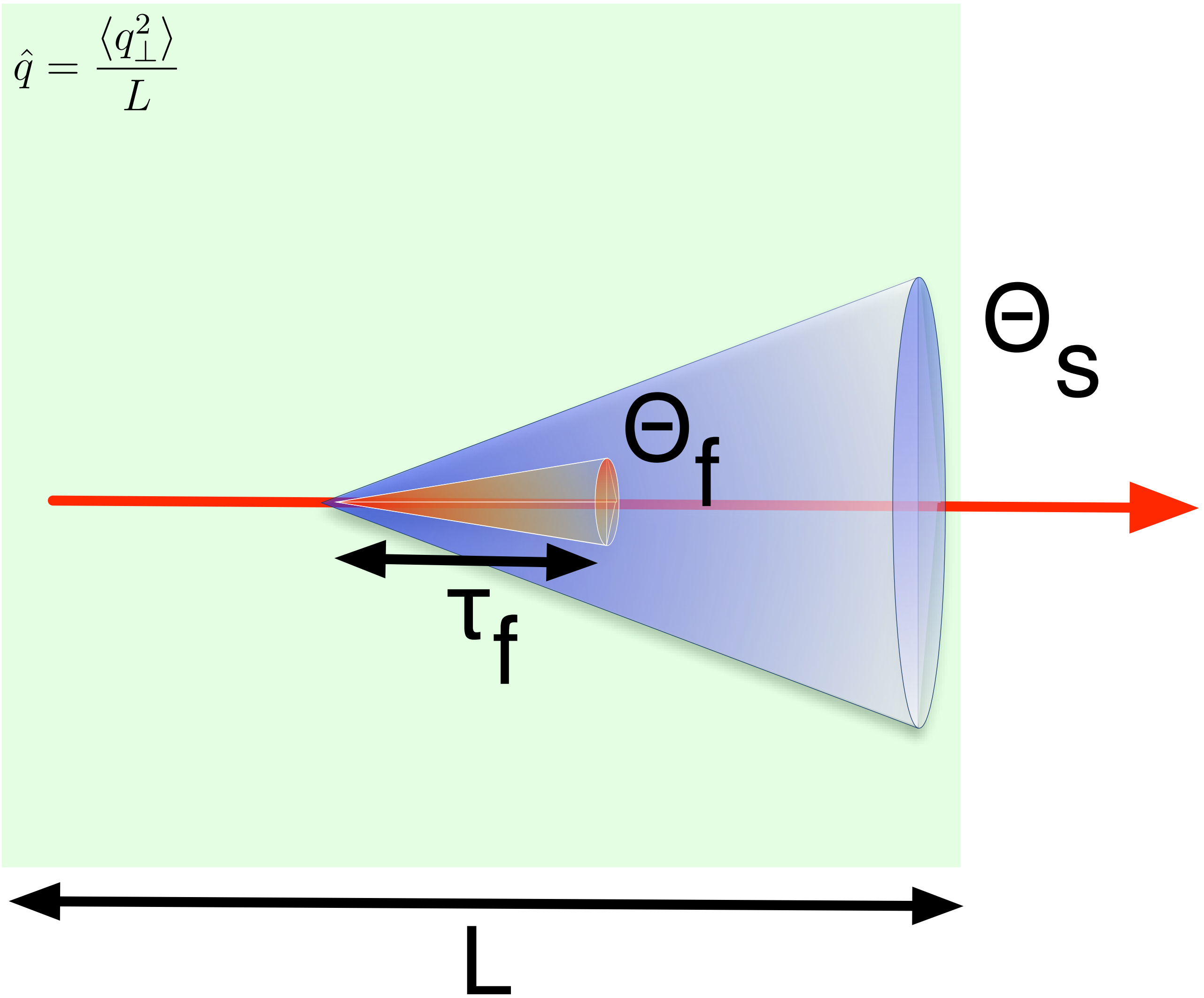


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$$\omega \ll \omega_c \equiv \frac{1}{2}\hat{q}L^2$$

$$\tau_f = \sqrt{\frac{2\omega}{\hat{q}}}$$

$$\theta_f^2 = \sqrt{\frac{\hat{q}}{\omega^3}}$$

- Gluons are emitted with a typical angle $\Theta_s$
- Emissions occur all along the medium: dN ∝ L
- Soft gluons are formed (decohered) at a short time $\tau_f$

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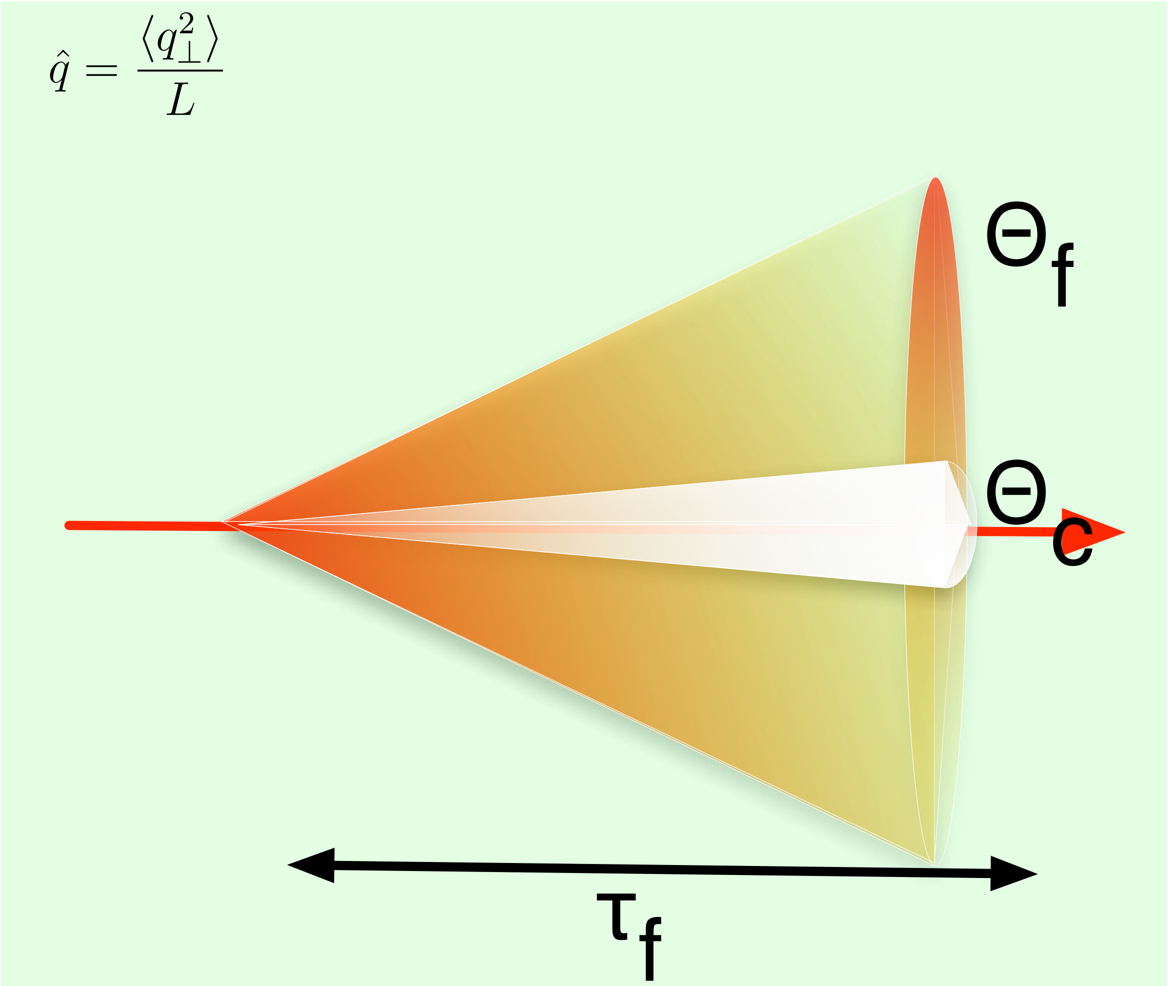


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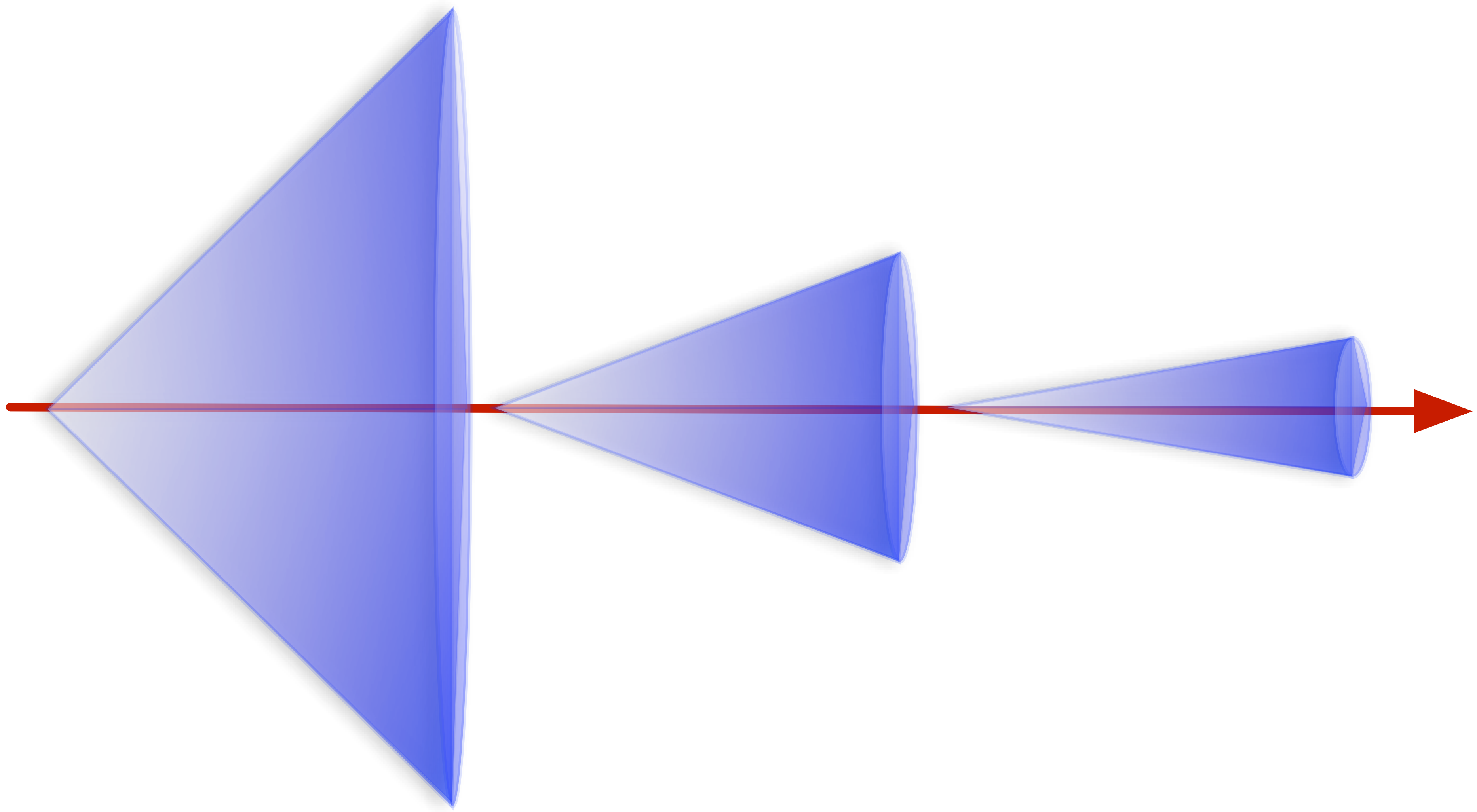
$$\theta_c^2 = \frac{1}{\hat{q}L^3}$$

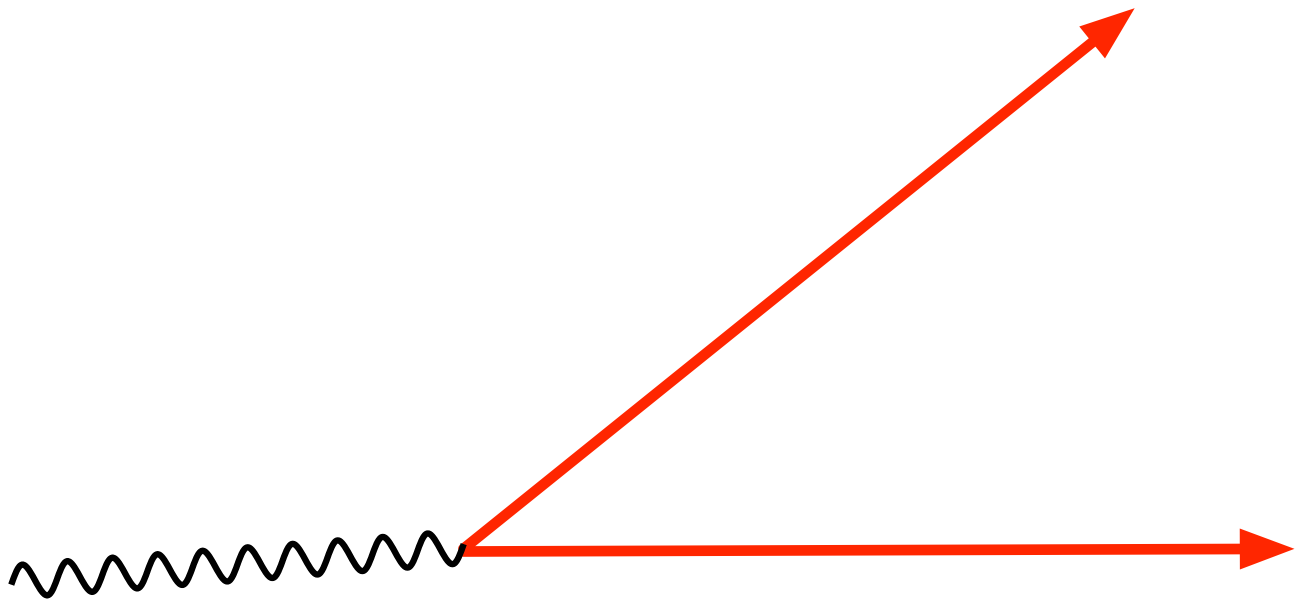
- Gluons are emitted with a typical angle $\Theta_s$
- Emissions occur all along the medium: dN ∝ L
- Soft gluons are formed (decohered) at a short time $\tau_f$
- There is a minimum value for emissions $\Theta_C$

# Angular Ordering in Vacuum



- Single gluon emission is not enough to describe jets
- In vacuum, successive radiations are not independent.
- More than one QCD emitter leads to angular ordering
- Does something similar happen in the medium?

# Singlet Antenna in Vacuum



- The emissions from two sources can interfere.

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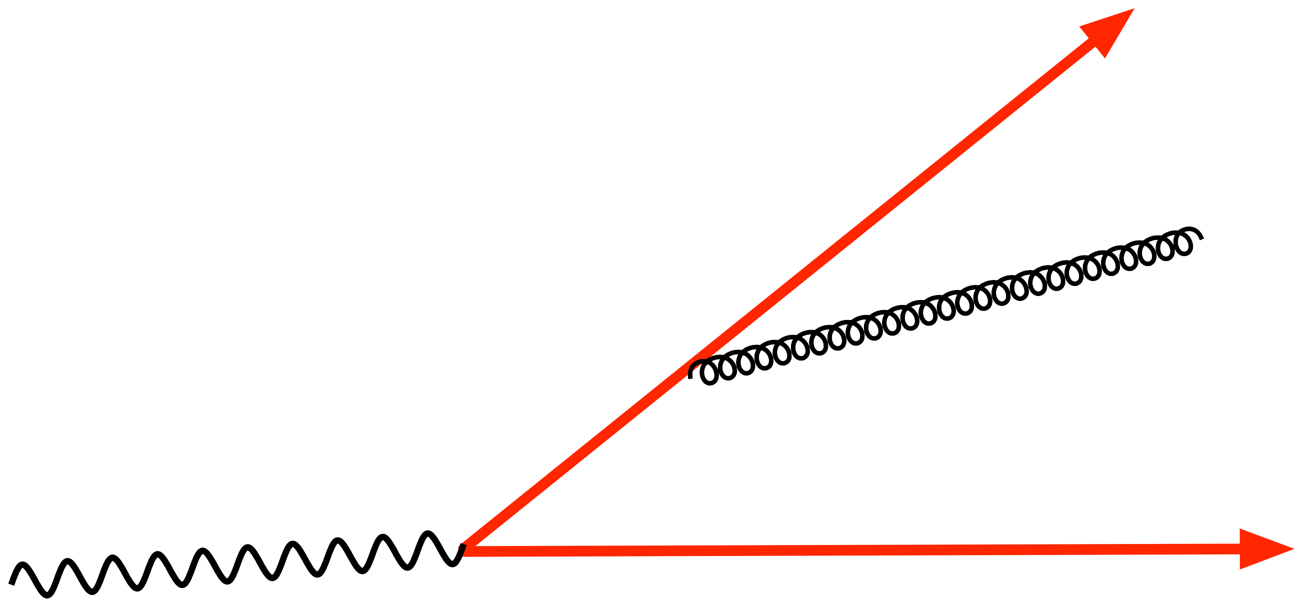

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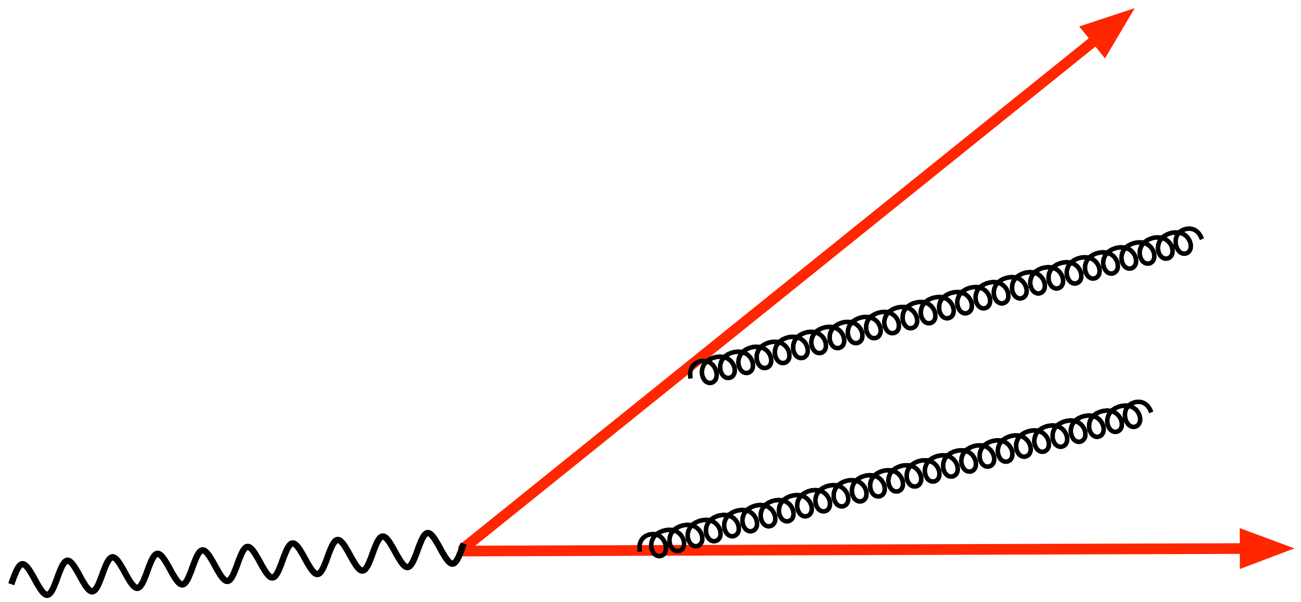

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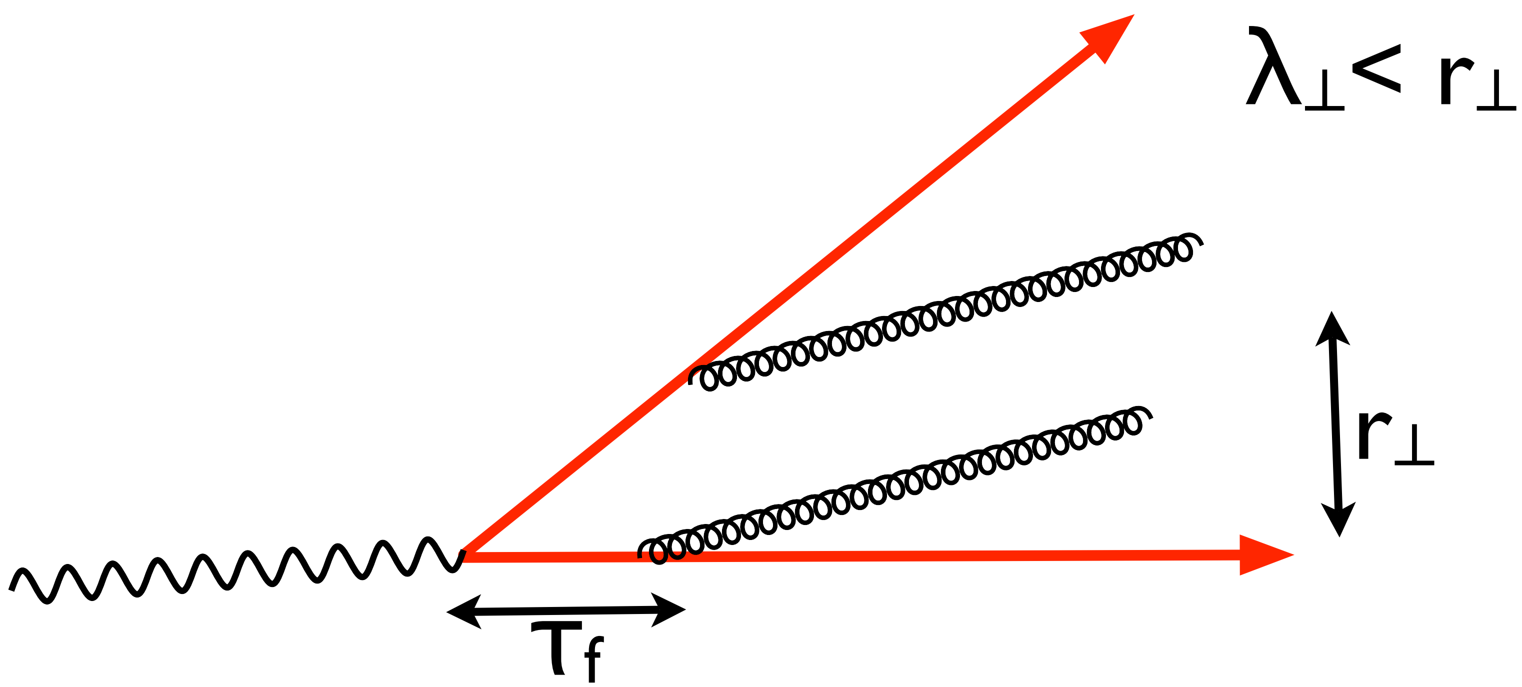


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- In cone emissions:

$\lambda_\perp < r_\perp$ ⇒Two color charges are resolved⇒ Independent emission

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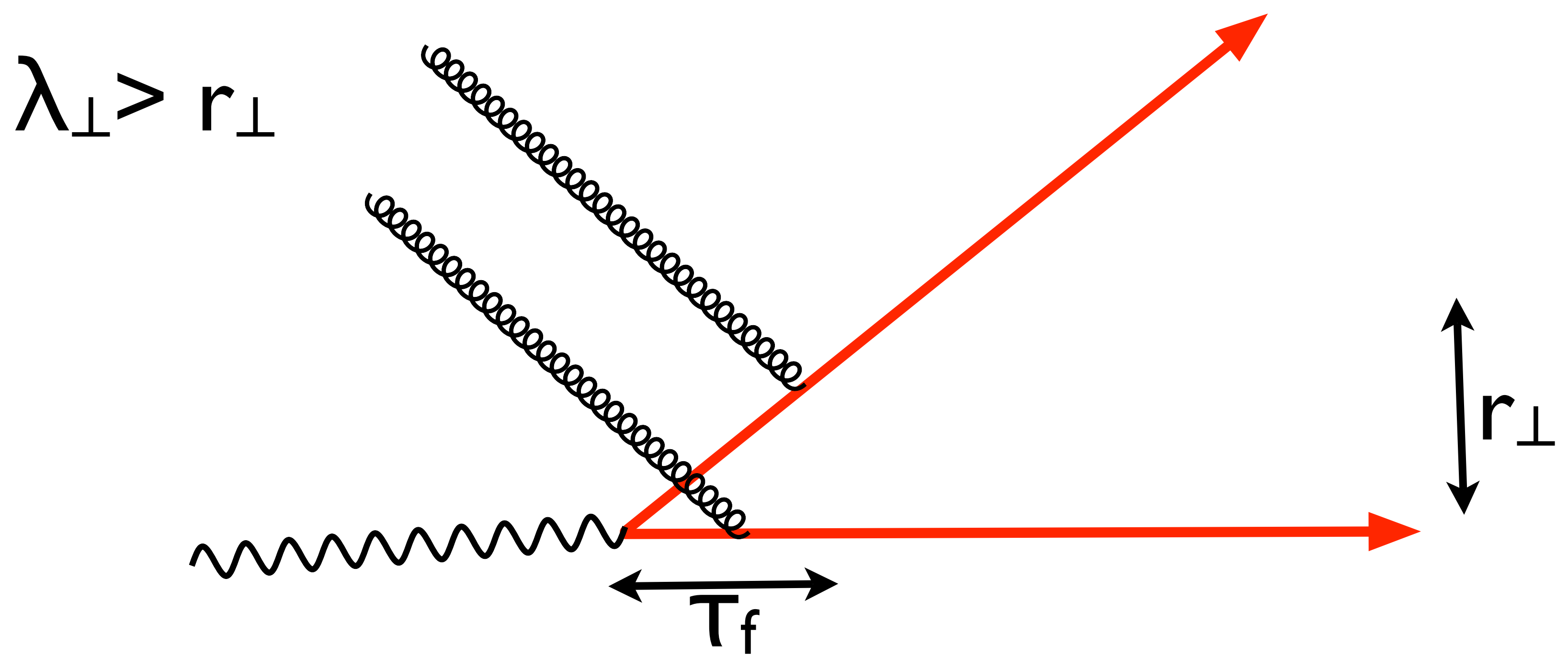


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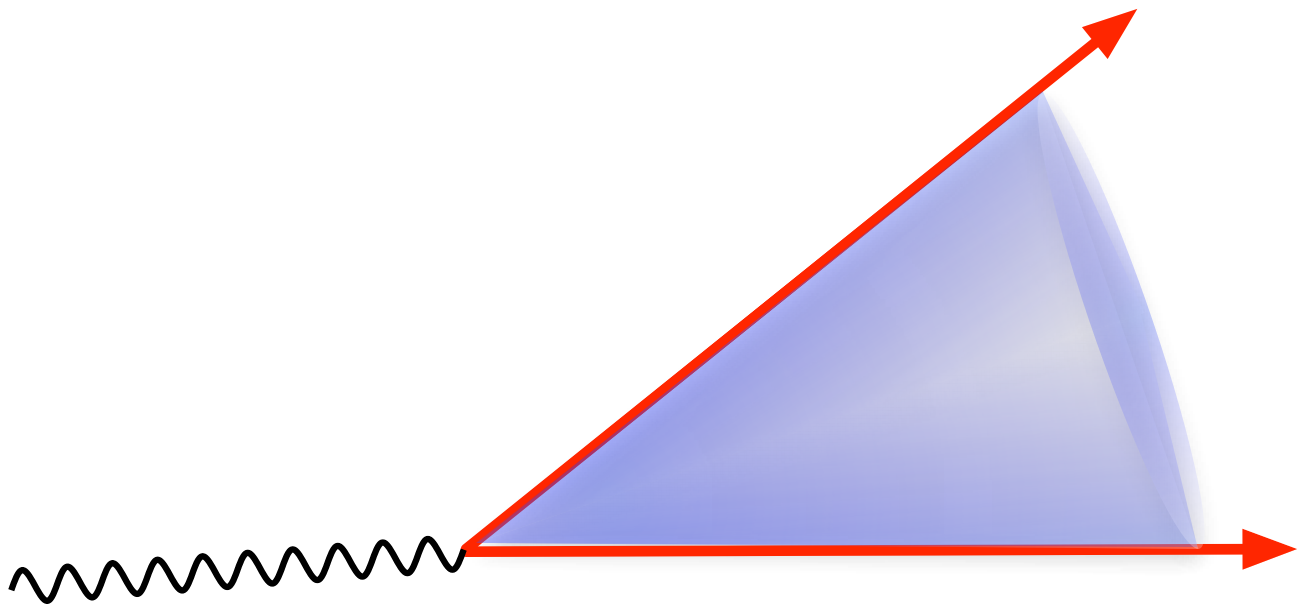

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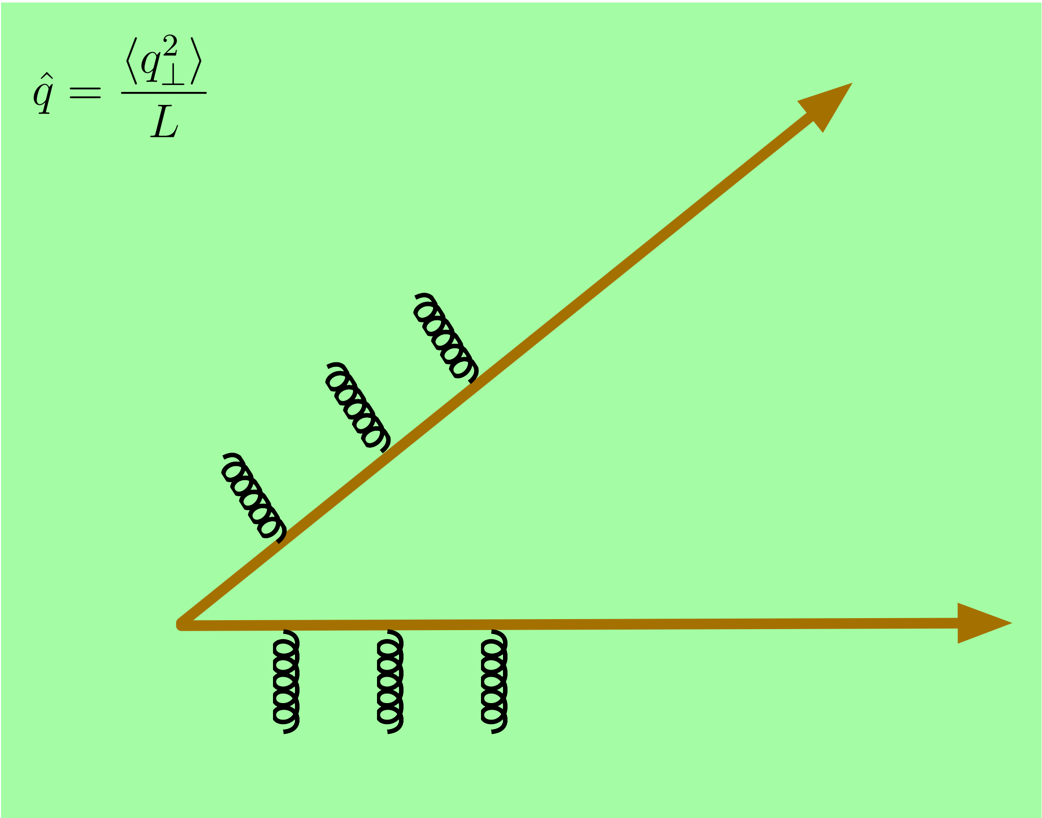
- Emissions are confined to inside of the cone (A.O.)

# Color Rotation of the Antenna



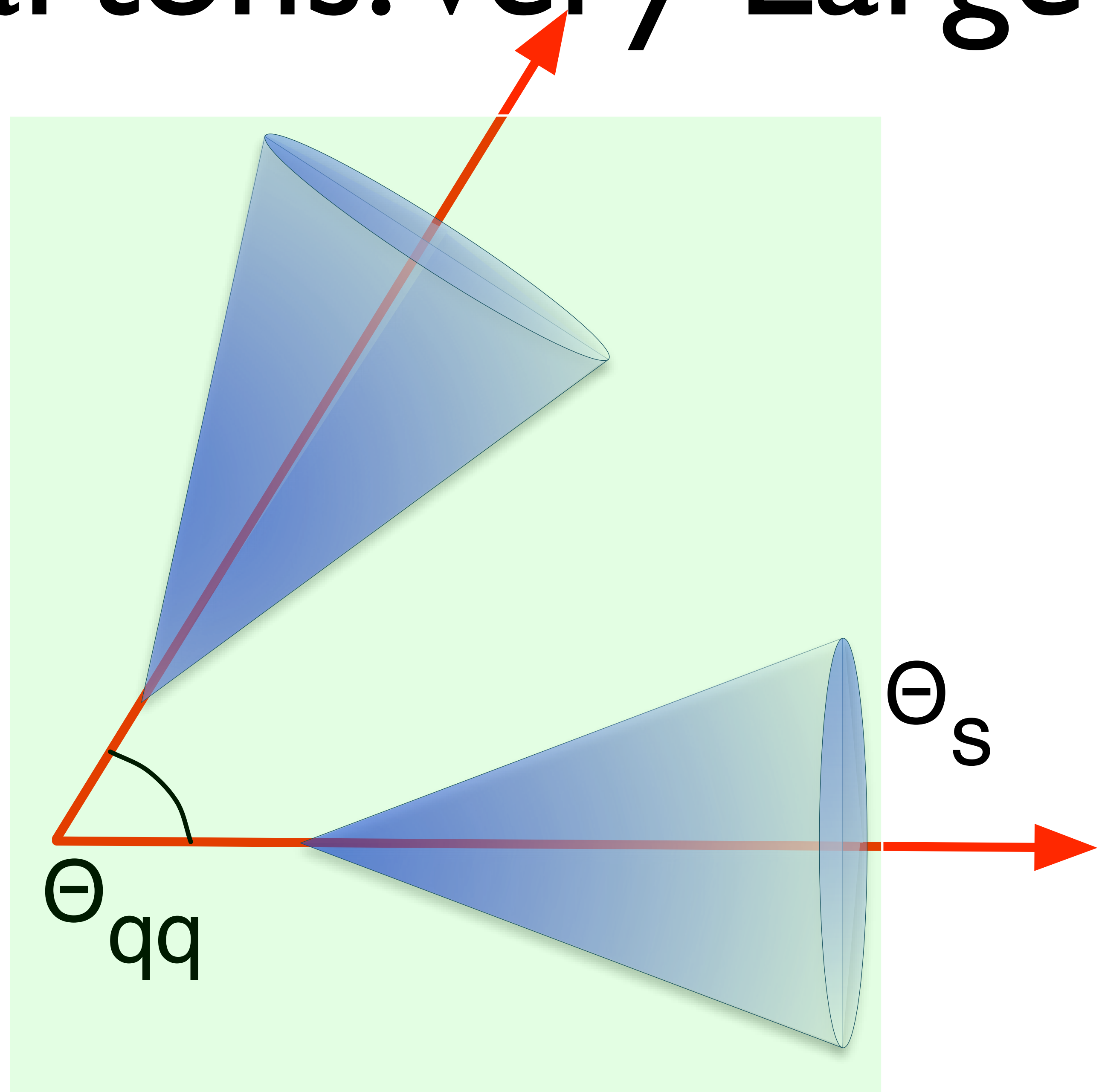

- In vacuum, the color state of the pair is preserved.
- In the medium, interactions lead to color precession
- The survival probability of the color state after a time τ is

(within the dipole model)

$$e^{-(\tau/\tau_{coh})^3} \qquad \tau_{coh} \sim \frac{1}{\left(\hat{q}\theta_{qq}^2\right)^{1/3}}$$

- How is the emission process affected by this rotation?
  - In the dense limit: JCS & Iancu 11, Mehtar-Tani, Salgado, Tywoniuk 11
  - In the dilute limit: Mehtar-Tani, Salgado, Tywoniuk 10
    Armesto, Ma, Mehtar-Tani, Salgado, Tywoniuk 11

# Two Partons: Very Large Angles




- Radiation from two sources propagating in plasma.
- $\Theta_{qq} >> \Theta_s$ the two fronts do not overlap

  No interference between BDMPS gluons

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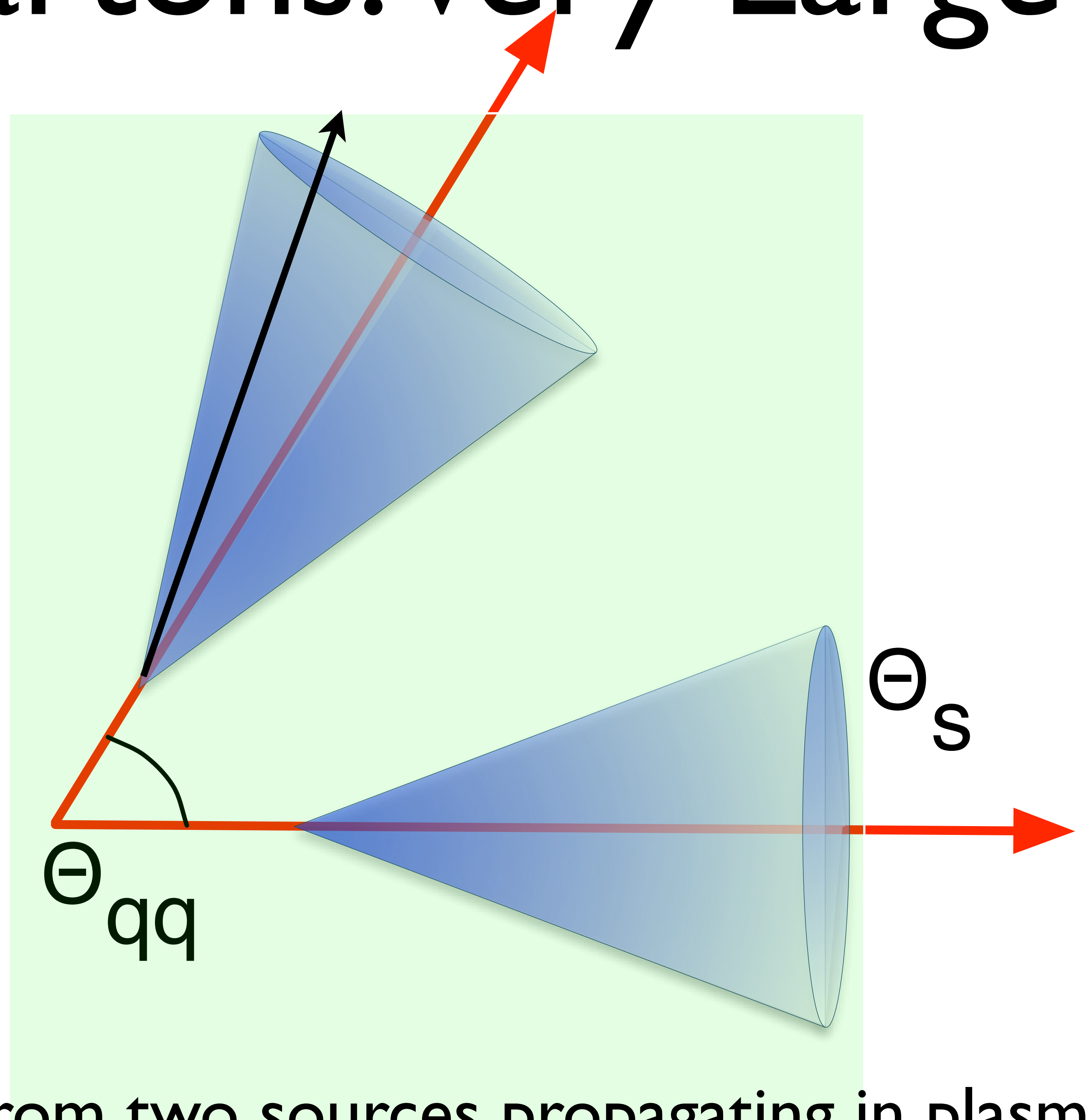


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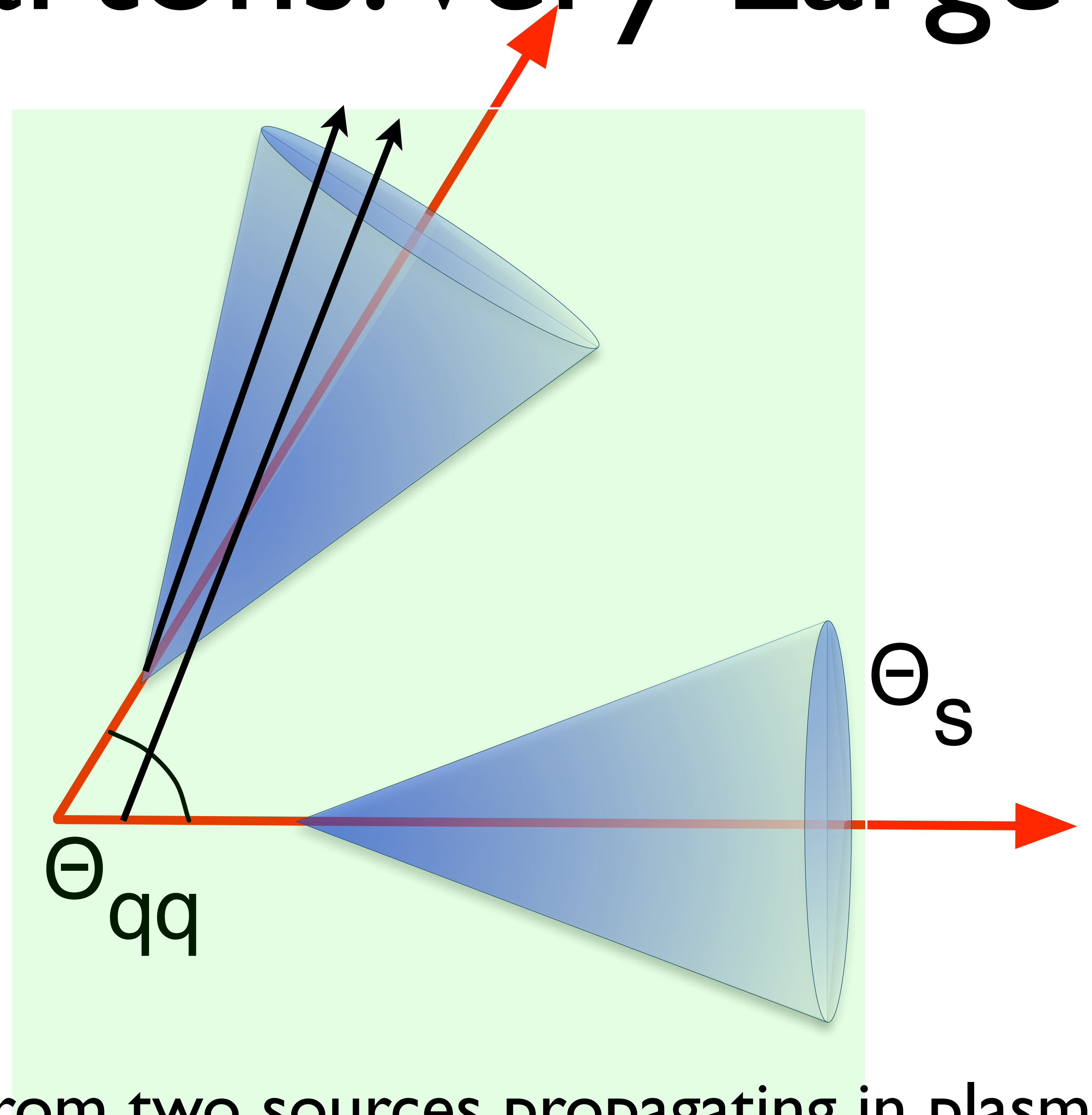


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- "Vacuum-Medium" interference is possible

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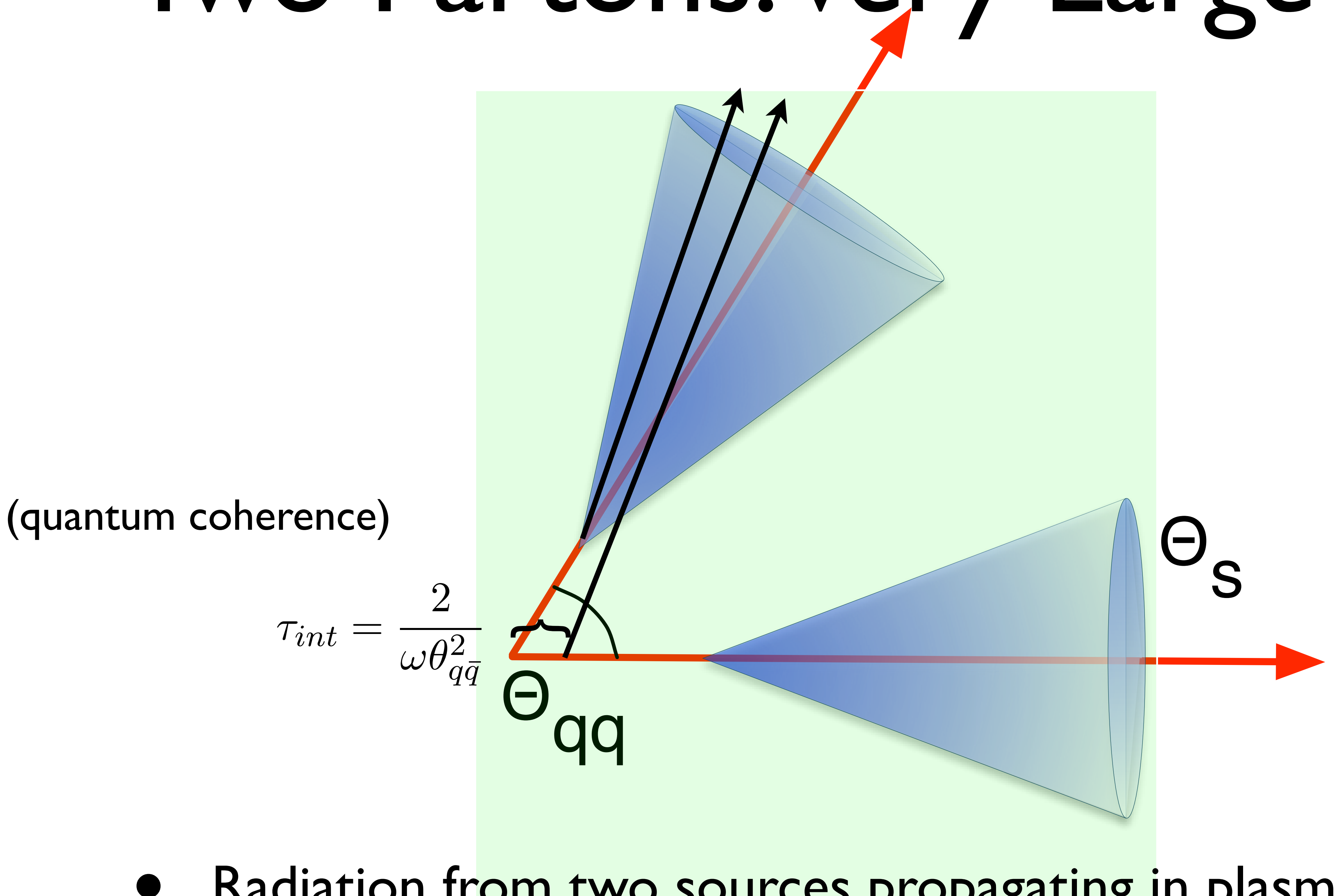


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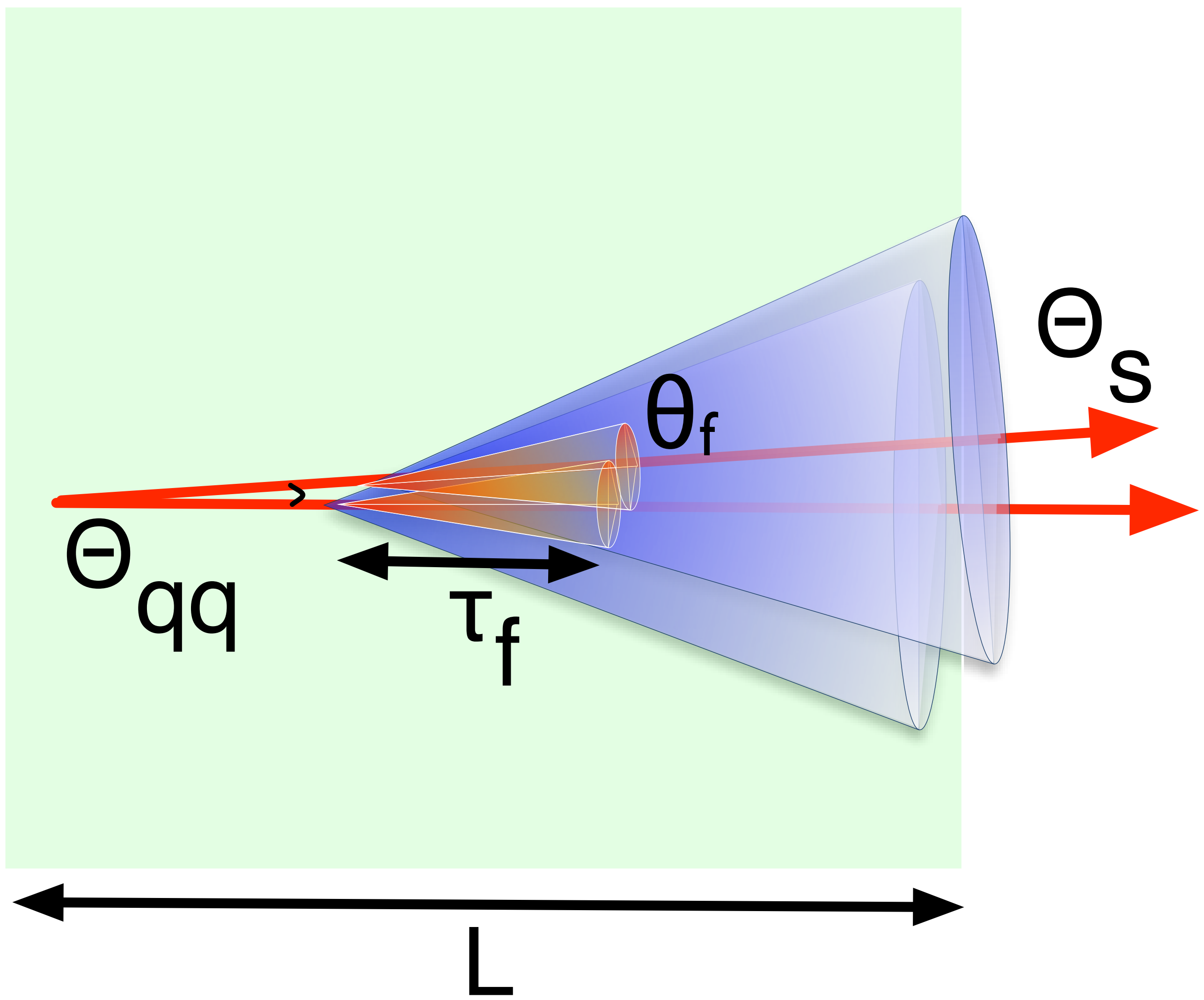
  No interference between BDMPS gluons
- "Vacuum-Medium" interference is possible
- Interference contribution scales with $dI \propto \tau_{int}$

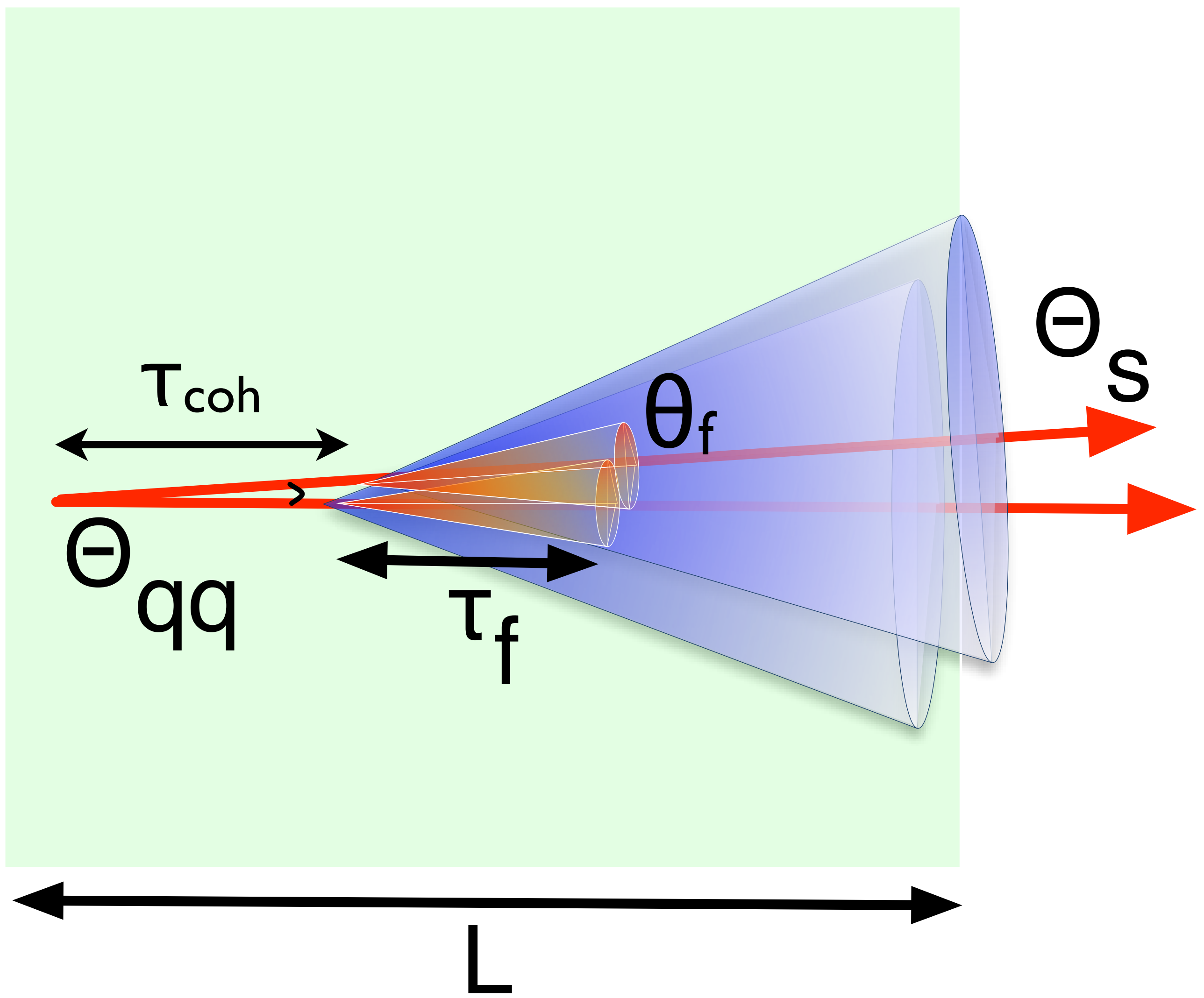
# Two Partons: Small Angles




- The two fronts overlap at formation: they can interfere.

# Two Partons: Small Angles

(color coherence)



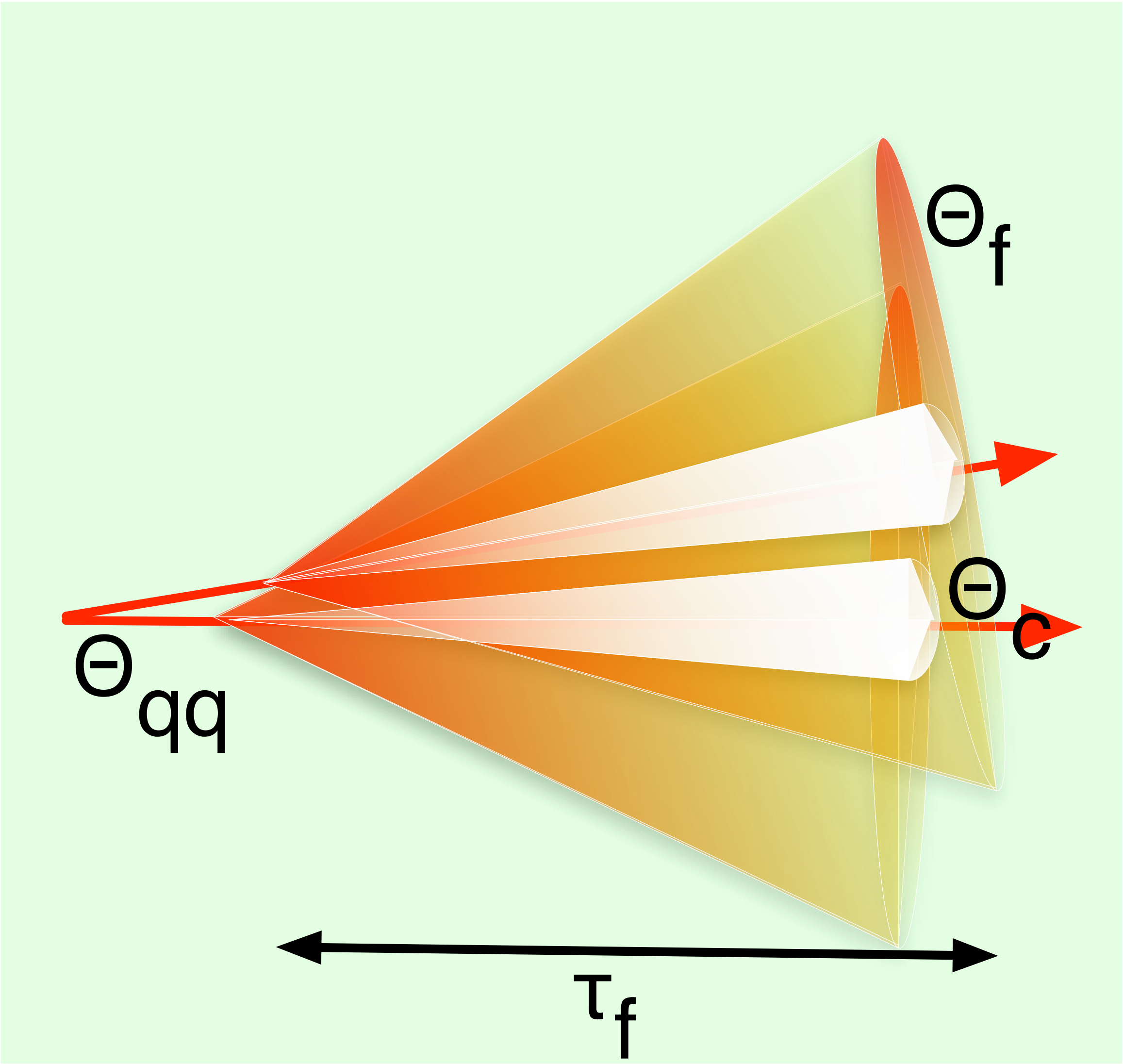

- The two fronts overlap at formation: they can interfere.
- The qq pair rotates color before emission. At

$$\tau_{coh} = \left(\frac{\theta_c}{\theta_{q\bar{q}}}\right)^{2/3} L$$

The color of each quark is randomized ⇒ No interference

- Interference contribution scales with dl∝$\tau_{coh}$

# Two Partons: Very Small Angles




- Interference is possible. Antenna color remains almost constant
- Interference occurs as in vacuum up to corrections $\Theta^2_{qq}/\Theta^2_C$

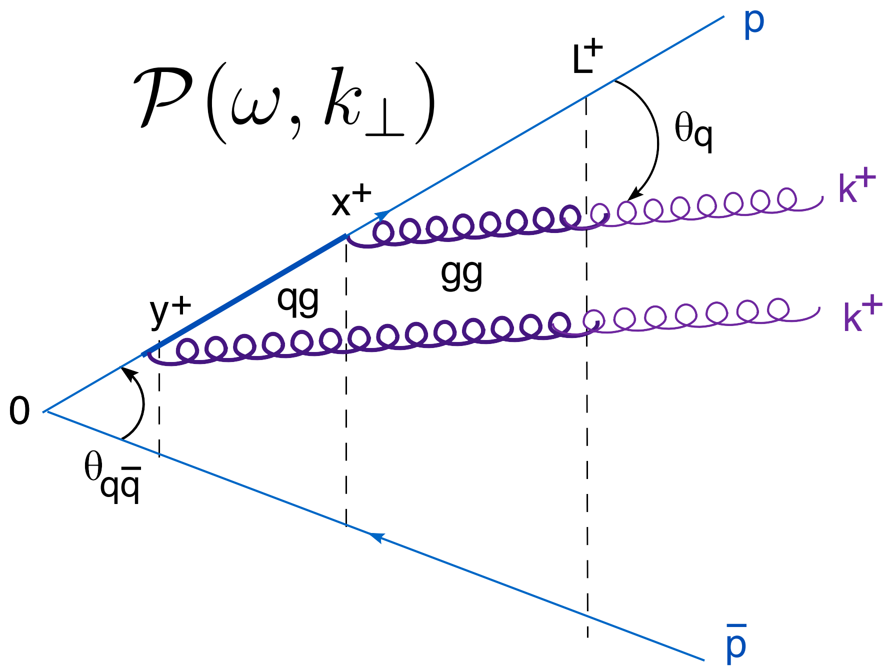
  The dipole interacts as a single charge

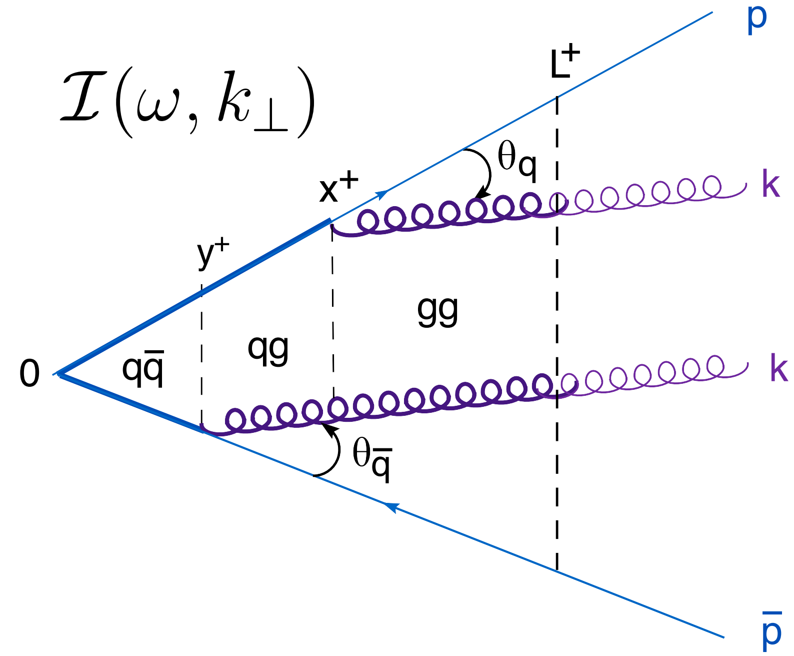
- The corrections $\Theta^2_{qq}/\Theta^2_C$ may lead to non-trivial distribution

  Natural limit for connecting to the dilute limit

(Mehtar-Tani, Salgado, Tywoniuk 10)

# Summary




- Medium induced radiation scales with the medium L

$$\mathcal{P}(\omega, k_\perp) \propto \alpha_s C_F \, \theta_f^2 \, L^+ \frac{\omega}{Q_s^2} \exp\left\{ -\frac{(k_\perp - k^+ \boldsymbol{u}_L)^2}{Q_s^2} \right\}$$

- Large angles $\Theta_f < \Theta_{qq}$ "vacuum medium" interference leads to:

(quantum coherence) $$\mathcal{R} = \frac{|\mathcal{I}|}{\mathcal{P}} = \frac{\tau_{int}}{L} < \left(\frac{\omega}{\omega_c}\right)^{1/2}$$ Interference is suppressed

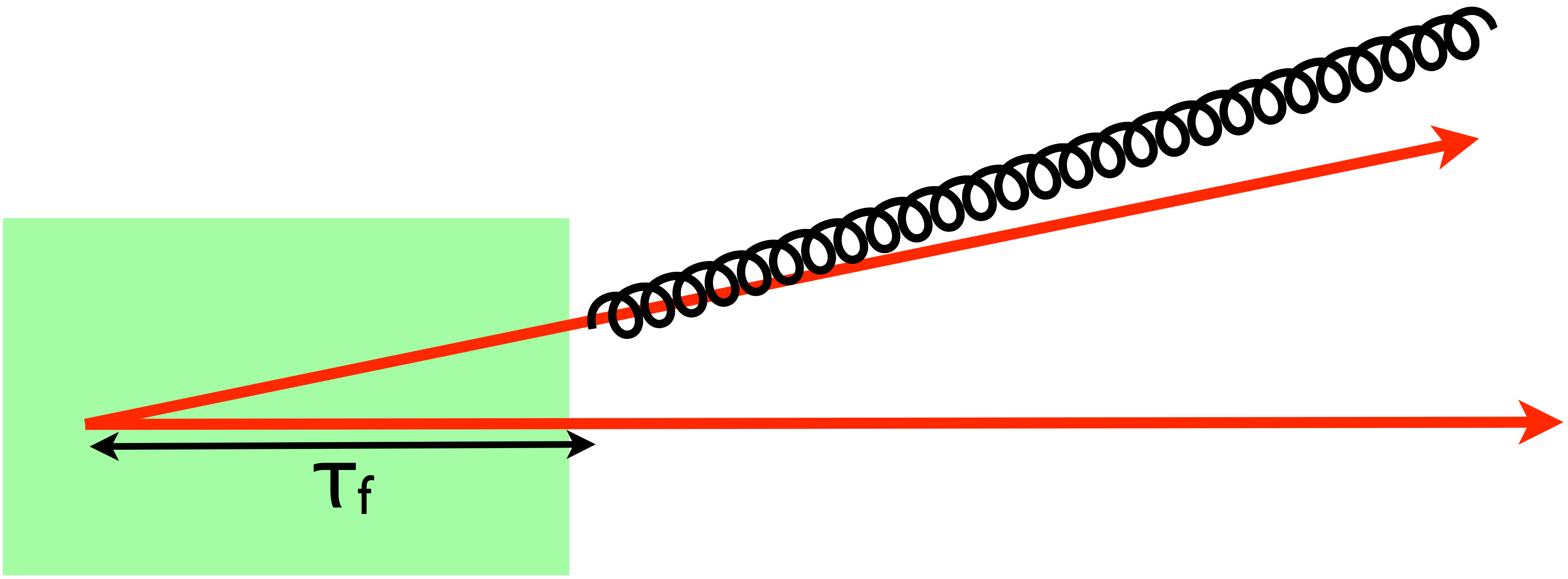
- Small angles $\Theta_c << \Theta_{qq} < \Theta_f$ "medium-medium" interference :

(color coherence) $$\mathcal{R} = \frac{|\mathcal{I}|}{\mathcal{P}} = \frac{\tau_{coh}}{L} \ll 1$$ Interference is suppressed

- Very small angles $\Theta_{qq} < \Theta_c$ the medium interacts with the whole dipole charge

# Additional source of Radiation

(Mehtar-Tani, Salgado, Tywoniuk 11)




- Very soft (or collinear) radiation has long formation time.
- For $\tau_f$ >>L most of the radiation happens outside the medium
- Dense medium ⇒ L>> $\tau_{coh}$ ⇒ color of sources are randomized
- The two quarks behave as independent sources!
    - Radiation at large angles is aloud
    - Extra emission, as compared to the vacuum

# Conclusions

- Unless $\Theta_{qq}$ is very small

  Each source induces gluons independently from each other

- Typical sources for in-medium antennas

  In-medium radiations $\Rightarrow \theta_{qq} \sim \theta_f$

  Vacuum splittings (QCD evolution) $\Rightarrow \theta_{qq}$ takes any value

but

$$\left( \begin{array}{c} \hat{q} \sim 10\,\mathrm{GeV}^2/\mathrm{fm} \\ L \sim 6\,\mathrm{fm} \end{array} \quad \Longrightarrow \quad \begin{array}{c} \theta_c \sim 0.005 \\ \omega_c \sim 900\,\mathrm{GeV} \end{array} \right)$$

BDMPS-Z gluons are NOT angular ordered

- In addition to BDMPS-Z gluons, color decoherence of the antenna leads to additional gluon radiation.

- These effects are important to understand the source for large angle emissions in heavy ions collisions.