LUND UNIVERSITY

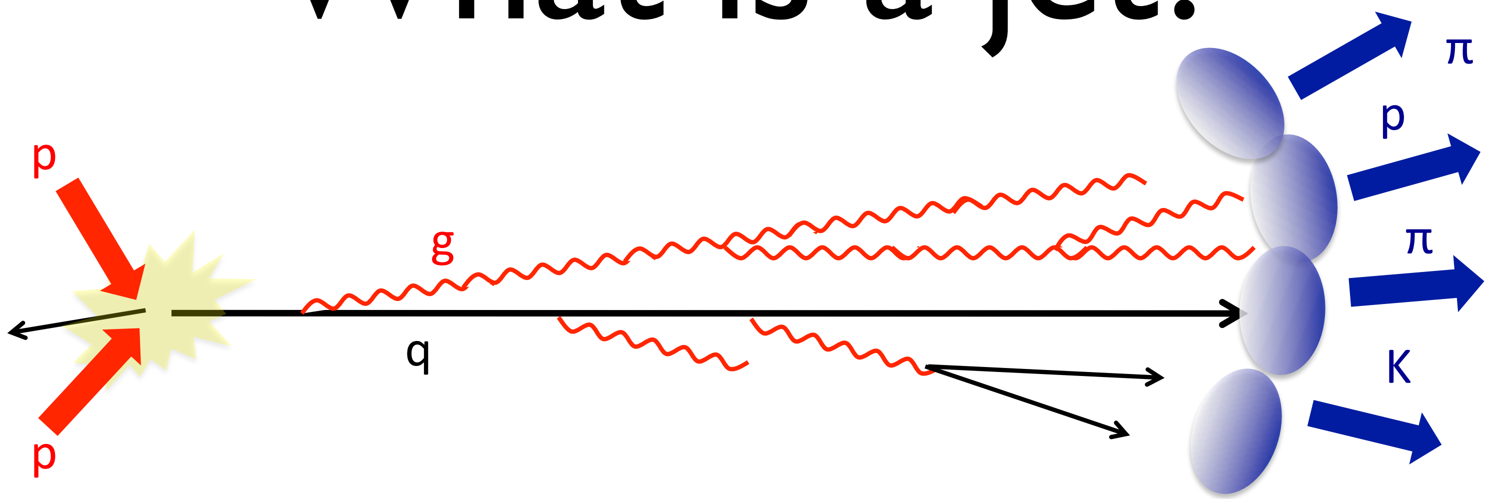
Jets in a quark-gluon plasma

Konrad Tywoniuk

Y. Mehtar-Tani, C.A. Salgado, KT PRL 106 (2011) 122002
Y. Mehtar-Tani, C.A. Salgado, KT PLB 707 (2011) 156
Y. Mehtar-Tani, KT arXiv:1105:1346 [hep-ph]
Y. Mehtar-Tani, C.A. Salgado, KT arXiv:1112.5031 [hep-ph]

Spåtind 2012, 2-7 January 2012

What is a jet?



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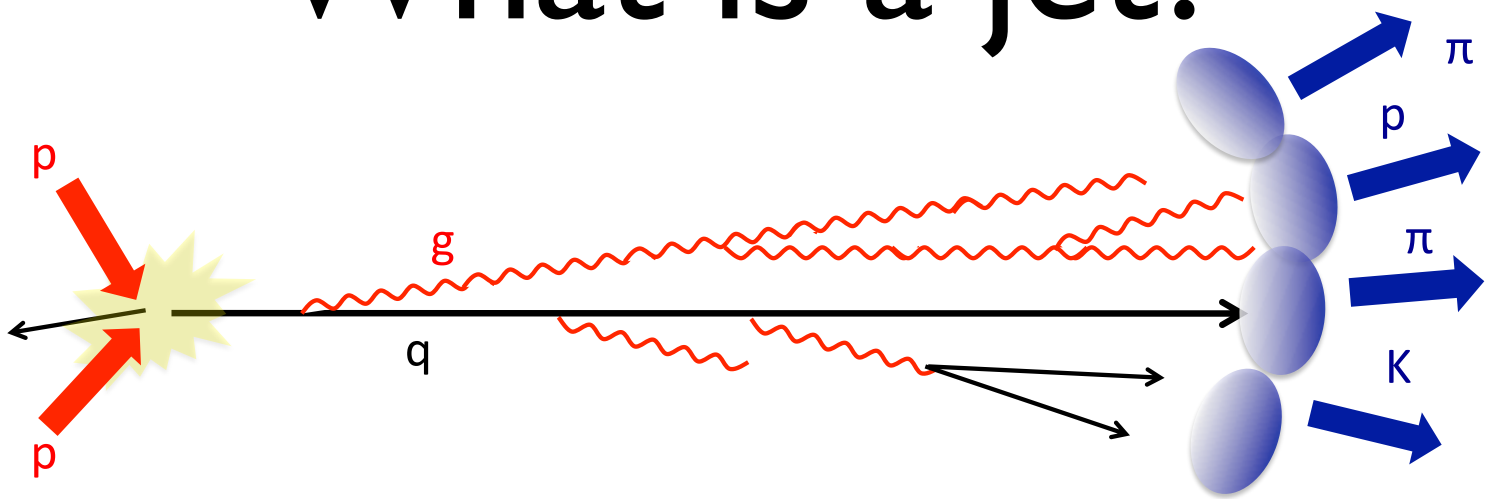

- Originally a hard parton (quark/gluon) which fragments into many partons with virtuality down to a non-perturbative scale where it hadronizes

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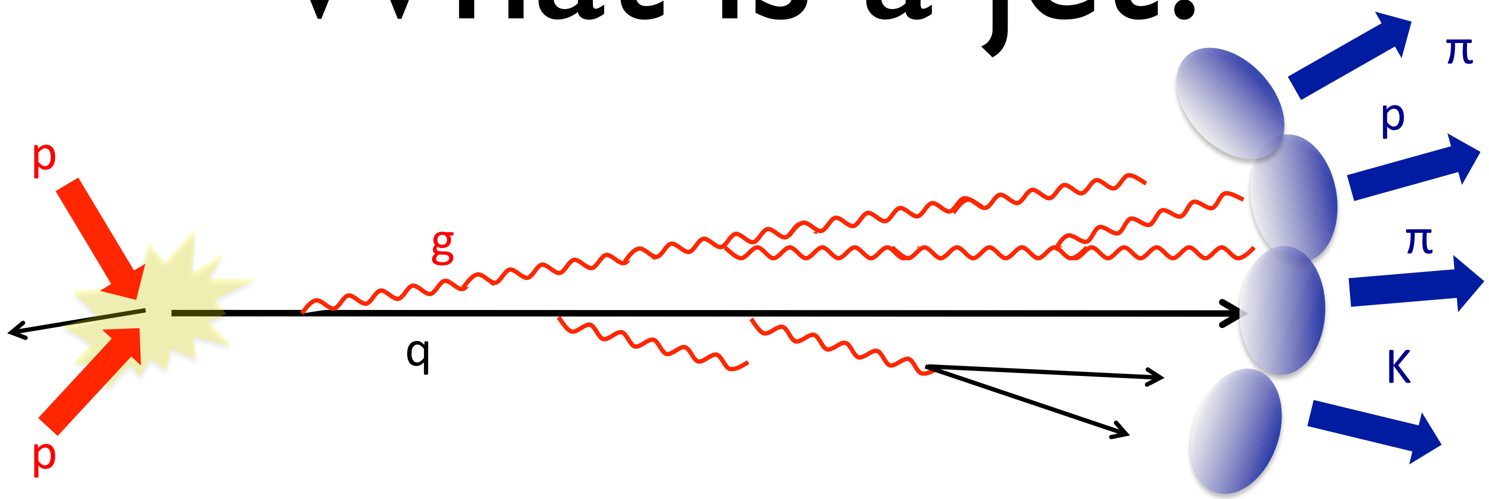

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- LPHD: Hadronization does not affect exclusive observables (jet shape, energy distribution etc..)

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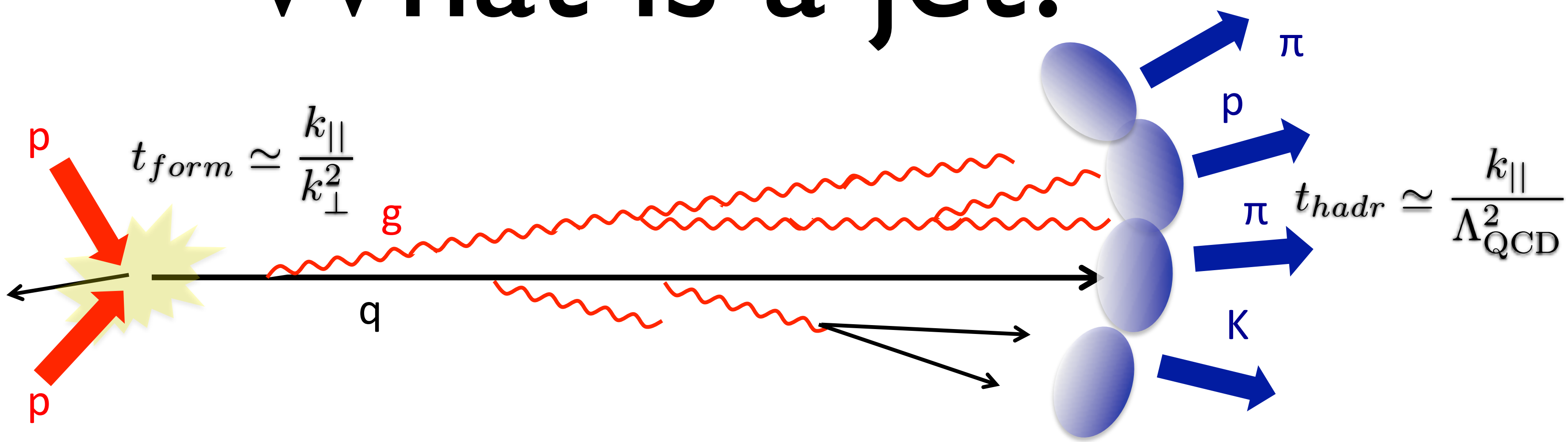

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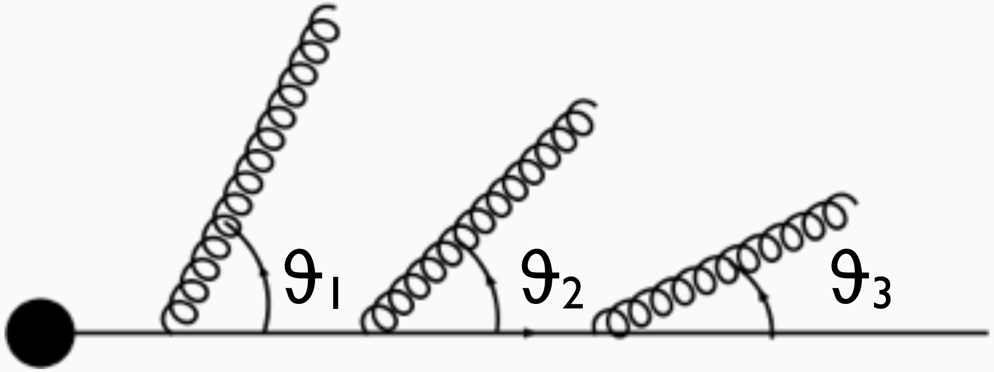
Large time domain for pQCD: $\frac{1}{\sqrt{s}} < t < \frac{\sqrt{s}}{\Lambda_{\rm QCD}^2}$

QCD COHERENCE IN VACUUM

[Dokshitzer, Fadin, Khoze, Troyan, Lipatov, Bassetto, Mueller, Ciafaloni, Marchesini....]



$\vartheta_1 > \vartheta_2 > \vartheta_3$

$\omega_1 > \omega_2 > \omega_3$

- leading singularities:

$$\propto \frac{d\omega_i}{\omega_i}\frac{d\theta_i}{\theta_i}\Theta\left(\theta_{i-1}-\theta_i\right)$$

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

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

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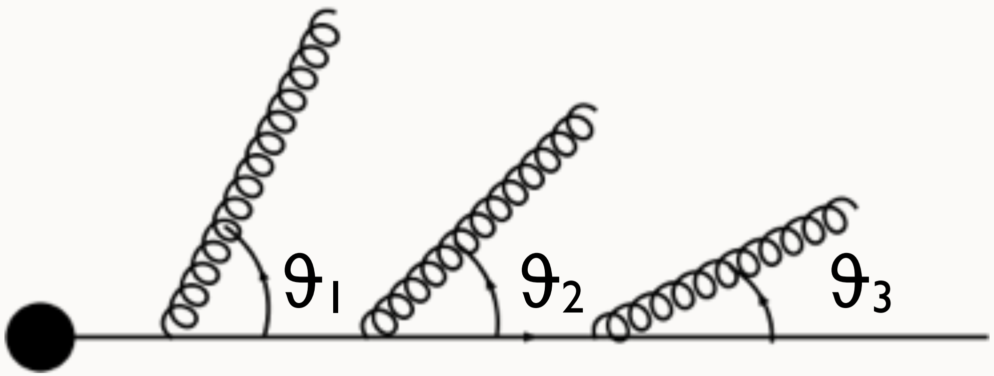

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- soft & collinear divergences
- interferences ⇒ angular ordering

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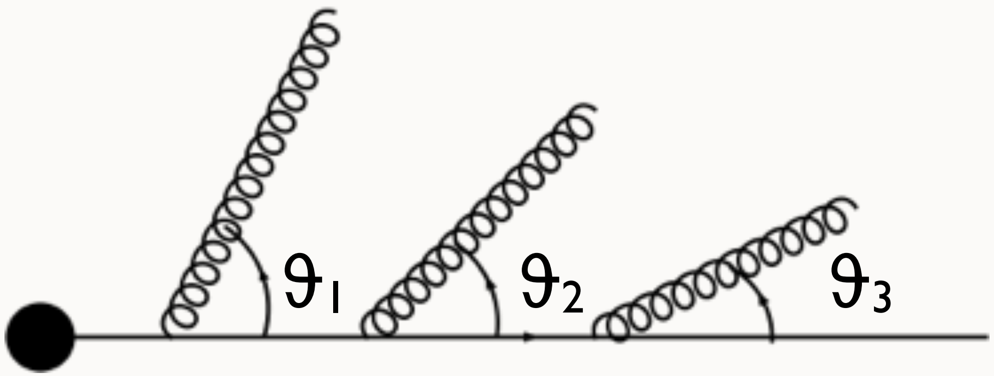

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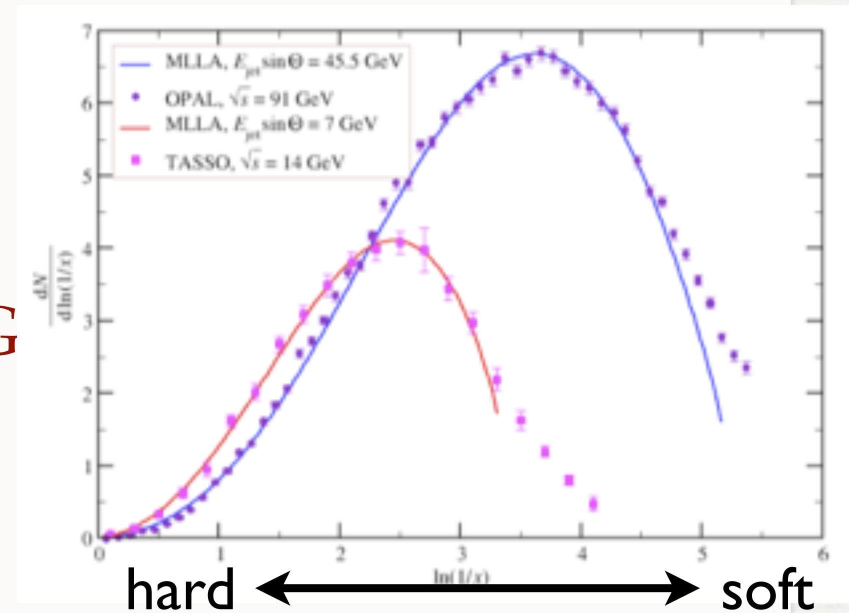

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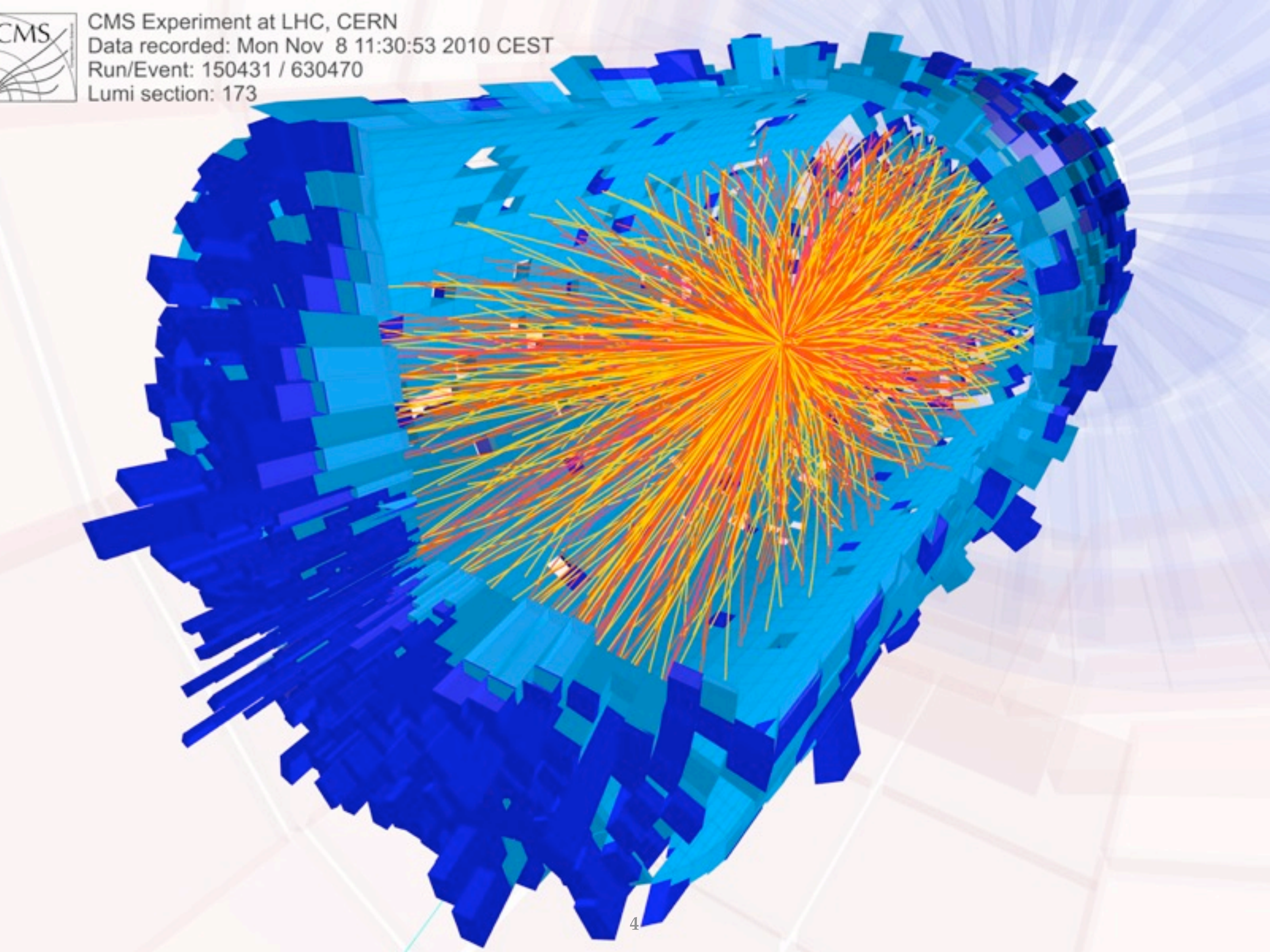
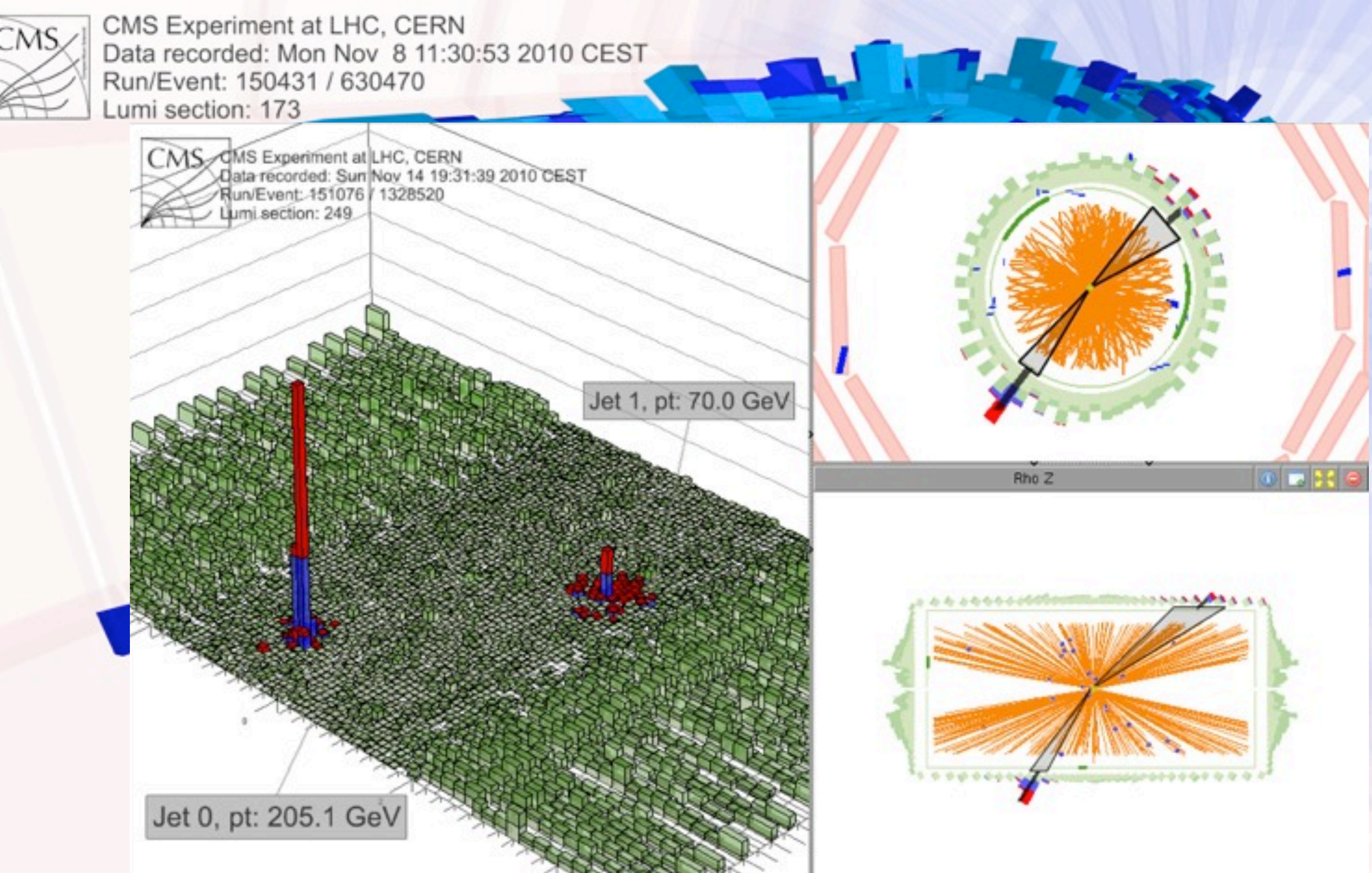
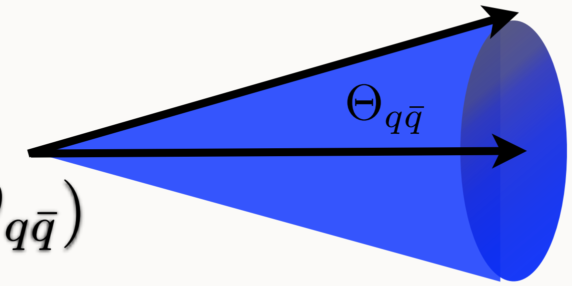

CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173



MEDIUM MODIFIES THE JET EVOLUTION!

ANTENNA SETUP

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



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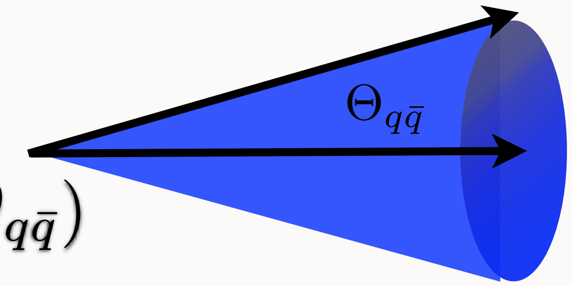

Fundamental building block of the QCD cascade!

ANTENNA SETUP

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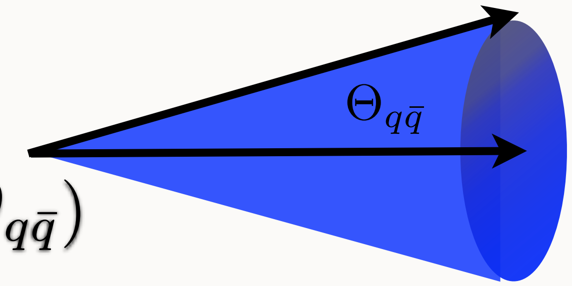

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- Reason: emissions at large angles are sensitive to the total charge of the emitting system

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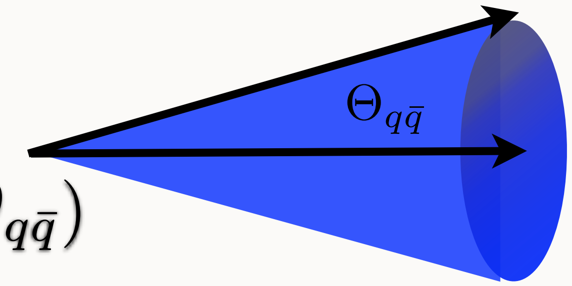

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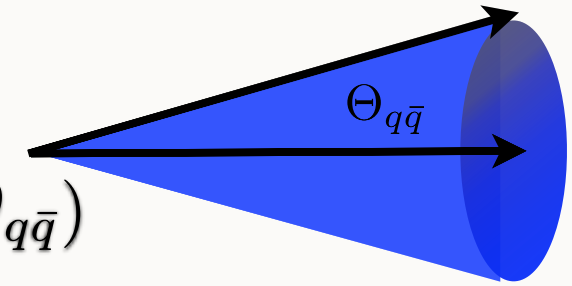


Fundamental building block of the QCD cascade!

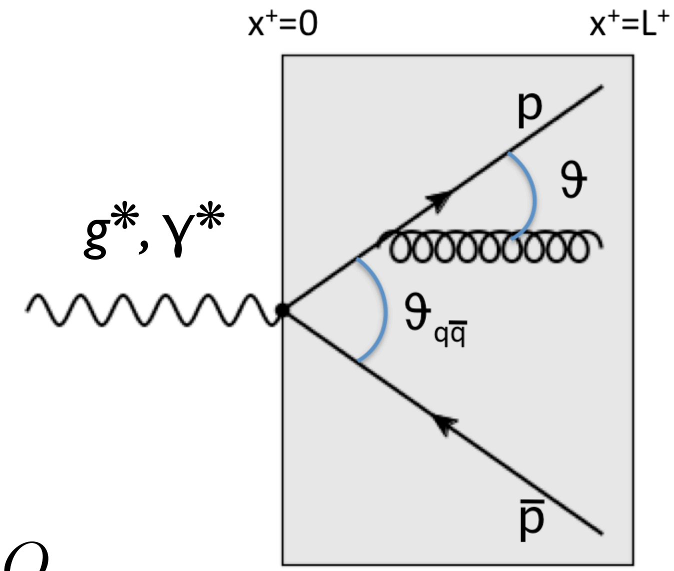
- Reason: emissions at large angles are sensitive to the total charge of the emitting system
- The antenna provides a nice laboratory!
- Question: how will the antenna radiation pattern look like if it were to traverse a quark-gluon medium?

ANTENNA SETUP IN MEDIUM

Mehtar-Tani, Salgado, KT PRL 106 (2011) 122002
Mehtar-Tani, Salgado, KT arXiv:1102.4317 [hep-ph]

- eikonal approximation for fixed opening angle of the pair
- medium is modeled as a classical background field

$$J_q^{(0)}(x) = g\delta^{(3)}\left(\vec{x} - \frac{\vec{p}}{E}t\right)\Theta(t)Q_q$$



$$J \equiv J_q + J_{\bar{q}}$$

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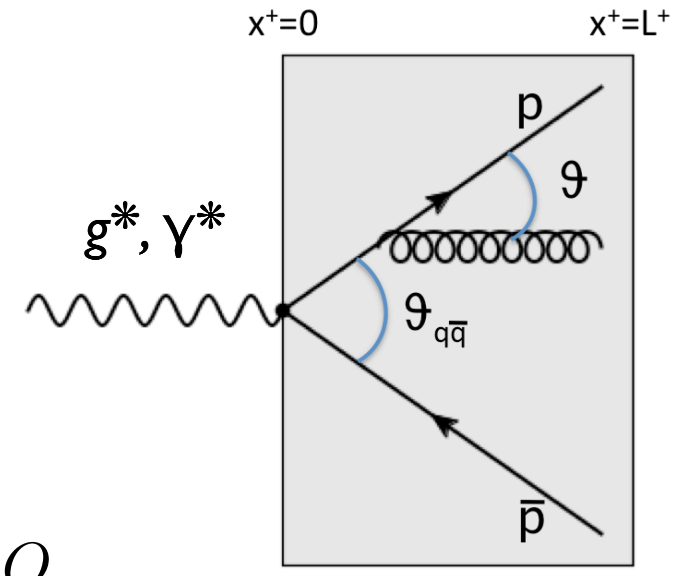

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Classical Yang-Mills eq: $[D_\mu, F^{\mu\nu}] = J^\nu \quad , \quad [D_\mu, J^\mu] = 0$

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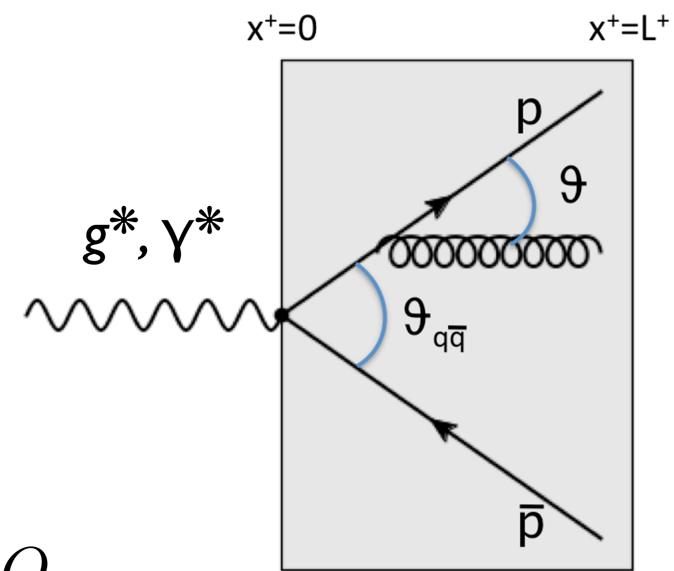

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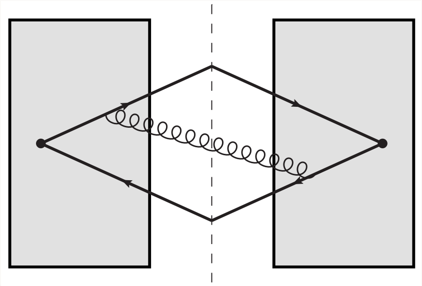
Linear response: $\Box A^i - 2ig\left[A^-_{\text{med}}, \partial^+ A^i\right] = -\frac{\partial^i}{\partial^+}J^+ + J^i$

Gelis, Mehtar-Tani (2005), Mehtar-Tani (2007)

ANTENNA IN MEDIUM

Y. Mehtar-Tani, KT arXiv:1105.1346 [hep-ph], E. Iancu, J. Casalderrey-Solana arXiv:1105.1760 [hep-ph]

Multiple scattering $\Rightarrow$ effective propagators:



$$|\delta n| \simeq \theta_{q\bar{q}}$$

$$\mathcal{J} = \mathrm{Re}\left\{ \int_0^\infty dy'^+ \int_0^{y'^+} dy^+ \left(1 - \Delta_{\text{med}}(y^+,0)\right) \right.$$
$$\times \int d^2\boldsymbol{z} \, \exp\left[-i\bar{\boldsymbol{\kappa}}\cdot\boldsymbol{z} - \frac{1}{2}\int_{y'^+}^\infty d\xi \, n(\xi)\sigma(\boldsymbol{z}) + i\frac{k^+}{2}\delta\boldsymbol{n}^2 y^+ \right]$$
$$\left. \times \left(\boldsymbol{\partial}_y - ik^+\,\delta\boldsymbol{n}\right)\cdot\boldsymbol{\partial}_z \, \mathcal{K}(y'^+,\boldsymbol{z}\,;\,y^+,\boldsymbol{y}\,|k^+)\big|_{\boldsymbol{y}=\delta\boldsymbol{n}y^+} \right\} + \text{sym.}$$

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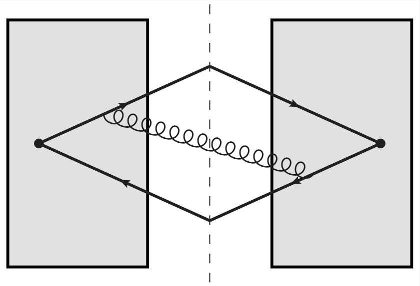

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Describes Brownian motion through medium potential...

$$\mathcal{K}\left(y'^+, \boldsymbol{z}; y^+, \boldsymbol{y}|k^+\right) = \int \mathcal{D}[\boldsymbol{r}]\, \exp\left[\int_{y^+}^{y'^+} d\xi \left(i\frac{k^+}{2}\dot{\boldsymbol{r}}^2(\xi) - \frac{1}{2}n(\xi)\sigma(\boldsymbol{r}) \right) \right]$$

$$\sigma(\mathbf{r}) = 2\alpha_S C_A \int \frac{d^2\mathbf{q}}{(2\pi)^2}\, \mathcal{V}^2(\mathbf{q}) \left[1 - \cos(\mathbf{r}\cdot\mathbf{q})\right]$$

$$\mathcal{V}(\boldsymbol{q}) = \frac{1}{\boldsymbol{q}^2 + m_D^2}$$

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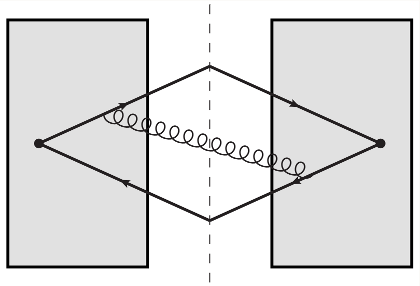

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THE SOFT LIMIT

Considering soft gluon emissions: only the quarks interact!

$$J_q(x) = g\, U_p(x^+, 0)\, \delta^{(3)}(\vec{x} - \frac{\vec{p}}{E} t)\Theta(t)\, Q_q$$

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Wilson line along the trajectory:

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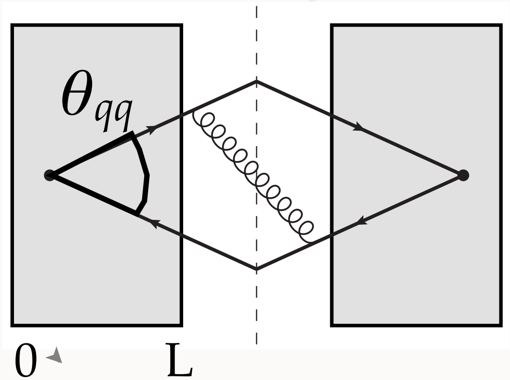
$$\Delta_{\text{med}} = 1 - \frac{1}{N_c^2 - 1}\langle \textbf{Tr}\, U_p(x^+, 0) U^\dagger_{\bar{p}}(x^+, 0)\rangle$$

$$\approx 1 - e^{-\frac{1}{12}\hat{q}\,\theta^2_{q\bar{q}}\, L^3}$$

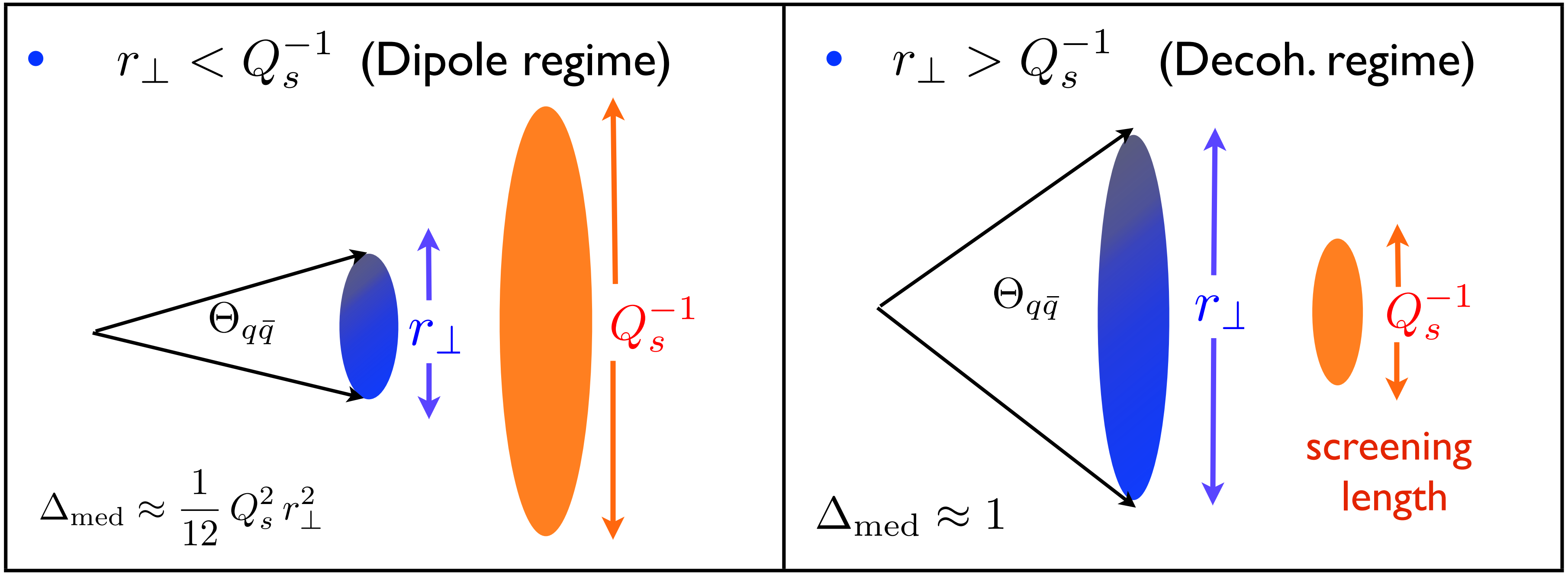
- the **decoherence parameter**!



$\hat{q}$: medium transport coefficient

DECOHERENCE

- a two scale problem!



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

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

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

DECOHERENCE

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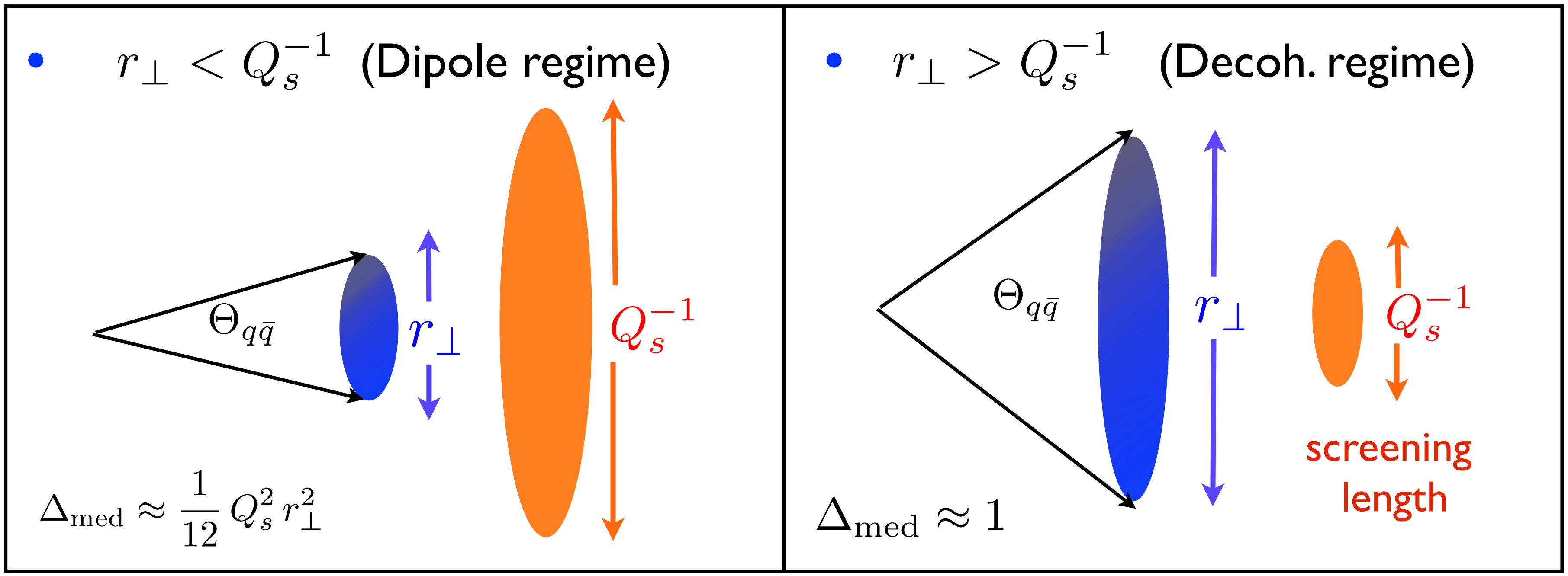

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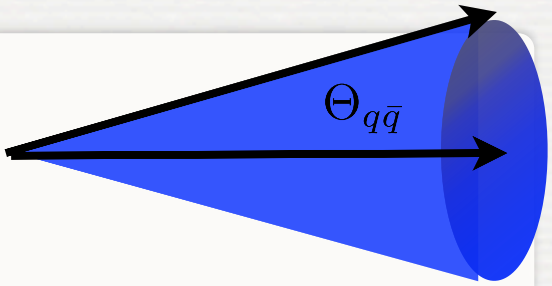
- $k_\perp \gg Q_{\rm hard}$: suppression!

ONSET OF DECOHERENCE - THE SOFT LIMIT

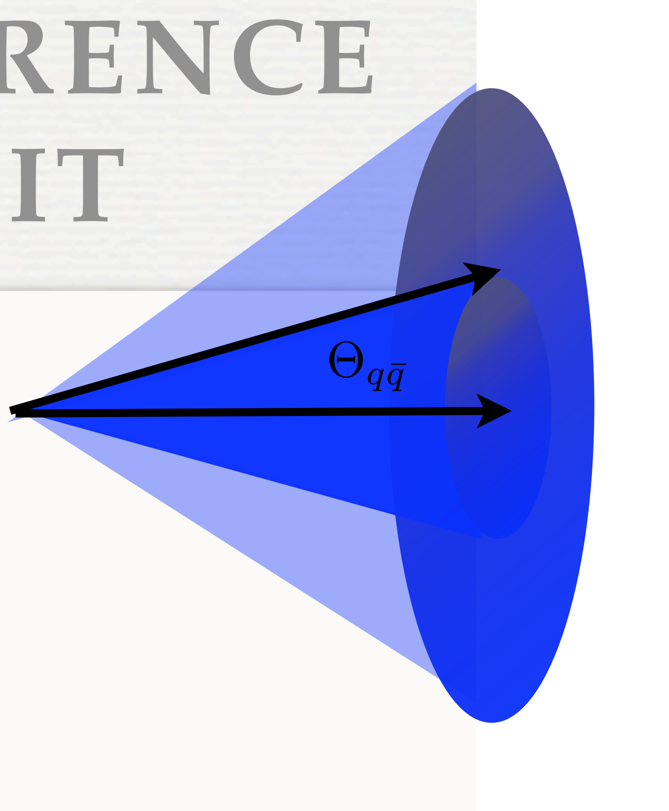
$\Delta_{\text{med}} \to 0$ Coherence



ONSET OF DECOHERENCE - THE SOFT LIMIT

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

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



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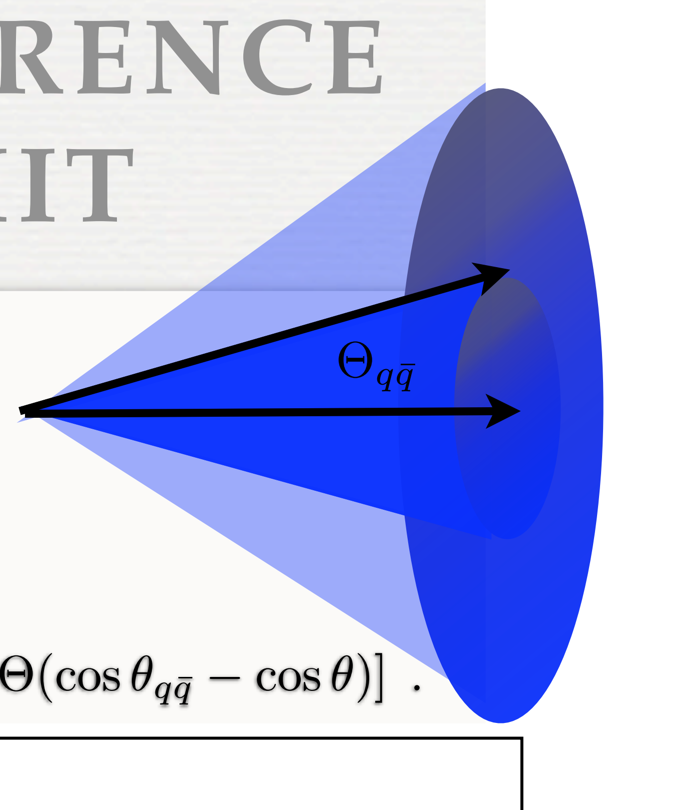
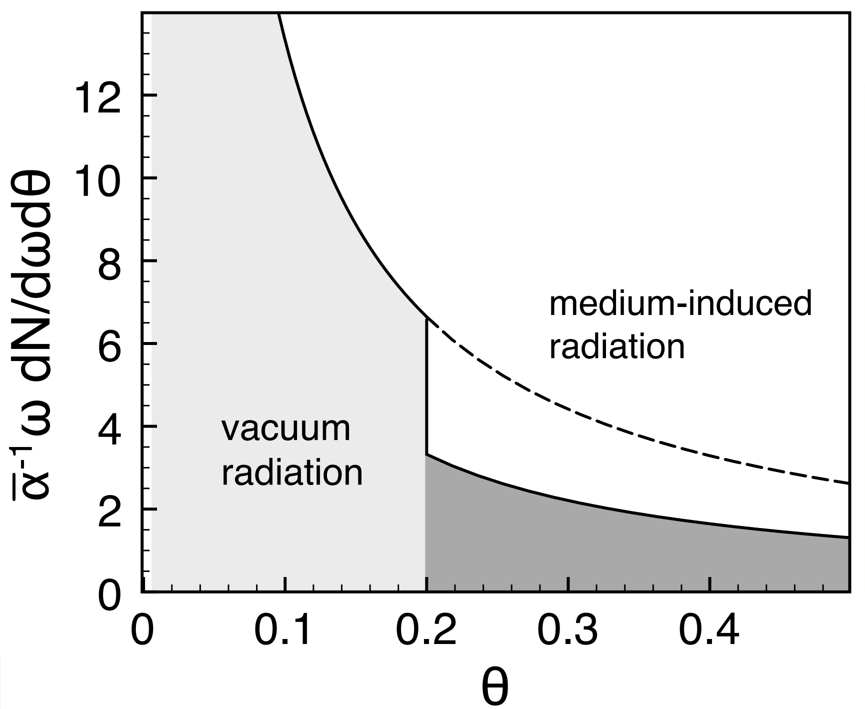
$\Delta_{\text{med}} \to 1$ **Decoherence**



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



ONSET OF DECOHERENCE - THE SOFT LIMIT

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

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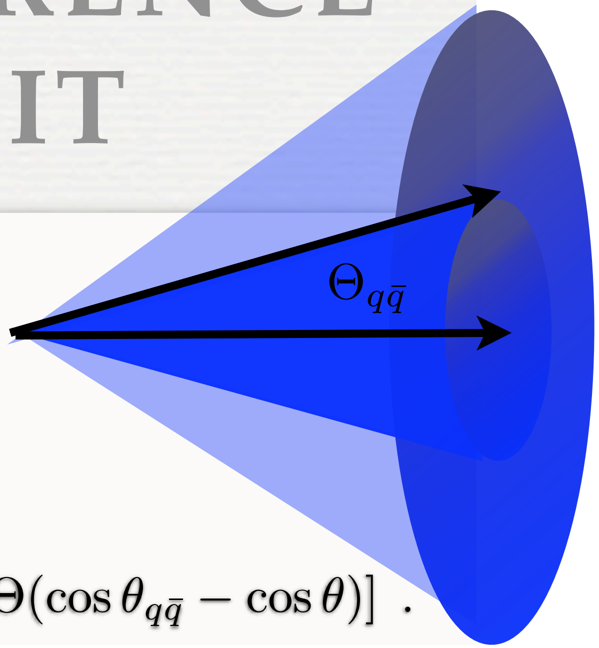

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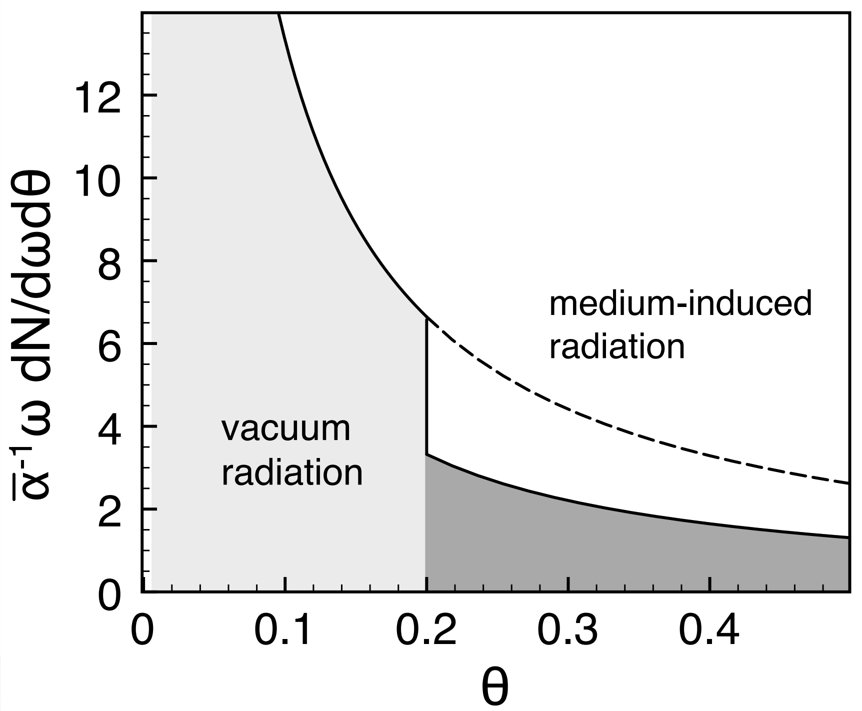
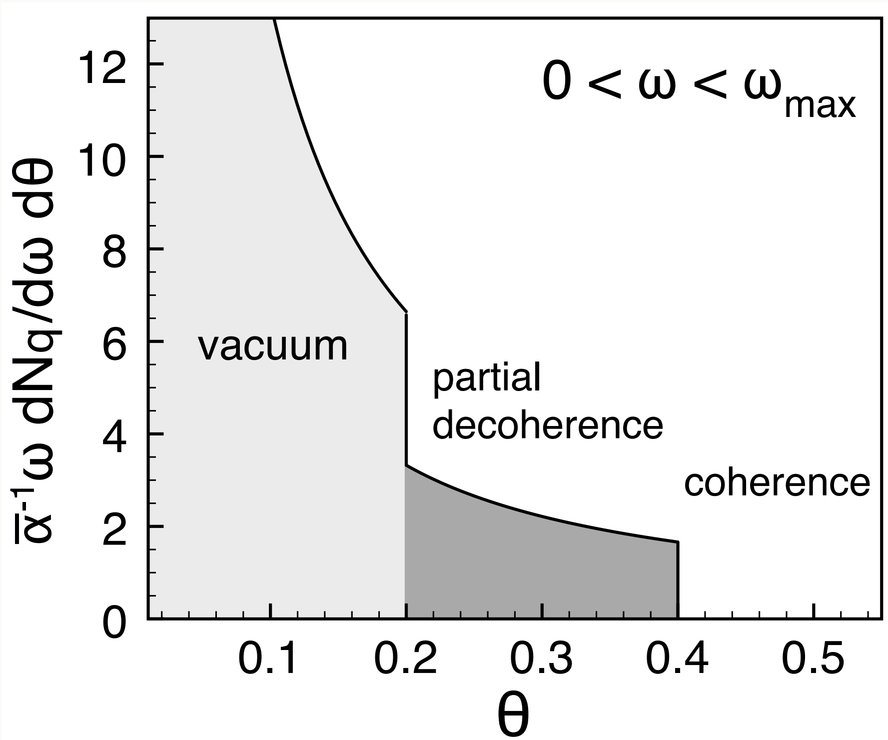
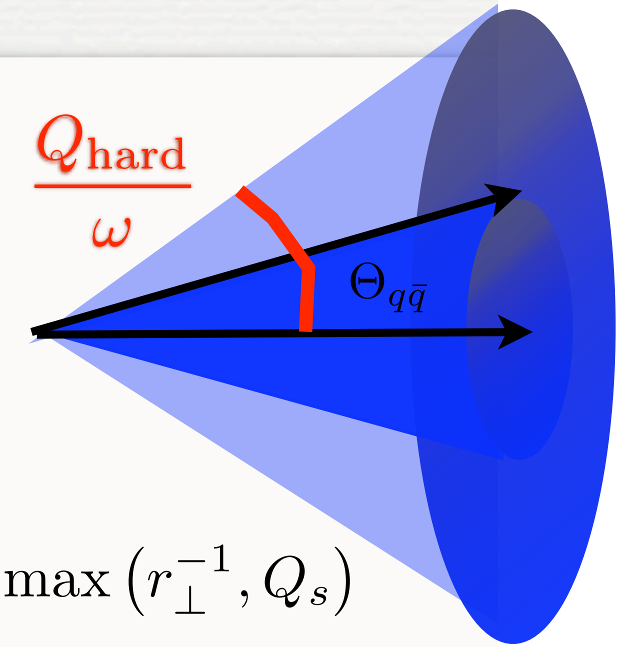
$$dN^{\rm tot}_{q,\gamma^*}\Big|_{\rm opaque} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\; d\theta}{1-\cos\theta} .$$

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



ONSET OF DECOHERENCE - FINITE ENERGIES





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

Above $\omega_{\rm max}$ medium induces independent radiation inside the cone.

Dilute medium

$$\Delta_{\rm med} \approx \frac{1}{6}\,\hat{q}L^+\,r_\perp^2\left[\ln\frac{1}{r_\perp m_D} + {\rm const.}\right]$$ **dipole regime**

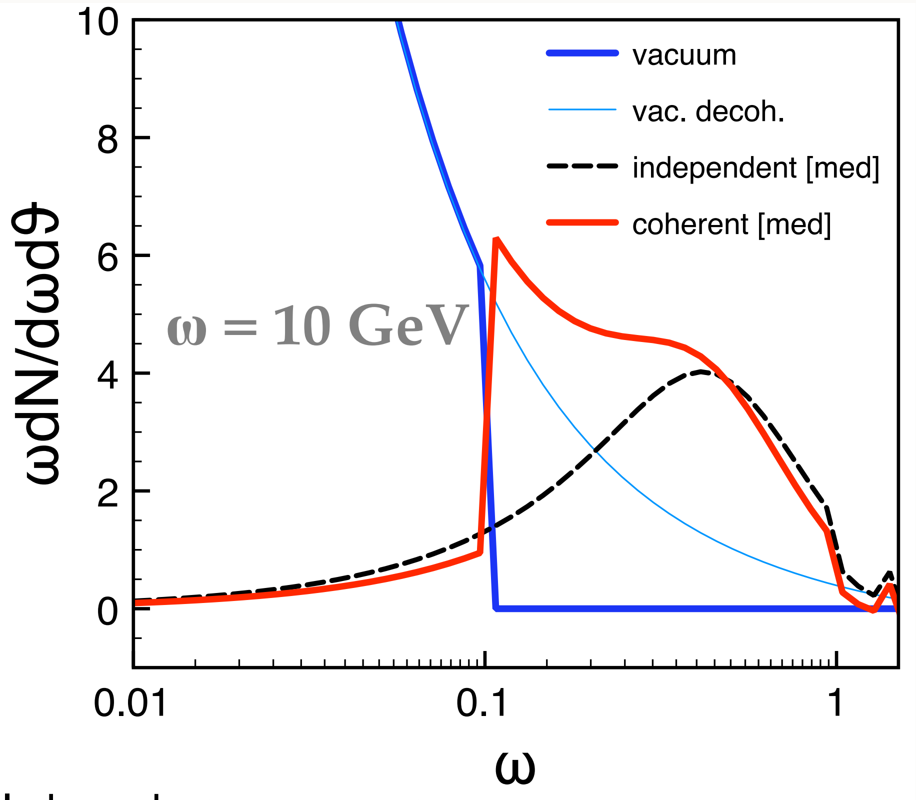
$$\Delta_{\rm med} \approx n_0 L^+ \equiv N_{\rm scat}$$ **decoher. regime**

THE DENSE REGIME

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

THE DENSE REGIME

$L = 10$ fm, $\hat{q} = 5$ GeV^2/ fm



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

- independent spectrum appears
- interferences are destroyed
- jet broadening

Independent component:

Baier, Dokshitzer, Mueller, Peigne, Schiff (1997-2001), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2001-2002)

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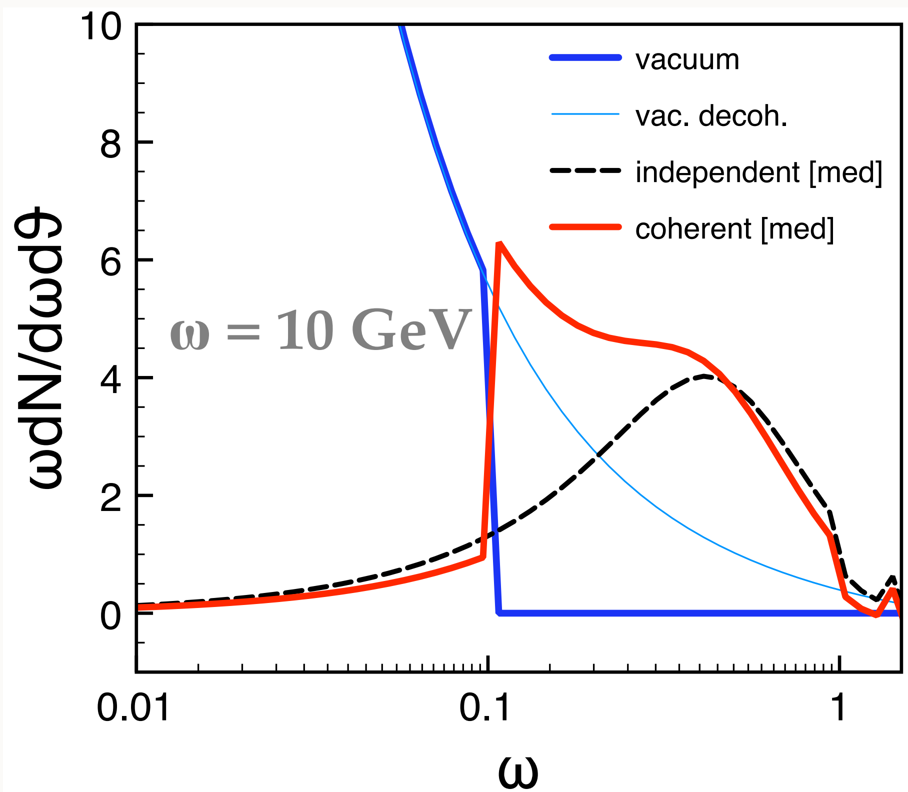

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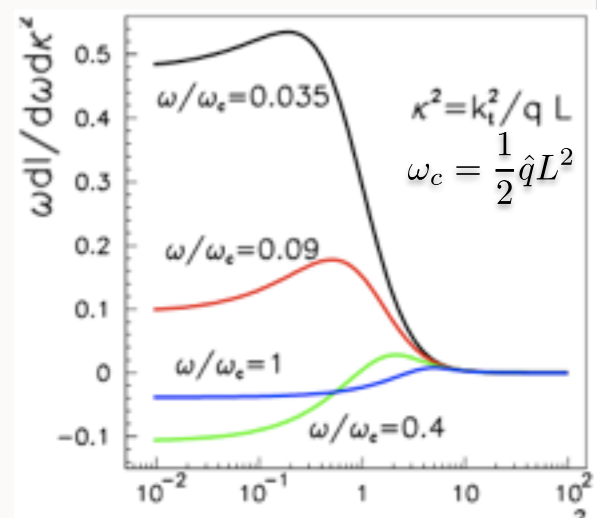
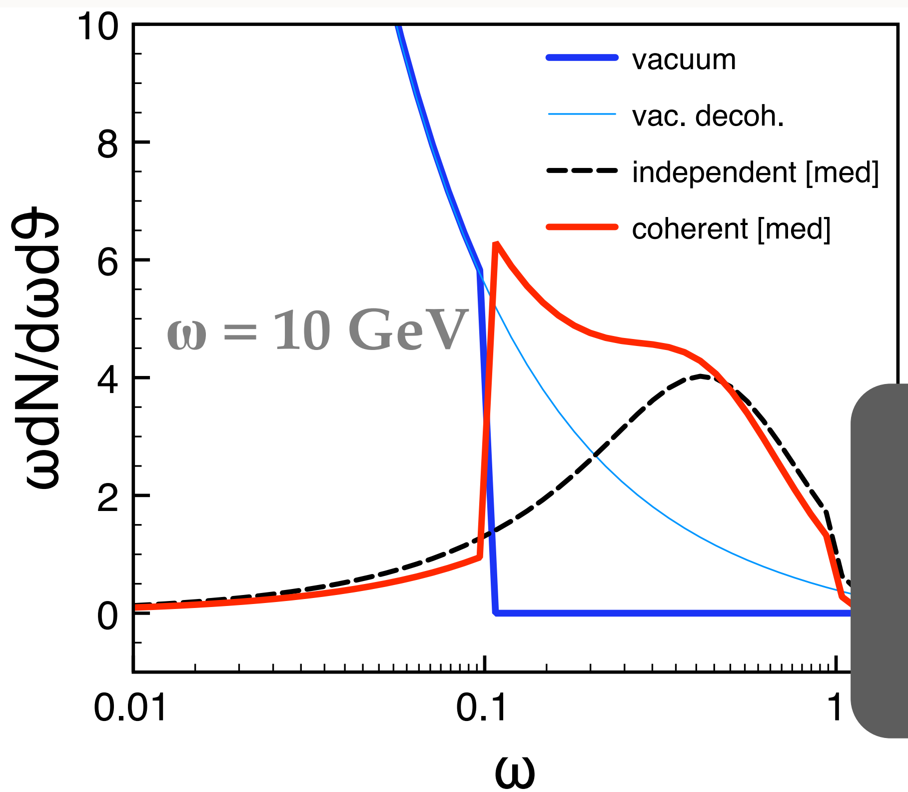


Salgado, Wiedemann (2003)

THE DENSE REGIME

$L = 10$ fm, $\hat{q} = 5$ GeV^2/ fm



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

- independent spectrum appears
- interferences are destroyed
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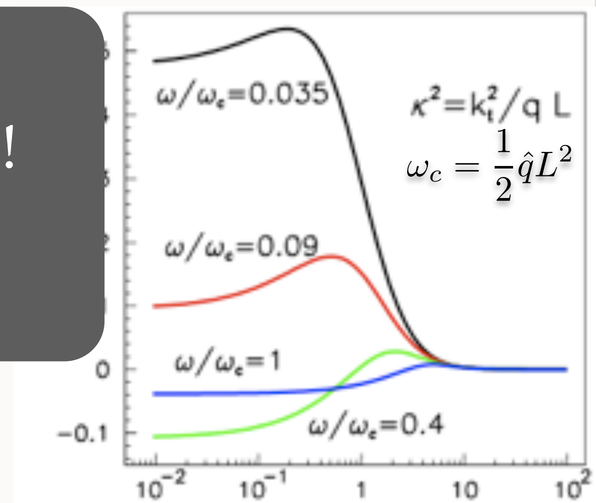
Short formation time!

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



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CONCLUSIONS

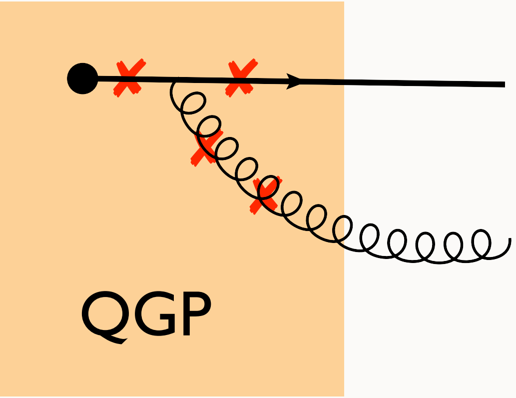
- copious jets in heavy-ion collisions at the LHC
- medium induces soft radiation at large angles
  - ⇒ onset of decoherence
- a two scale problem: $r_\perp^{-1}$ vs. Q_s
  - ⇒ jet probes medium, and vice versa
- the radiation pattern off an antenna
  - ⇒ building block for jet calculus in medium

MEDIUM-INDUCED RADIATION

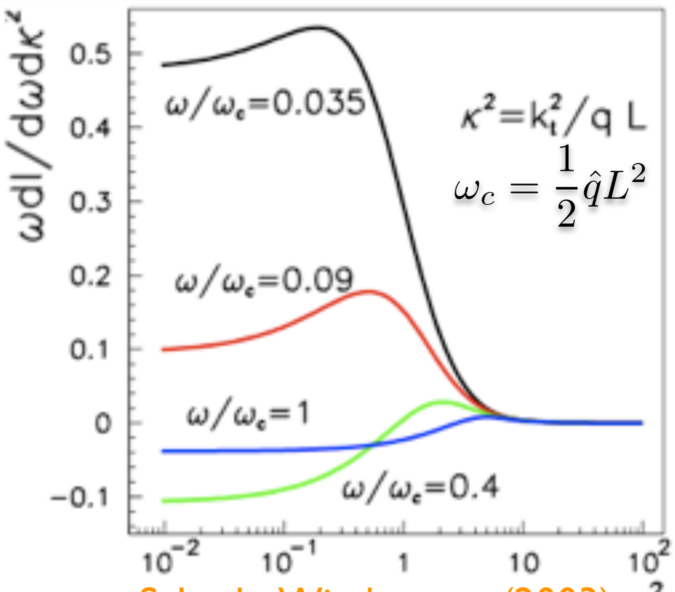
Baier, Dokshitzer, Mueller, Peigne, Schiff (1997-2001), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2001-2002)

Energy loss: $\Delta E \simeq \frac{\alpha_s C_R}{2\pi} \hat{q} L^2$

Broadening: $k_\perp^2 \simeq \hat{q} L \propto \frac{\Delta E}{L}$

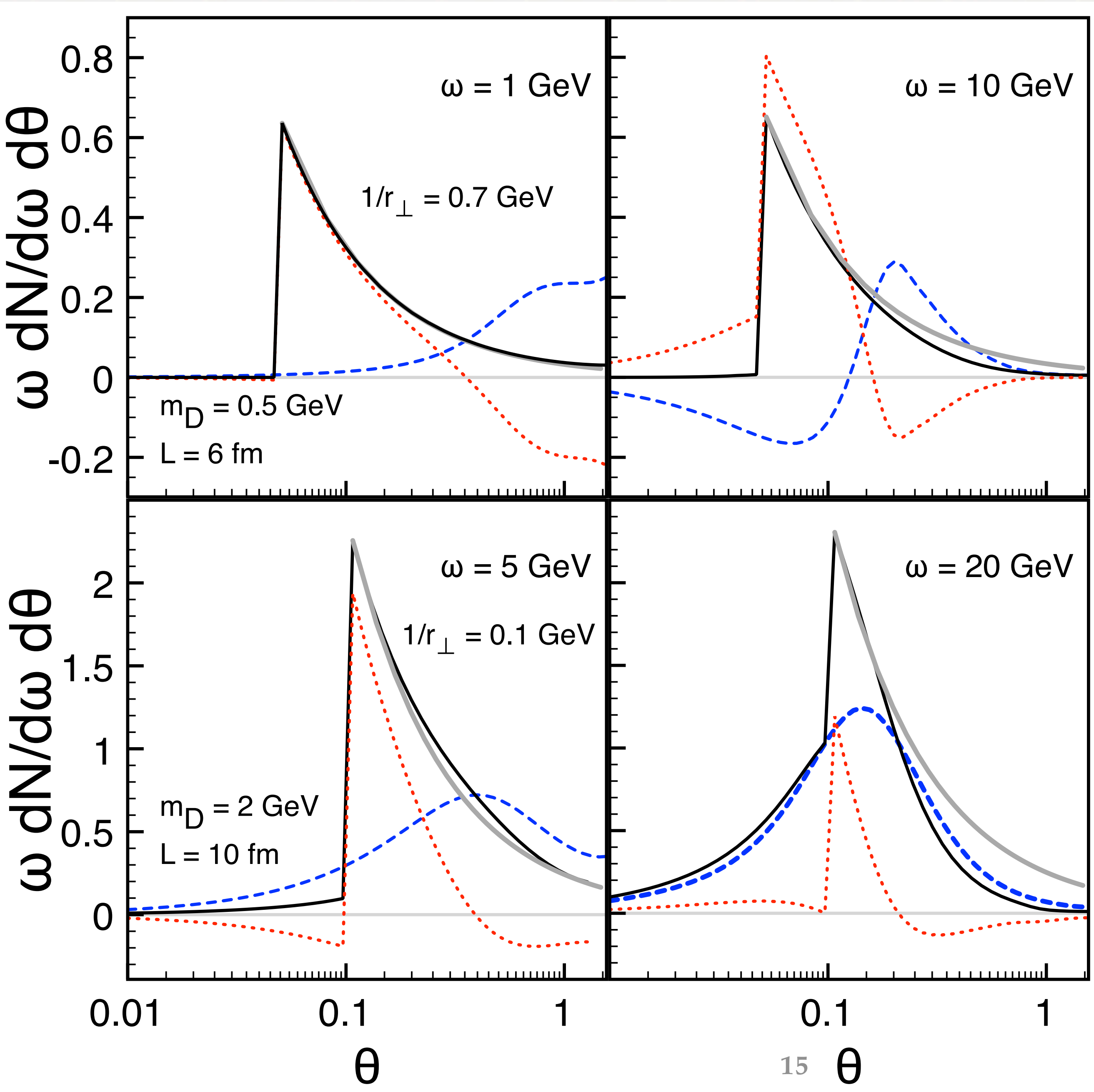


- emitted off a **single emitter**
- gluon interaction ⇒ $k_\perp$-broadening
- transport parameter: $\hat{q} = m_D^2/\lambda$
- infrared & collinear safe spectrum
- energy loss distribution: $P(\Delta E)$
- need **more emitters** to see coherence!



Salgado, Wiedemann (2003)

ANGULAR SPECTRUM

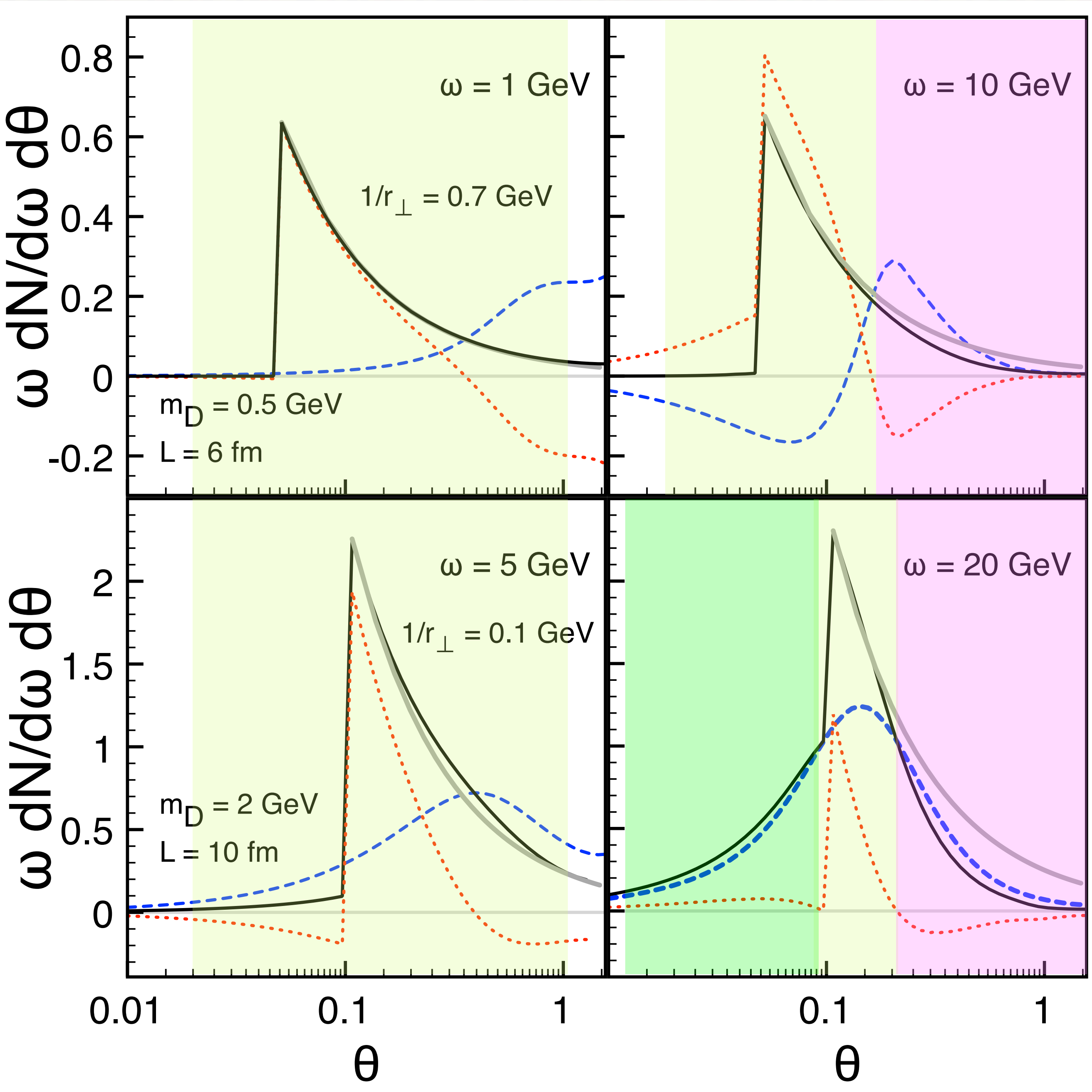


$\mathcal{R}_q^{\mathrm{med}}$

$\mathcal{J}_q^{\mathrm{med}}$

$1/\theta$

Y. Mehtar-Tani, C.A. Salgado, KT
arXiv:1112.5031 [hep-ph]



$\mathcal{R}_q^{\mathrm{med}}$ $\mathcal{J}_q^{\mathrm{med}}$

$1/\theta$

antiangular ordering

large angles

inside cone

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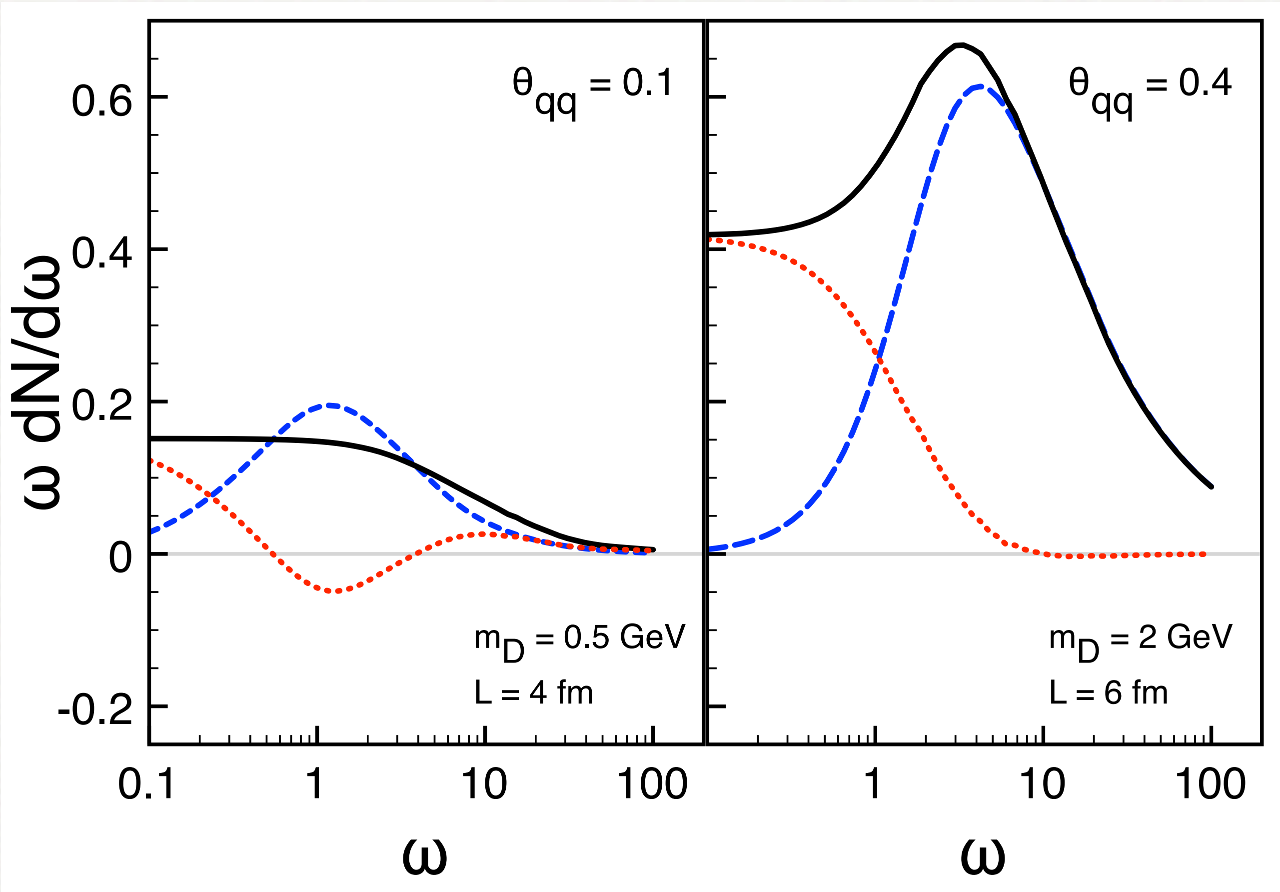
ENERGY SPECTRUM



"Dipole" regime

- dipole size: $r_\perp^{-1}$
- coherent spectrum

"Saturation" regime

- medium scale: Q_s
- two components:
  - outside the cone
  - inside the cone

Y. Mehtar-Tani, C.A. Salgado, KT arXiv:1112.5031 [hep-ph]