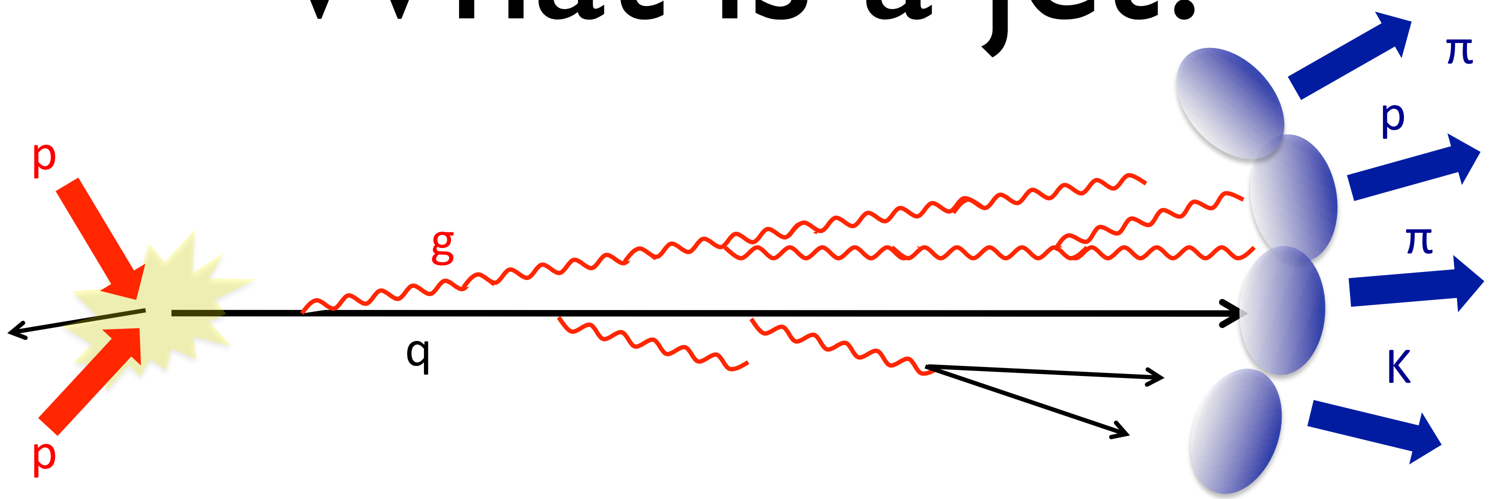
JETS IN A QUARK-GLUON PLASMA

Konrad Tywoniuk

LUND UNIVERSITY

NBI Copenhagen, 7-9 November 2011

What is a jet?



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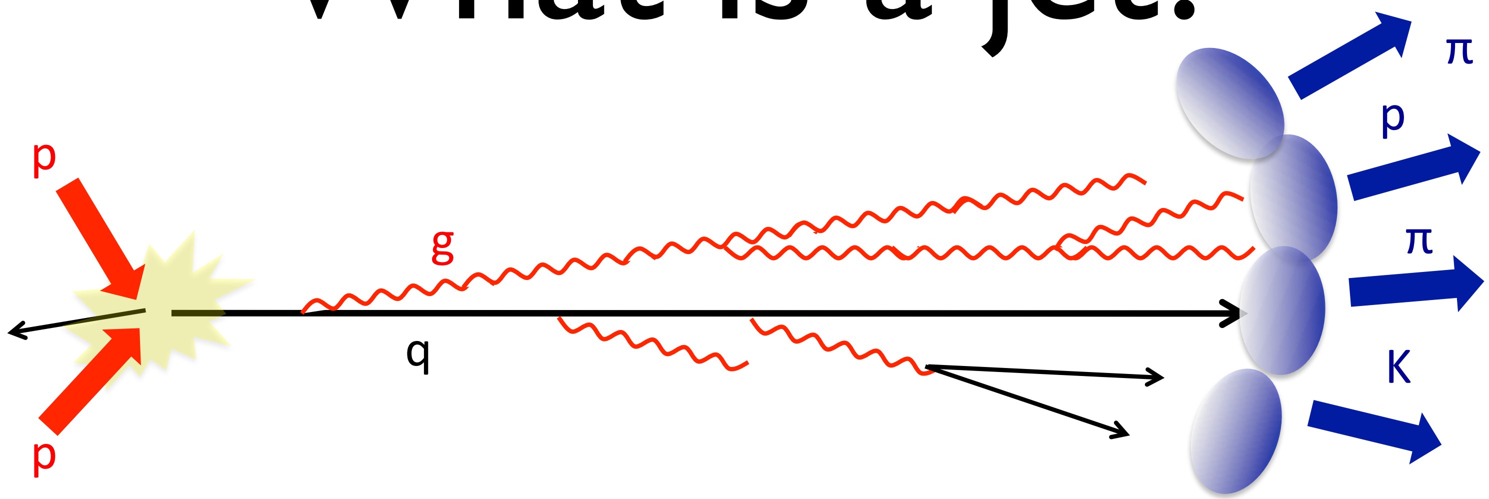

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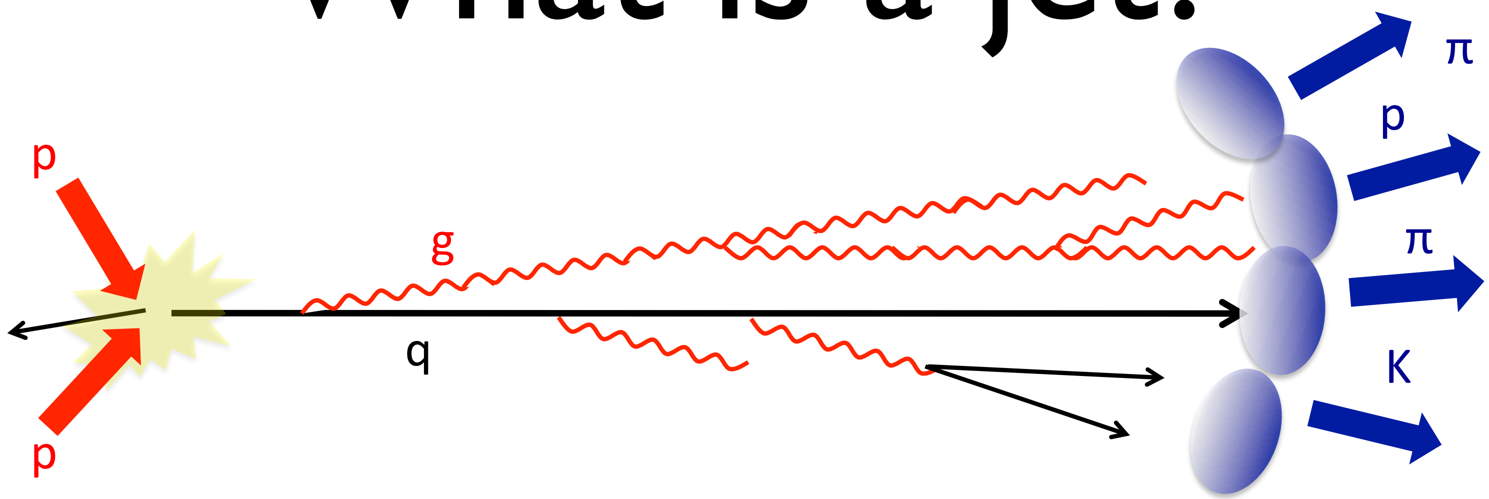

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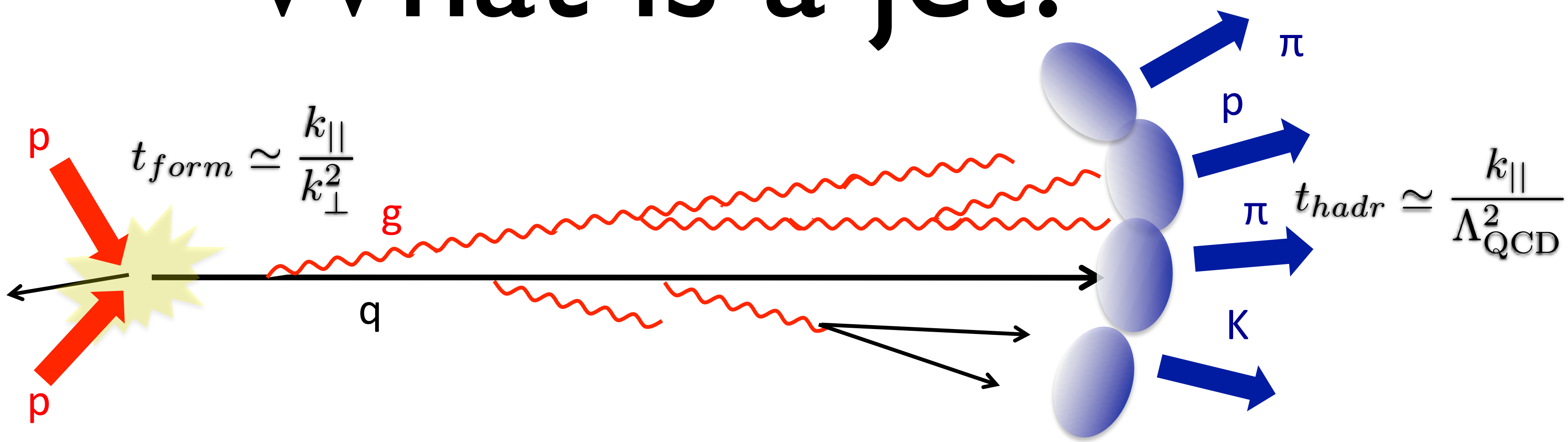

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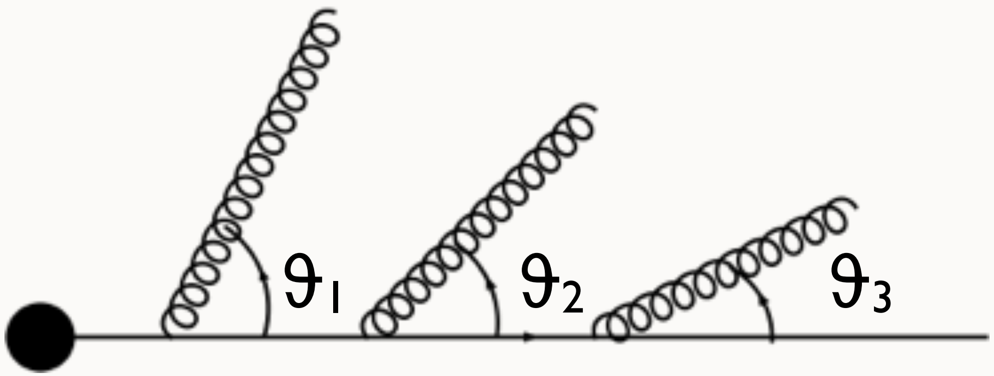
Large time domain for pQCD: $\frac{1}{\sqrt{s}} < t < \frac{\sqrt{s}}{\Lambda^2_{QCD}}$

QCD COHERENCE IN VACUUM

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



$$\vartheta_1 > \vartheta_2 > \vartheta_3$$
$$\omega_1 > \omega_2 > \omega_3$$

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

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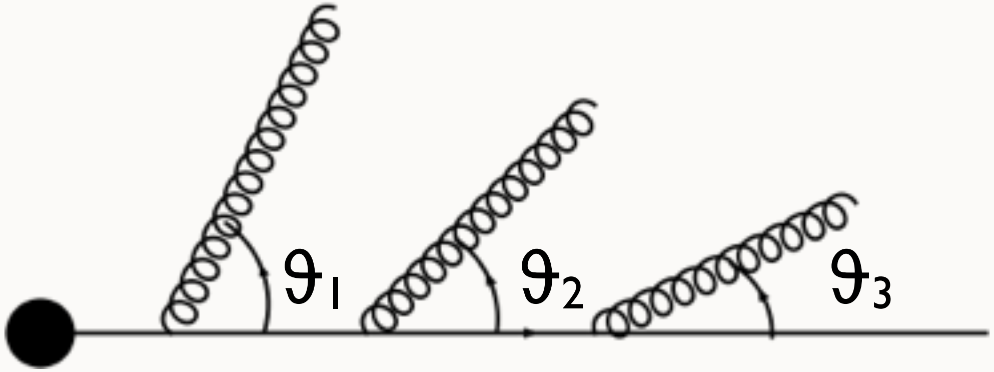

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- included in most MC generators: PYTHIA, HERWIG
- soft & collinear divergences
- interferences ⇒ angular ordering

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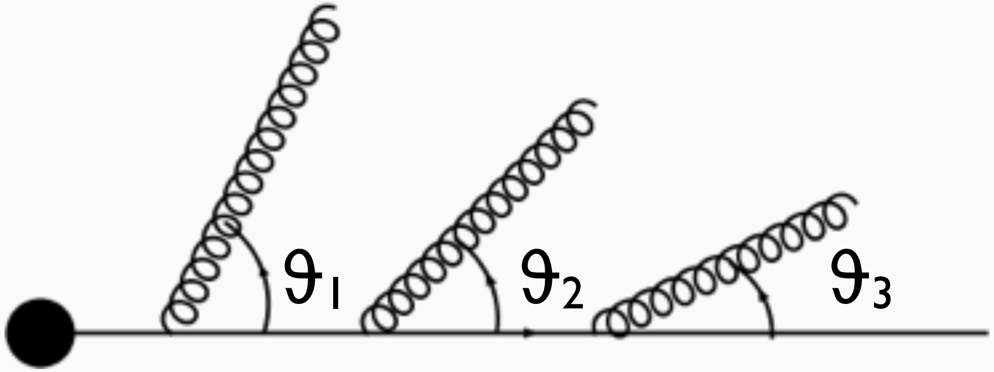

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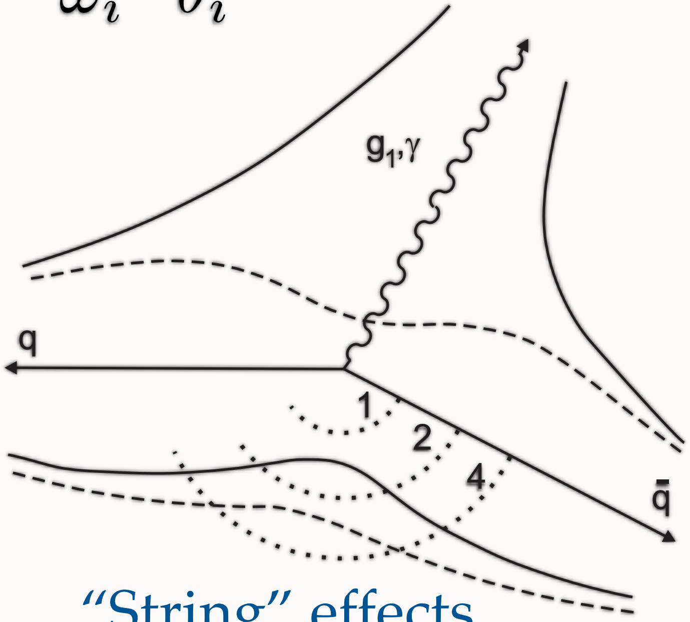
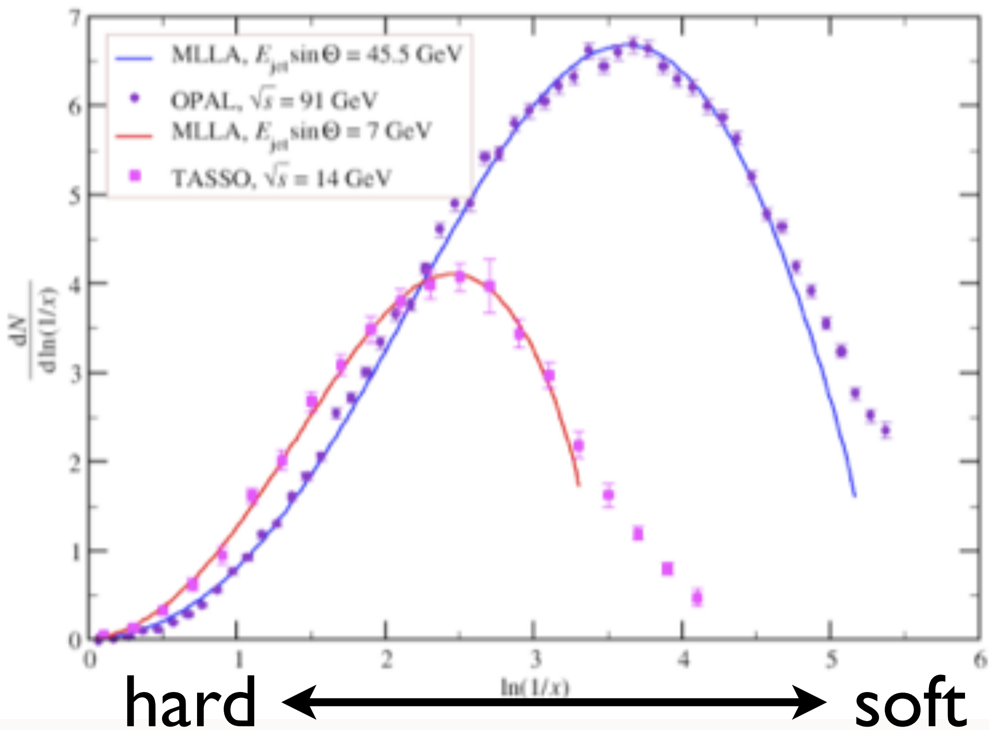


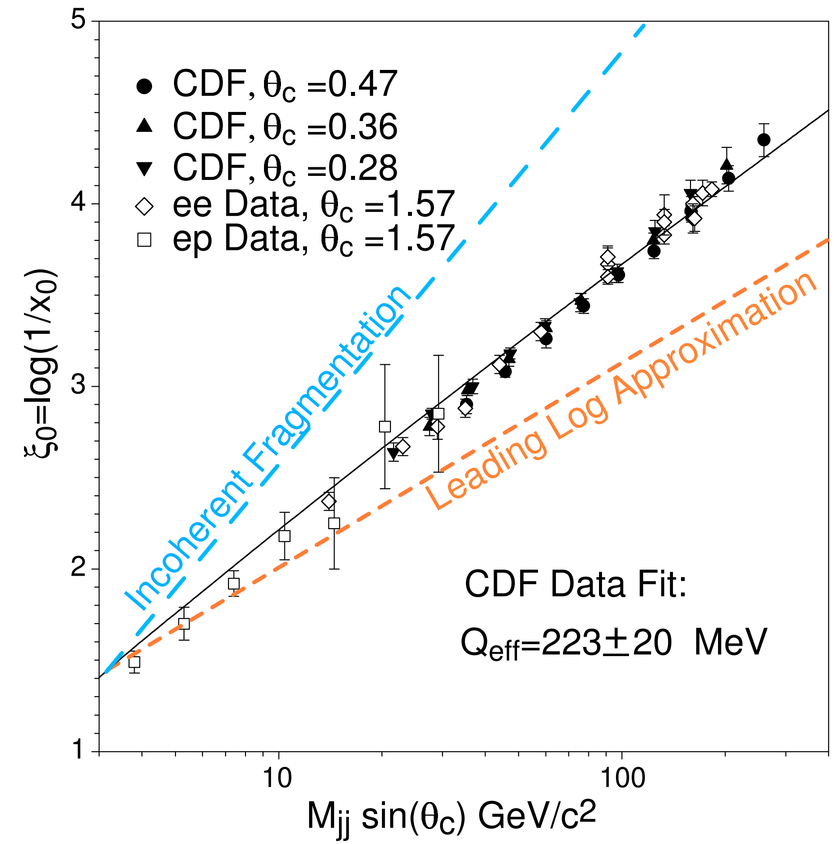
“String” effects

EXPERIMENTAL EVIDENCE



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

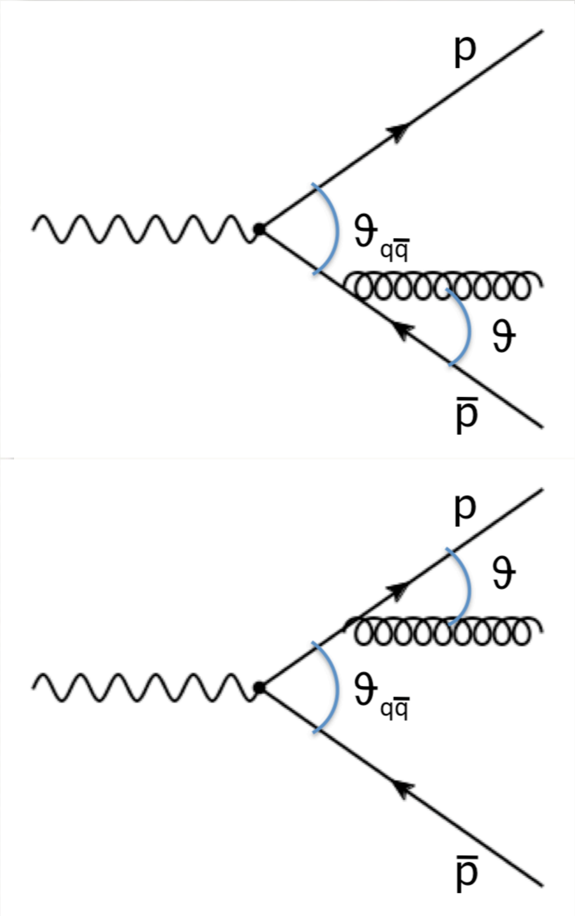
OPAL Collaboration, Phys. Lett. B 247 (1990) 617



Intrajet distribution:
"Humpbacked" plateau

Position of maximum...

ANTENNA RADIATION IN VACUUM



The antenna is a laboratory to study coherence effects.

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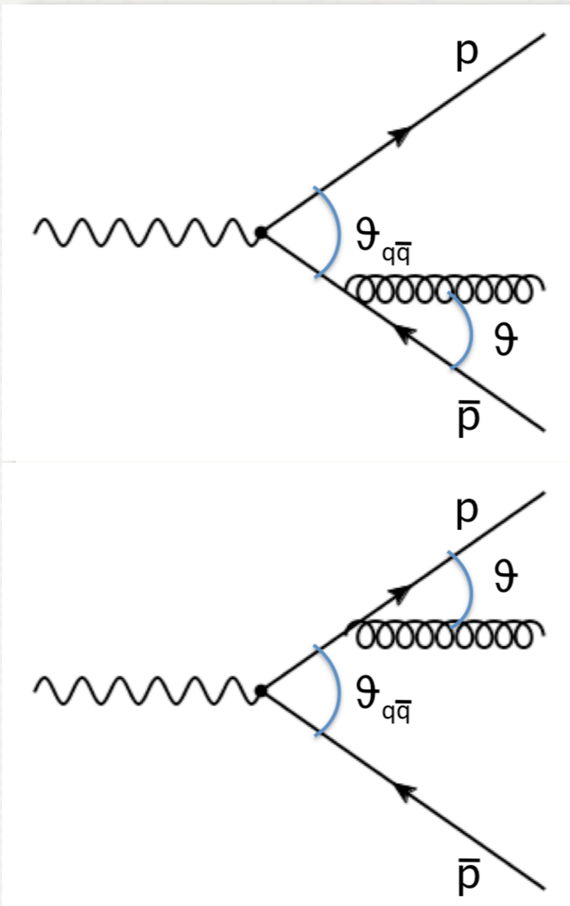

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$$\mathcal{M}^a = -ig\left[\frac{\kappa^i}{x(p\cdot k)}Q^a_q + \frac{\bar{\kappa}^i}{\bar{x}(\bar{p}\cdot k)}Q^a_{\bar{q}}\right]\cdot \epsilon^i$$

$$\kappa^i = k^i - xp^i$$

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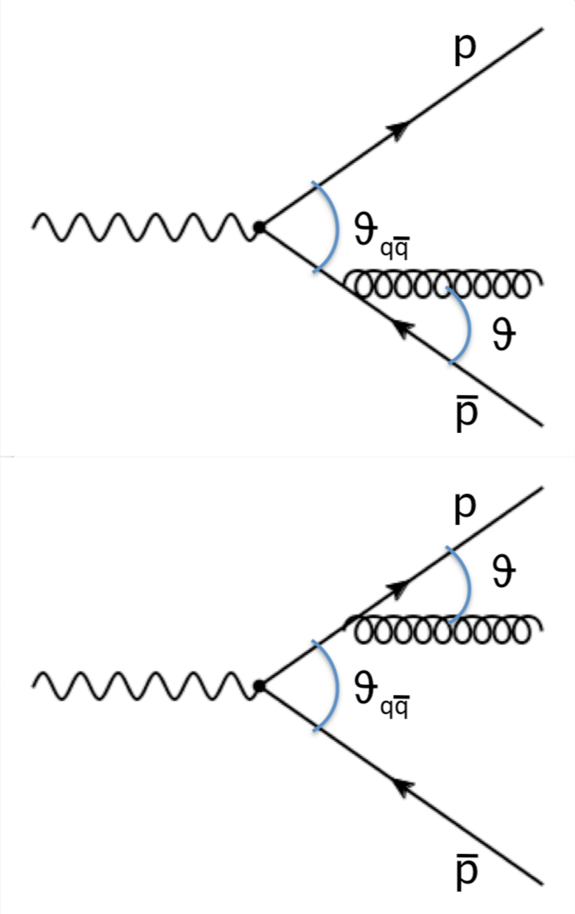

$Q_q = -Q_{\bar{q}}$: singlet

$Q_q + Q_{\bar{q}} = Q_g$: octet

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$$\omega\frac{dN^{\text{vac}}}{d^3k} = \frac{\alpha_s}{(2\pi)^2\omega^2}\left(Q_q^2\mathcal{R}_{\text{coh}} + (Q_q + Q_{\bar{q}})^2\mathcal{J}\right)$$

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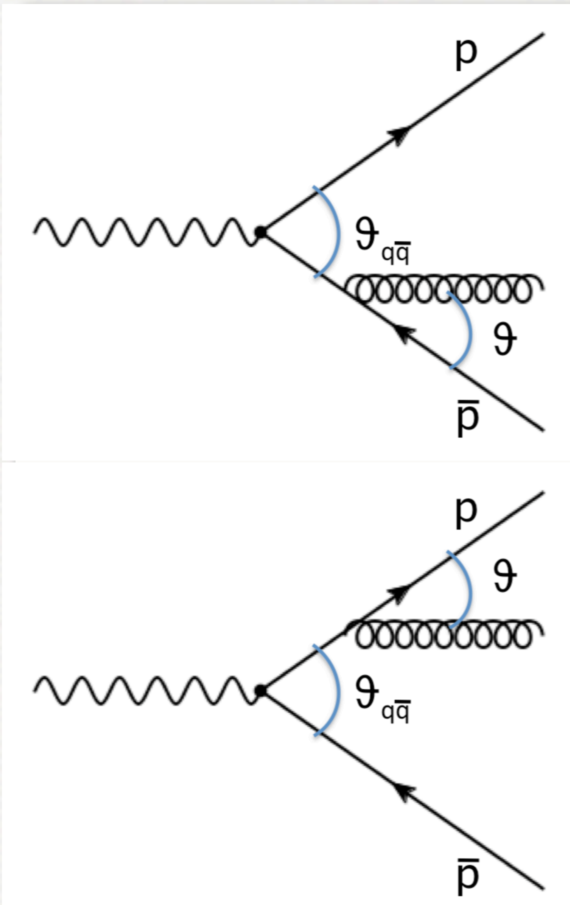

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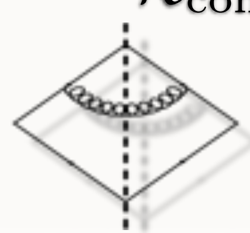

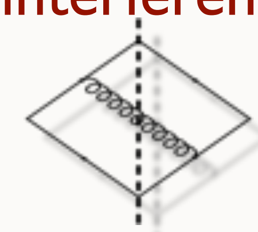

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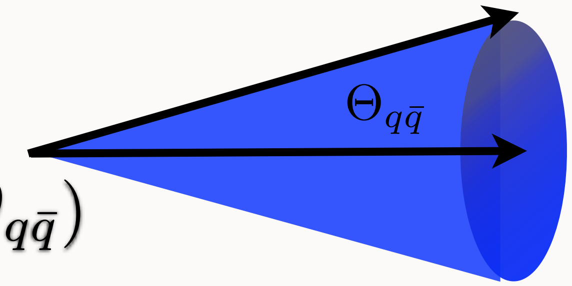

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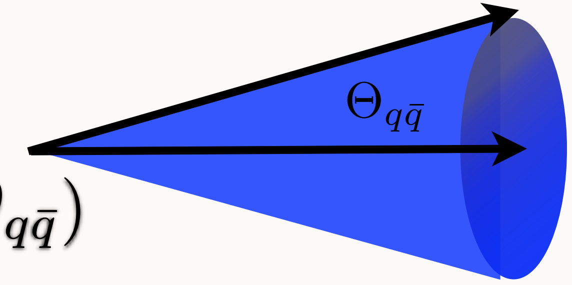

Fundamental building block of the QCD cascade!

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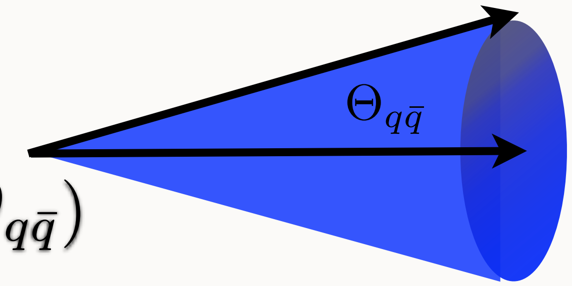

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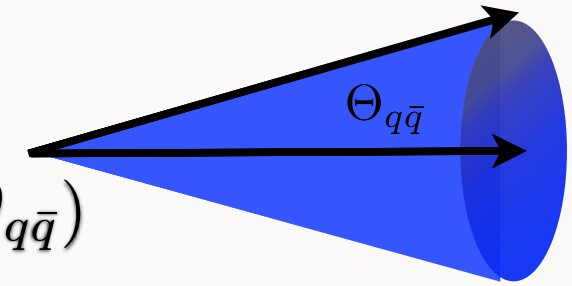

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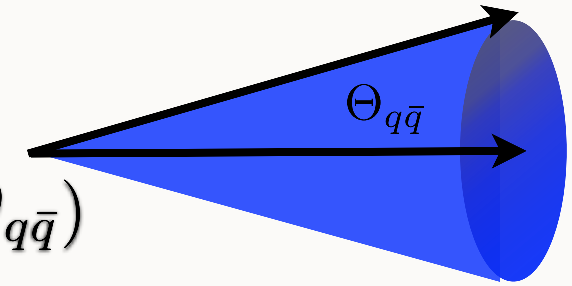

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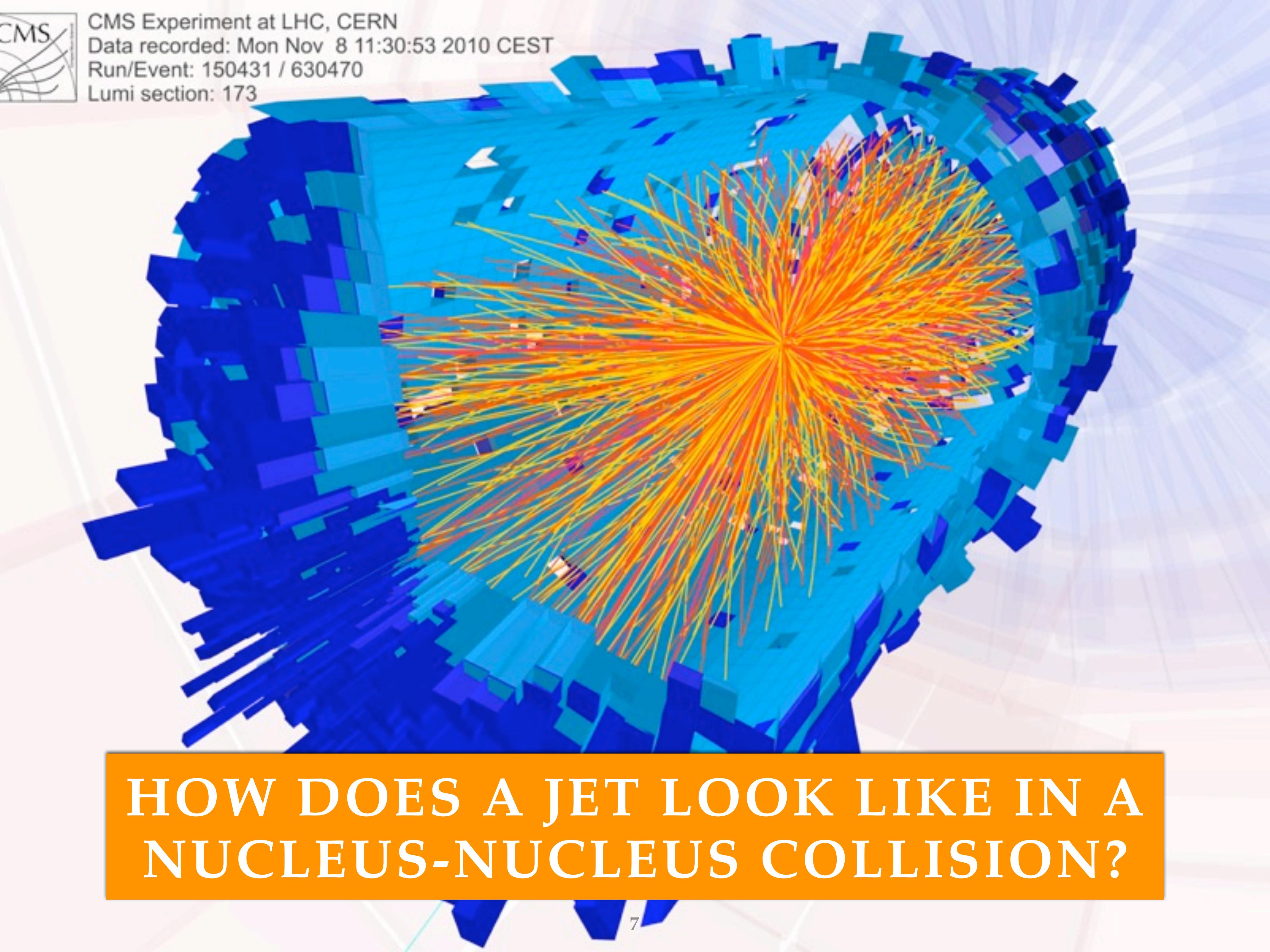
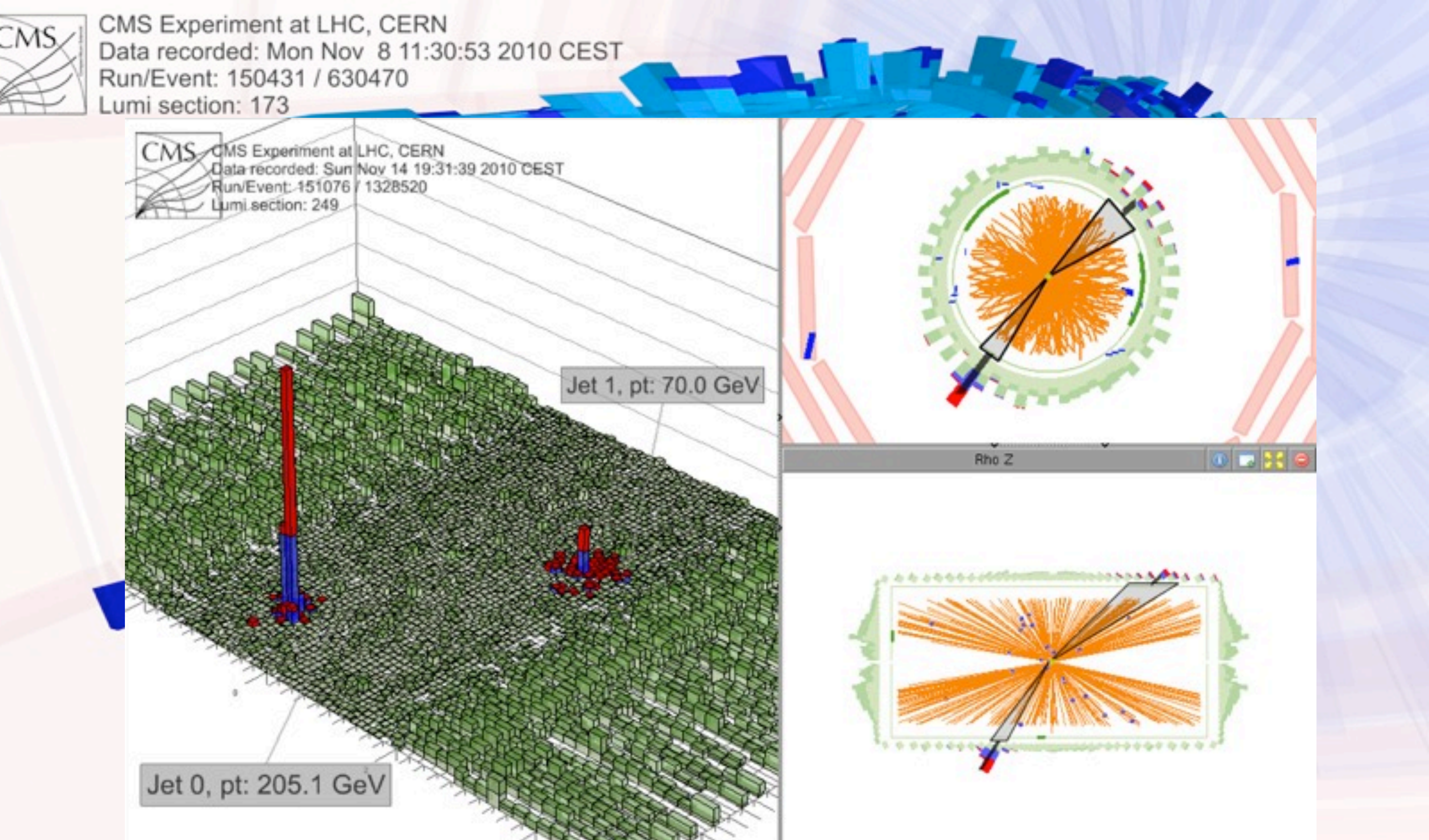
- Q1: how will the coherent structure of the jet be altered when immersed in a deconfined medium?
- Q2 (easier): how will the antenna radiation pattern look like in medium?



HOW DOES A JET LOOK LIKE IN A NUCLEUS-NUCLEUS COLLISION?



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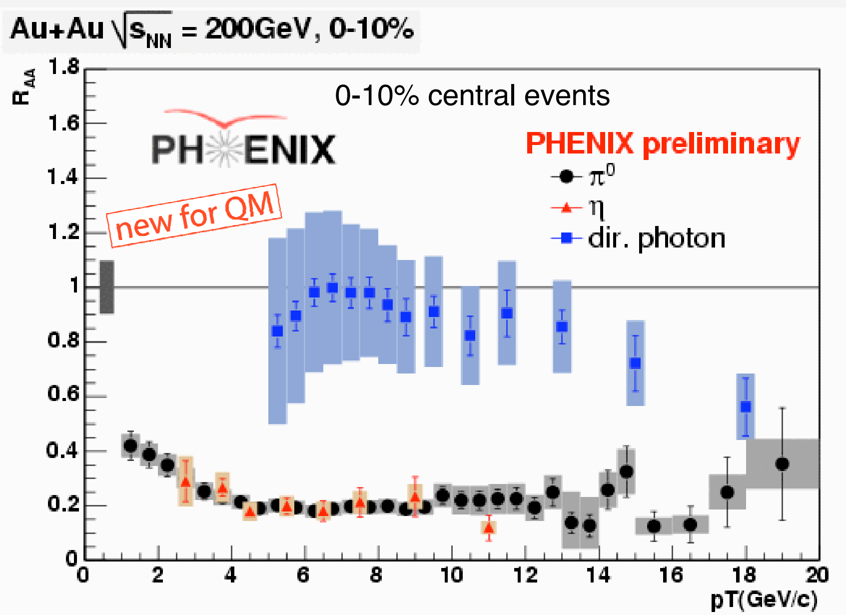
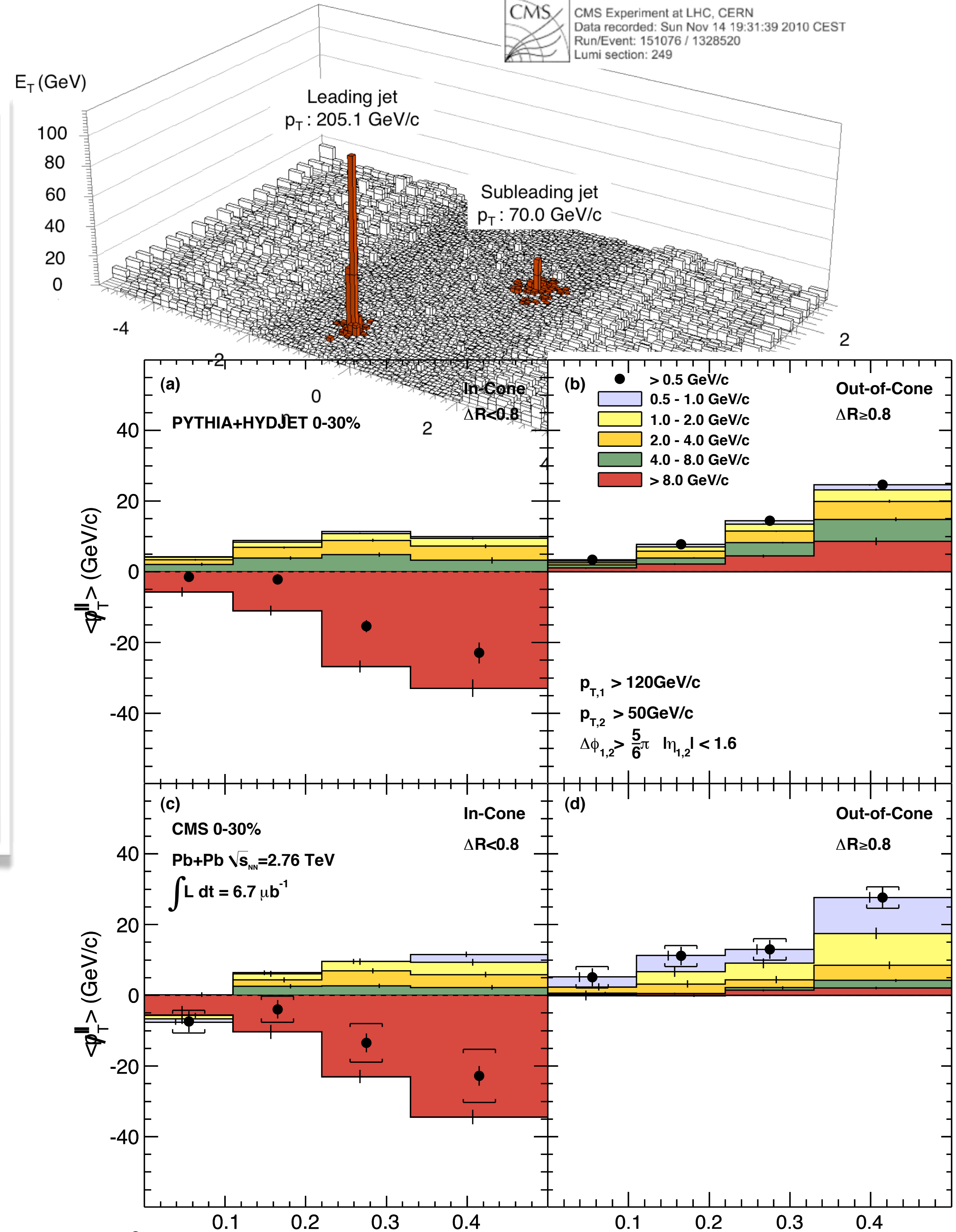
I) large energy loss of leading particle





II) soft gluons at large angles

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigne, Schiff (1997-2001), Zakharov (1996),
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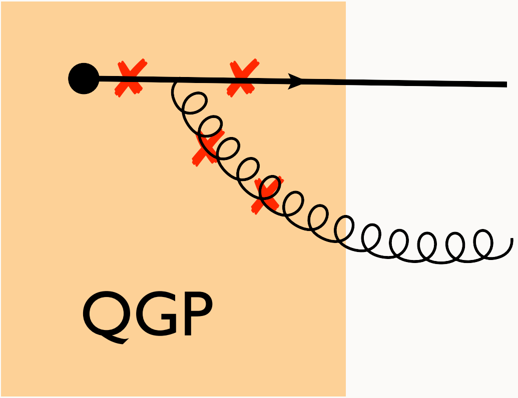

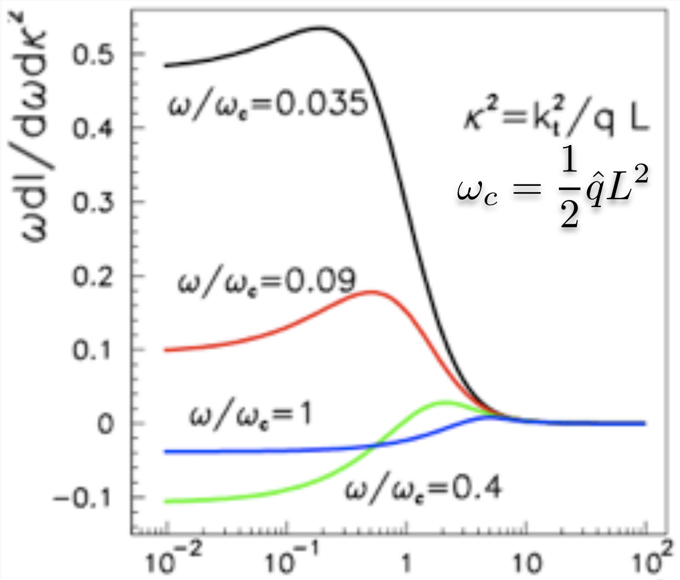

Salgado, Wiedemann (2003)

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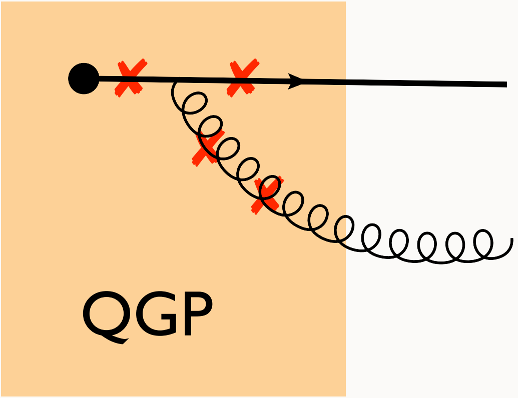

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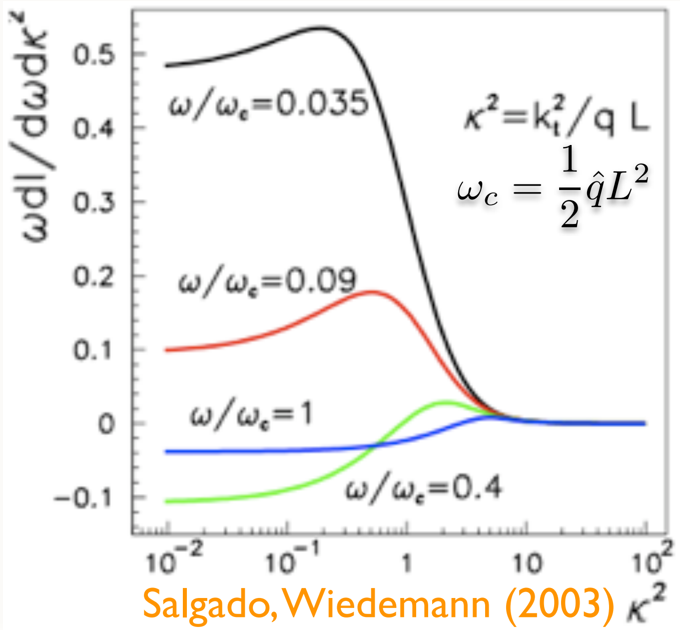

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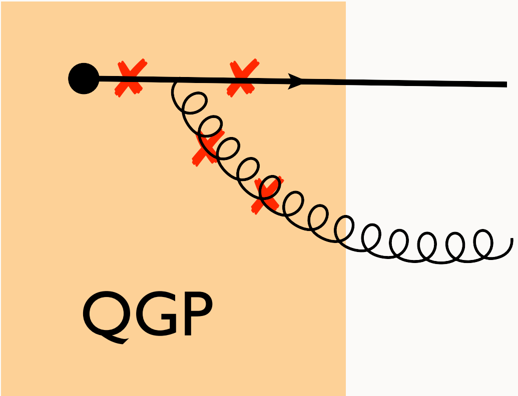

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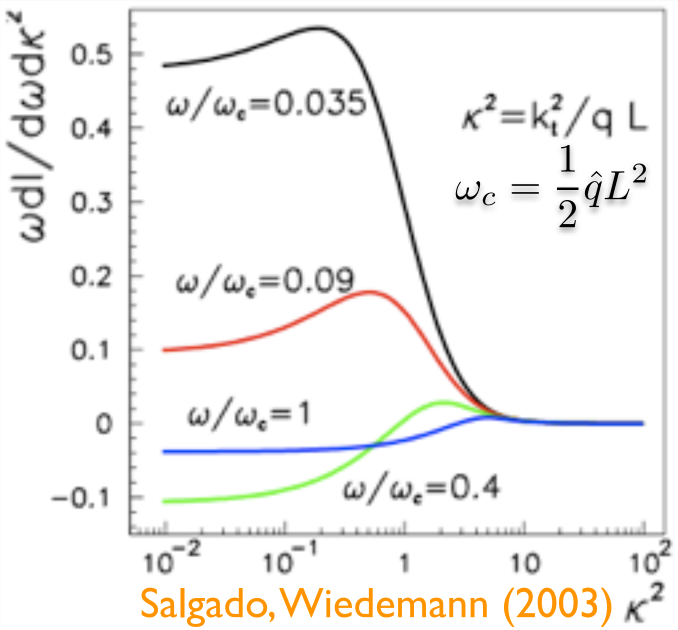

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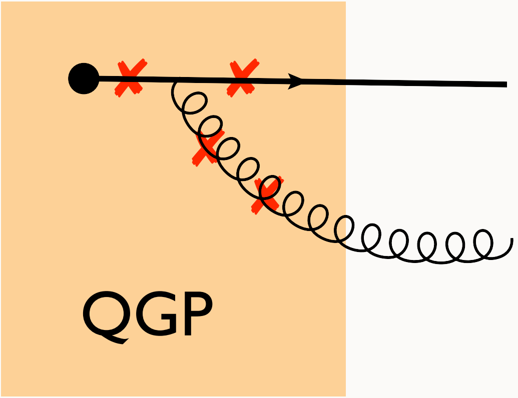

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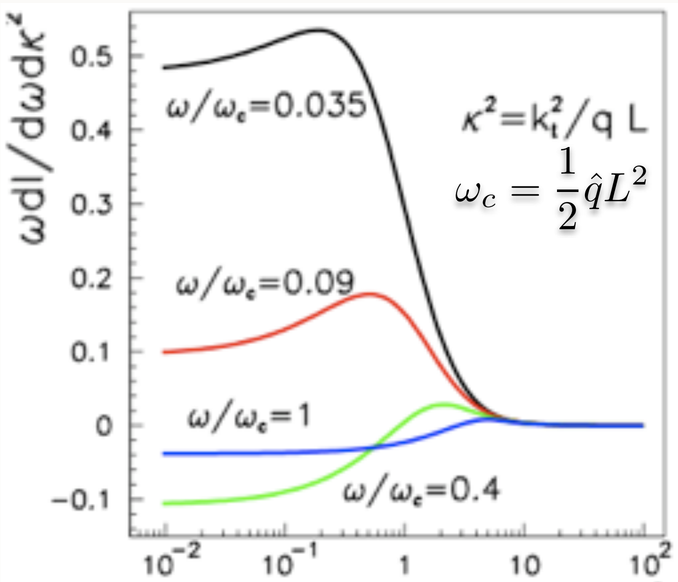
- gluon interaction ⇒ $k_\perp$-broadening
- transport parameter: $\hat{q} = m_D^2/\lambda$



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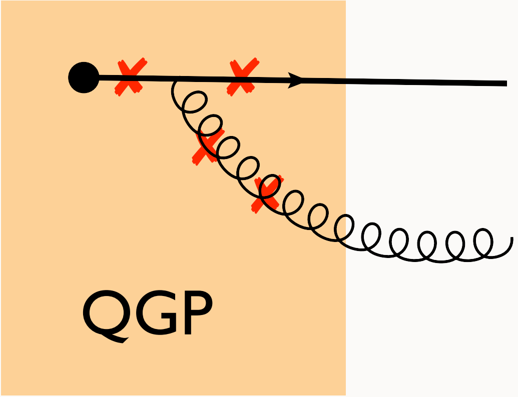

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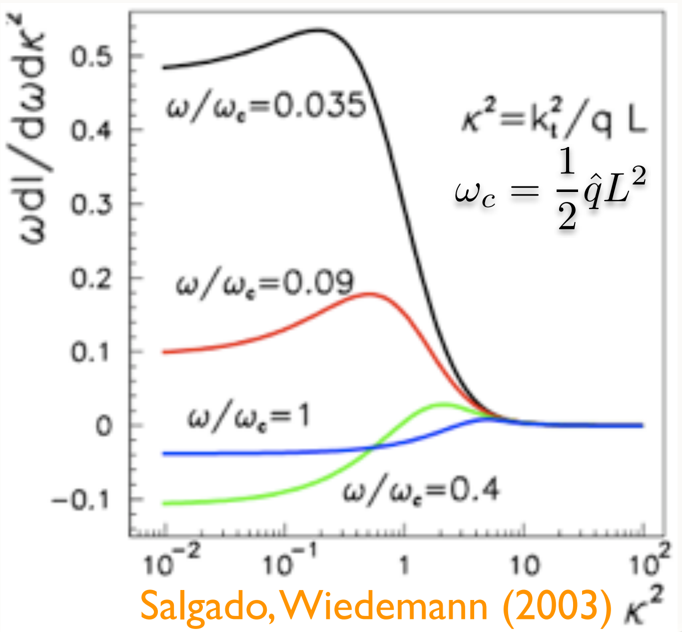

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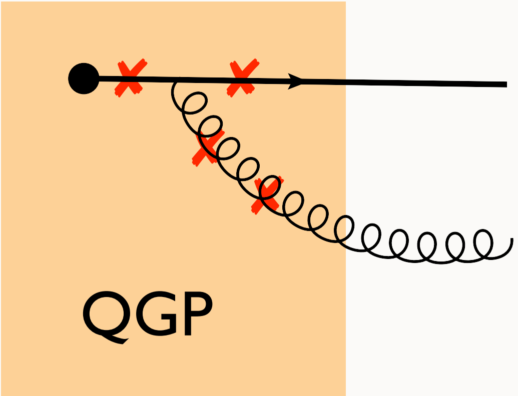

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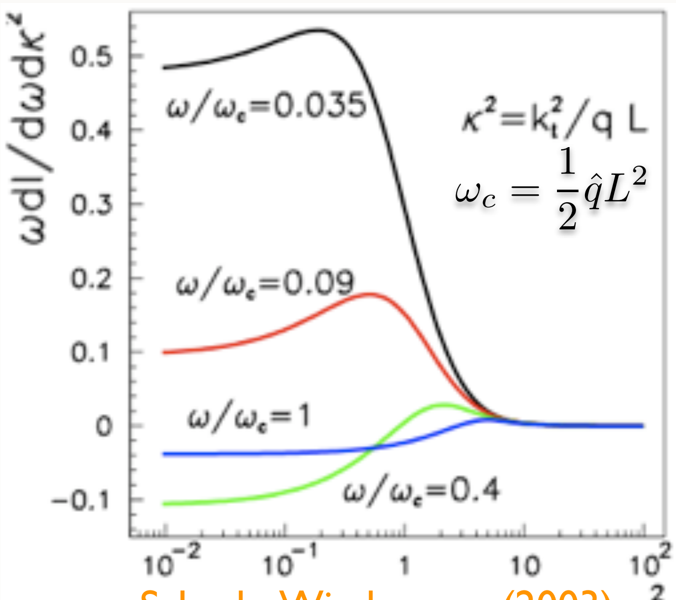

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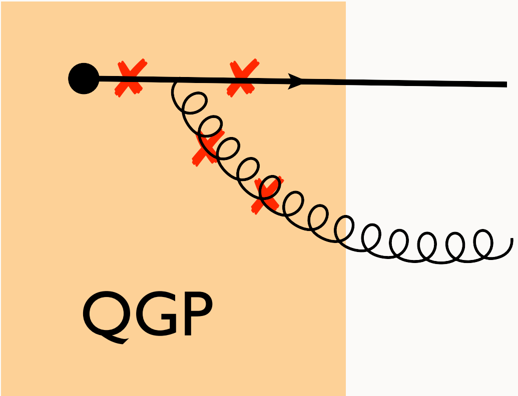

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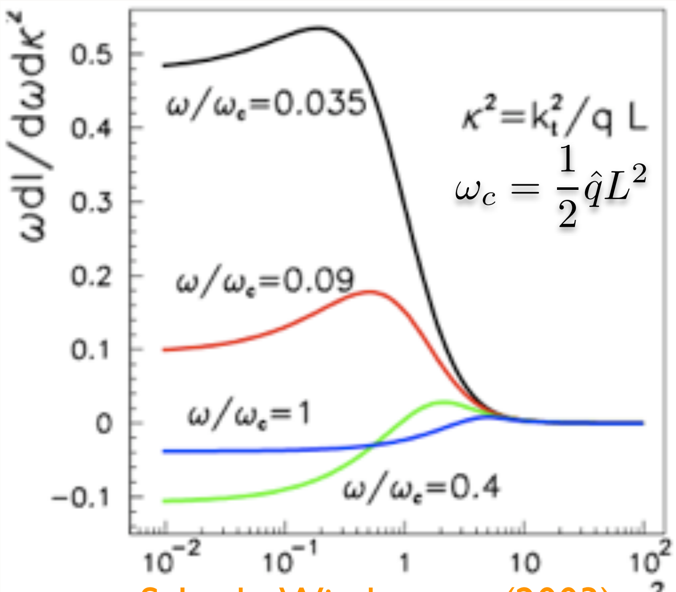
- need **more emitters** to see coherence!



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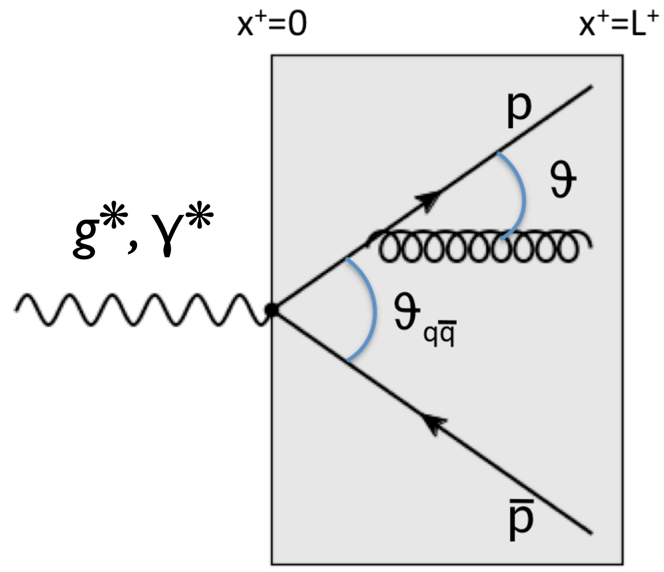
ANTENNA RADIATION IN MEDIUM

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



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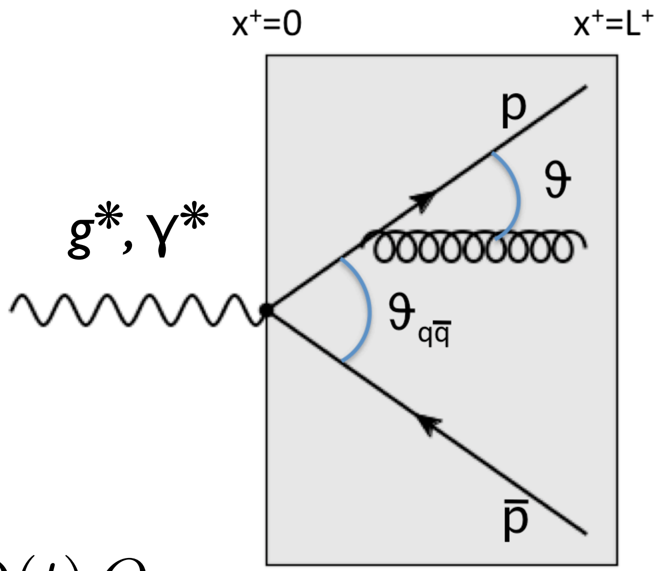

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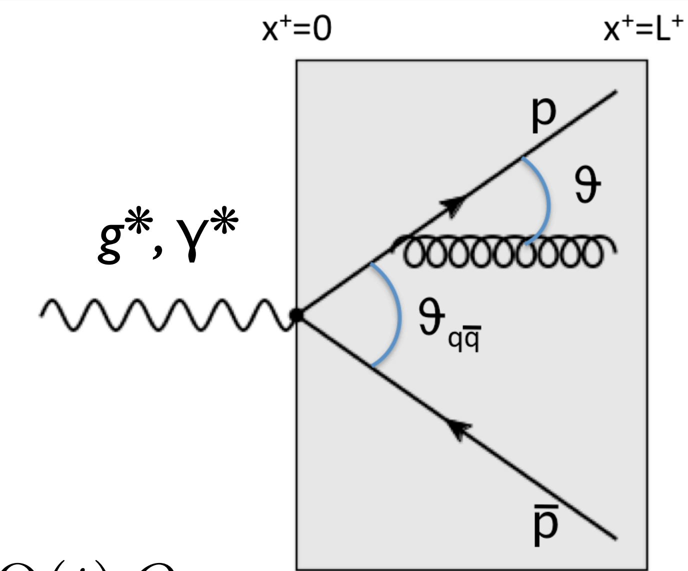

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Classical Yang-Mills eq: $[D_\mu, F^{\mu\nu}] = J^\nu \quad , \quad [D_\mu, J^\mu] = 0$

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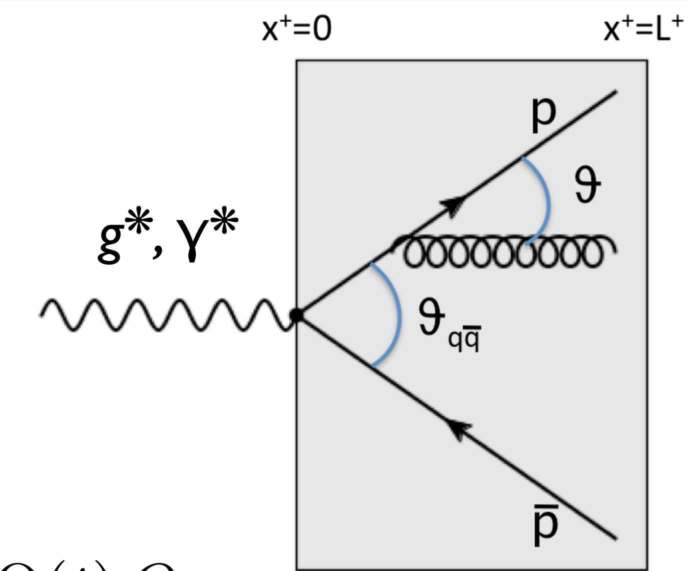


$$J_q(x) = g\, U_p(x^+,0)\, \delta^{(3)}(\vec{x} - \frac{\vec{p}}{E} t)\Theta(t)\, Q_q$$

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

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

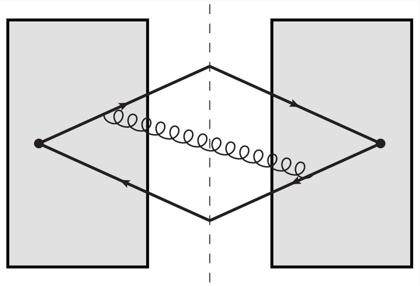
Linear response: $\Box A^i - 2ig\,[A^-_{\text{med}}, \partial^+ A^i] = -\frac{\partial^i}{\partial^+} J^+ + J^i$

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

ANTENNA IN MEDIUM

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

Multiple scattering $\Rightarrow$ effective propagators:



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

$$\mathcal{J} = \mathrm{Re}\Bigg\{ \int_0^\infty dy'^+ \int_0^{y'^+} dy^+ \left(1 - \Delta_{\mathrm{med}}(y^+, 0)\right)$$

$$\times \int d^2\boldsymbol{z}\, \exp\left[-i\bar{\boldsymbol{\kappa}} \cdot \boldsymbol{z} - \frac{1}{2} \int_{y'^+}^\infty d\xi\, n(\xi)\sigma(\boldsymbol{z}) + i\frac{k^+}{2}\delta\boldsymbol{n}^2 y^+ \right]$$

$$\times \left(\boldsymbol{\partial}_y - ik^+\,\delta\boldsymbol{n}\right) \cdot \boldsymbol{\partial}_z\, \mathcal{K}(y'^+, \boldsymbol{z}\,;\, y^+, \boldsymbol{y}\,|k^+)\Big|_{\boldsymbol{y}=\delta\boldsymbol{n}y^+} \Bigg\} + \mathrm{sym.}$$

ANTENNA IN MEDIUM

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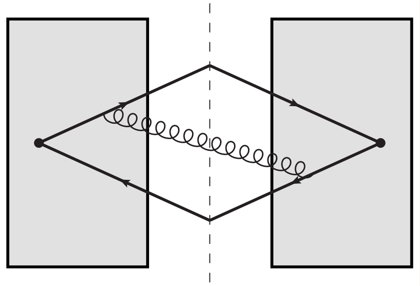

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$$|\delta n| \simeq \theta_{q\bar{q}}$$

Describes Brownian motion through medium potential...

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

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

The opacity expansion

[Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann]

Propagation and interaction is encoded in the path integral:

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

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Expansion in terms of n(ξ)σ(r) ⇒ the medium opacity:

$$\begin{aligned}
&\mathcal{K}(\mathbf{r}, y_l; \bar{\mathbf{r}}, \bar{y}_l) = \mathcal{K}_0(\mathbf{r}, y_l; \bar{\mathbf{r}}, \bar{y}_l) \\
&- \int_{z}^{z'} d\xi\, n(\xi) \int d\boldsymbol{\rho}\, \mathcal{K}_0(\mathbf{r}, y_l; \boldsymbol{\rho}, \xi)\, \frac{1}{2}\, \sigma(\boldsymbol{\rho})\, \mathcal{K}_0(\boldsymbol{\rho}, \xi; \bar{\mathbf{r}}, \bar{y}_l) \\
&+ \int_{z}^{z'} d\xi_1\, n(\xi_1) \int_{\xi_1}^{z'} d\xi_2\, n(\xi_2) \int d\boldsymbol{\rho}_1\, d\boldsymbol{\rho}_2\, \mathcal{K}_0(\mathbf{r}, y_l; \boldsymbol{\rho}_1, \xi_1) \\
&\times \frac{1}{2}\, \sigma(\boldsymbol{\rho}_1)\, \mathcal{K}(\boldsymbol{\rho}_1, \xi_1; \boldsymbol{\rho}_2, \xi_2)\, \frac{1}{2}\, \sigma(\boldsymbol{\rho}_2)\, \mathcal{K}_0(\boldsymbol{\rho}_2, \xi_2; \bar{\mathbf{r}}, \bar{y}_l)\,. \quad (6.2)
\end{aligned}$$

MODELING THE MEDIUM

Poisson equation: $$-\boldsymbol{\partial}_\perp^2 A^-_{\rm med}(x^+,\boldsymbol{x}) = \rho_{\rm med}(x^+,\boldsymbol{x})$$

Gaussian approximation:

$$\langle \rho^a_{\rm med}(x^+,\boldsymbol{q})\rho^{*b}_{\rm med}(x'^+,\boldsymbol{q}')\rangle = \delta^{ab} m_D^2\; n(x^+)\;\delta(x^+-x'^+)\;(2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{q}')$$

$$\langle \mathcal{A}^a_{\rm med}(x^+,\boldsymbol{q})\mathcal{A}^{*b}_{\rm med}(x'^+,\boldsymbol{q}')\rangle = \delta^{ab} m_D^2\; n(x^+)\;\delta(x^+-x'^+) \times (2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{q}')\,\mathcal{V}^2(\boldsymbol{q})$$

- Medium is a set of static potentials with screening length $\mathbf{m_D}^{-1}$
- No recoil
- Mean free path: $\boldsymbol{\lambda}$

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

AMPLITUDE AT N=1

Describes two physical processes of a virtual parton traversing the medium:

$$\mathcal{M}^a_{(1)\lambda,q} = 2\,ig^2 \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \int_0^\infty dx^+ \left[T \cdot \mathcal{A}_{\mathrm{med}}(x^+, \boldsymbol{q})\right]^{ab} Q^b_q \, e^{i(k^- - v^-)x^+}$$
$$\times \left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2} - \boldsymbol{L} \; \exp\left(i\frac{\boldsymbol{\nu}^2}{2k^+}x^+\right)\right] \cdot \boldsymbol{\epsilon}_\lambda$$

$$\kappa^i = k^i - xp^i$$
$$\nu^i = k^i - q^i - xp^i$$

AMPLITUDE AT N=1

Describes two physical processes of a virtual parton traversing the medium:

$$\mathcal{M}^{a}_{(1)\lambda,q} = 2\,ig^2 \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \int_0^\infty dx^+ \left[T\cdot\mathcal{A}_{\text{med}}(x^+,\boldsymbol{q})\right]^{ab} Q^b_q \; e^{i(k^- - v^-)x^+}$$

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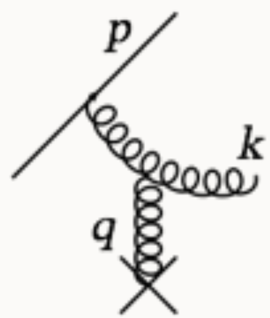
Hard emission with rescattering



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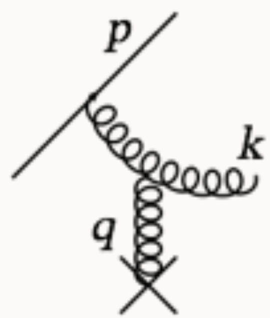
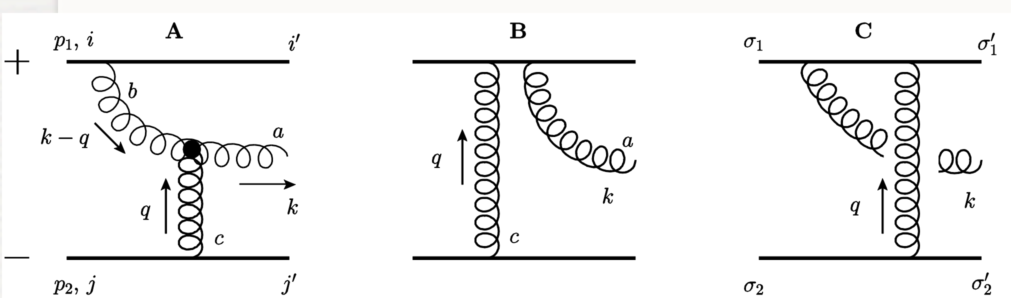


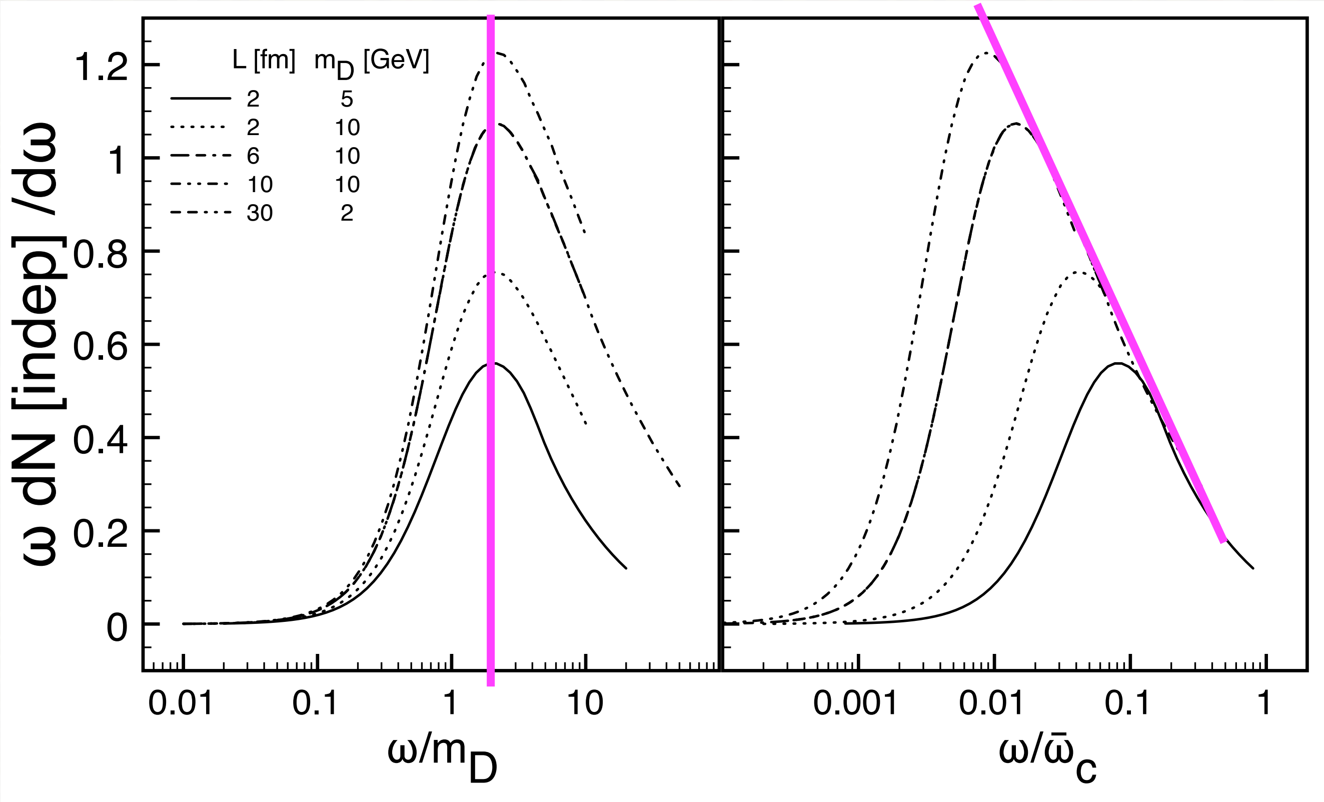
Lipatov vertex

$$\boldsymbol{L} = \frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2} - \frac{\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2}$$

- medium-induced emission off an on-shell particle



INDEPENDENT RADIATION



$$\bar{\omega}_c \sim m_D^2 L$$

$$\langle k_\perp \rangle \sim m_D$$

$$\hat{q} = \alpha_s C_A \frac{m_D^2}{\lambda_{mfp}}$$

$$\omega \frac{dN_q^{\text{indep}}}{d\omega\, d^2\boldsymbol{k}} = \frac{8\,\alpha_s C_F\,\hat{q}}{\pi} \int_{\mathcal{V}(\boldsymbol{q})} \int_0^{L^+} dx^+ \left(1 - \cos\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2k^+} x^+\right) \frac{\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2 (\boldsymbol{k}-\boldsymbol{q})^2}$$

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Incoherent limit:
(L→∞)

$$\hat{q} \int_{\mathcal{V}(\boldsymbol{q})} \frac{\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2} = \frac{\hat{q}}{2} \int_{\mathcal{V}(\boldsymbol{q})} \left(-\frac{1}{\boldsymbol{k}^2} + \frac{1}{(\boldsymbol{k}-\boldsymbol{q})^2} + \boldsymbol{L}^2 \right)$$

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$$\lim_{L\to\infty} \sum_{m=0}^{N=1} \frac{d^3\sigma^{(nas)}(m)}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{\pi^2} N_C\, C_F$$
$$\times \left[(1-w_1) H(\mathbf{k}_\perp) + n_0\, L \int_{\mathbf{q}_1} H(\mathbf{k}_\perp + \mathbf{q}_{1\perp}) \right.$$
$$\left. + n_0\, L \int_{\mathbf{q}_1} R(\mathbf{k}_\perp, \mathbf{q}_{1\perp}) \right] .$$

Probabilistic interpretation!

Wiedemann (2000)

INDEPENDENT RADIATION

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THE TOTAL SPECTRUM

$$\omega\frac{dN^{\mathrm{med}}}{d^3k} = \frac{8\,\alpha_s C_F\,\hat{q}}{\pi}\int_{\mathcal{V}(\boldsymbol{q})}\int_0^{L^+} dx^+$$
$$\left\{\left[1-\cos\left(\frac{\boldsymbol{\nu}+\bar{\boldsymbol{\nu}}}{2}\cdot\delta\boldsymbol{n}\,x^+\right)\right]\boldsymbol{L}\cdot\bar{\boldsymbol{L}}\right.$$
$$+\left[1-\cos\left(\frac{\boldsymbol{\nu}^2}{2k^+}x^+\right)\right]\left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}-\frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2}\right]\cdot\boldsymbol{L}$$
$$\left.+\left[1-\cos\left(\frac{\bar{\boldsymbol{\nu}}^2}{2k^+}x^+\right)\right]\left[\frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2}-\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}\right]\cdot\bar{\boldsymbol{L}}\right\}$$

- two phase structures:
  - **“dipole” phase**, involving the opening angle
  - **LPM phase**, describing rescattering interference
- two vertices:
  - **Lipatov** vertex
  - **“gluon-gluon”** vertex

THE TOTAL SPECTRUM

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$$+ \left[1 - \cos\left(\frac{\boldsymbol{\nu}^2}{2k^+}x^+\right)\right]\left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2} - \frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2}\right]\cdot\boldsymbol{L}$$

$$\left. + \left[1 - \cos\left(\frac{\bar{\boldsymbol{\nu}}^2}{2k^+}x^+\right)\right]\left[\frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2} - \frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}\right]\cdot\bar{\boldsymbol{L}} \right\}$$

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THE TOTAL SPECTRUM

$$
\begin{aligned}
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\Bigg\{ \boxed{\left[1 - \cos\left(\frac{\boldsymbol{\nu} + \bar{\boldsymbol{\nu}}}{2} \cdot \delta \boldsymbol{n}\, x^+\right)\right]} \boxed{\boldsymbol{L} \cdot \bar{\boldsymbol{L}}} \\
+ \left[1 - \cos\left(\frac{\boldsymbol{\nu}^2}{2k^+} x^+\right)\right] \left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2} - \frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2}\right] \cdot \boldsymbol{L} \\
+ \left[1 - \cos\left(\frac{\bar{\boldsymbol{\nu}}^2}{2k^+} x^+\right)\right] \left[\frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2} - \frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}\right] \cdot \bar{\boldsymbol{L}} \Bigg\}
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$$

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THE SOFT LIMIT

$$\lim_{\omega \to 0} \boldsymbol{L} \cdot \bar{\boldsymbol{L}} = \frac{\boldsymbol{\kappa} \cdot \bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}^2 \bar{\boldsymbol{\kappa}}^2}$$

- vacuum-like
- antiangular ordered

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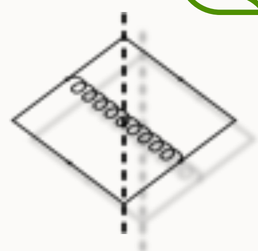
$\mathcal{J} =$ 

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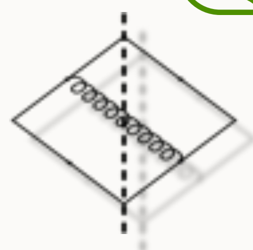
$\mathcal{J} =$ 

dipole-medium cross section

THE SOFT LIMIT

$$\lim_{\omega \to 0} \boldsymbol{L} \cdot \bar{\boldsymbol{L}} = \frac{\boldsymbol{\kappa} \cdot \bar{\boldsymbol{\kappa}}}{\boldsymbol{\kappa}^2 \bar{\boldsymbol{\kappa}}^2}$$

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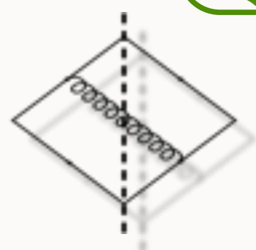
$\mathcal{J} =$ 

dipole-medium cross section

$$(2\pi)^2\, \omega \frac{dN^{\mathrm{tot}}_{g^*}}{d^3 k} = \frac{\alpha_s}{\omega^2} \Big[C_F \left(\mathcal{R}_{\mathrm{sing}} + 2\Delta_{\mathrm{med}}\, \mathcal{J} \right) + C_A (1 - \Delta_{\mathrm{med}})\, \mathcal{J} \Big]$$

$$\mathcal{R}_{\mathrm{sing}} \equiv \mathcal{R}_q + \mathcal{R}_{\bar{q}} - 2\mathcal{J}$$

SATURATION

$$\Delta_{\rm med}(\theta_{q\bar q}, L) \equiv \frac{\hat q}{m_D^2}\int_0^{L^+} {\rm d}x^+ \left[1 - \frac{|\boldsymbol{r}_\perp|\, m_D\, x^+}{L^+} K_1\left(\frac{|\boldsymbol{r}_\perp|\, m_D\, x^+}{L^+}\right)\right]$$

Medium decoherence parameter $|\boldsymbol{r}_\perp| = |\delta \boldsymbol{n}| L^+ \simeq \theta_{q\bar q} L$

➙ controls the cancellation of interferences

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

- $r_\perp^{-1} \gg m_D$
  - "dipole" regime

$$\Delta_{\rm med} \approx n_0 L^+ \equiv N_{\rm scat}$$

- $r_\perp^{-1} \ll m_D$
  - "saturation" regime

MULTIPLE SCATTERING

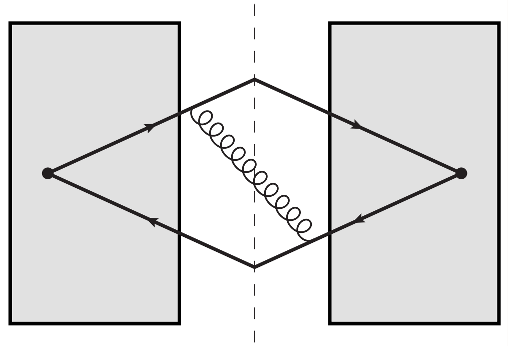
Wilson line along the trajectory:

$$U_p(x^+,0) = \mathcal{P}_+ \exp\left\{ ig \int_0^{x^+} dz^+ \left[T \cdot A^-_{\rm med}(z^+, z^+ p_\perp / p^+) \right] \right\}$$

Only the quarks are rotated in color:

$$J_q^{\mu,a}(k) \quad = \quad -ig\frac{p^\mu}{p\cdot k} U_p^{ab}(L,0)\, Q_q^b$$

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



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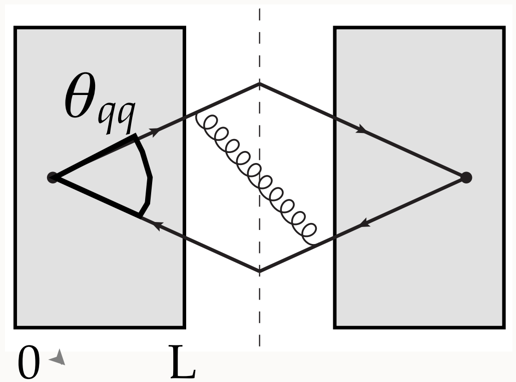


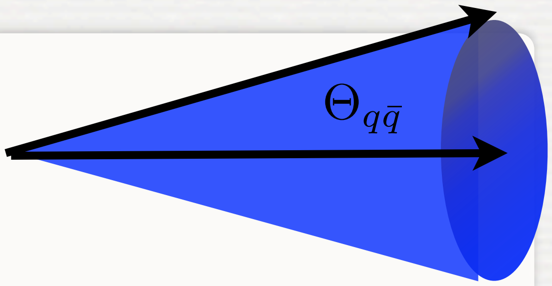
Multiple soft scattering approximation

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

$\hat{q}$: medium transport coefficient

ONSET OF DECOHERENCE IN MEDIUM

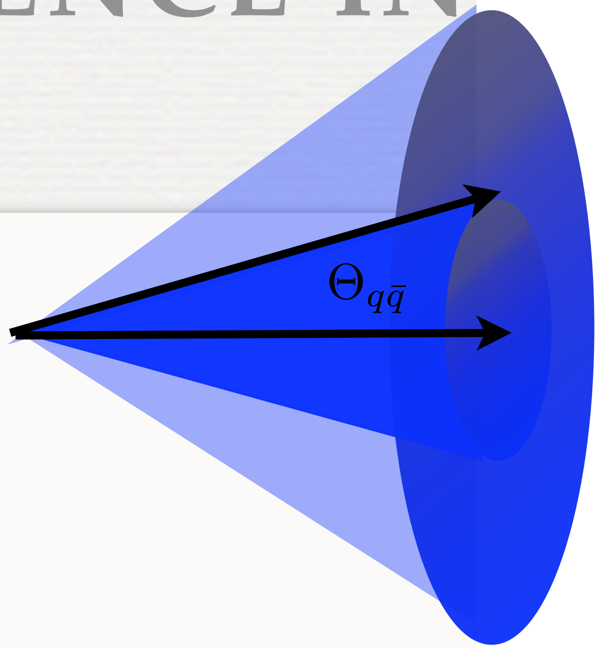
$\Delta_{\text{med}} \to 0$ **Coherence**



ONSET OF DECOHERENCE IN MEDIUM

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

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



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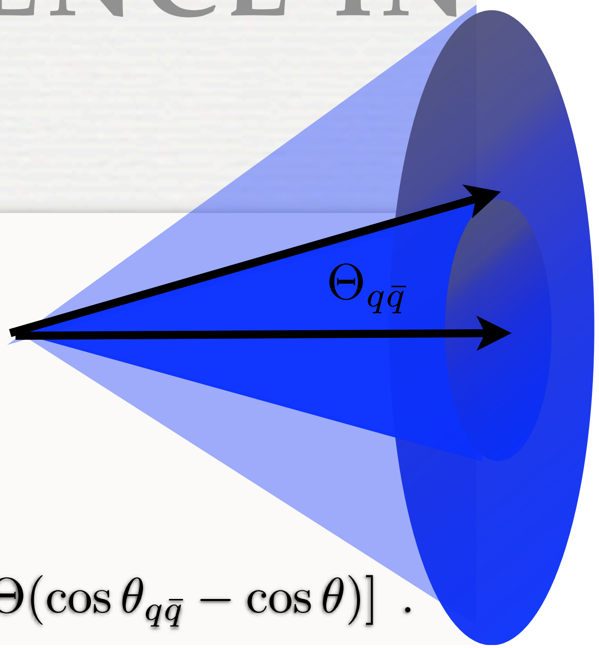
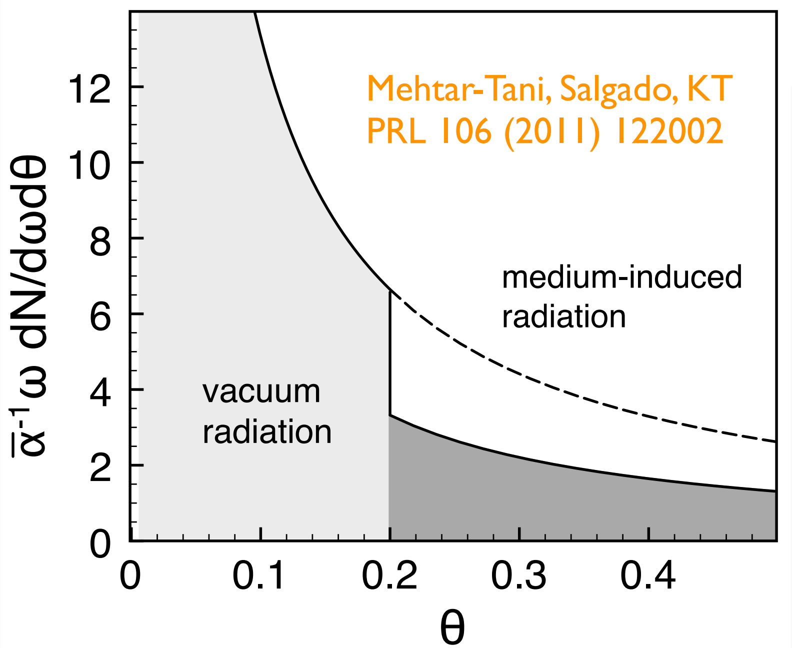
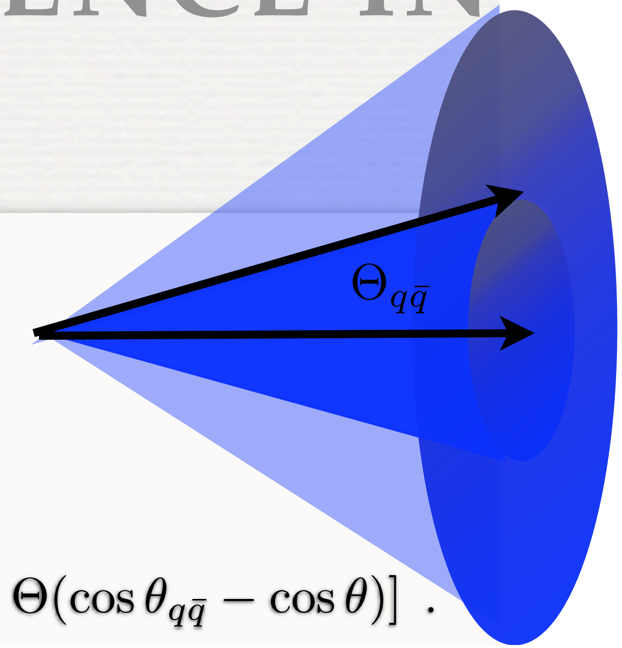


$$dN^{\text{tot}}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\ d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\text{med}}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right] .$$



ONSET OF DECOHERENCE IN MEDIUM



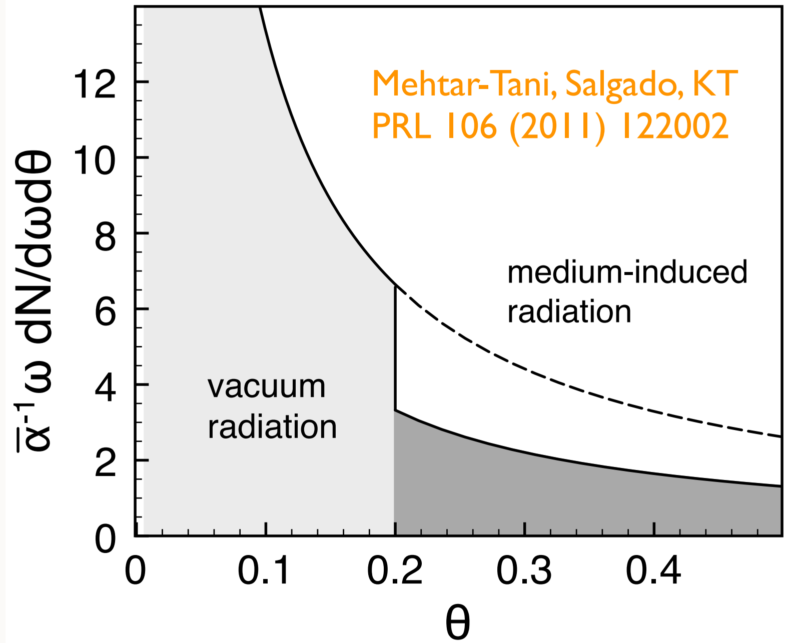
$\Delta_{\mathrm{med}} \to 0$ **Coherence**

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

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

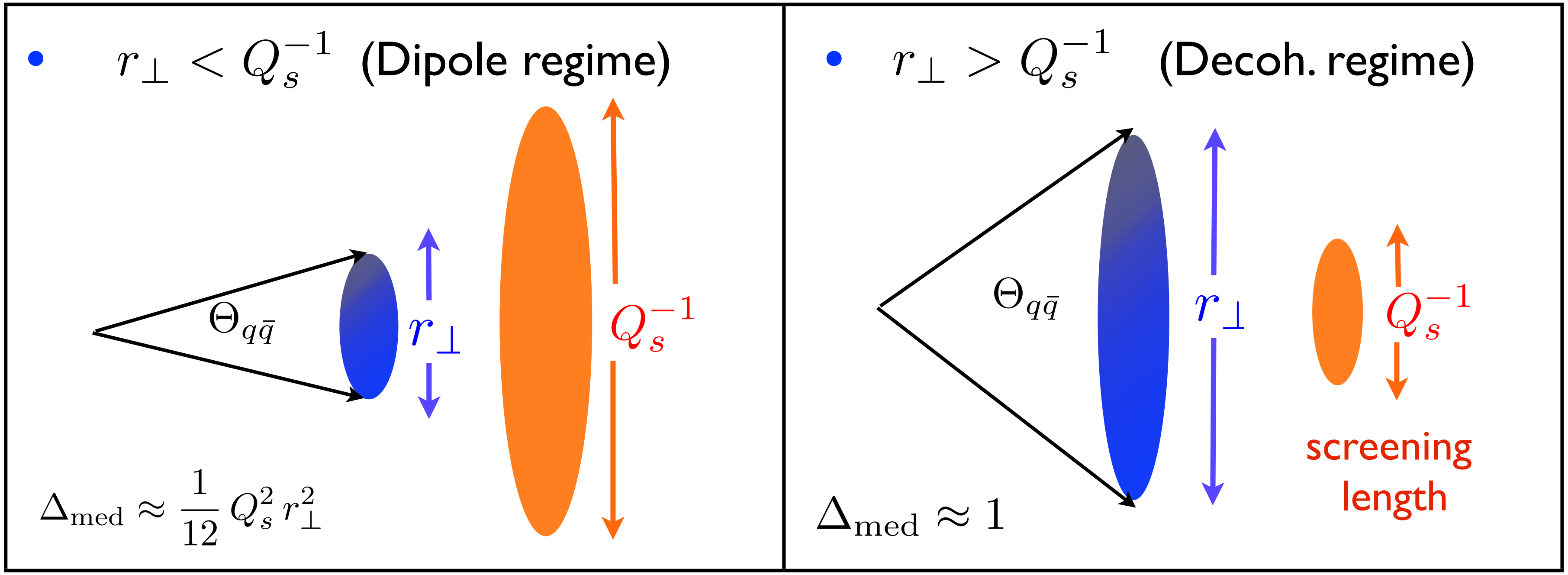
$$dN^{\mathrm{tot}}_{q,\gamma^*}\Big|_{\mathrm{opaque}} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\ d\theta}{1-\cos\theta} .$$

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



DECOHERENCE

- a two scale problem!



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

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

- $k_\perp \Leftrightarrow \max(Q_s, r_\perp^{-1})$

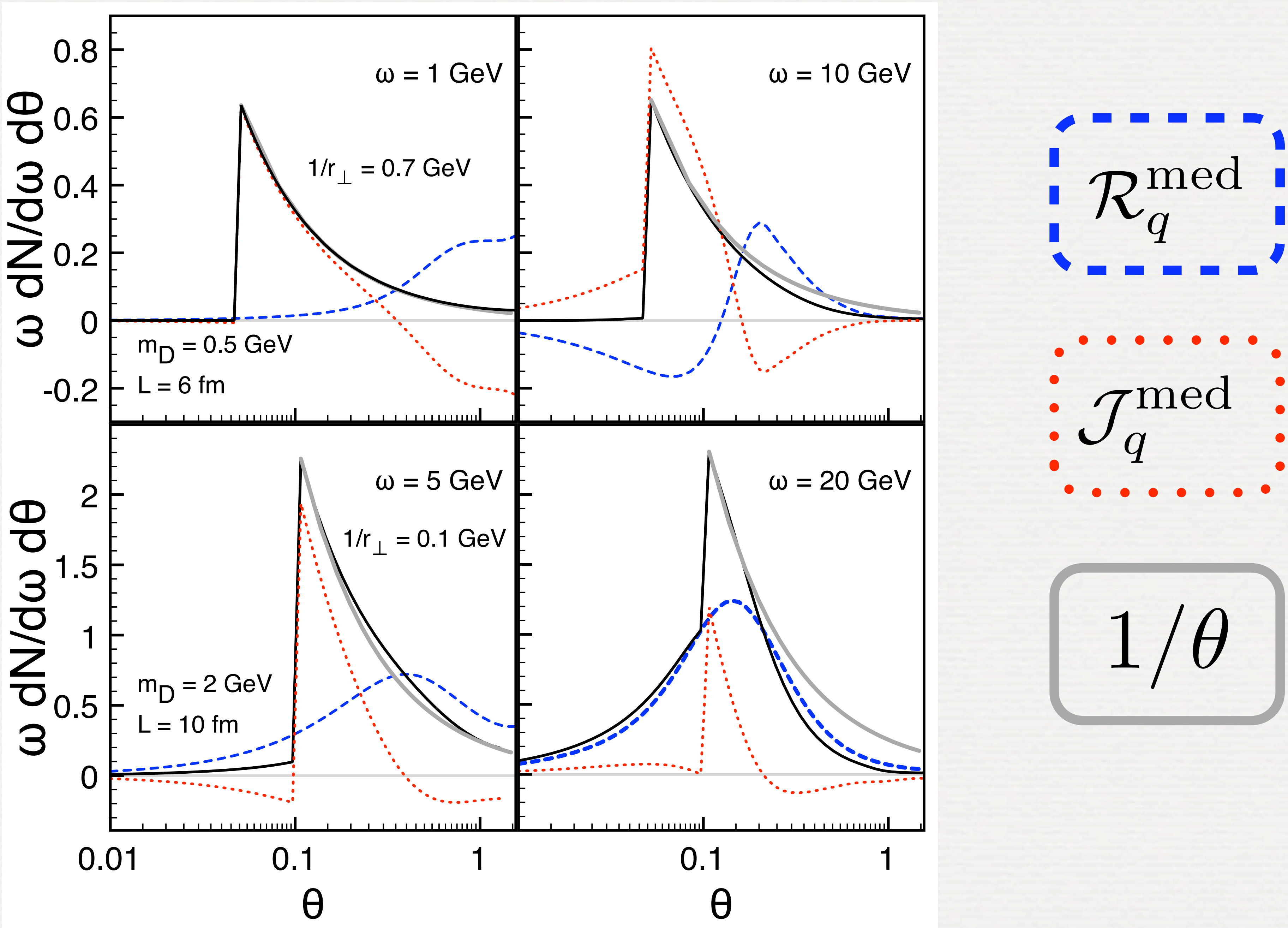
DECOMPOSITION

$$\mathcal{R}_q^{\text{med}} = 32\pi\hat{q}\int_{\mathcal{V}(\boldsymbol{q})}\int_0^{L^+} dx^+ \left[1-\cos\left(\frac{\boldsymbol{\nu}^2}{2k^+}x^+\right)\right]\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}\cdot\boldsymbol{L}$$

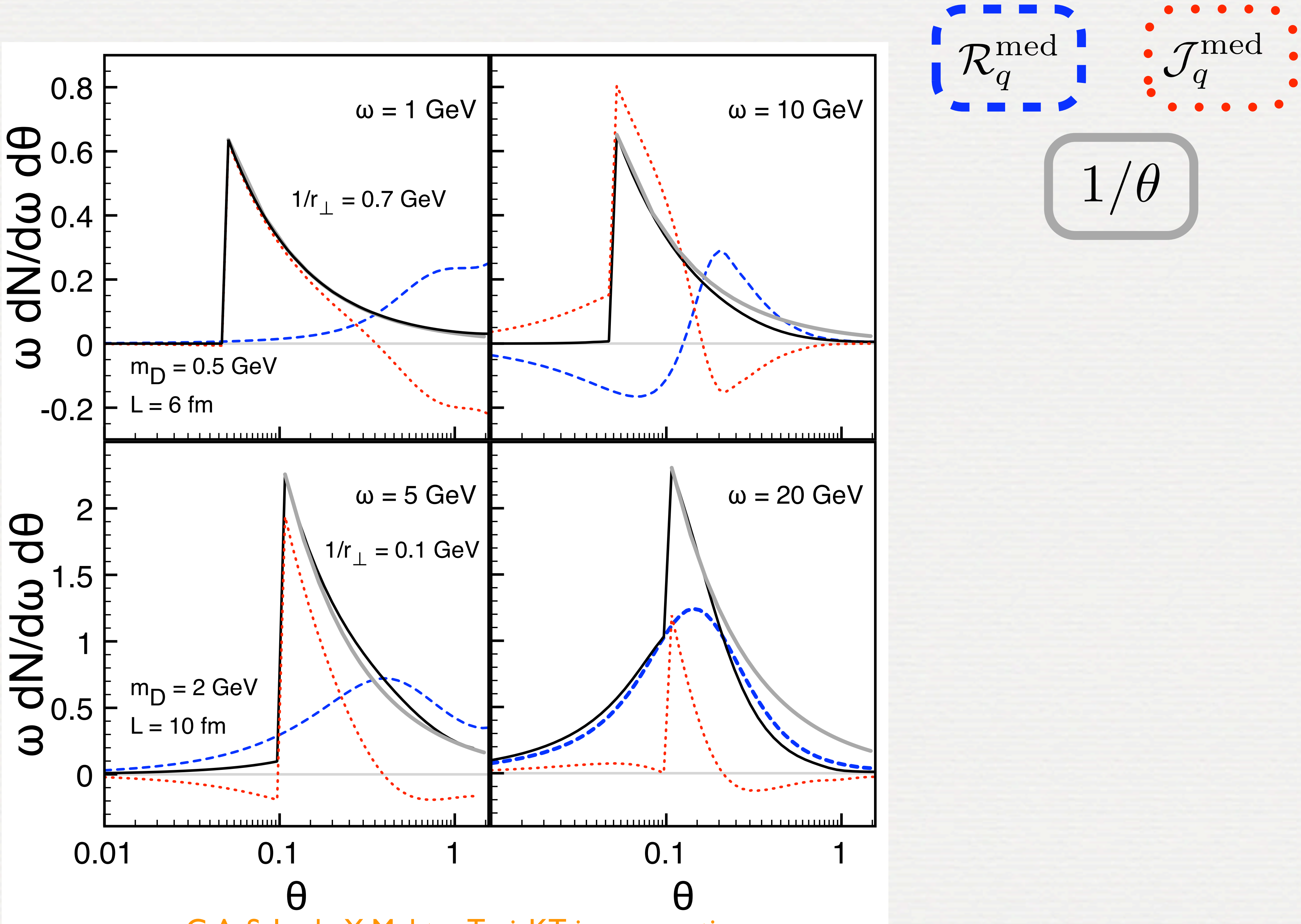
$$\mathcal{J}_q^{\text{med}} = -32\,\pi\,\hat{q}\int_{\mathcal{V}(\boldsymbol{q})}\int_0^{L^+} dx^+ \left\{\frac{1}{2}\left[1-\cos\left(\frac{\boldsymbol{\nu}+\bar{\boldsymbol{\nu}}}{2}\cdot\delta\boldsymbol{n}\,x^+\right)\right]\boldsymbol{L}\cdot\bar{\boldsymbol{L}} - \left[1-\cos\left(\frac{\boldsymbol{\nu}^2}{2k^+}x^+\right)\right]\frac{\bar{\boldsymbol{\nu}}}{\bar{\boldsymbol{\nu}}^2}\cdot\boldsymbol{L}\right\},$$

$$\omega\frac{dN_q^{\text{med}}}{d^3k} = \frac{\alpha_s C_F}{(2\pi)^2\,\omega^2}\left(\mathcal{R}_q^{\text{med}} - \mathcal{J}_q^{\text{med}}\right)$$

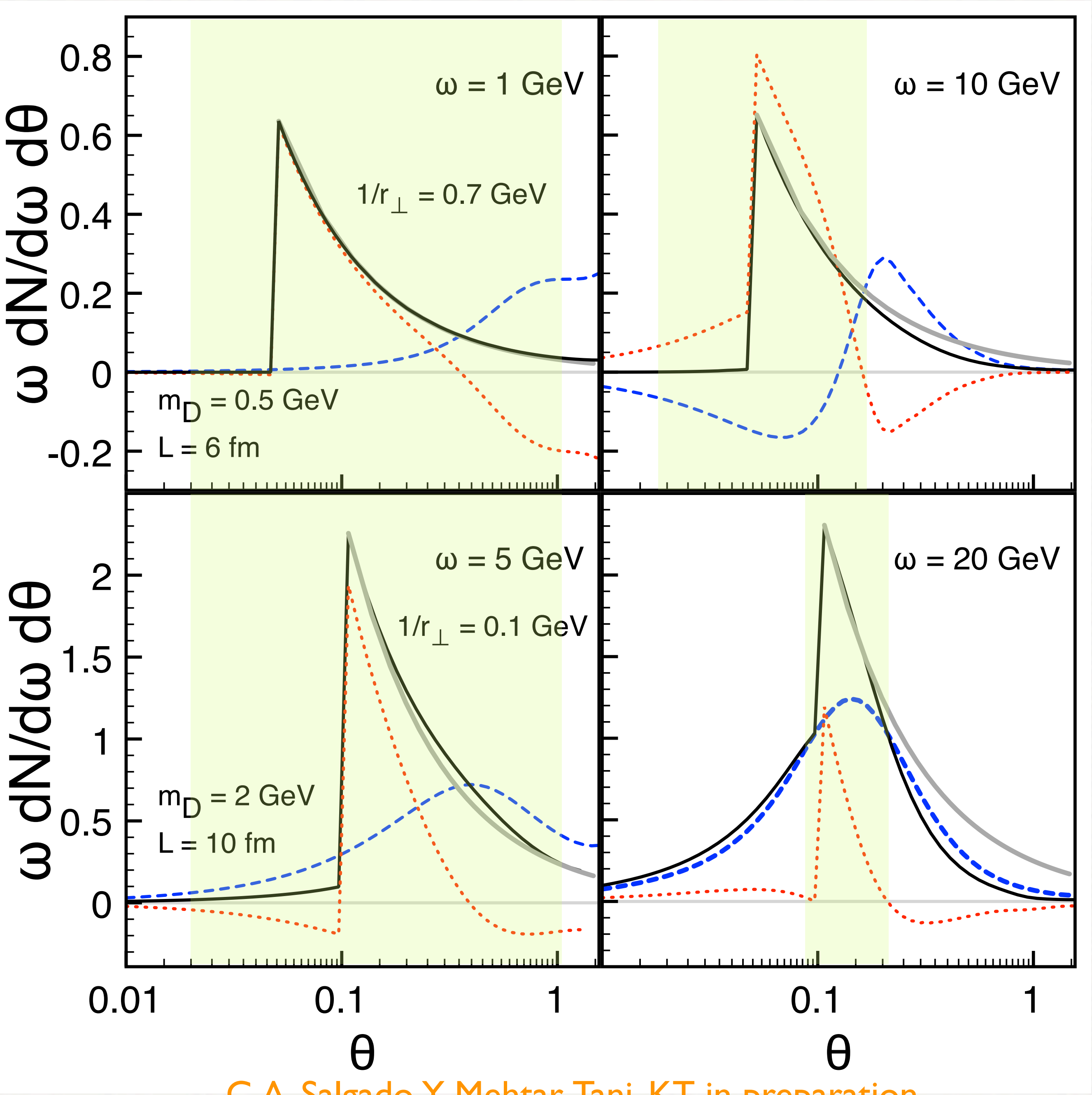
- independent: BDMPS/GLV
- novel interferences



ω = 1 GeV
1/r⊥ = 0.7 GeV
m_D = 0.5 GeV
L = 6 fm
ω = 10 GeV
ω = 5 GeV
1/r⊥ = 0.1 GeV
m_D = 2 GeV
L = 10 fm
ω = 20 GeV
ω dN/dω dθ
θ
0.8
0.6
0.4
0.2
0
-0.2
2
1.5
1
0.5
0.01
0.1
1
$\mathcal{R}_q^{\mathrm{med}}$
$\mathcal{J}_q^{\mathrm{med}}$
$1/\theta$



C.A. Salgado, Y. Mehtar-Tani, KT, in preparation



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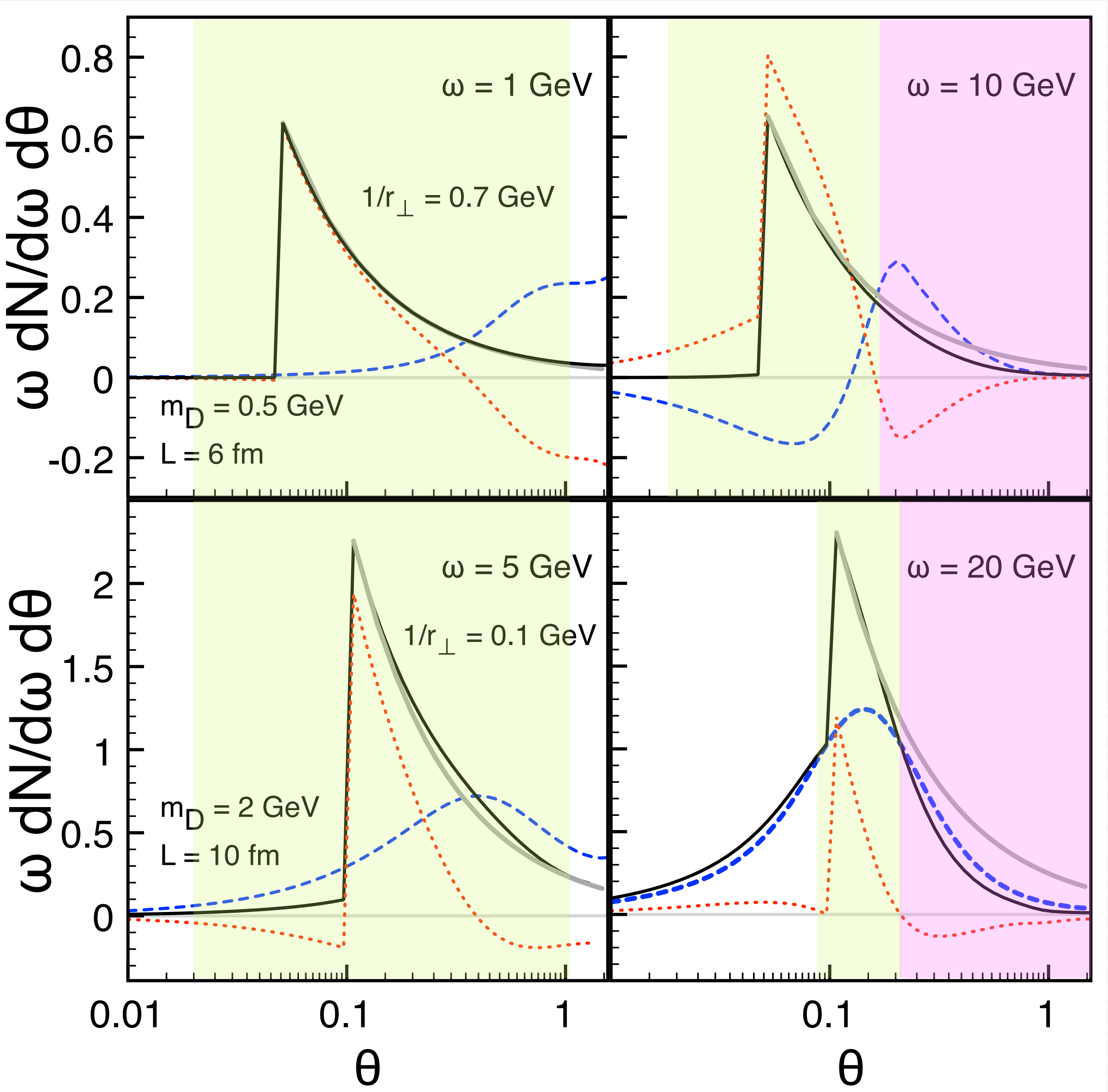
$\mathcal{R}_q^{\mathrm{med}}$ $\mathcal{J}_q^{\mathrm{med}}$

$1/\theta$

antiangular ordering



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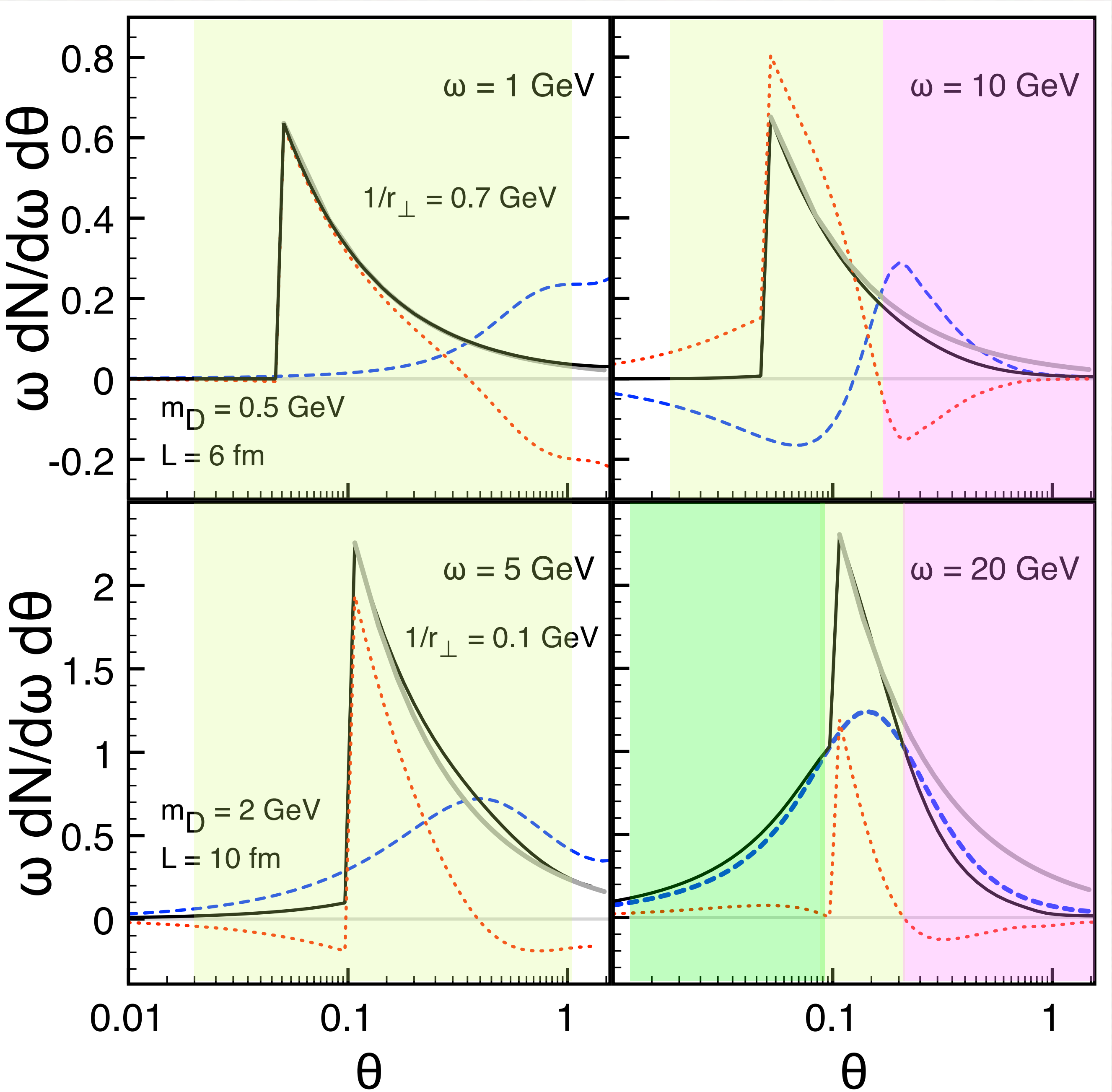
$\boxed{\mathcal{R}_q^{\text{med}}}$ $\boxed{\mathcal{J}_q^{\text{med}}}$

$\boxed{1/\theta}$

antiangular ordering

large angles



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

$1/\theta$

antiangular ordering

large angles

inside cone

C.A. Salgado, Y. Mehtar-Tani, KT, in preparation

LARGE ANGLE BEHAVIOR

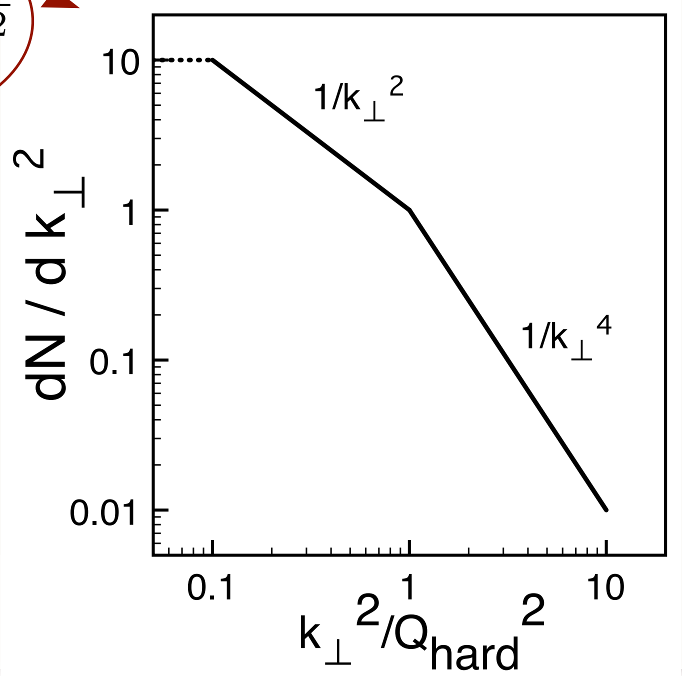
$$\omega \frac{dN^{\rm med}}{d^3k} = \frac{8\,\alpha_s C_F\,\hat{q}}{\pi} \int_{\mathcal{V}(\boldsymbol{q})} \int_0^{L^+} dx^+ \left[1 - \cos\left(\frac{\boldsymbol{\nu}+\bar{\boldsymbol{\nu}}}{2} \cdot \delta\boldsymbol{n}\, x^+\right)\right] \boxed{\boldsymbol{L}\cdot\bar{\boldsymbol{L}}}$$

$$\swarrow$$

$$\boxed{\boldsymbol{L}^2}$$

$$\omega \frac{dN^{\rm med}}{d^3k} = \frac{8\,\alpha_s C_F\,\hat{q} L^+}{\pi} \int_{\mathcal{V}(\boldsymbol{q})} \frac{\boldsymbol{q}^2}{\boldsymbol{k}^2\,(\boldsymbol{k}-\boldsymbol{q})^2}$$

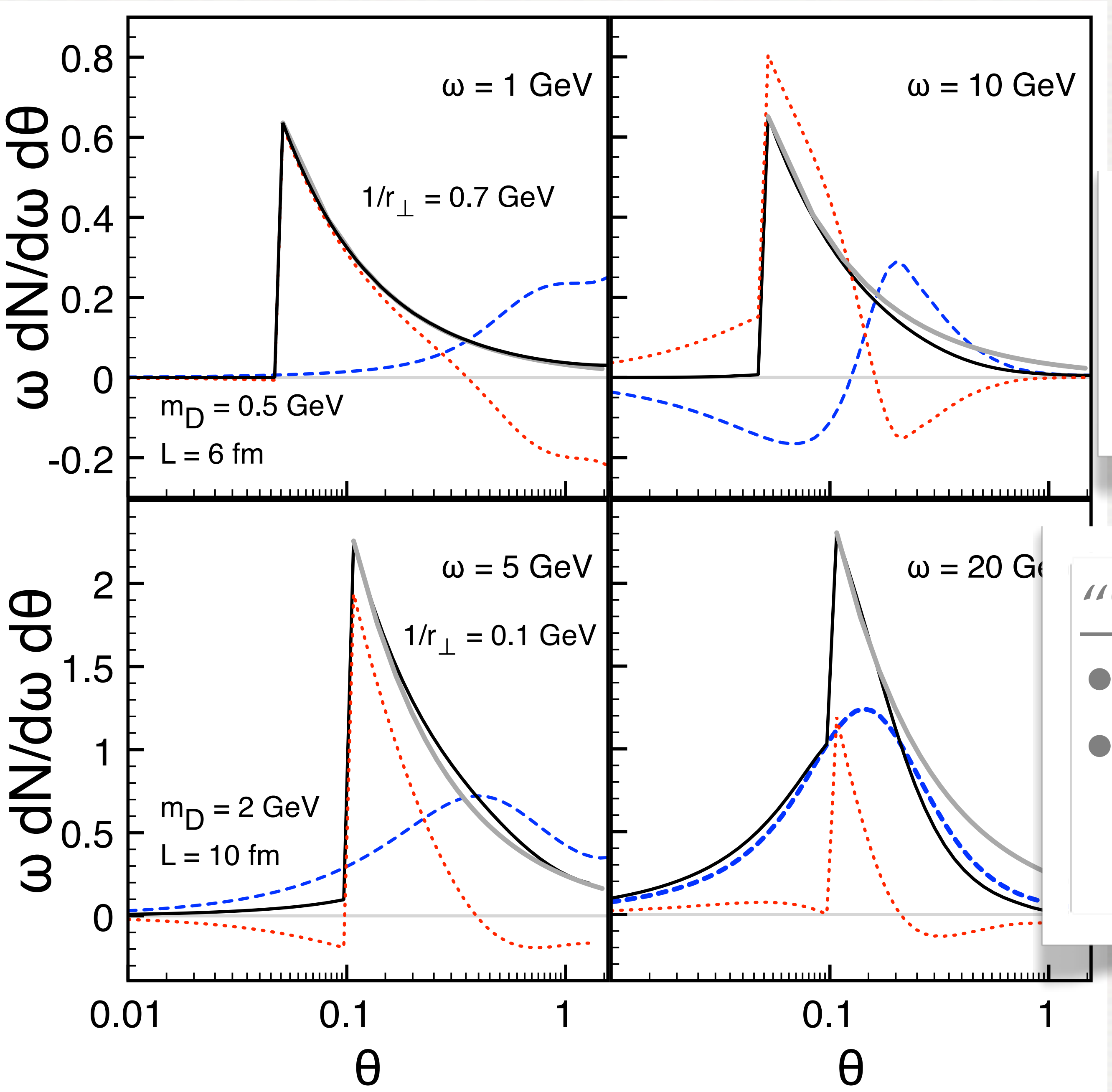
- dipole phase term (Lipatov)
- from antiangular ordering to Gunion-Bertsch drop
- valid for both regimes
    - cut-off is $Q_{hard} = \max(Q_s, r_\perp^{-1})$



INSIDE THE CONE

$$\omega \frac{dN^{\rm med}}{d^3k} = \frac{8\,\alpha_s C_F\,\hat{q}L^+}{\pi}\int_{\mathcal{V}(\boldsymbol{q})}\left(1-\frac{\sin\Omega_q L^+}{\Omega_q L^+}\right)\left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}-\frac{k^+\delta\boldsymbol{n}}{(k^+\delta\boldsymbol{n})^2}\right]\cdot\left[\frac{\boldsymbol{\nu}}{\boldsymbol{\nu}^2}-\frac{\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2}\right]$$

- $r_\perp^{-1} \gg m_D$
  - this implies that $\omega \gg \bar{\omega}_c$, spectrum is suppressed
  - only for hard gluons in the “dipole” regime
- $r_\perp^{-1} \ll m_D$
  - LPM phase is working
  - independent BDMPS/GLV spectrum close to the quark and antiquark
  - important in the “saturation” regime



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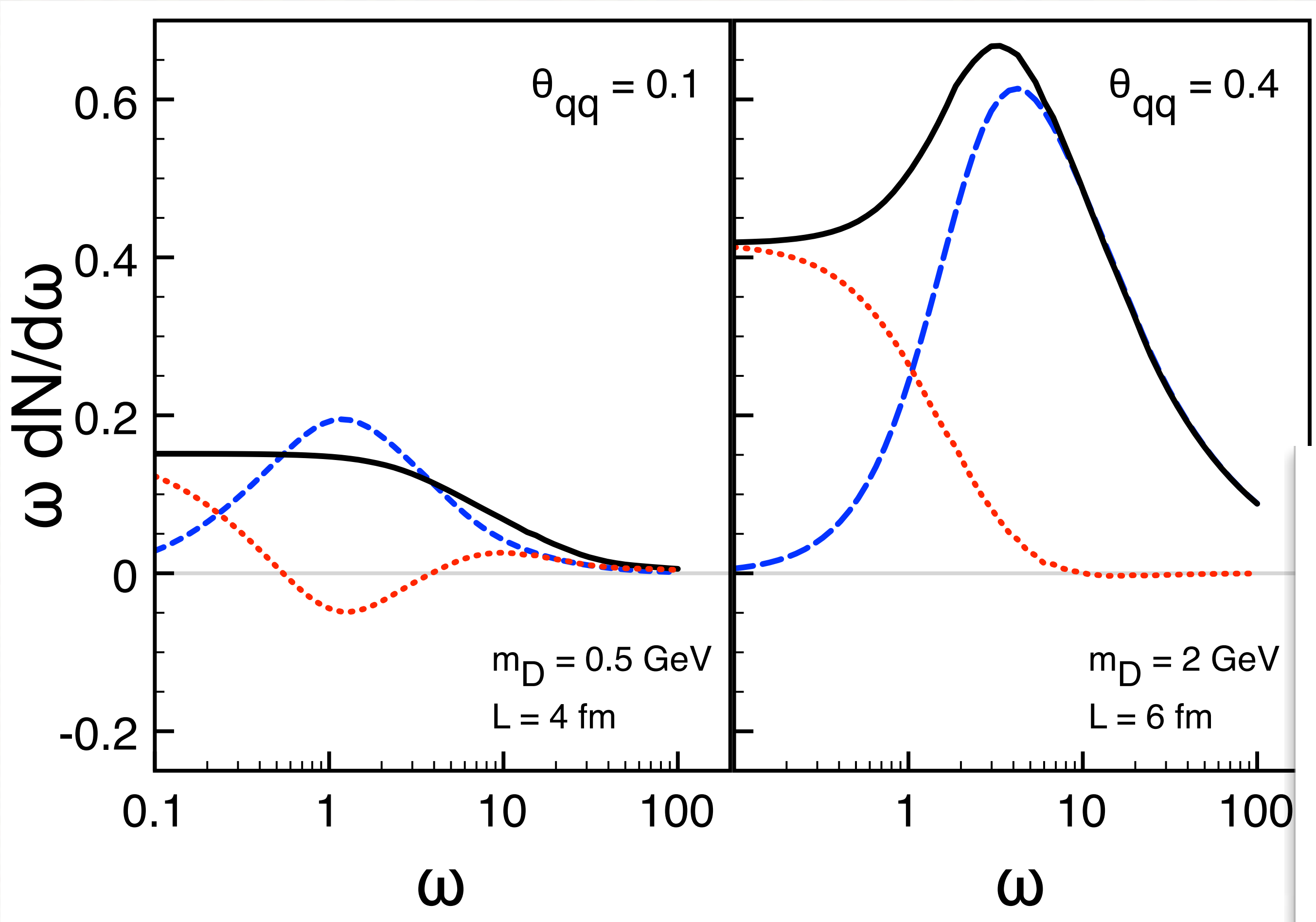
"Dipole" regime

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

"Saturation" regime

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



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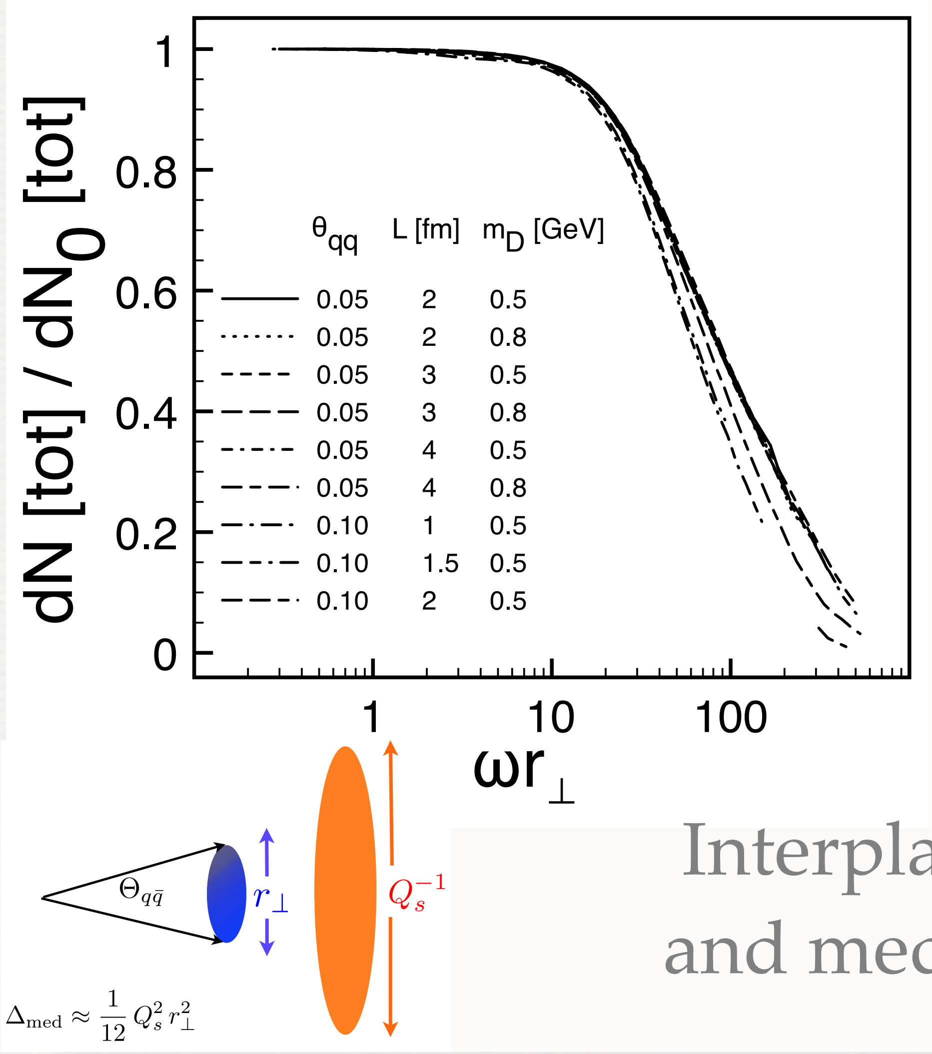
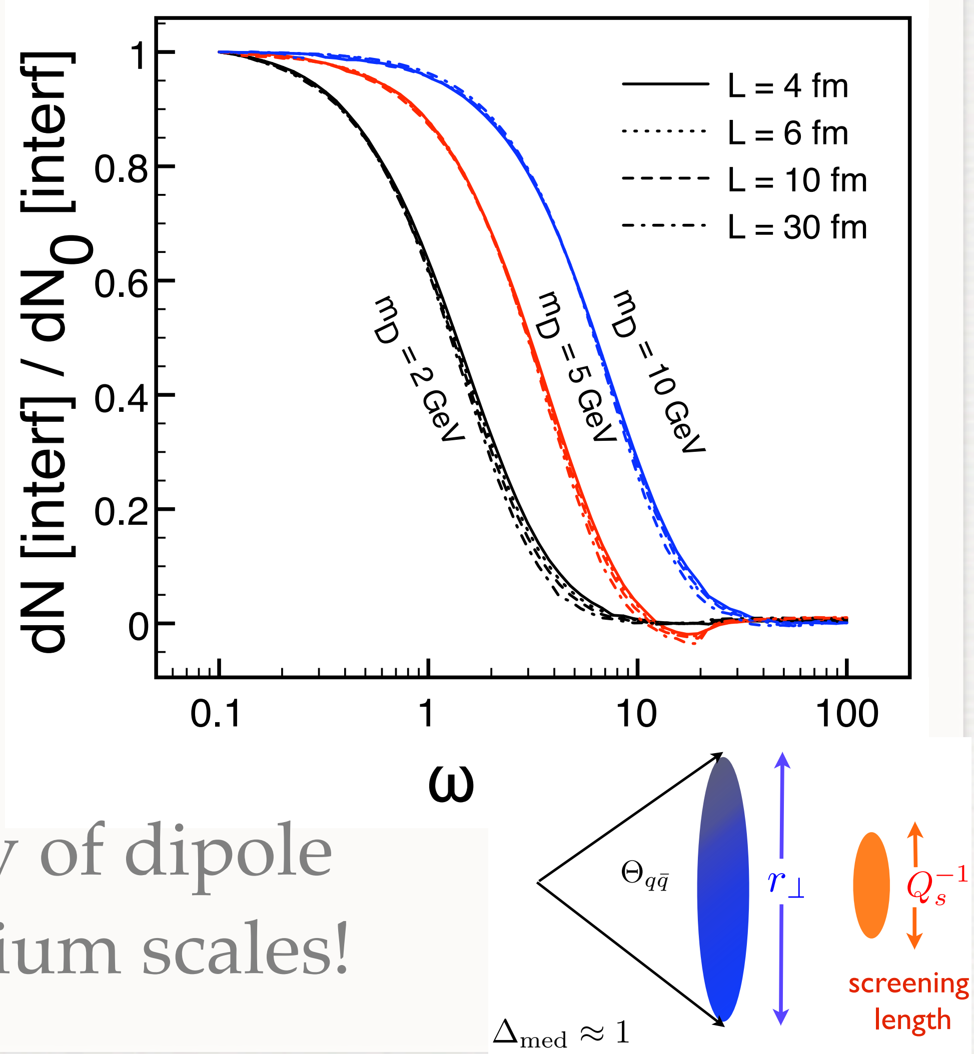
C.A. Salgado, Y. Mehtar-Tani, KT, in preparation

SCALING BEHAVIORS





Interplay of dipole and medium scales!

PROBABILISTIC INTERPRETATION

Incoherent limit (L→∞) $\hat{q}\int_{\mathcal{V}(\boldsymbol{q})} \frac{\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2} = \frac{\hat{q}}{2}\int_{\mathcal{V}(\boldsymbol{q})}\left(-\frac{1}{\boldsymbol{k}^2}+\frac{1}{(\boldsymbol{k}-\boldsymbol{q})^2}+\boldsymbol{L}^2\right)$

Inside the cone:

- same probabilistic picture as before
- conservation of probability

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$$\omega\frac{dN^{\rm med}}{d^3k} = \frac{8\,\alpha_s C_F\,\hat{q}}{\pi}\int_{\mathcal{V}(\boldsymbol{q})}\int_0^{L^+}dx^+\left[1-\cos\left(\frac{\boldsymbol{\nu}+\bar{\boldsymbol{\nu}}}{2}\cdot\delta\boldsymbol{n}\,x^+\right)\right]\boxed{\boldsymbol{L}\cdot\bar{\boldsymbol{L}}} \longrightarrow \boxed{\boldsymbol{L}^2}$$

Outside the cone:

- medium induces new radiation!
- only Gunion-Bertsch, no hard component
- because no corresponding vacuum radiation!

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