Onset of Jet decoherence in dense QCD media

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In collaboration with
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PRL 106 (2011) arXiv:1009.2965 [hep-ph]
arXiv:1102.4317 [hep-ph]
Y. M.-T. and K. Tywoniuk, arXiv: 1105.1346 [hep-ph]
Work in progress

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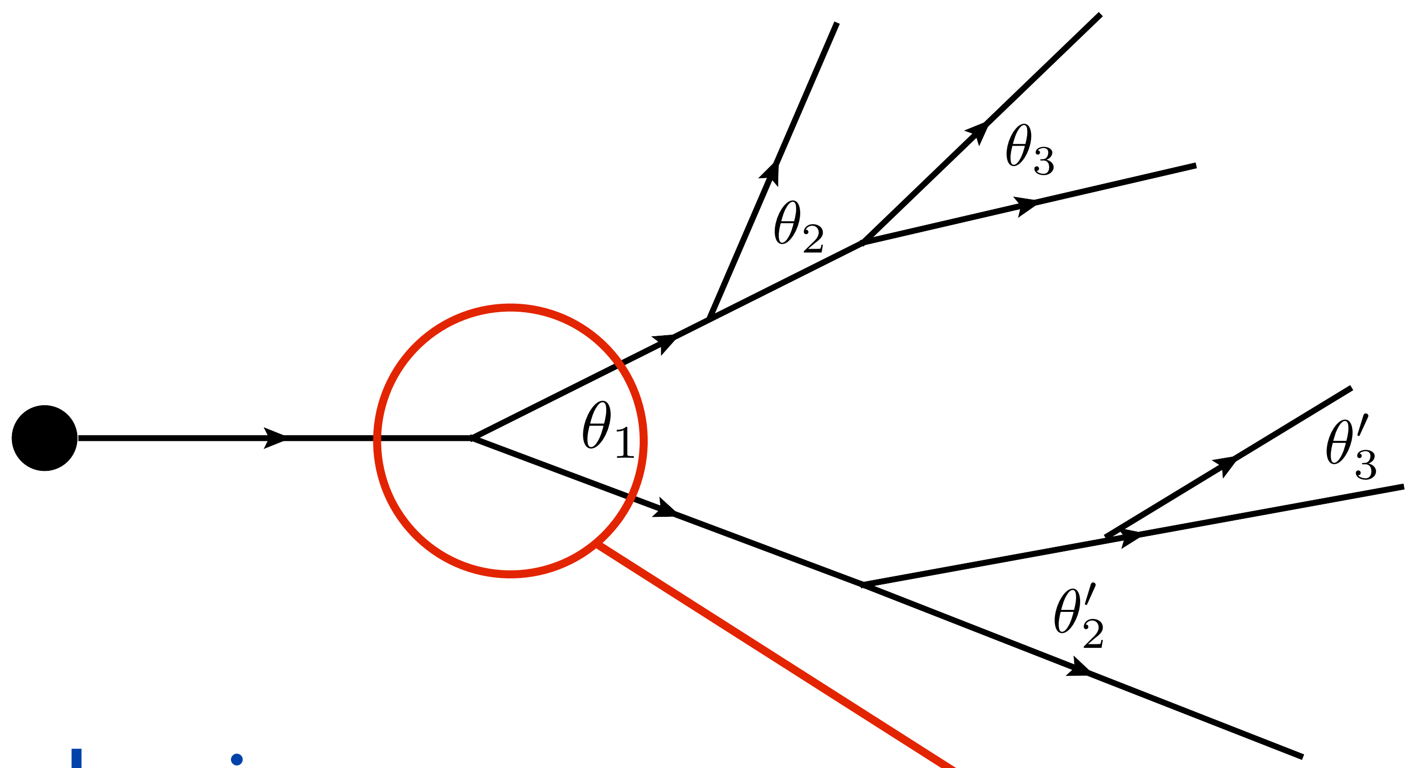
GDR PH-QCD meeting 2011
IPN Orsay

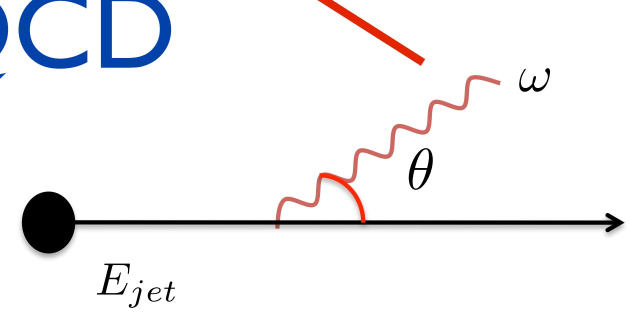
Motivation

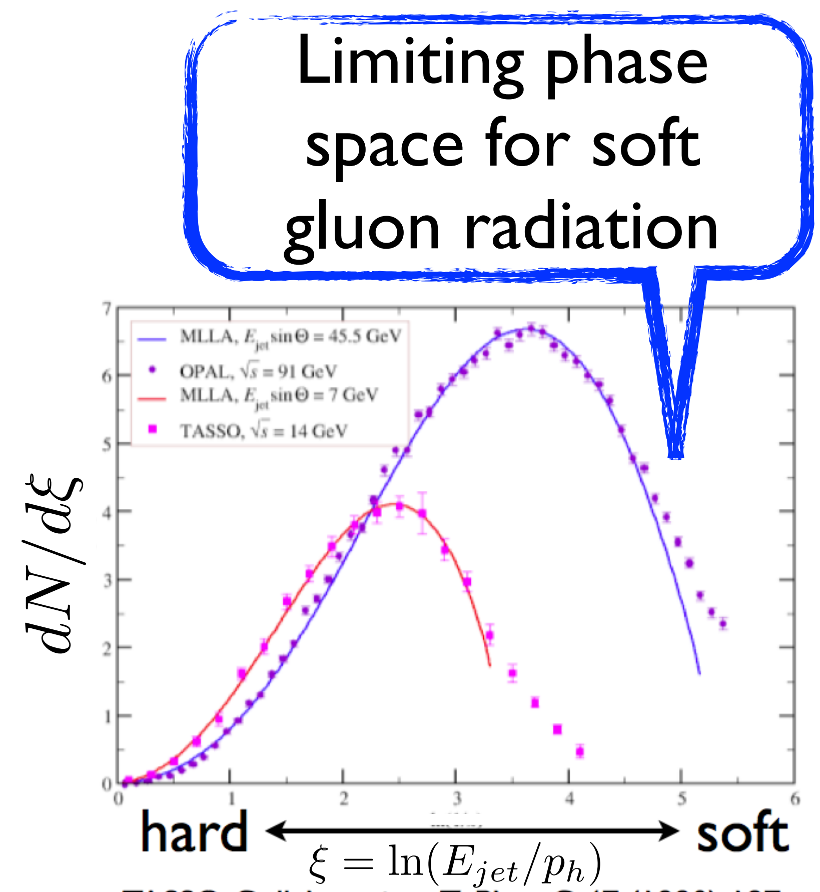
QCD coherence in Jets: Angular Ordering

MLLA: Basseto, Ciafaloni, Marchesini, Mueller (1982) Fadin (1983), Dokshitzer, Diakonov, Troian (1980)

$\theta'_3 < \theta'_2 < \theta_1$ $\qquad$ $\theta_3 < \theta_2 < \theta_1$







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

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

- Markovian process
- «Building block for QCD evolution» (MC)

The "Hump-backed" plateau

$$dN \propto \alpha_S \frac{d\omega}{\omega}\frac{d\theta}{\theta} \rightarrow \alpha_S \ln^2 E_{jet}$$

Motivation

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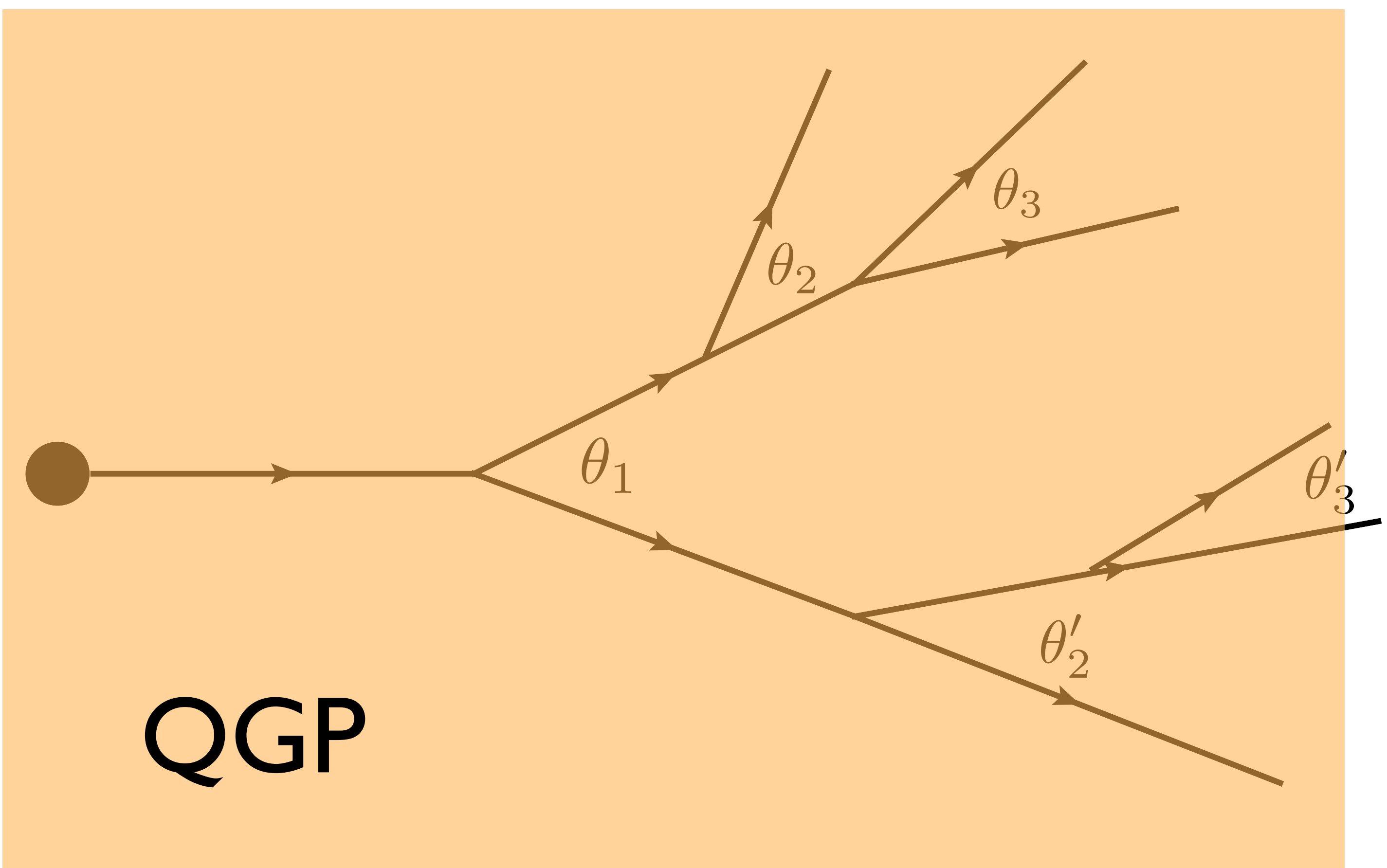
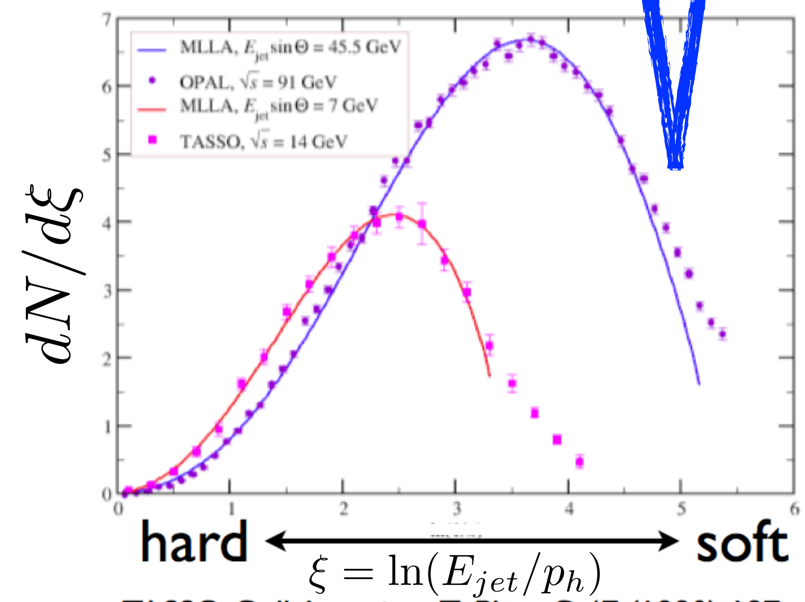


Limiting phase space for soft gluon radiation



TASSO Collaboration, Z. Phys. C 47 (1990) 187
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The “Hump-backed” plateau

Q: How does the QGP alter QCD coherence in a jet?

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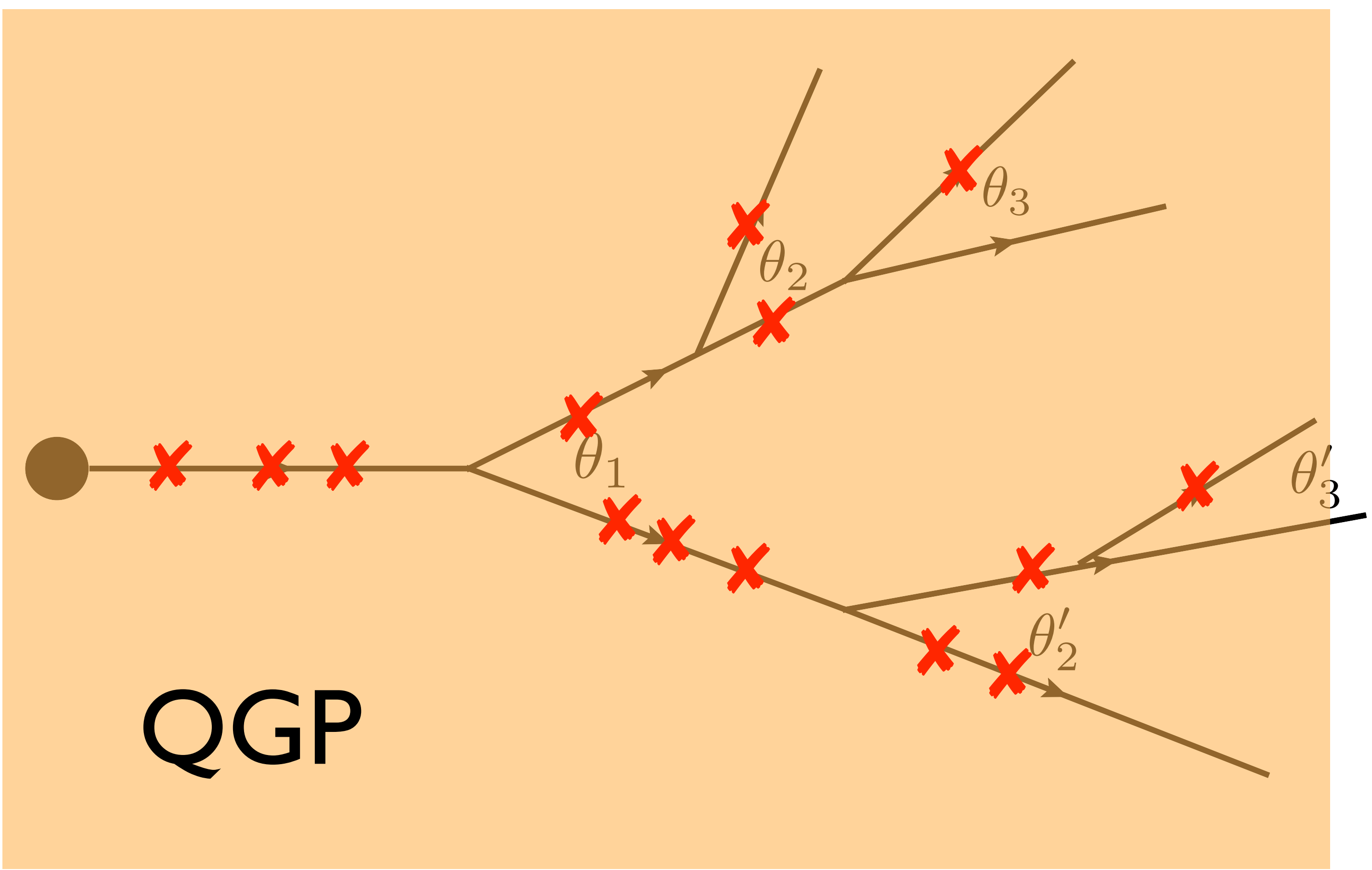

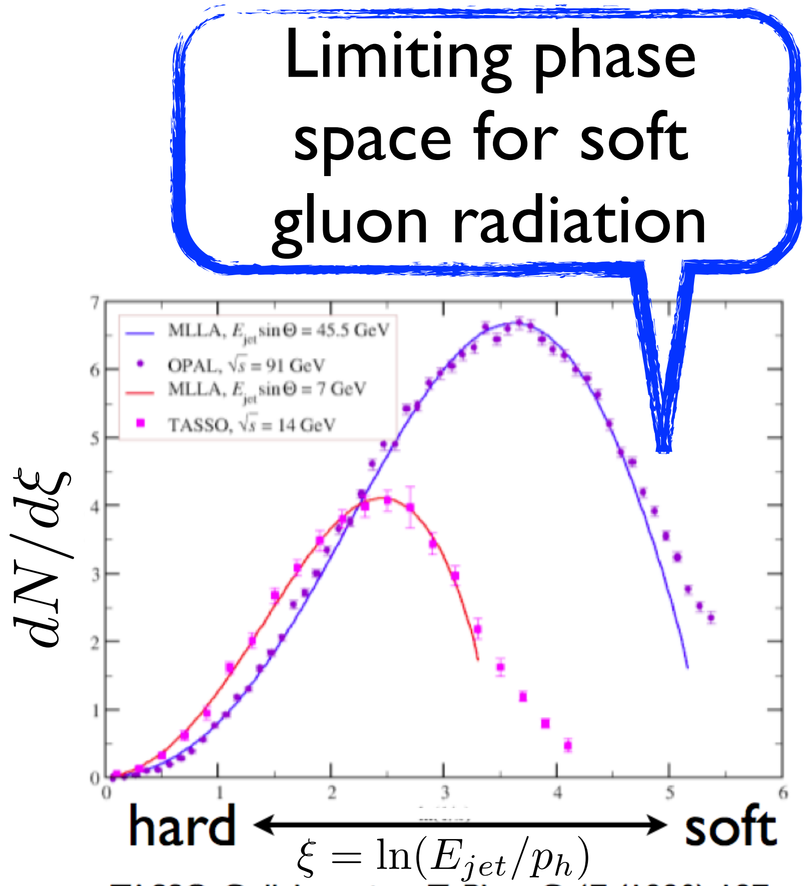

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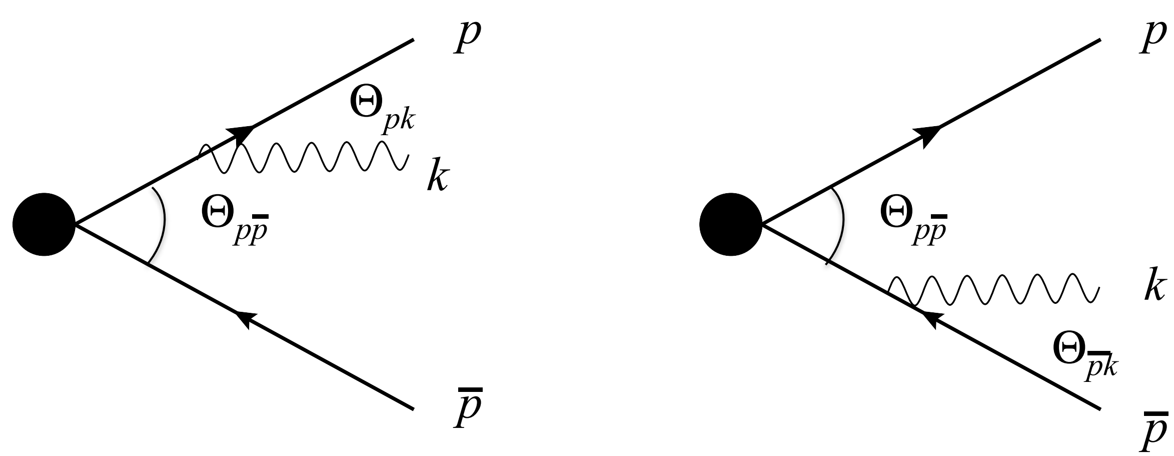
The "Hump-backed" plateau

Q: How does the QGP alter QCD coherence in a jet?

Antenna in vacuum
(Building block of QCD evolution)

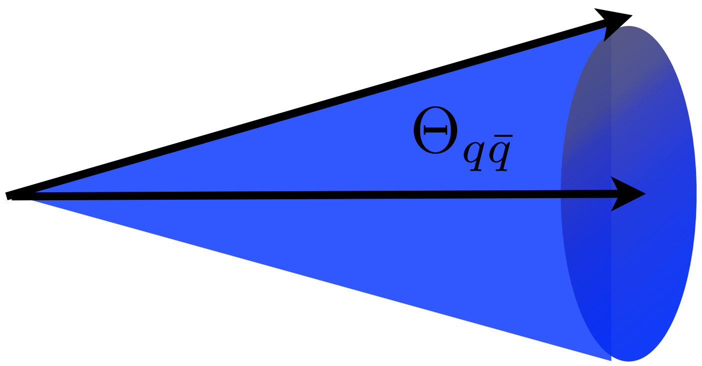


$$(2\pi)^2\,\omega\frac{dN^{\rm vac}_{\gamma^*}}{d^3k} = \frac{\alpha_s C_F}{\omega^2}\left(\mathcal{R}_q + \mathcal{R}_{\bar q} - 2\,\mathcal{J}\right),$$

Destructive interferences

Antenna in vacuum
(Building block of QCD evolution)

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



Angular ordering in vacuum

- Radiation confined inside the cone
- Why?

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

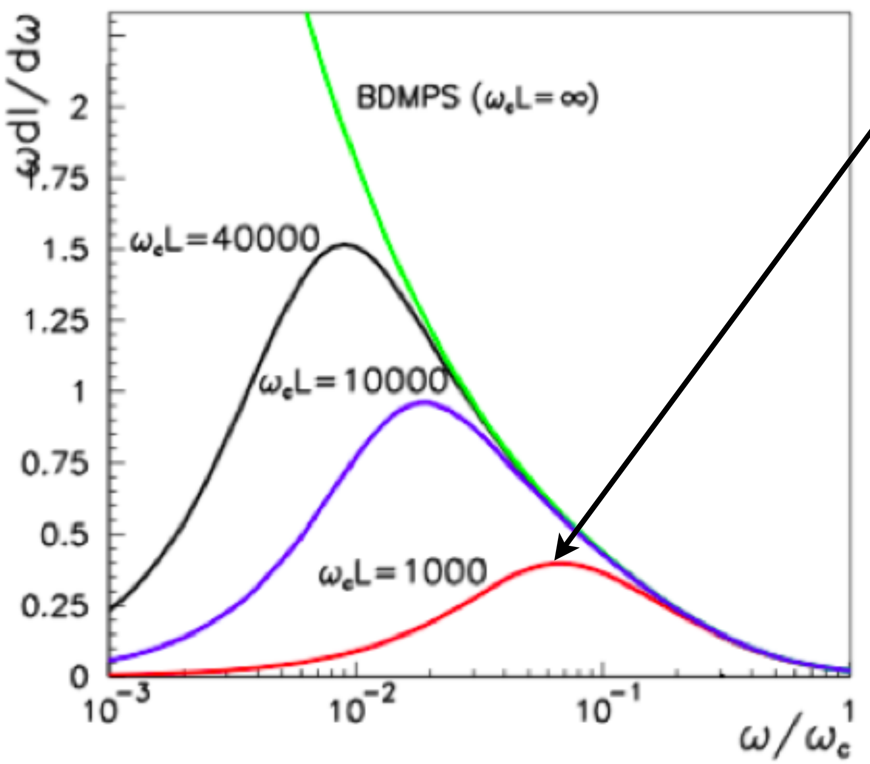
Simpler Q: How Does the QGP alter the antenna emission pattern?

In medium: single emitter (BDMPS-Z)

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

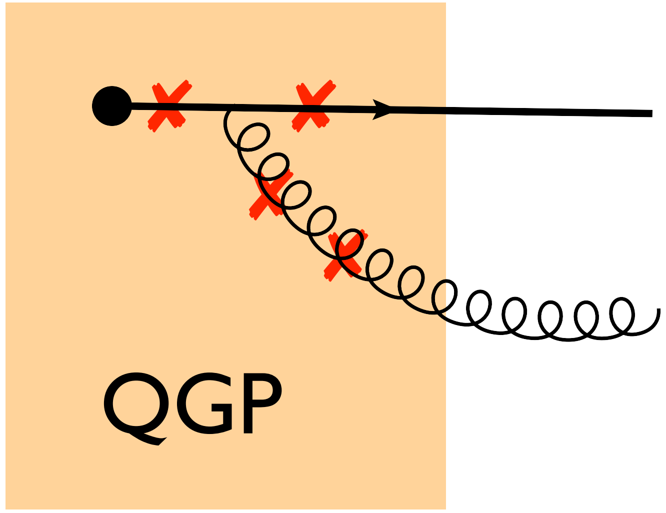
- Energy loss: $\Delta E = \alpha_s C_R \omega_c = \alpha_s C_R \hat{q} L^2$
- Broadening: $\langle k_\perp^2 \rangle = \omega_c / L$

$$Q_s^2 = \hat{q}\, L$$



C. A. Salgado, U. A. Wiedemann (2003)

$$\omega \frac{dI}{d\omega} \propto \sqrt{\frac{\omega_c}{\omega}}$$

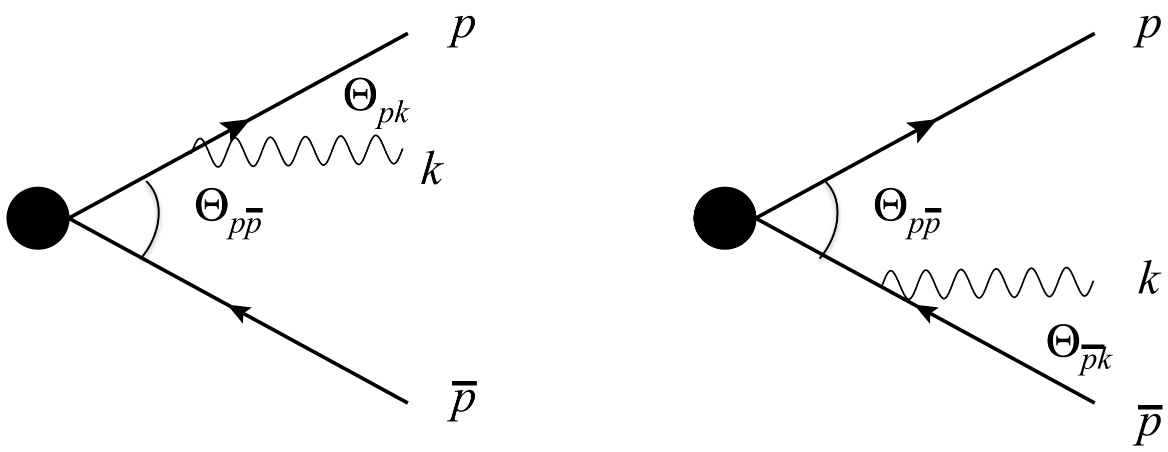


Medium induced spectrum:
Gluon interacts → kt-broadening
No soft/collinear divergence

- No vacuum-like medium-induced radiation
- Need two emitters to see QCD coherence and build-up in-medium jet evolution

Antenna in medium

Y. M.-T., C. A. Salgado and K. Tywoniuk, PRL 106 (2011) arXiv:1009.2965 [hep-ph]



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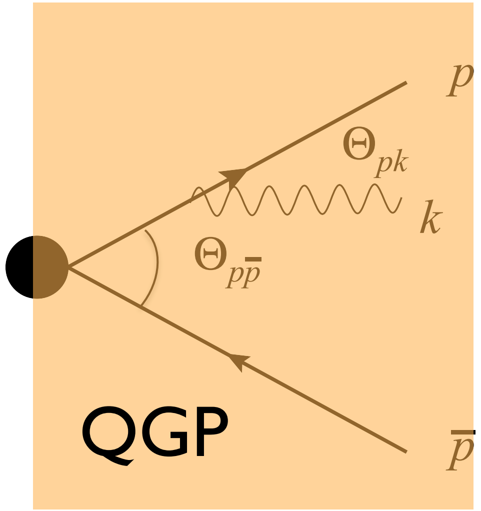

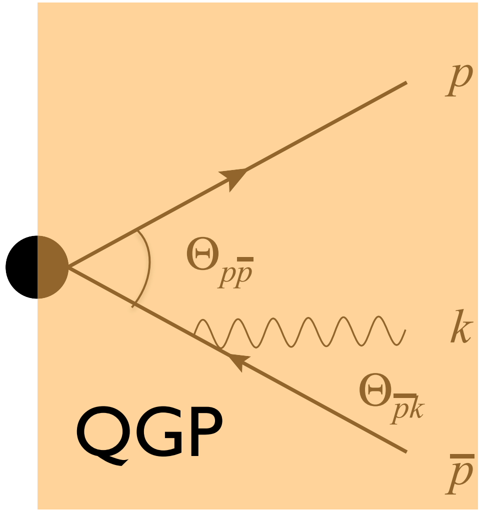

Let's switch on the medium

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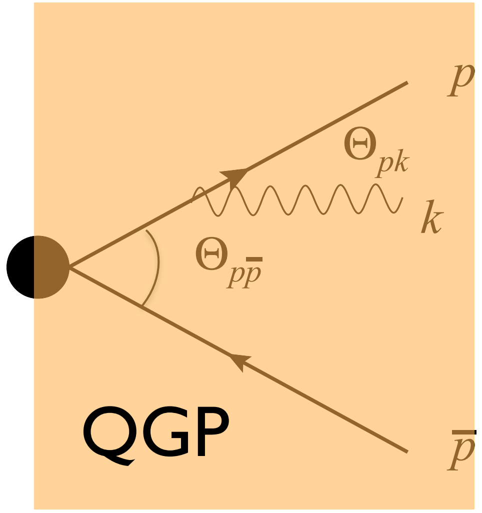
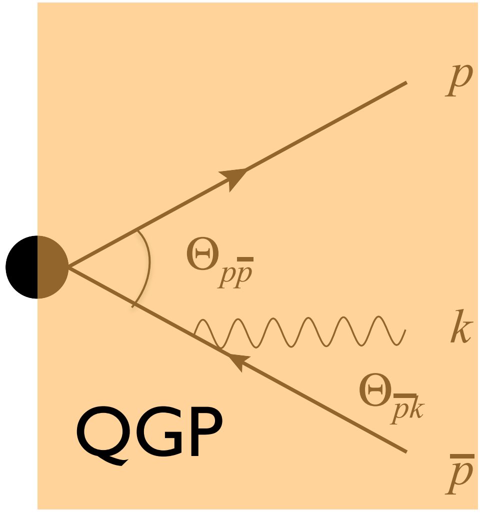
Y. M.-T., C. A. Salgado and K. Tywoniuk, PRL 106 (2011) arXiv:1009.2965 [hep-ph]





Let's switch on the medium

- Small angle approximation $\theta\,,\,\theta_{q\bar{q}} \ll 1$
- The medium is modeled as a Classical background field

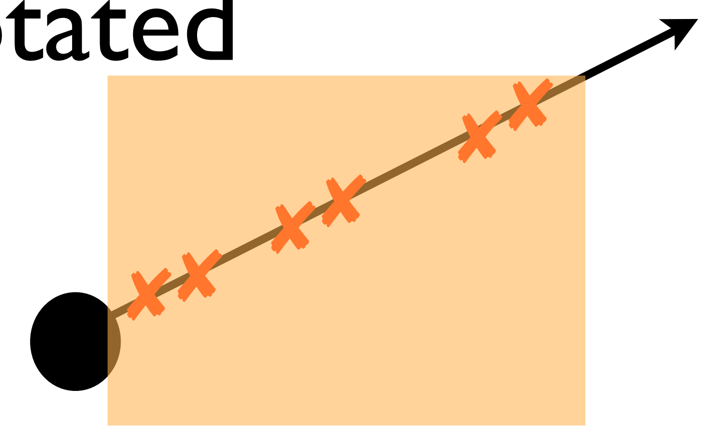
$$A^-_{\rm med}(x^+, x_\perp) = -\frac{1}{\partial^2_\perp}\rho_{\rm med}(x^+, x_\perp) \quad , \quad A^i_{\rm med} = A^+_{\rm med} = 0$$

Classical Yang Mills

$$[D_\mu, F^{\mu\nu}] = J^\nu \quad , \quad [D_\mu, J^\mu] = 0 \qquad\qquad J \equiv J_q + J_{\bar{q}}$$

The eikonal current gets simply color rotated

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



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

Multiple scattering of the quarks (Unitarity implemented)

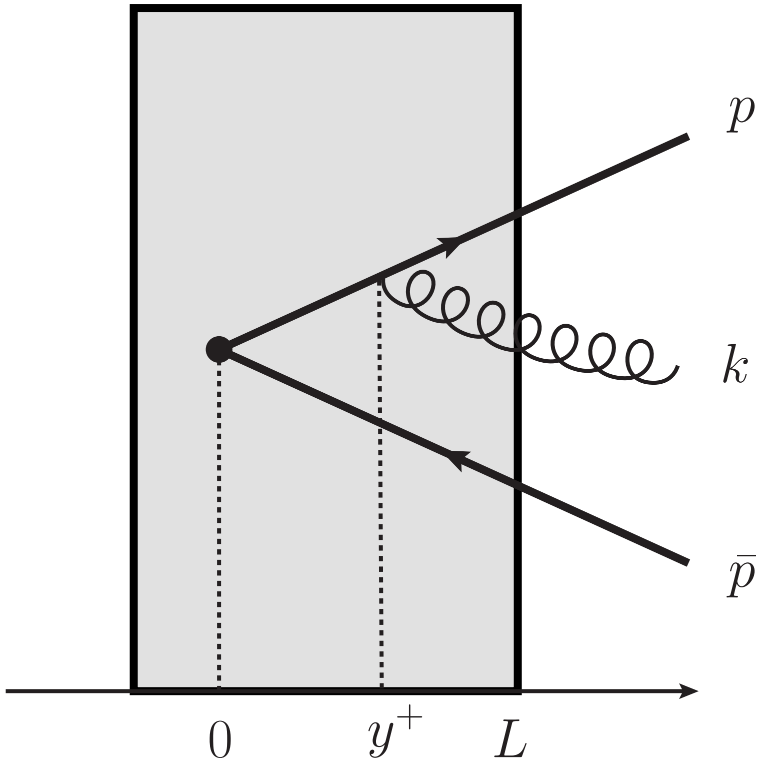
Classical Yang Mills

Reduction formula

$$\mathcal{M}^a_\lambda(\vec{k}) = \lim_{k^2 \to 0} -k^2 A^a_\mu(k)\epsilon^\mu_\lambda(\vec{k})$$

or

$$\mathcal{M}^a_\lambda(\vec{k}) = \int\limits_{x^+=+\infty} dx^- d^2\boldsymbol{x}\, e^{ik\cdot x}\, 2\partial^+_x \boldsymbol{A}^a(x)\cdot \boldsymbol{\epsilon}_\lambda(\vec{k})$$



Linear response of the medium (LC-gauge)

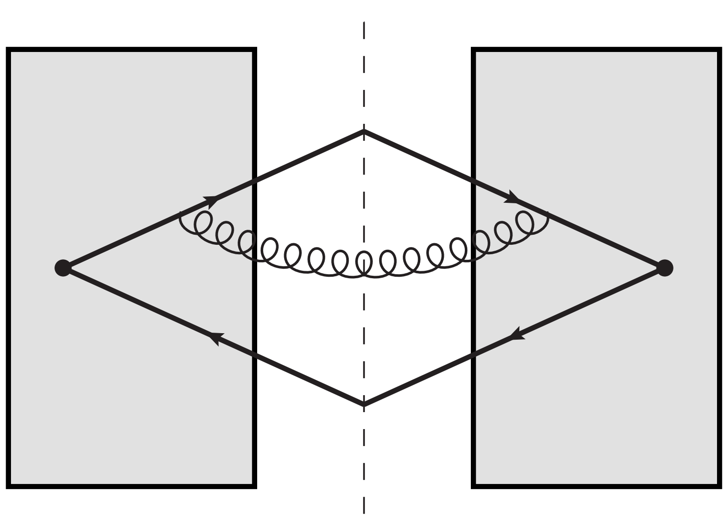
$$\Box A^i - 2ig\left[A^-_{\text{med}}, \partial^+ A^i\right] = -\frac{\partial^i}{\partial^+}J^+ + J^i$$

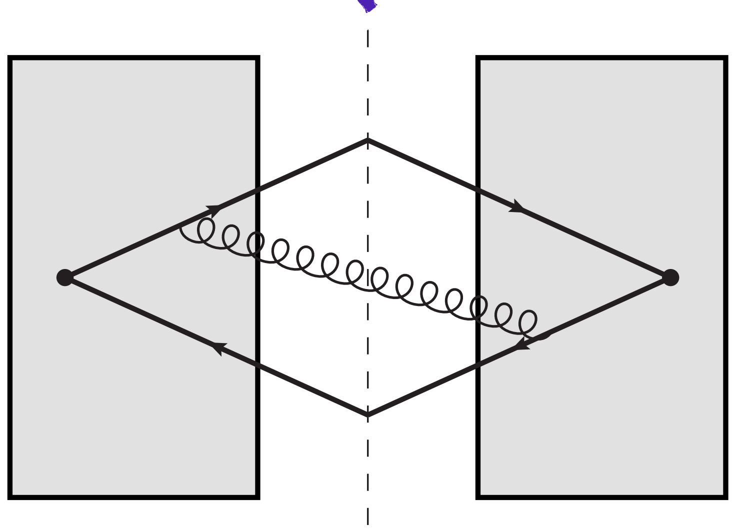
F. Gelis, Y. M.-T. (2005), Y. M.-T (2007)

Classical Yang Mills

$$dN = \frac{\alpha_s}{(2\pi)^2}\left[C_F \mathcal{R}_{\rm sing} + C_A\, \mathcal{J}\right] \frac{d^3k}{(k^+)^3}$$

$$\mathcal{R}_{\rm sing} = \mathcal{R}_q + \mathcal{R}_{\bar{q}} - 2\,\mathcal{J}$$





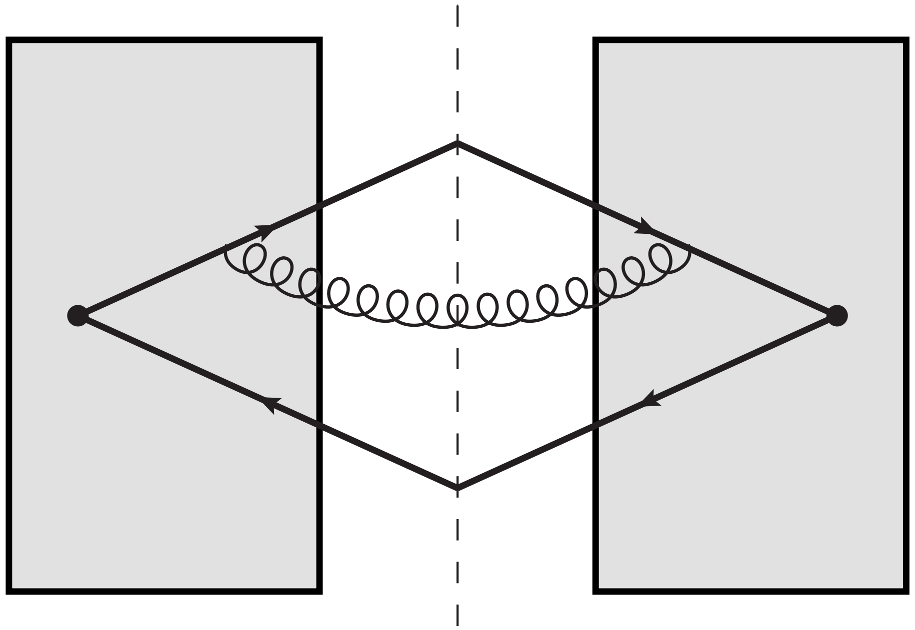
Classical Yang Mills

Independent emission off the quark (BDMPS-Z spectrum)

$$\mathcal{R}_q = 2\,\mathrm{Re}\left\{\int_0^\infty dy'^+ \int_0^{y'^+} dy^+ \int d^2\boldsymbol{z}\, \exp\left[-i\boldsymbol{\kappa}\cdot\boldsymbol{z} - \frac{1}{2}\int_{y'^+}^\infty d\xi\, n(\xi)\sigma(\boldsymbol{z})\right] \times \boldsymbol{\partial}_y \cdot \boldsymbol{\partial}_z \mathcal{K}(y'^+, \boldsymbol{z}\,;\, y^+, \boldsymbol{y}=\boldsymbol{0}\,|k^+)\right\},$$

$$\boldsymbol{\kappa} = \boldsymbol{k} - x\boldsymbol{p}$$

$$x = k^+/p^+$$



Classical Yang Mills

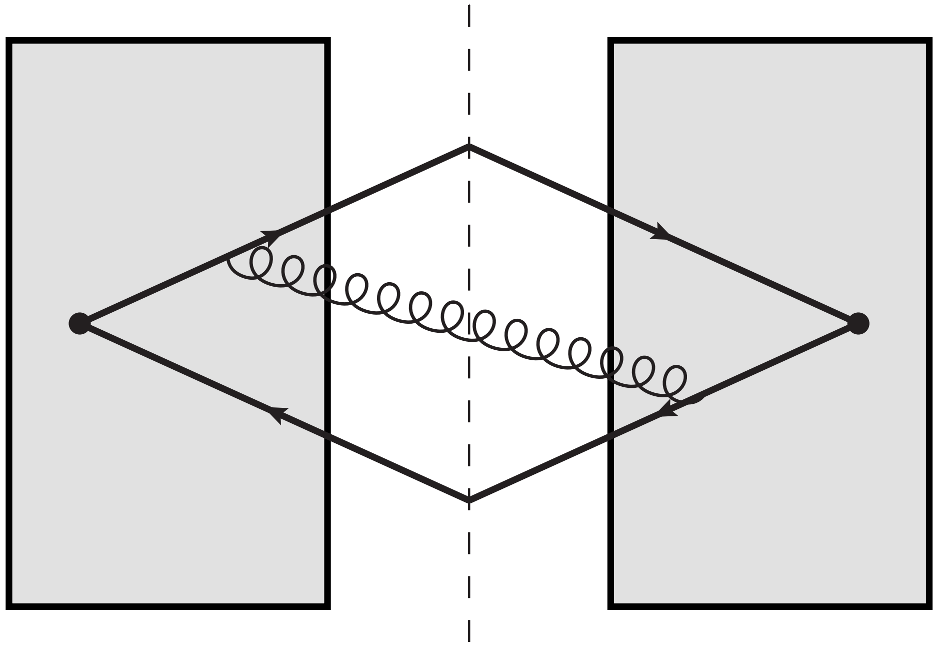
Interferences

Y. M.-T. and K. Tywoniuk 1105.1346 [hep-ph]
J. Casalderrey-Solana and E. Iancu arXiv:1105.1760 (JHEP 2011)

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

$$\boldsymbol{\kappa} = \boldsymbol{k} - x\boldsymbol{p} \qquad x = k^+/p^+$$

$$|\delta\boldsymbol{n}| \equiv \sin\theta_{q\bar{q}} \sim \theta_{q\bar{q}}$$



Decoherence parameter

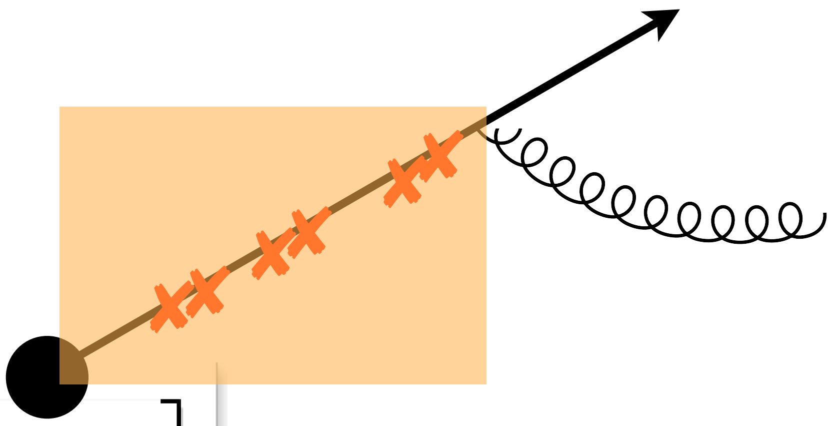
$$\frac{1}{N_c^2-1}\langle \mathbf{Tr}\, U_p(y^+,0)U^\dagger_{\bar{p}}(y^+,0)\rangle = 1-\Delta_{\rm med}(y^+,0)$$

Leading Log (ω→ 0)

The amplitude in the soft limit (no gluon-medium interaction)

$$\boldsymbol{\kappa} = \boldsymbol{k} - x\boldsymbol{p}$$

$$x = k^+/p^+$$



$$\mathcal{M}_\lambda(k) = -ig\left[\frac{\boldsymbol{\kappa}\cdot\boldsymbol{\epsilon}_\lambda}{x\,(p\cdot k)}\,U_p(L,0)\;Q_q + \frac{\bar{\boldsymbol{\kappa}}\cdot\boldsymbol{\epsilon}_\lambda}{\bar{x}\,(\bar{p}\cdot k)}\,U_{\bar{p}}(L,0)\;Q_{\bar{q}}\right]$$

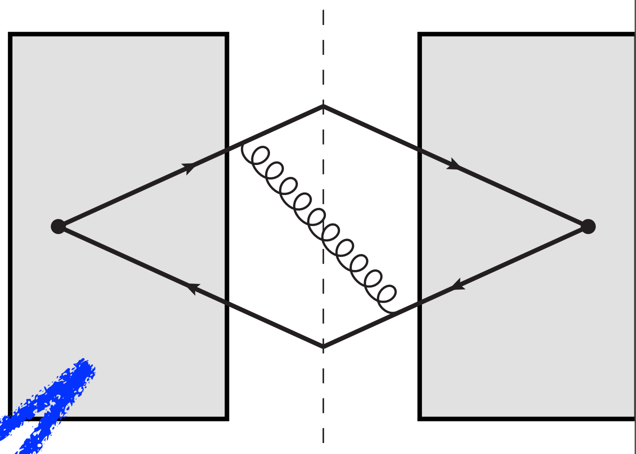
$$\mathcal{R}_q \equiv \frac{g^2 C_F}{x(p\cdot k)} \approx \frac{4g^2 C_F}{\omega^2\,\theta_{pk}^2}$$

Medium effects cancel out
$(UU^\dagger = 1)$
No soft-div in BDMPS-Z spectrum

Interferences lead to medium-induced soft-divergence

$$\mathcal{J} \equiv \frac{g^2 C_F}{N_c^2 - 1}\langle \mathbf{Tr}\, U_q(L,0)U_{\bar{q}}^\dagger(L,0)\rangle \frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{x\bar{x}\,(p\cdot k)(\bar{p}\cdot k)}$$

Leading Log (ω→ 0)

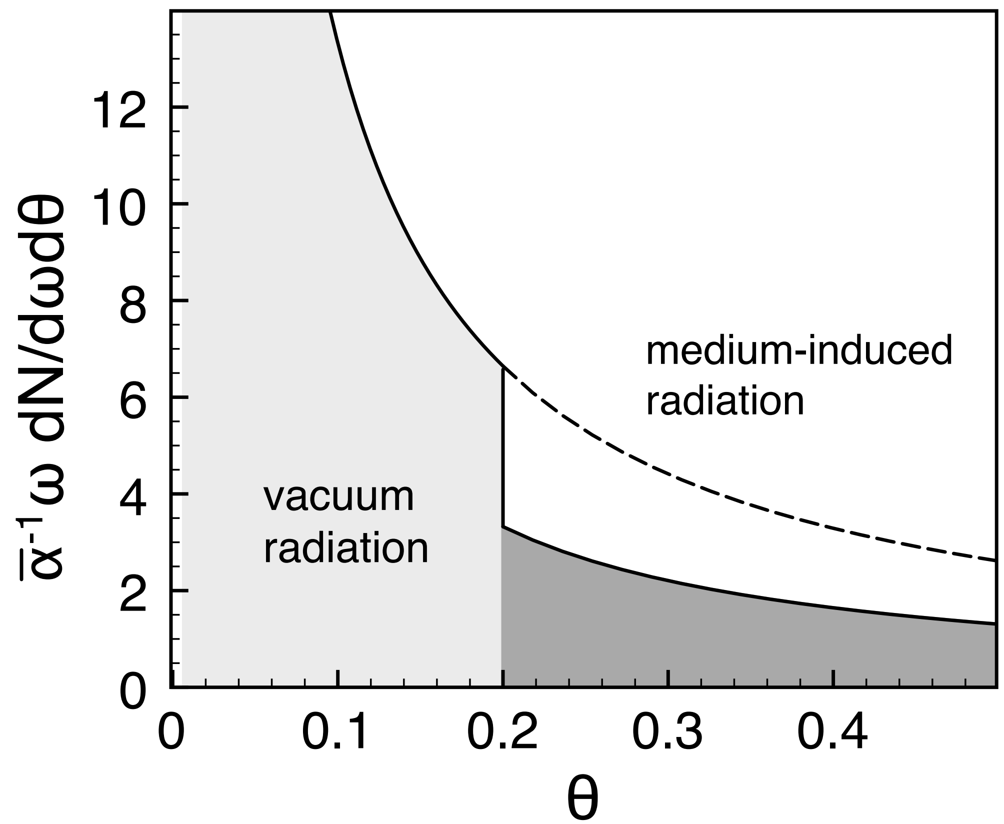


soft-gluon radiation off an antenna in a singlet state

$$(2\pi)^2\,\omega\frac{dN^{\rm tot}_{\gamma^*}}{d^3k} = \frac{\alpha_s C_F}{\omega^2}\left[\mathcal{R}_q^{\rm vac} + \mathcal{R}_{\bar q}^{\rm vac} - 2(1-\Delta_{\rm med})\mathcal{J}^{\rm vac}\right]$$

The decoherence parameter

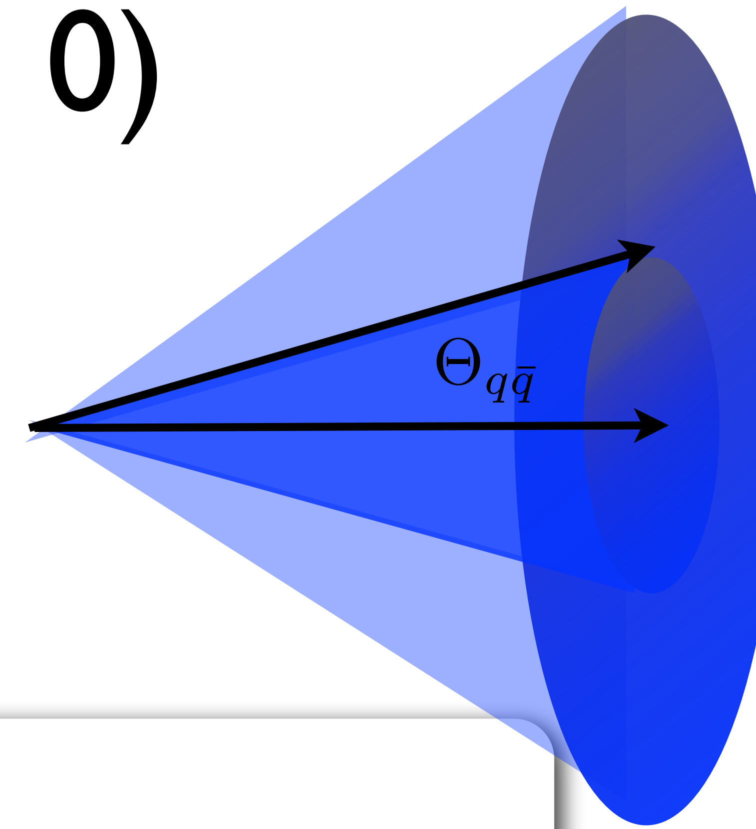
$$\Delta_{\rm med} = 1 - \frac{1}{N_c^2-1}\langle \mathbf{Tr}\, U_p(L,0)U^\dagger_{\bar p}(L,0)\rangle$$



Leading Log (ω→ 0)

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

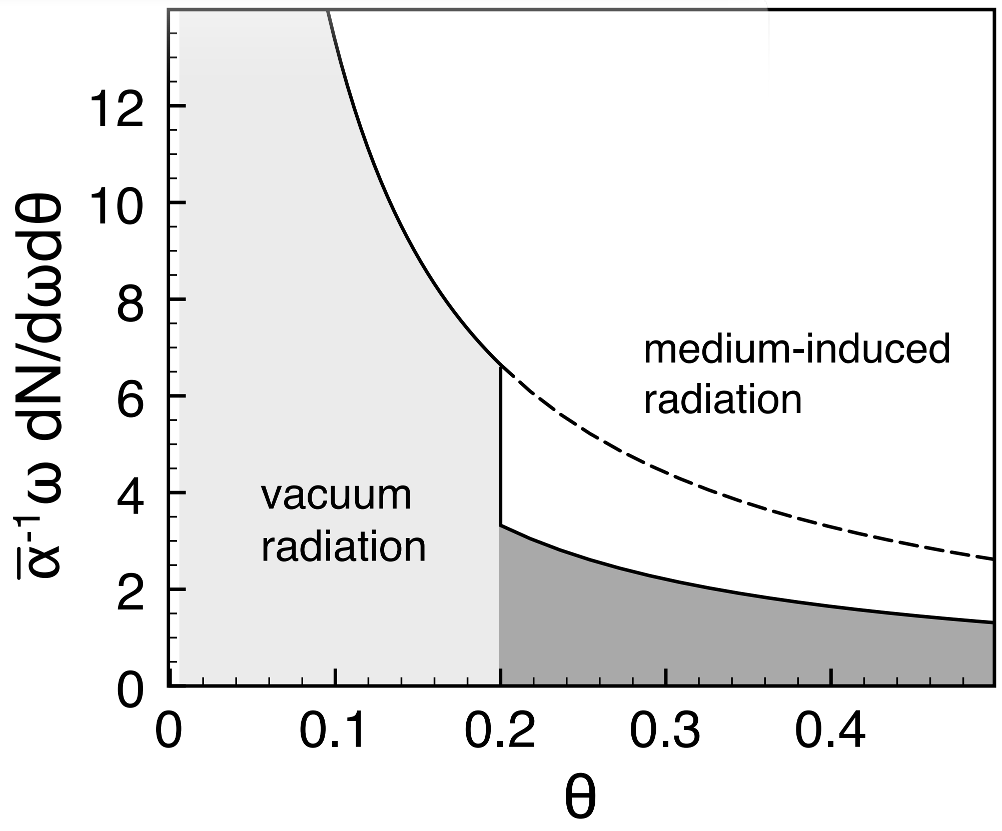
$\Delta_{\rm med} \to 1$ (Decoherence)



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

Total decoherence in opaque media

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



Memory loss

Antenna in the octet representation (gluon): additional out-of-cone radiation off the total charge of the pair

$$(2\pi)^2\,\omega\frac{dN^{\rm tot}_{g^*}}{d^3k} = (2\pi)^2\,\omega\frac{dN^{\rm tot}_{\gamma^*}}{d^3k} + \frac{\alpha_s C_A}{\omega^2}(1-\Delta_{\rm med})\,\mathcal{J}$$

In the opaque limit: $\Delta_{\rm med} \to 1$

$$dN^{\rm tot}_{g^*}\Big|_{\rm opaque} = dN^{\rm tot}_{\gamma^*}\Big|_{\rm opaque}$$

Emission off the total charge of the pair is suppressed

Decoherence a high gluon energies

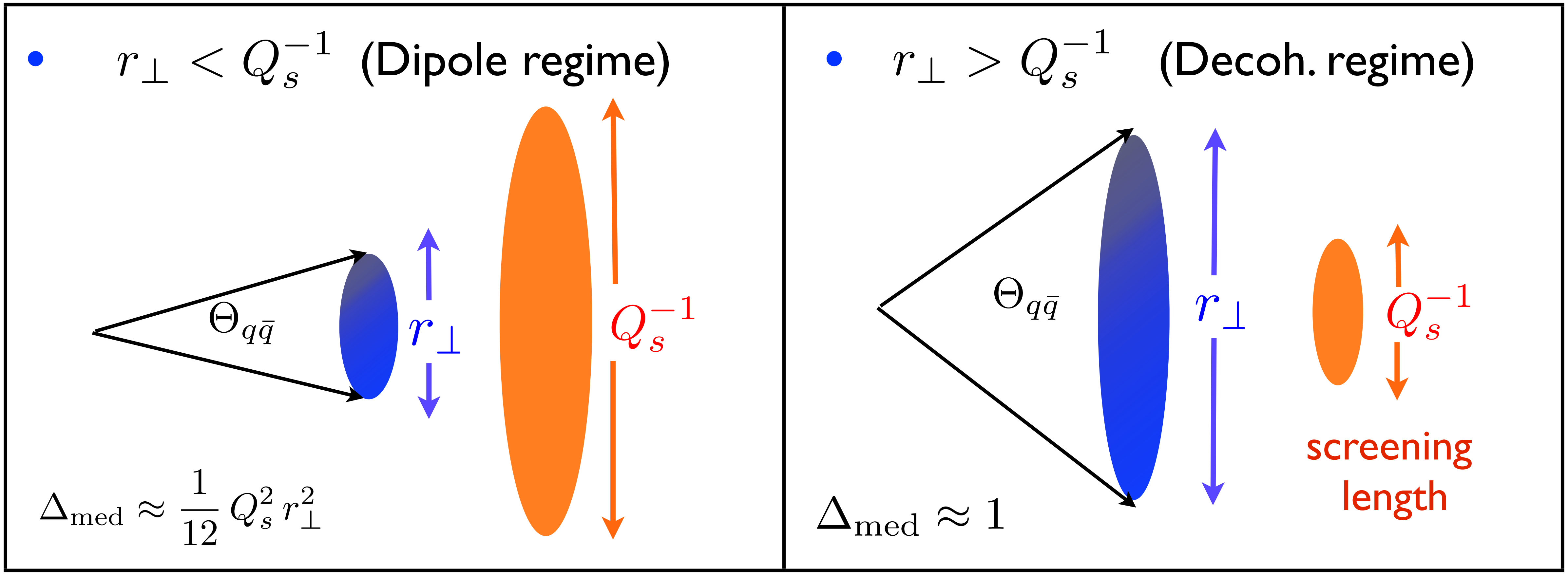
(A two scale problem)

- The decoherence parameter

$$Q_s^2 = \hat{q}\, L$$

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

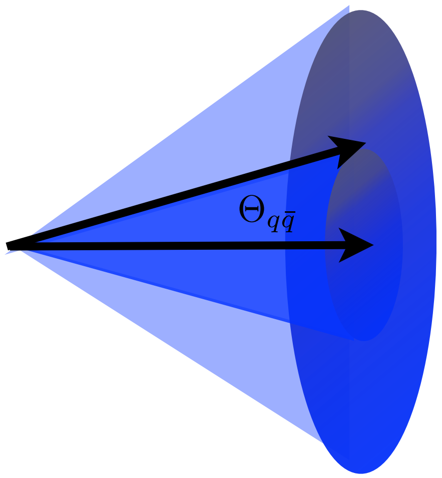
$$r_\perp = \theta_{q\bar{q}}\, L$$



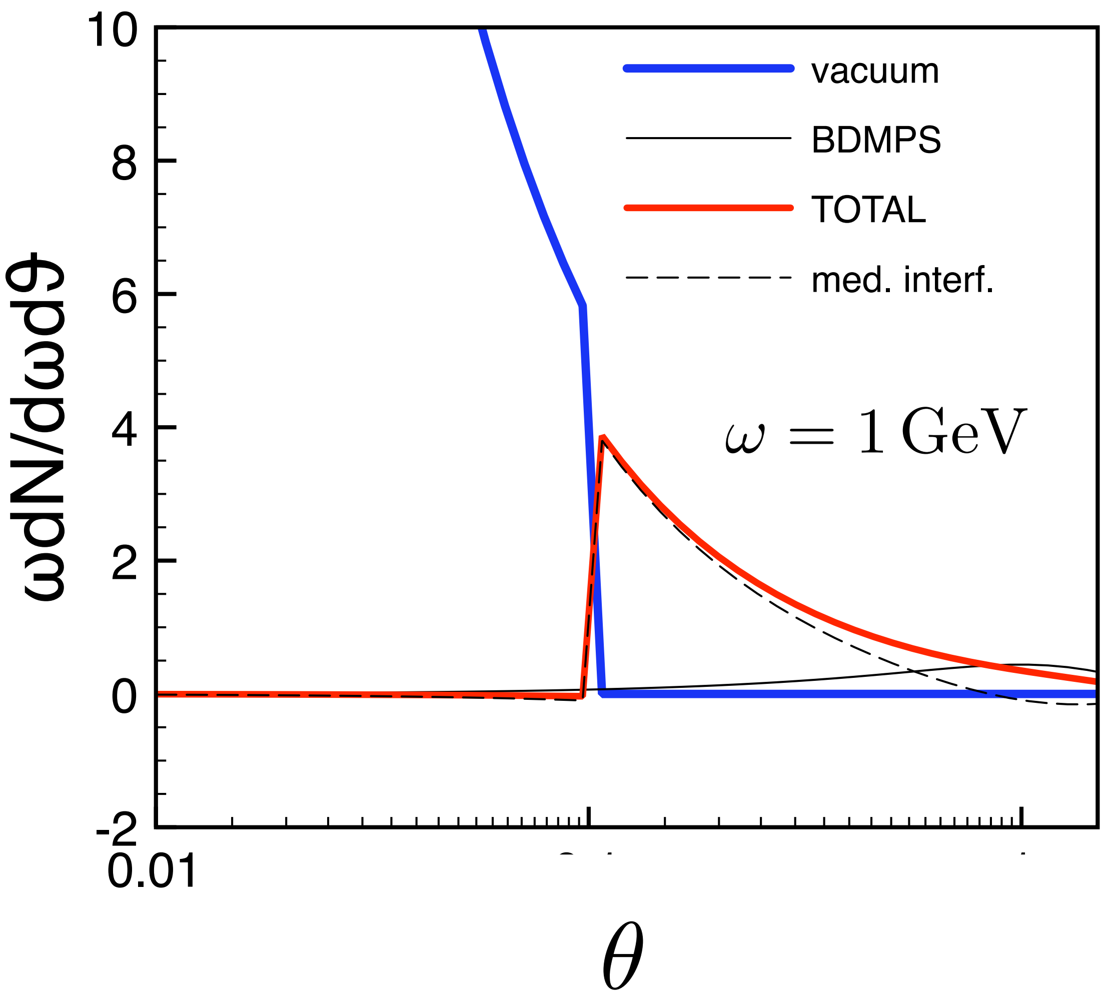
- Hard scale: $Q \equiv \max\left(r_\perp^{-1}, Q_s\right)$ and $k_\perp < Q$

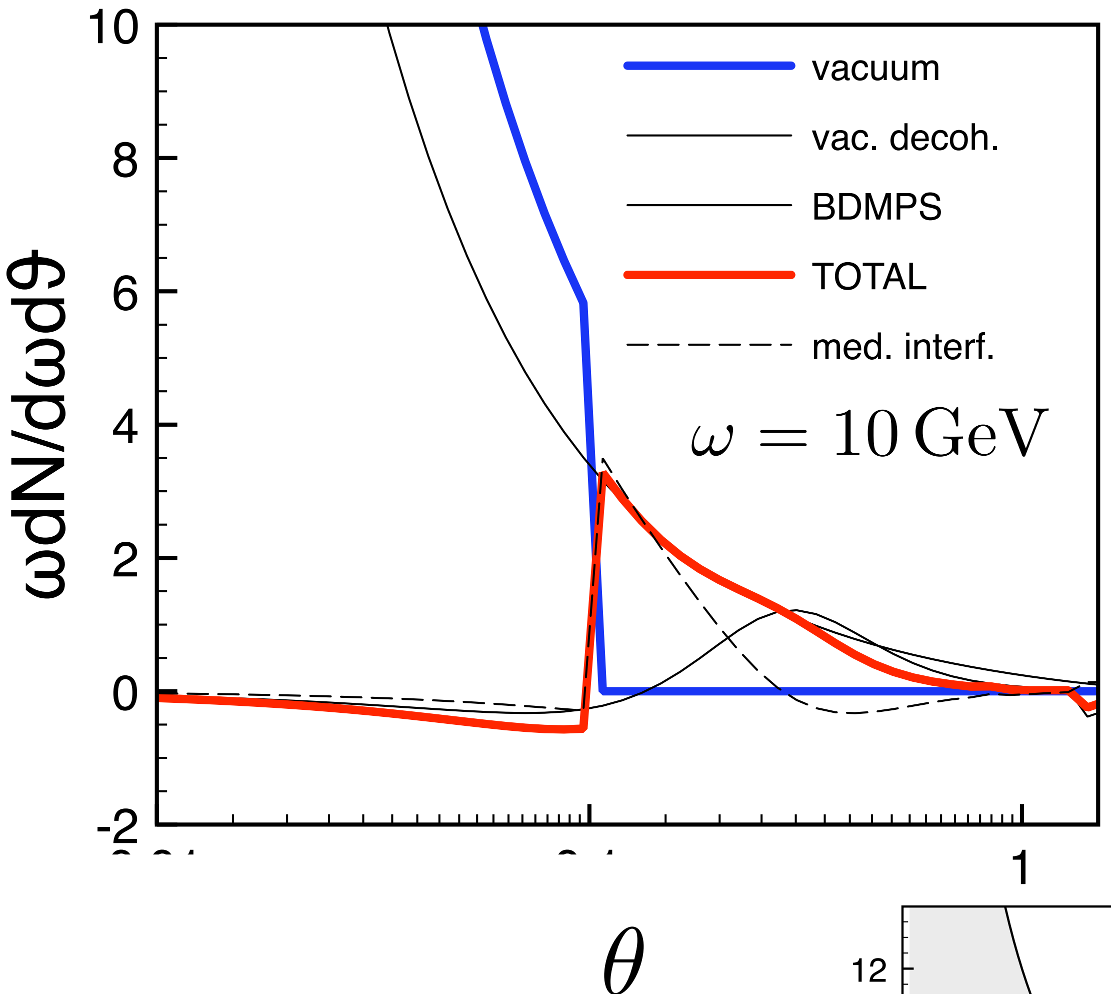
Angular distribution ($r_\perp < Q_s^{-1}$)

- Dipole regime



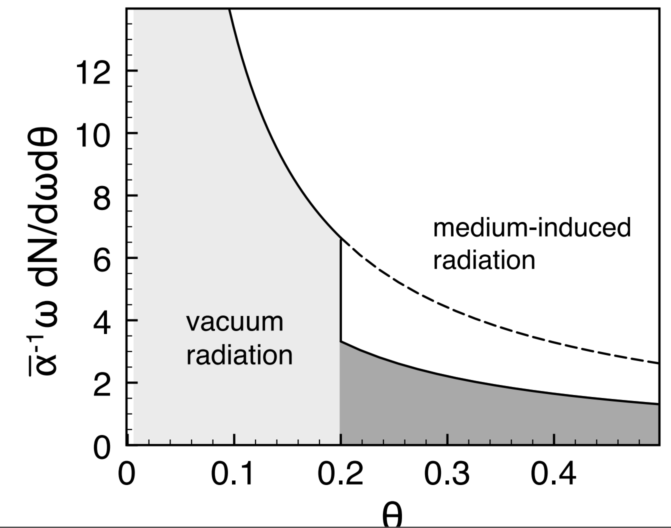
$\hat{q} = 1\,\mathrm{GeV}^2/\mathrm{fm}$ $\theta_{q\bar{q}} = 0.1$ $L = 5\,\mathrm{fm}$



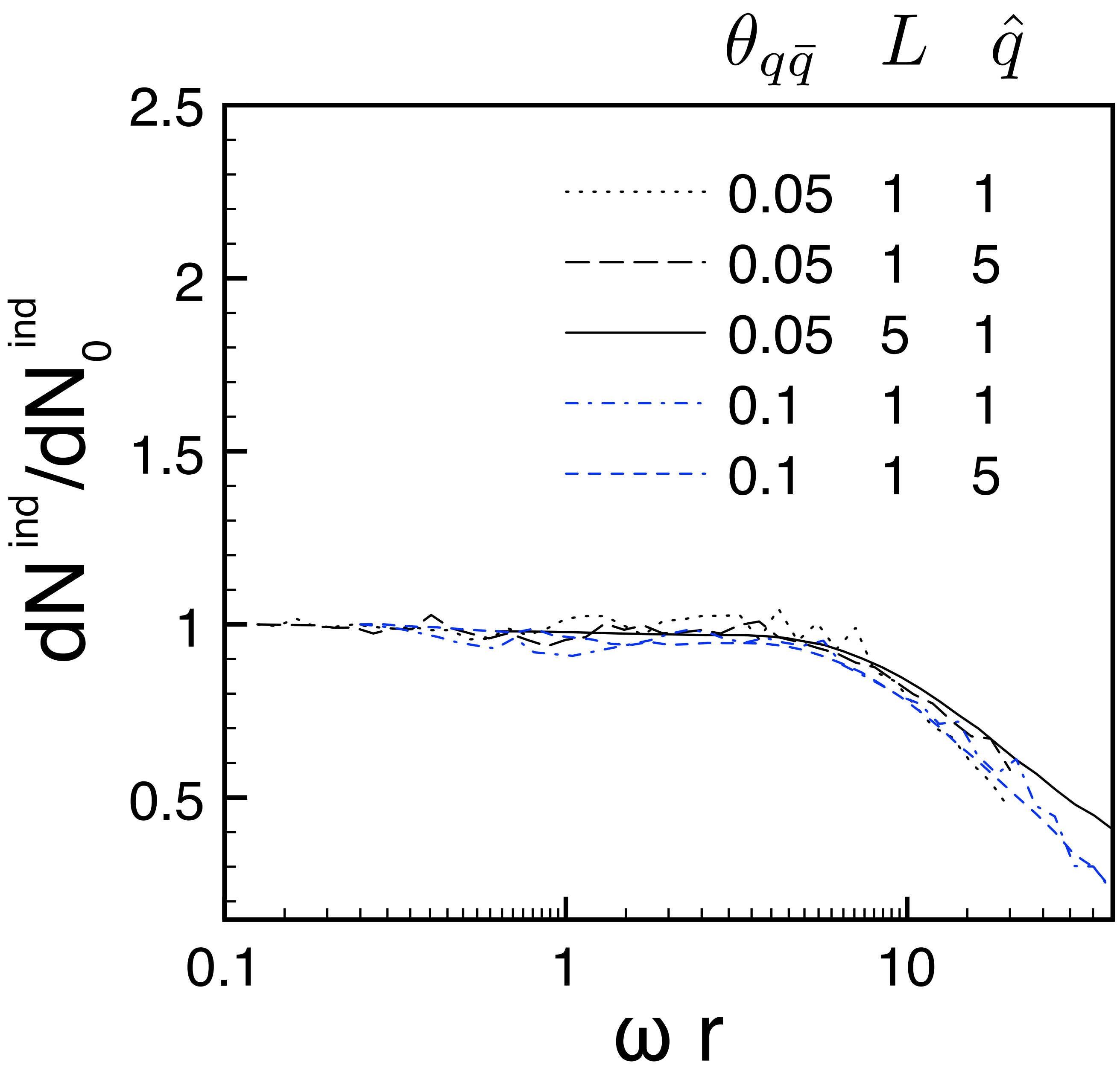


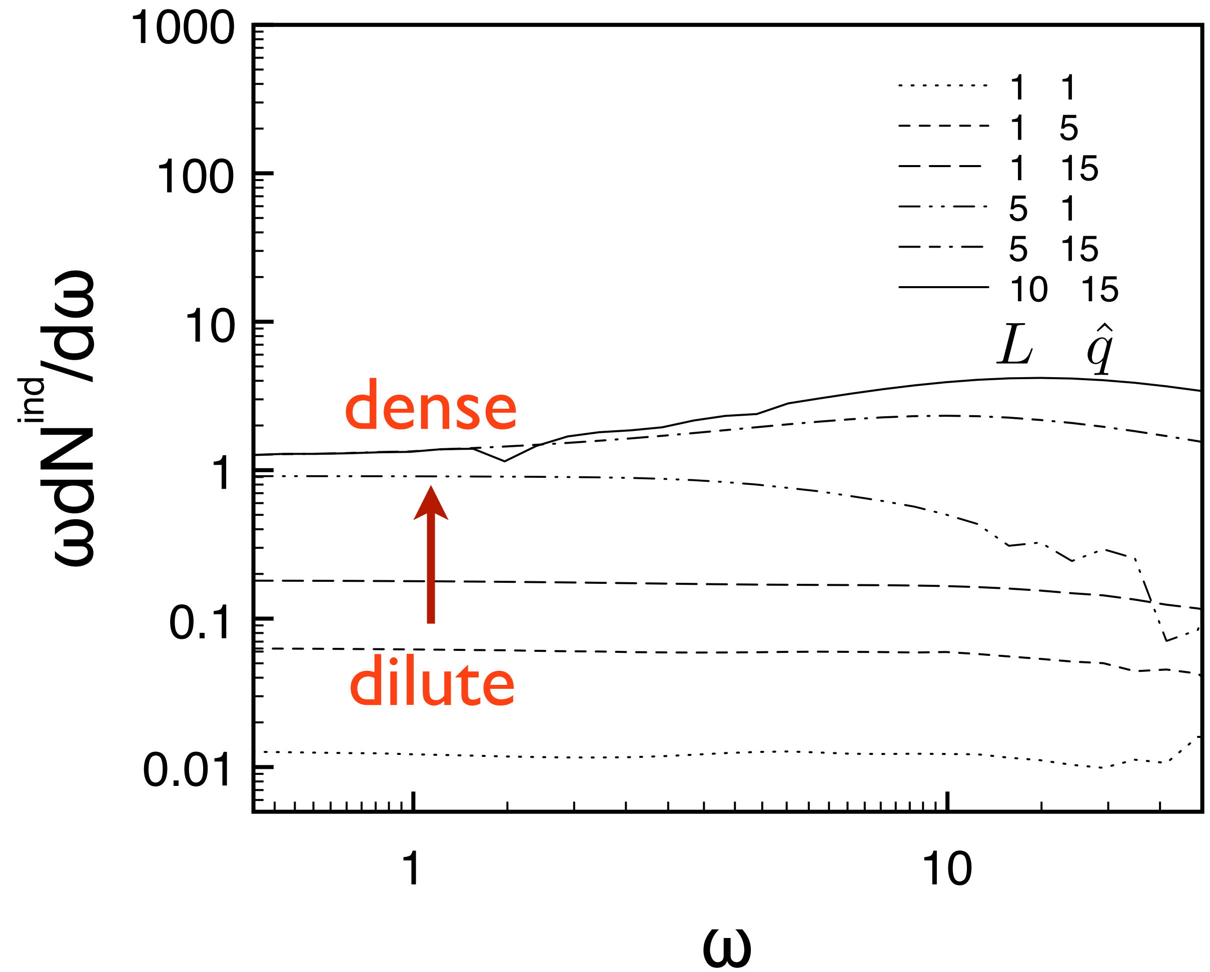
$$dN_q^{\mathrm{ind}} \propto \mathcal{R}_q^{\mathrm{ind}} - \mathcal{J}^{\mathrm{ind}}$$

integrating over the azimuth



Energy spectrum in the dipole regime

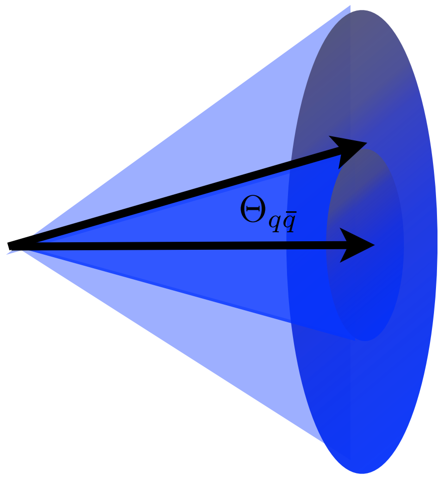




$$dN_q^{\rm ind} \propto \mathcal{R}_q^{\rm ind} - \mathcal{J}^{\rm ind}$$

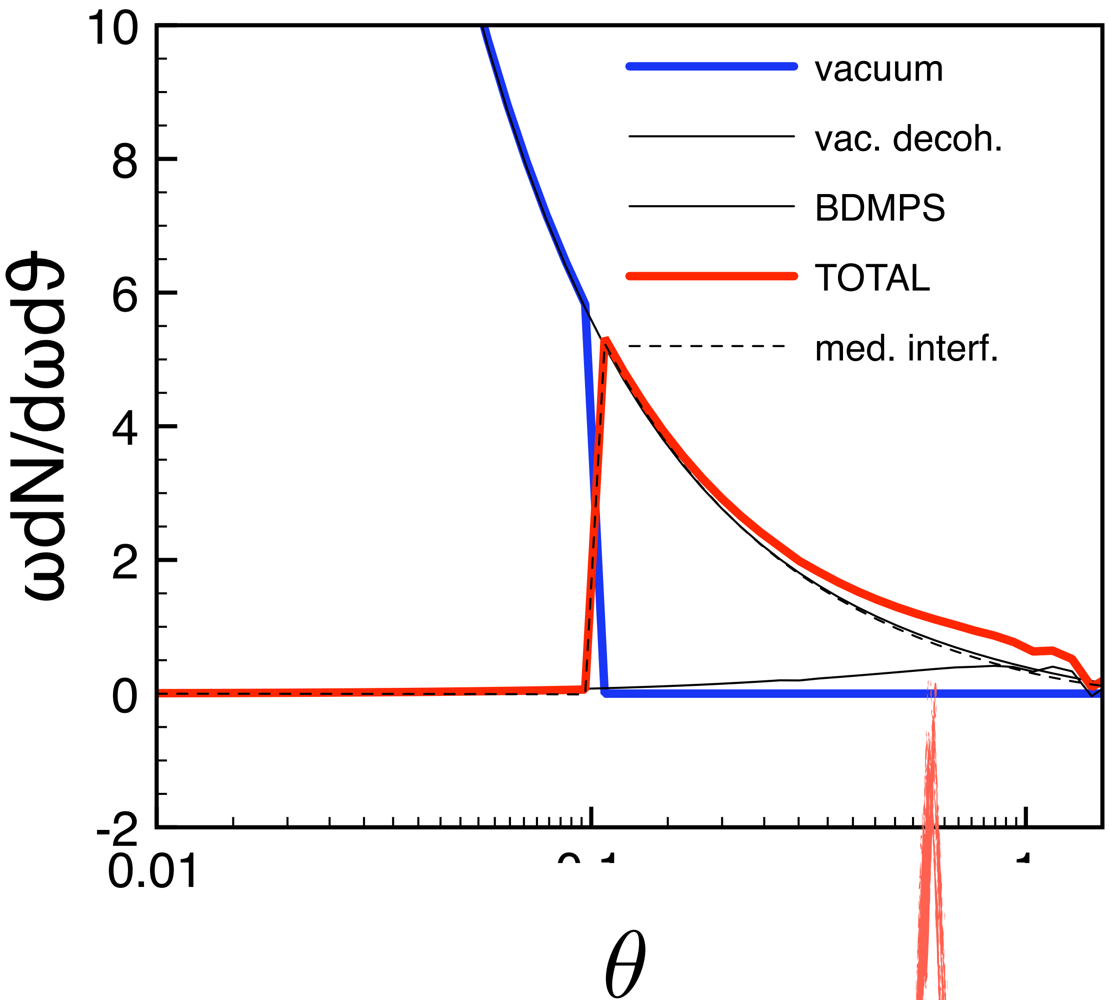
- Hard scale set by $Q \equiv r_\perp^{-1} = (\theta_{q\bar{q}} L)^{-1}$

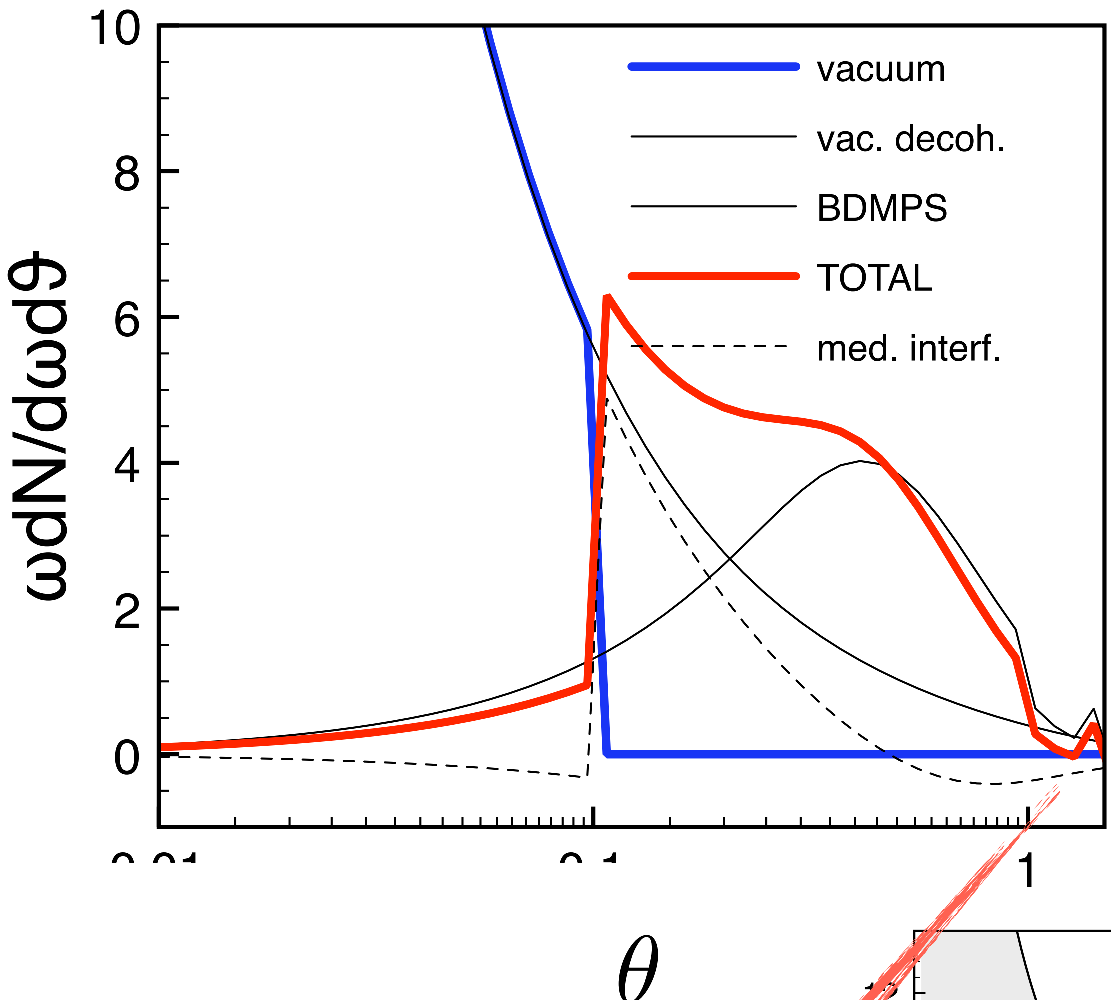
Angular distribution ($r_\perp > Q_s^{-1}$)



- Decoherence regime

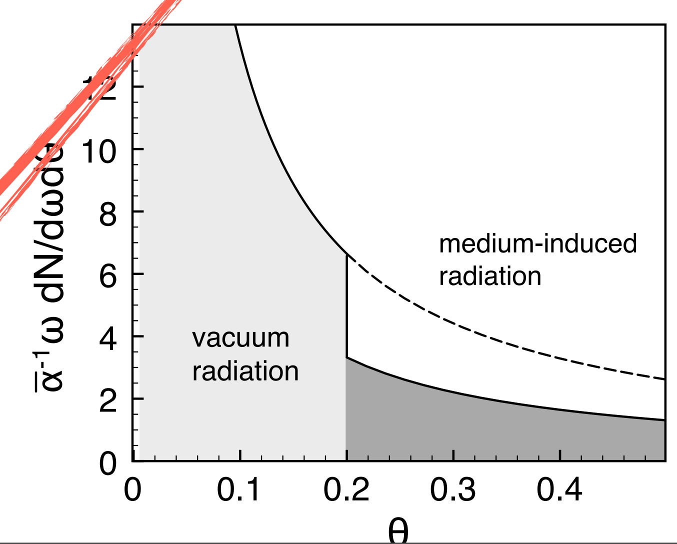
$\hat{q} = 5\,\mathrm{GeV}^2/\mathrm{fm}$ $\theta_{q\bar{q}} = 0.1$ $L = 10\,\mathrm{fm}$



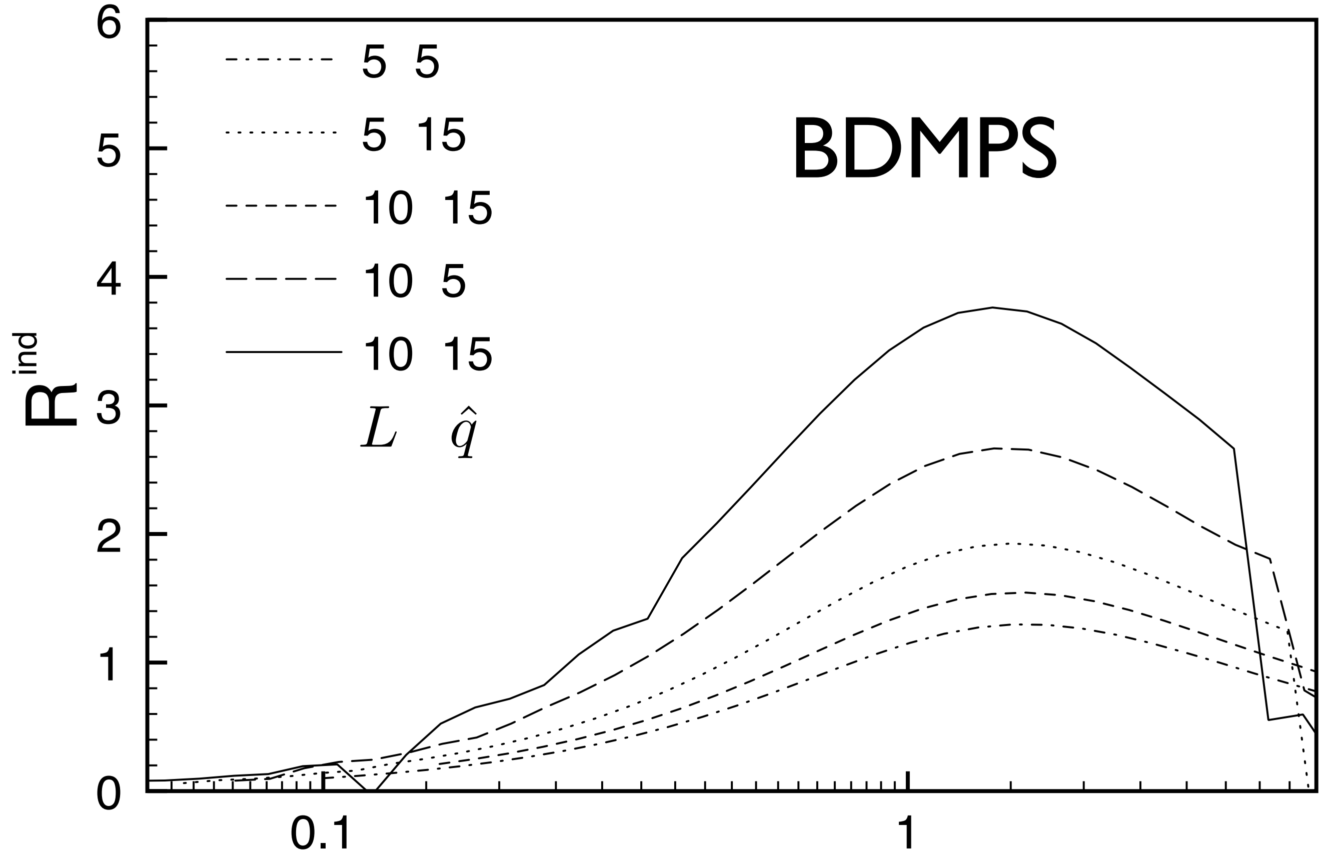


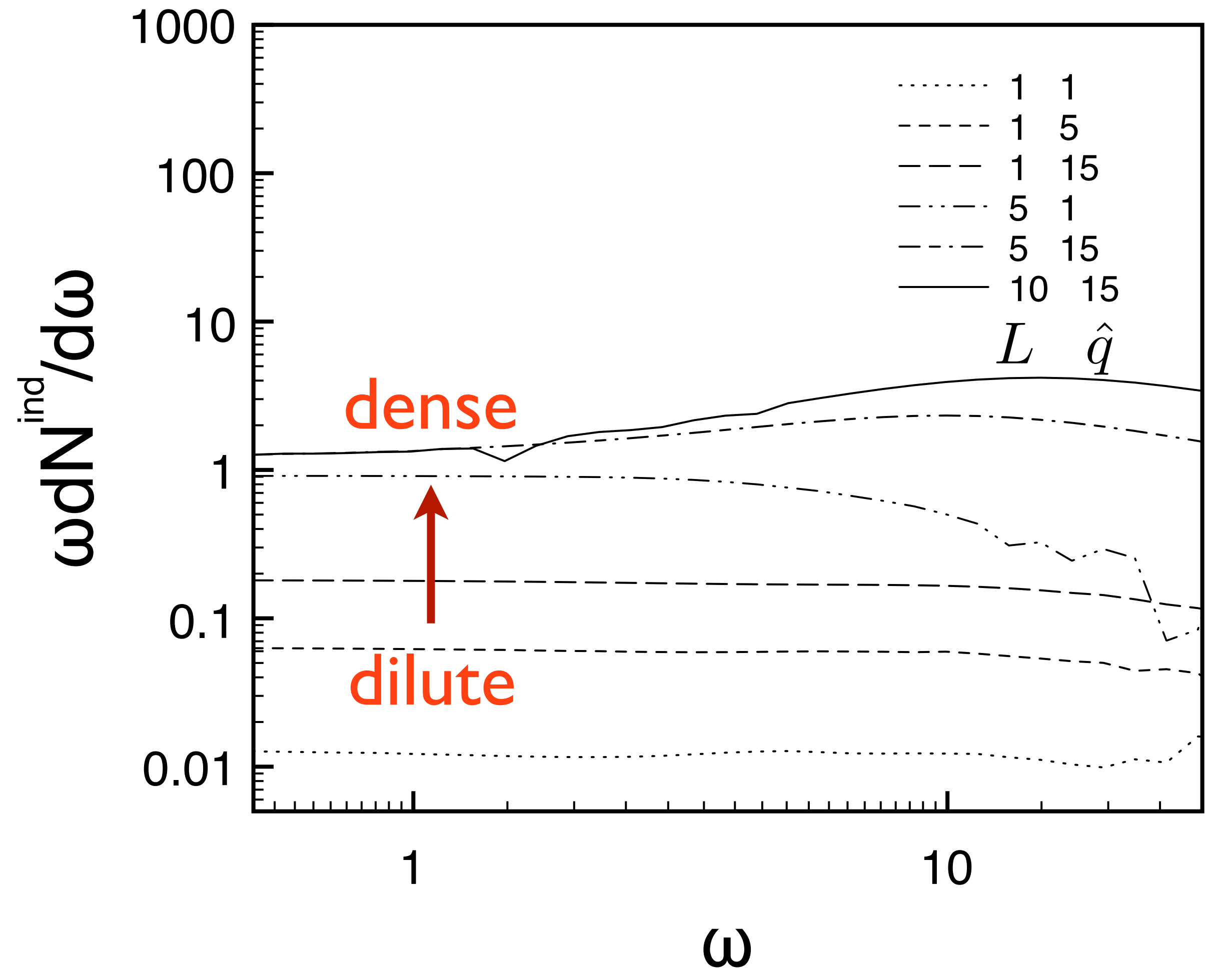
Decoherence

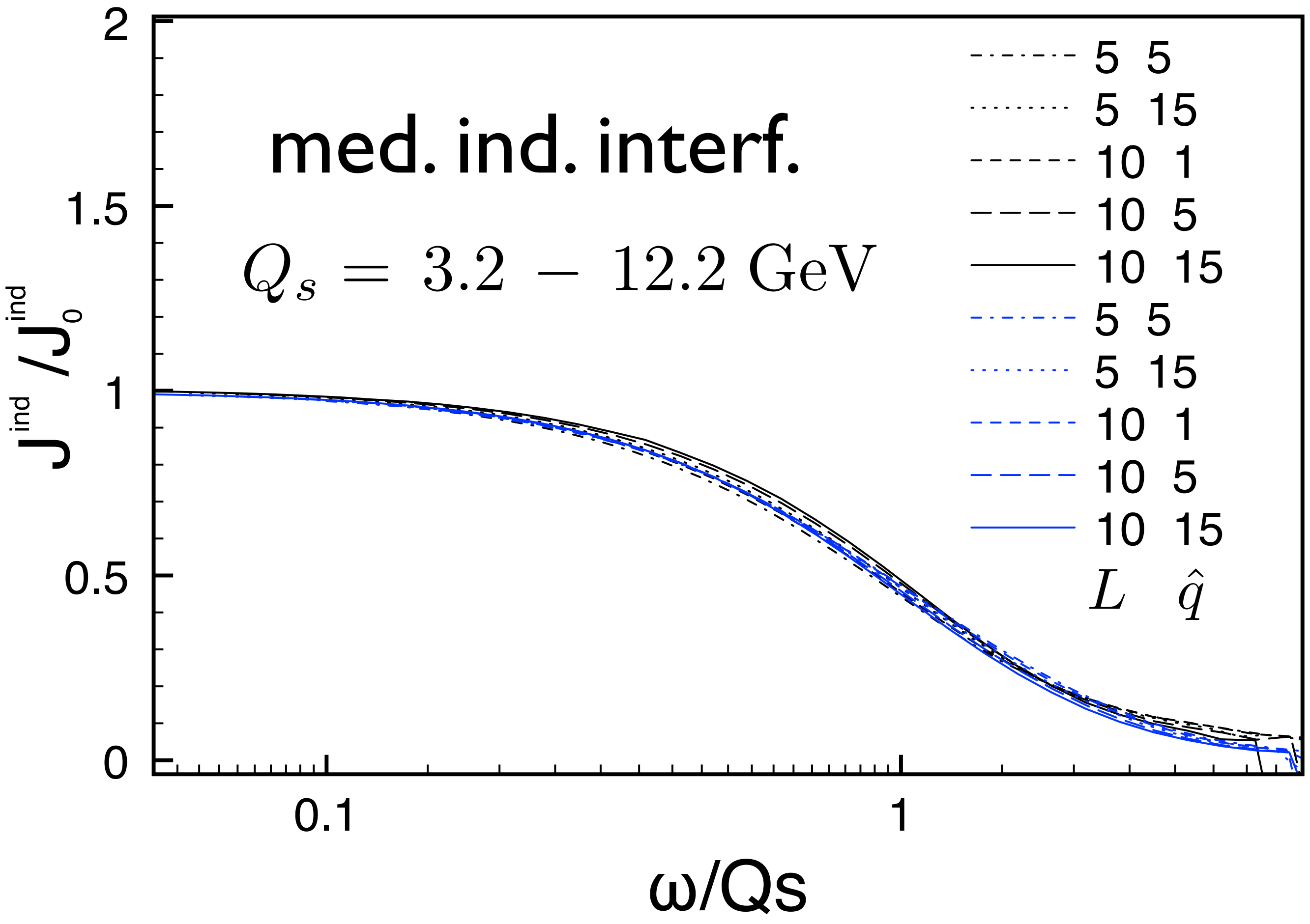
Coherence: $k_\perp > Q_s$



Energy spectrum in the decoh. regime







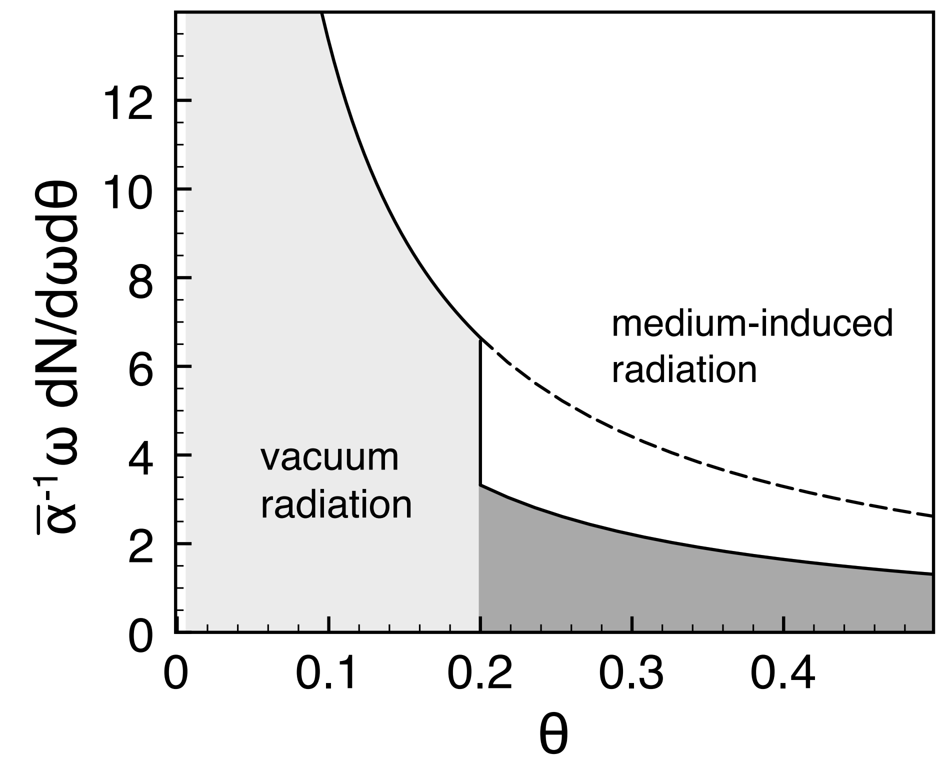
$$dN_q^{\text{ind}} \propto \mathcal{R}_q^{\text{ind}} - \mathcal{J}^{\text{ind}}$$

- Hard scale set by

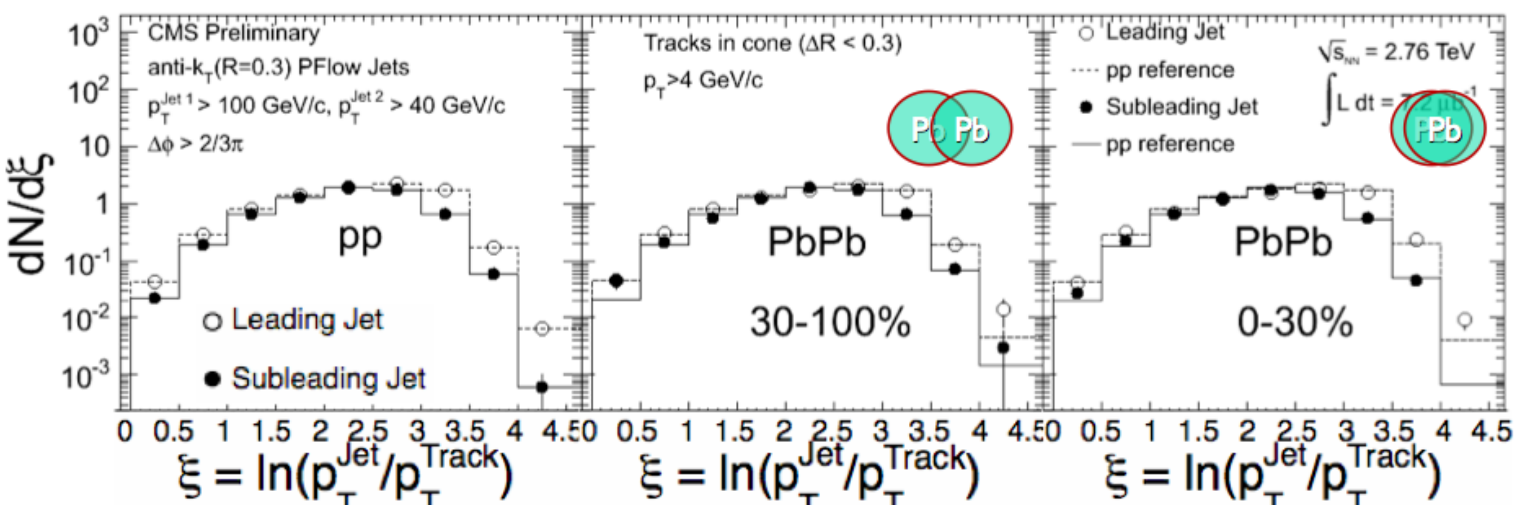
$$Q \equiv Q_s = \sqrt{\hat{q}\, L}$$

Decoherence: a new mechanism

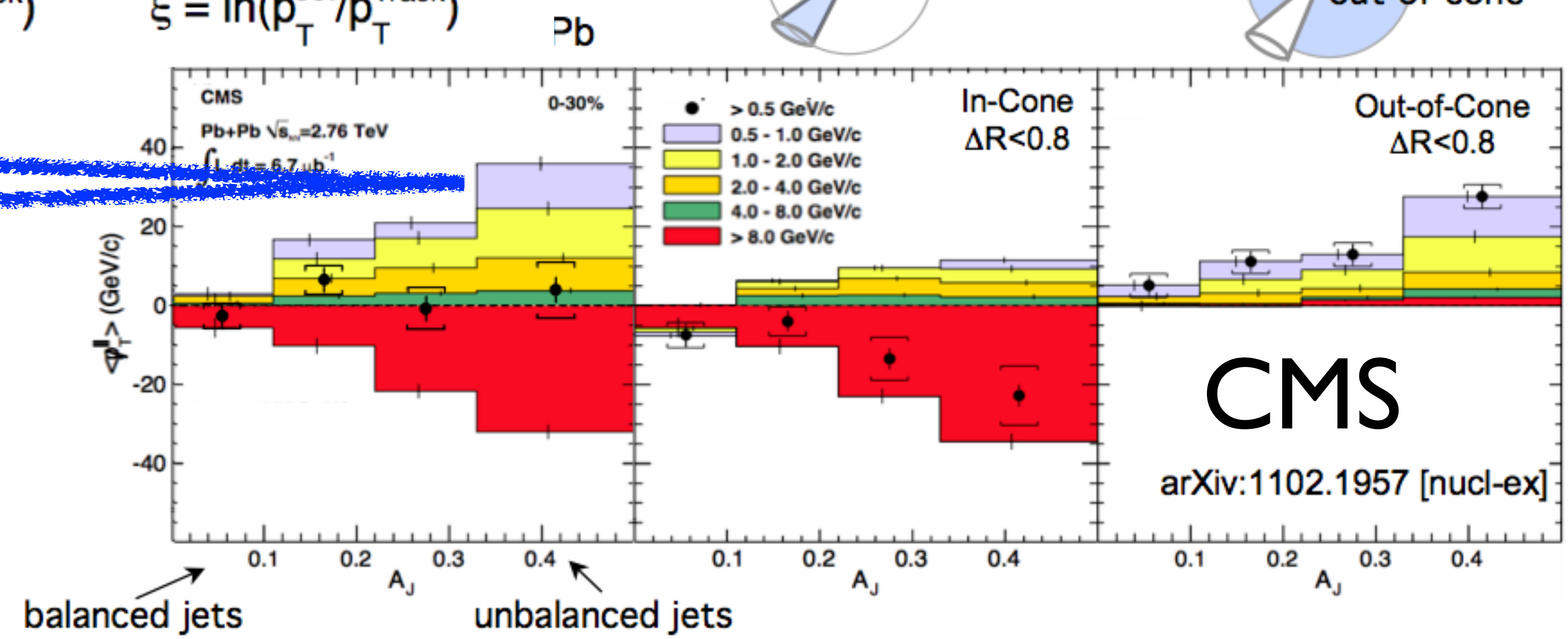
- Geometrical separation (medium/vacuum rad.)
- Medium-induced soft-gluon radiation at large angles



Supported by new LHC data!



vacuum-like frag. func.
R<0.3



Momentum in dijets balanced by low pt part. at large angles

Summary and Outlook

- ✓ Gradual decoherence of the antenna: Onset of a out-of-cone medium-induced soft divergence (novel mechanism for soft-gluon radiation)
- ✓ Decoherence survives at higher energies up to a typical transverse scale Qs
- ✓ Toward Medium-modified QCD evolution equations...

- Partial decoherence in the dilute(dipole) regime
- Total decoherence in the opaque limit (memory loss)

Back up

Multiple soft-scattering approximation

Gaussian approximation

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

Harmonic oscillator

$$\frac{1}{2}n\sigma(\boldsymbol{r}) \approx \frac{1}{4}\hat{q}\,\boldsymbol{r}^2$$

$$\frac{1}{N_c^2-1}\langle \mathbf{Tr}\,U(\boldsymbol{r})U^\dagger(\mathbf{0})\rangle = \exp\left[-\frac{1}{4}\hat{q}\,L\,\boldsymbol{r}^2\right]$$