# Jets from partonic antennas

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High-$p_T$ Probes of High-Density QCD at the LHC - Ecole Polytechnique

[Work with Yacine Mehtar-Tani and Konrad Tywoniuk 2010-2011]

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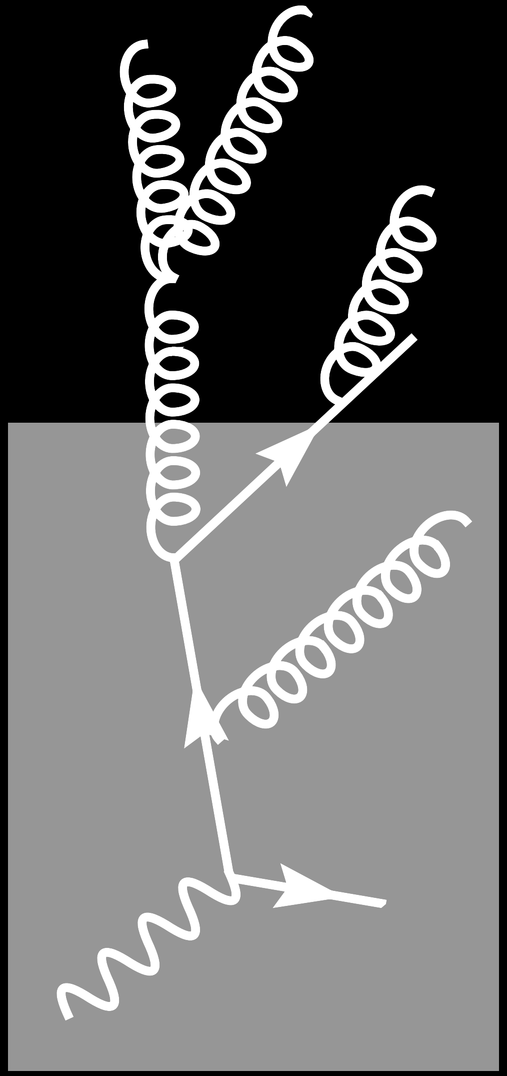
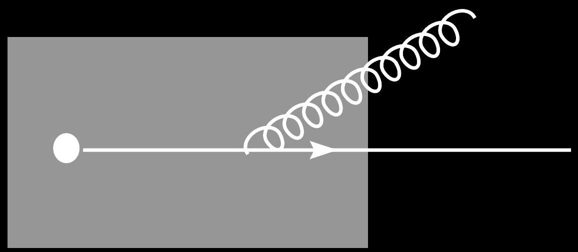
# *Towards a theory of jets in the medium*



- In-medium parton shower **not known** from QCD
- Until recently only medium modification off **single emitter** computed



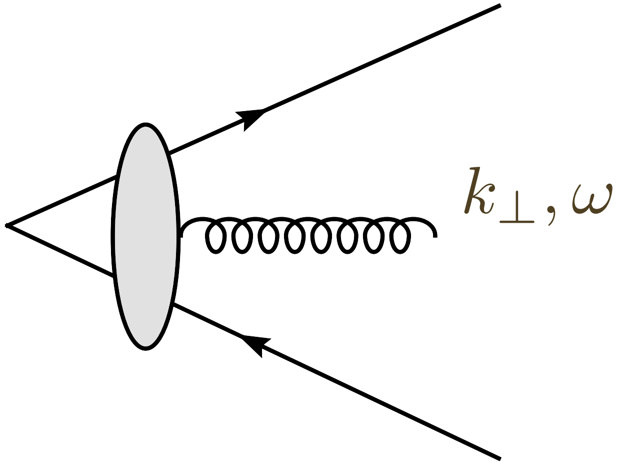
- But coherence among different emitters is essential in the vacuum case:

***ordering variables***

# Antenna emission in vacuum (QCD or QED)

⇛ **Color coherence:** building block of parton showers in vacuum

[See e.g. Dokshitzer et al, Basics of pQCD book]



⇛ Take quark as reference

$$t_{\rm form} \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\theta_{q,g}^2 \omega}$$

⇛ The transverse wavelength

$$\lambda_\perp \simeq \frac{1}{k_\perp} \quad \Rightarrow \quad t_{\rm form} \simeq \frac{\lambda_\perp}{\theta_{q,g}}$$

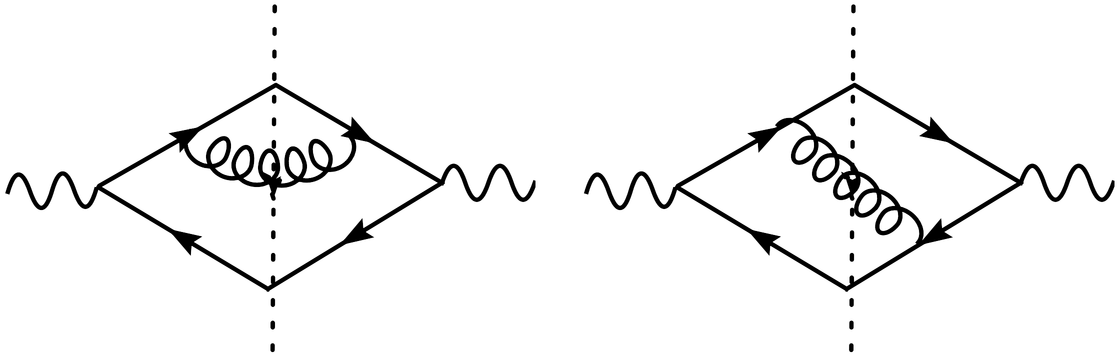
⇛ The transverse size of the pair : $\theta_{q\bar{q}}\, t_{\rm form} \simeq \lambda_\perp \frac{\theta_{q\bar{q}}}{\theta_{q,g}}$

⇛ So, when $\theta_{q,g} \gg \theta_{q\bar{q}}$ the gluon/photon “sees” a **neutral** object

**No radiation outside the cone**

# Angular ordering

- The Feymann diagrams



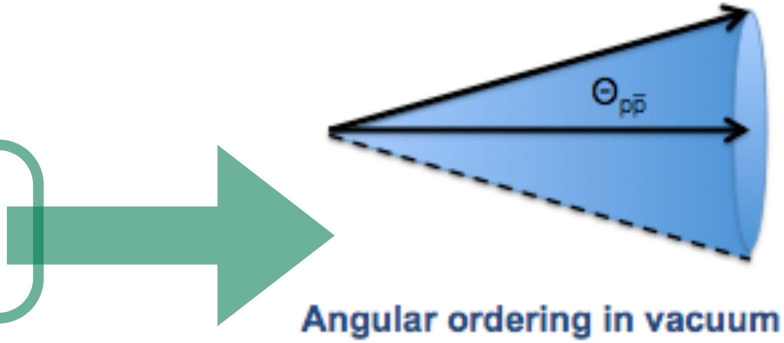
$$+(q \leftrightarrow \bar{q})$$

- The result in vacuum shows IR and collinear singularities

$$(2\pi)^2 E \frac{dN}{d^3k} = \alpha_s C_F \frac{p \cdot \bar{p}}{(p \cdot k)(\bar{p} \cdot k)}$$

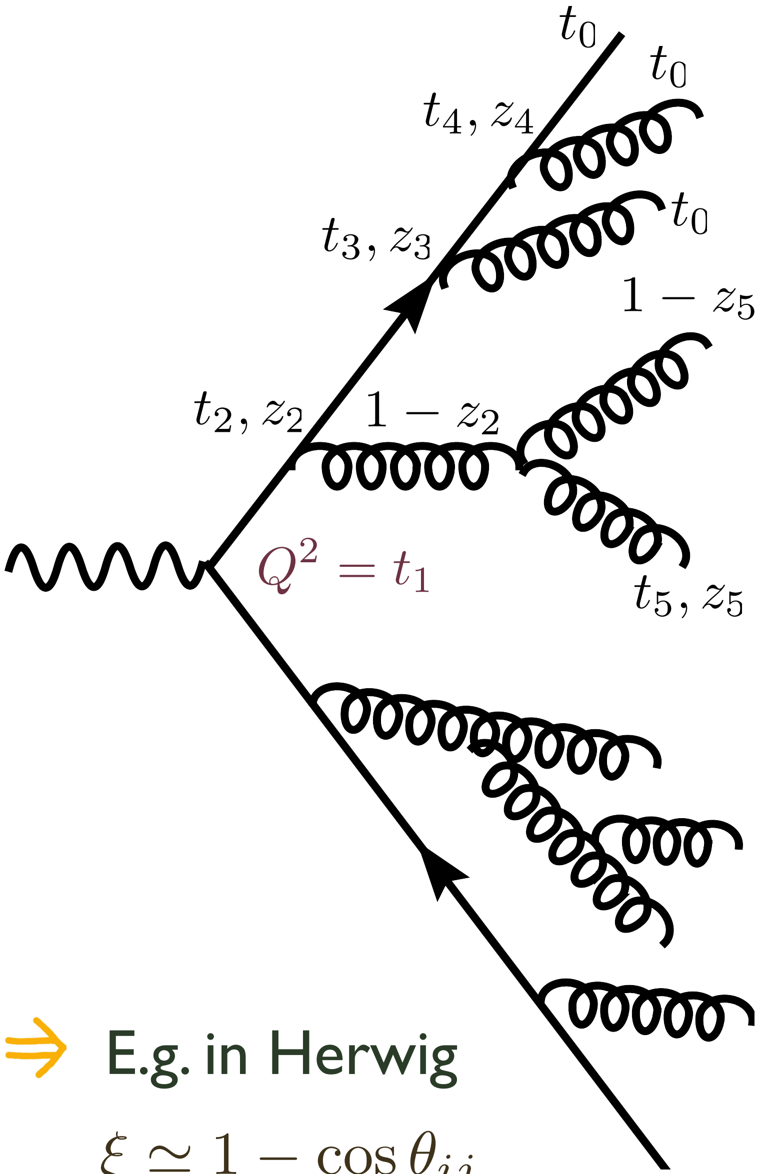
- Integrating in azimuthal angle

$$\langle dN_q \rangle_\phi \propto \frac{d\omega}{\omega} \frac{d\theta_{pk}}{\theta_{pk}} \boxed{\Theta \left( \theta_{p\bar{p}} - \theta_{pk} \right)}$$

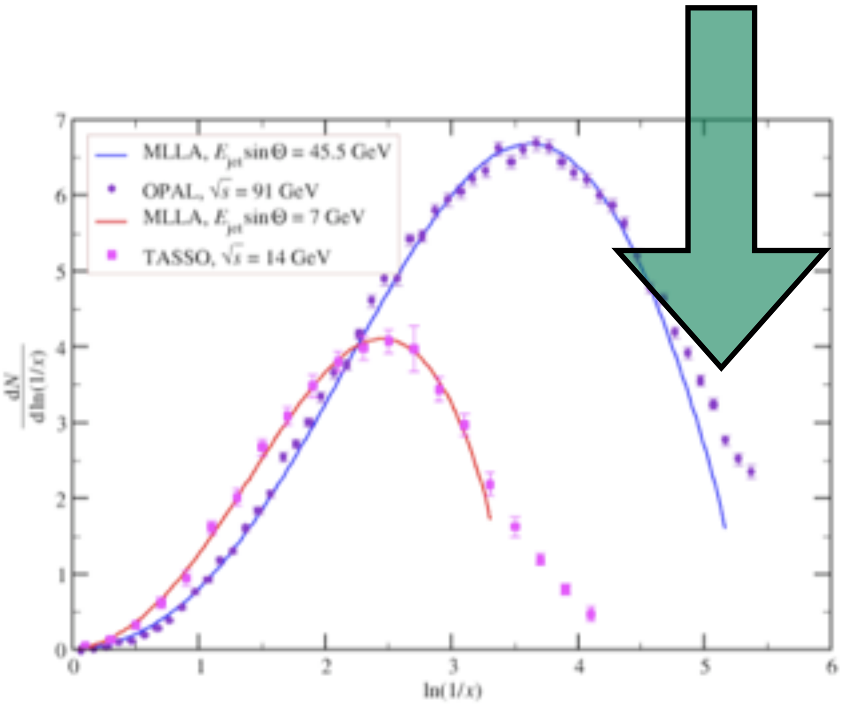


Angular ordering in vacuum

# Important consequences of color coherence



**Depletion of soft gluons: Hump-backed plateau**



[TASSO Collaboration1990;
OPAL Collaboration 1990 187]

⇛ E.g. in Herwig

$\xi \simeq 1 - \cos\theta_{ij}$

⇛ Also inter-jet radiation, etc...

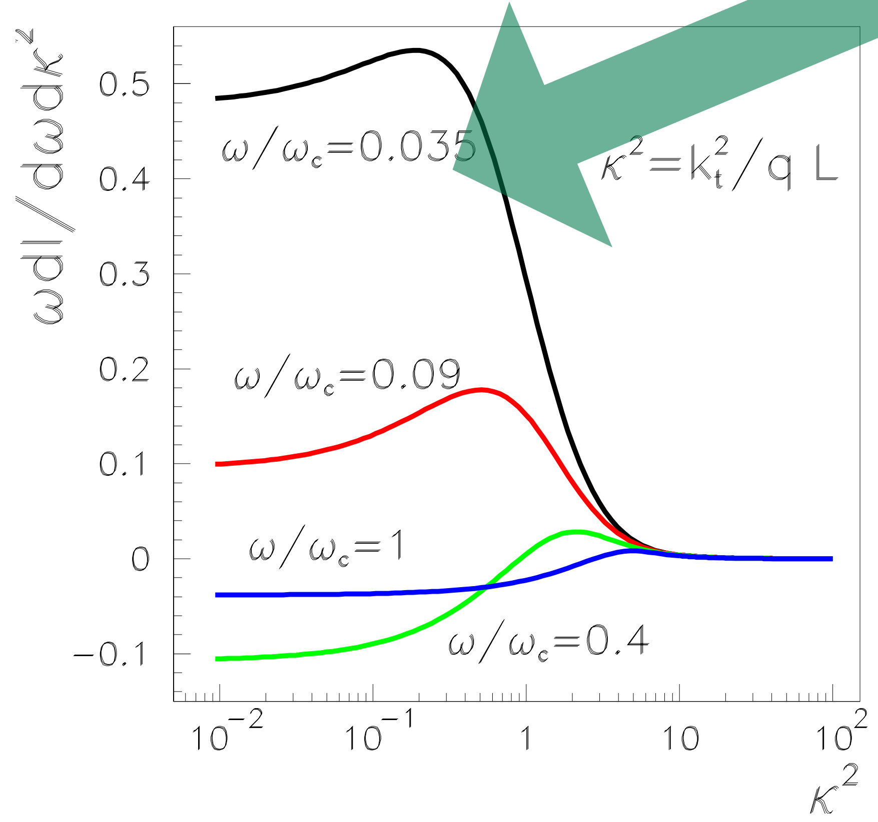
# The medium

# The LPM suppression

⇛ **One emitter** [BDMPS-Z, GLV, ASW, HT....]

$$\exp\left\{ i\frac{k_\perp^2}{2p_+}(x_{i+} - x_{(i+1)+}\right\}$$

$$t_{\rm form} \simeq \frac{2\omega}{k_\perp^2}$$



$$\langle k_\perp^2 \rangle \simeq \hat{q}\, t_{\rm form} \simeq \hat{q}\,\frac{2\omega}{\langle k_\perp^2 \rangle}$$

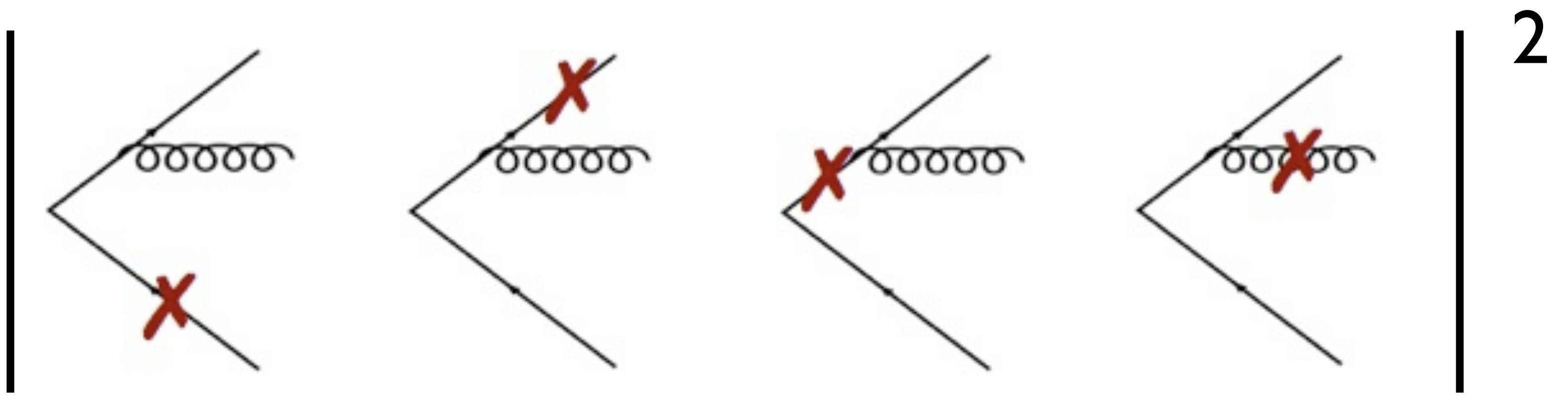
Radiation is suppressed due to formation time effects

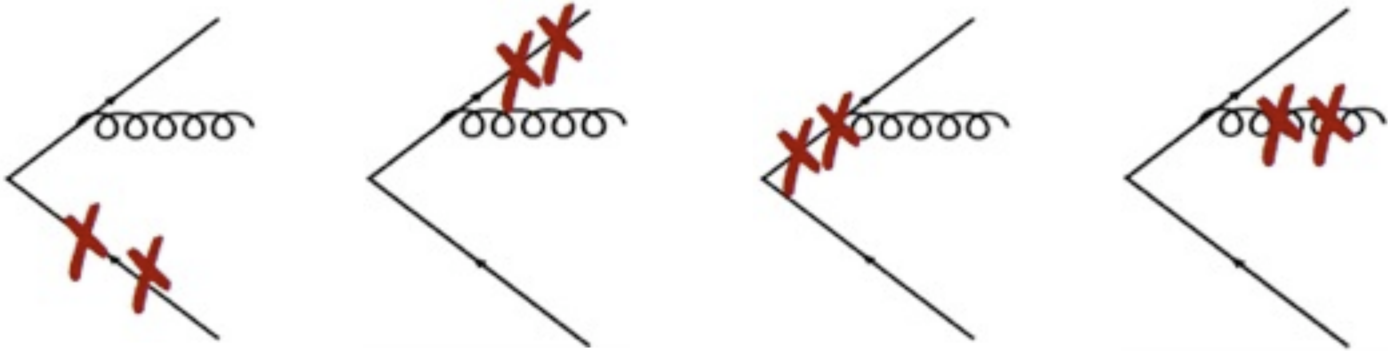
$$\langle k_\perp^2 \rangle \lesssim \sqrt{2\omega\hat{q}}$$

Energy loss and gluon broadening related one2one

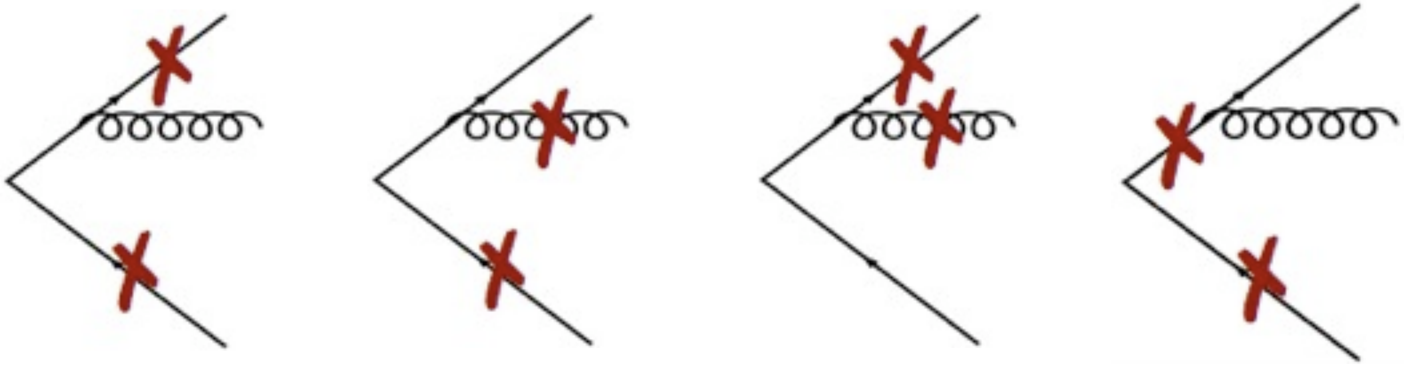
$$\Delta E \sim \alpha_s \langle k_\perp^2 \rangle\, L$$

# **The antenna: Calculation with Feymann diagrams** (N=1)





× vacuum



× vacuum

# The semiclassical calculation

- ⇛ Soft gluon radiation computed by solving the classical YM eqs.

$$[D_\mu, F^{\mu\nu}] = J^\nu \qquad [D_\mu, J^\mu] = 0 \qquad J_q^\mu = g\frac{p^\mu}{E}\;\delta^{(3)}(\mathbf{x} - \frac{\mathbf{p}}{E}t)\;\Theta(t)\;\mathcal{C}_q^a t^a$$

...and the same for the antiquark

- ⇛ The amplitude is given by the reduction formula

$$\mathcal{M}_\lambda^a(\mathbf{k}) = \lim_{k^2\to 0} -k^2 A_\mu^a(k)\epsilon_\lambda^\mu(\mathbf{k})\,,$$

- ⇛ So, the spectrum is

$$(2\pi)^3\,2\omega\,\frac{dN}{d^3k} = \sum_{\lambda=\pm 1} |\mathcal{M}_\lambda^a(k)\cdot\epsilon_\lambda|^2$$

- ⇛ The medium is treated as a background field with Gaussian sources

$$-\boldsymbol{\partial}_\perp^2 A_0^-(x^+, \mathbf{x}) = \rho_0(x^+, \mathbf{x})$$

[Mehtar-Tani, Phys. Rev. C75 (2007) 034908]

- ⇛ Calculation done at small initial angle

# The gluon radiation amplitude off the quark

⇛ Defining the variables

$$v = \left(k^+, \frac{(k_\perp - q_\perp)^2}{2k^+}, k_\perp - q_\perp\right)$$

$$\nu_\perp = \frac{p^+}{k^+} v_\perp - p_\perp$$

$$\kappa_\perp = \frac{p^+}{k^+} k_\perp - p_\perp$$

⇛ The amplitude reads (with a similar one for the antiquark)

$$\mathcal{M}^{\perp, a}_{q,1} \;=\; i g^2 f^{abc} \mathcal{C}^c \int \frac{d^2 q_\perp}{(2\pi)^2} \int_0^{L^+} dx^+ \mathcal{A}_0^b(x^+, q_\perp) \left[ \frac{\nu_\perp}{p \cdot v} \left( 1 - e^{i \frac{p \cdot v}{p^+} x^+} \right) + \frac{\kappa_\perp}{p \cdot k} e^{i \frac{p \cdot v}{p^+} x^+} \right]$$

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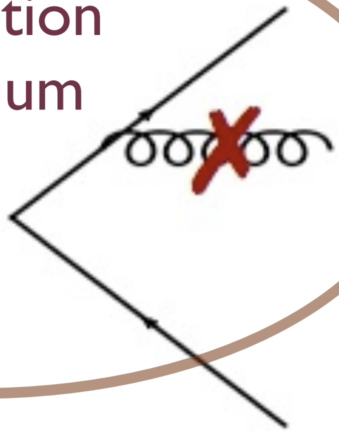
Gluon interaction with the medium



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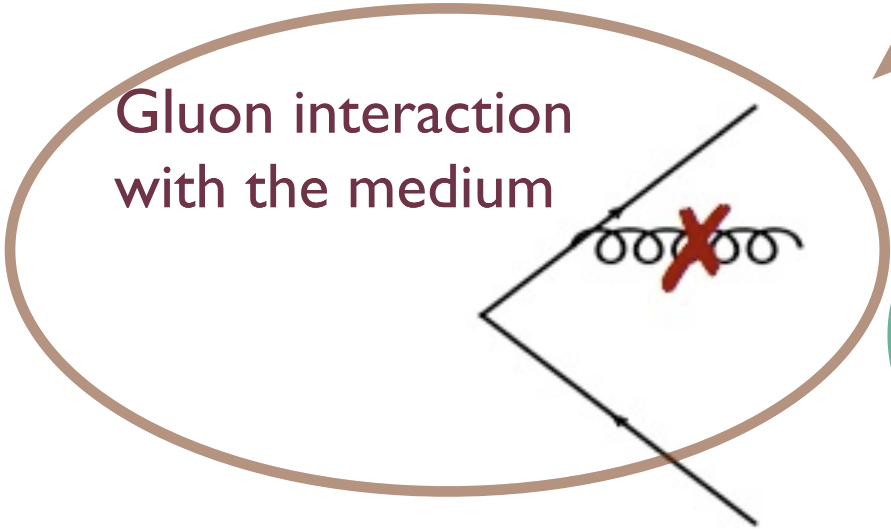
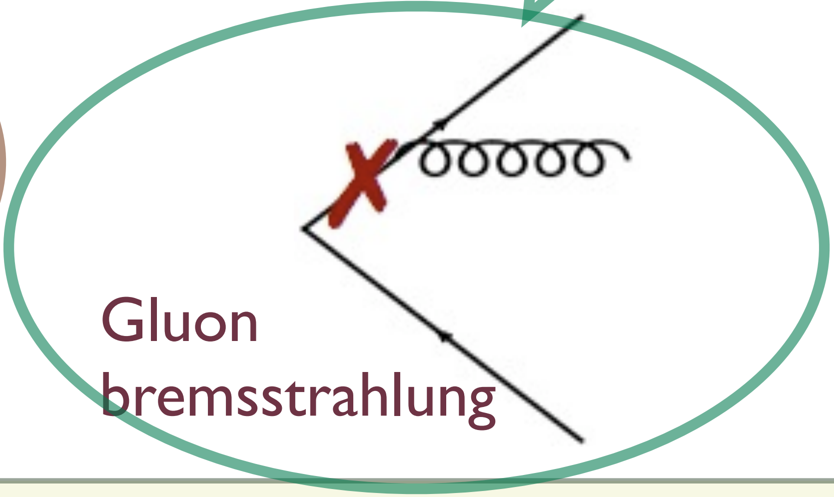
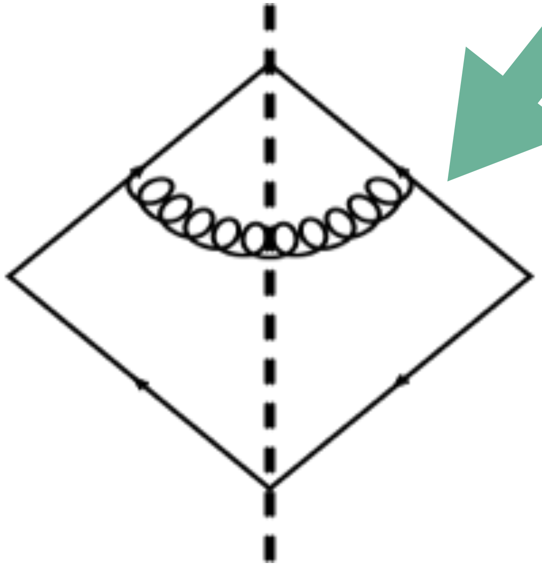




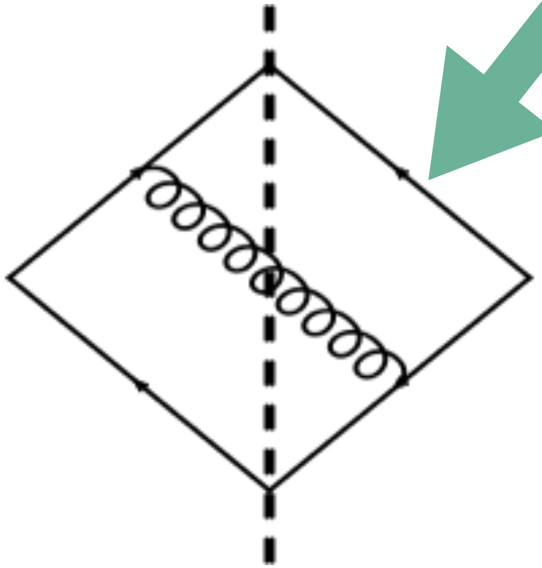
# Induced gluon radiation spectrum

- ⇒ Squaring the amplitude (adding both quark and antiquark contrbs.)

$$\left|\mathcal{M}^{tot}\right|^2 = |\mathcal{M}_q + \mathcal{M}_{\bar{q}}|^2 = \boxed{|\mathcal{M}_q|^2 + |\mathcal{M}_{\bar{q}}|^2} + \boxed{2\ \mathrm{Re}\left\{\mathcal{M}_q\mathcal{M}_{\bar{q}}^*\right\}}$$



BDMPS/GLV



New contribution

- ⇒ Include also the contact terms (medium/vacuum interference)

# Induced gluon radiation spectrum

$$
\begin{aligned}
(2\pi)^2 \frac{dN}{d^3k} \quad = \quad & 8\pi C_A C_F \alpha_s^2 \int \frac{d^2 q_\perp}{(2\pi)^2} \int_0^{L^+} dx^+ \; n(x^+) \; V(q_\perp) \\
& \left[ \left( \frac{\nu_\perp^2}{(p\cdot v)^2} - \frac{\nu_\perp \cdot \kappa_\perp}{(p\cdot v)(p\cdot k)} \right) \left(1 - \cos\Omega_1 x^+\right) \right. \\
& + \left( \frac{\bar\nu_\perp^2}{(\bar p\cdot v)^2} - \frac{\bar\nu_\perp \cdot \bar\kappa_\perp}{(\bar p\cdot v)(\bar p\cdot k)} \right) \left(1 - \cos\Omega_2 x^+\right) \\
& - \frac{\nu_\perp \cdot \bar\nu_\perp}{(p\cdot v)(\bar p\cdot v)} \left(1 + \cos\Omega_{12} x^+ - \cos\Omega_1 x^+ - \cos\Omega_2 x^+\right) \\
& - \frac{\nu_\perp \cdot \bar\kappa_\perp}{(p\cdot v)(\bar p\cdot k)} \left(\cos\Omega_2 x^+ - \cos\Omega_{12} x^+\right) \\
& - \frac{\bar\nu_\perp \cdot \kappa_\perp}{(\bar p\cdot v)(p\cdot k)} \left(\cos\Omega_1 x^+ - \cos\Omega_{12} x^+\right) \\
& \left. - \frac{\kappa_\perp \cdot \bar\kappa_\perp}{(p\cdot k)(\bar p\cdot k)} \left(\cos\Omega_{12} x^+ - 1\right) \right]
\end{aligned}
$$

$$
\Omega_1 = \frac{p\cdot v}{p^+} \qquad \Omega_2 = \frac{\bar p\cdot v}{\bar p^+} \qquad \Omega_{12} = \Omega_1 - \Omega_2
$$

# Induced gluon radiation spectrum

**GLV for the quark**

$$
\begin{aligned}
(2\pi)^2 \frac{dN}{d^3k} = {} & 8\pi C_A C_F \alpha_s^2 \int \frac{d^2q_\perp}{(2\pi)^2} \int_0^{L^+} dx^+ \; n(x^+) \; V(q_\perp) \\
& \boxed{\left[ \left( \frac{\nu_\perp^2}{(p\cdot v)^2} - \frac{\nu_\perp \cdot \kappa_\perp}{(p\cdot v)(p\cdot k)} \right) \left(1 - \cos \Omega_1 x^+\right)} \\
& + \left( \frac{\bar\nu_\perp^2}{(\bar p\cdot v)^2} - \frac{\bar\nu_\perp \cdot \bar\kappa_\perp}{(\bar p\cdot v)(\bar p\cdot k)} \right) \left(1 - \cos \Omega_2 x^+\right) \\
& - \frac{\nu_\perp \cdot \bar\nu_\perp}{(p\cdot v)(\bar p\cdot v)} \left(1 + \cos \Omega_{12} x^+ - \cos \Omega_1 x^+ - \cos \Omega_2 x^+\right) \\
& - \frac{\nu_\perp \cdot \bar\kappa_\perp}{(p\cdot v)(\bar p\cdot k)} \left(\cos \Omega_2 x^+ - \cos \Omega_{12} x^+\right) \\
& - \frac{\bar\nu_\perp \cdot \kappa_\perp}{(\bar p\cdot v)(p\cdot k)} \left(\cos \Omega_1 x^+ - \cos \Omega_{12} x^+\right) \\
& - \frac{\kappa_\perp \cdot \bar\kappa_\perp}{(p\cdot k)(\bar p\cdot k)} \left(\cos \Omega_{12} x^+ - 1\right) \Bigg]
\end{aligned}
$$

$$
\Omega_1 = \frac{p\cdot v}{p^+} \qquad \Omega_2 = \frac{\bar p\cdot v}{\bar p^+} \qquad \Omega_{12} = \Omega_1 - \Omega_2
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# Induced gluon radiation spectrum

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& \left. - \frac{\kappa_\perp \cdot \bar\kappa_\perp}{(p\cdot k)(\bar p\cdot k)} \left(\cos \Omega_{12} x^+ - 1\right) \right]
\end{aligned}
$$

GLV for the quark

GLV for the antiquark

$$
\Omega_1 = \frac{p\cdot v}{p^+} \qquad \Omega_2 = \frac{\bar p \cdot v}{\bar p^+} \qquad \Omega_{12} = \Omega_1 - \Omega_2
$$

# Induced gluon radiation spectrum

$$(2\pi)^2 \frac{dN}{d^3k} = 8\pi C_A C_F \alpha_s^2 \int \frac{d^2 q_\perp}{(2\pi)^2} \int_0^{L^+} dx^+ \; n(x^+) \; V(q_\perp)$$

GLV for the quark

$$\left[ \left( \frac{\nu_\perp^2}{(p\cdot v)^2} - \frac{\nu_\perp \cdot \kappa_\perp}{(p\cdot v)(p\cdot k)} \right) \left(1 - \cos \Omega_1 x^+\right) \right.$$

GLV for the antiquark

$$+ \left( \frac{\bar{\nu}_\perp^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\nu}_\perp \cdot \bar{\kappa}_\perp}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right) \left(1 - \cos \Omega_2 x^+\right)$$

Interferences

$$- \frac{\nu_\perp \cdot \bar{\nu}_\perp}{(p\cdot v)(\bar{p}\cdot v)} \left(1 + \cos \Omega_{12} x^+ - \cos \Omega_1 x^+ - \cos \Omega_2 x^+\right)$$

$$- \frac{\nu_\perp \cdot \bar{\kappa}_\perp}{(p\cdot v)(\bar{p}\cdot k)} \left(\cos \Omega_2 x^+ - \cos \Omega_{12} x^+\right)$$

$$- \frac{\bar{\nu}_\perp \cdot \kappa_\perp}{(\bar{p}\cdot v)(p\cdot k)} \left(\cos \Omega_1 x^+ - \cos \Omega_{12} x^+\right)$$

$$\left. - \frac{\kappa_\perp \cdot \bar{\kappa}_\perp}{(p\cdot k)(\bar{p}\cdot k)} \left(\cos \Omega_{12} x^+ - 1\right) \right]$$

$$\Omega_1 = \frac{p\cdot v}{p^+} \qquad \Omega_2 = \frac{\bar{p}\cdot v}{\bar{p}^+} \qquad \Omega_{12} = \Omega_1 - \Omega_2$$

# Induced gluon radiation spectrum

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GLV for the quark

$$\Bigg[\left(\frac{\nu_\perp^2}{(p\cdot v)^2} - \frac{\nu_\perp\cdot\kappa_\perp}{(p\cdot v)(p\cdot k)}\right)\left(1-\cos\Omega_1 x^+\right)$$

GLV for the antiquark

$$+\left(\frac{\bar\nu_\perp^2}{(\bar p\cdot v)^2} - \frac{\bar\nu_\perp\cdot\bar\kappa_\perp}{(\bar p\cdot v)(\bar p\cdot k)}\right)\left(1-\cos\Omega_2 x^+\right)$$

Interferences

$$-\frac{\nu_\perp\cdot\bar\nu_\perp}{(p\cdot v)(\bar p\cdot v)}\left(1+\cos\Omega_{12}x^+ - \cos\Omega_1 x^+ - \cos\Omega_2 x^+\right)$$

$$-\frac{\nu_\perp\cdot\bar\kappa_\perp}{(p\cdot v)(\bar p\cdot k)}\left(\cos\Omega_2 x^+ - \cos\Omega_{12}x^+\right)$$

$$-\frac{\bar\nu_\perp\cdot\kappa_\perp}{(\bar p\cdot v)(p\cdot k)}\left(\cos\Omega_1 x^+ - \cos\Omega_{12}x^+\right)$$

Bremsstrahlung int.
soft divergence
(remember that q
is in v and nu)

$$-\frac{\kappa_\perp\cdot\bar\kappa_\perp}{(p\cdot k)(\bar p\cdot k)}\left(\cos\Omega_{12}x^+ - 1\right)\Bigg]$$

$$\Omega_1 = \frac{p\cdot v}{p^+} \qquad \Omega_2 = \frac{\bar p\cdot v}{\bar p^+} \qquad \Omega_{12} = \Omega_1 - \Omega_2$$

# Soft limit and antiangular ordering

⇒ The bremsstrahlung term presents IR divergence. In the soft limit

$$\omega\frac{dN^{\rm med}}{d^3k} \to \frac{8\pi C_A C_F\,\alpha_s^2\, n_0\, m_D^2}{(2\pi)^2}\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(p\cdot k)(\bar p\cdot k)}\int_0^{L^+} dx^+\cos\Omega_0\, x^+\int\frac{d^2\mathbf{q}}{(2\pi)^2}\mathcal{V}(\mathbf{q})\left(1-\cos\Delta\Omega\, x^+\right)$$

Does not depend on q factors out of integral

This is equal to the vacuum term

$$\omega\frac{dN^{\rm vac}}{d^3k}\propto\alpha_s\, C_F\left(\frac{\boldsymbol{\kappa}^2}{(p\cdot k)^2}-2\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(p\cdot k)(\bar p\cdot k)}+\frac{\bar{\boldsymbol{\kappa}}^2}{(\bar p\cdot k)^2}\right)$$

⇒ In the vacuum the first and the third can be interpreted as independent radiation off the quark and antiquark. The middle kills the radiation *outside* the cone

# Soft limit and antiangular ordering

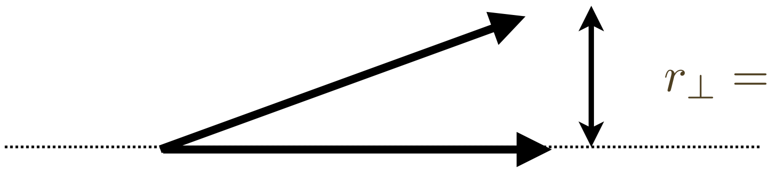
- In the soft limit the integrals can be done analytically

$$\int_0^{L^+} dx^+ \int \frac{d^2\mathbf{q}}{(2\pi)^2}\,\mathcal{V}(\mathbf{q})\left(1-\cos\frac{\bar{\mathbf{p}}_\perp\cdot\mathbf{q}}{\bar{p}^+}x^+\right) \approx \frac{L^+ r_\perp^2}{24\pi}\left[\ln\left(\frac{1}{r_\perp m_D}\right)+\text{const.}\right]$$

- Proceeding as in the vacuum, the antiangular ordering appears

$$dN_q^{\text{med}} = \frac{\alpha_s C_F}{2\pi} A^{\text{med}} \frac{d\omega}{\omega}\frac{\sin\theta d\theta}{1-\cos\theta}\Theta(\cos\theta_{q\bar{q}}-\cos\theta)$$

- With $A^{\text{med}} \simeq \alpha_s C_A n_0 m_D^2 L^+ r_\perp^2 \left[\ln\left(1/r_\perp m_D\right)+\text{const.}\right]/6\pi$



$$r_\perp = \frac{\bar{p}_\perp}{\bar{E}}L \approx \theta_{q\bar{q}}L$$

Dipole scattering amplitude

# Soft limit and antiangular ordering

- In the soft limit the integrals can be done analytically

$$\int_0^{L^+} dx^+ \int \frac{d^2\mathbf{q}}{(2\pi)^2}\, \mathcal{V}(\mathbf{q}) \left(1-\cos\frac{\bar{\mathbf{p}}_\perp\cdot\mathbf{q}}{\bar{p}^+}x^+\right) \approx \frac{L^+ r_\perp^2}{24\pi}\left[\ln\left(\frac{1}{r_\perp m_D}\right)+\text{const.}\right]$$

- Proceeding as in the vacuum, the antiangular ordering appears

$$dN_q^{\text{med}} = \frac{\alpha_s C_F}{2\pi} A^{\text{med}} \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1-\cos\theta} \boxed{\Theta(\cos\theta_{q\bar{q}}-\cos\theta)}$$

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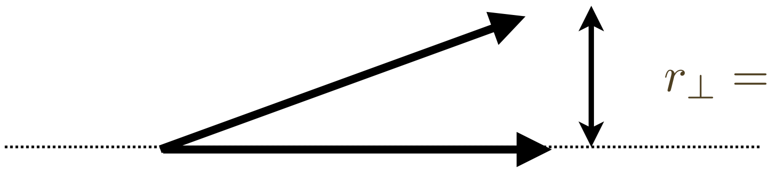


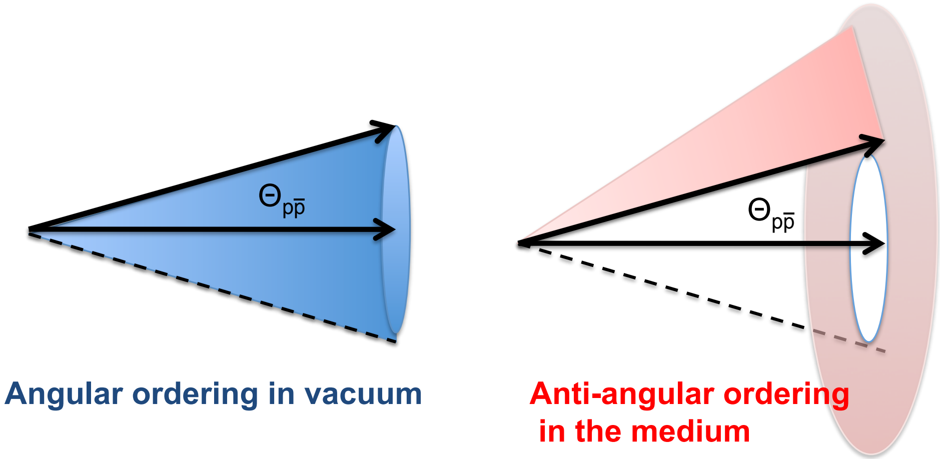
$$r_\perp = \frac{\bar{p}_\perp}{\bar{E}} L \approx \theta_{q\bar{q}} L$$

**Dipole scattering amplitude**

# Soft limit and antiangular ordering

- ⇛ So, in the soft limit the total spectrum (vacuum+medium)

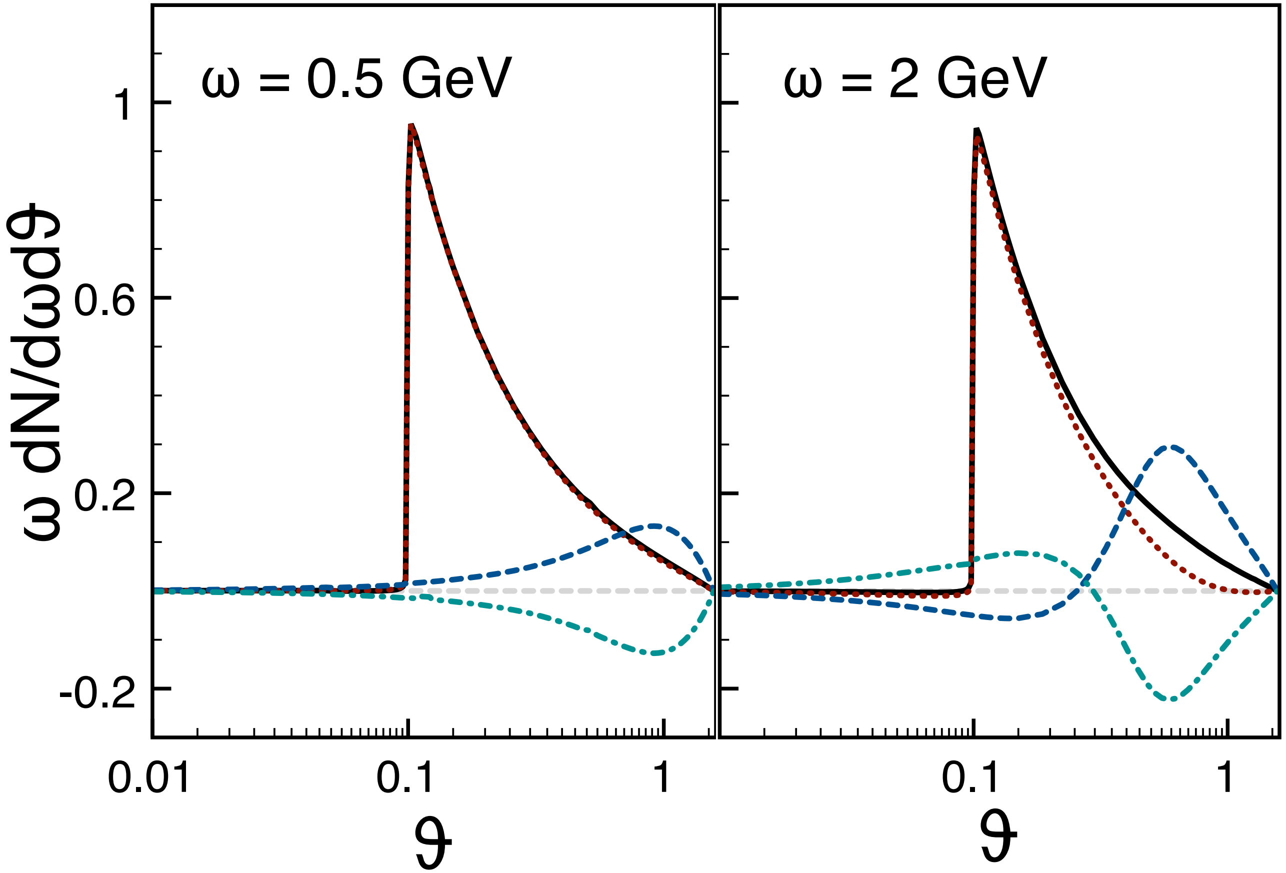
$$dN_q = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\left(\Theta\left(\cos\theta - \cos\theta_{q\bar{q}}\right) + A(\theta_{q\bar{q}}, L)\Theta\left(\cos\theta_{q\bar{q}} - \cos\theta\right)\right)$$

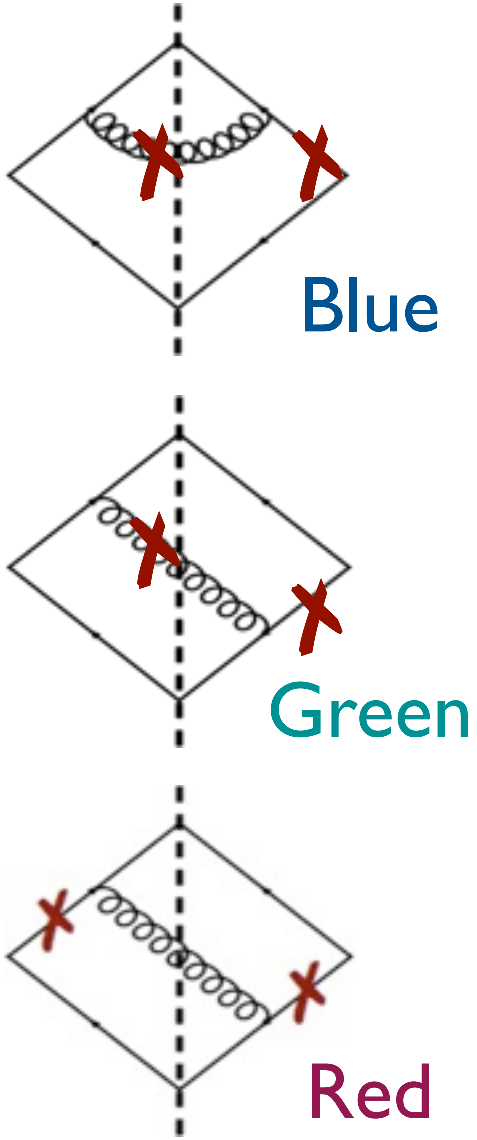


- ⇛ Vacuum-like spectrum
- ➘ "Broadening without pt-broadening": $\Delta E \sim \alpha_s \langle k_\perp^2 \rangle\, L$ no longer holds
- ⇛ New hard scale in the problem $r_\perp = \theta_{q\bar{q}} L$
- ⇛ Energy of bremsstrahlung interference radiated gluons bounded

$$\mu < k_\perp = \omega\theta_{q\bar{q}} < 1/r_\perp \;\Rightarrow\; \omega < 1/\theta_{q\bar{q}}^2 L$$

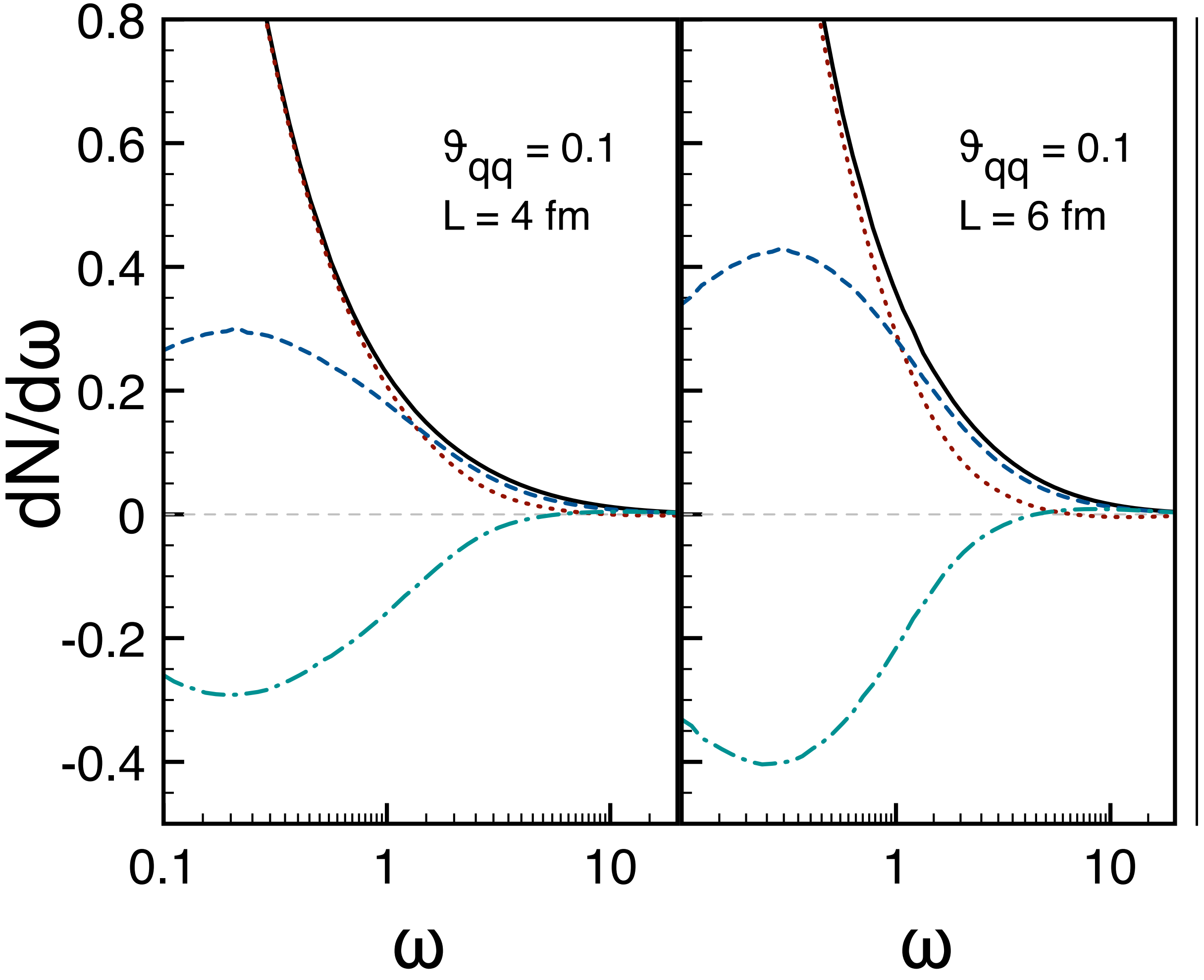
# Some numerics





- ⇛ Numerical implementation of the full spectrum
- ⇛ Antiangular ordering survives upto higher energies

# Integrated in angle - energy spectrum



⇒ GLV takes over at larger energies, pair angles and medium lengths

# Some heuristic arguments

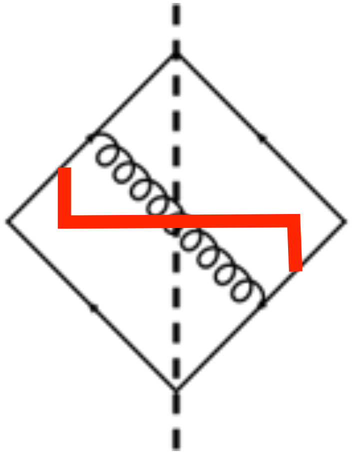
⇒ Why the anti-AO term relevant in medium? Have a look to vacuum

Independent radiation from quark and antiquark regulated in the medium due to LPM

$$\omega \frac{dN^{\rm vac}}{d^3k} \propto \alpha_s C_F \left( \frac{\boldsymbol{\kappa}^2}{(p\cdot k)^2} - 2\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar p\cdot k)} + \frac{\bar{\boldsymbol{\kappa}}^2}{(\bar p\cdot k)^2}\right)$$

Extra term enters with a different phase and not regulated

⇒ Effective change of quark-antiquark color to an octet (not trivial...)



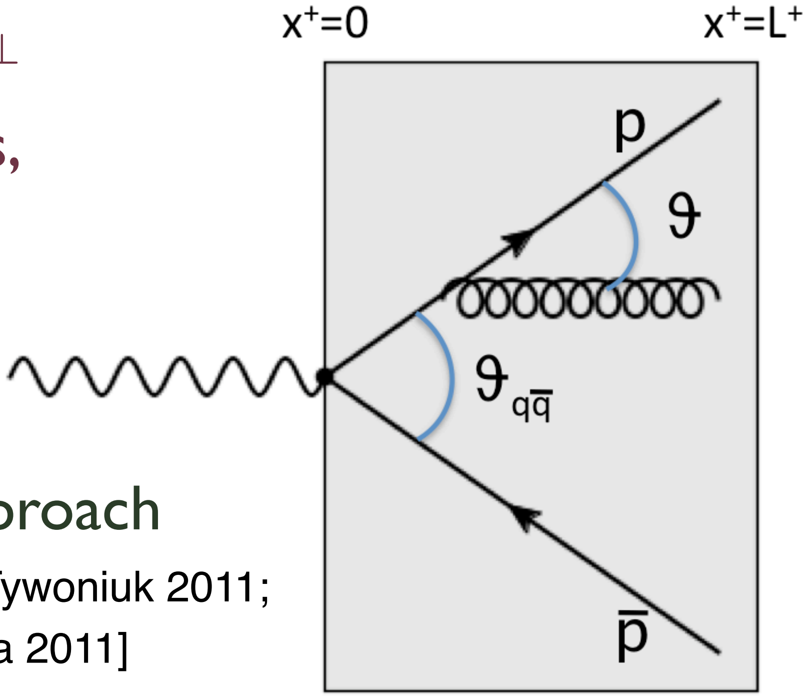
# Multiple soft scattering

# Multiple soft scattering: recipe for calculation

- Write [see e.g. Casalderrey-Solana, Salgado arXiv:07123443]
  - Quark propagation $W(\mathbf{x}_\perp; x_+, y_+)$
  - Gluon propagation $G(\mathbf{x}_\perp, x_+; \mathbf{y}_\perp, y_+)$
  - Quark-gluon hard vertex (take care of the angles for antenna)

$$\frac{1}{k_+}\frac{\partial}{\partial \mathbf{x}_\perp}$$

  - Then include Fourier transforms, integrals, color traces, factors....



- Equivalently, use the semiclassical approach

[Mehtar-Tani 2006 for BDMPS; Mehtar-Tani, Salgado, Tywoniuk 2011; Mehtar-Tani, Tywoniuk 2011; Iancu, Casalderrey-Solana 2011]

# The soft limit first

- ⇛ A more clear picture emerges

[Mehtar-Tani, Salgado, Tywoniuk 2011]

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

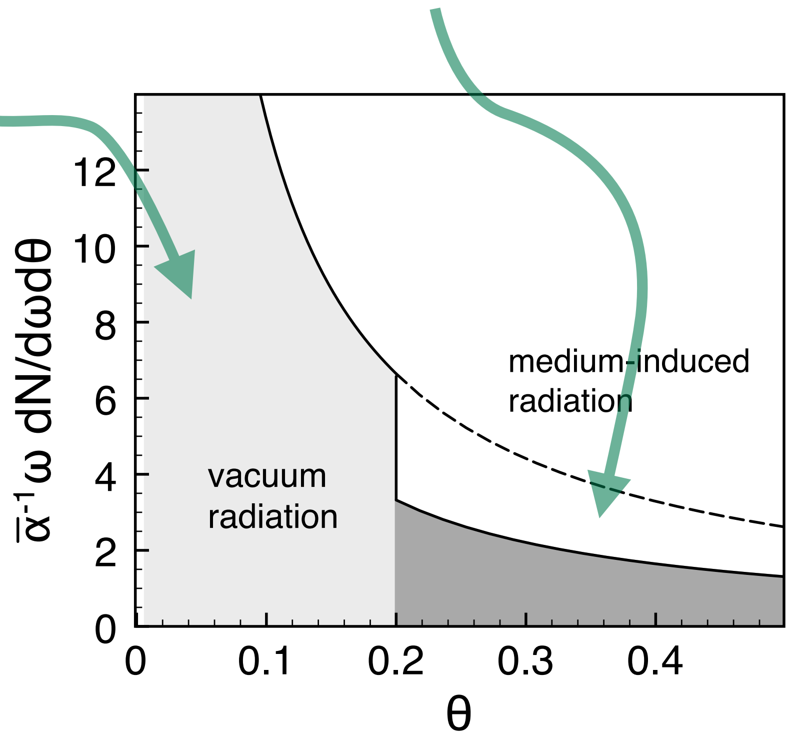
- ⇛ Where

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

- ⇛ In the opaque limit $\Delta_{\rm med} \longrightarrow 1$

**decoherence**

- ⇛ Moreover, octet and singlet are the same



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

**memory loss**

- ⇛ **Vacuum-like soft radiation outside the initial cone**

# Multiple soft scattering: the complete spectrum

- ⇛ The complete formula [Mehtar-Tani, Tywoniuk 2011; Iancu, Casalderrey-Solana 2011]

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

- ⇛ Where $\mathcal{R}_{\text{sing}} = \mathcal{R}_q + \mathcal{R}_{\bar{q}} - 2\,\mathcal{J}$ . Here $\mathcal{R}_q \, , \mathcal{R}_{\bar{q}}$ are the BDMPS and

$$\begin{aligned}\mathcal{J} = \mathrm{Re}\Bigg\{ &\int_0^\infty dy'^+ \int_0^{y'^+} dy^+ \left(1 - \Delta_{\text{med}}(y^+, 0)\right) \\ &\times \int d^2\boldsymbol{z} \, \exp\left[-i\bar{\boldsymbol{\kappa}} \cdot \boldsymbol{z} - \frac{1}{2}\int_{y'^+}^\infty d\xi \, n(\xi)\sigma(\boldsymbol{z}) + i\frac{k^+}{2}\delta\boldsymbol{n}^2 y^+\right] \\ &\times \left(\boldsymbol{\partial}_y - ik^+\,\delta\boldsymbol{n}\right) \cdot \boldsymbol{\partial}_z \, \mathcal{K}(y'^+, \boldsymbol{z}\,; y^+, \boldsymbol{y}\,|k^+)\Big|_{\boldsymbol{y}=\delta\boldsymbol{n}y^+} \Bigg\} + \text{sym.}\,, \qquad (36)\end{aligned}$$

- ⇛ Interferences parametrically suppressed for $\theta_{q\bar{q}} > \sqrt{\dfrac{1}{\hat{q}\,L^3}}$
  - ➘ BDMPS not cancelled

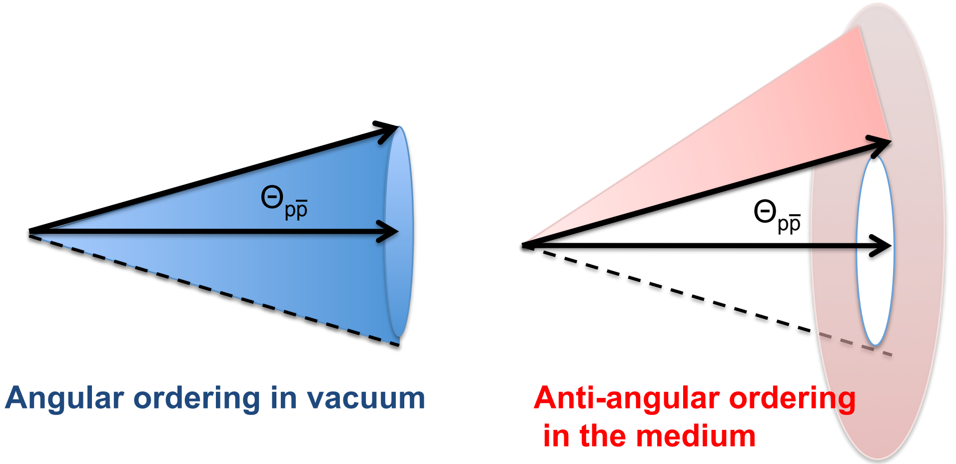
[Iancu, Casalderrey-Solana 2011]

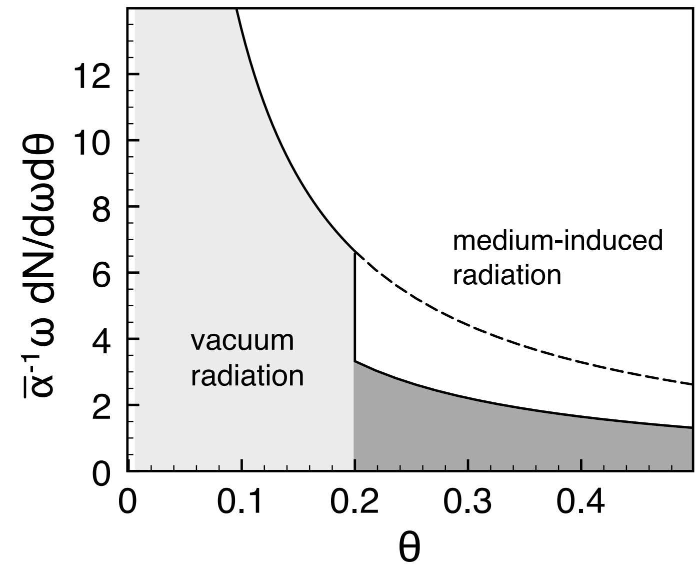
- ⇛ Numerical evaluation ongoing

# Summary of antenna radiation in medium

- Very striking result found in the medium [Mehtar-Tani, Salgado, Tywoniuk 2010]
  - Strict large angle emission - anti-angular ordering in soft limit

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





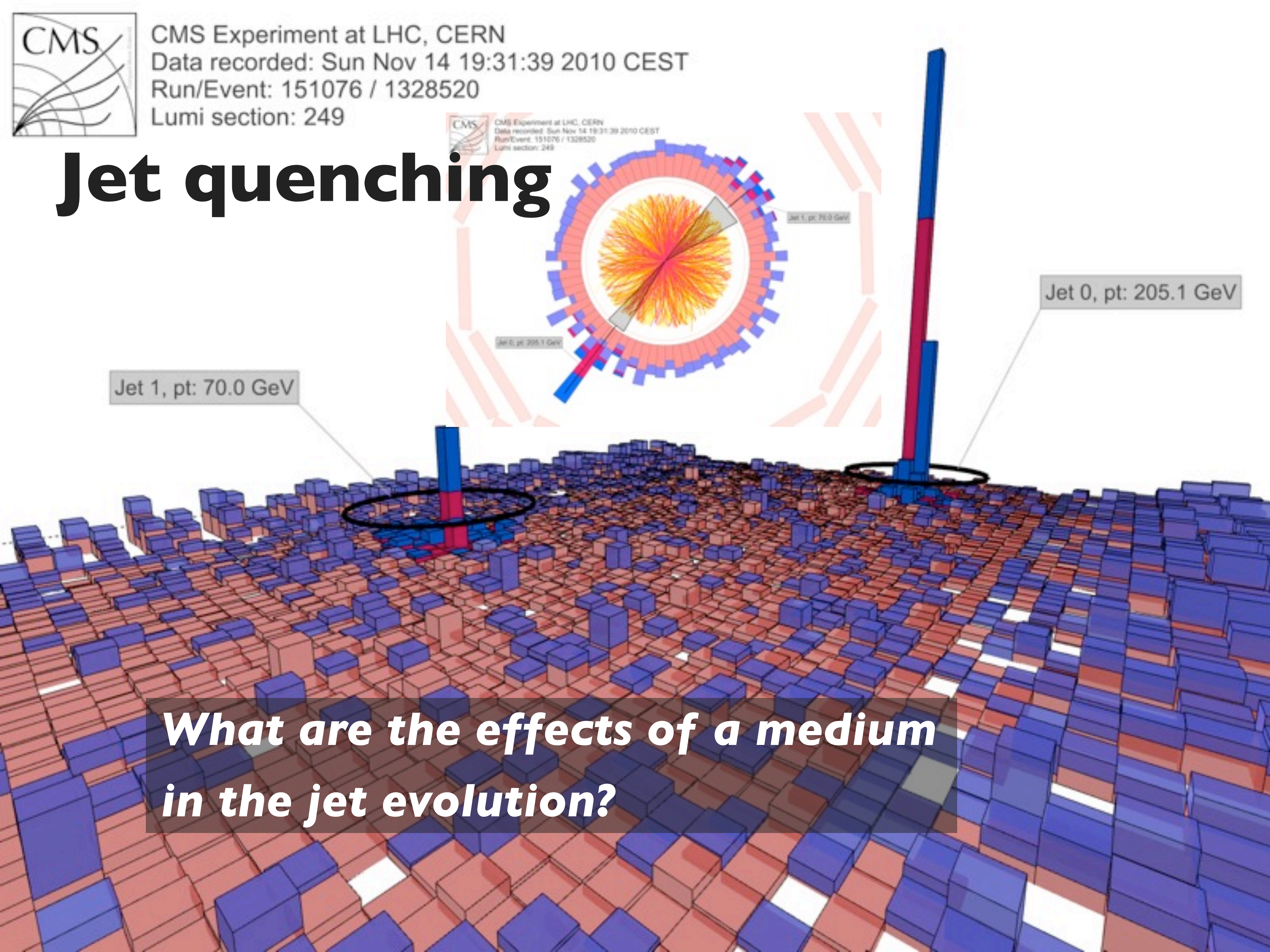
- For an opaque medium, two **vacuum-like de-coherent** spectra
  - Soft emission at large angle. Promising tool for in-medium shower
  - Memory loss effect: radiation independent on initial color config.

# I know ….

**I know ....**

**.... but I cannot resist...**

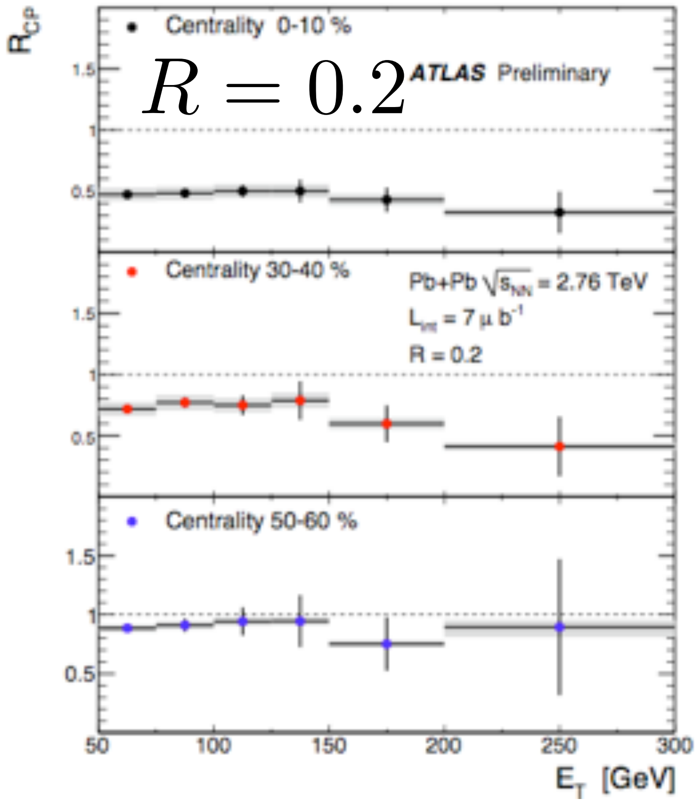
# Jet quenching

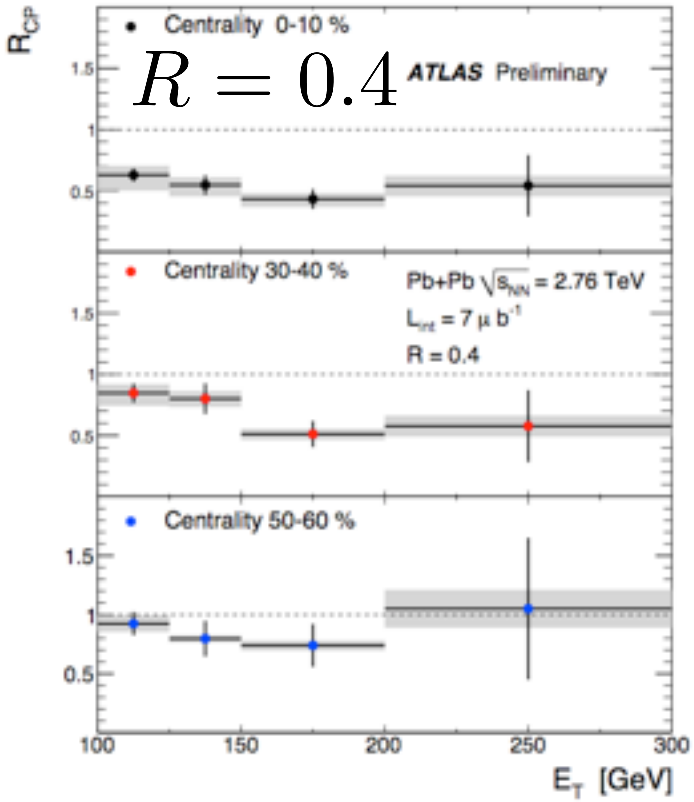


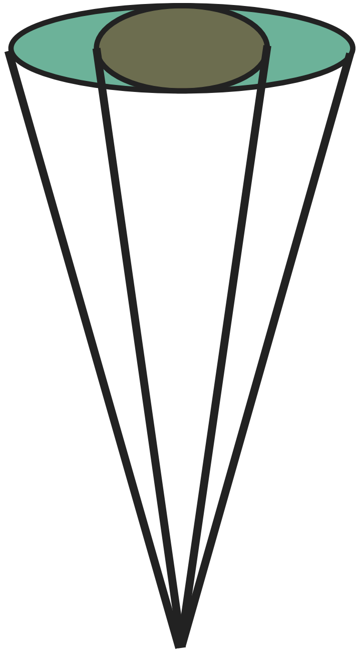
*What are the effects of a medium in the jet evolution?*

# Inclusive jets are suppressed

- ⇛ In central collisions, only 1/2 of the jets are observed for two radius R [ATLAS 2010 - B. Cole QM2011]





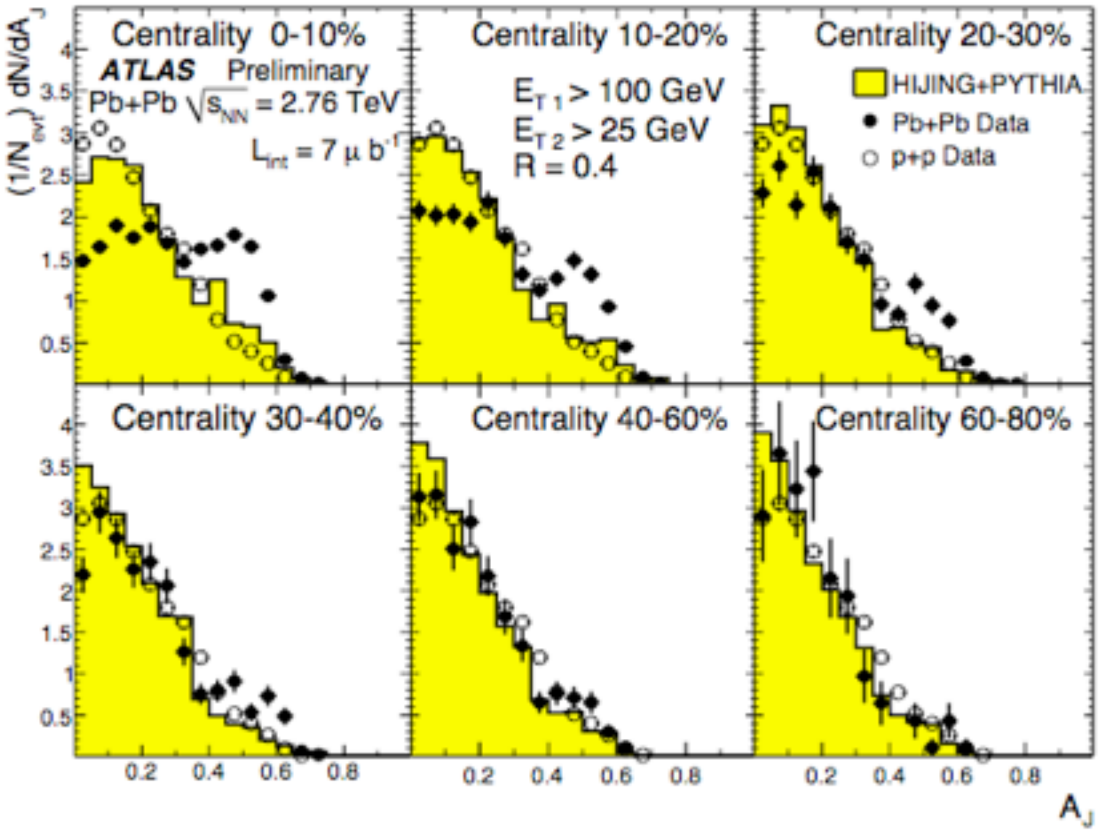


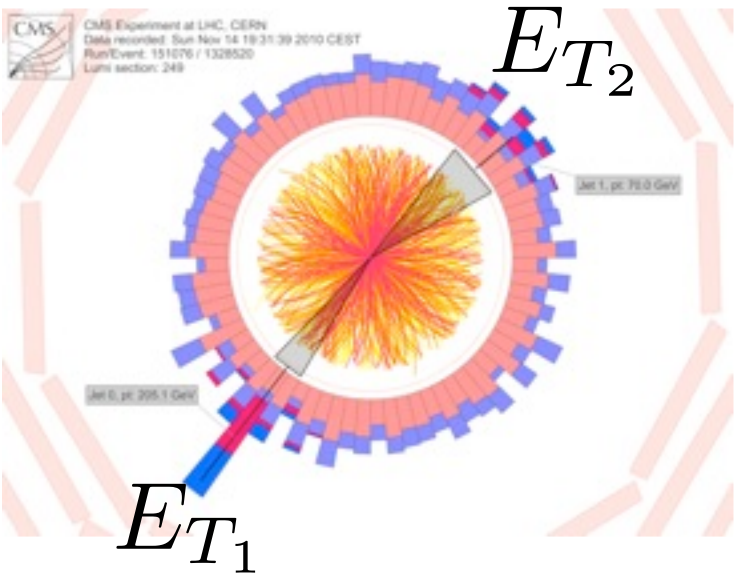
- ⇛ Need to understand proton-proton reference
- ⇛ **Observed (and studied) jets are biased**

# Di-jet asymmetry at the LHC

⇛ Energy imbalance between two most energetic jets: $A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$

[ATLAS 2010 - B. Cole QM2011; CMS similar results]



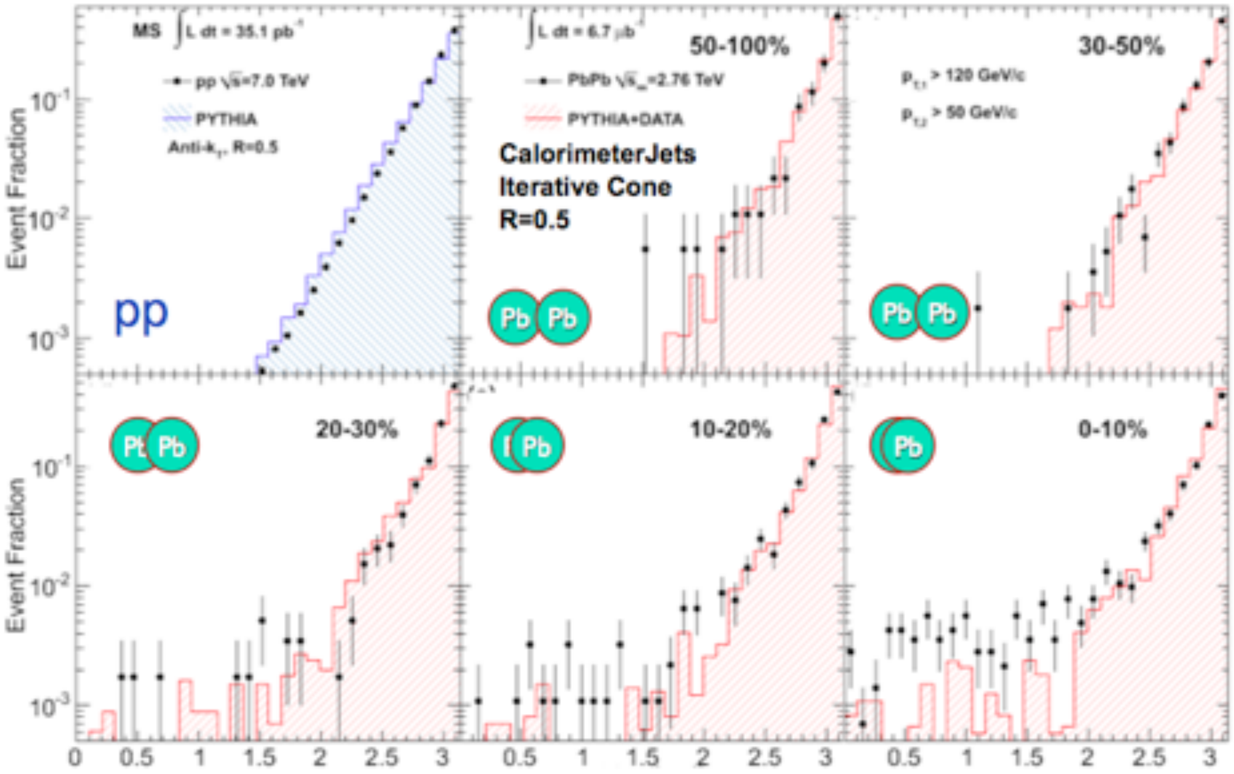


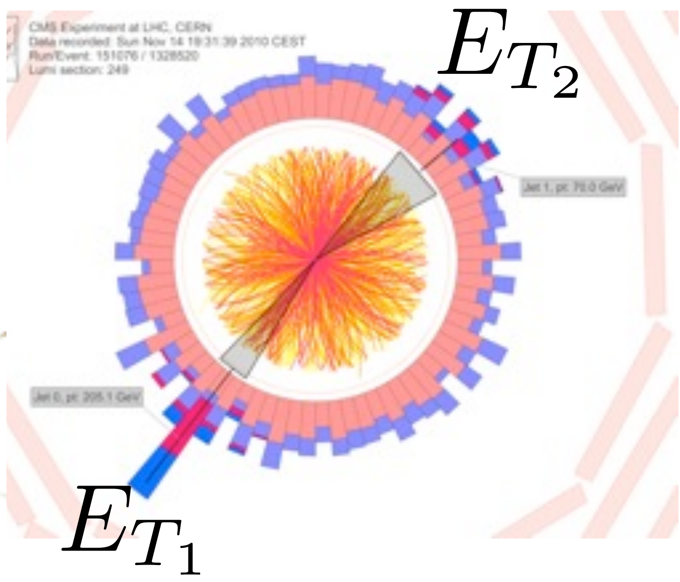
⇛ Strong energy loss - points to a **very dense partonic system**

# Di-jet asymmetry at the LHC

⇛ Azimuthal distribution of two most energetic jets

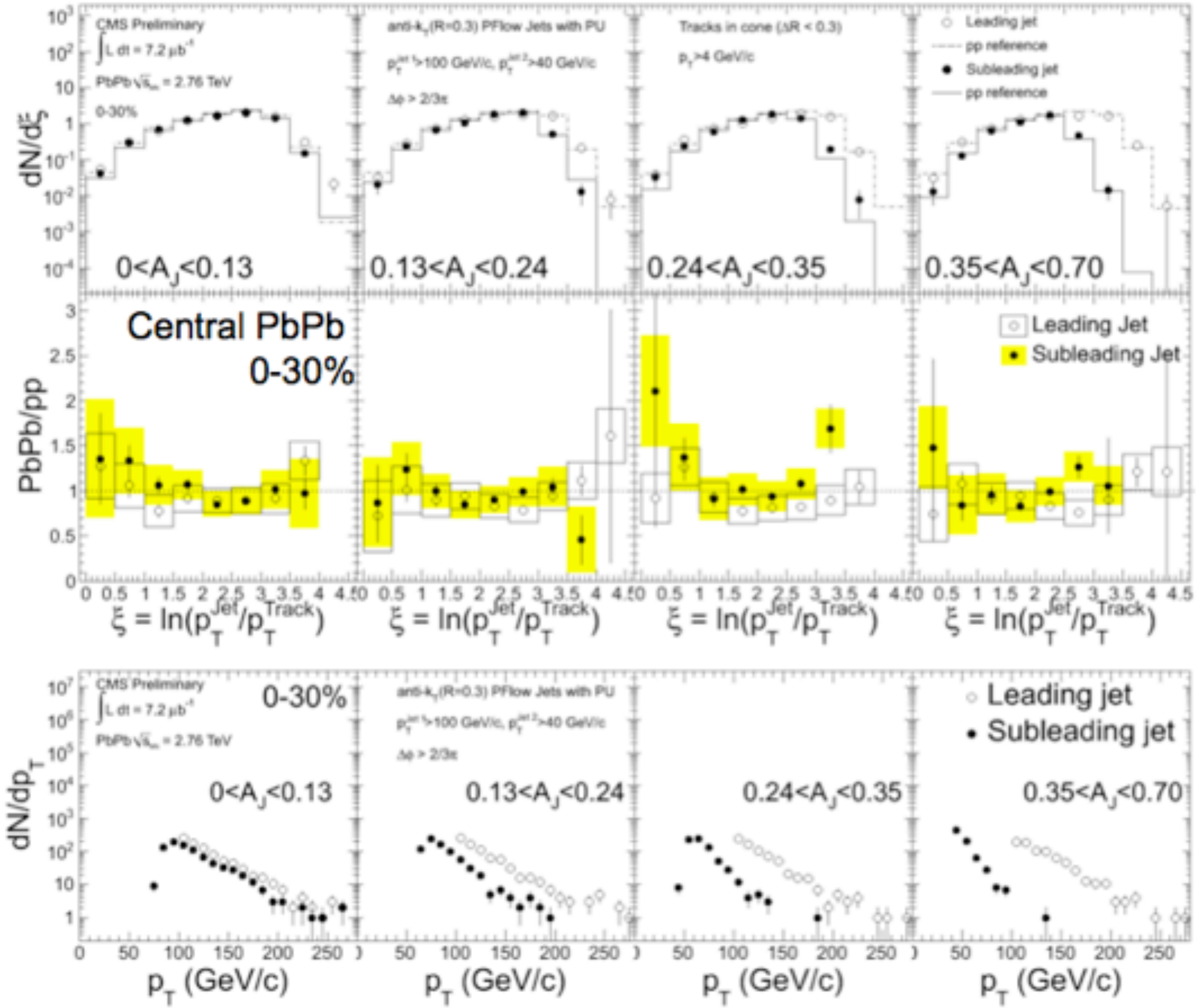
[CMS 2011 - C. Roland QM2011; ATLAS similar results]





⇛ **No strong change with respect to the vacuum jets**

# Fragmentation functions

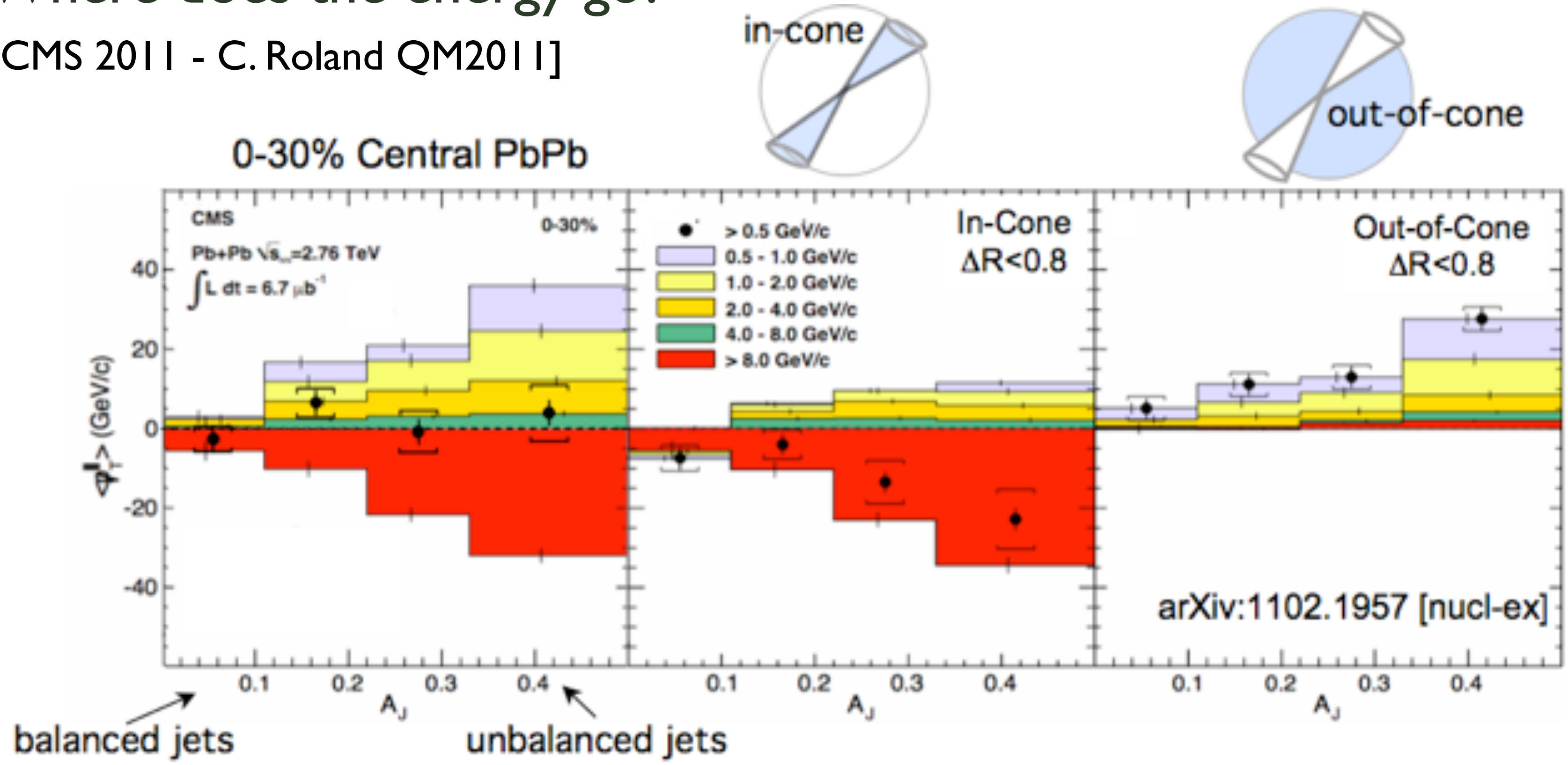


[From C. Roland QM2011]

# Di-jet asymmetry at the LHC

- ⇛ Where does the energy go?

  [CMS 2011 - C. Roland QM2011]



$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

- ⇛ **Energy taken by soft particles at large angles**

# ***Summary***

- ***Towards a theory of jets in a medium***
  - Radiation off one emitter known for 15 years: BDMPSZ, GLV...
  - Jets described by multiparton objects radiating sequentially
- Fundamental questions about ***in-medium color coherence***
  - ***Antenna provides an ideal setup***
- ***Striking features***
  - Anti-angular ordering and decoherence
  - Infrared divergency - vacuum-like spectrum
  - "Broadening without pt-broadening"
- A first look at data shows some <u>qualitative</u> agreement
  - ***Vacuum-like radiation & soft particles at large angle***