LUND UNIVERSITY

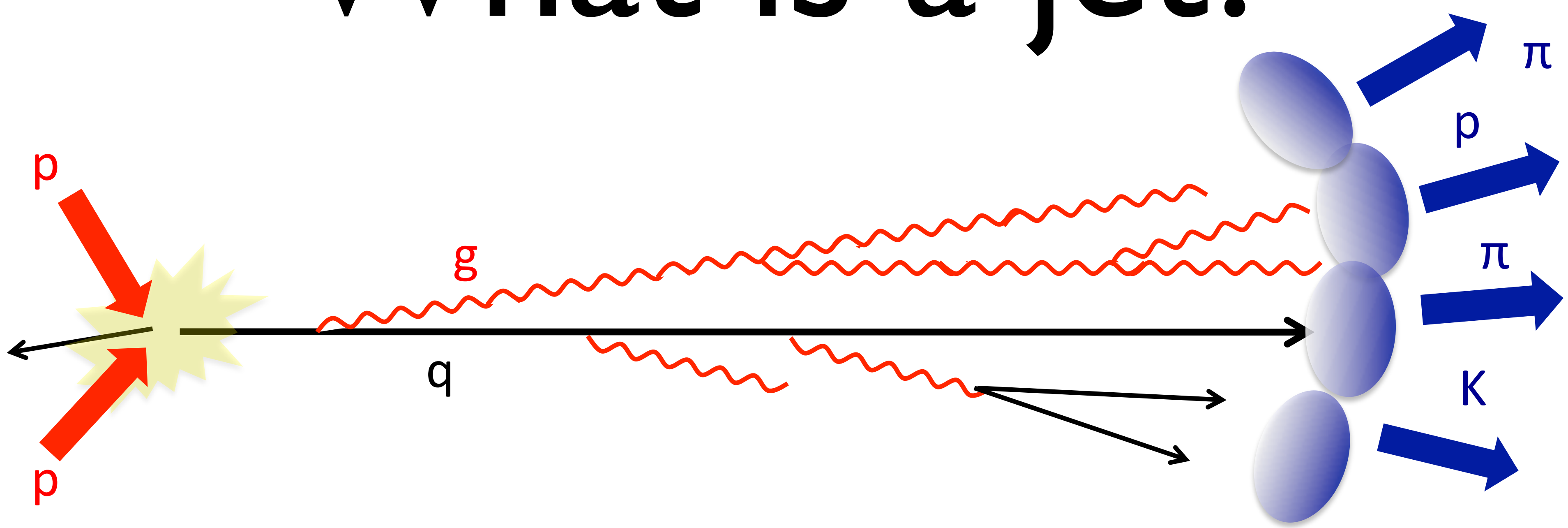
Jets in QCD media

Konrad Tywoniuk

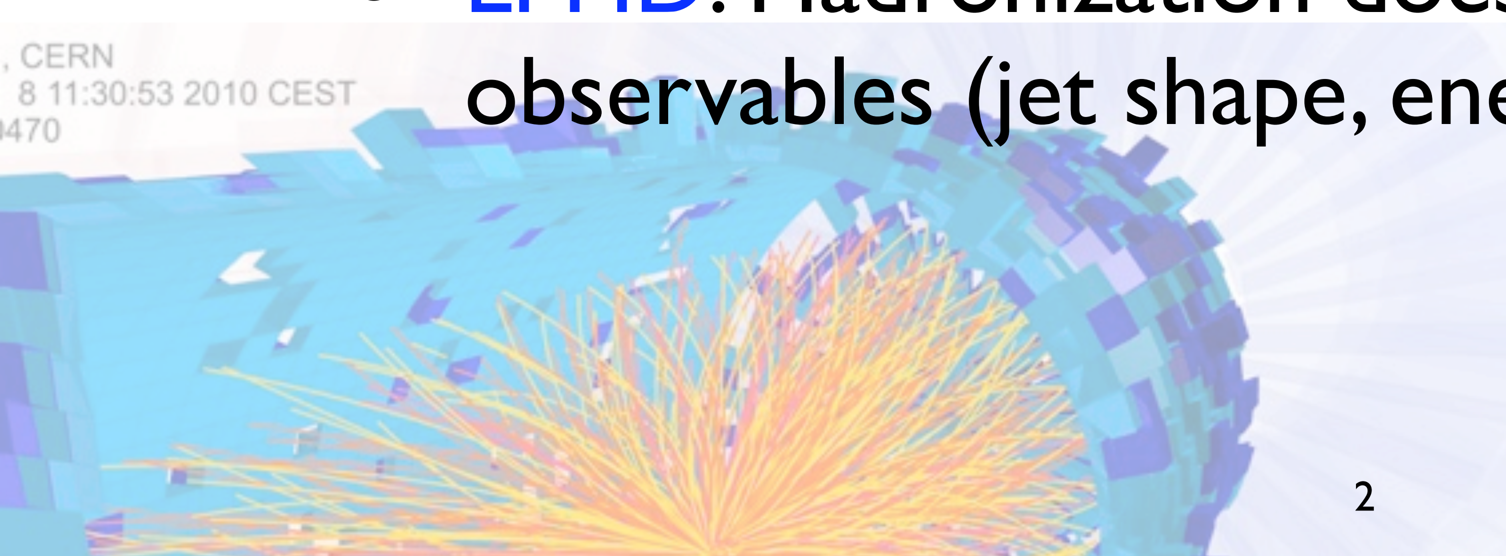
Y. Mehtar-Tani, C.A. Salgado, KT PRL 106 (2011) 122002
Y. Mehtar-Tani, C.A. Salgado, KT PLB 707 (2011) 156
Y. Mehtar-Tani, KT arXiv:1105:1346 [hep-ph]
Y. Mehtar-Tani, C.A. Salgado, KT arXiv:1112.5031 [hep-ph]

Recontres Ions Lourds, IPN Orsay, Paris
17 february 2012

What is a jet?



- Originally a hard parton (quark/gluon) which fragments into many partons with virtuality down to a non-perturbative scale where it hadronizes
- LPHD: Hadronization does not affect inclusive observables (jet shape, energy distribution etc..)



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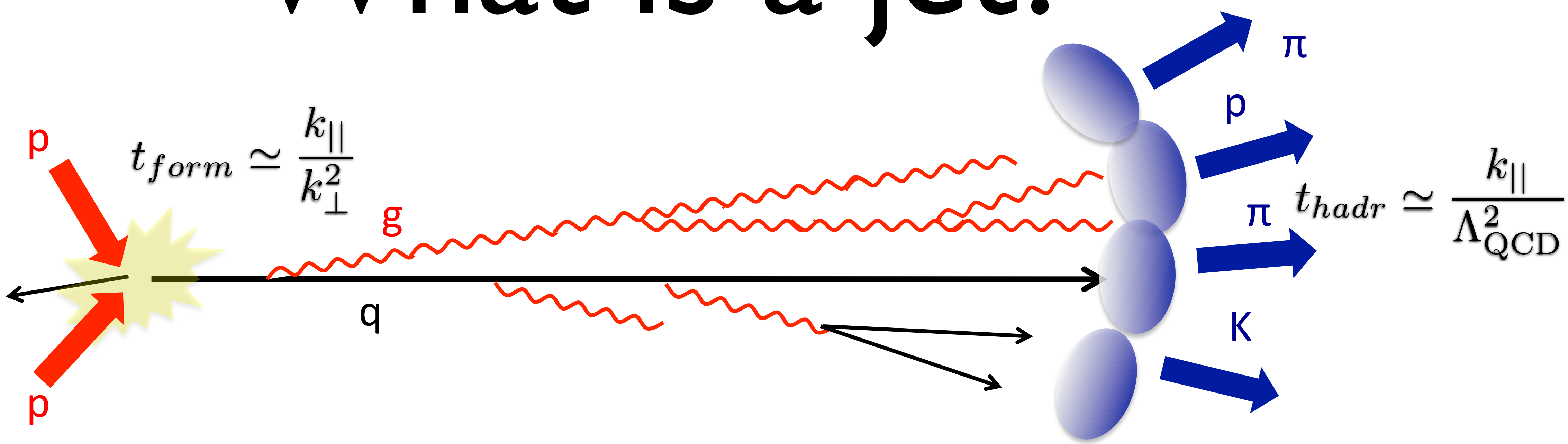

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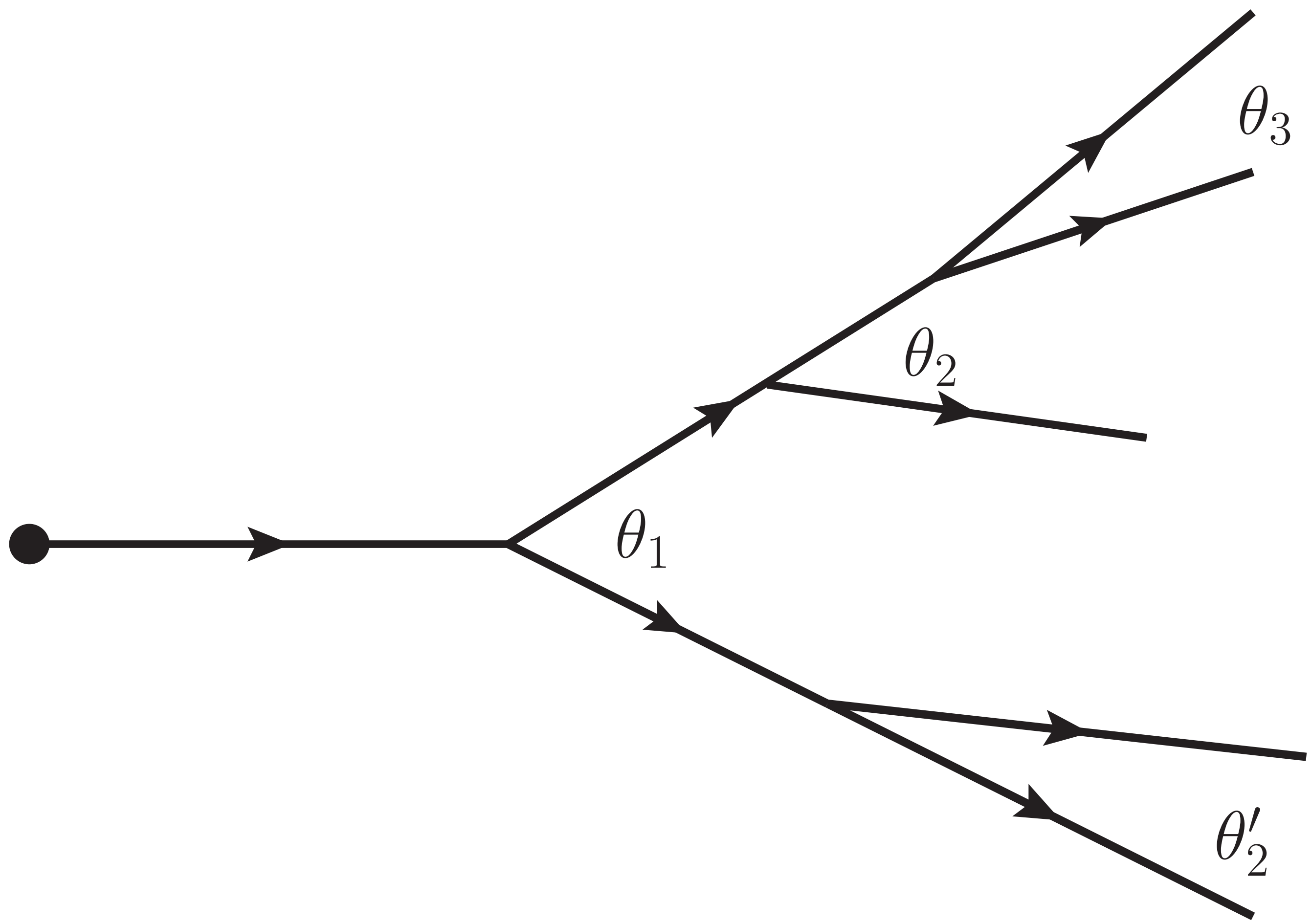
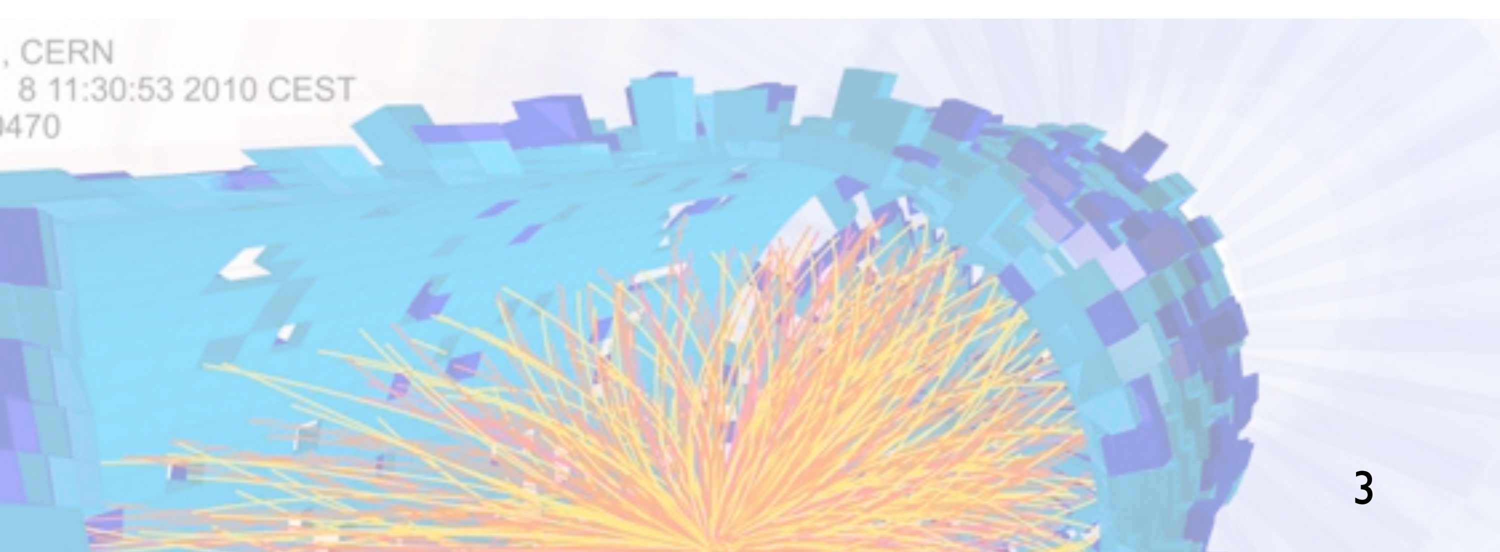
Large time domain for pQCD: $$\frac{1}{\sqrt{s}} < t < \frac{\sqrt{s}}{\Lambda^2_{QCD}}$$

Parton branching in QCD

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





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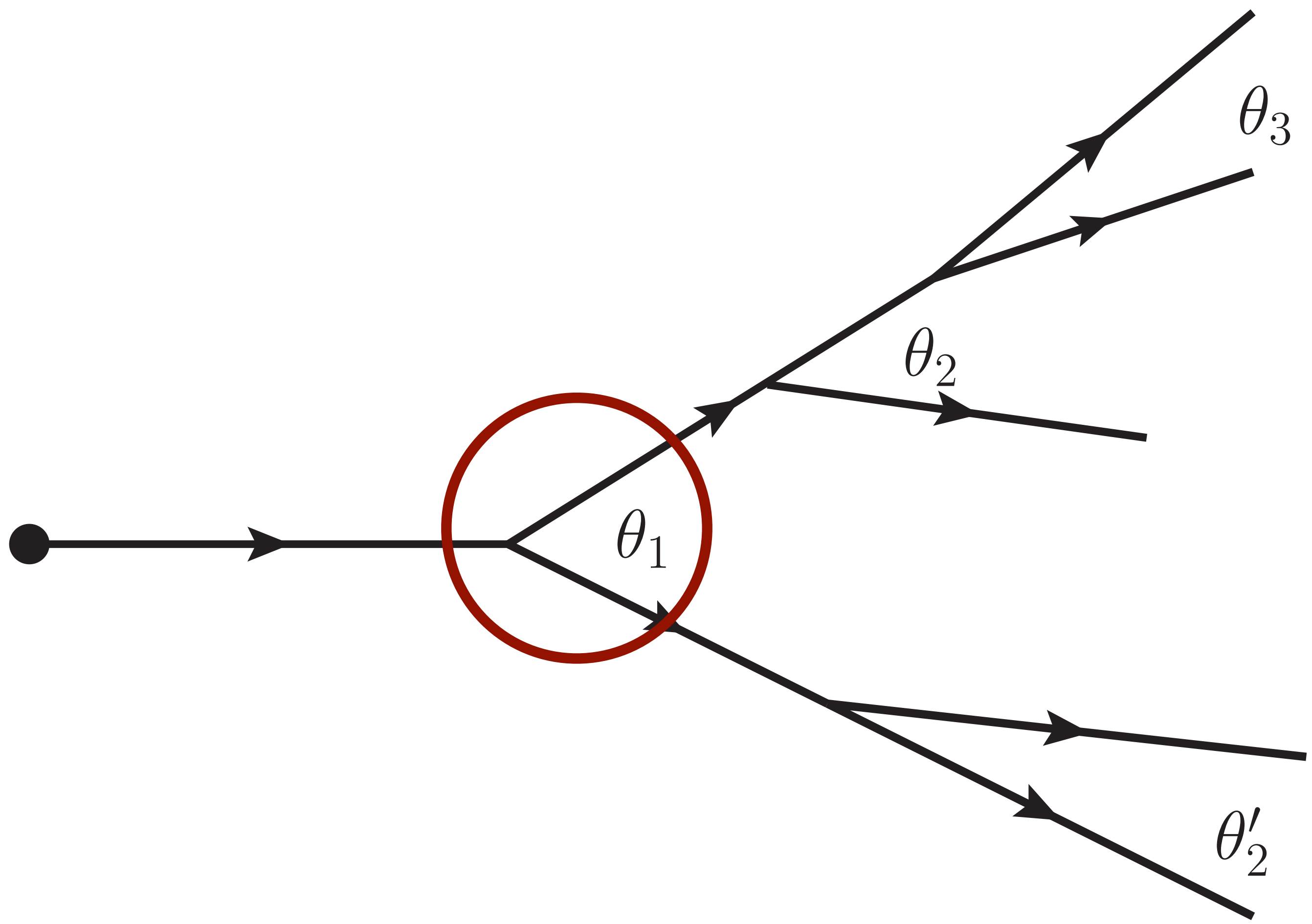
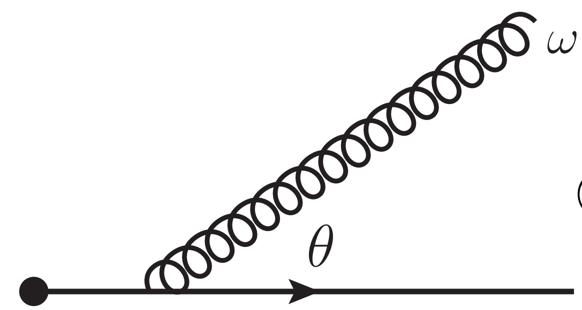


Leading singularities



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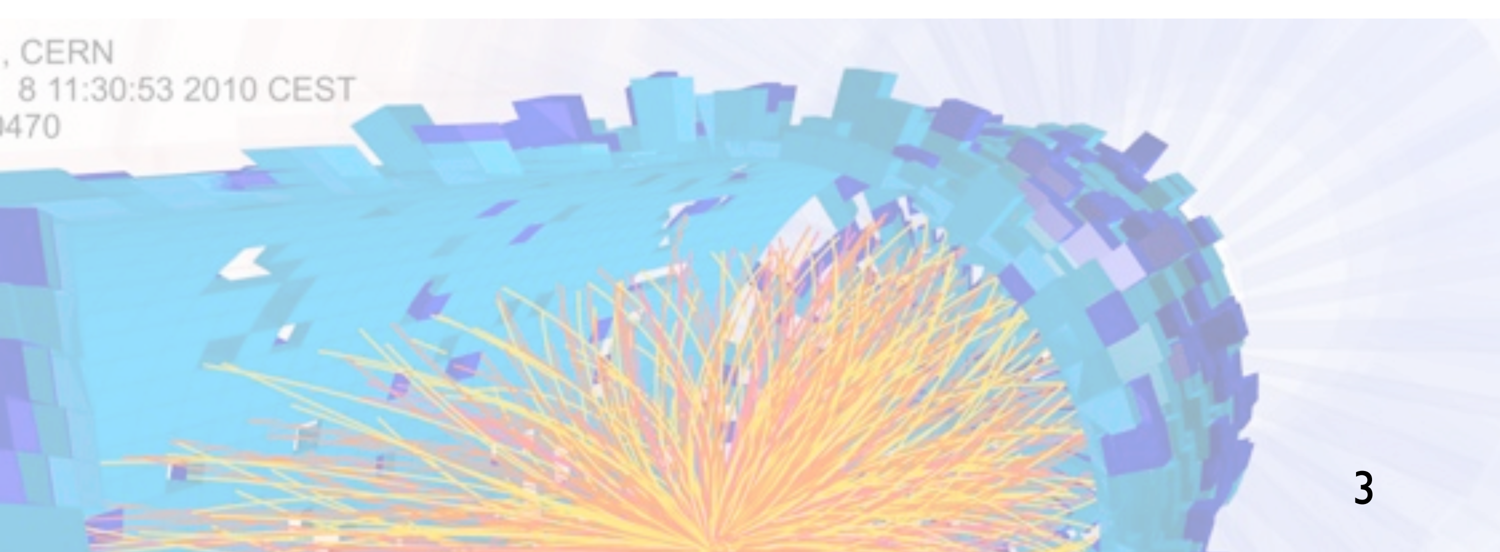

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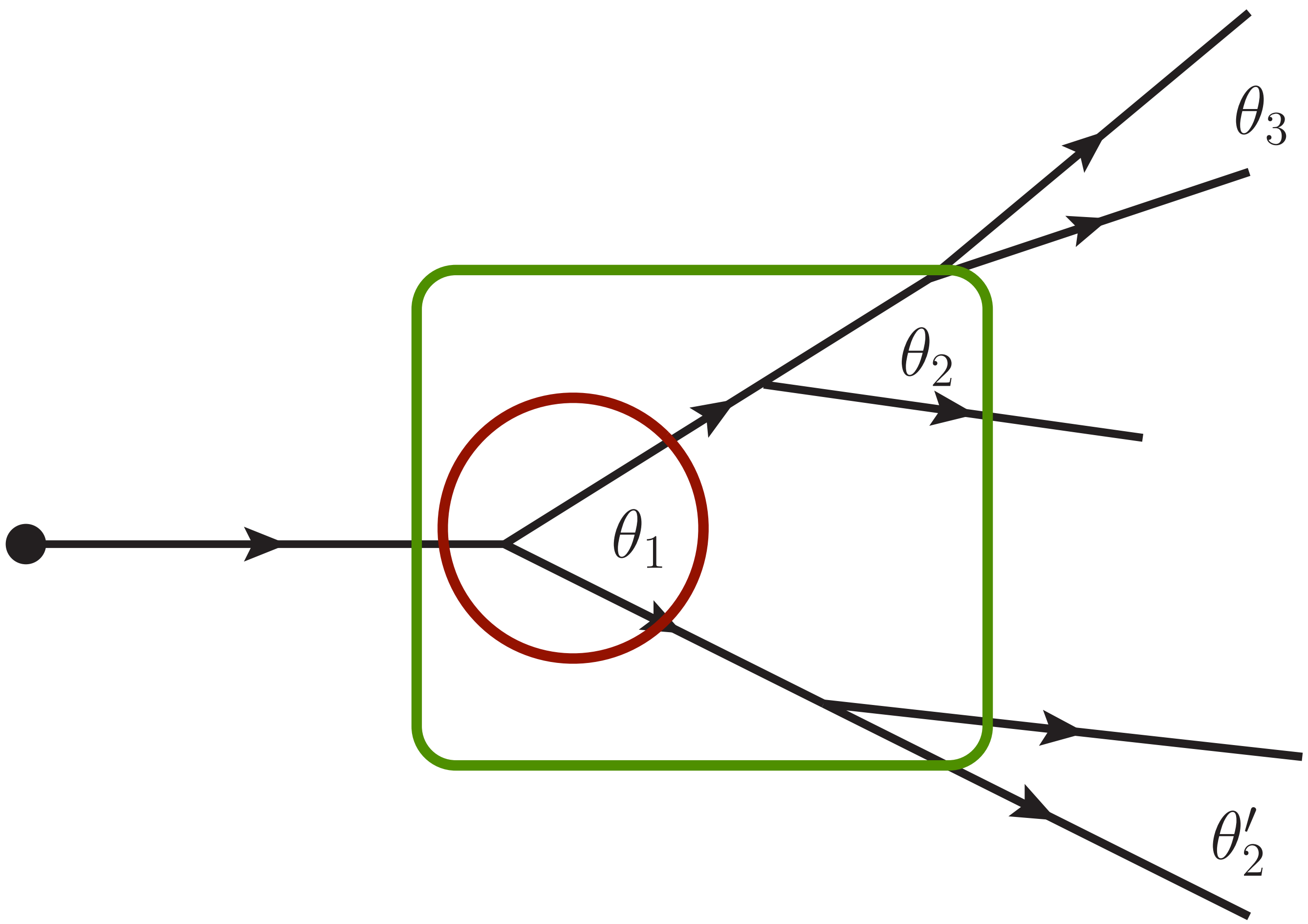

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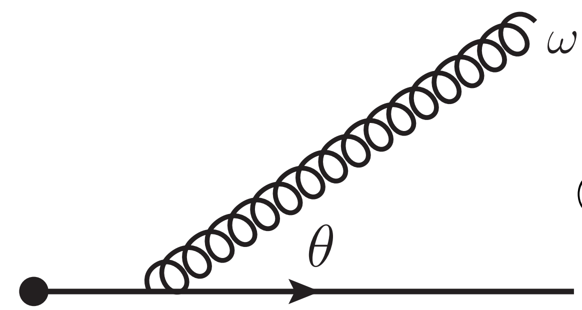

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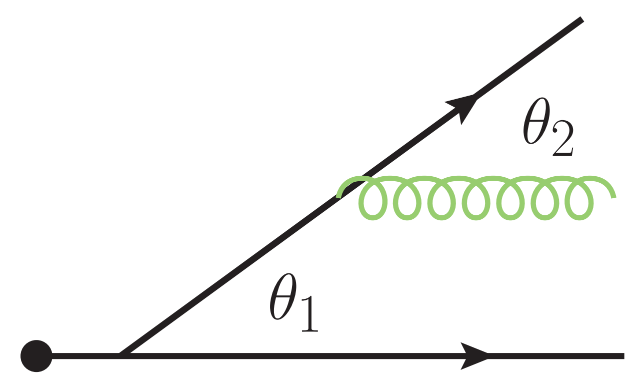
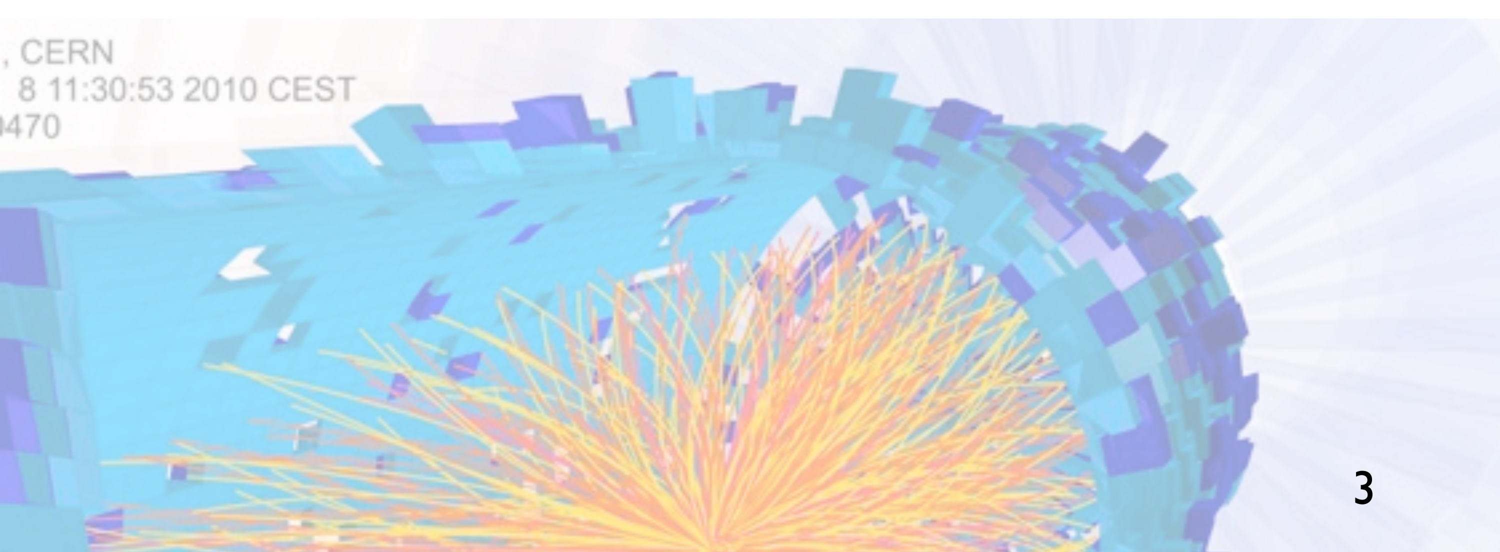


$$\propto \Theta(\theta_1 - \theta_2)$$



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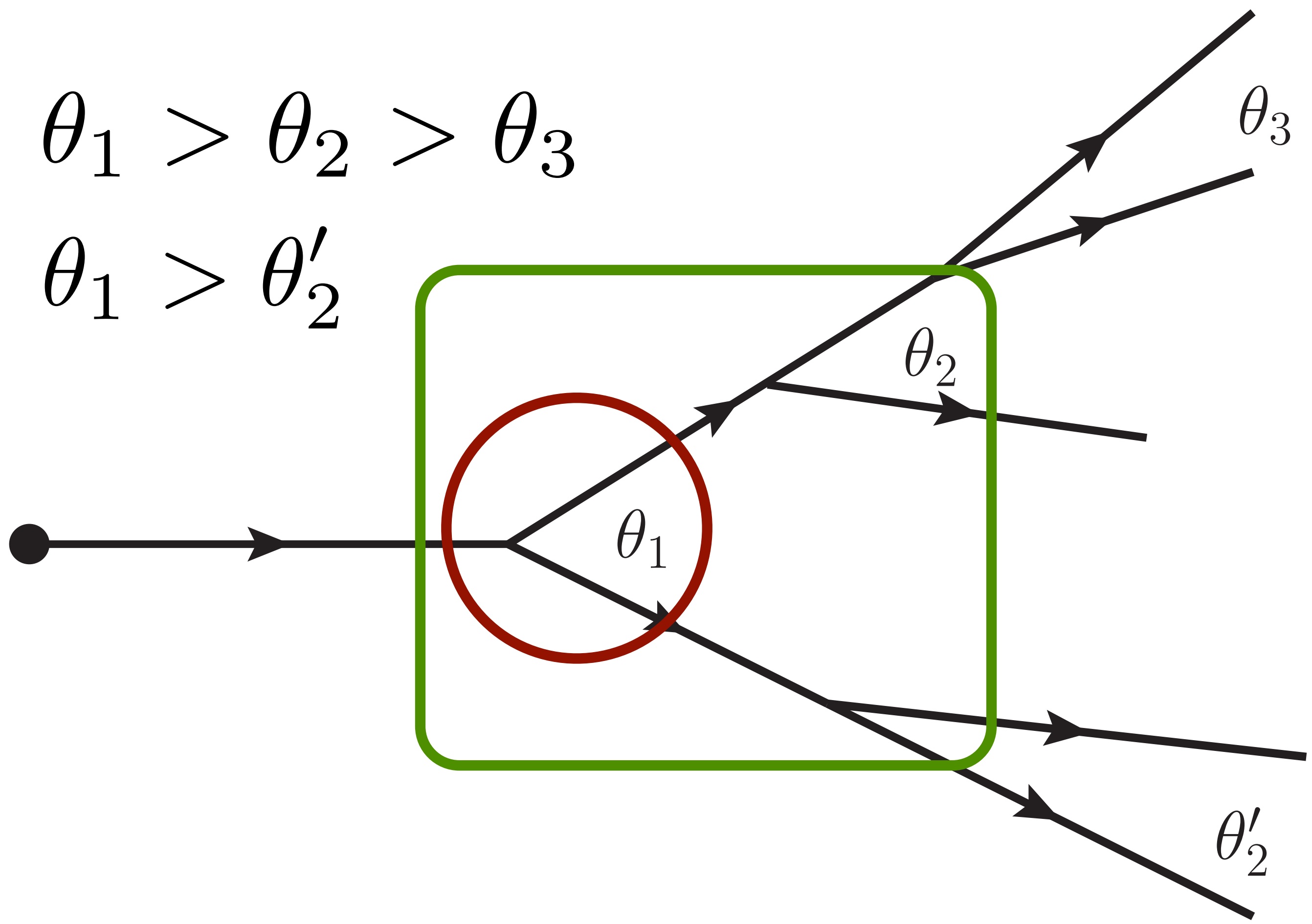

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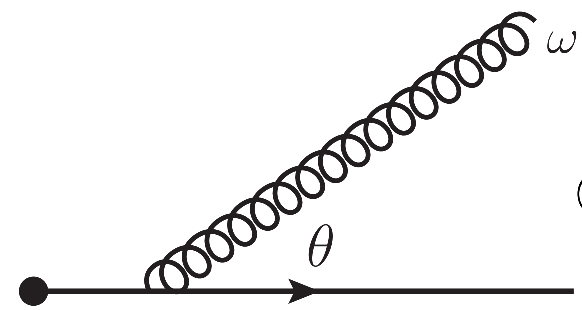

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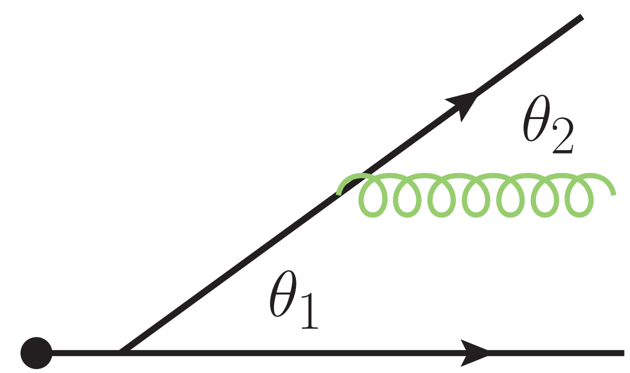

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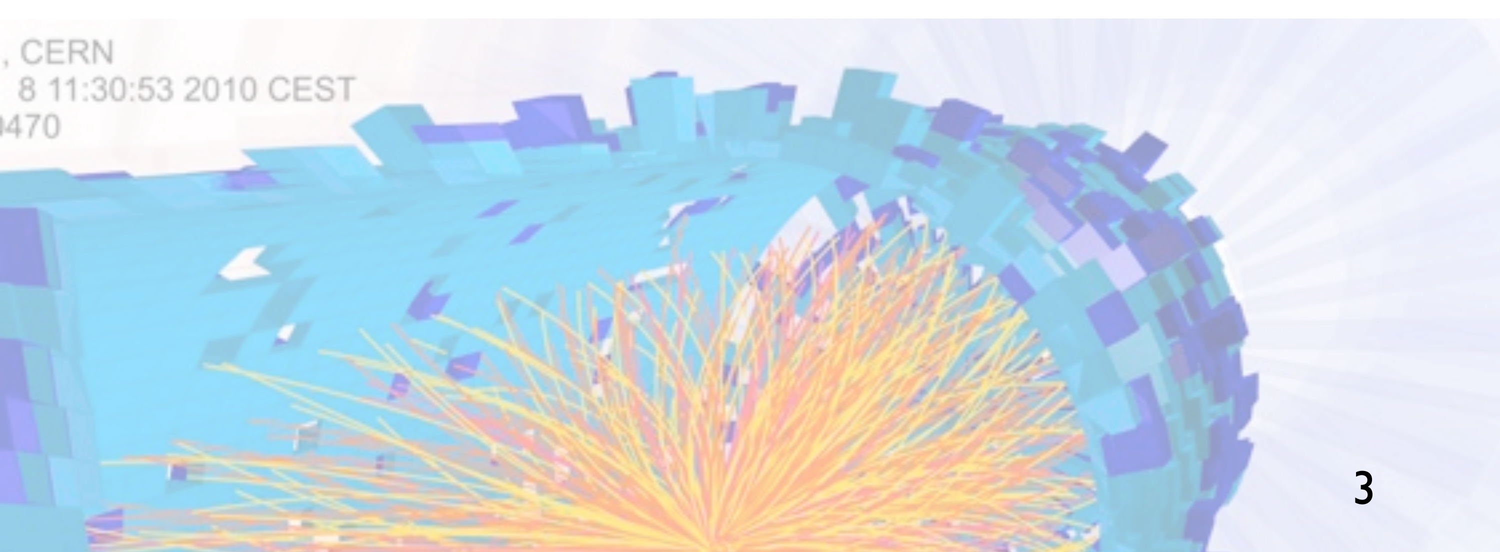
Markovian process!



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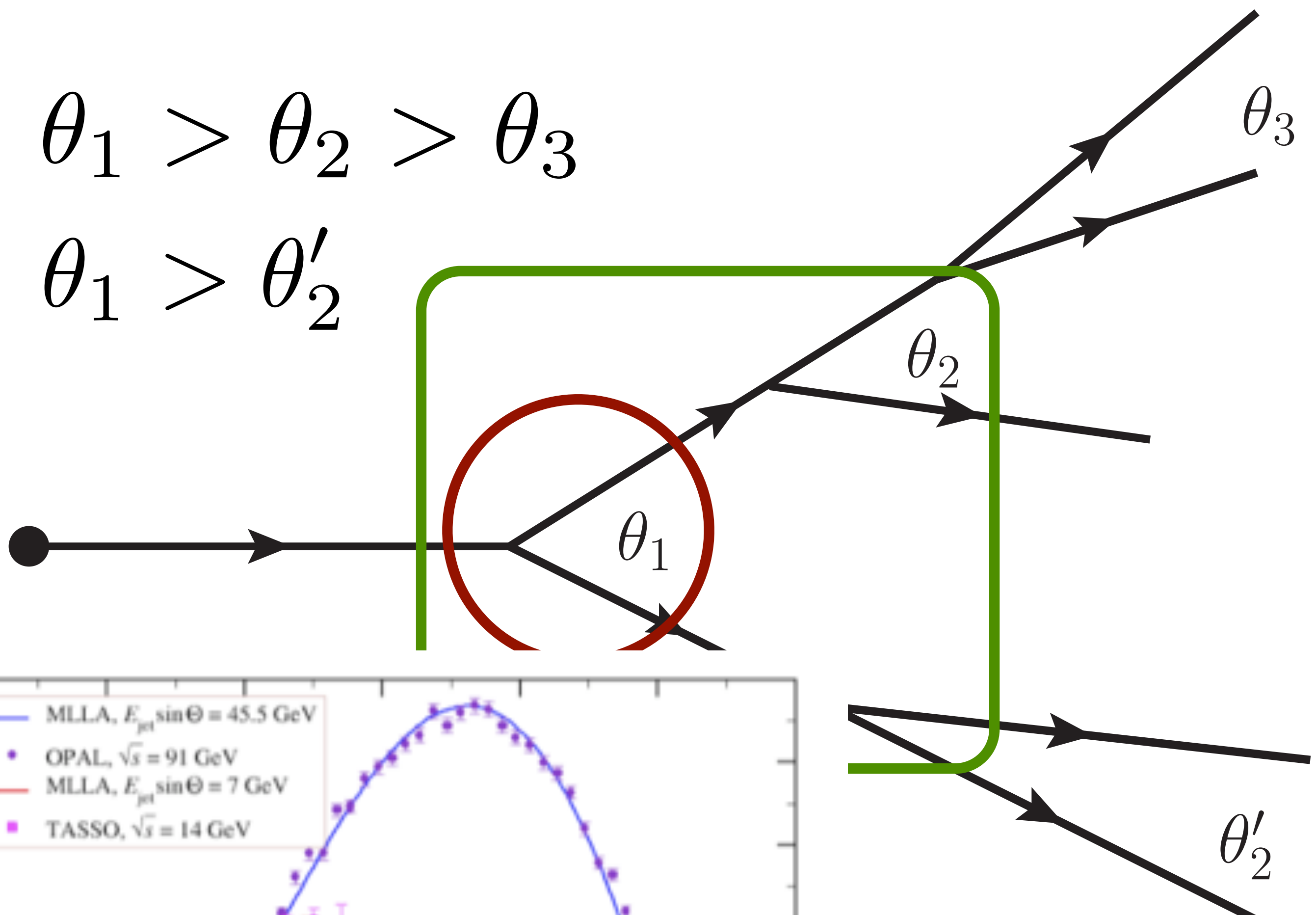

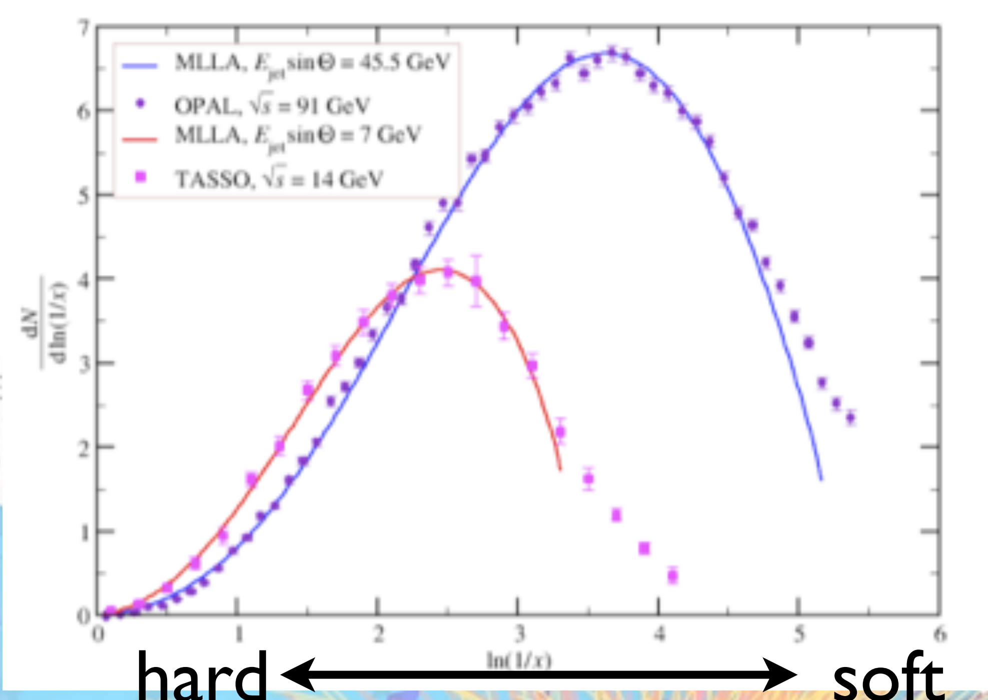

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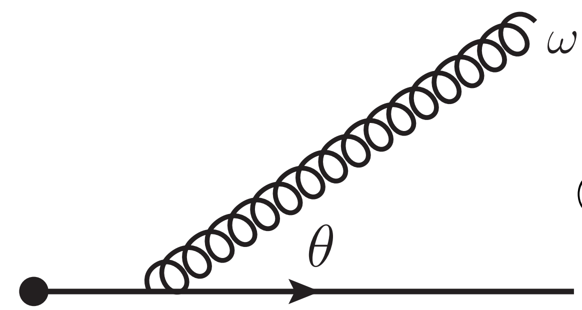

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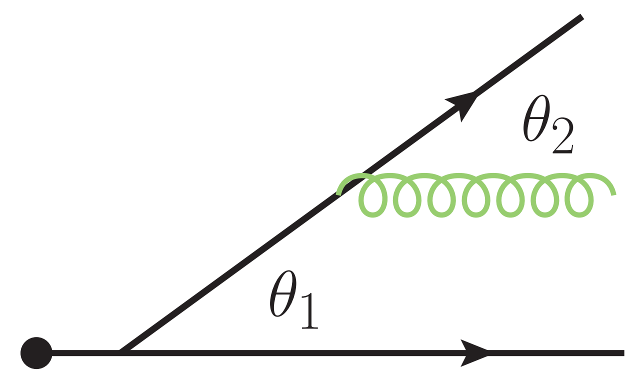

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TASSO Collaboration, Z. Phys. C 47 (1990)
OPAL Collaboration, Phys. Lett. B 247 (1990)

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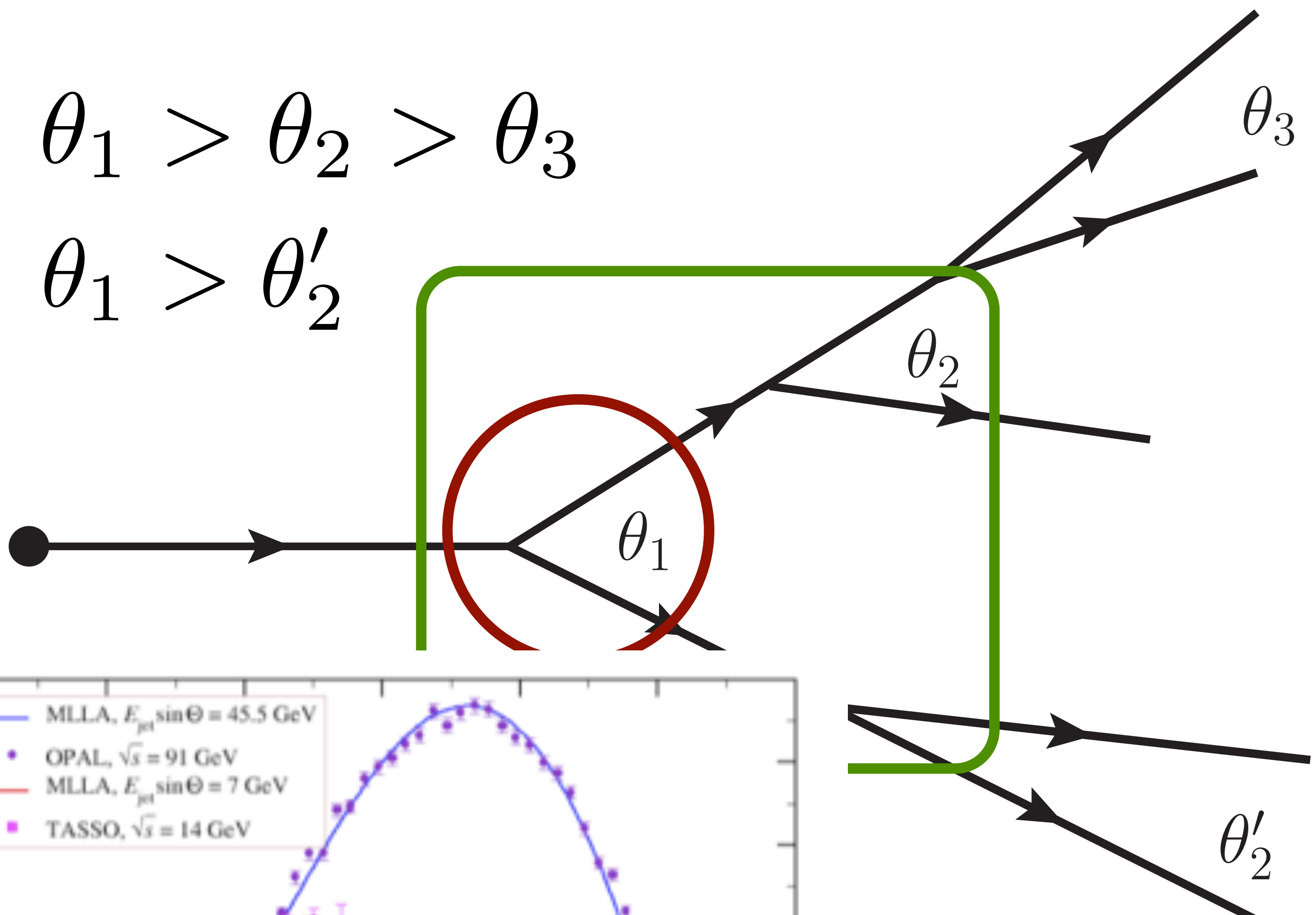

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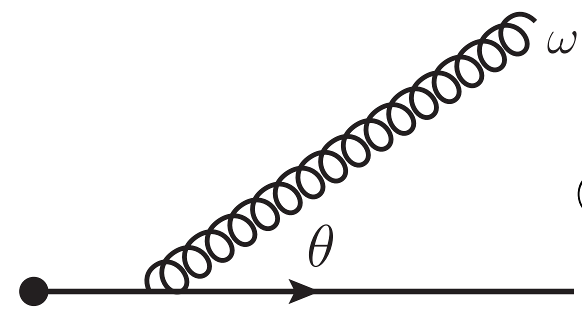

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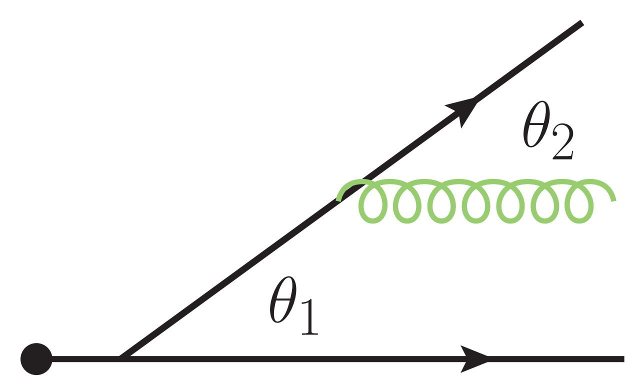

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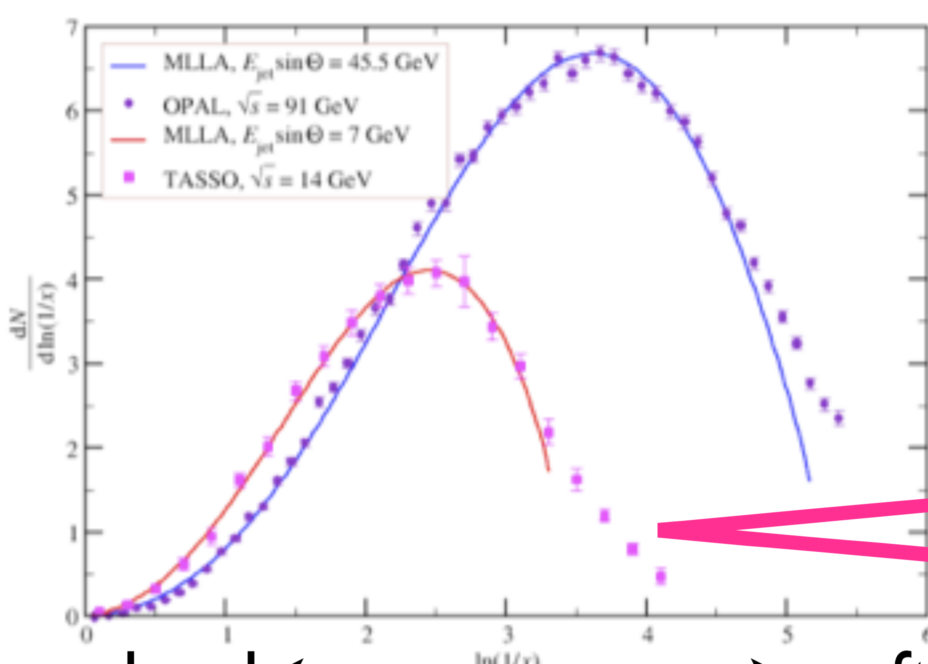

hard ⟷ soft

AO limits phase space for soft emissions!

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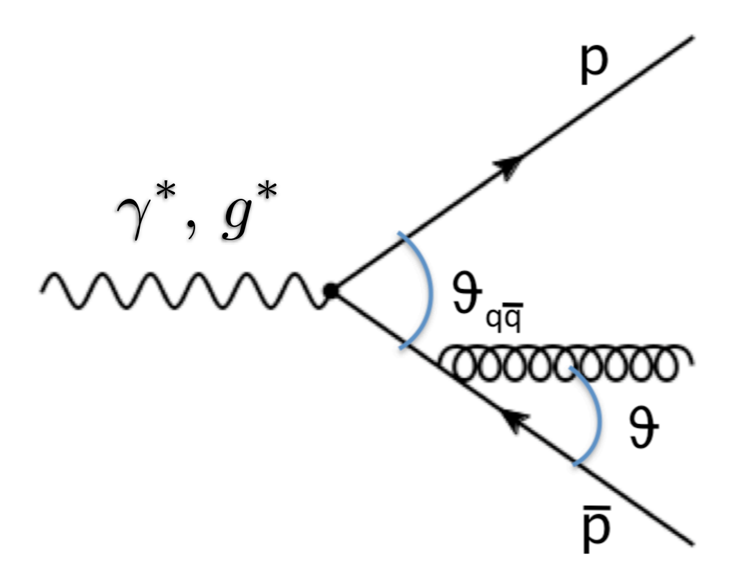
ANTENNA SPECTRUM



$\Rightarrow$ a laboratory to study coherence effects.

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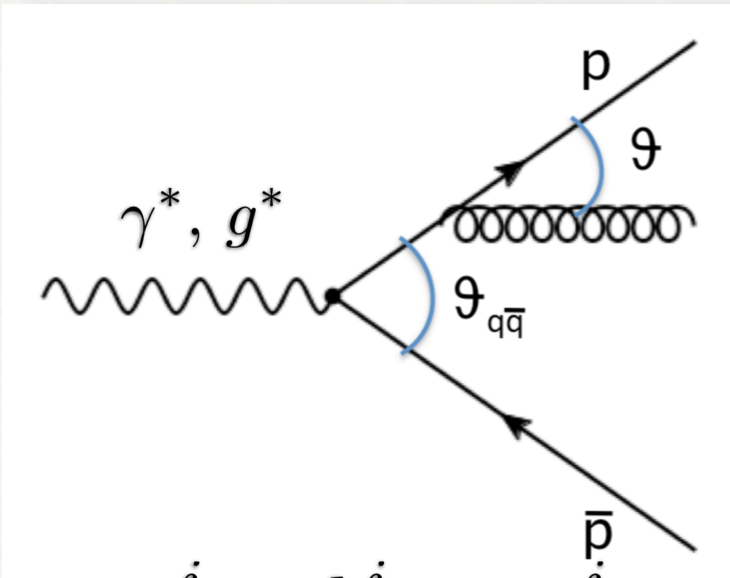

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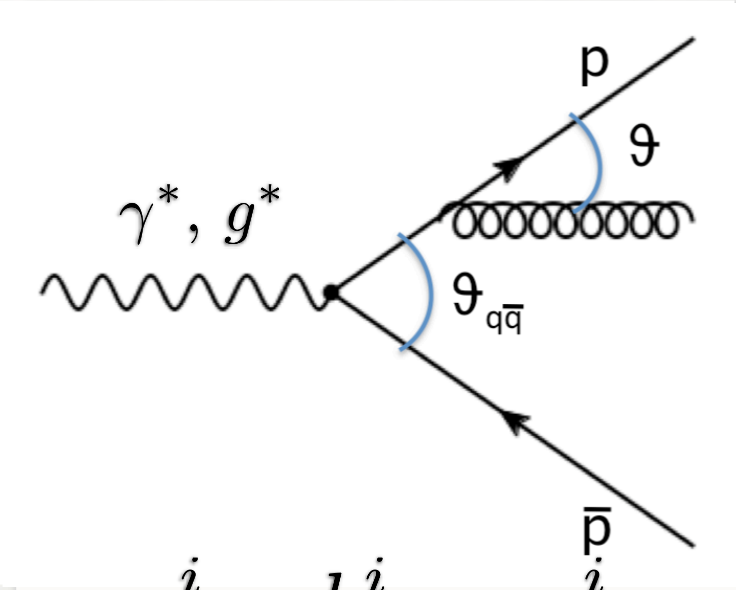

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$Q_q + Q_{\bar{q}} = Q_g$: octet

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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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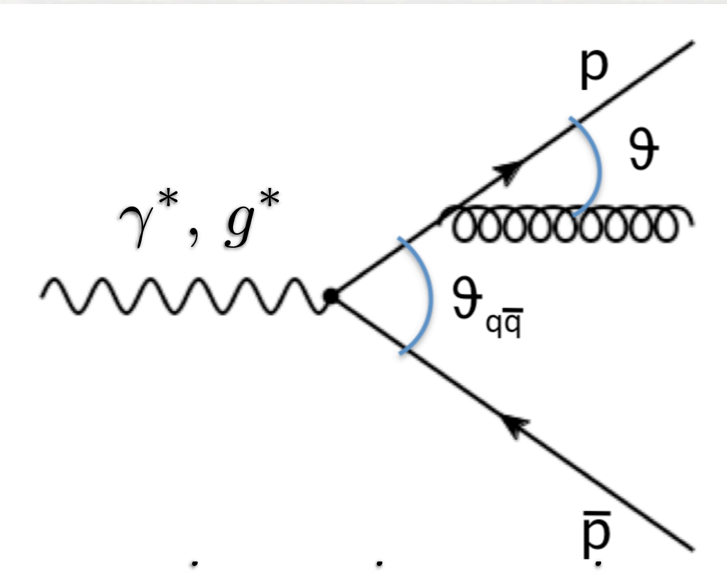

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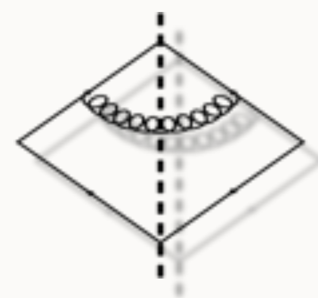
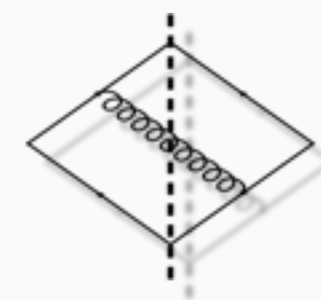
interference



independent rad



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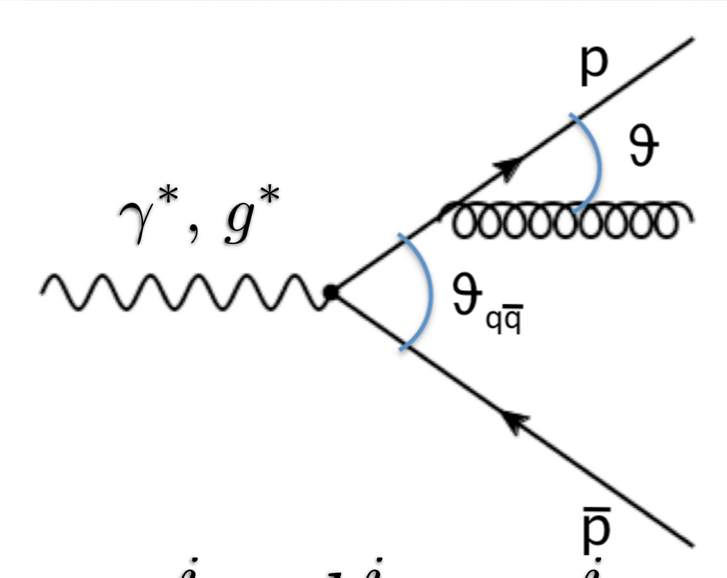

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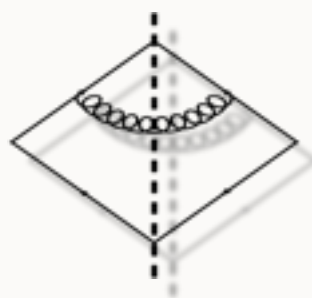

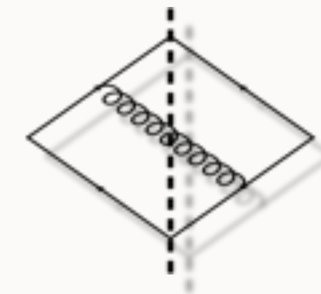

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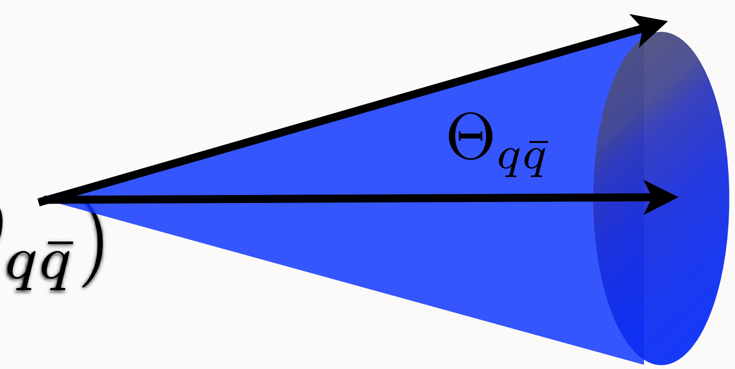

Fundamental building block of the QCD cascade!

SCALE ANALYSIS

The hard scale $\mathbf{Q_{hard}}$ is: $\delta \boldsymbol{k} = \boldsymbol{\kappa} - \bar{\boldsymbol{\kappa}}$ $\quad\quad \left|\delta \boldsymbol{k}\right| \simeq \omega \theta_{q\bar{q}}$

[gluon relative momentum off the antenna]

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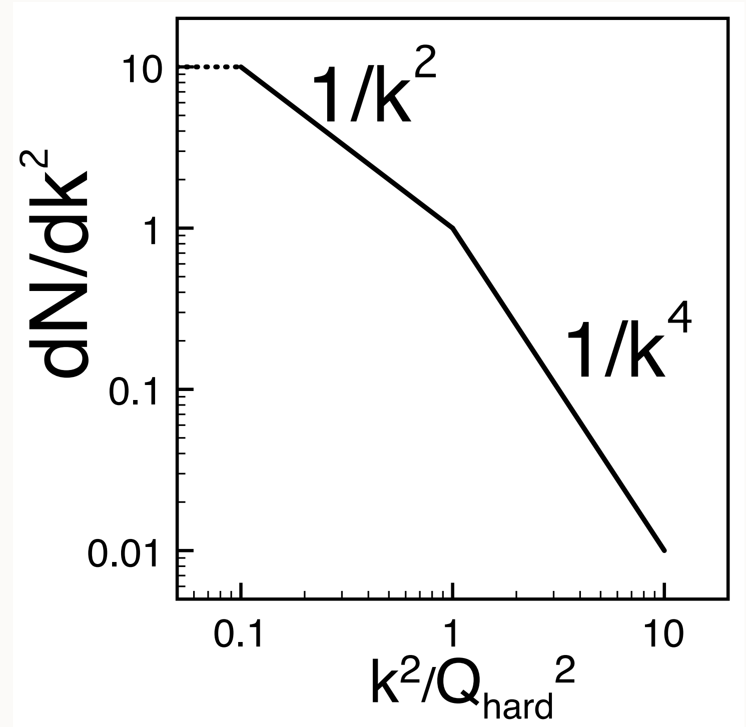

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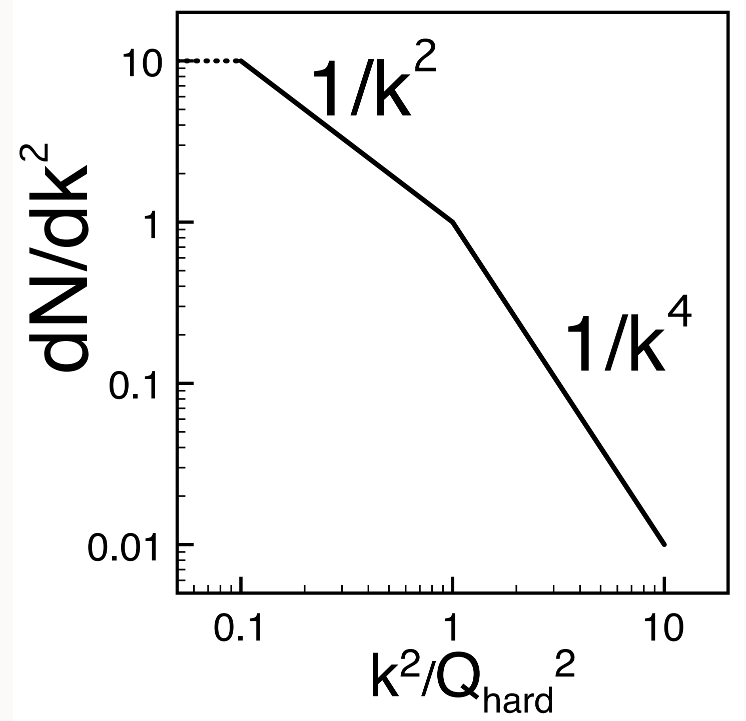

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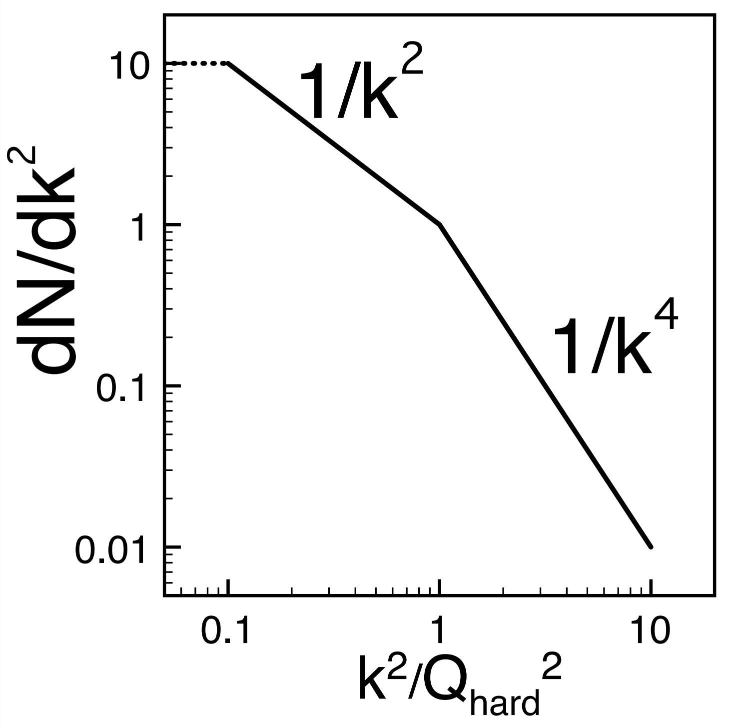

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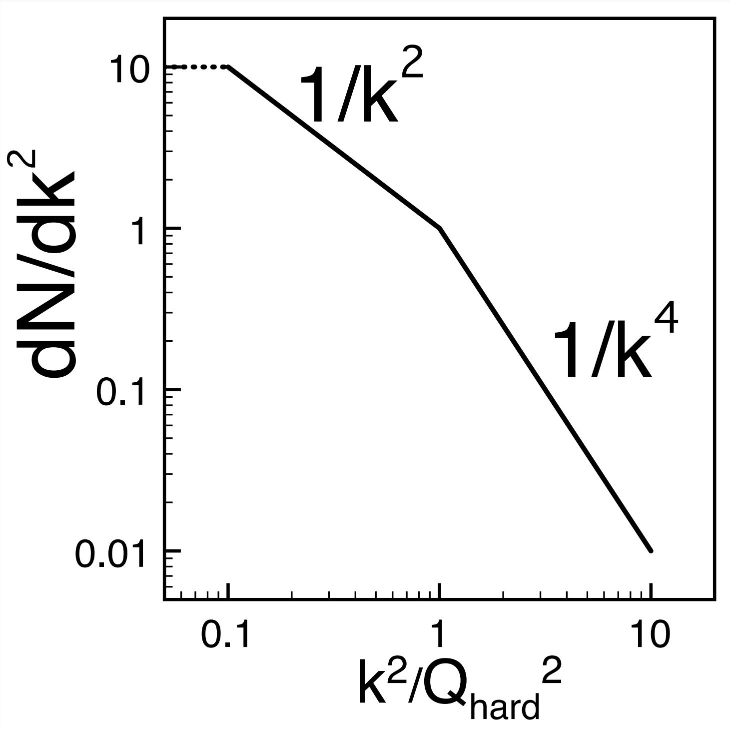
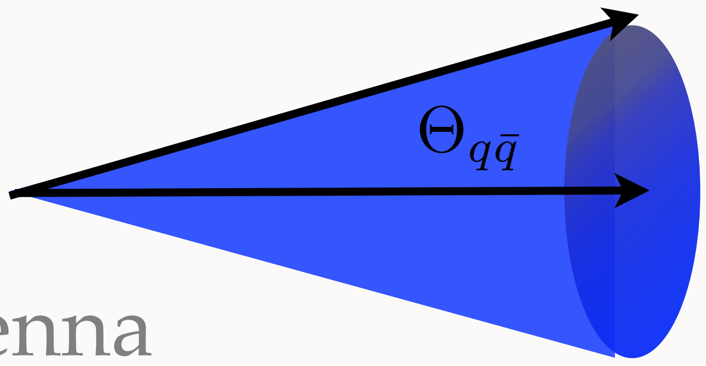


- emissions at large angles are sensitive to the total charge of the emitting system
  - interferences are at work at large angles!

THE HARD SCALE

- the hard scale determines the **maximal $k_\perp$** of gluons that can be produced by the system



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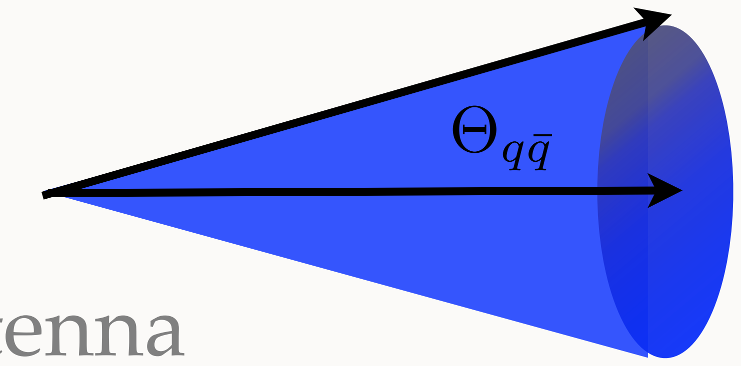

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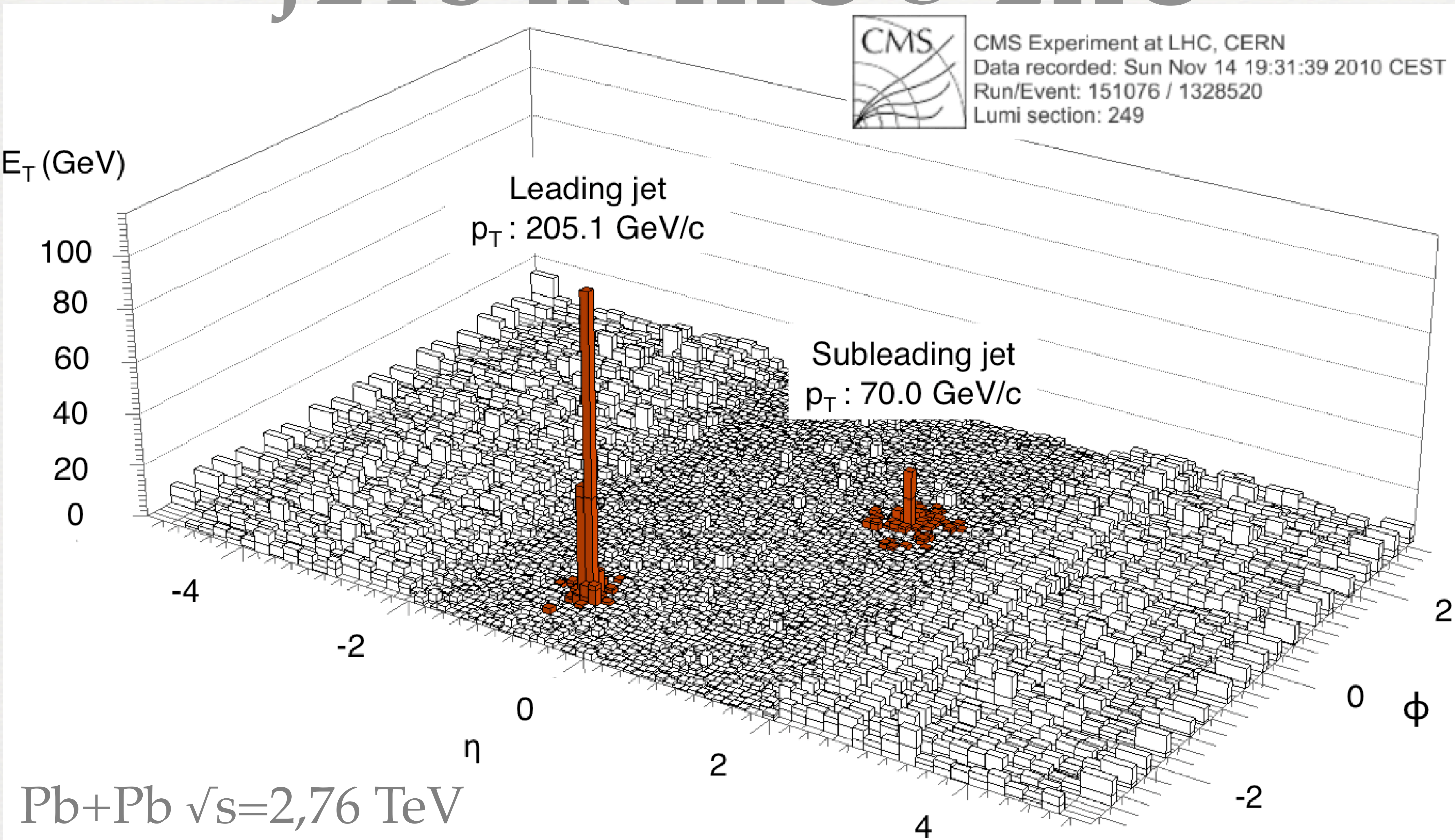
$k_\perp < Q_{\mathrm{hard}}$	incoherent radiation
$k_\perp > Q_{\mathrm{hard}}$	coherence

JETS IN HIC @ LHC



Pb+Pb √s=2,76 TeV

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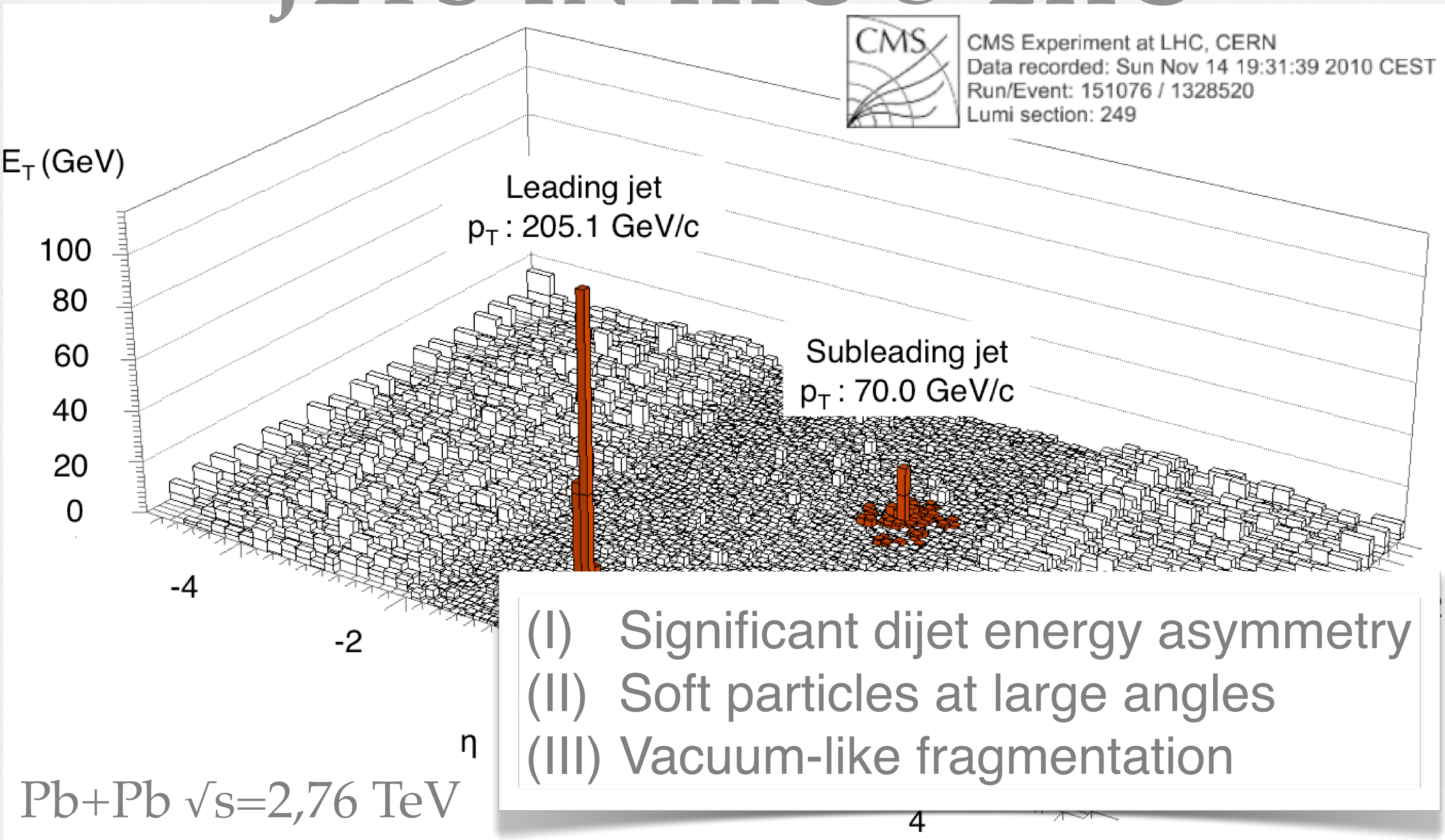

(I) Significant dijet energy asymmetry
(II) Soft particles at large angles
(III) Vacuum-like fragmentation

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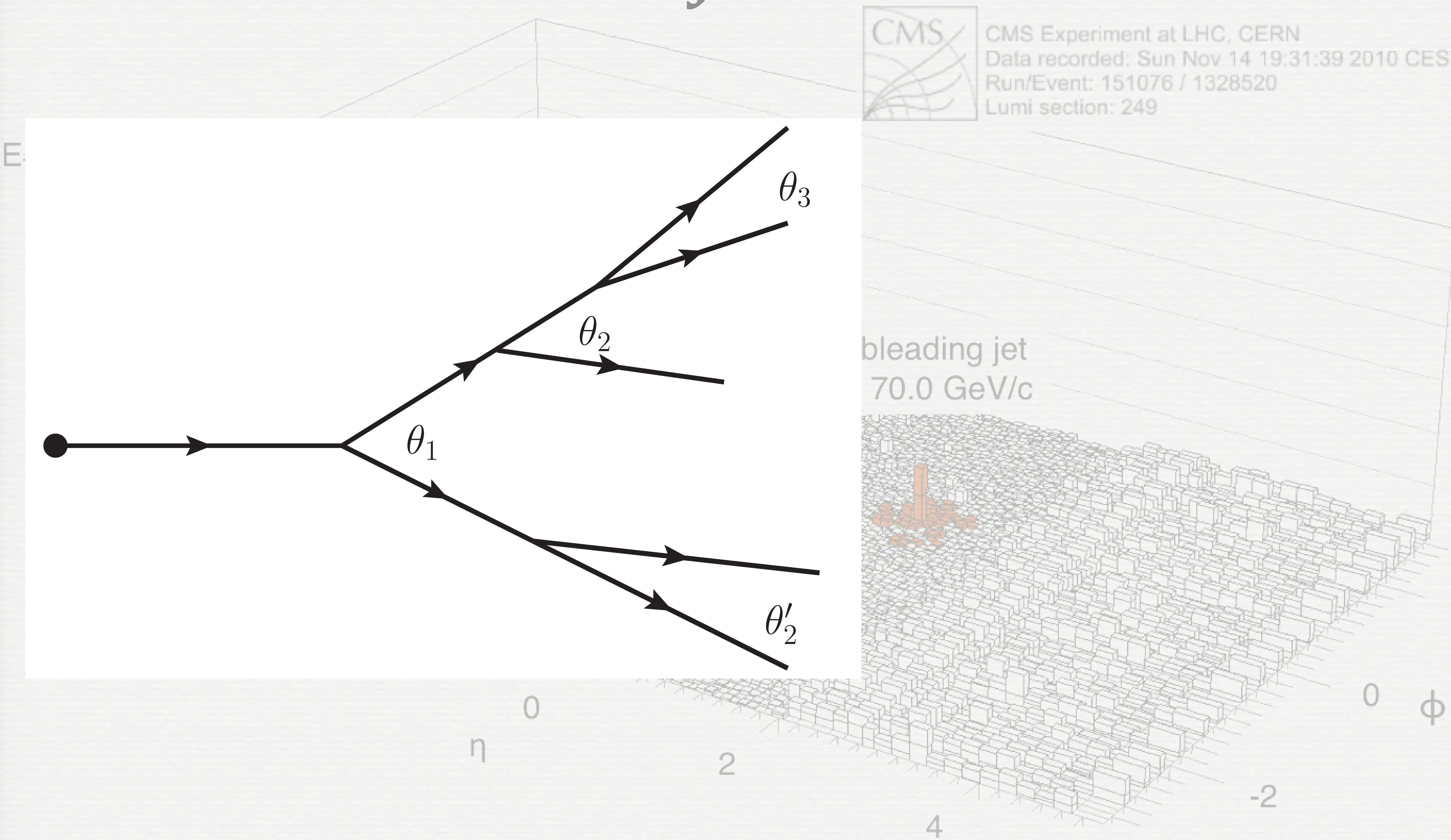
HOW IS THE JET MODIFIED?



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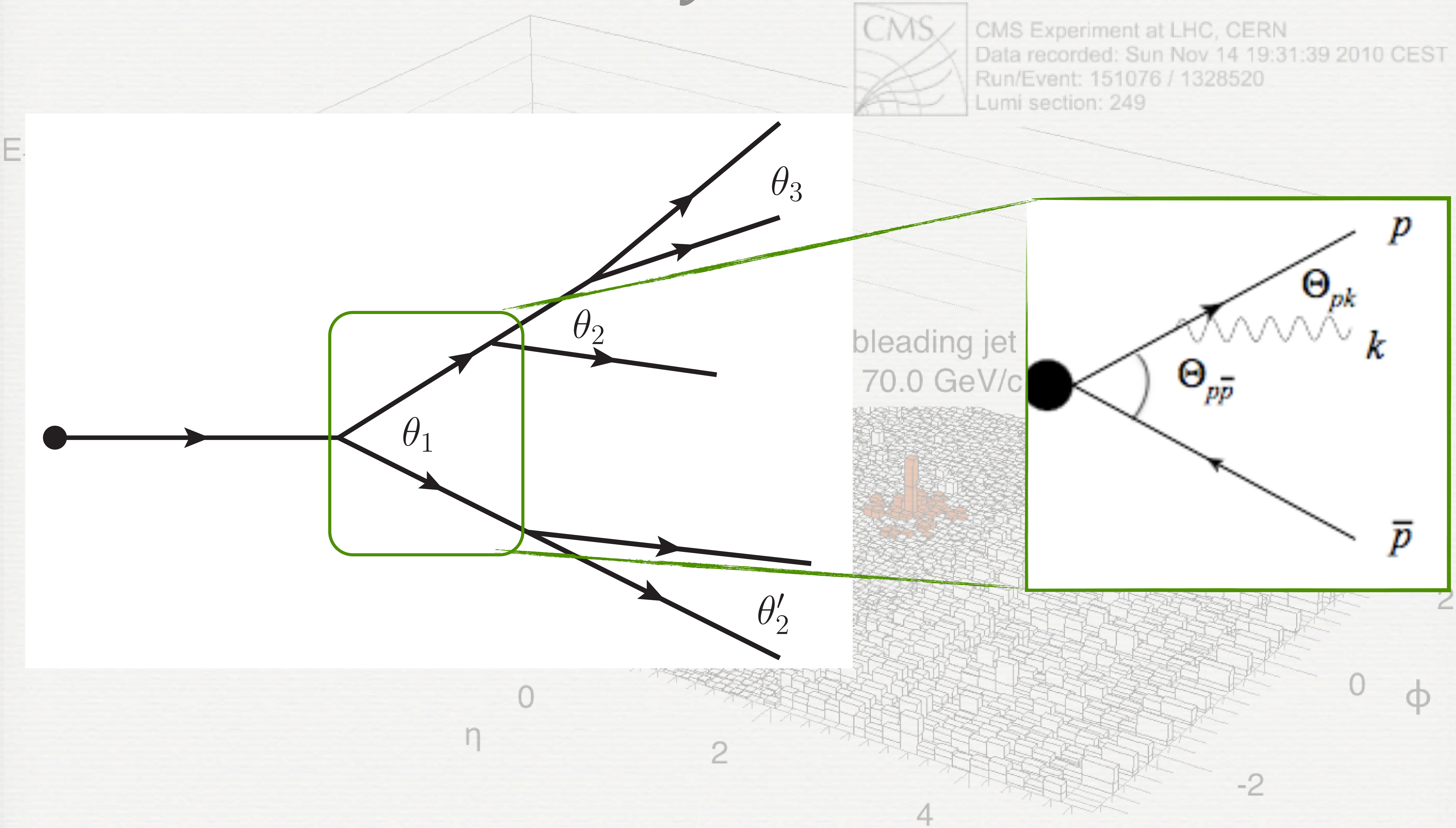

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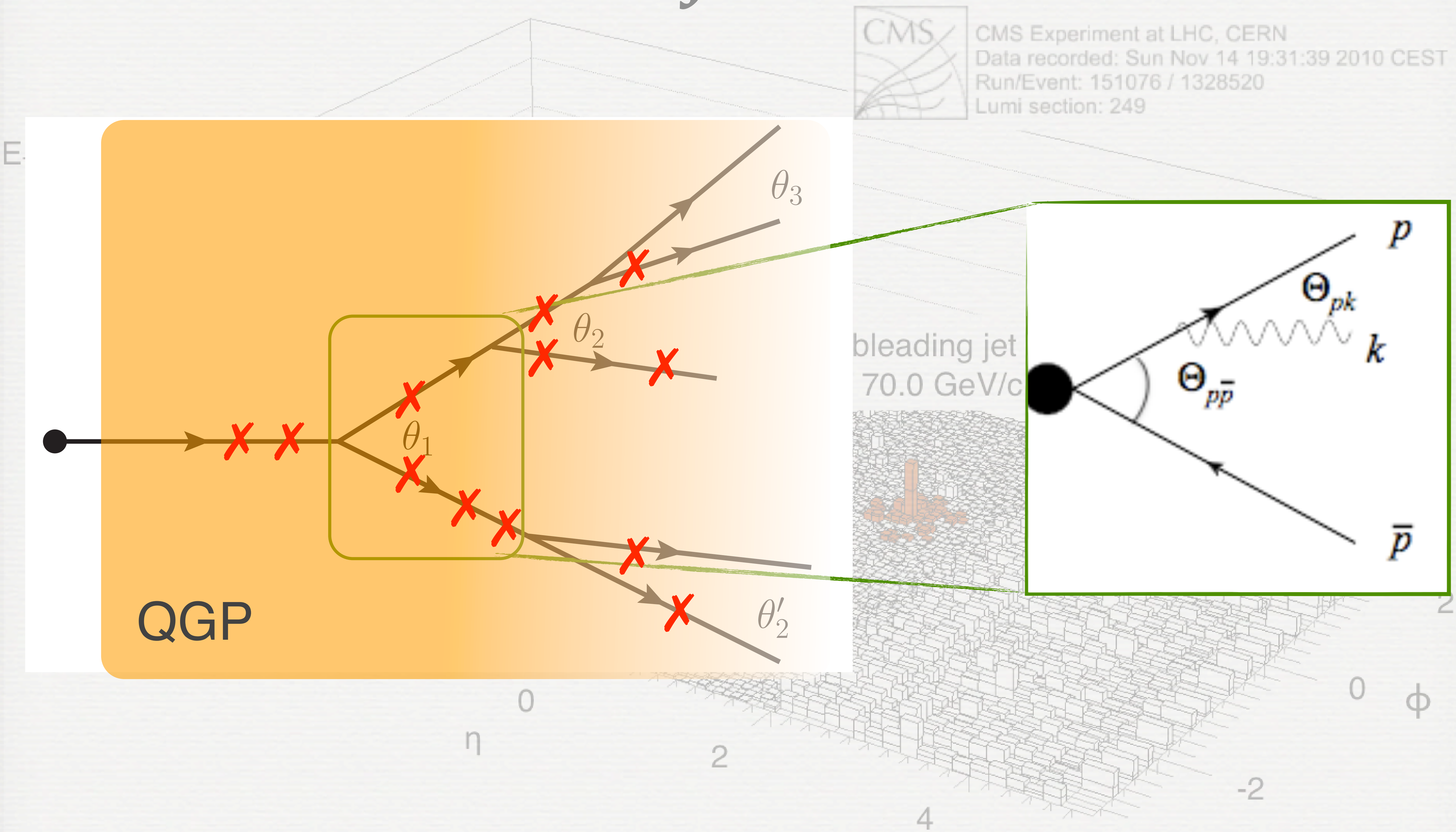

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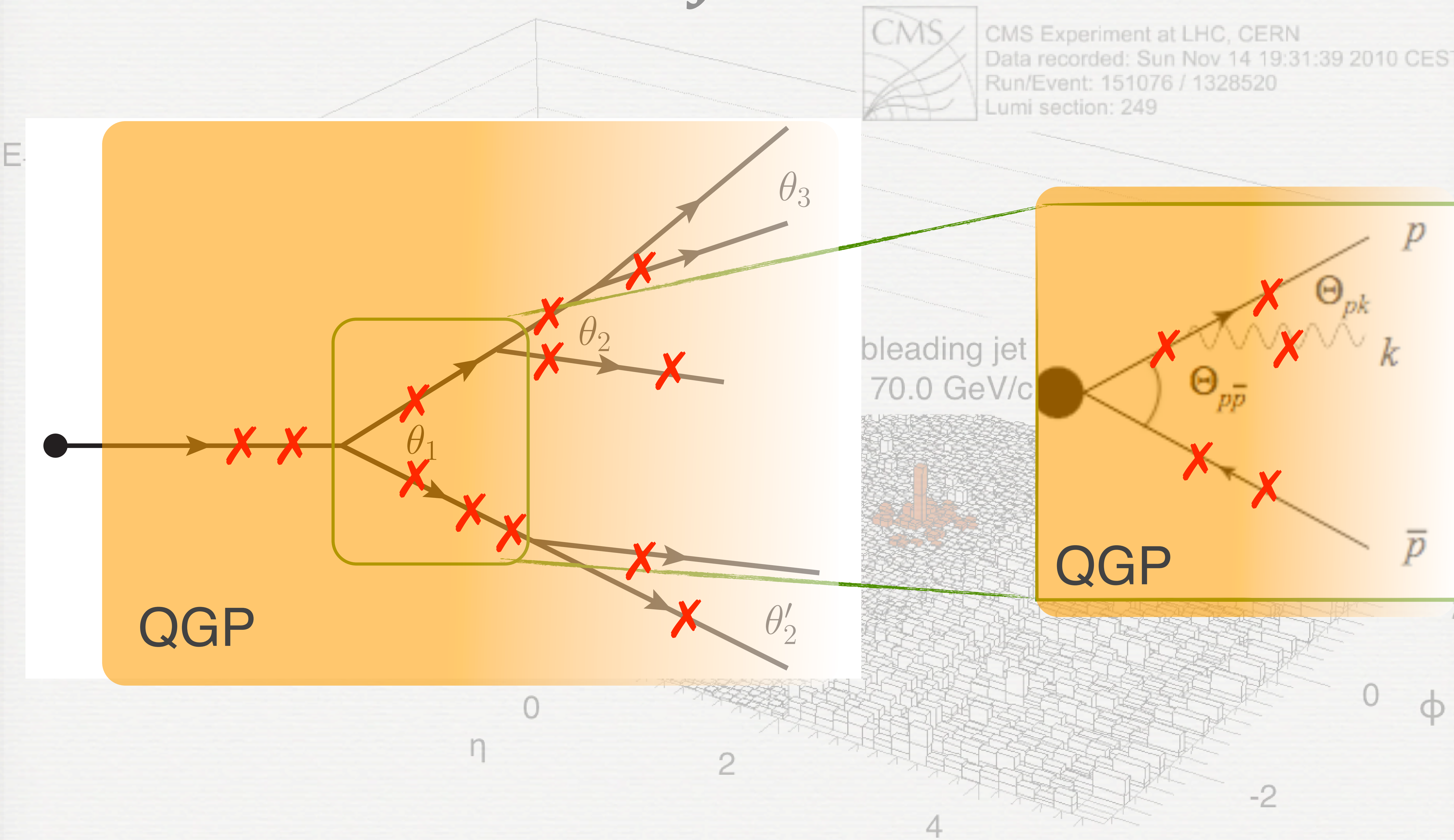

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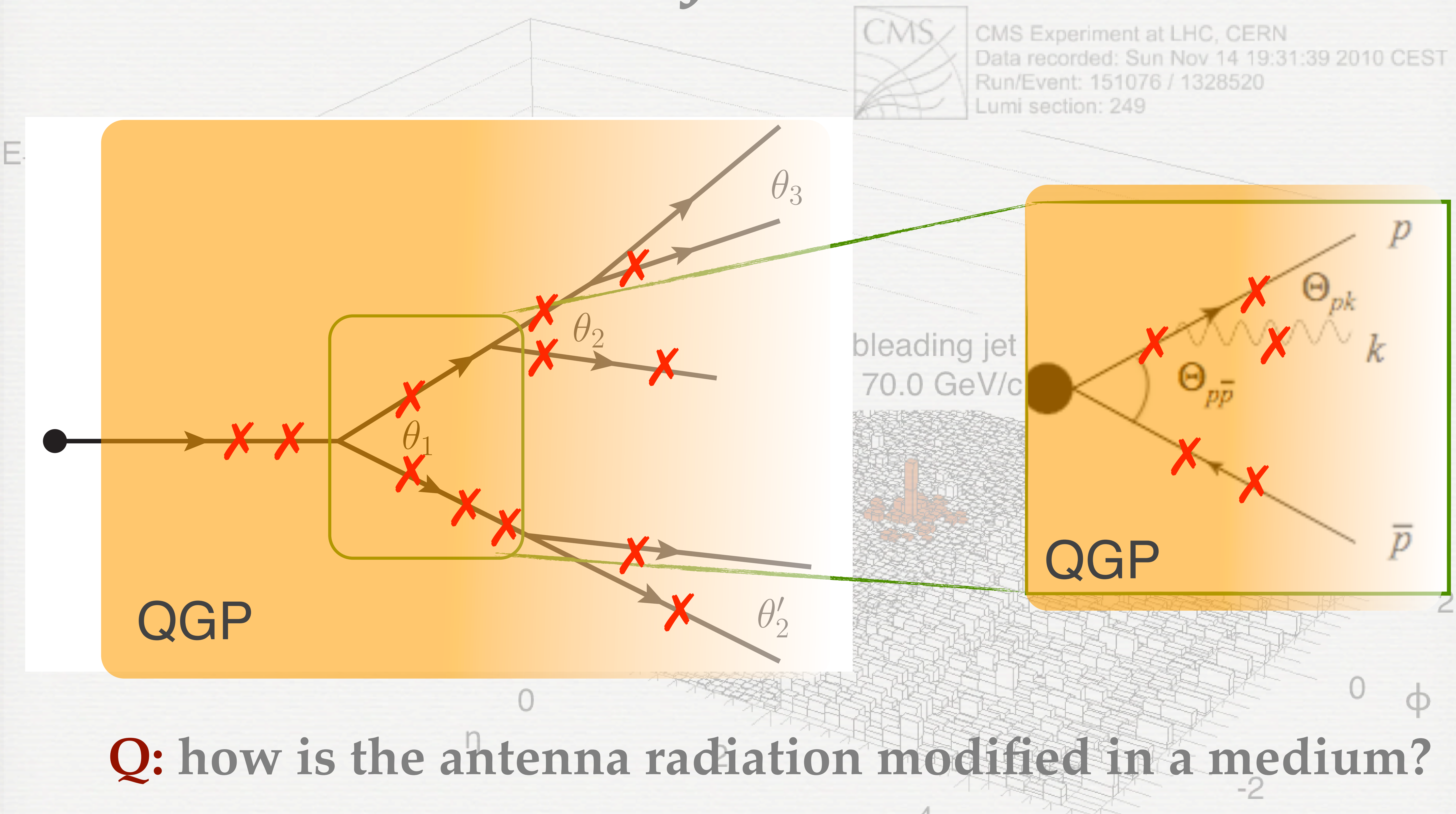


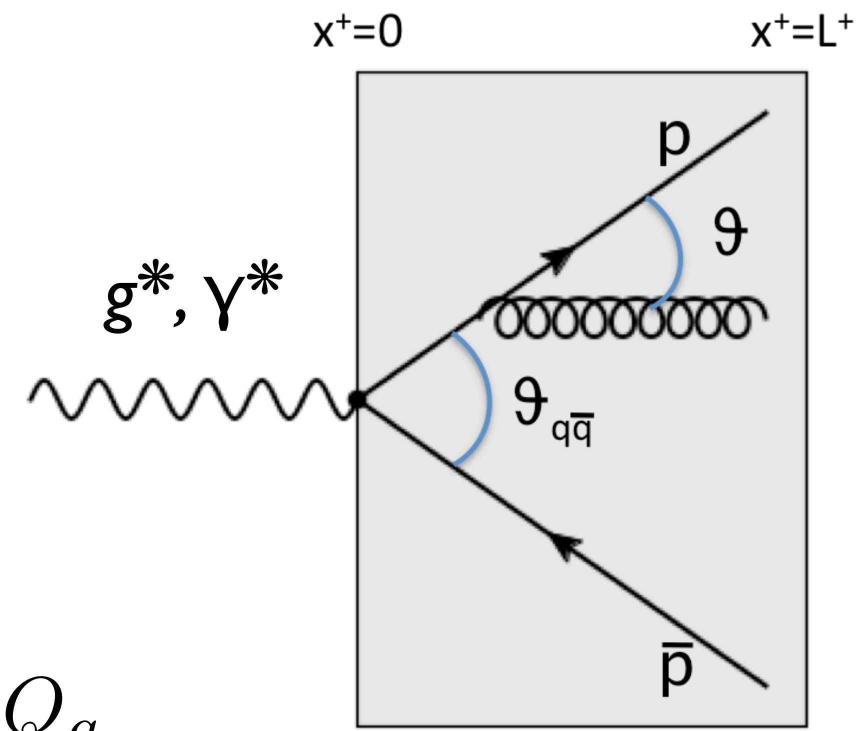
Q: how is the antenna radiation modified in a medium?

Building block of the in-medium cascade.

ANTENNA SETUP IN MEDIUM

Mehtar-Tani, Salgado, KT PRL 106 (2011) 122002, PLB 707 (2011) 156

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



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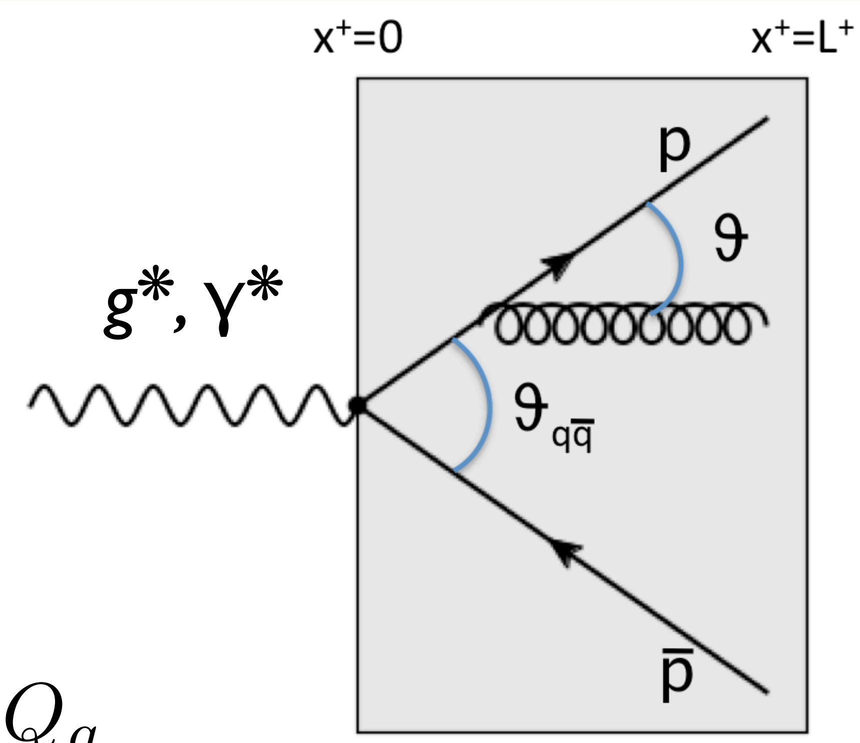

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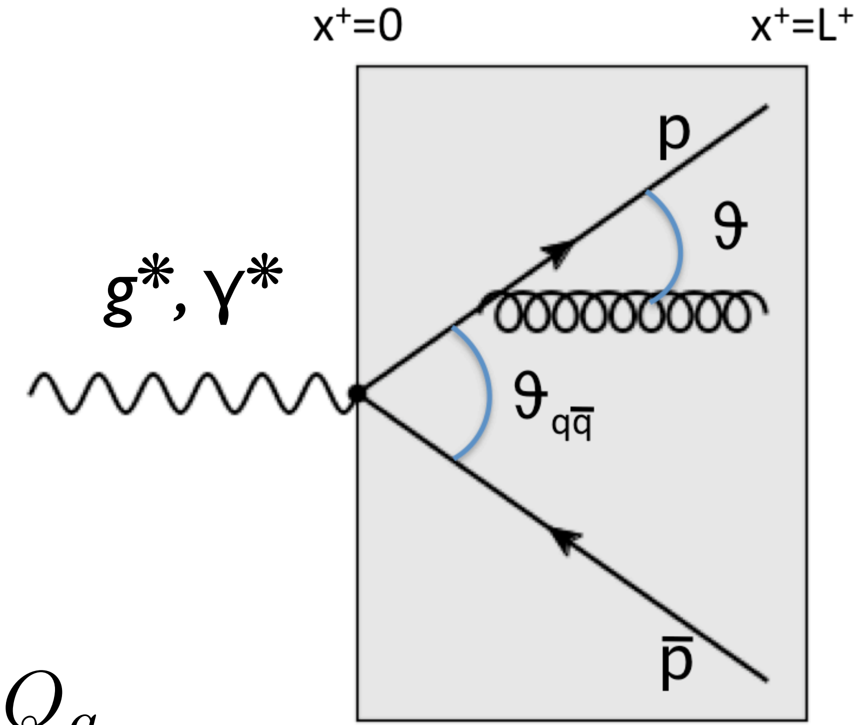

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Linear response: $$\Box A^i - 2ig\left[A^-_{\rm med}, \partial^+ A^i\right] = -\frac{\partial^i}{\partial^+}J^+ + J^i$$

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

COLOR PRECESSION

Considering soft gluon emissions: only the quarks interact!

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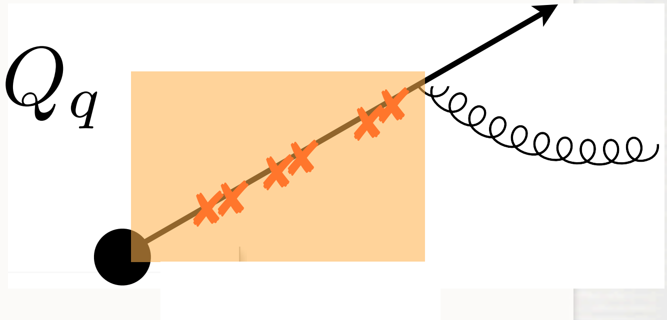

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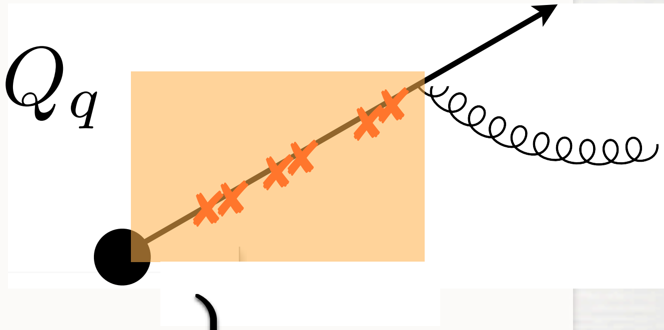

Wilson line along the trajectory:

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

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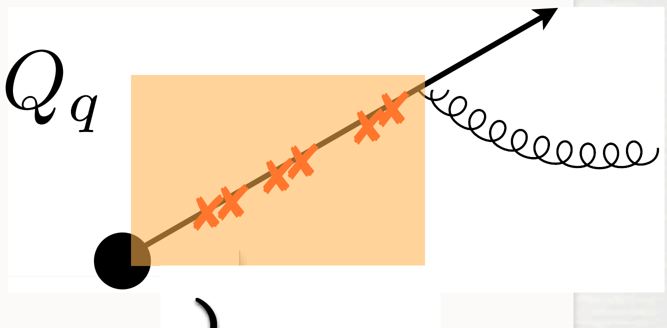

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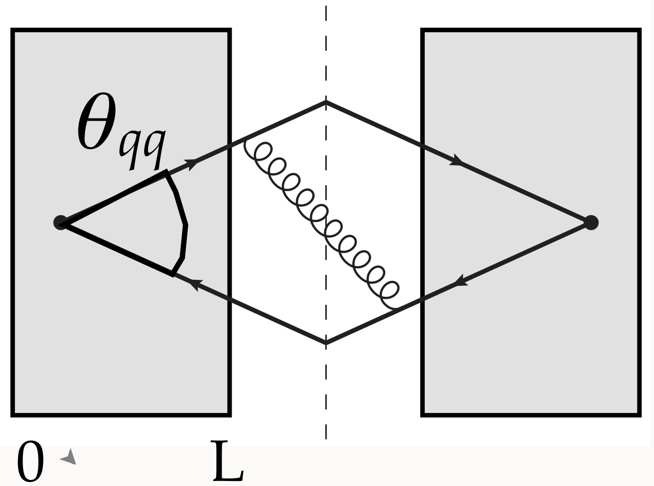
$$\approx 1 - e^{-\frac{1}{12}\hat{q}\, \theta^2_{q\bar{q}}\, L^3}$$

- the **decoherence parameter**



$\hat{q}$: medium transport coefficient

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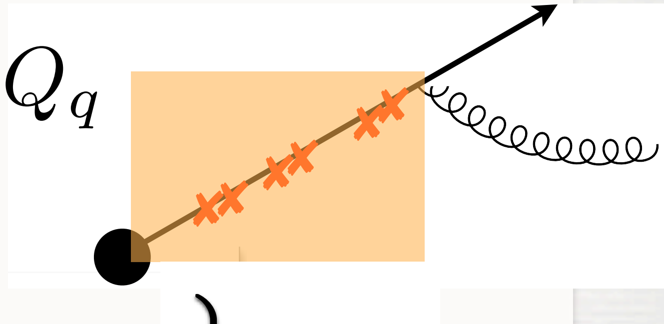

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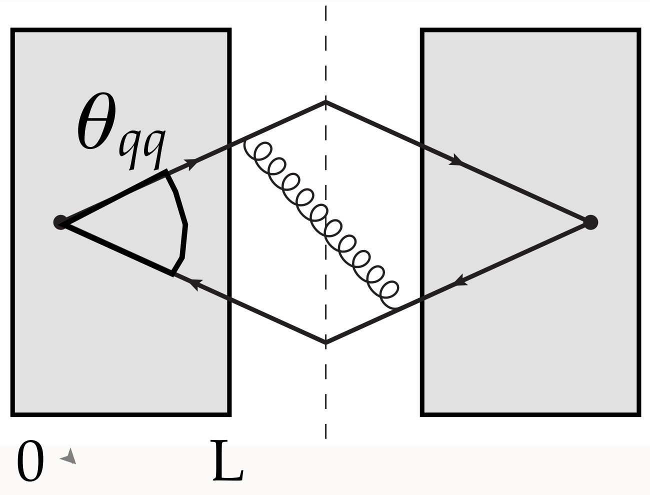
$$\tau_d = \left(\hat{q}\theta^2_{q\bar{q}}\right)^{-1/3}$$ **: timescale of decoh.**



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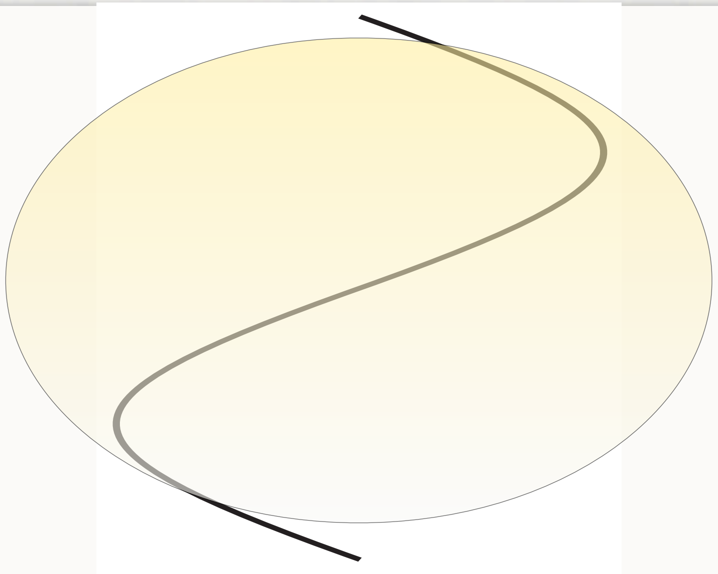
WHAT ARE THE TRANSVERSE SCALES?



How is the medium resolved?

- medium fluctuates at distances larger than Q_s
  - zero color on average!
- probed by wavelengths $\lambda < Q_s^{-1}$

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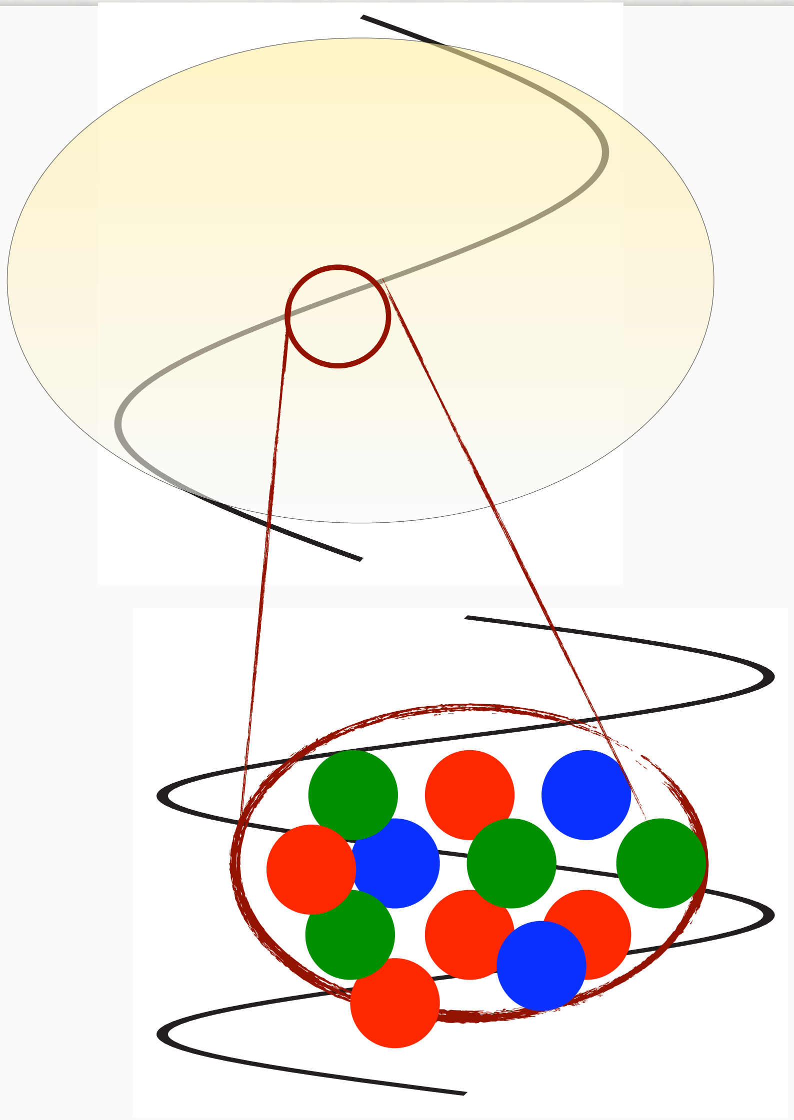

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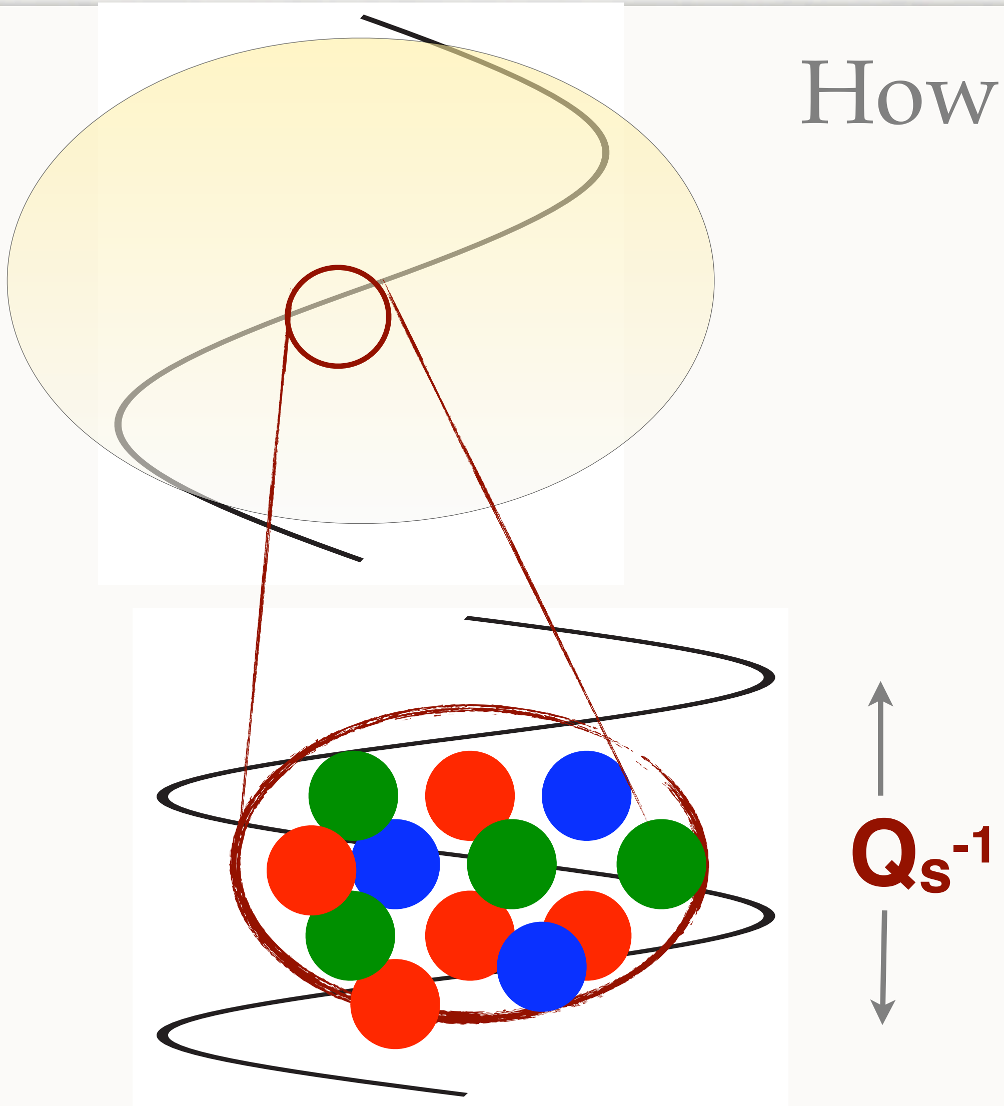

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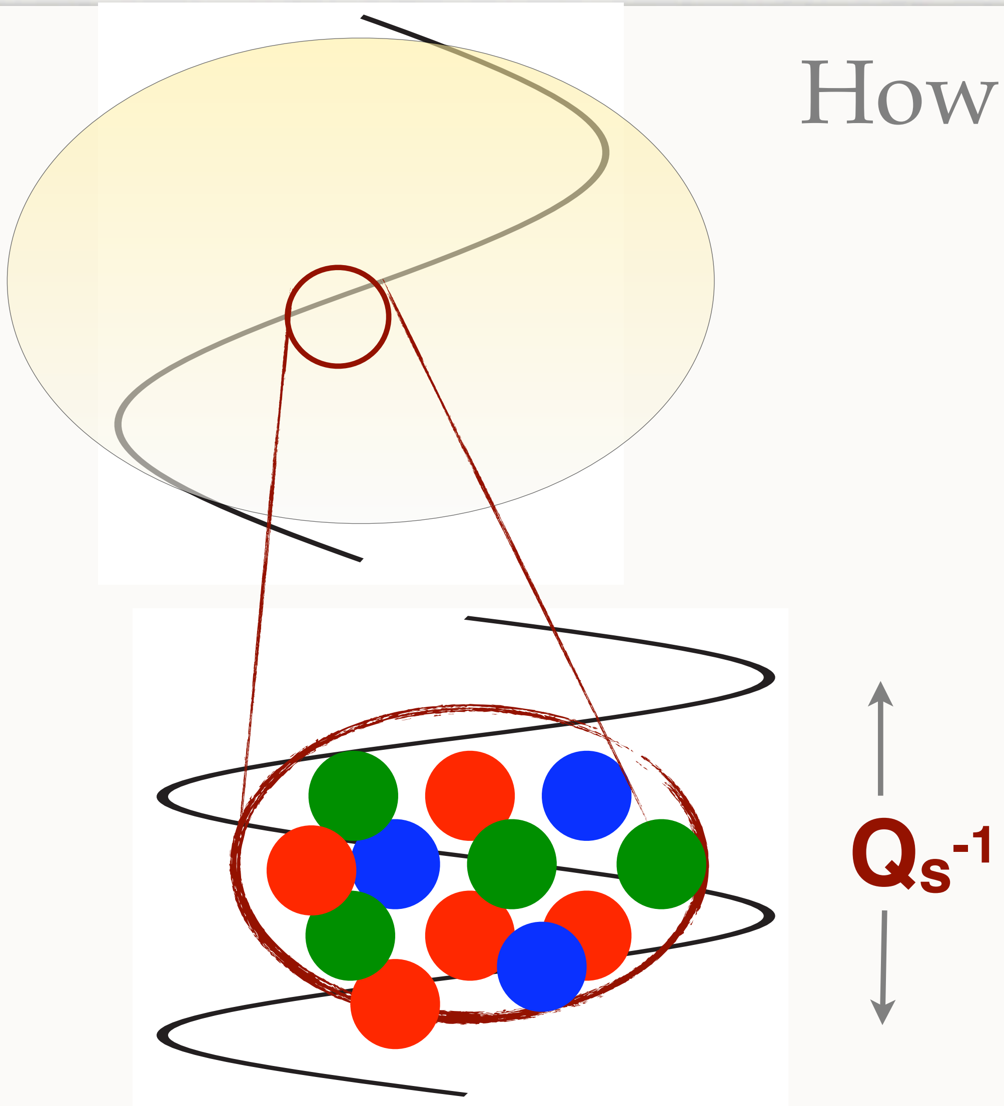

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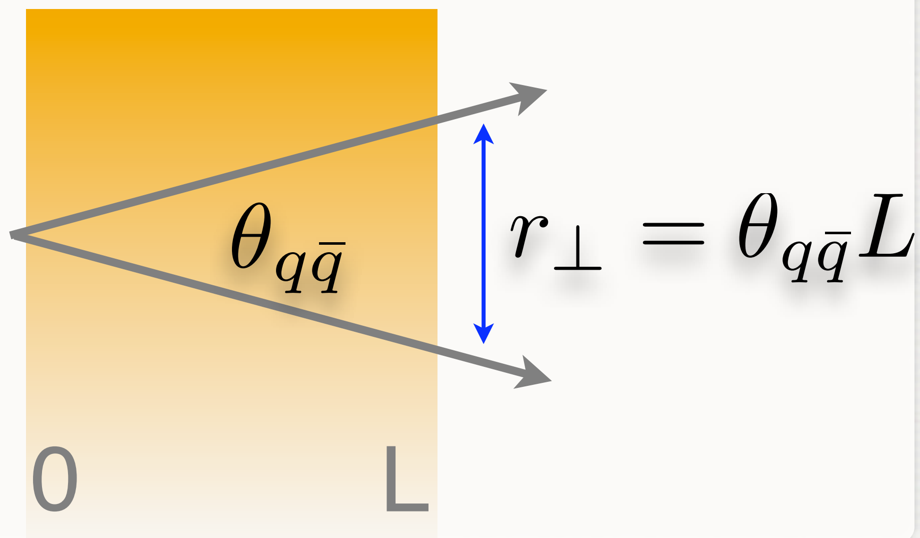
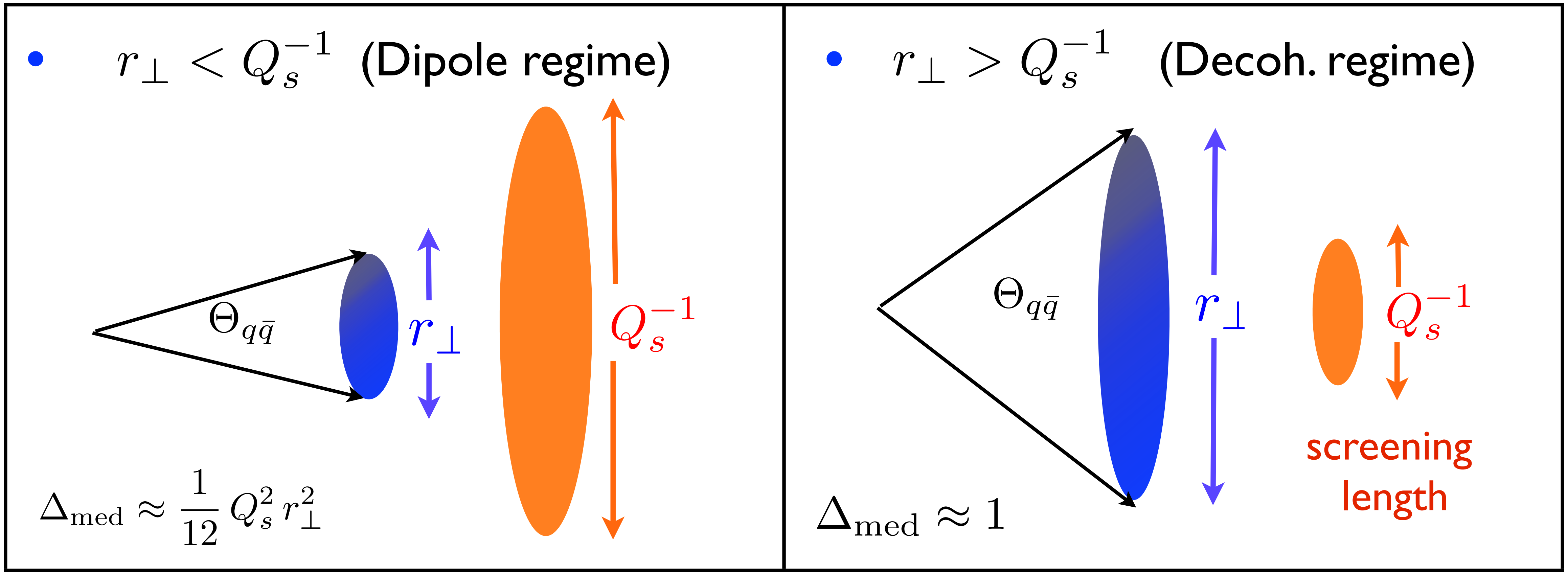


DECOHERENCE IN MEDIUM

- a two scale problem!



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

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

Q_s: characteristic momentum scale of the medium

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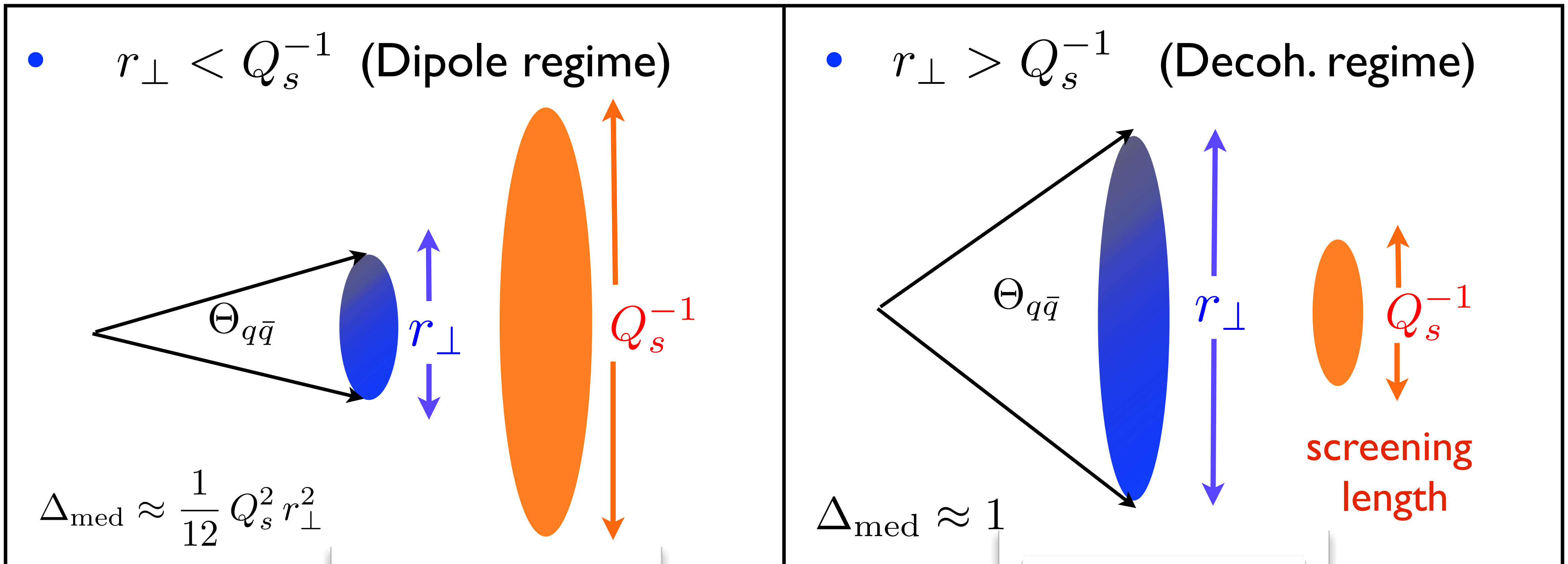

$$\tau_d \gg L$$

$$\tau_d \ll L$$

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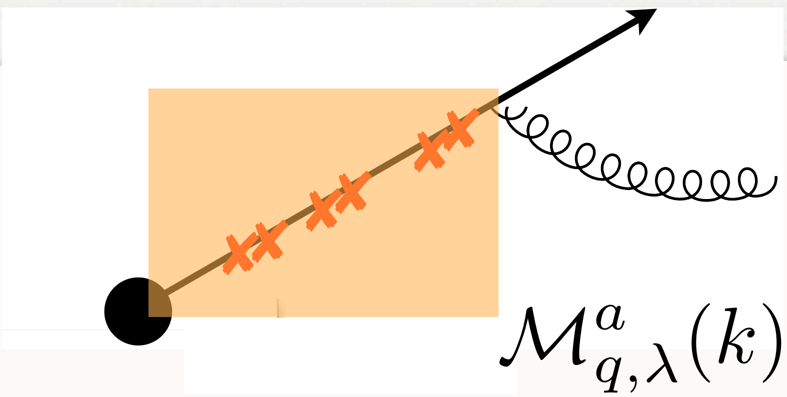
$r_\perp =$

Q$_s$: characteristic momentum scale of the medium

THE SOFT LIMIT

- revisited



$$\mathcal{M}^a_{q,\lambda}(k) = -2ig\frac{\boldsymbol{\kappa}\cdot\boldsymbol{\epsilon}_\lambda}{\boldsymbol{\kappa}^2}U_p^{ab}(L,0)Q_q^b$$

- emissions outside the medium
- soft divergence
- antiangular ordered (1/θ)

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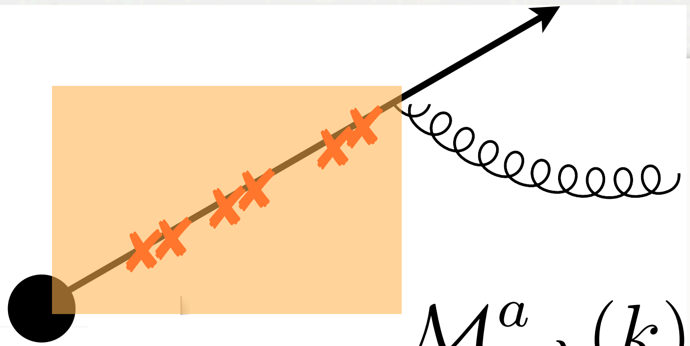

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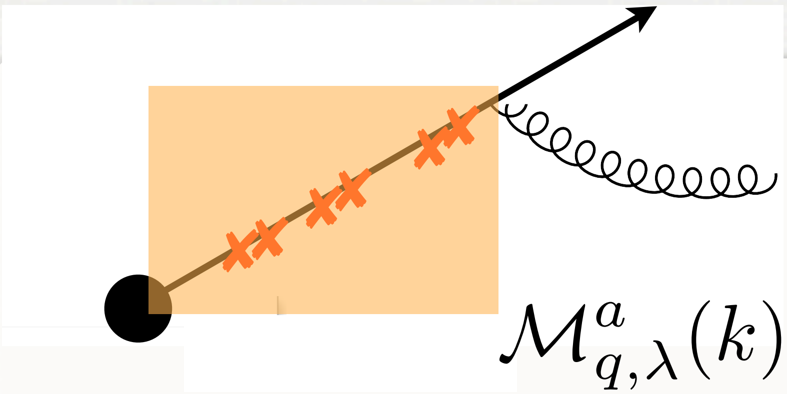

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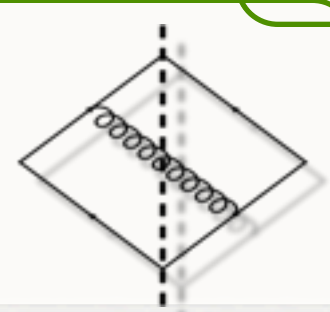
$\mathcal{J} =$ 

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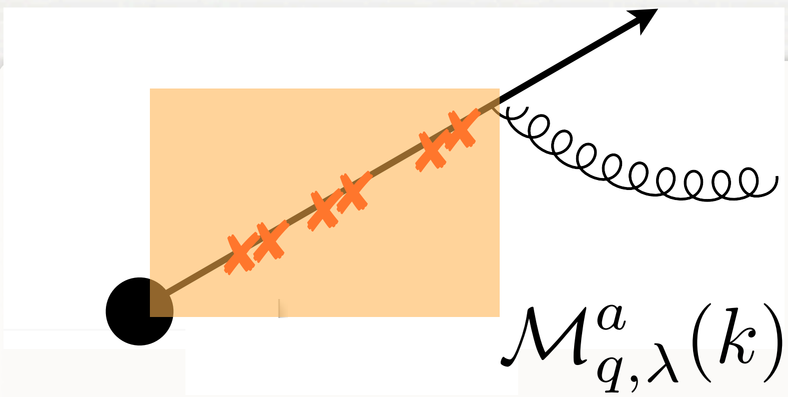

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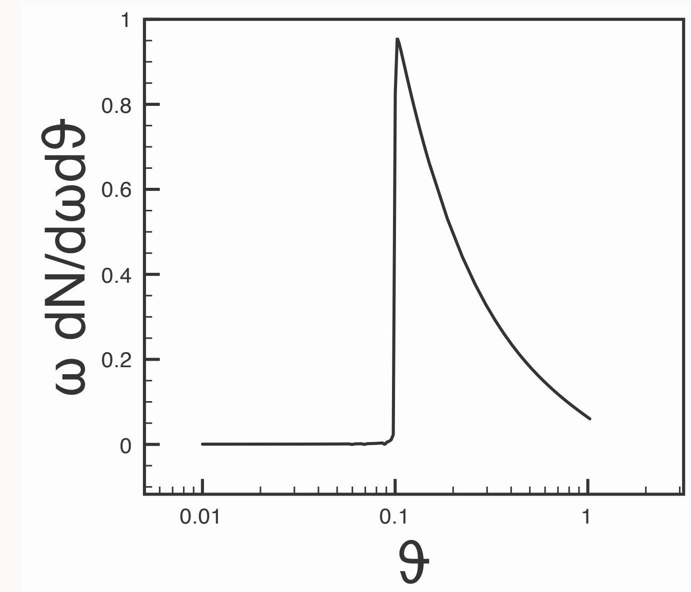

Y. Mehtar-Tani, C.A. Salgado, KT
PRL 106 (2011) 122002

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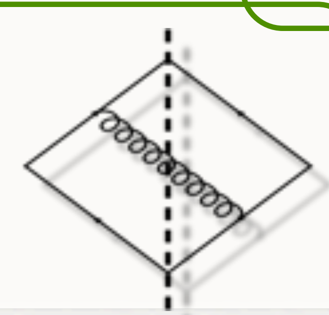
$\mathcal{J} =$ 

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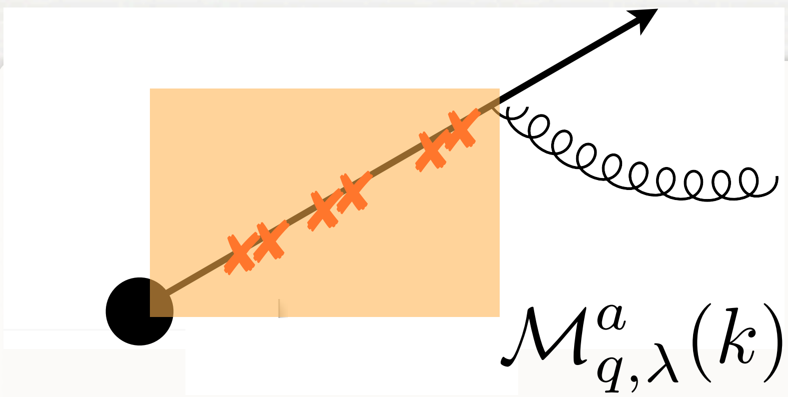

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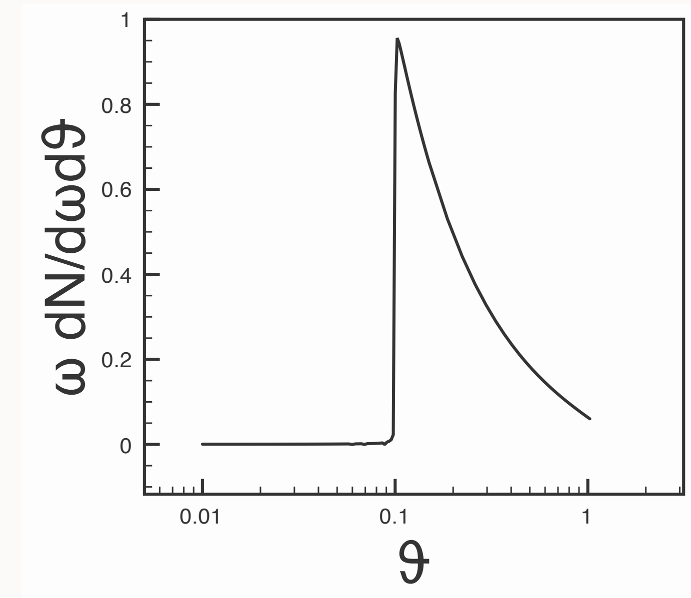

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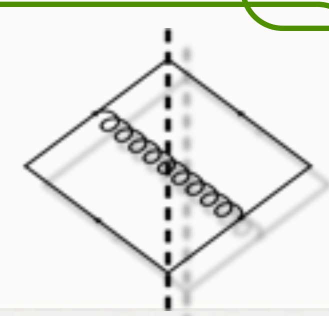
$\mathcal{J} =$ 

dipole-medium
cross section

TWO REGIMES

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

Medium decoherence parameter

➙ controls the cancellation of interferences

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

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

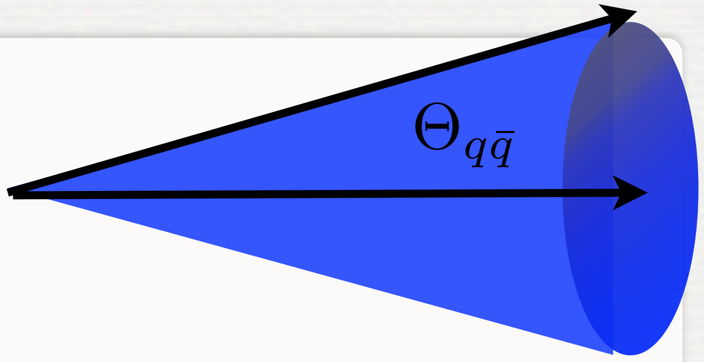
- $\mathbf{r_\perp^{-1} \gg m_D}$
  - "dipole" regime
  - color transparency

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

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

ONSET OF DECOHERENCE - SOFT GLUONS

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



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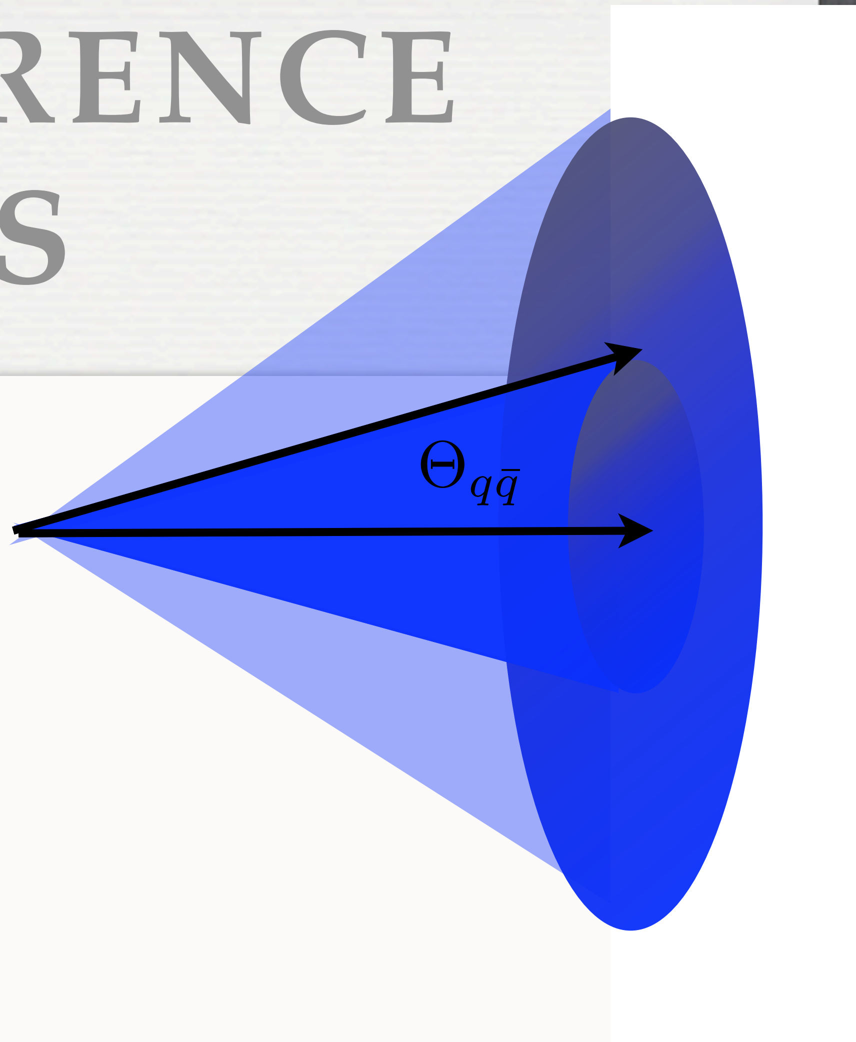

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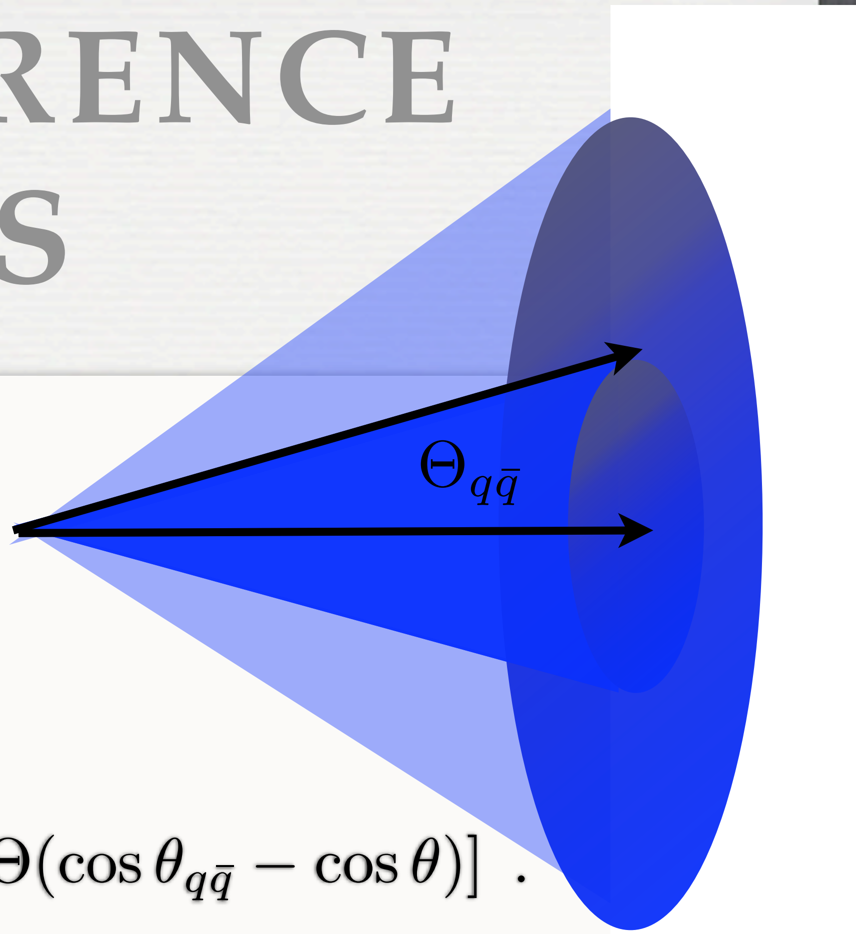
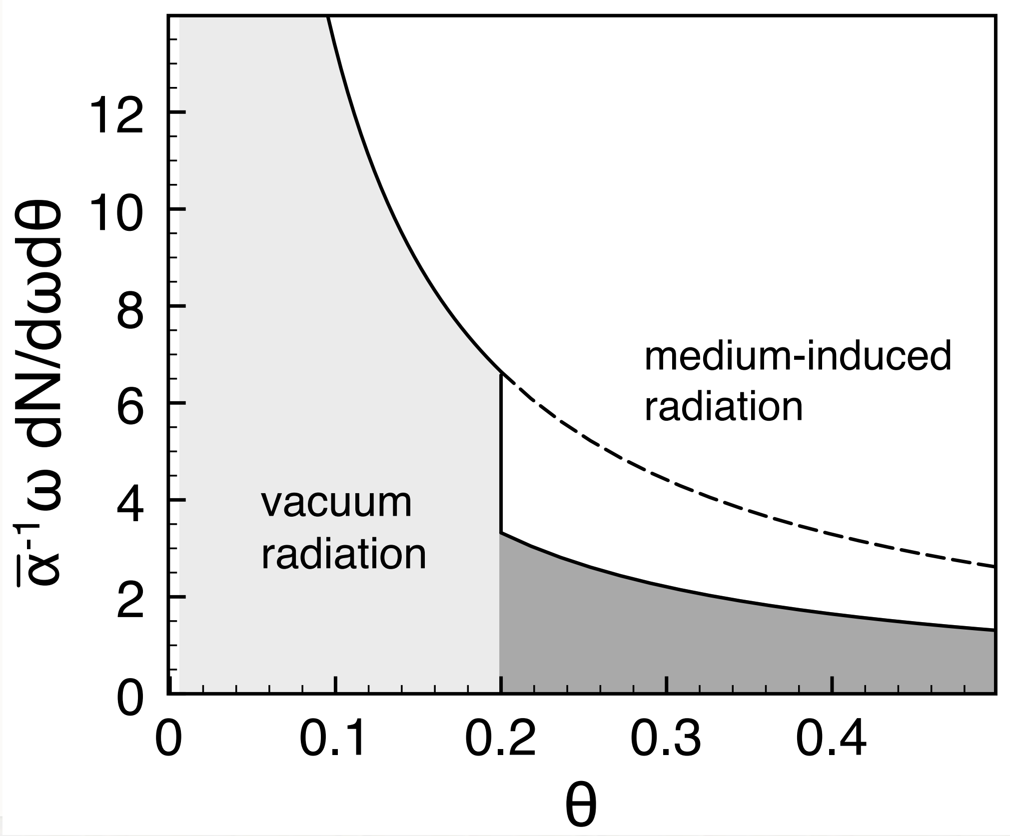


$$dN^{\mathrm{tot}}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\ d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\mathrm{med}}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right]\ .$$



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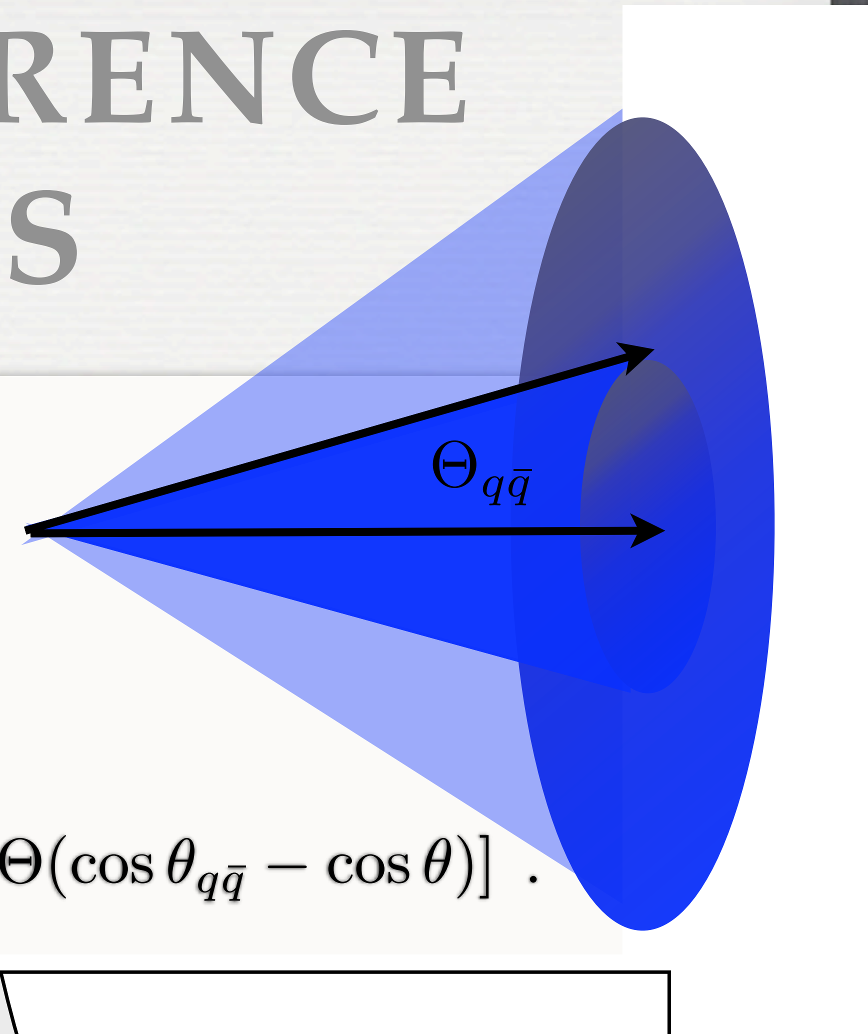

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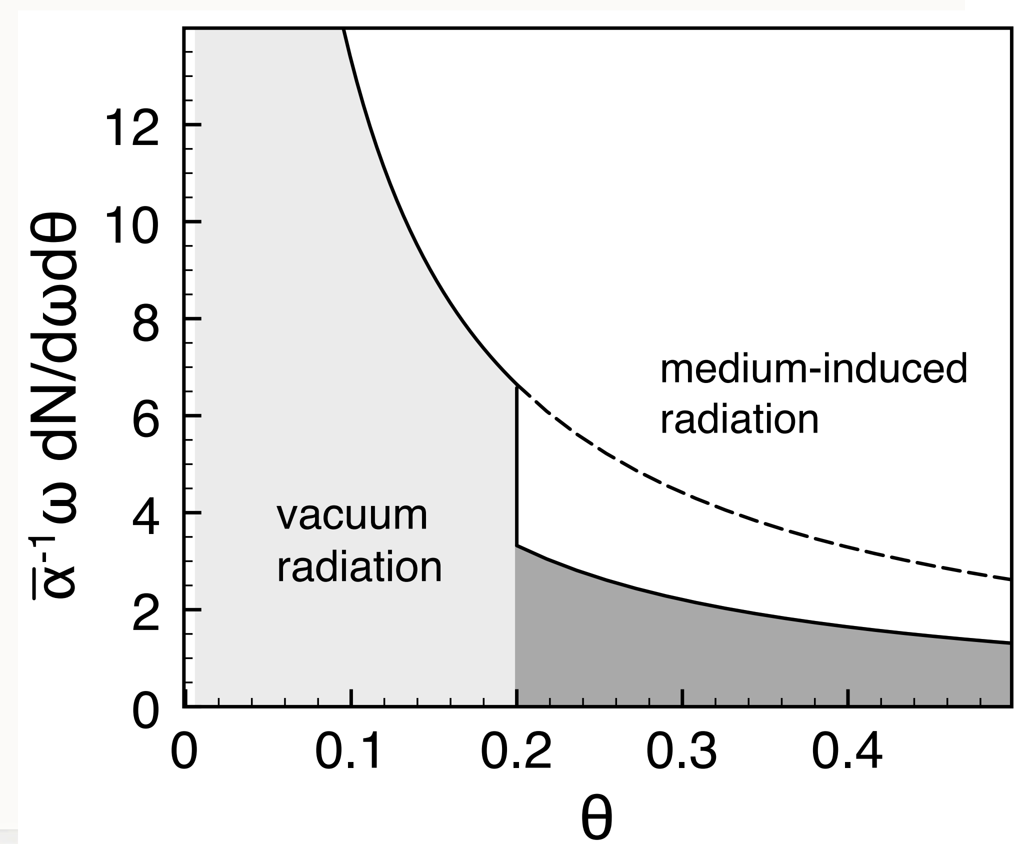
$\Rightarrow$ geometrical separation!



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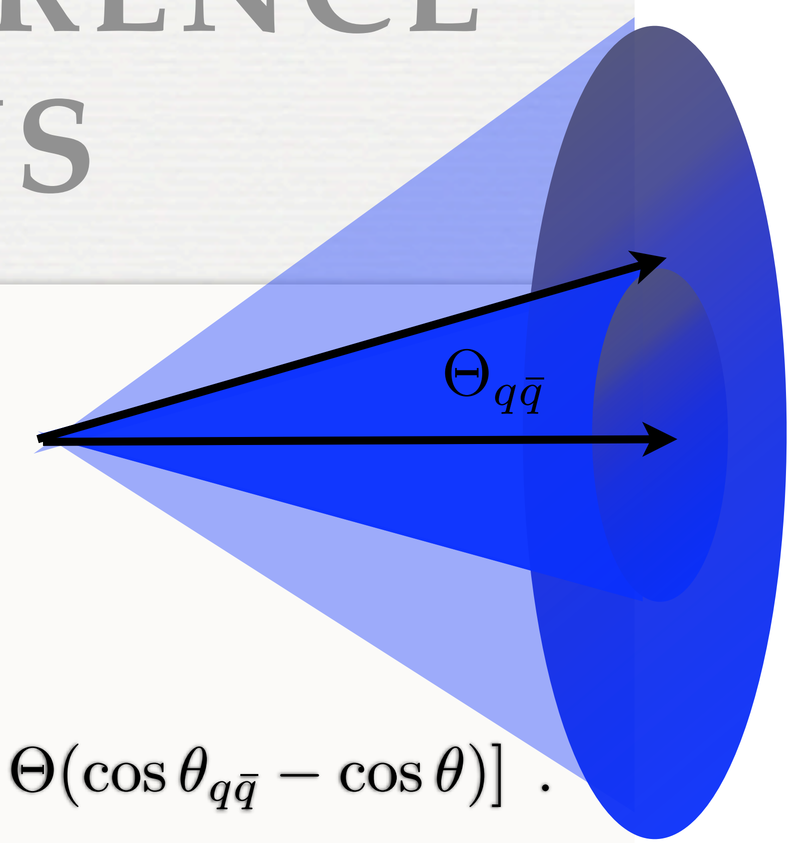

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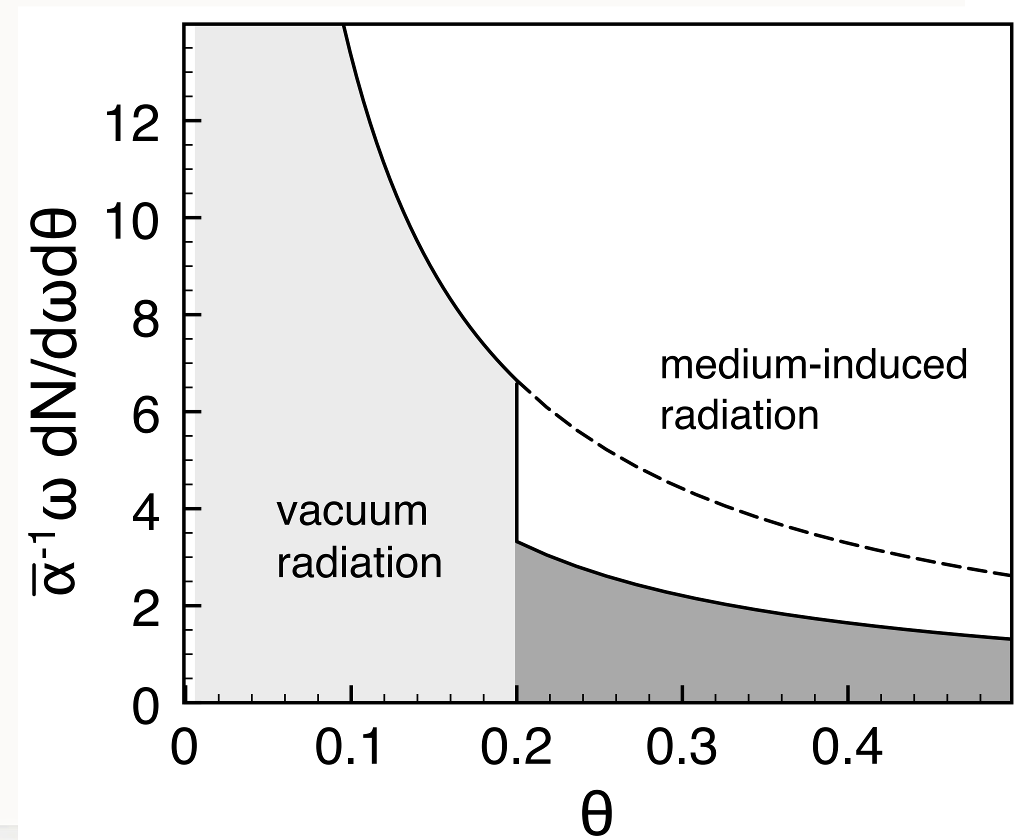
2) “Memory loss” effect



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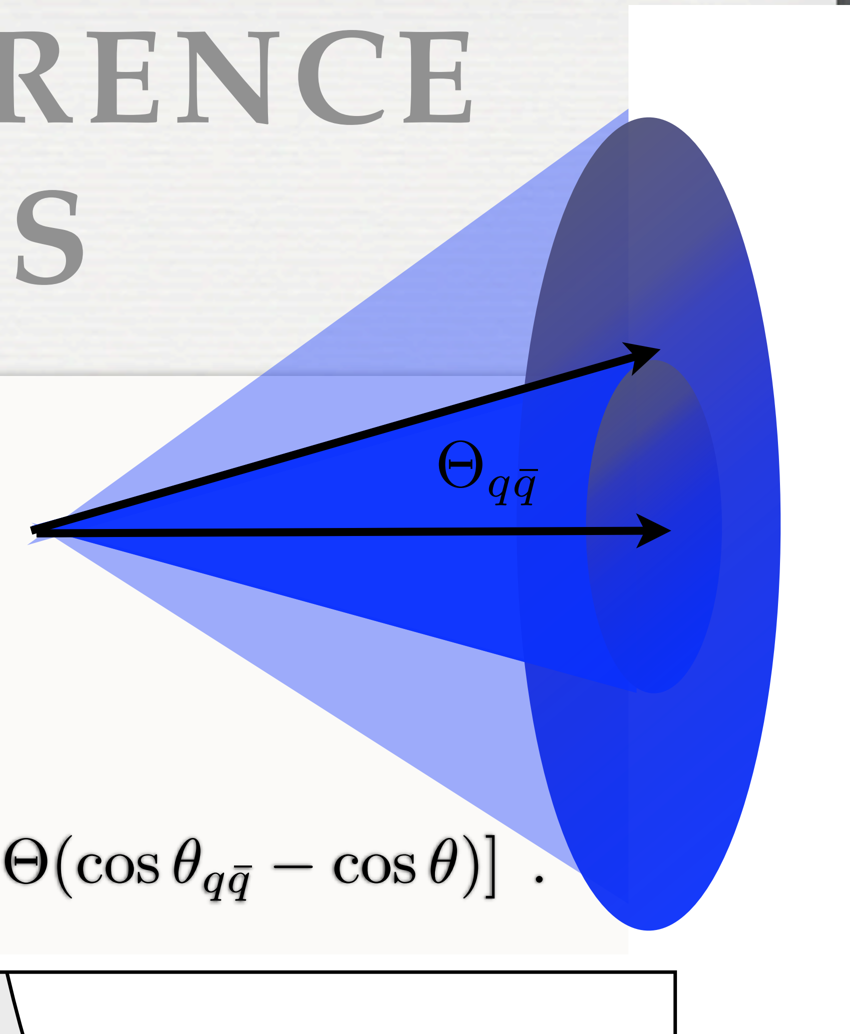

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and gluon!

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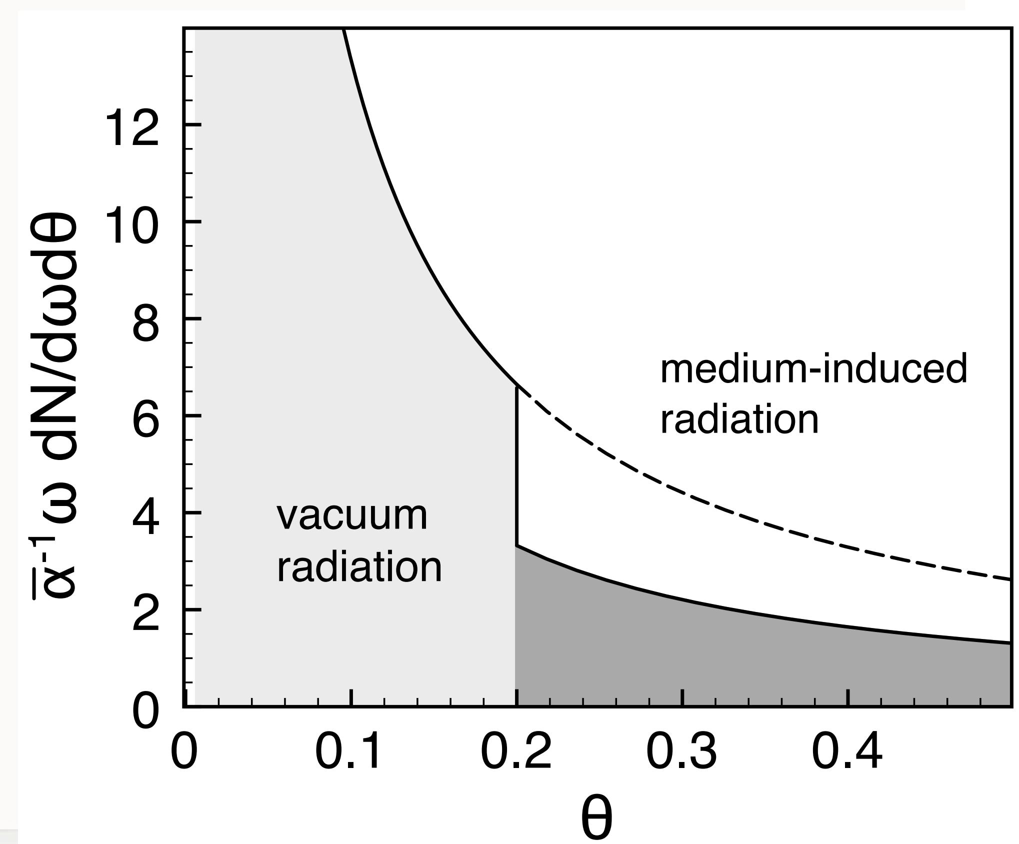

FINITE ENERGIES

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

The hard scale of the problem: $Q_{\mathrm{hard}} = \max\left(r_\perp^{-1}, Q_s\right)$

FINITE ENERGIES

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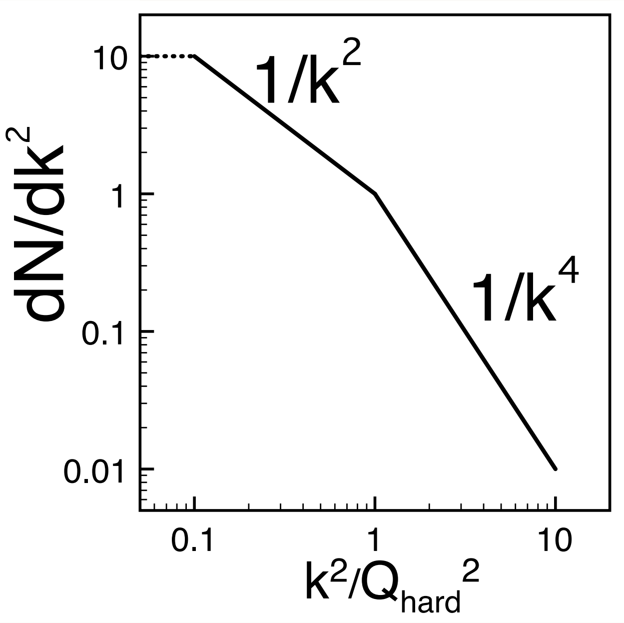
$k_\perp > Q_{\rm hard}$: coherence!



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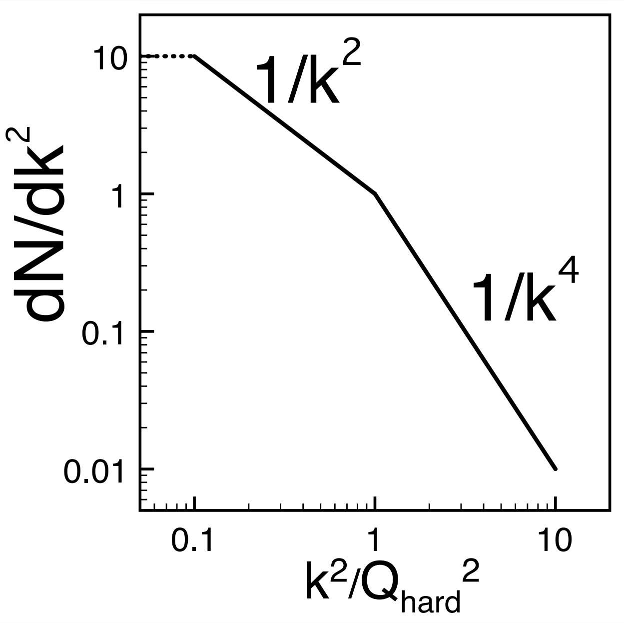

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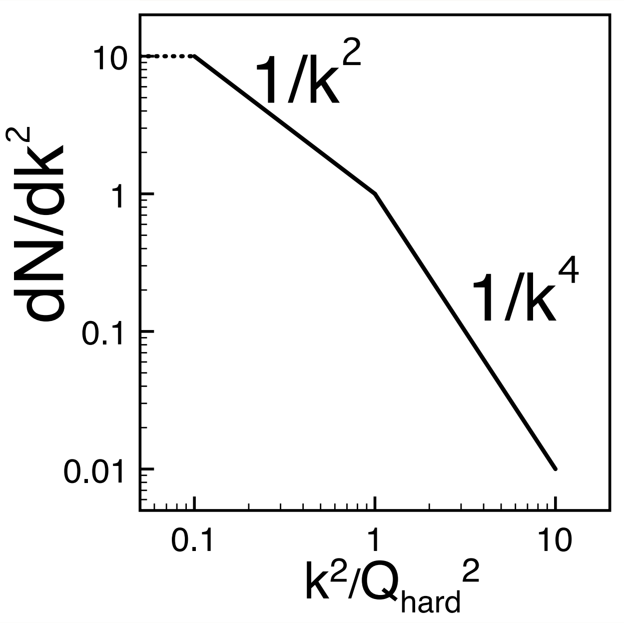

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$$r_\perp^{-1} \gg m_D$$

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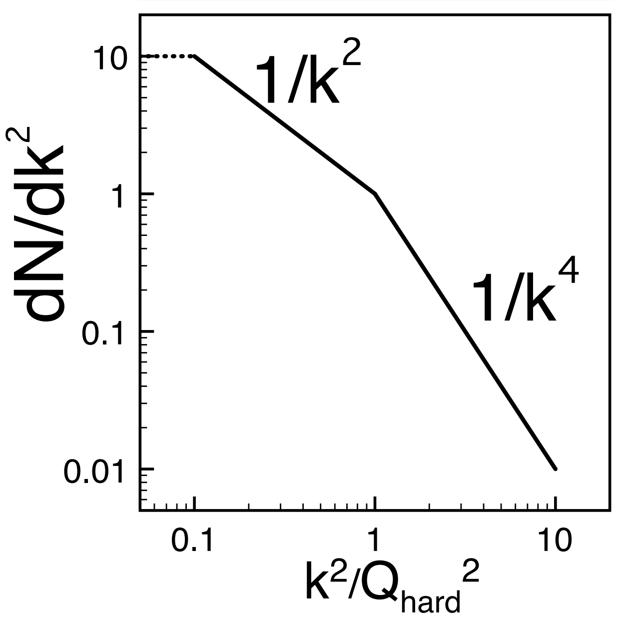

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Gunion-Bertsch spectrum

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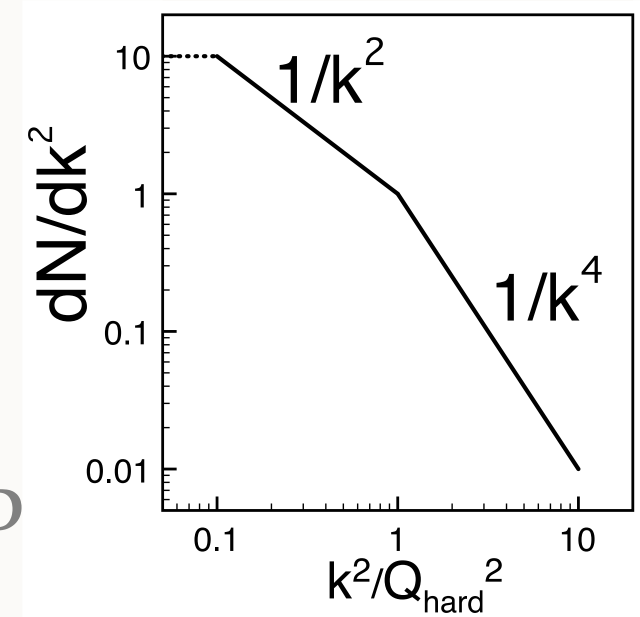

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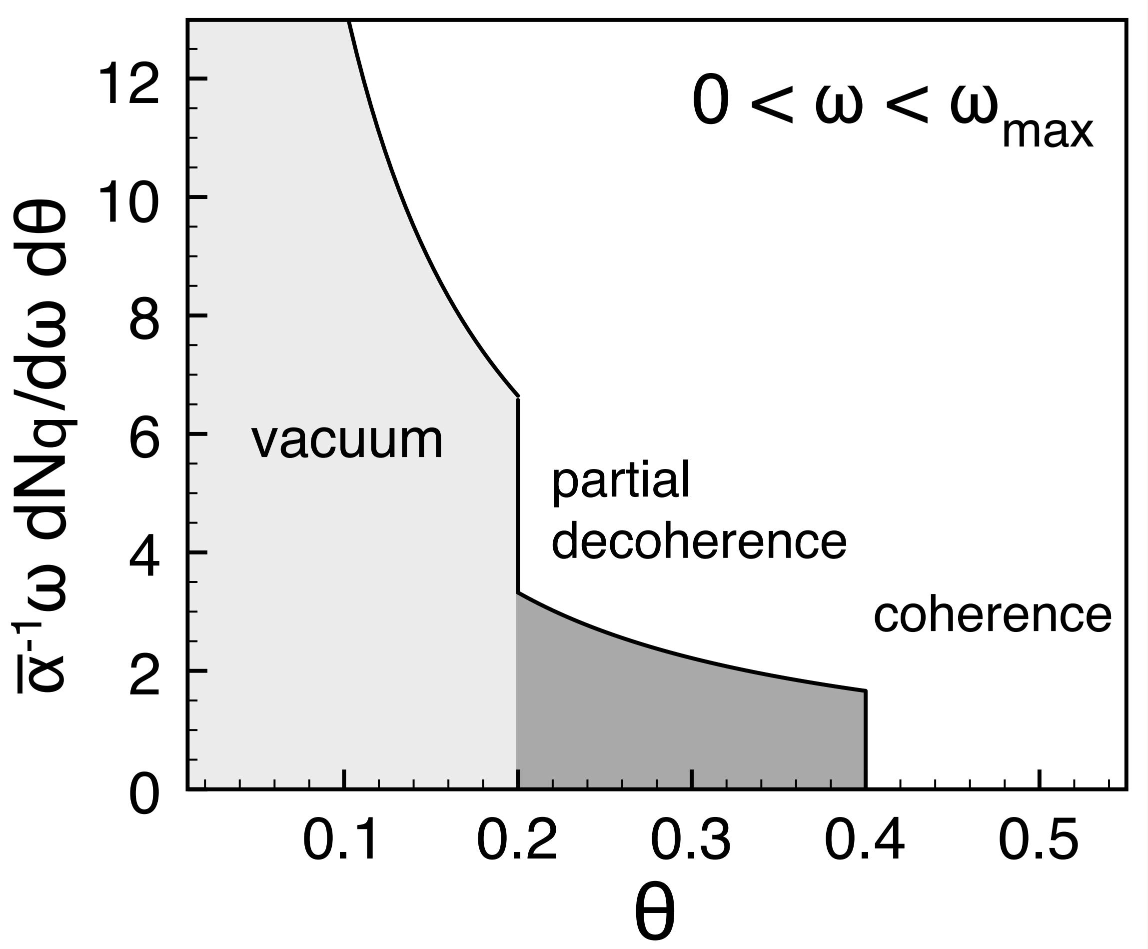
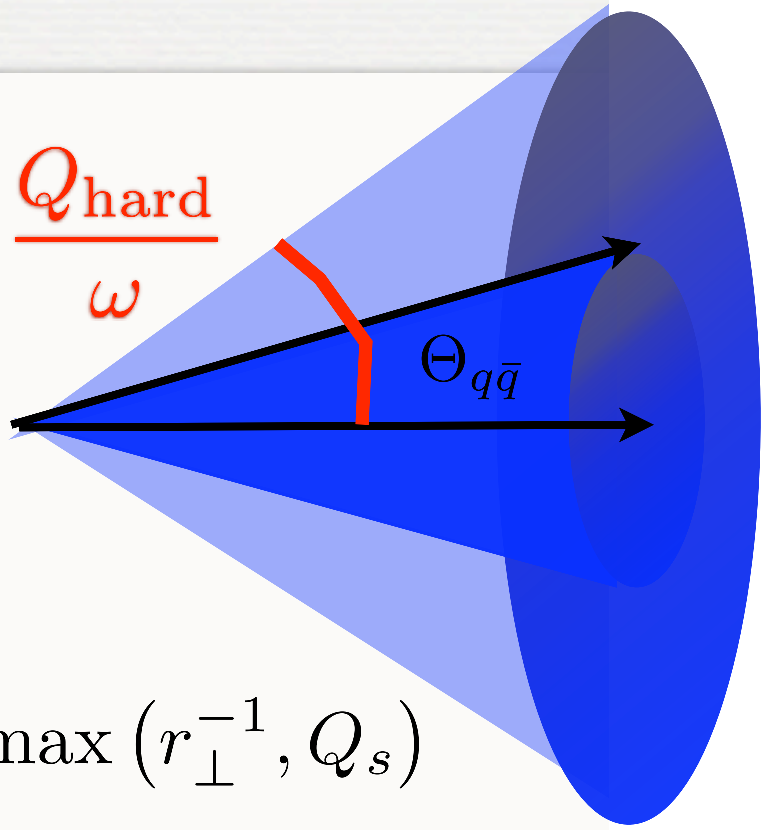
$|\boldsymbol{q}| \sim m_D$

$$\omega \frac{dN^{\text{med}}_{\text{decoh.}}}{d^3k} = \frac{8\alpha_s C_F\, \hat{q} L}{\pi} \left\langle \frac{\boldsymbol{q}^2}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2} \right\rangle \qquad r_\perp^{-1} \ll m_D$$

Gunion-Bertsch spectrum

ONSET OF DECOHERENCE - FINITE GLUON ENERGIES





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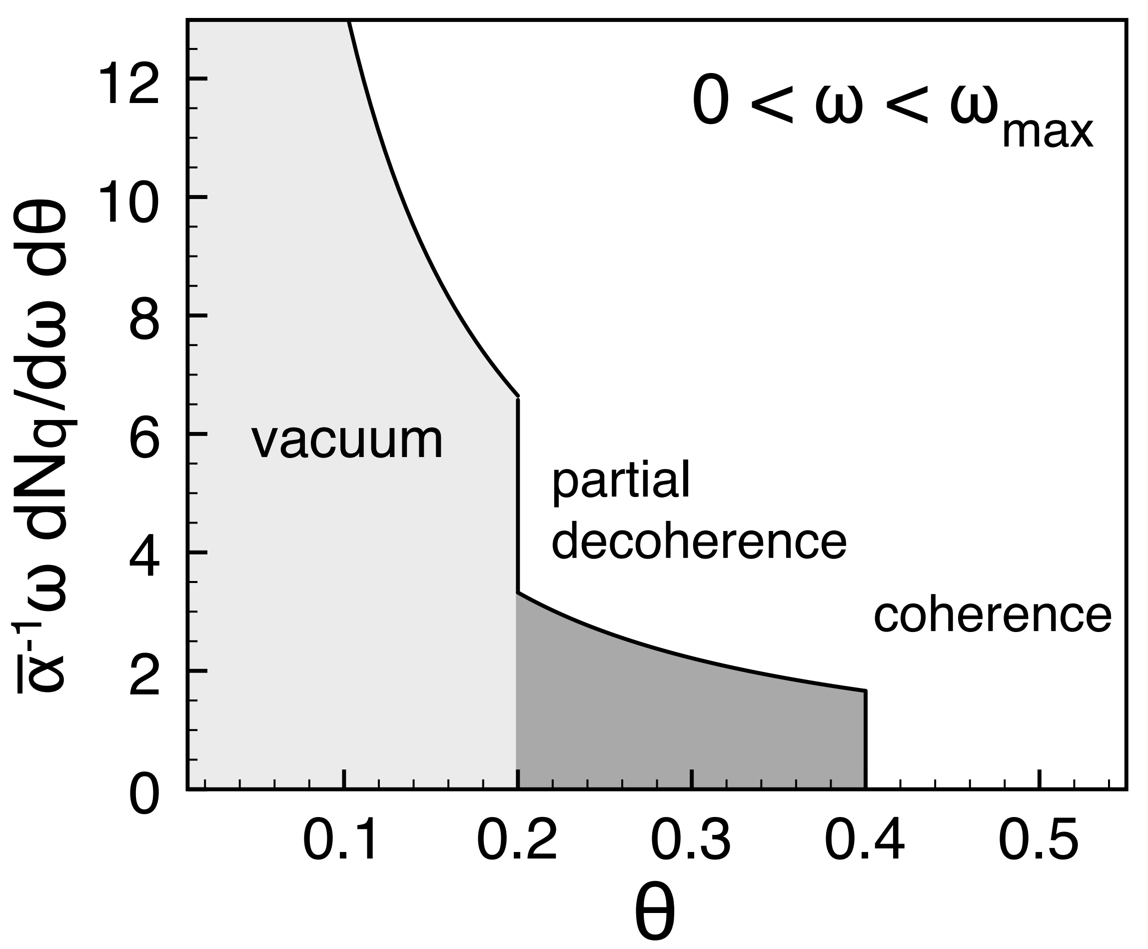
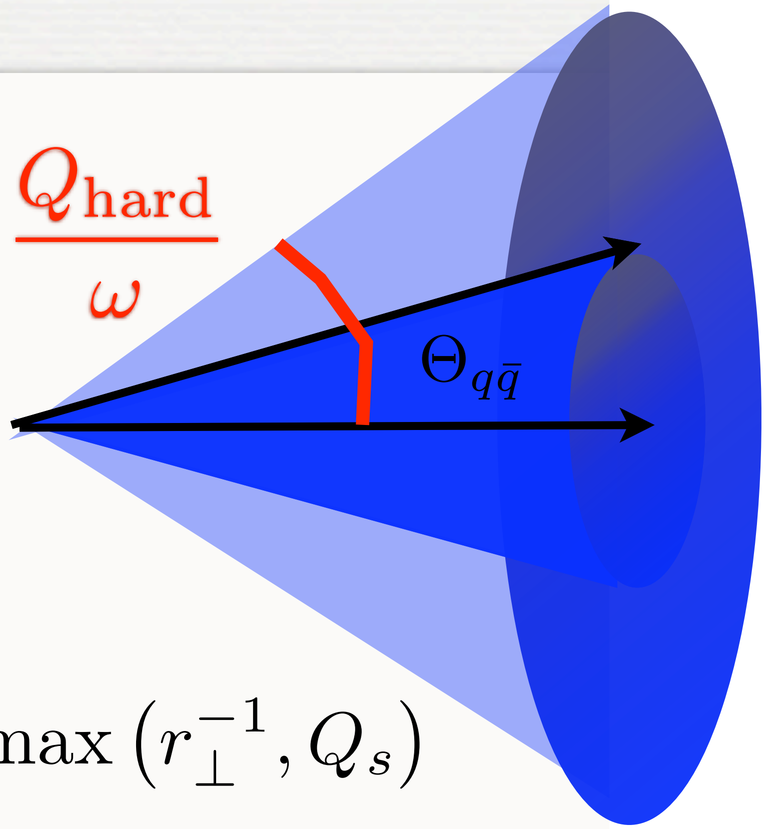
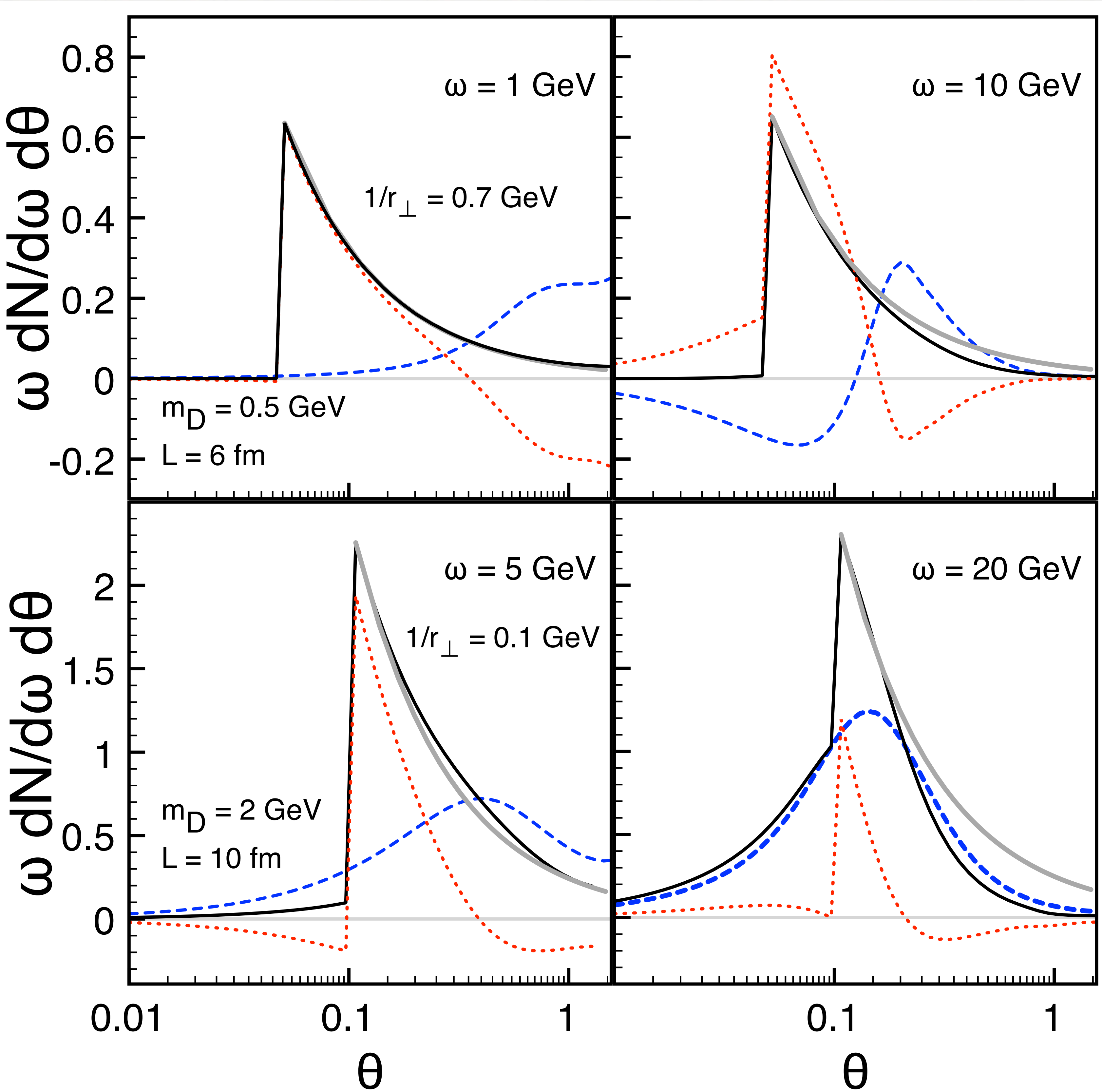




$$Q_{\mathrm{hard}} = \max\left(r_\perp^{-1}, Q_s\right)$$

Above ω_{max} medium induces independent radiation inside the cone.

- Harder gluons are produced inside the medium
- Leads to the appearance of the independent component...



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

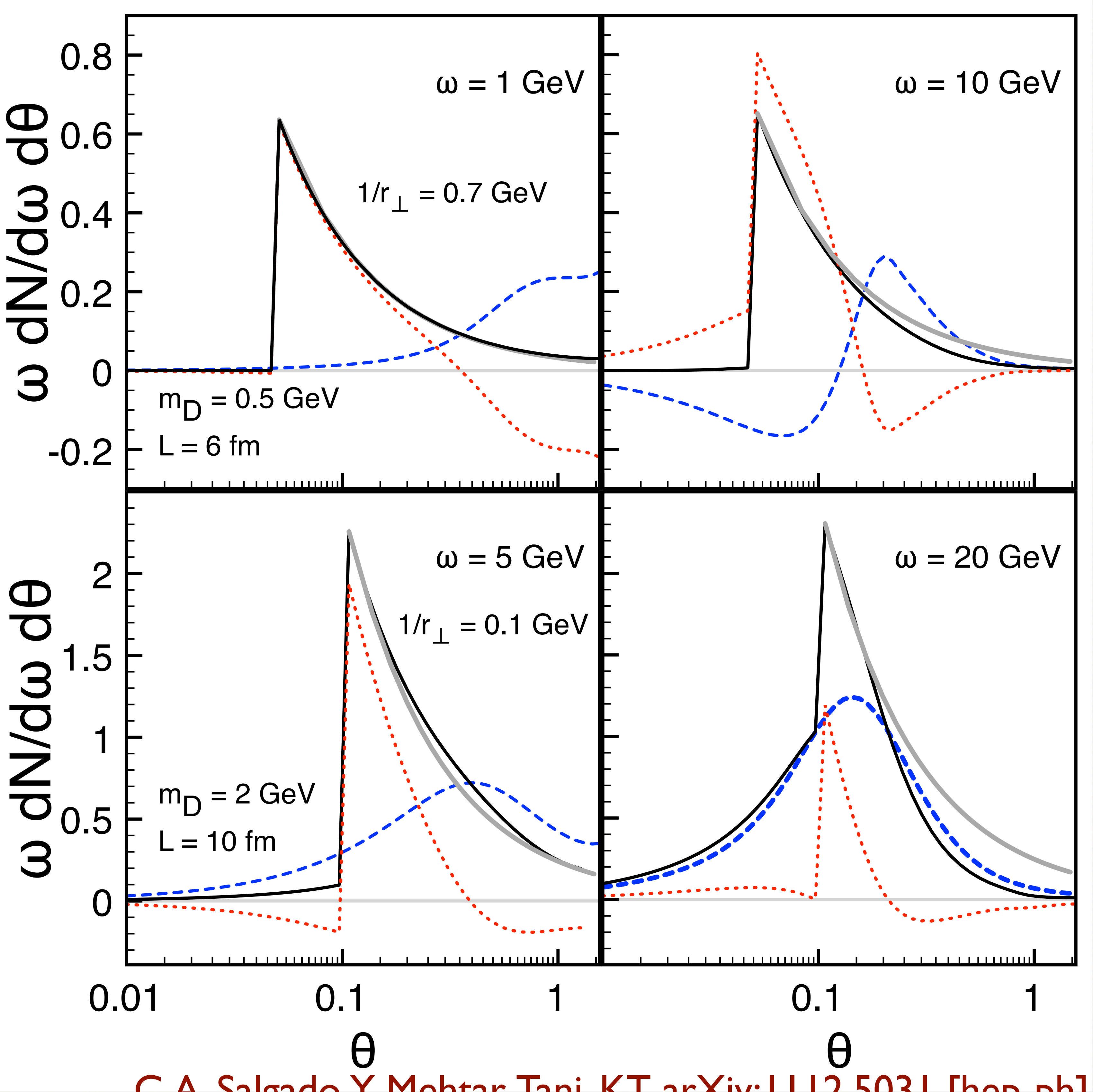
$\mathcal{J}_q^{\rm med}$

$1/\theta$

[N=1 case]

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

$1/\theta$



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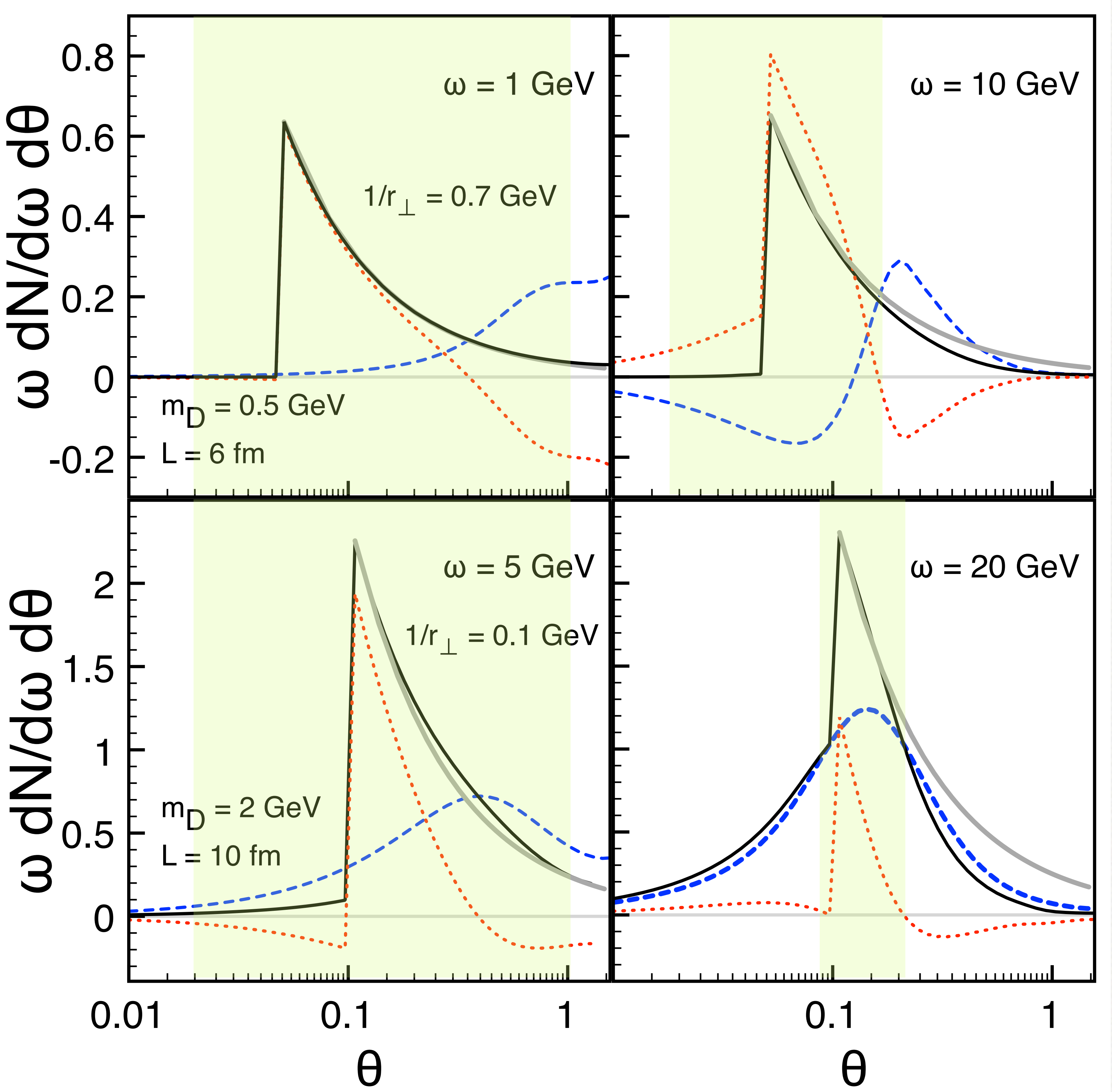
[N=1 case]



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

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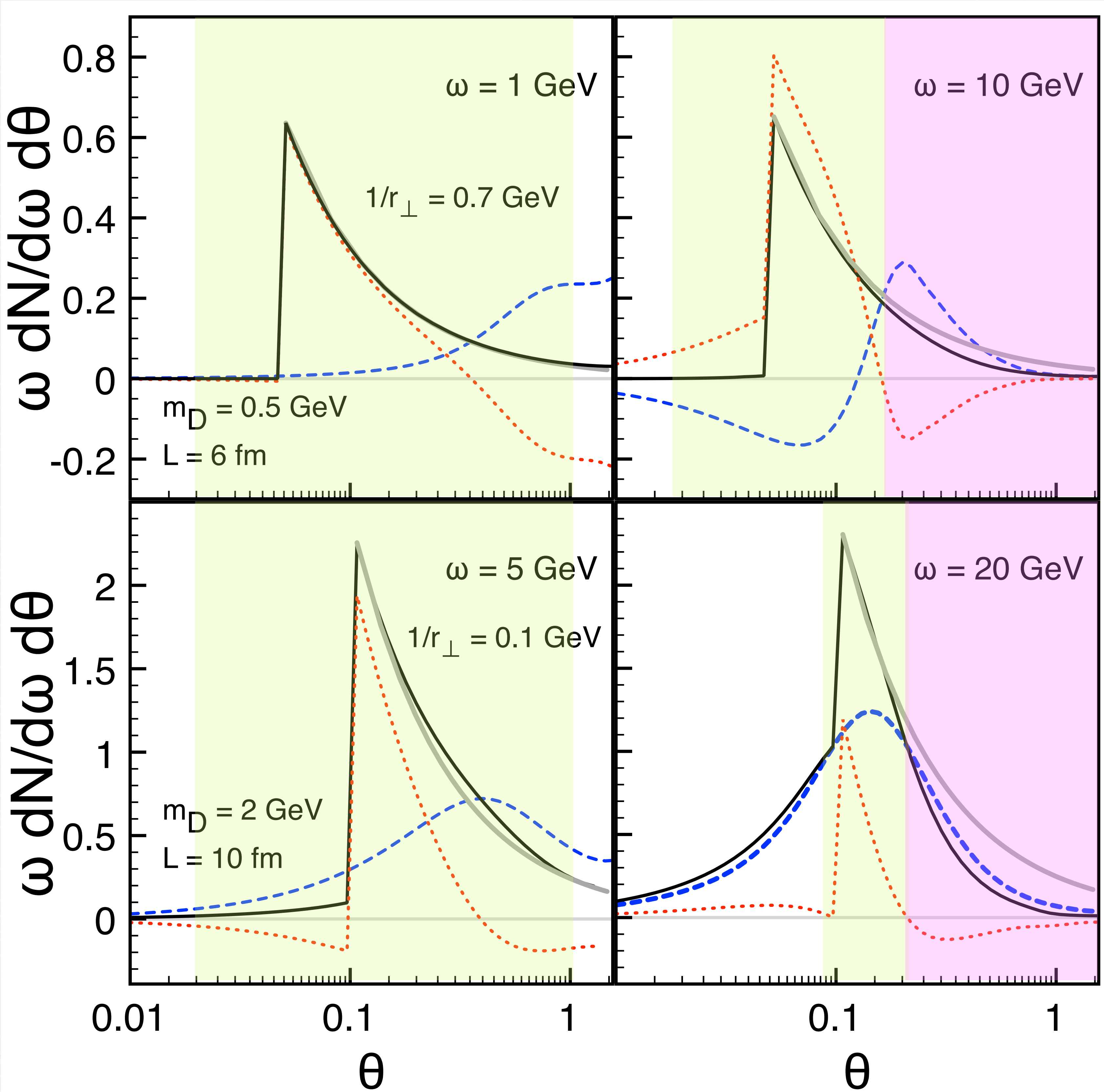
antiangular ordering

[N=1 case]



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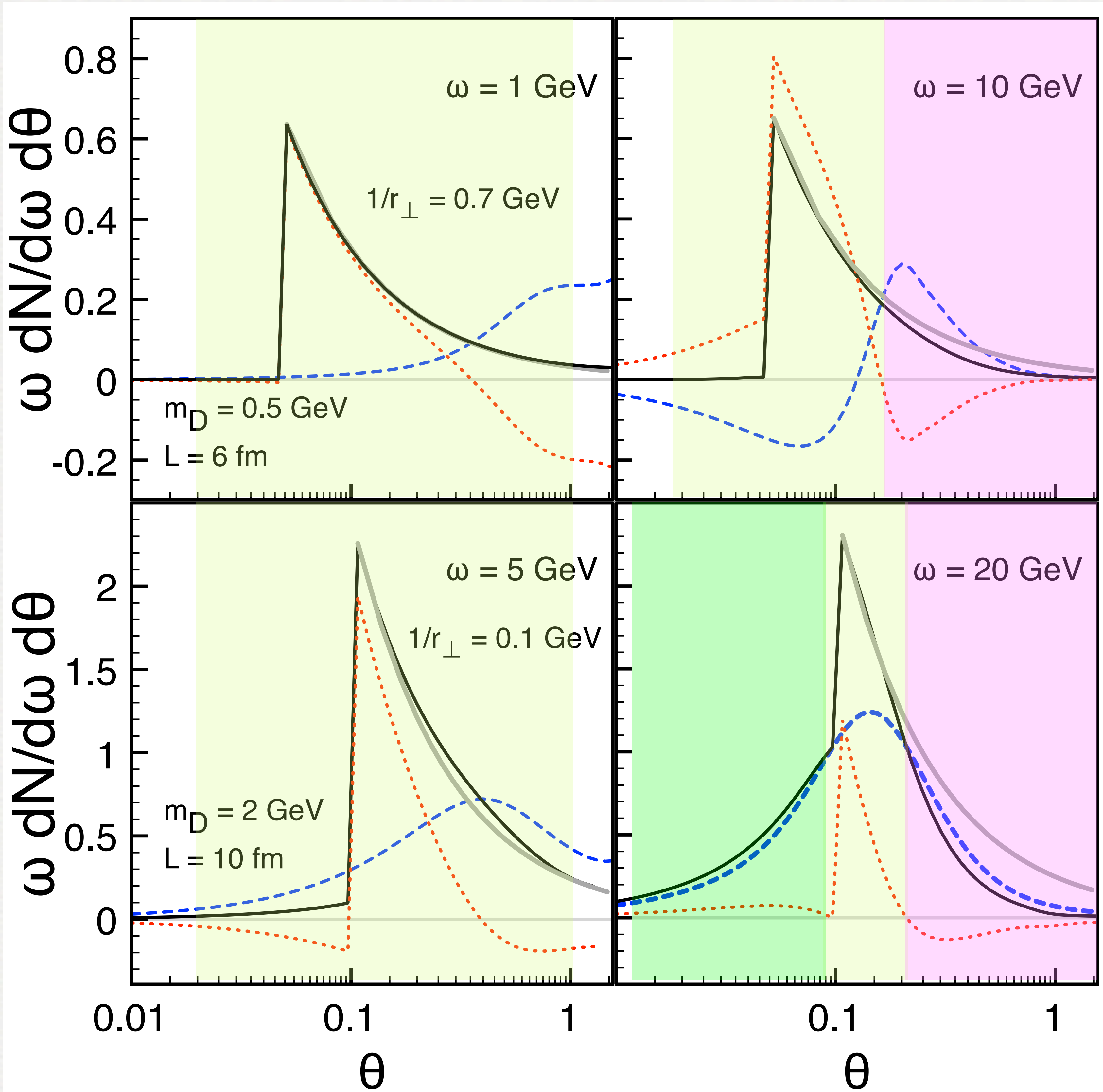

$\mathcal{R}_q^{\mathrm{med}}$ $\mathcal{J}_q^{\mathrm{med}}$

$1/\theta$

antiangular ordering

large angles

inside cone

[N=1 case]

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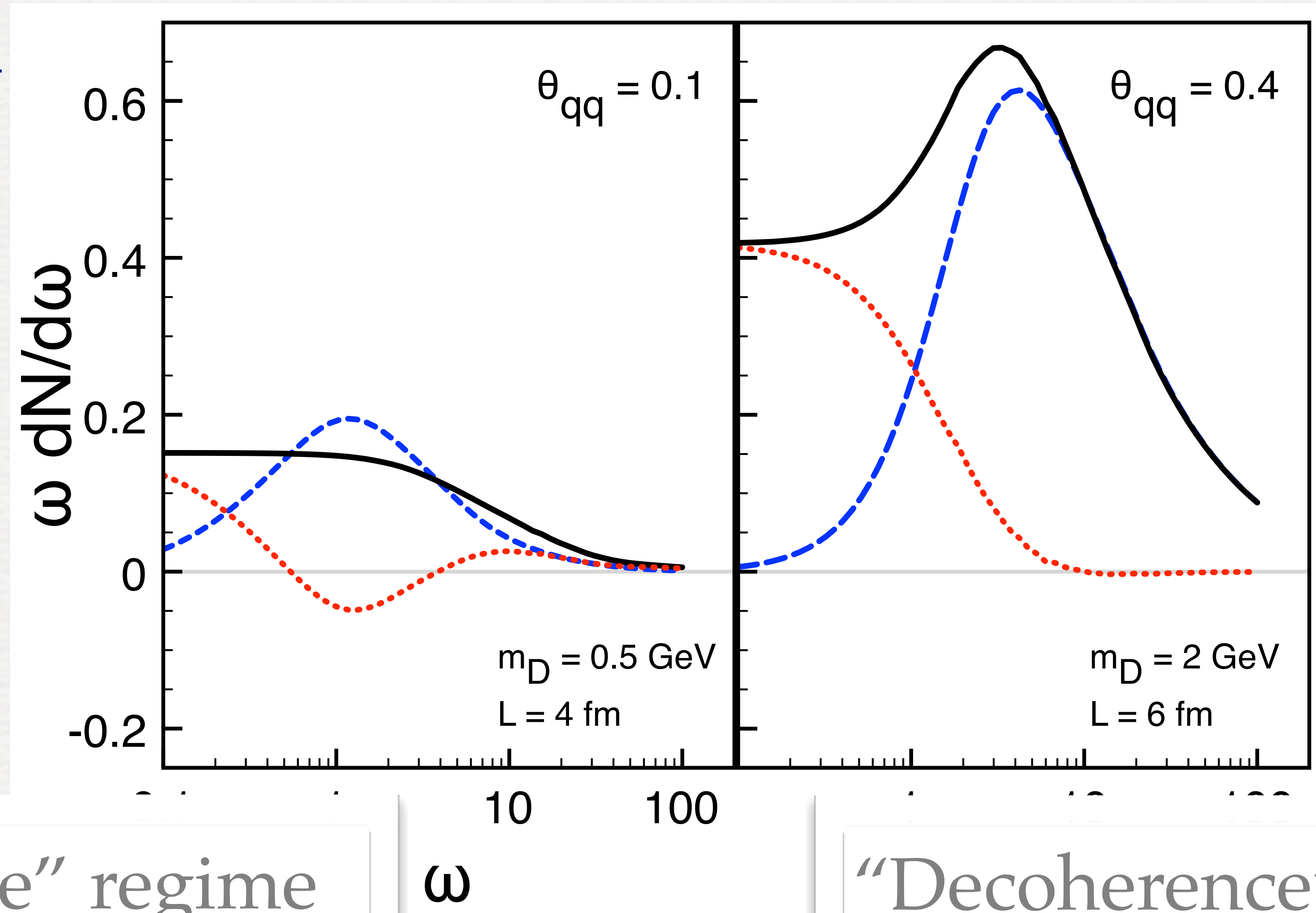
ENERGY SPECTRUM

$r_\perp^{-1}$



Q_s

"Dipole" regime

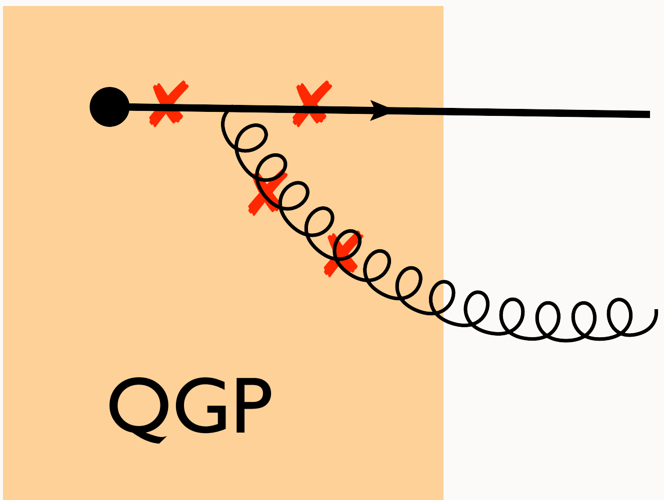
- **coherent** spectrum
- log-enhancement
  - hardening!

"Decoherence" regime

- two components:
  - outside the cone (**coh**.)
  - **indepent** gluon radiation

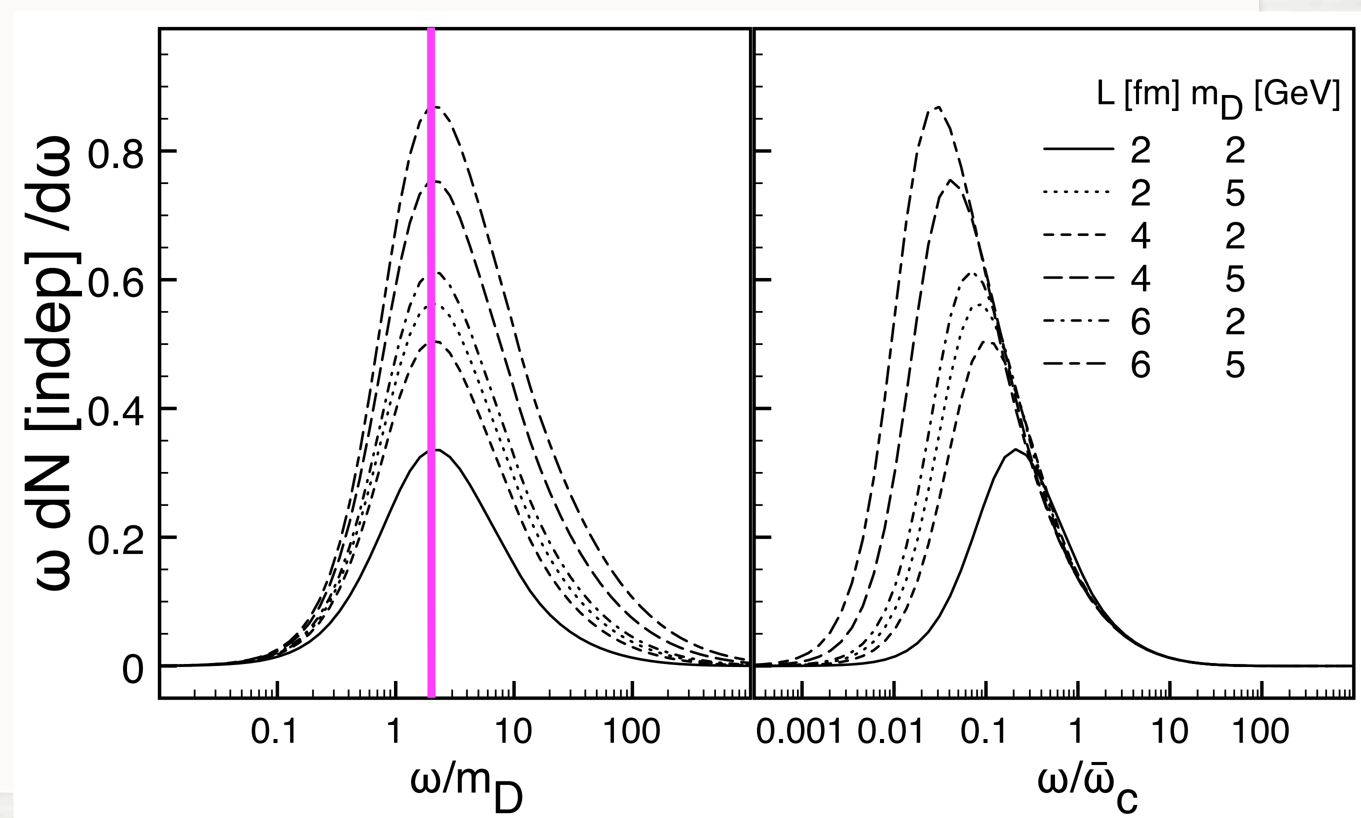
MEDIUM-INDUCED RADIATION

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



- emitted off a **single emitter**
- gluon interaction ⇒ $k_\perp$-broadening
- no soft/collinear divergence

$\langle k_\perp \rangle \sim m_D$ $\quad$ $\bar{\omega}_c \sim m_D^2 L$



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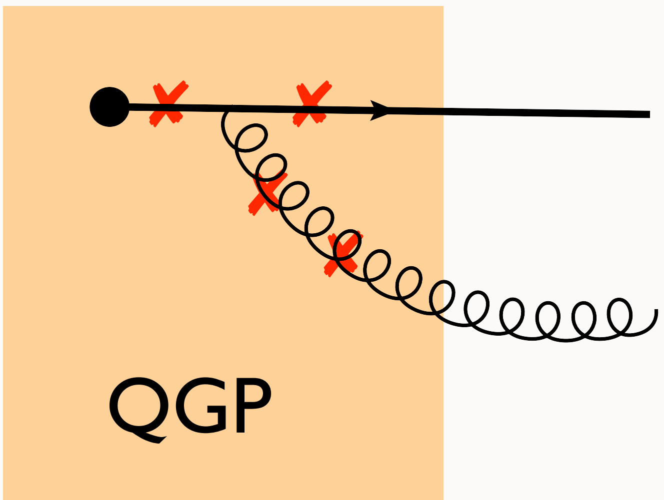

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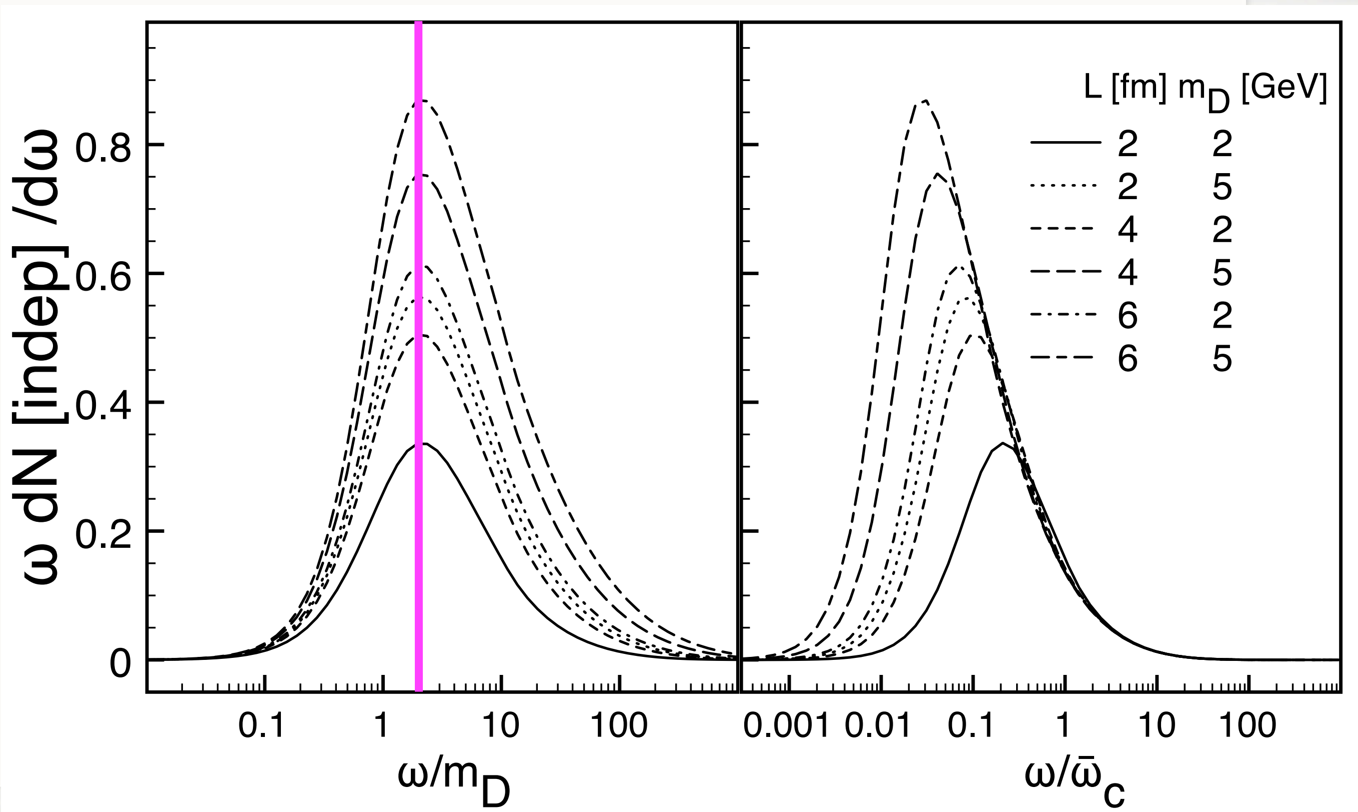
$$\langle k_\perp \rangle \sim m_D \qquad \bar{\omega}_c \sim m_D^2 L$$

For dense media:

$\Delta t > \lambda_{\rm mfp} \Rightarrow$ **coherent emission**

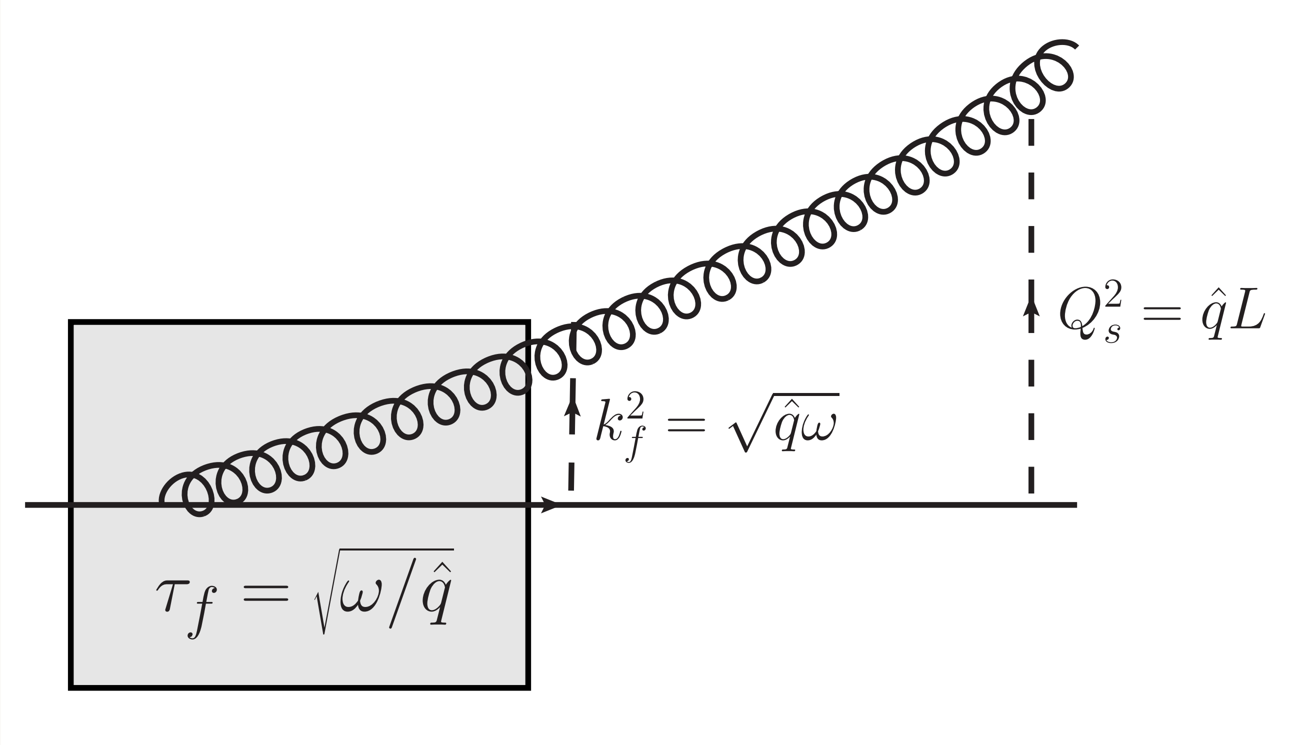
$$\left.\begin{aligned} \Delta t &= \frac{\omega}{k_\perp^2} \\ k_\perp^2 &= \mu^2 \frac{\Delta t}{\lambda_{\rm mfp}} \end{aligned}\right\} \quad \Delta t = \sqrt{\frac{\omega}{\hat{q}}}$$



RADIATION IN A DENSE MEDIUM

$$\mathcal{R}_q \simeq 4\omega \int_0^L dt \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k}-\boldsymbol{k}', L-t) \sin\left(\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right) \exp\left(-\frac{\boldsymbol{k}'^2}{2\sqrt{\hat{q}\omega}}\right)$$

- emission along the whole length of the medium
- two step process
- broadening can transport gluons up to arbitrary large angles!



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

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$$\mathcal{P}(\boldsymbol{k}, \xi) = \frac{4\pi}{\hat{q}\,\xi} e^{-\frac{\boldsymbol{k}^2}{\hat{q}\xi}}$$

⇒ prob. of acquiring mom. **k** after ξ

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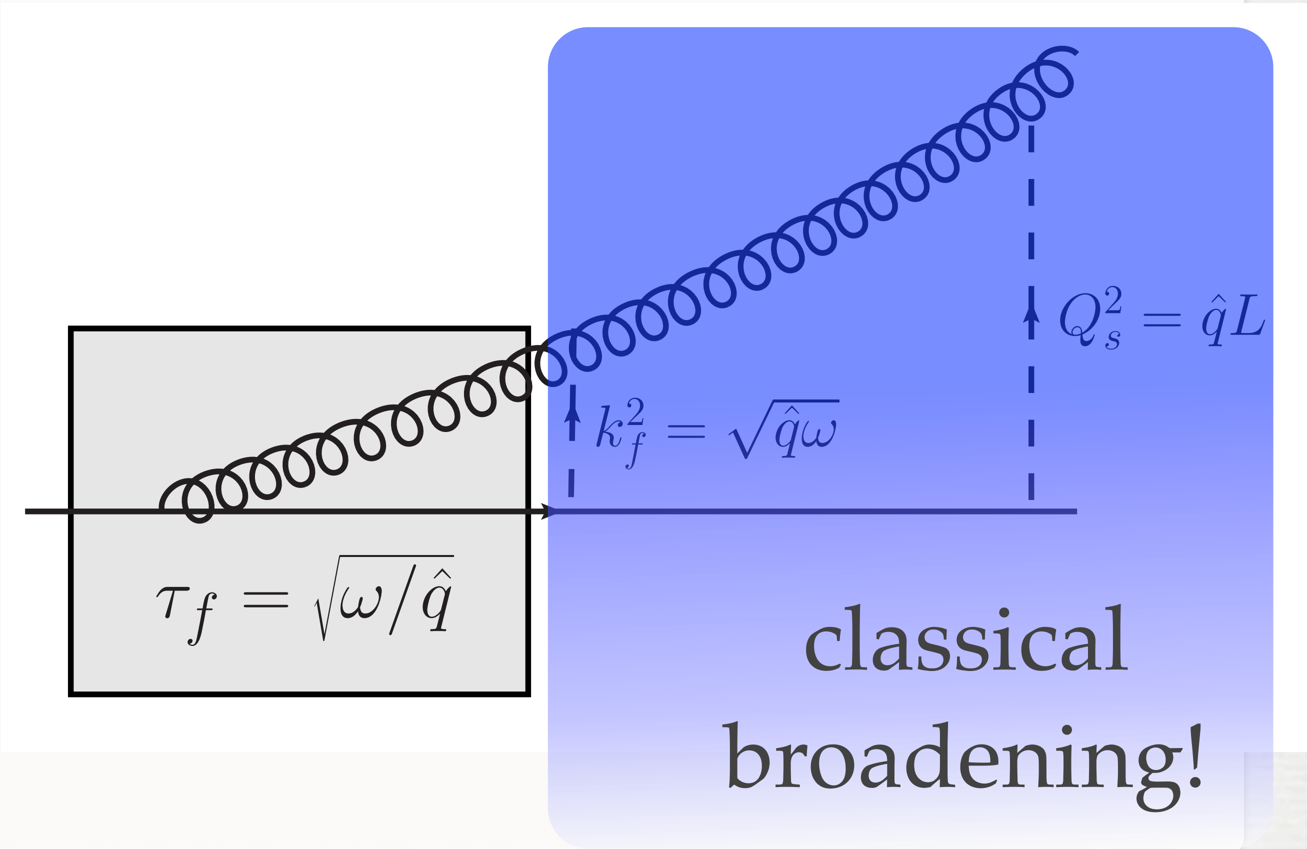

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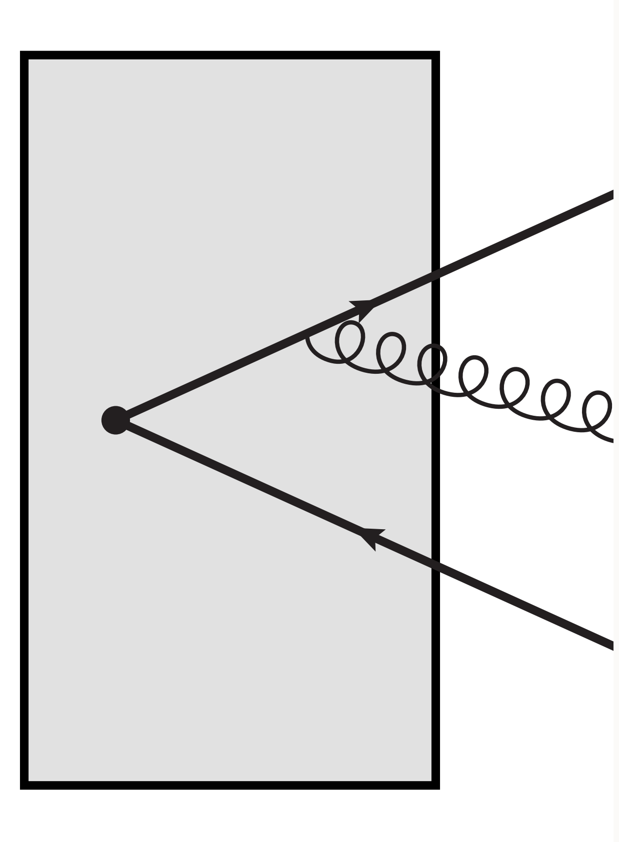
$$1 - \Delta_{\text{med}}(t, 0) \simeq \exp\left[-\frac{1}{12}\hat{q}\theta^2_{q\bar{q}}t^3\right] \quad \Longrightarrow \quad \tau_d = \left(\hat{q}\theta^2_{q\bar{q}}\right)^{-1/3}$$



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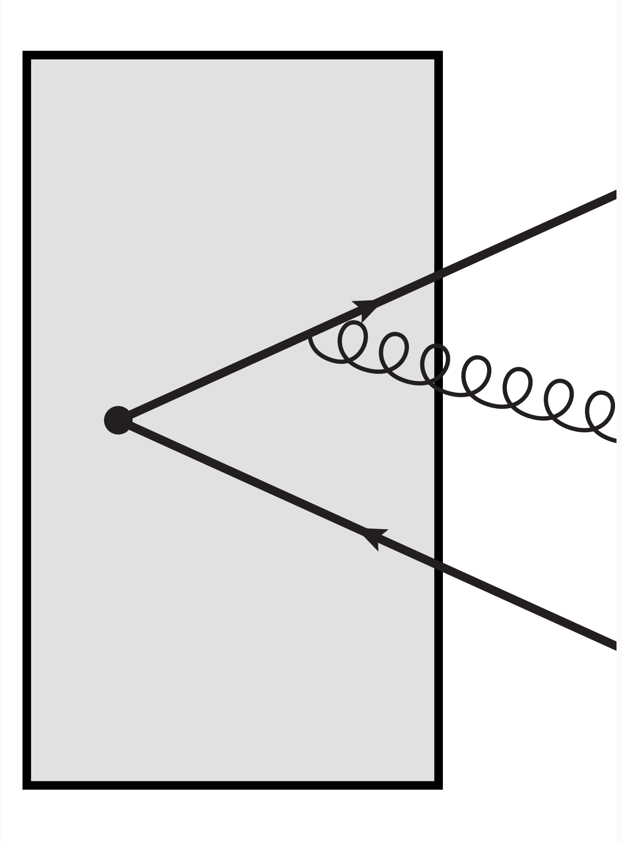

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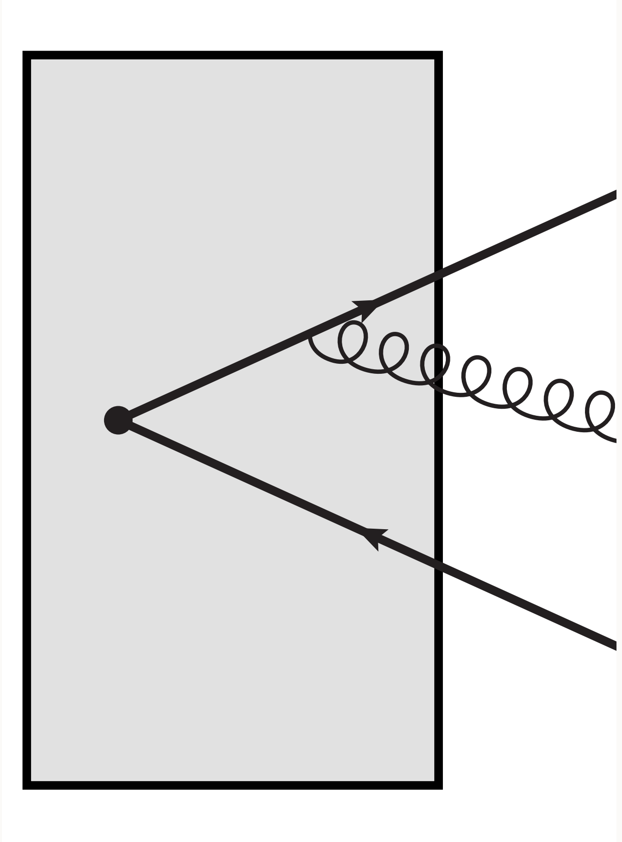

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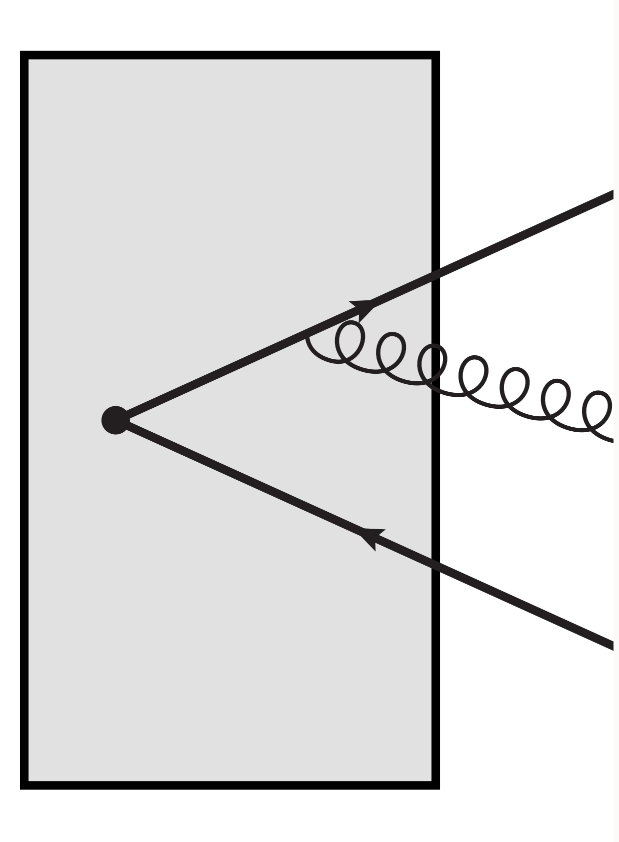

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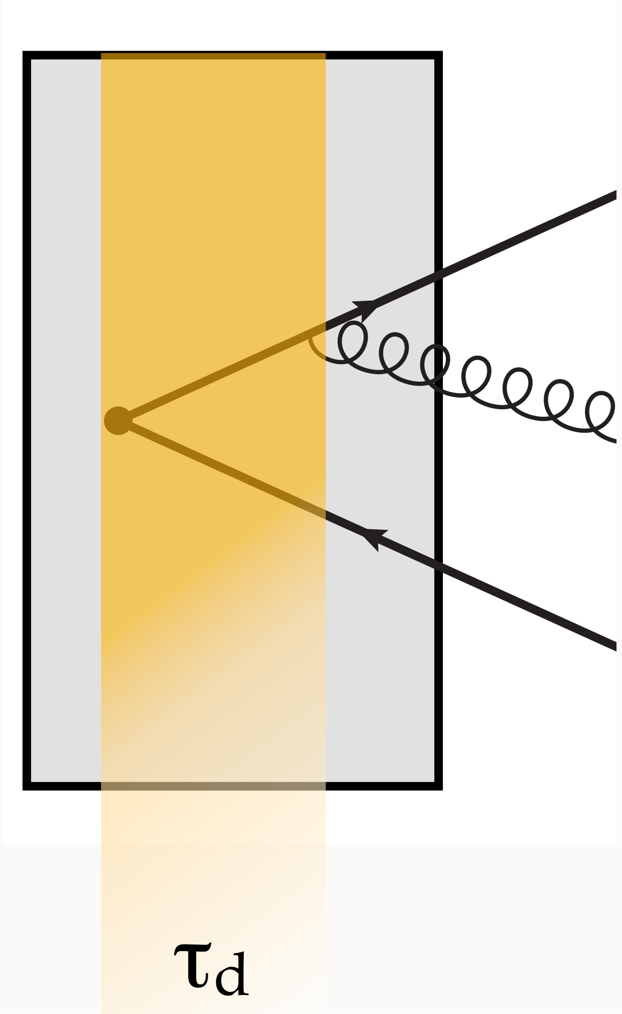

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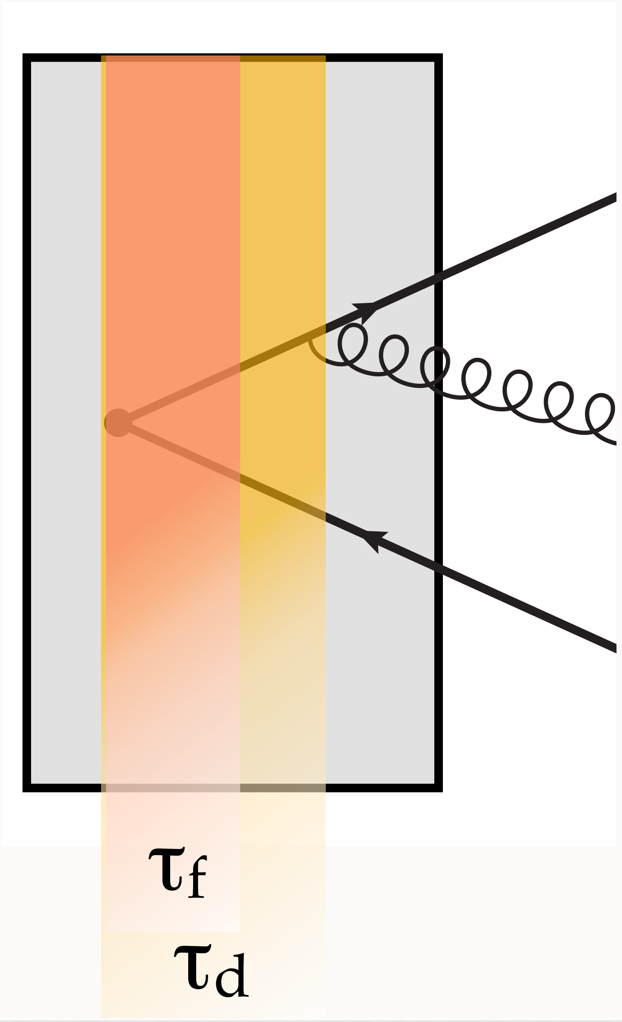
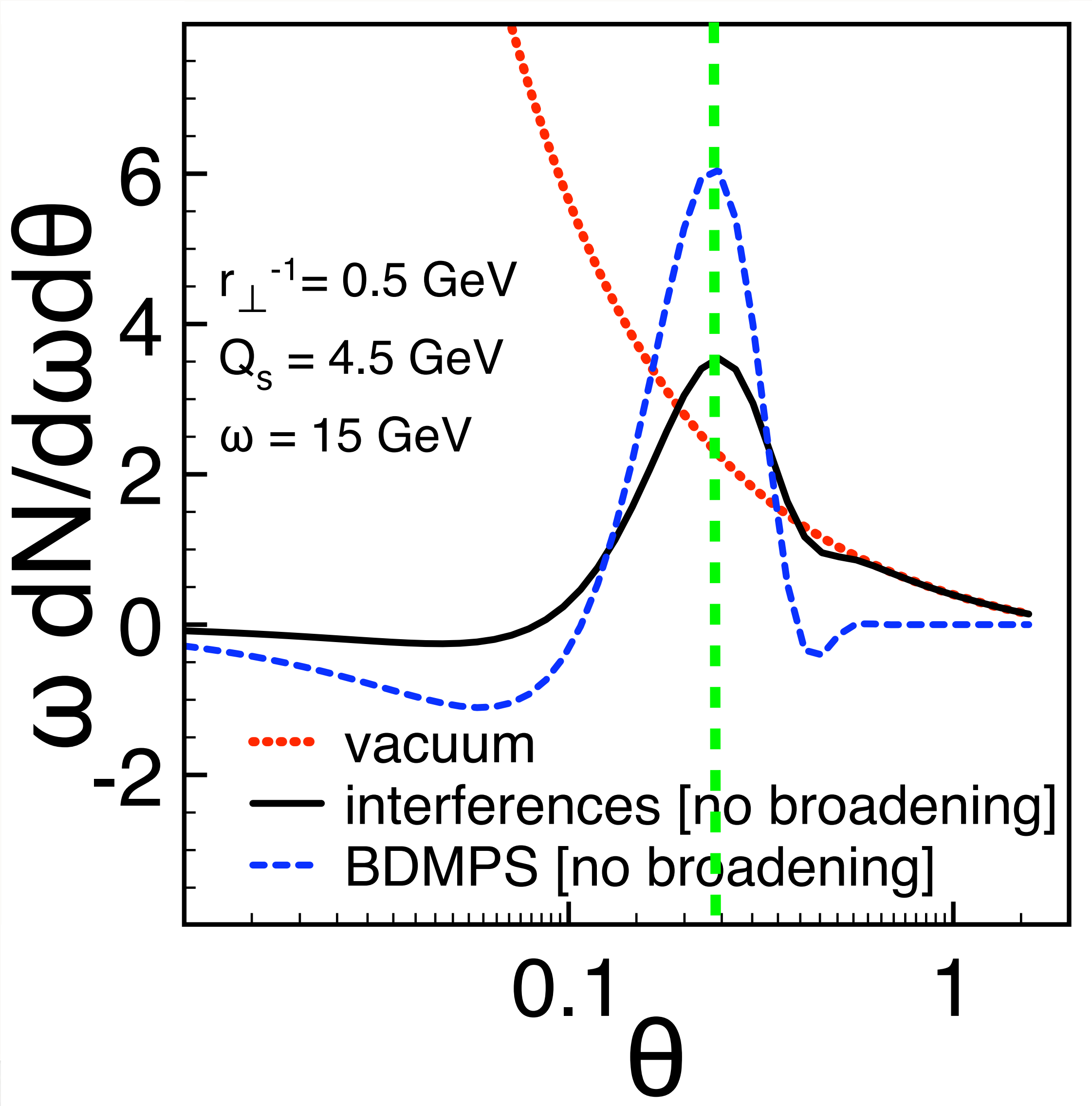


BACK TO COHERENCE

$$\mathcal{J}|_{\mathrm{decoh.}} \simeq \begin{cases} 4\omega\tau_d \sin\left(\frac{\boldsymbol{k}^2}{2\sqrt{\hat{q}\omega}}\right)\exp\left(-\frac{\boldsymbol{k}^2}{2\sqrt{\hat{q}\omega}}\right) & \boldsymbol{k}^2 \ll Q_s^2 \\ \frac{4\omega^2}{\boldsymbol{k}^2} & \boldsymbol{k}^2 \gg Q_s^2 \end{cases}$$

- before classical broadening
- two components:
  - BDMP-like
  - vacuum-like hard component



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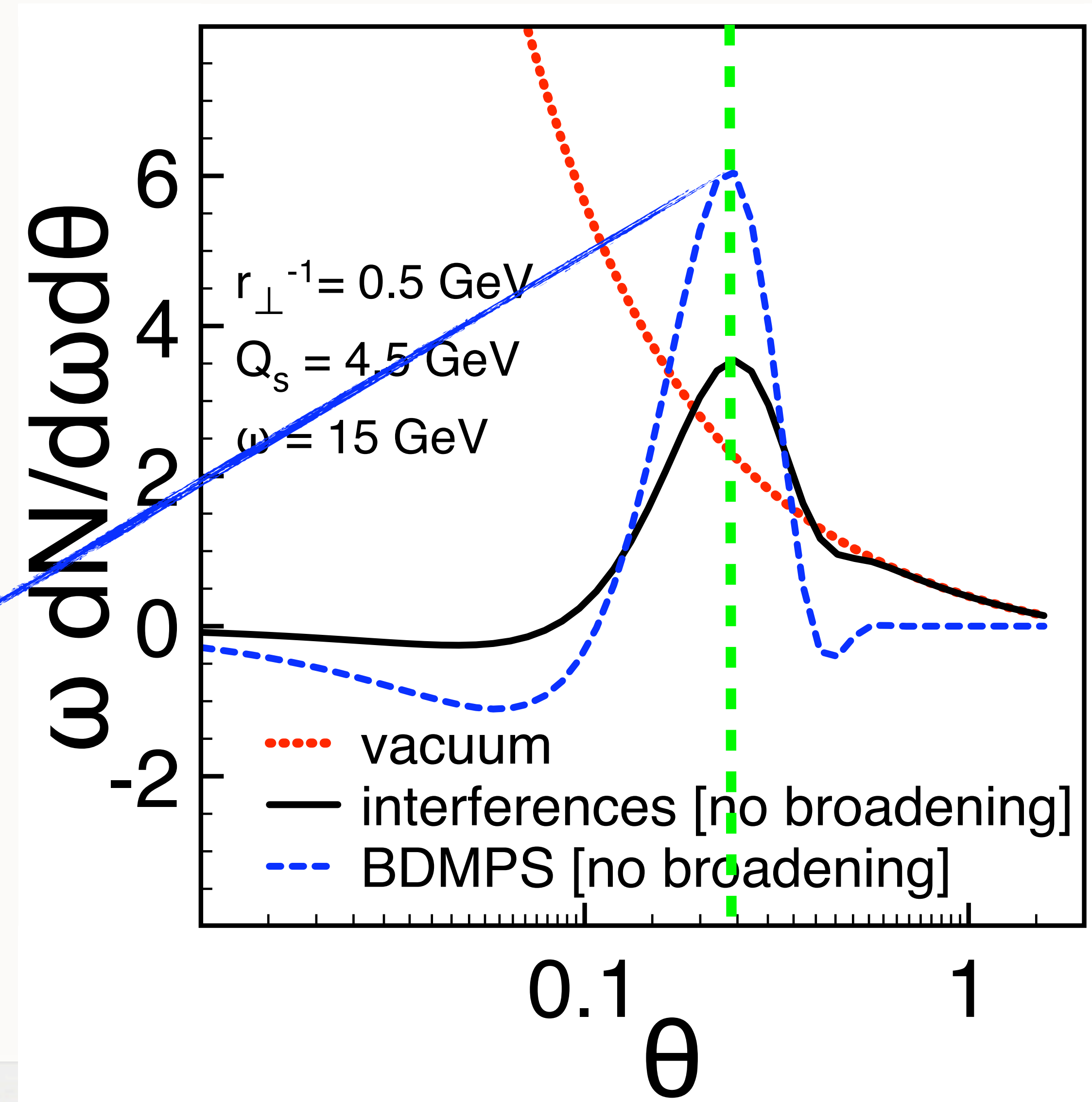

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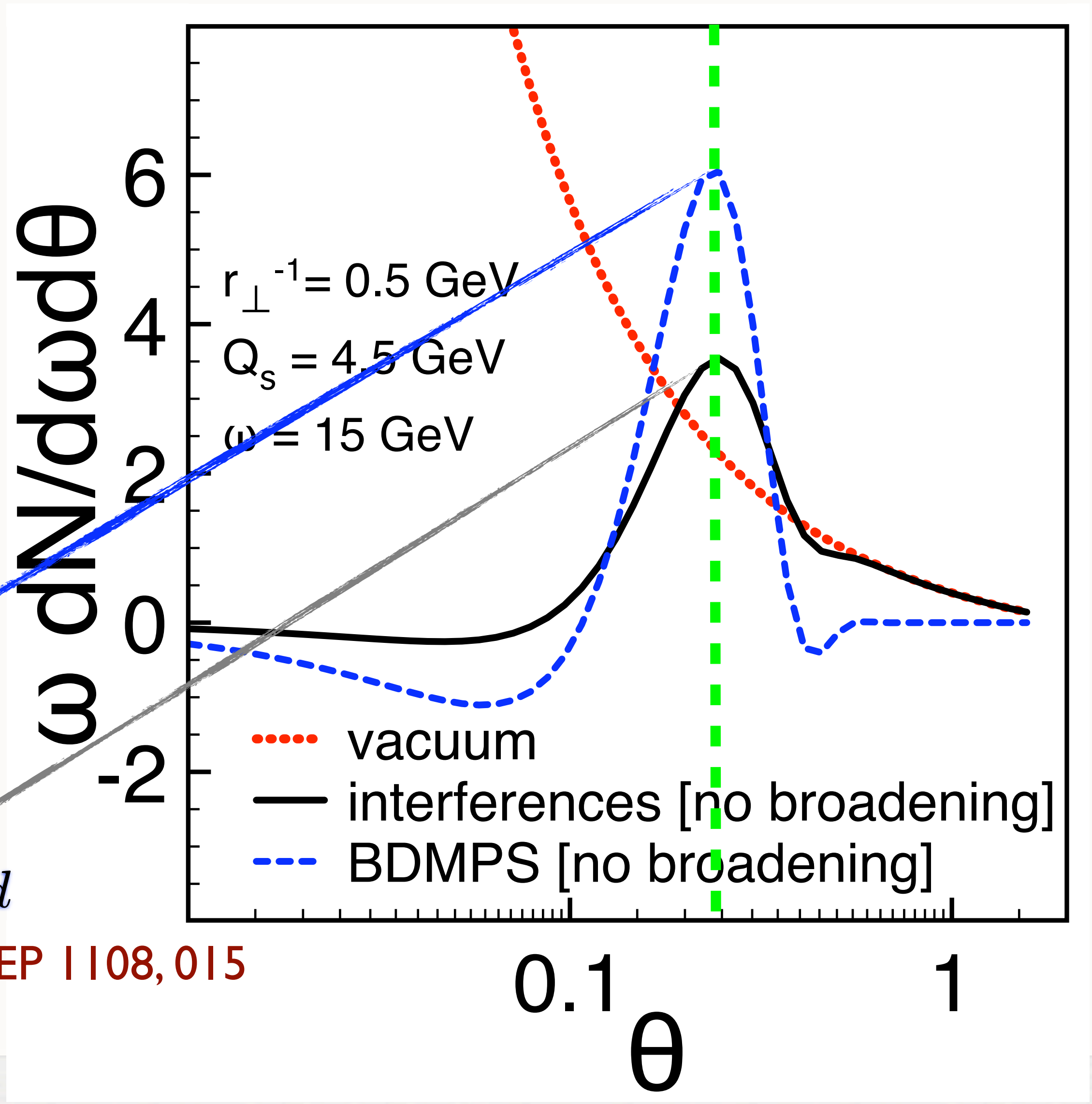

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BACK TO COHERENCE

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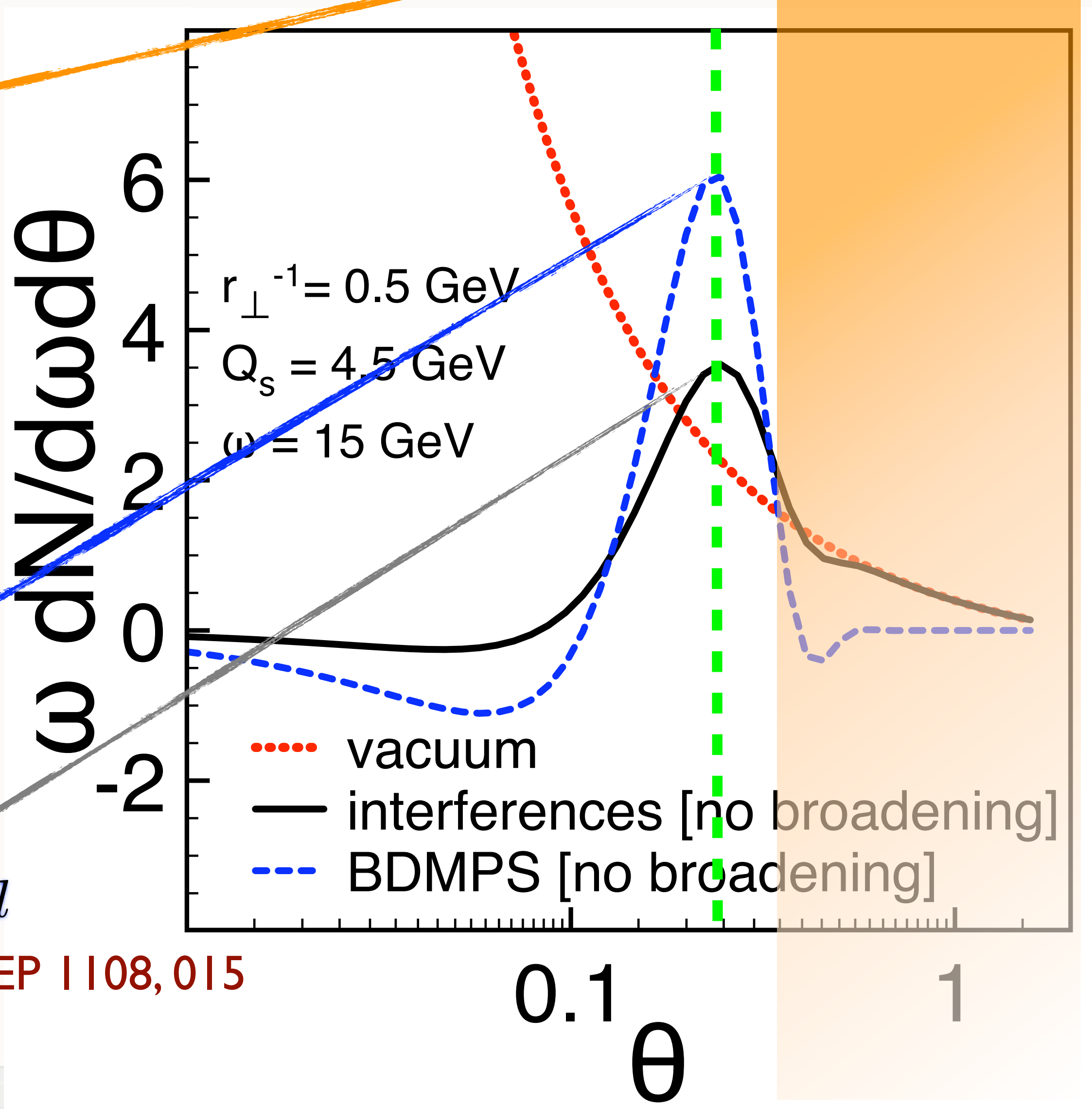
coherence restored!

- before classical broadening
- two components:
  - BDMP-like
  - vacuum-like hard component

$\mathcal{R}_q \propto L$

$\mathcal{J} \propto \tau_d$



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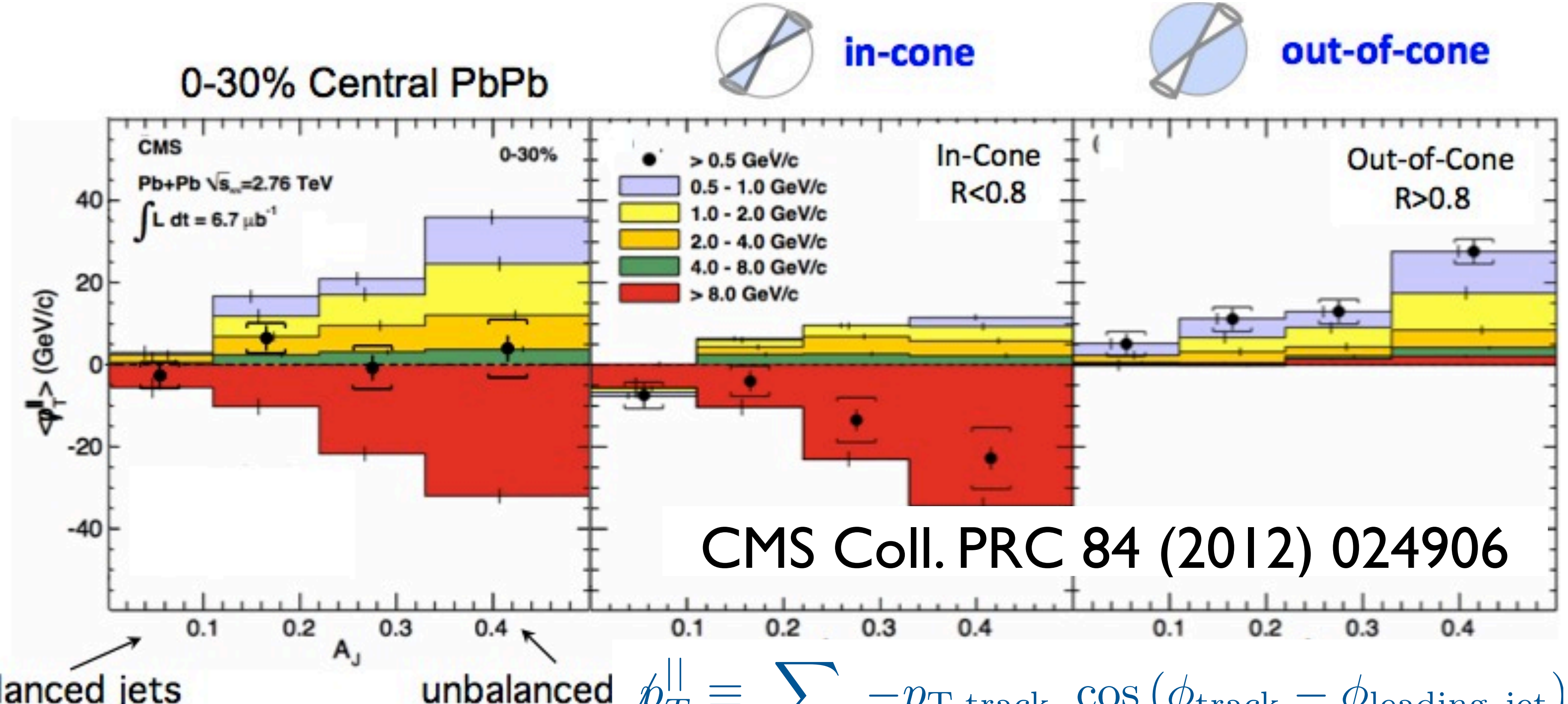
CONCLUSIONS

- copious jets in heavy-ion collisions at the LHC
- independent radiation inside the cone - collinear limit, as in vacuum
- medium induces coherent radiation up to hard scale - large angle radiation
- a two scale problem: $Q_{\text{hard}} = \max(r_\perp^{-1} , Q_s)$
  - ⇒ jet probes medium, and vice versa
- interplay: decoherence ($k_\perp < Q_{\text{hard}}$) vs. coherence ($k_\perp > Q_{\text{hard}}$)
  - ⇒ building block of jet calculus

backup

(II) Soft particles at large angles



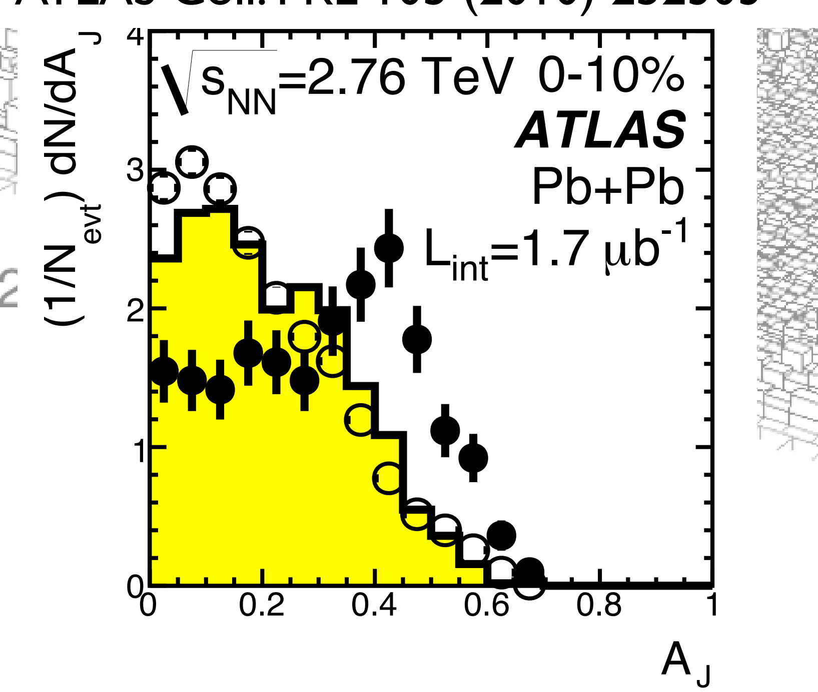
CMS Coll. PRC 84 (2012) 024906

$$p_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

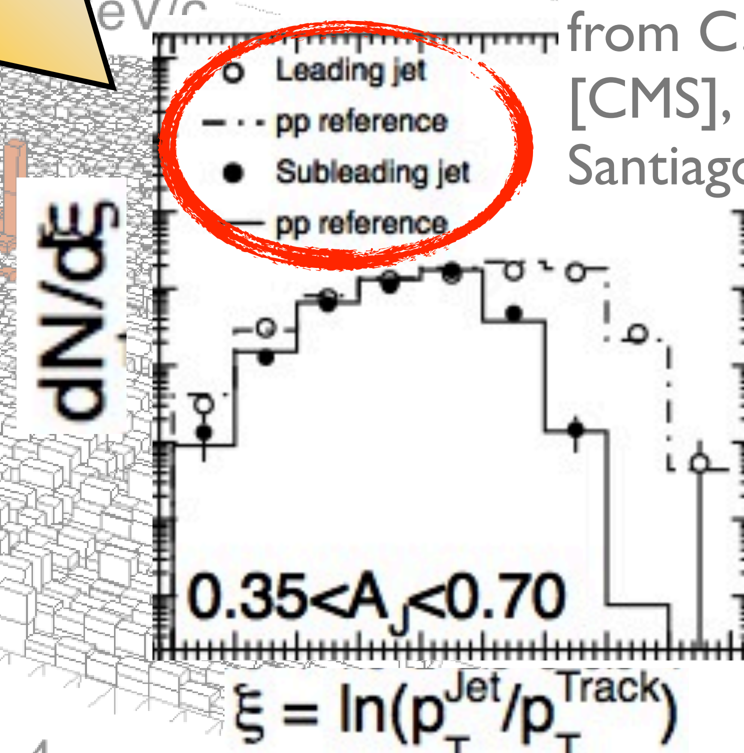
(I) Significant jet asymmetry

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

ATLAS Coll. PRL 105 (2010) 252303



$$\Delta\phi > \pi/2$$



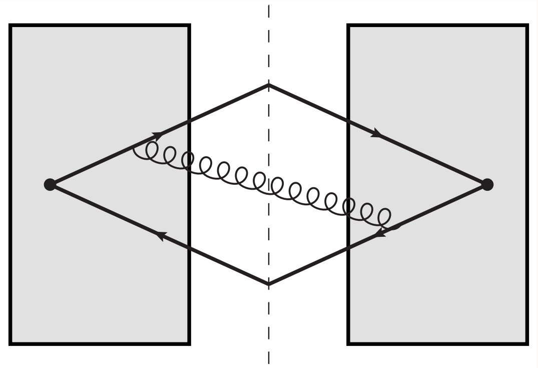
from C. Mironov [CMS], Encontro Santiago-Lisboa 2012

(III) Vacuumlike fragmentation

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:



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

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

ANTENNA IN MEDIUM

Y. Mehtar-Tani, KT arXiv:1105.1346 [hep-ph], C.A. Salgado, Y. Mehtar-Tani, KT, in preparation
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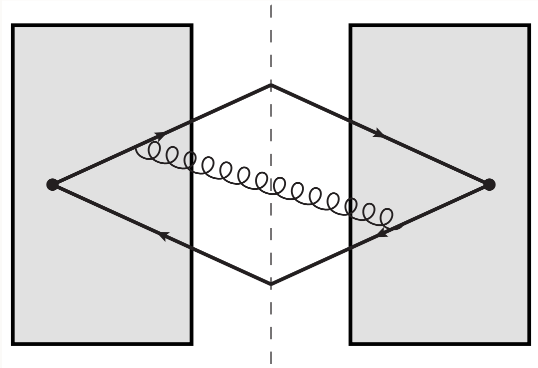
Multiple scattering:



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

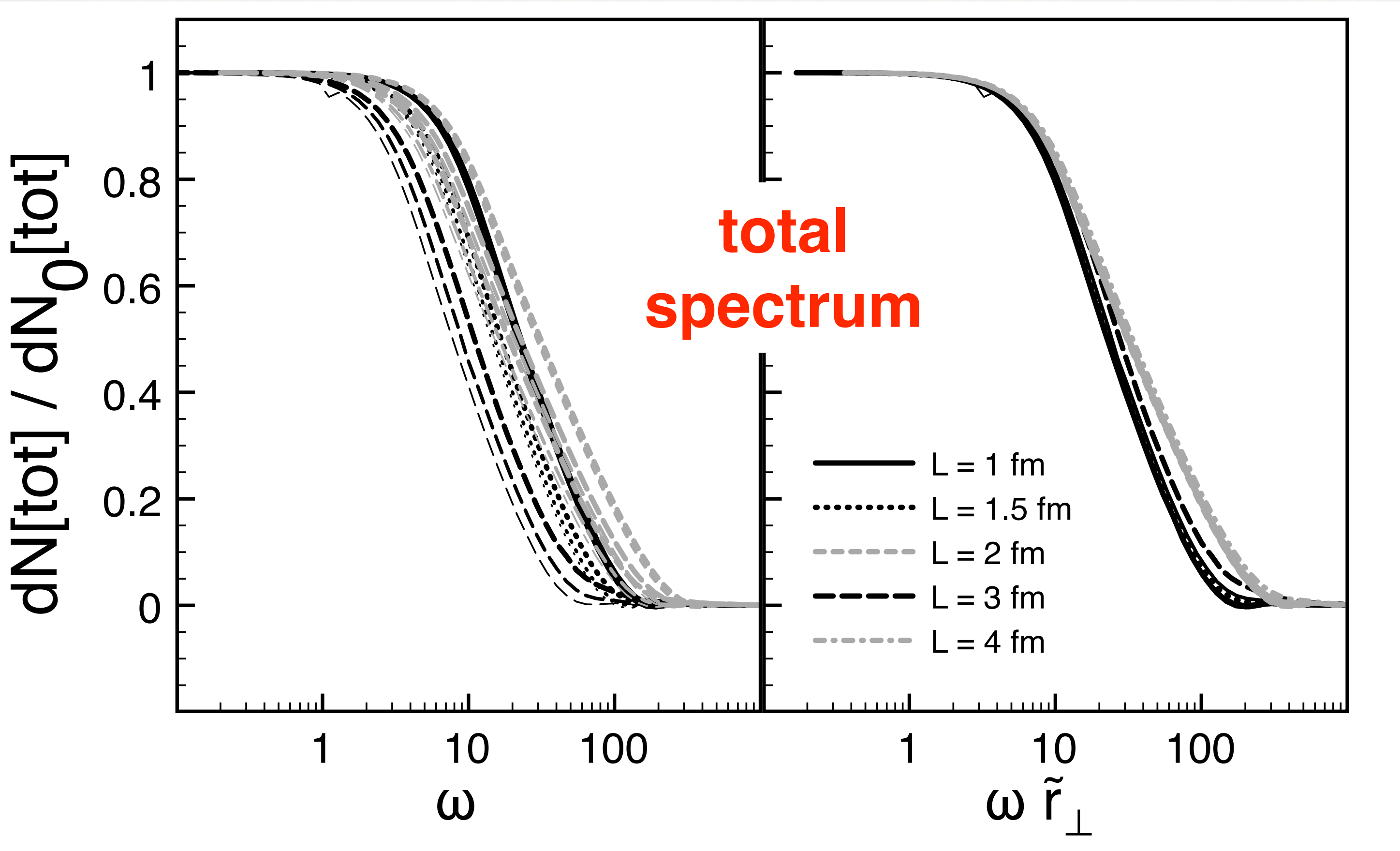
$$\mathcal{J} = \mathrm{Re}\left\{ \int_0^\infty dy'^+ \int_0^{y'^+} dy^+ \left(1 - \Delta_{\mathrm{med}}(y^+, 0)\right) \right.$$
$$\times \int d^2\boldsymbol{z}\, \exp\left[-i\bar{\boldsymbol{\kappa}}\cdot\boldsymbol{z} - \frac{1}{2}\int_{y'^+}^{\infty} d\xi\, n(\xi)\sigma(\boldsymbol{z}) + i\frac{k^+}{2}\delta\boldsymbol{n}^2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

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

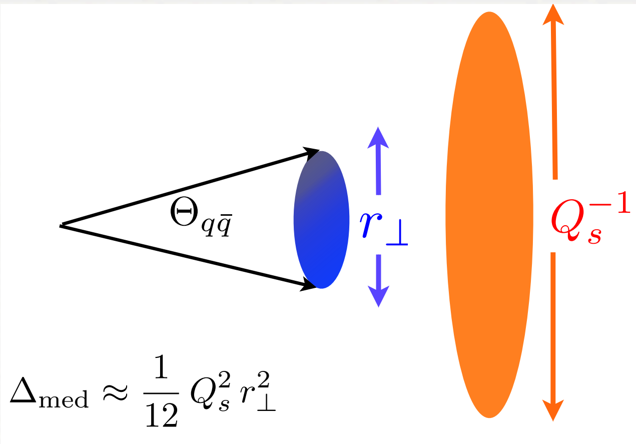
$$\sigma(\mathbf{r}) = 2\alpha_S C_A \int \frac{d^2\mathbf{q}}{(2\pi)^2} \boxed{\mathcal{V}^2(\mathbf{q})} \left[1 - \cos(\mathbf{r}\cdot\mathbf{q})\right]$$

Brownian motion of q+g system through medium potential...

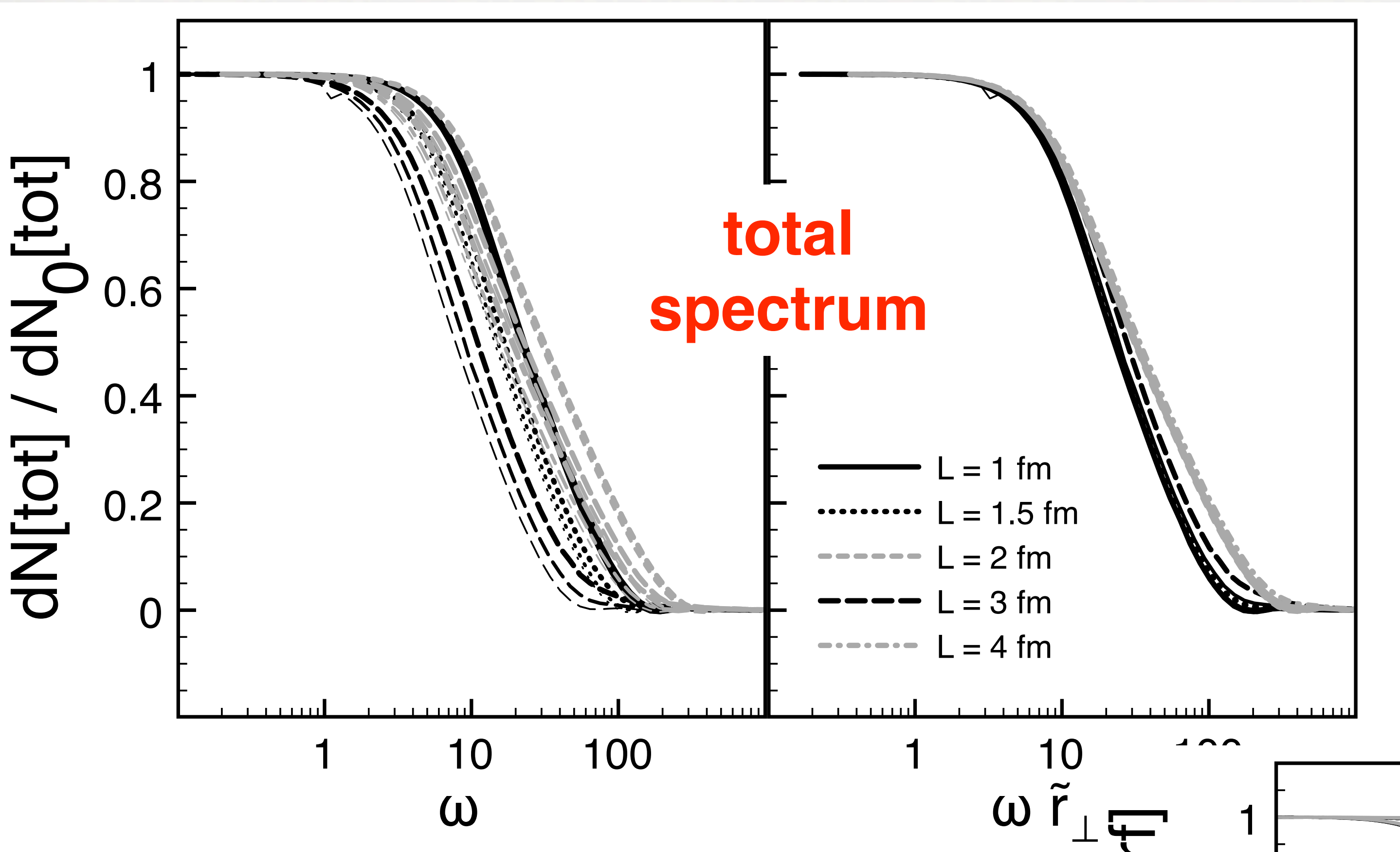
SCALING BEHAVIORS



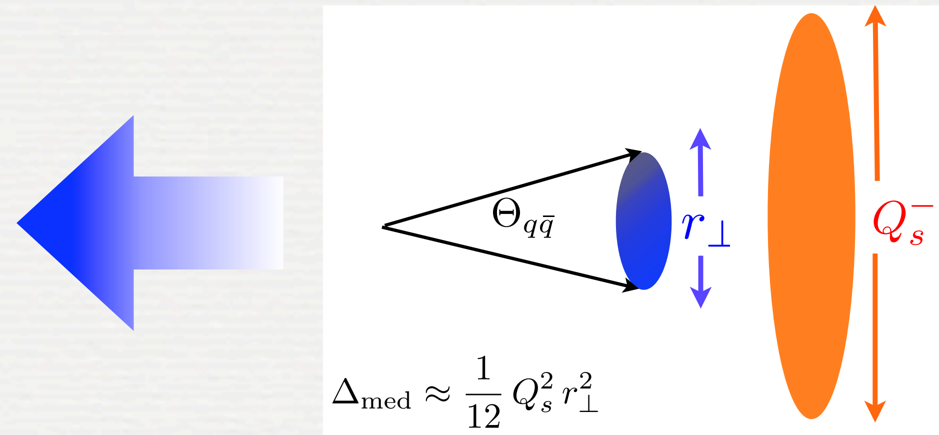
"dipole" regime



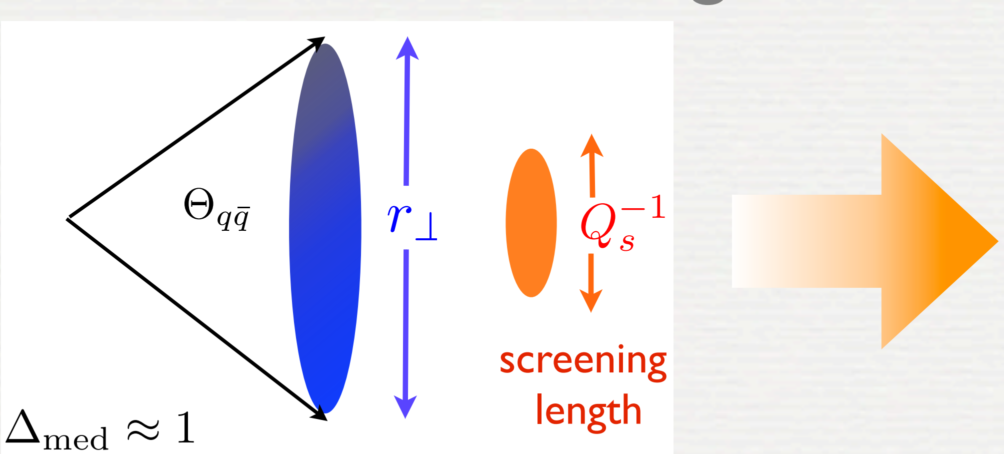
SCALING BEHAVIORS

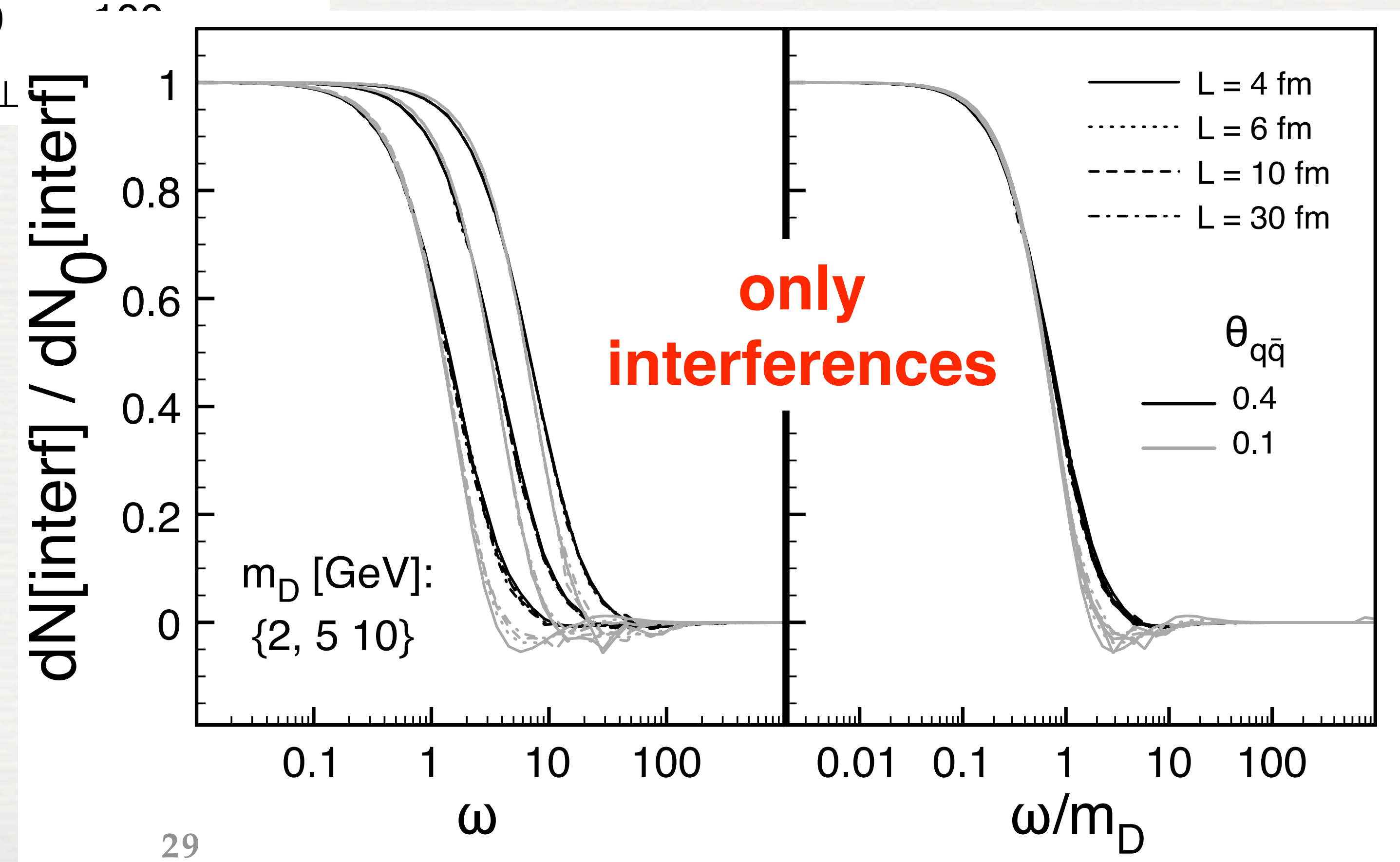


“dipole” regime

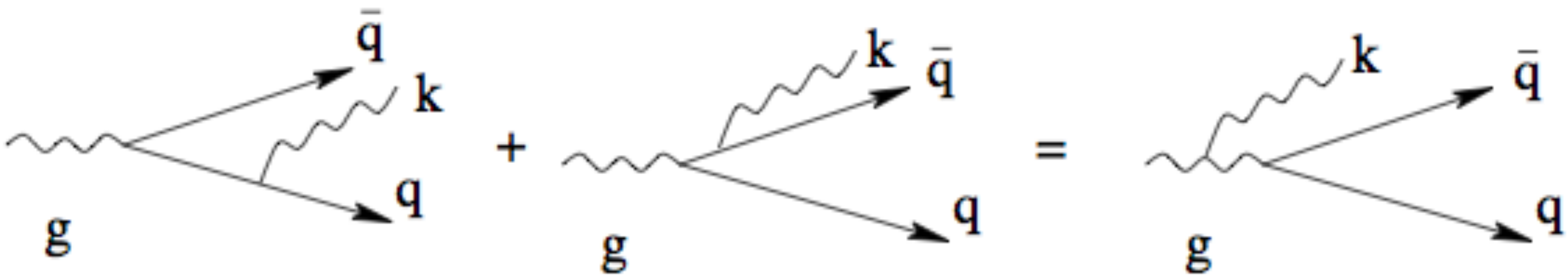


“decoherence” regime





Color octet antenna



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

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