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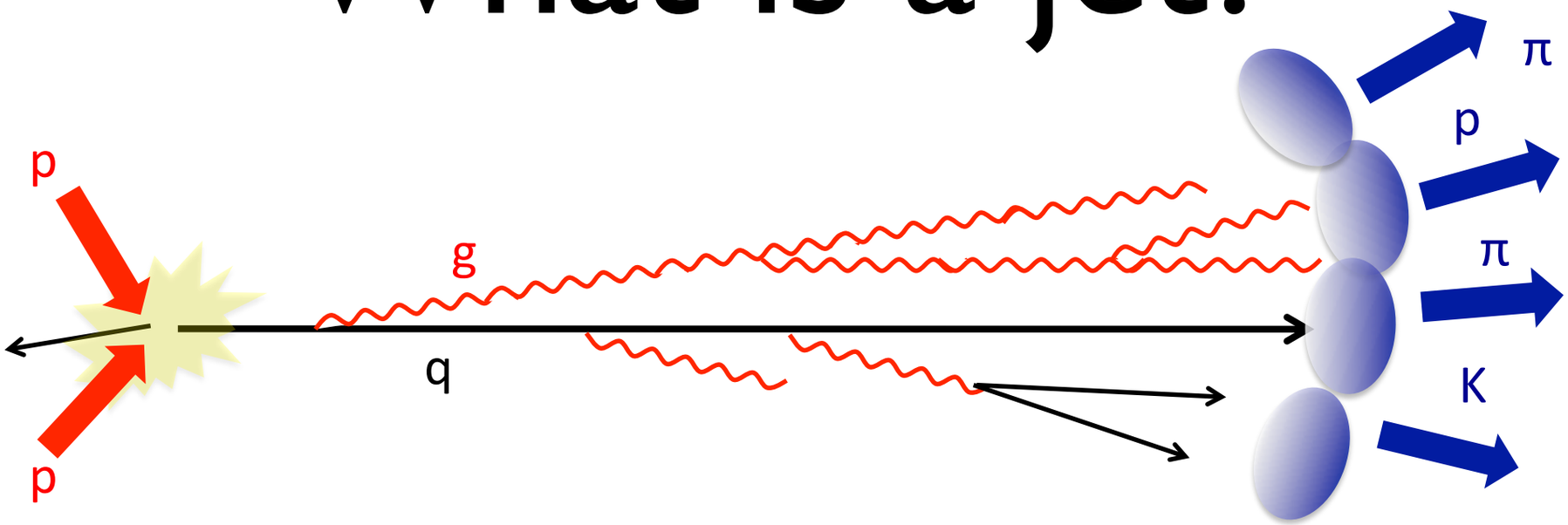
Decoherence of QCD radiation in a quark-gluon plasma

Konrad Tywoniuk

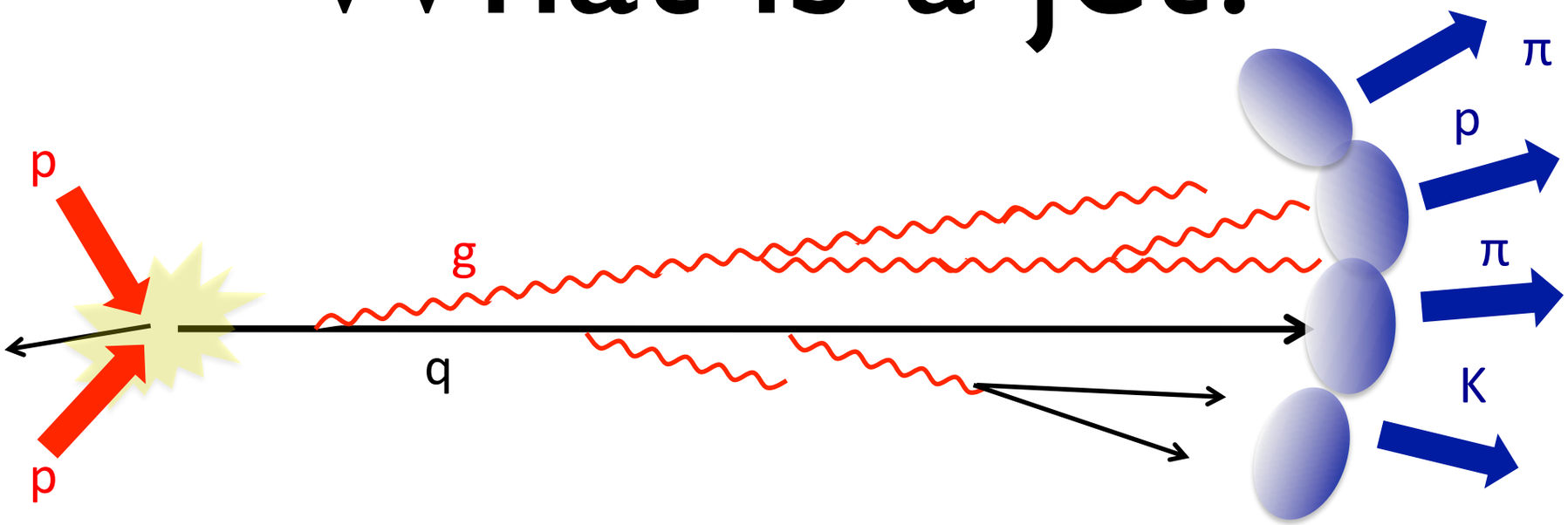
1st International Conference on New Frontiers in Physics

Kolymbari, Greece, 11-16 June 2012

What is a jet?



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

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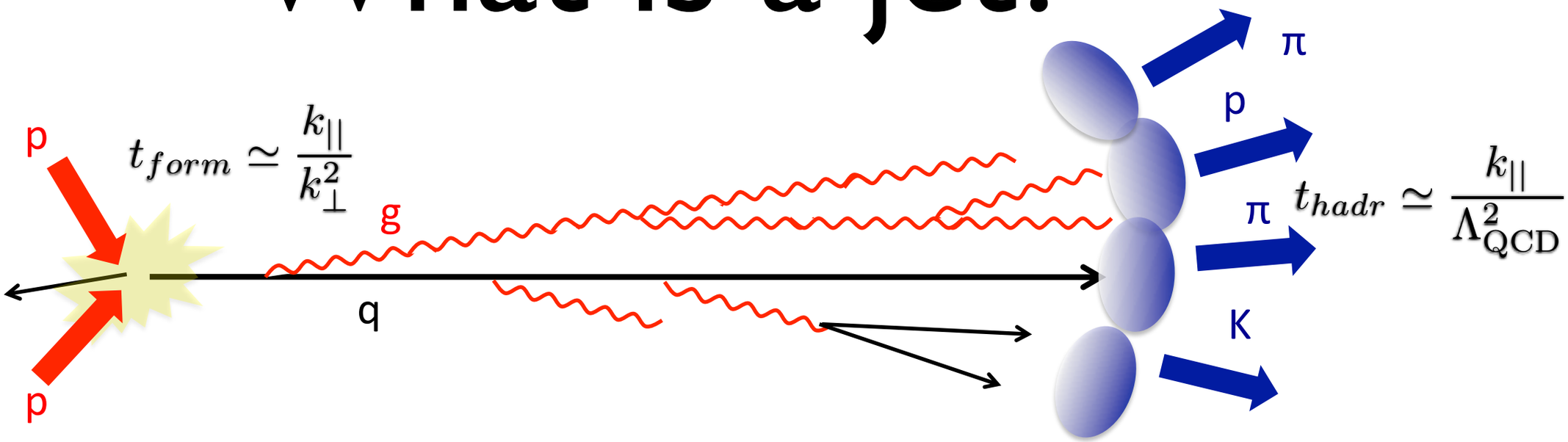

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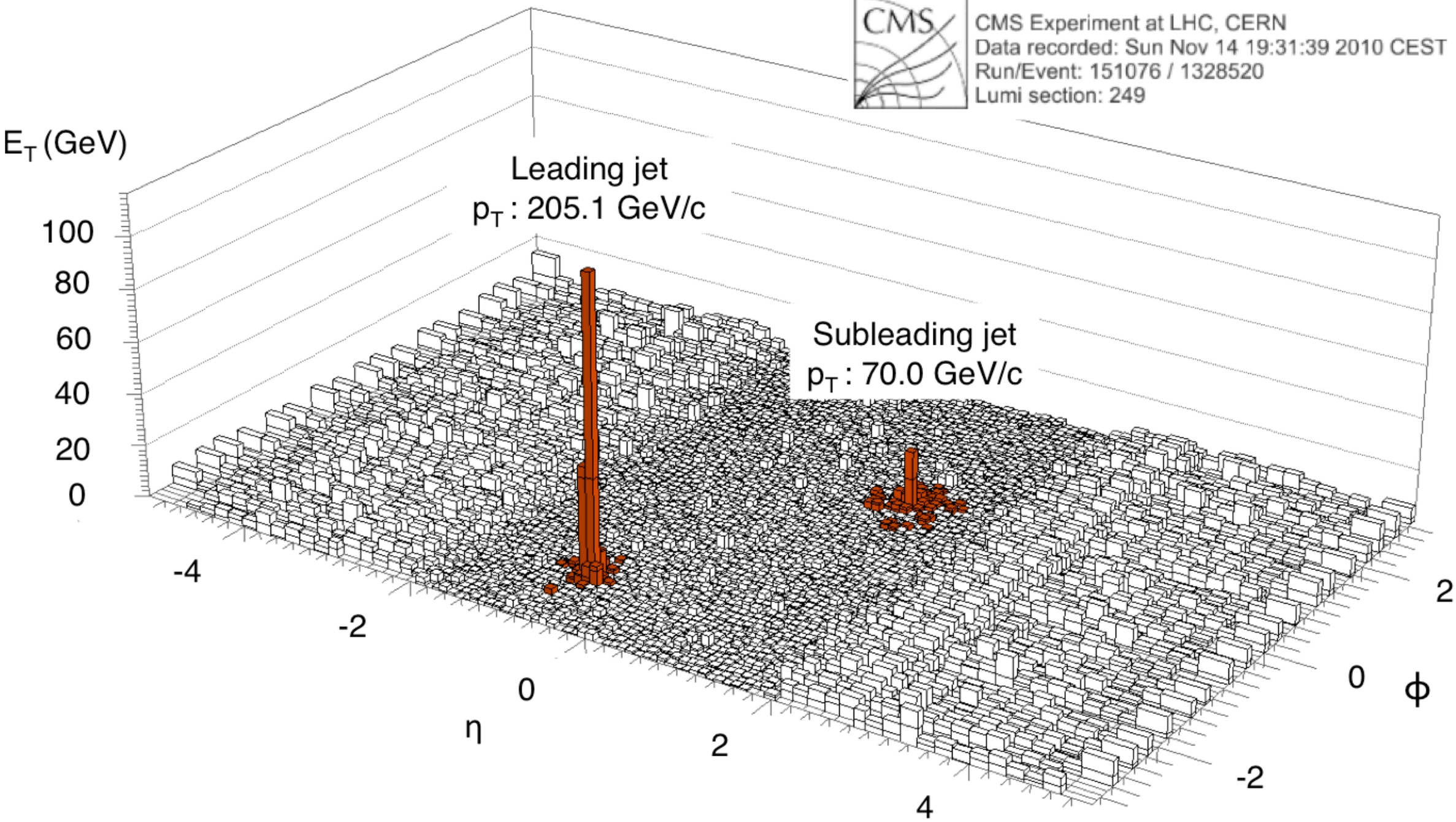
Large time domain for pQCD: $\frac{1}{\sqrt{s}} < t < \frac{\sqrt{s}}{\Lambda^2_{\rm QCD}}$

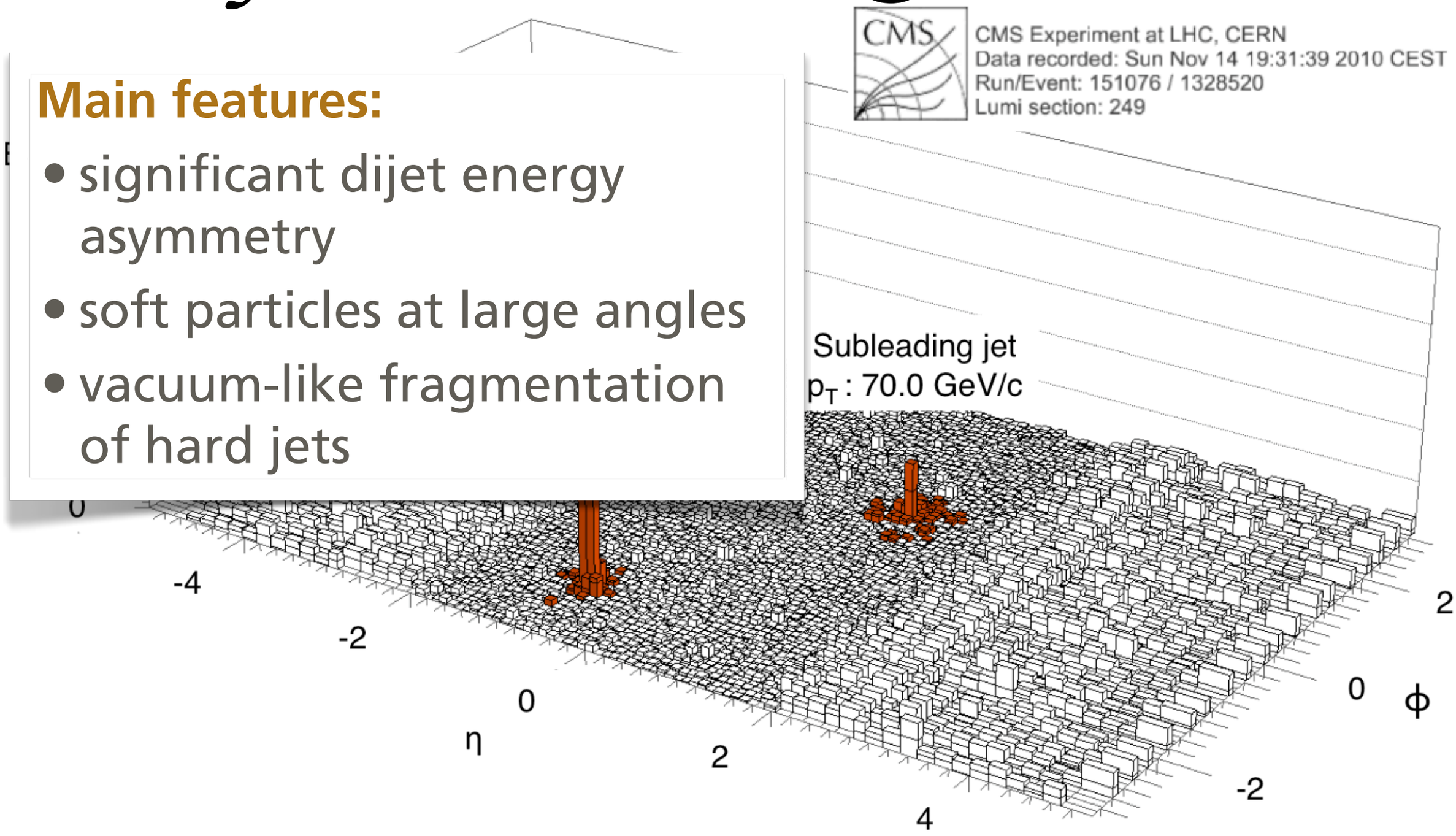
Jets in HIC @ LHC



Jets in HIC @ LHC

Main features:

- significant dijet energy asymmetry
- soft particles at large angles
- vacuum-like fragmentation of hard jets



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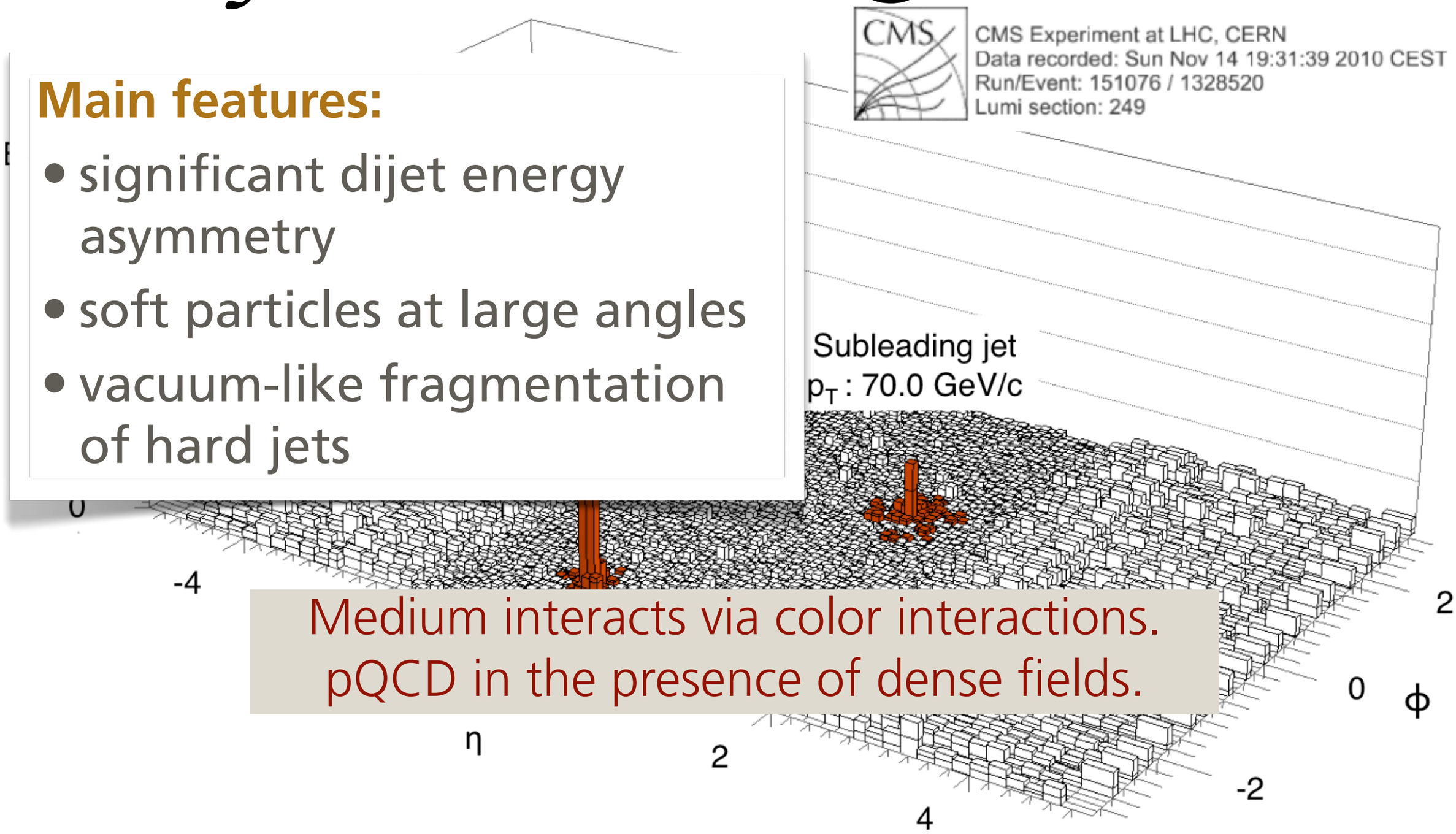
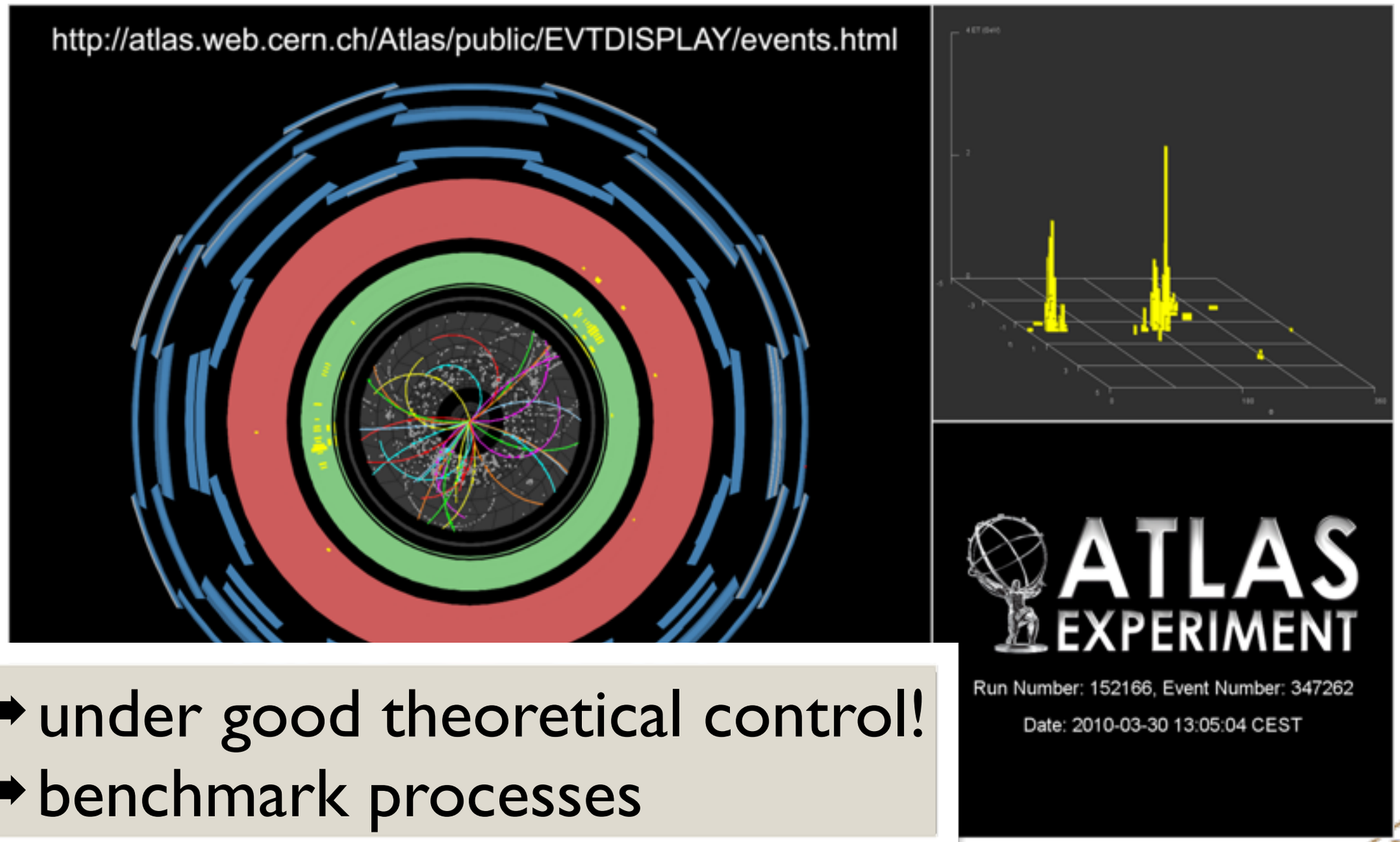


Medium interacts via color interactions.
pQCD in the presence of dense fields.

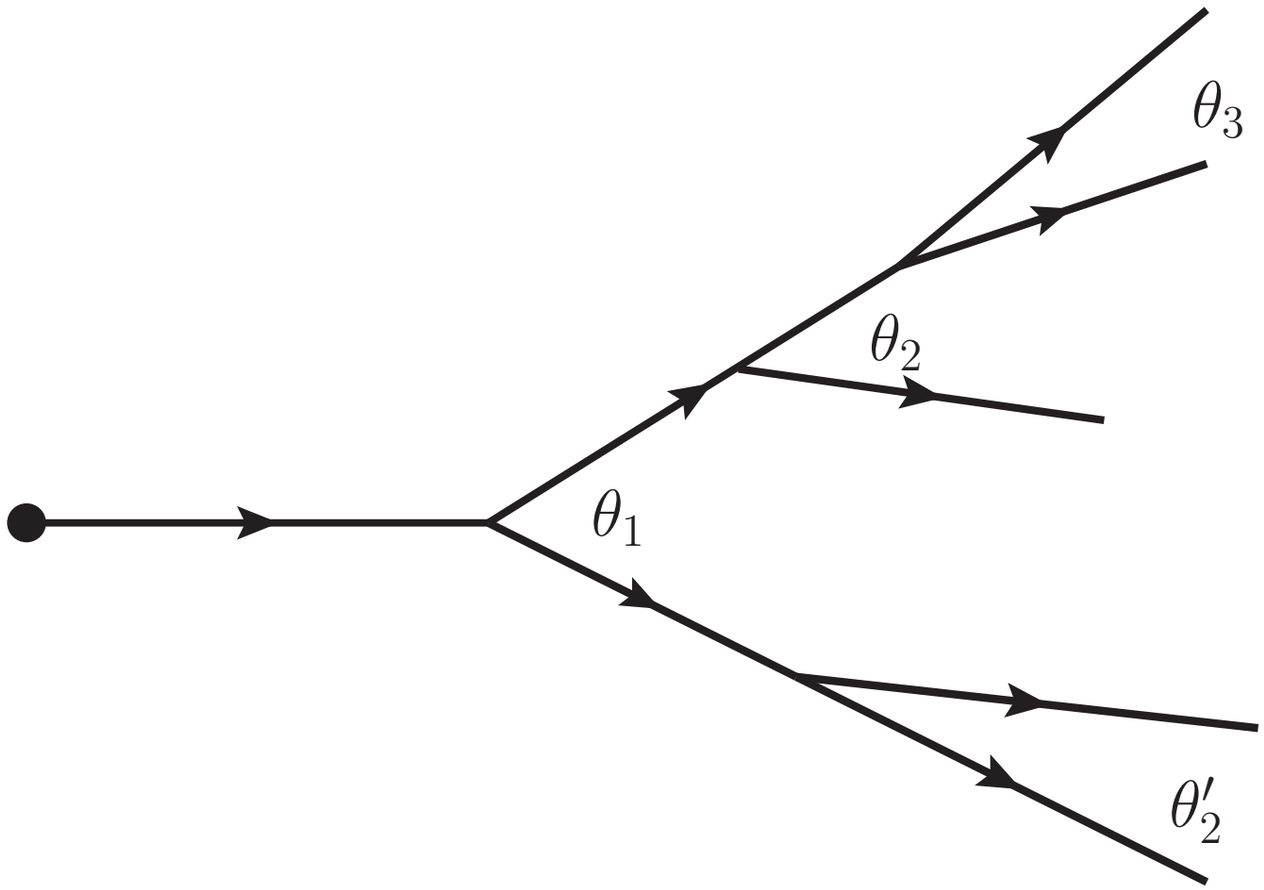
Jets in pp @ LHC



➡ under good theoretical control!

➡ benchmark processes

Parton branching in vacuum



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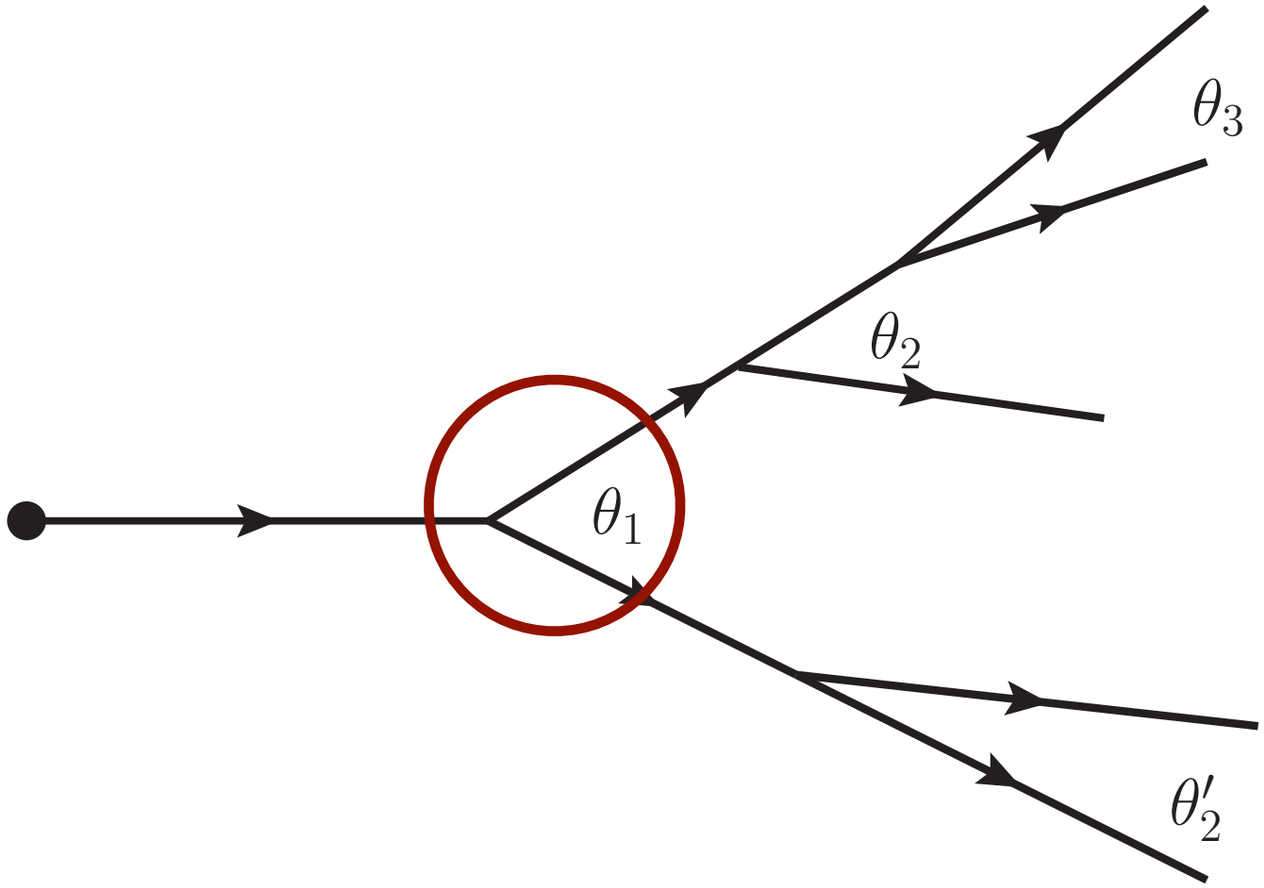

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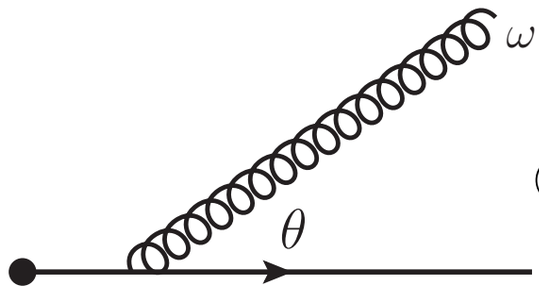

$$\propto \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta}$$

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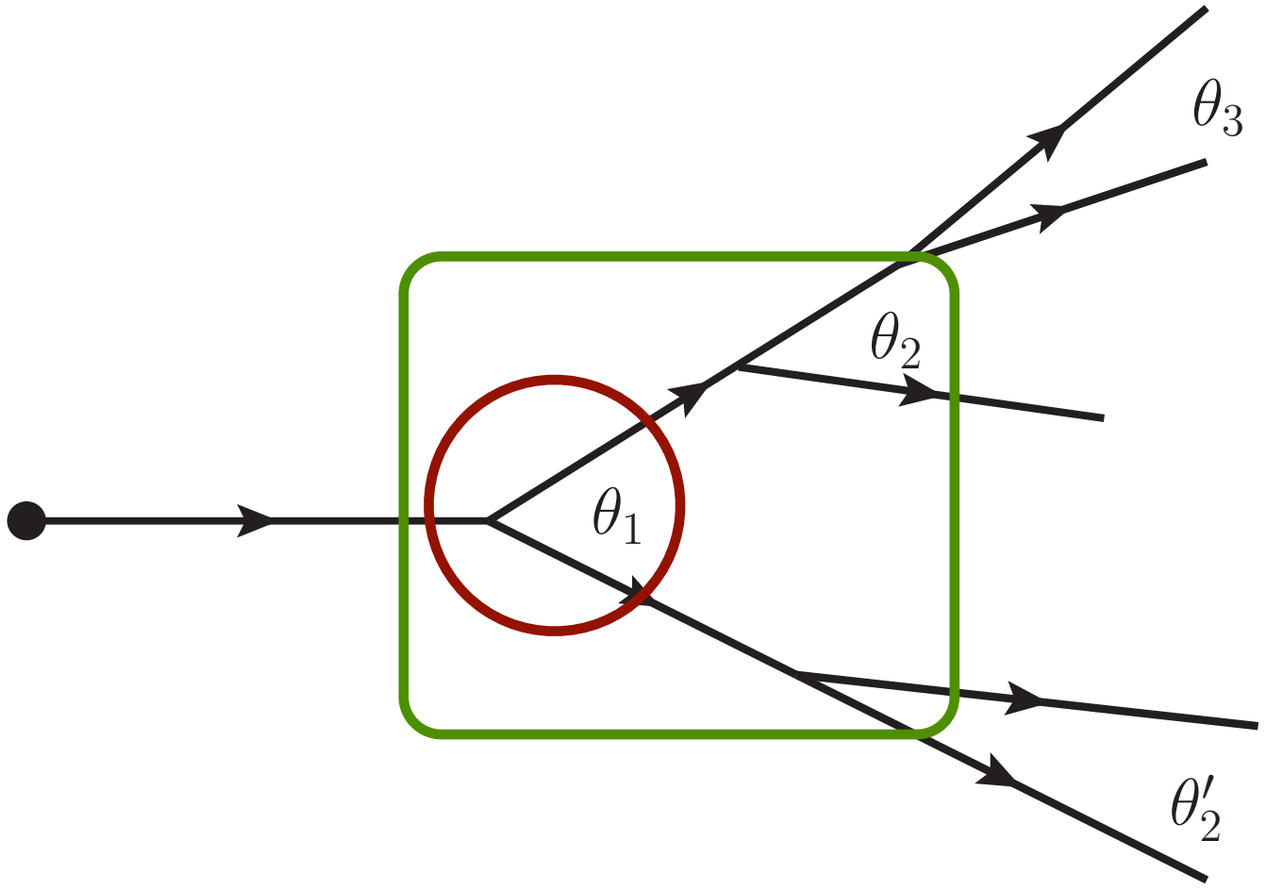

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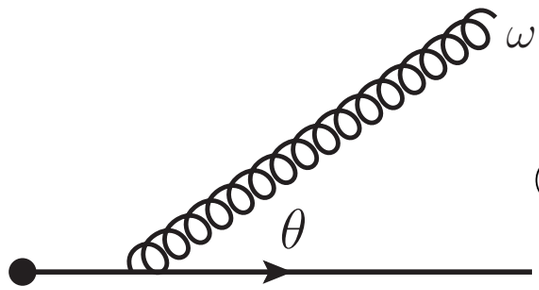

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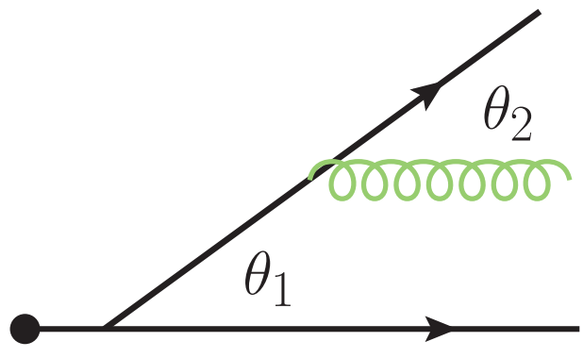
Angular ordering



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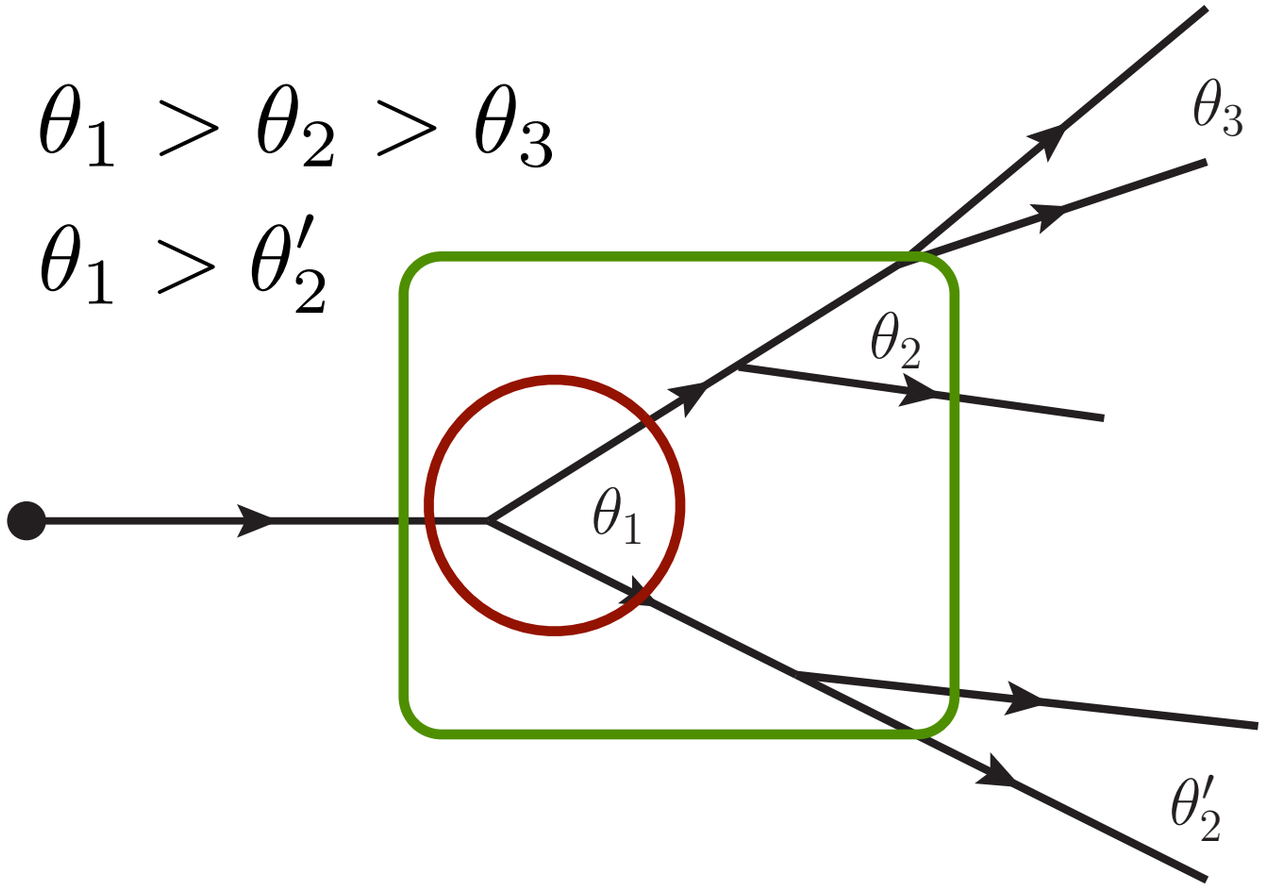

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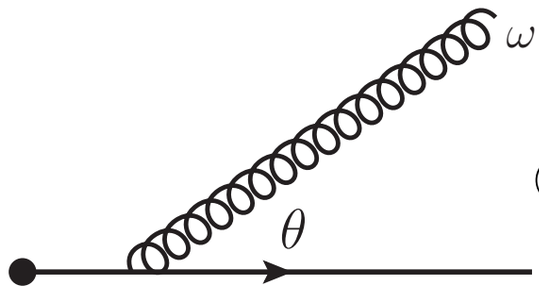

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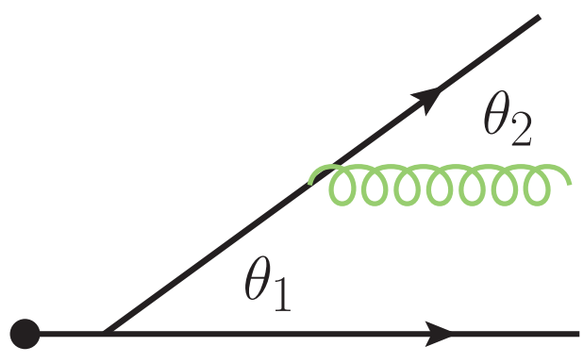

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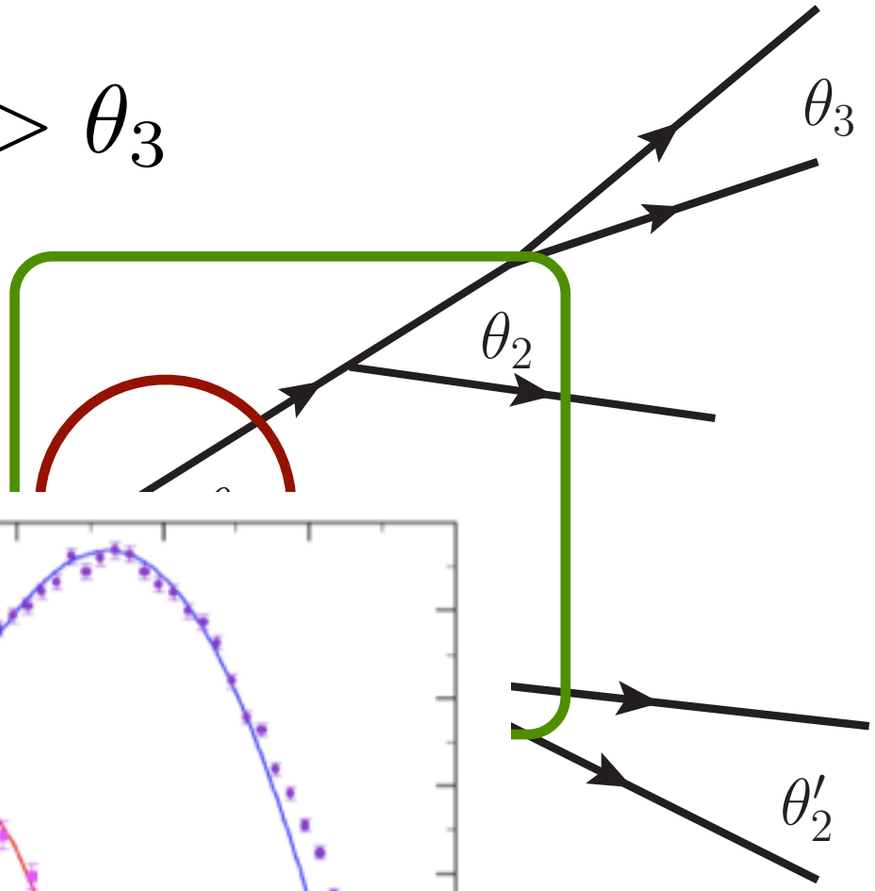

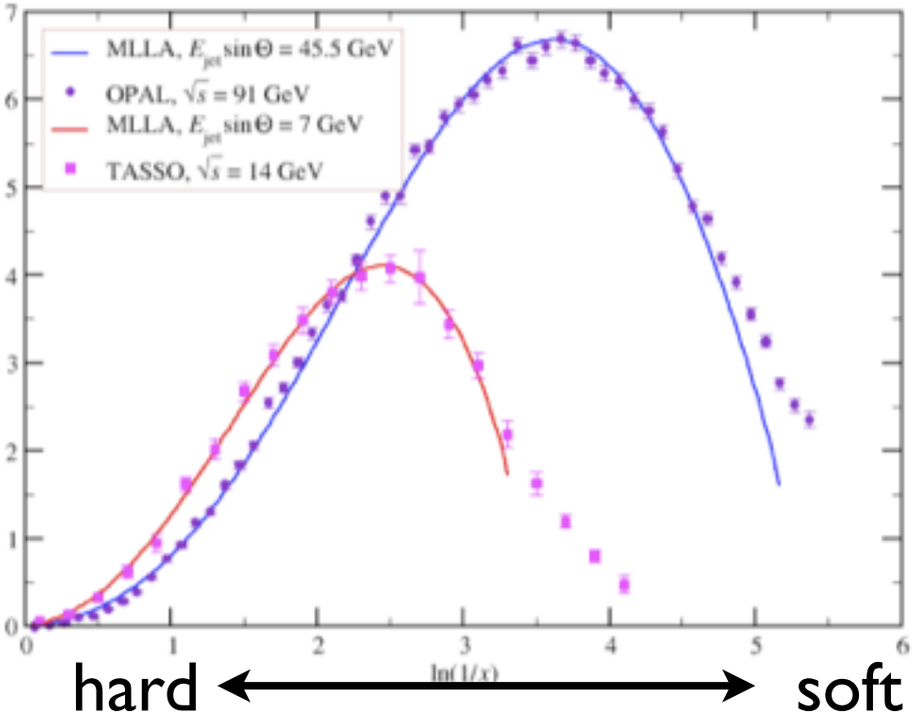

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TASSO Collaboration, Z. Phys. C 47 (1990) 187

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

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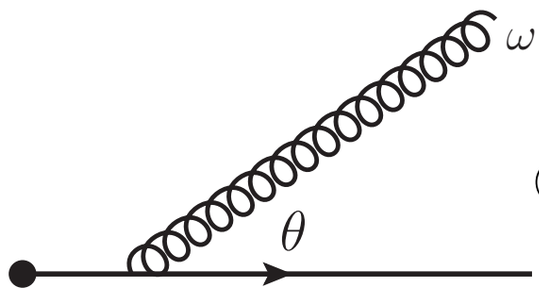

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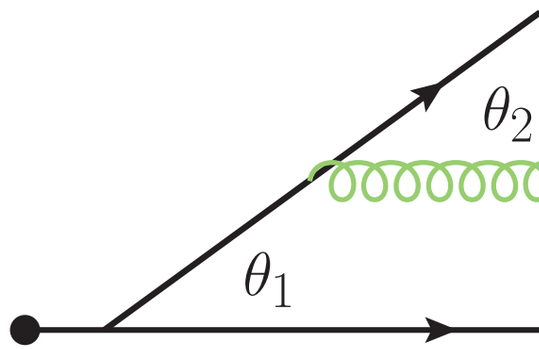

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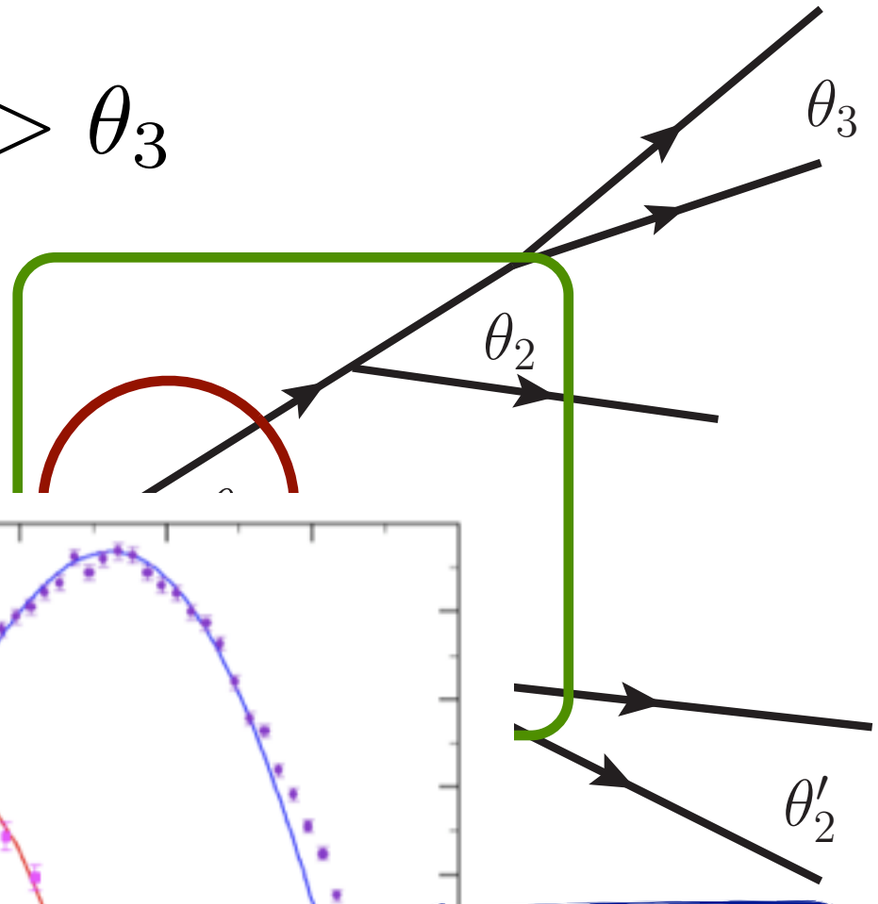

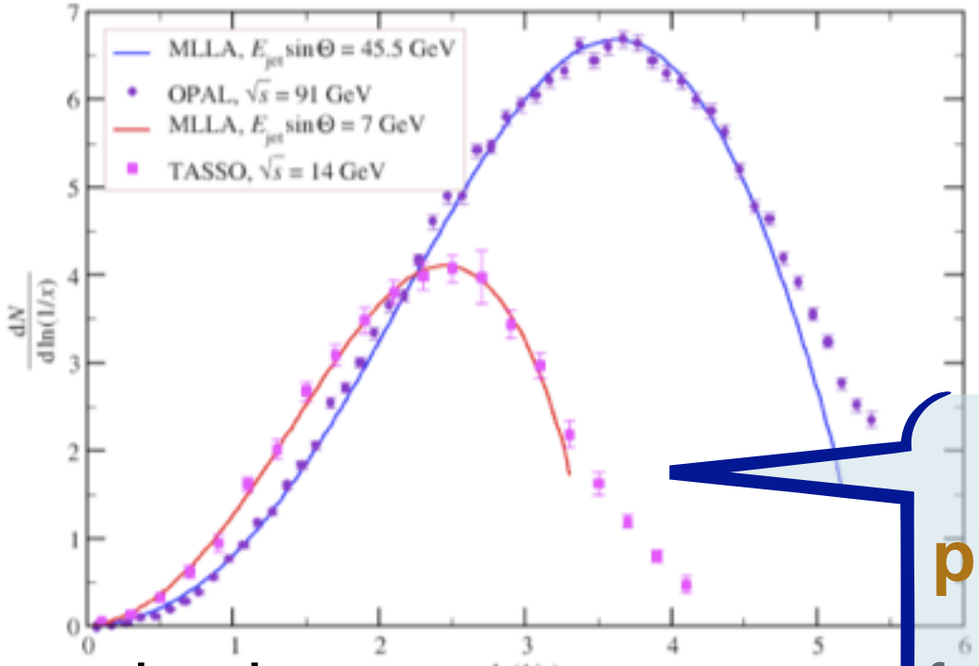

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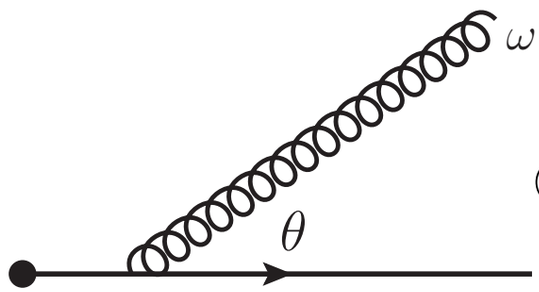
AO limits phase space for soft emissions!

Leading singularities



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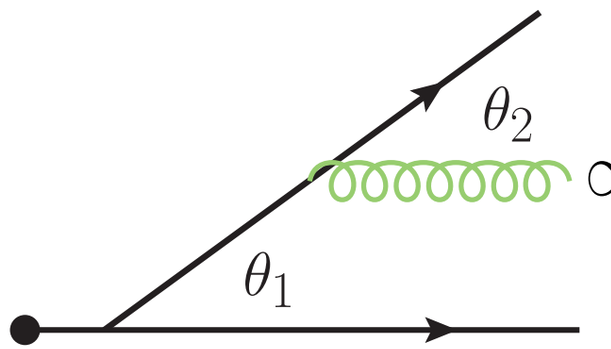

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Antenna spectrum in vacuum

- decay of a highly virtual particle
- a laboratory to study coherence effects
- contains necessary elements of transverse color coherence

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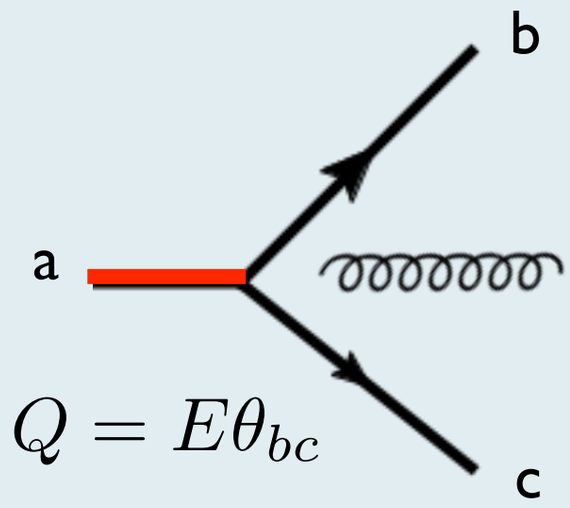

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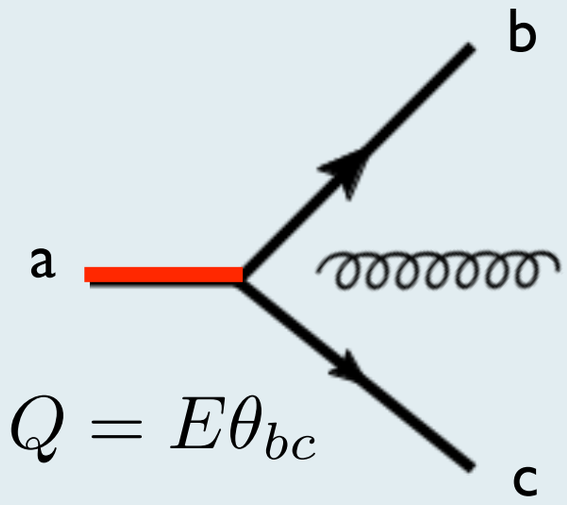

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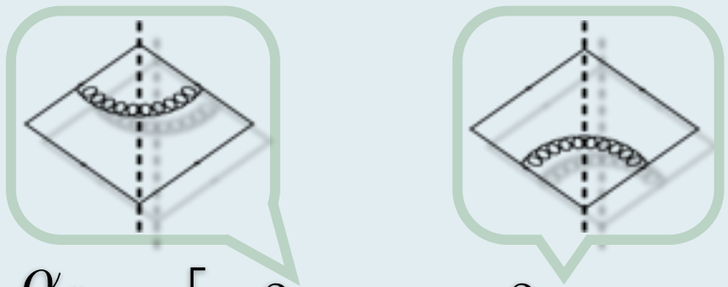

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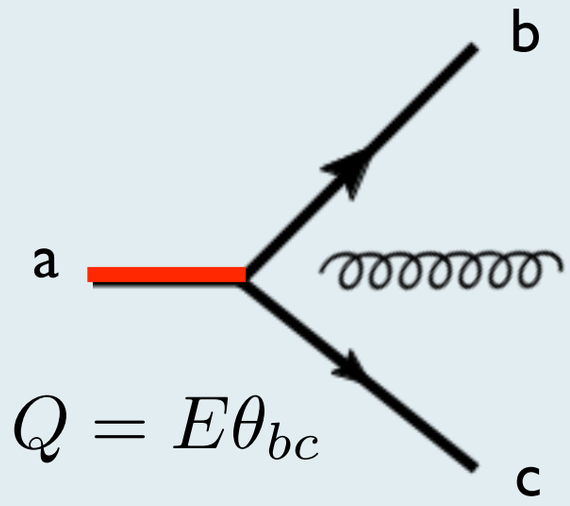

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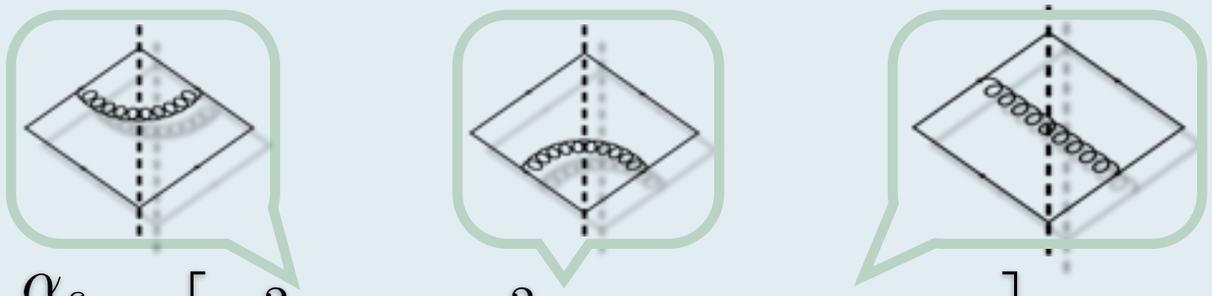

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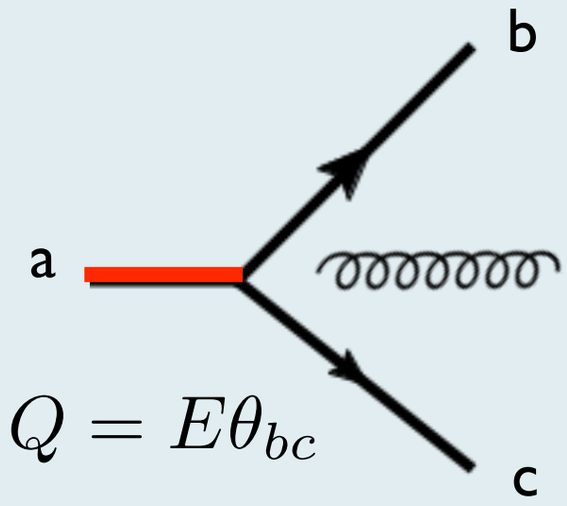

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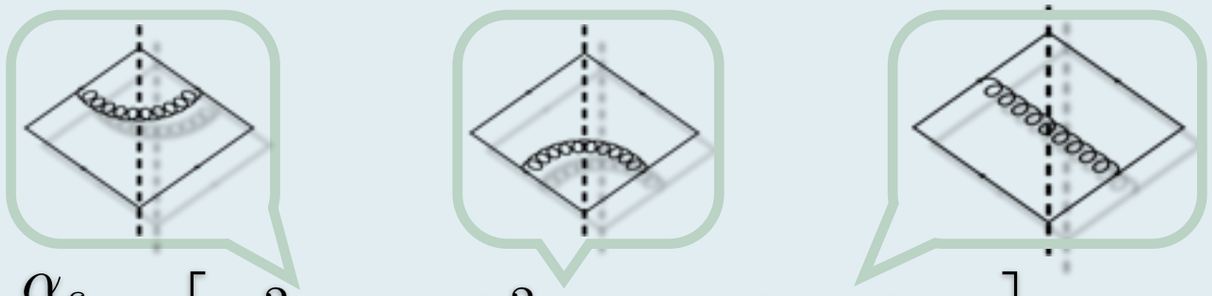

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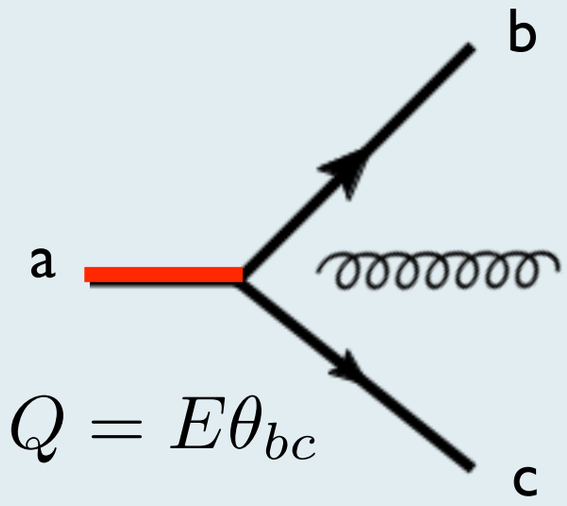

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coherent spectra

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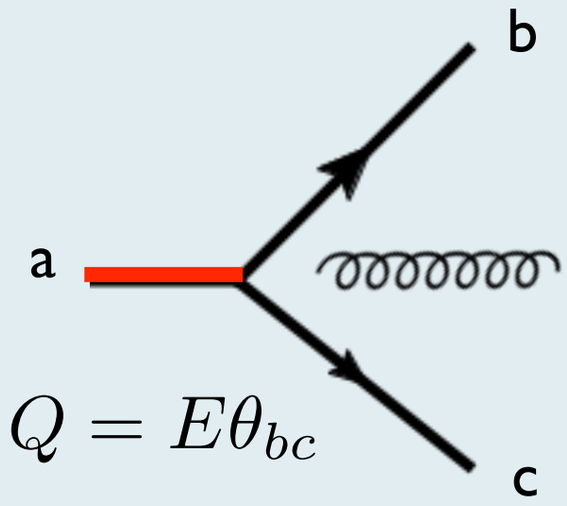

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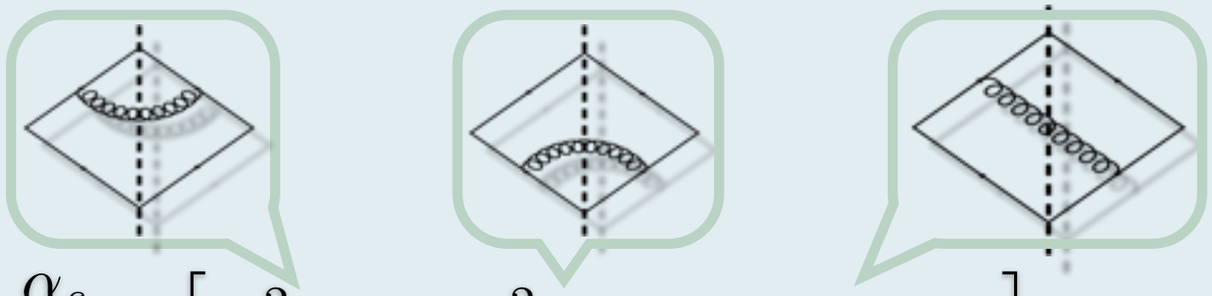

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tot. charge — coherent spectra

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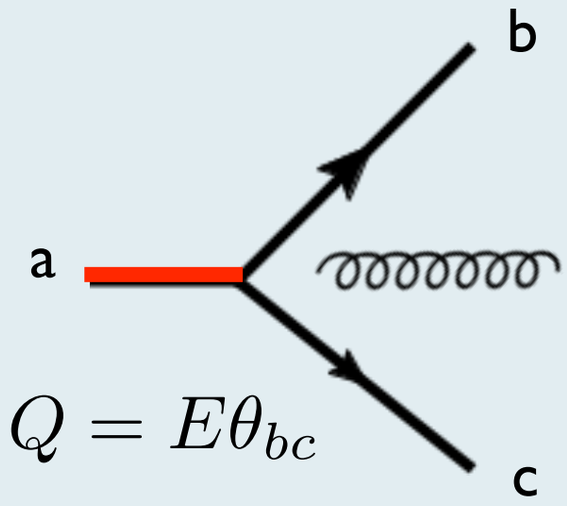

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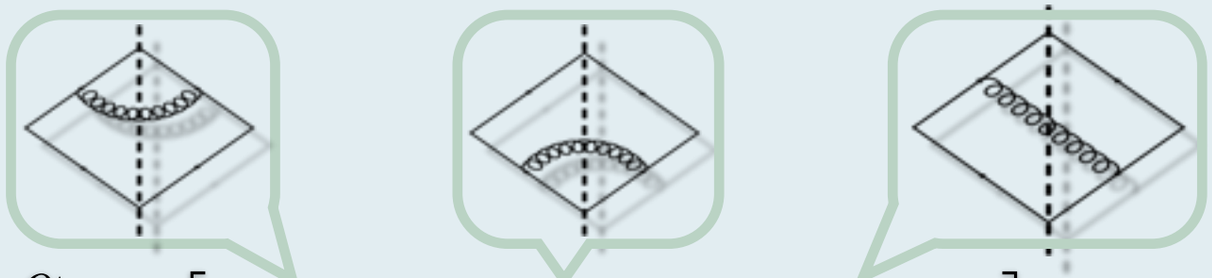

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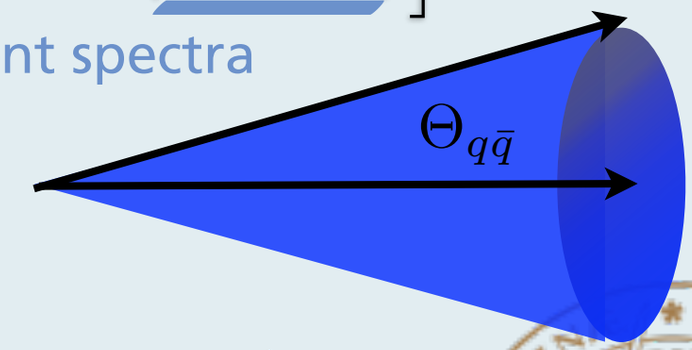
tot. charge — coherent spectra

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



Fundamental building block of the QCD cascade!

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No established theory of jets in medium!

- what is the relevant ordering in medium?
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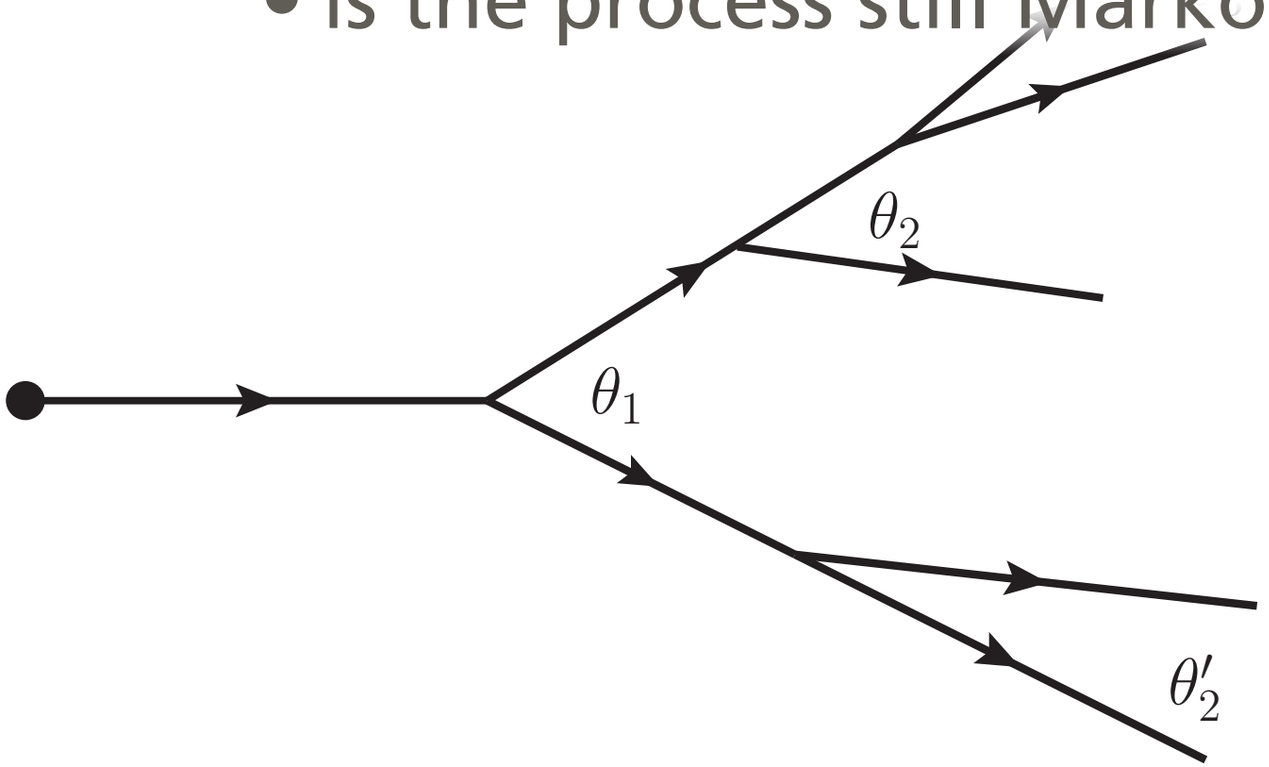

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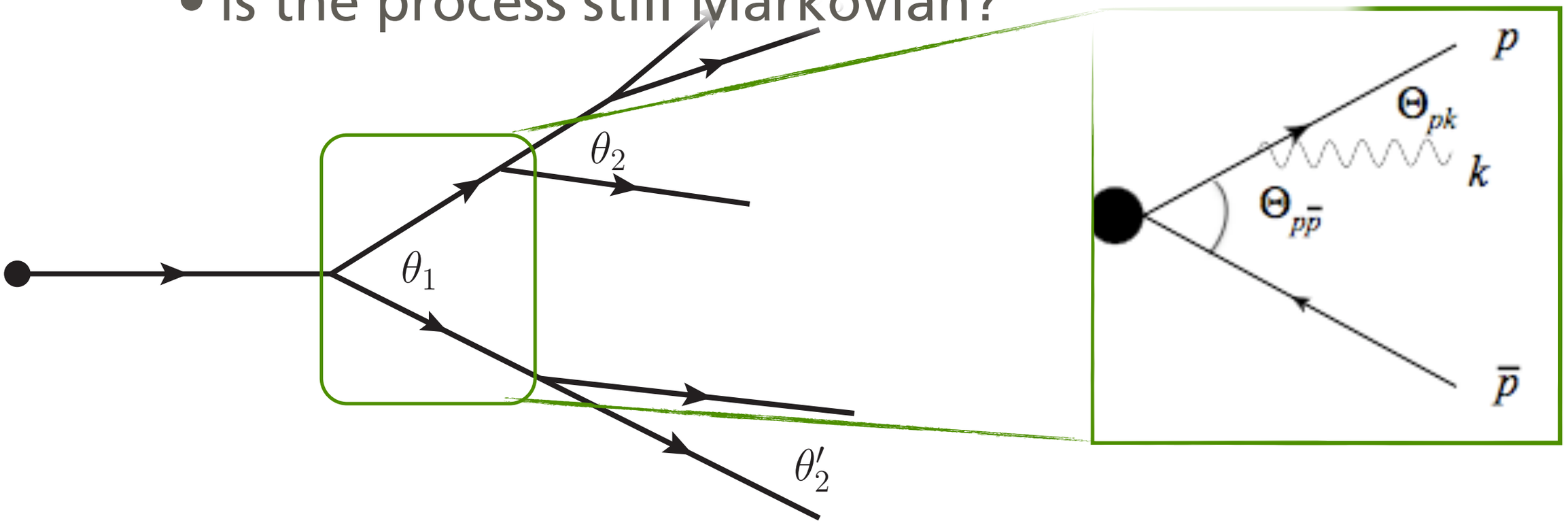

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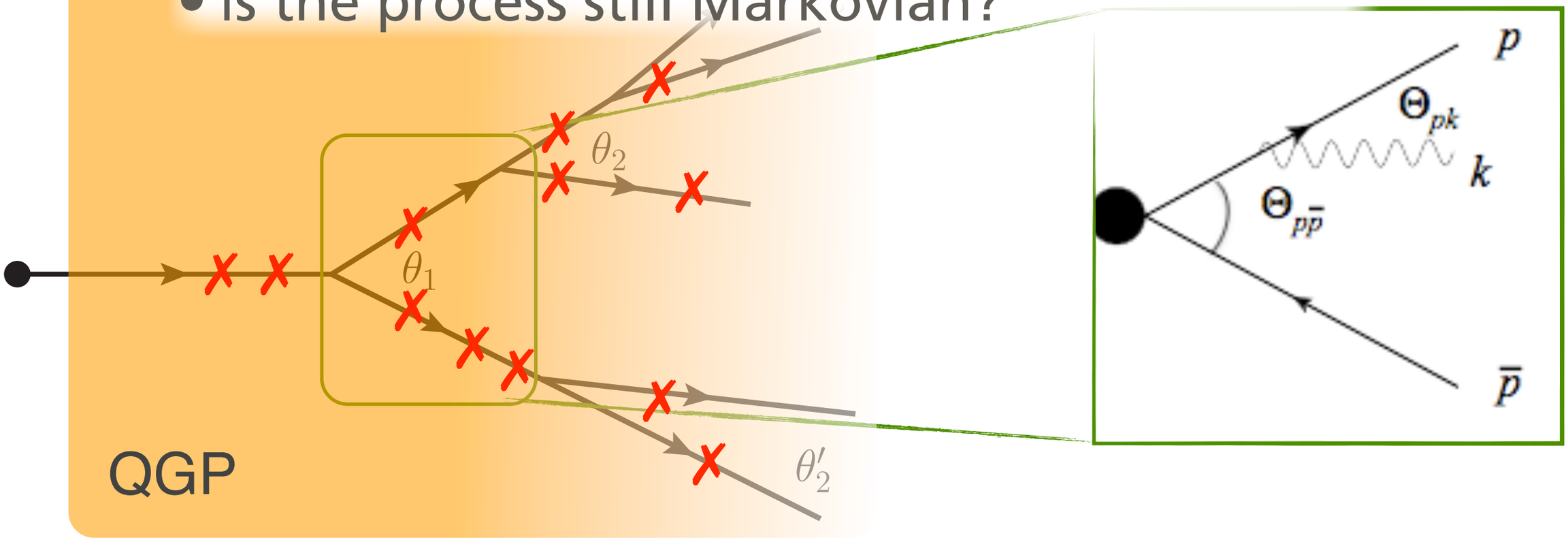

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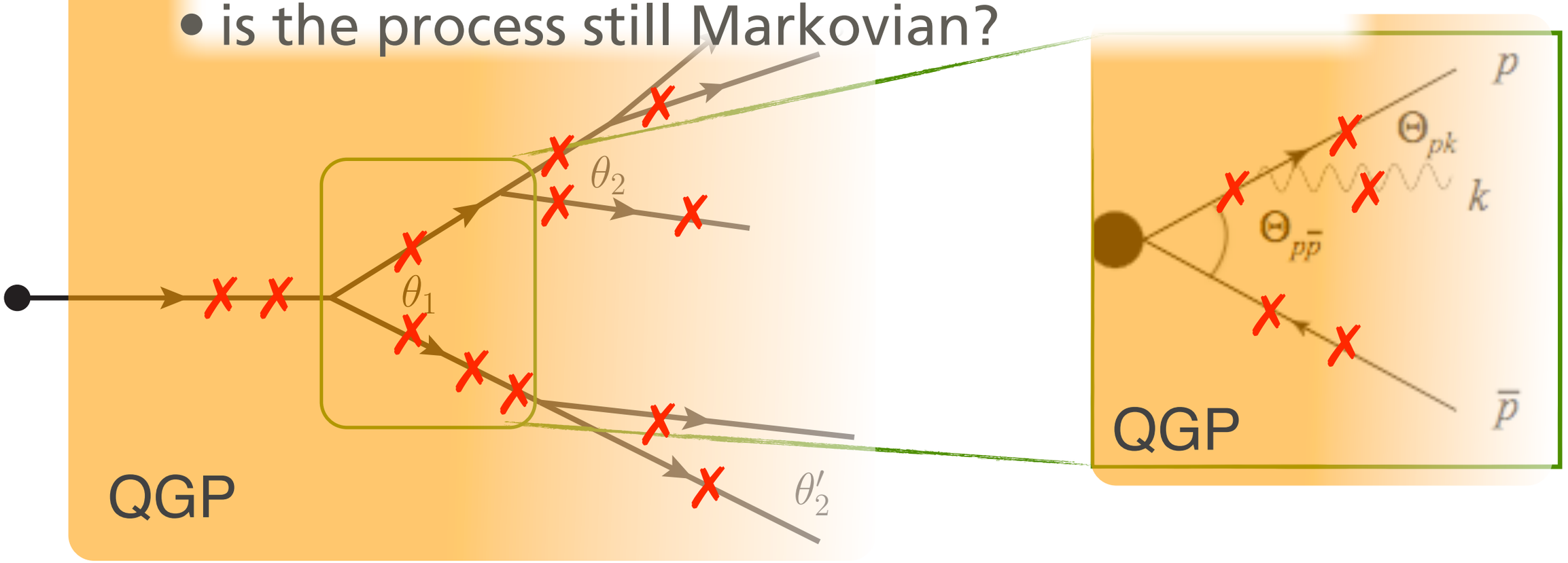

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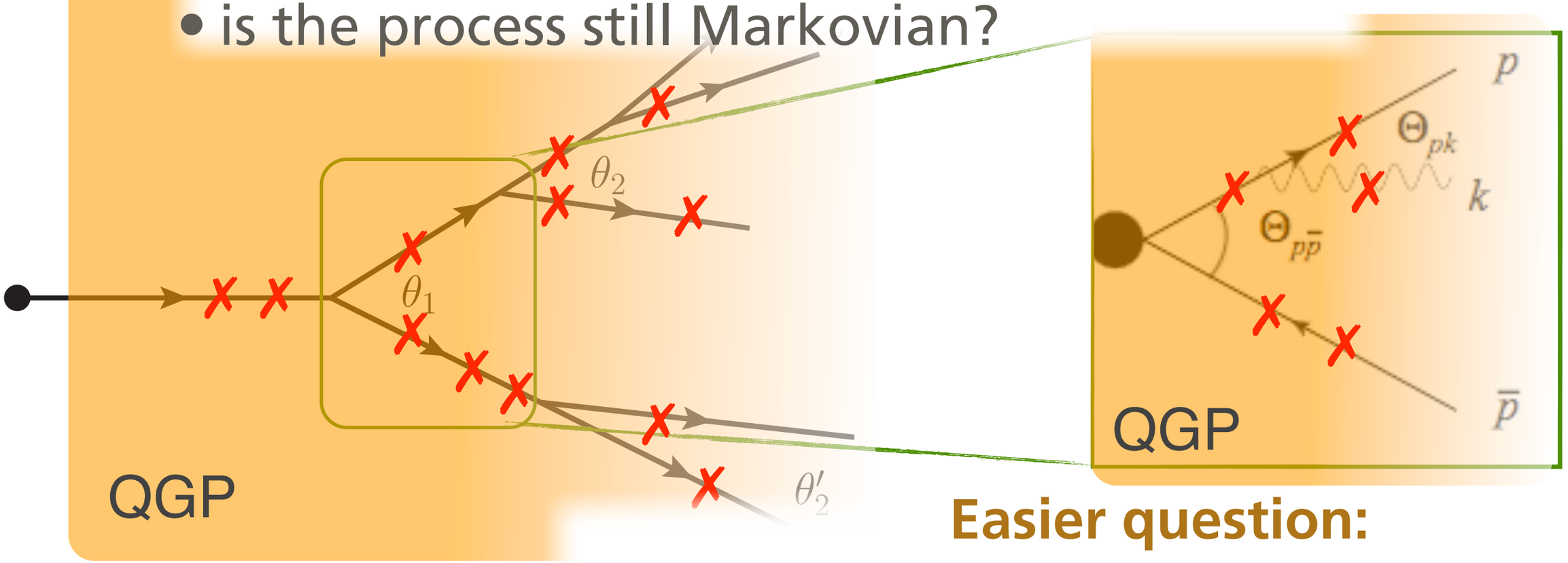
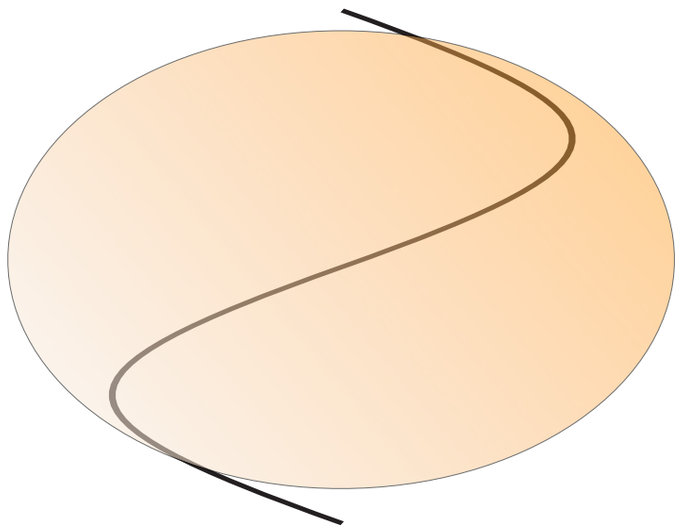


Easier question:

- how is the antenna spectrum modified in a medium?

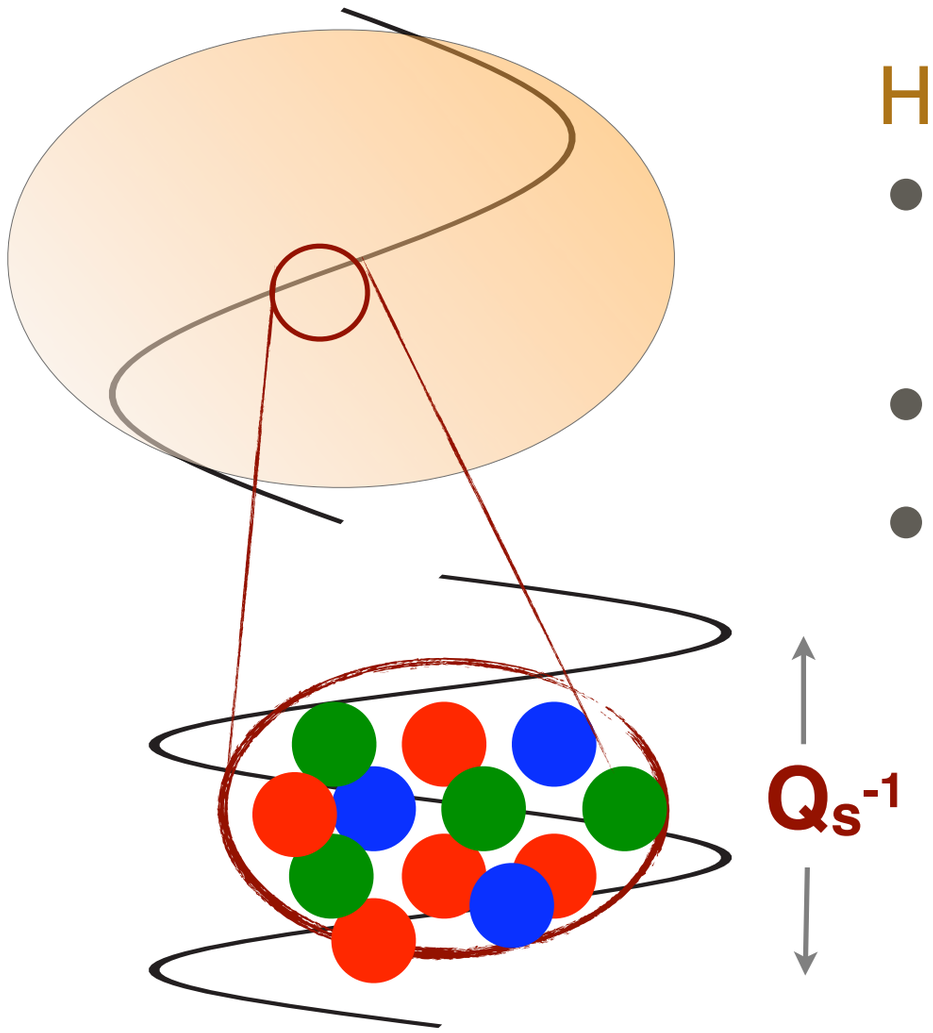
Decoherence of radiation in media



How is the medium resolved

- medium fluctuates with typical transverse wave length Q_s^{-1}
- zero color on average, $\lambda > Q_s^{-1}$
- resolved by $\lambda < Q_s^{-1}$

Decoherence of radiation in media



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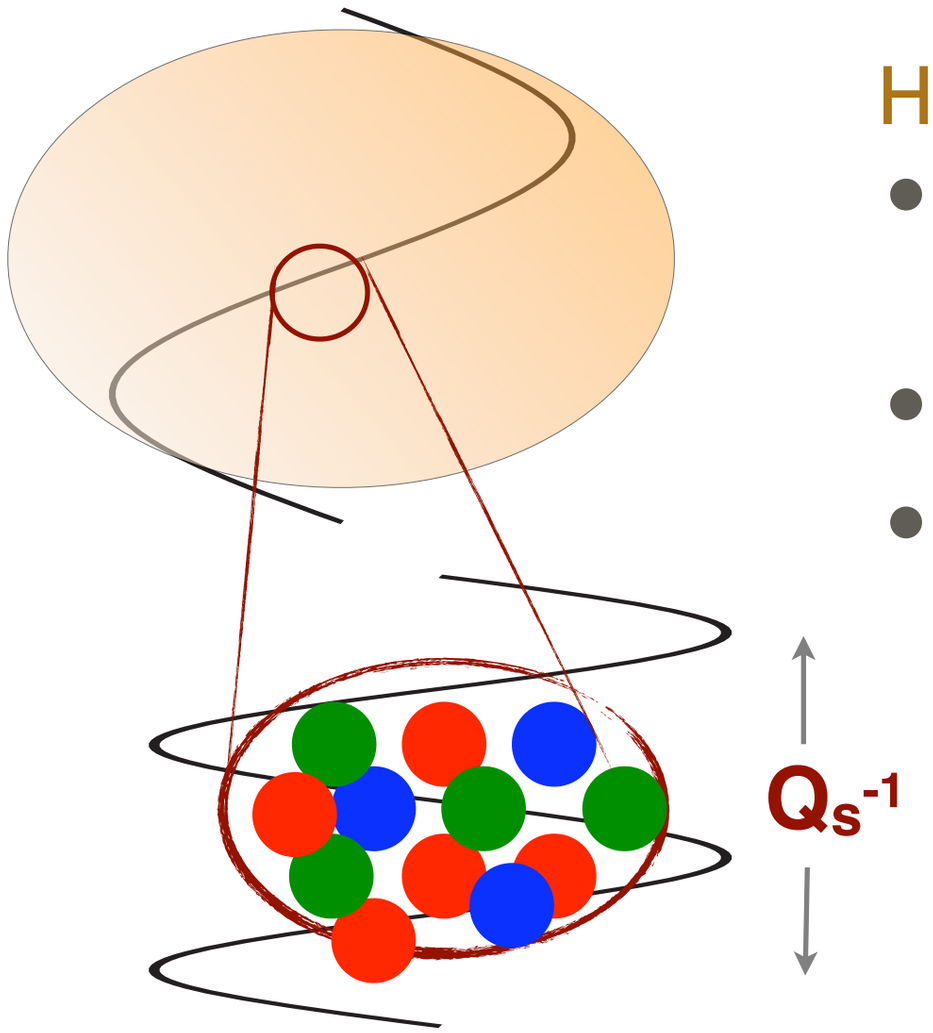

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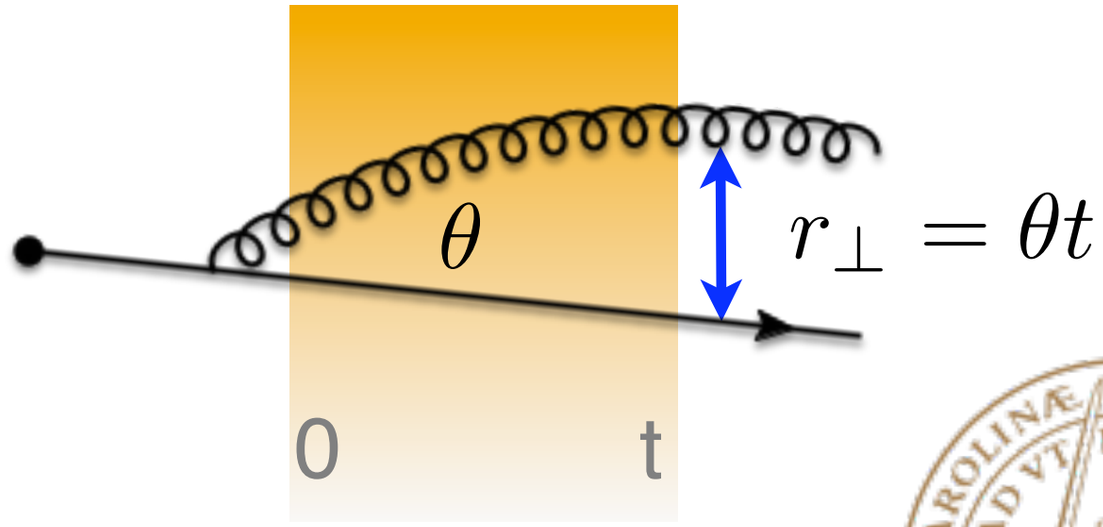

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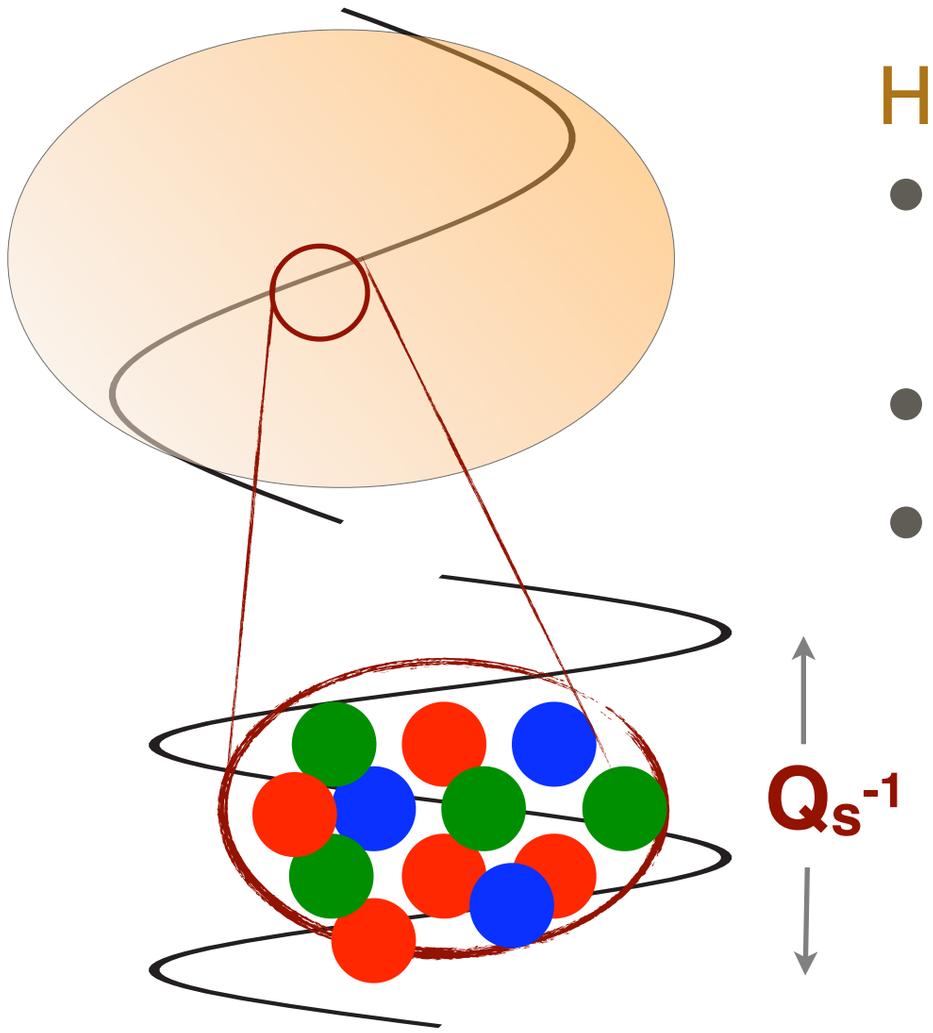

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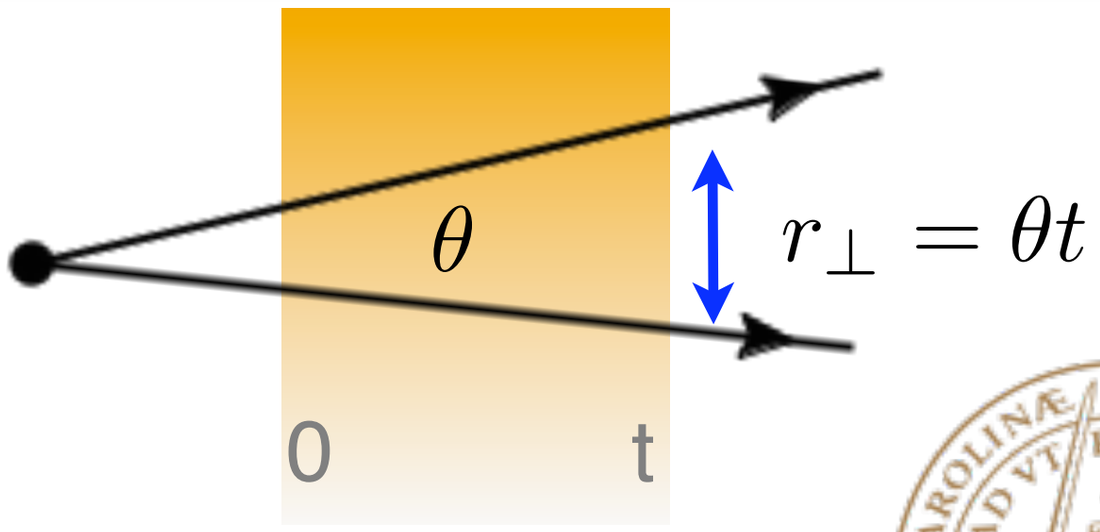

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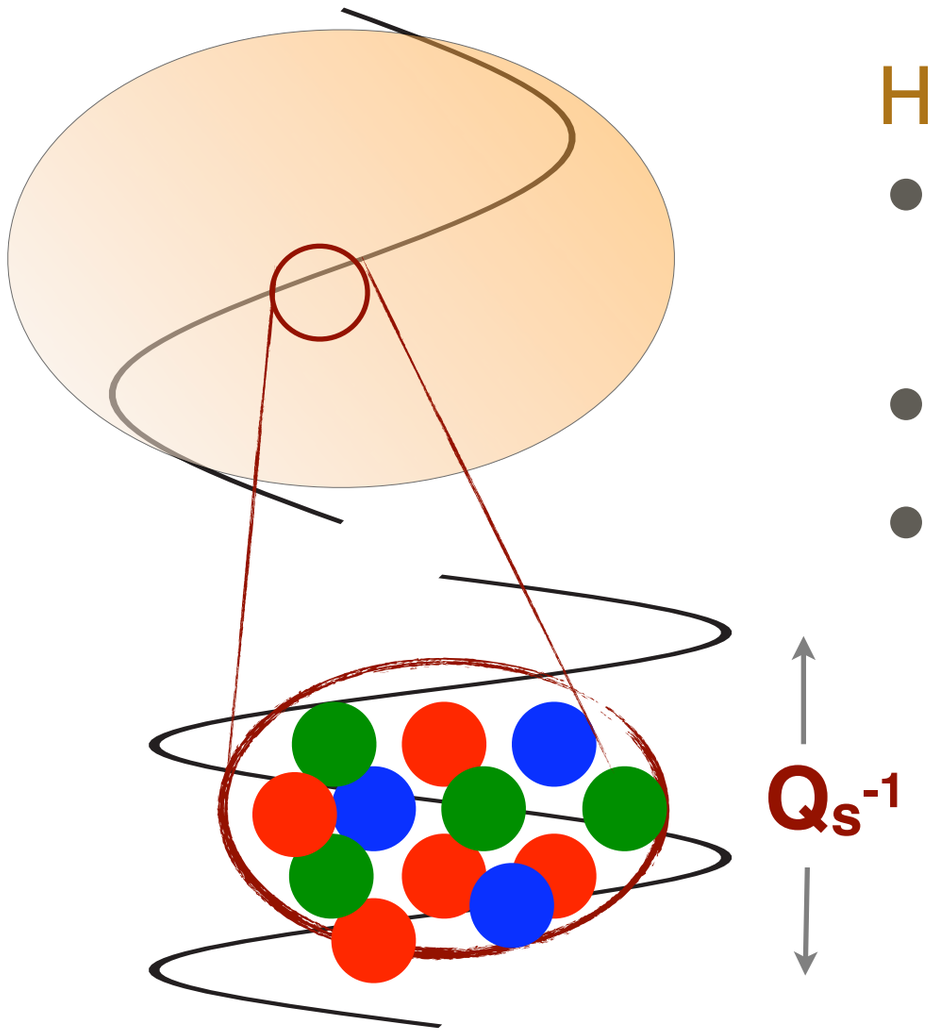

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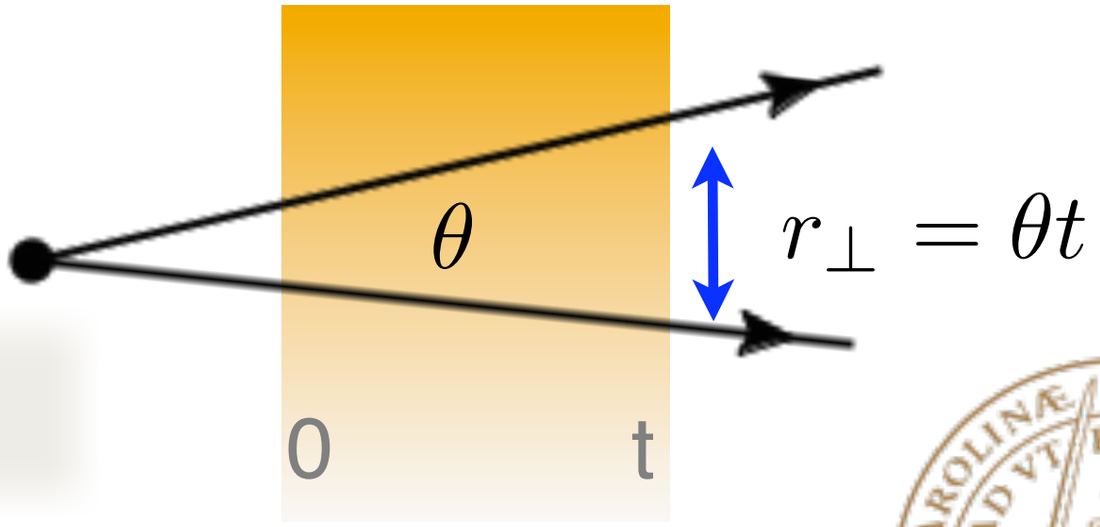
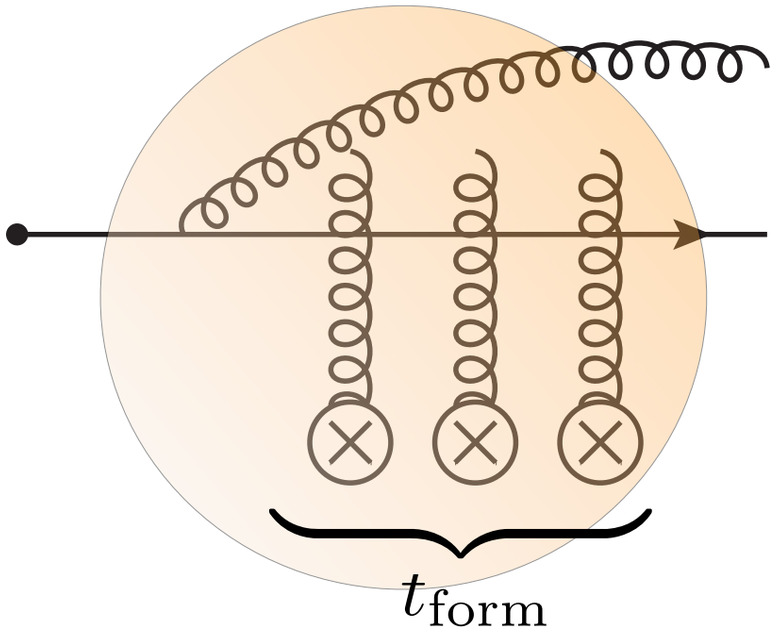


What are the typical dipole transverse sizes?

Medium-induced radiation



Longitudinal coherence

- induces a characteristic formation time larger than mean free path

$$\left.\begin{aligned} t_{\rm form} &= \lambda_{\rm mfp} N_{\rm coh} \\ k^2_{\rm ind} &= \mu^2 N_{\rm coh} \end{aligned}\right\} \qquad \begin{aligned} t_{\rm form} &= \sqrt{\omega/\hat{q}} \\ k^2_{\rm ind} &= \sqrt{\hat{q}\omega} \end{aligned}$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996)

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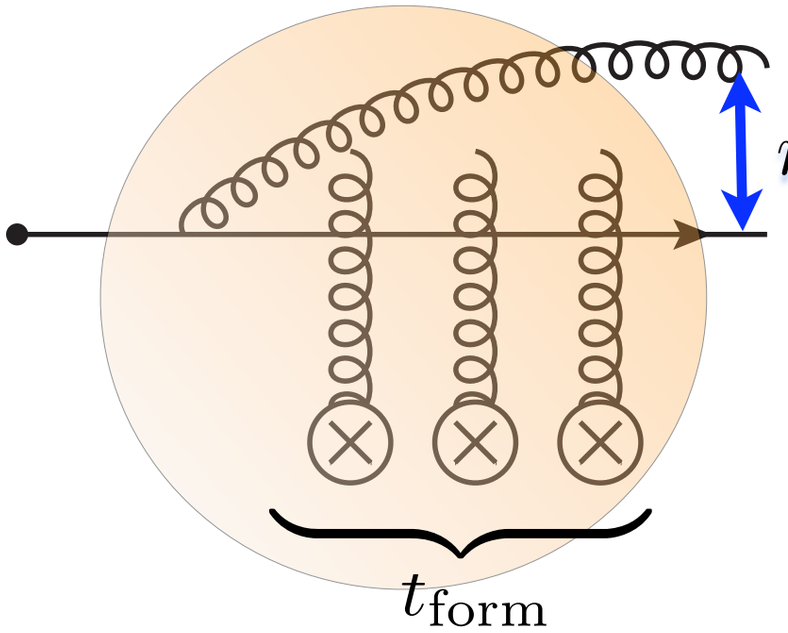

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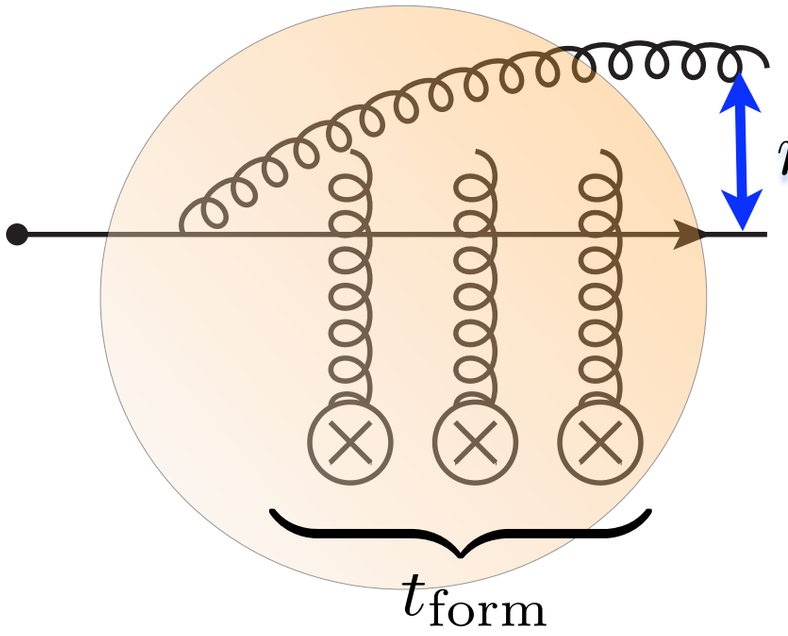

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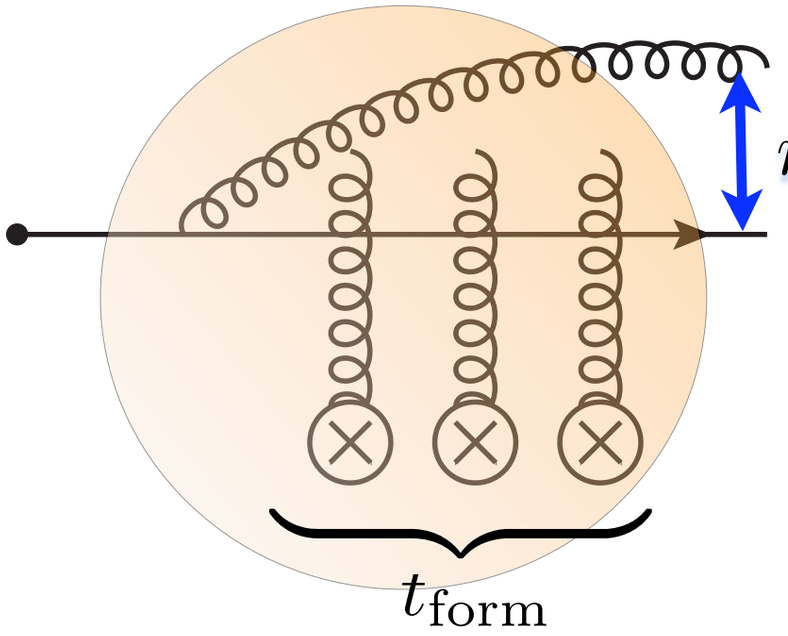

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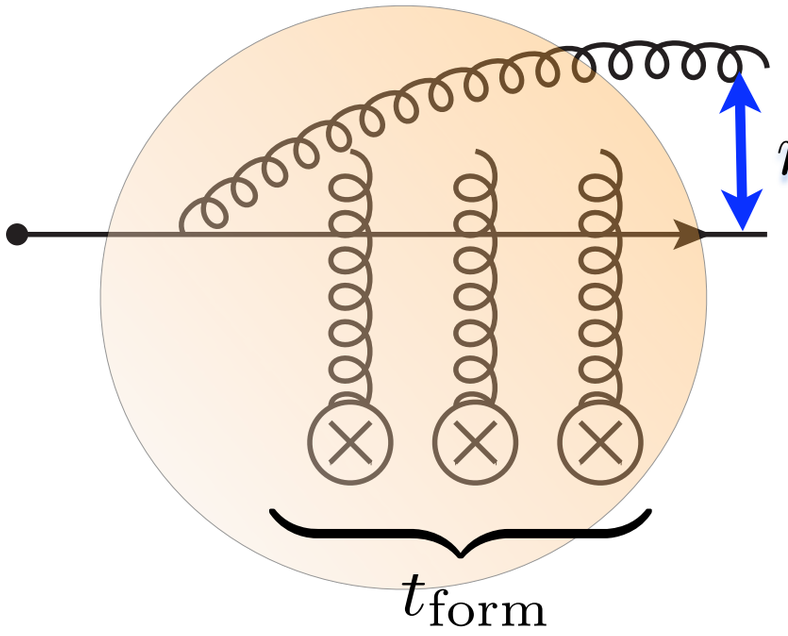

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Local transport parameter(s): $\hat{q}(t) = \dfrac{d\langle p_\perp^2 \rangle}{dt}$

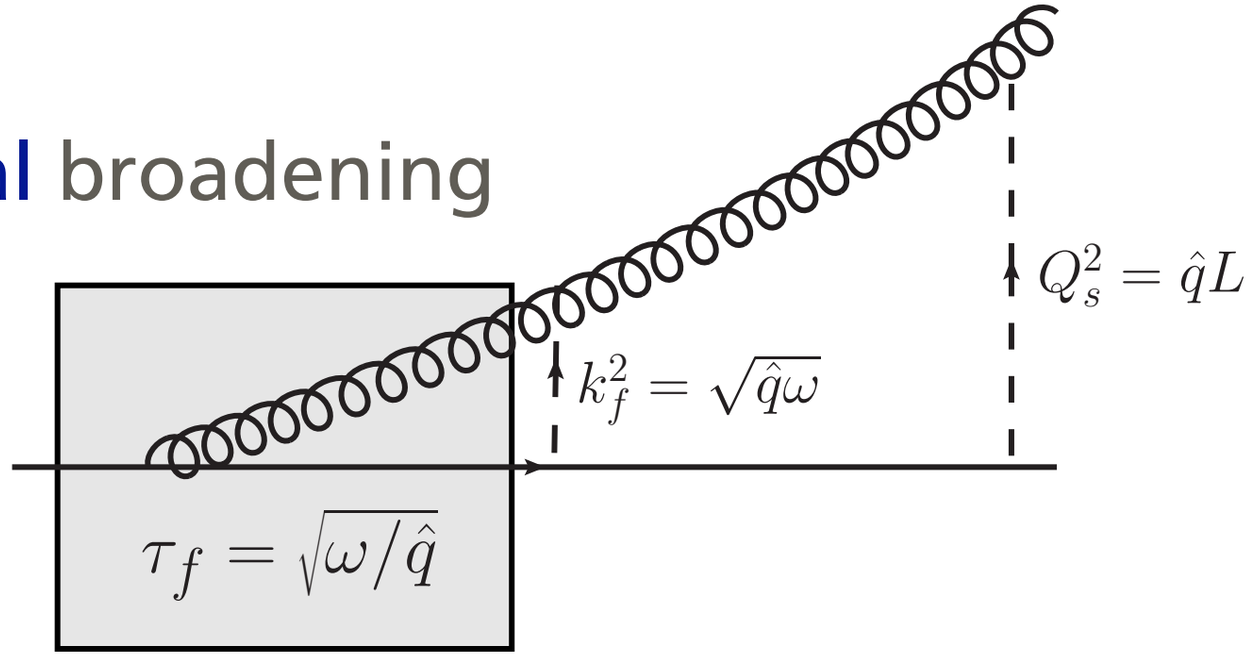
Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996)

Induced gluon spectrum

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

Two step process

- quantum emission + classical broadening
- emission all along L
- collinear safe!
- basis for phenomenology!



Mehtar-Tani, Salgado, KT arXiv:1205:5739

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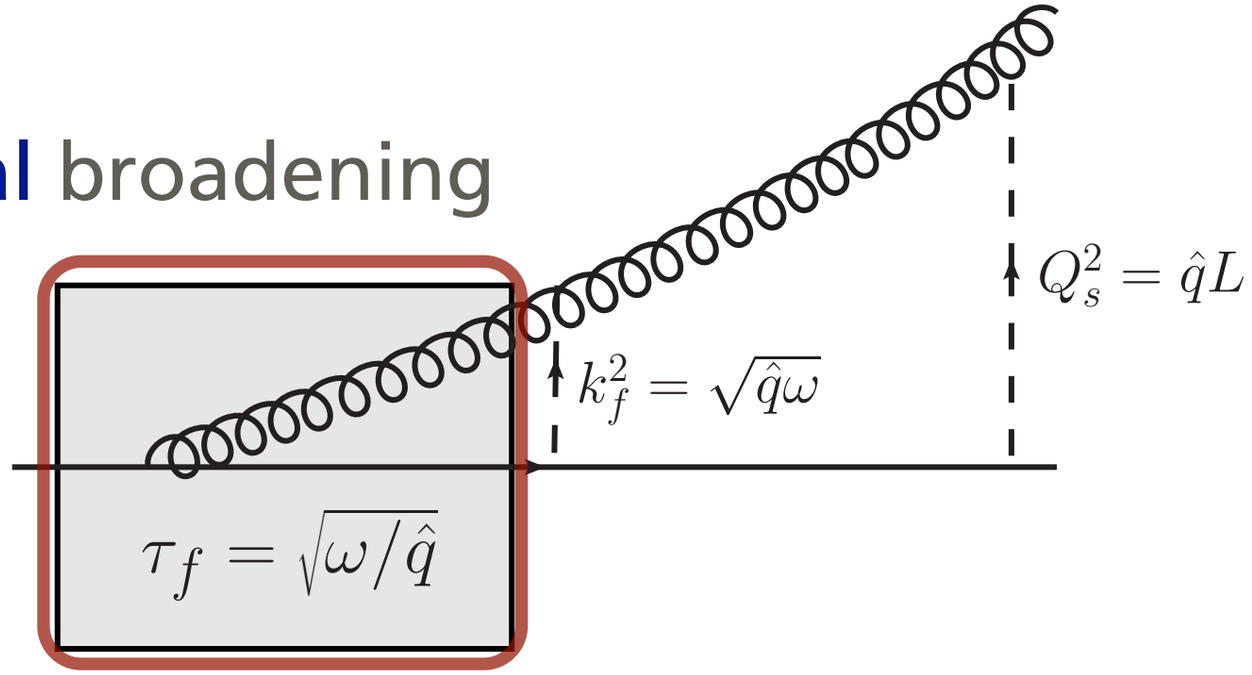

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prob. of acquiring mom. **k-k′** after L-t

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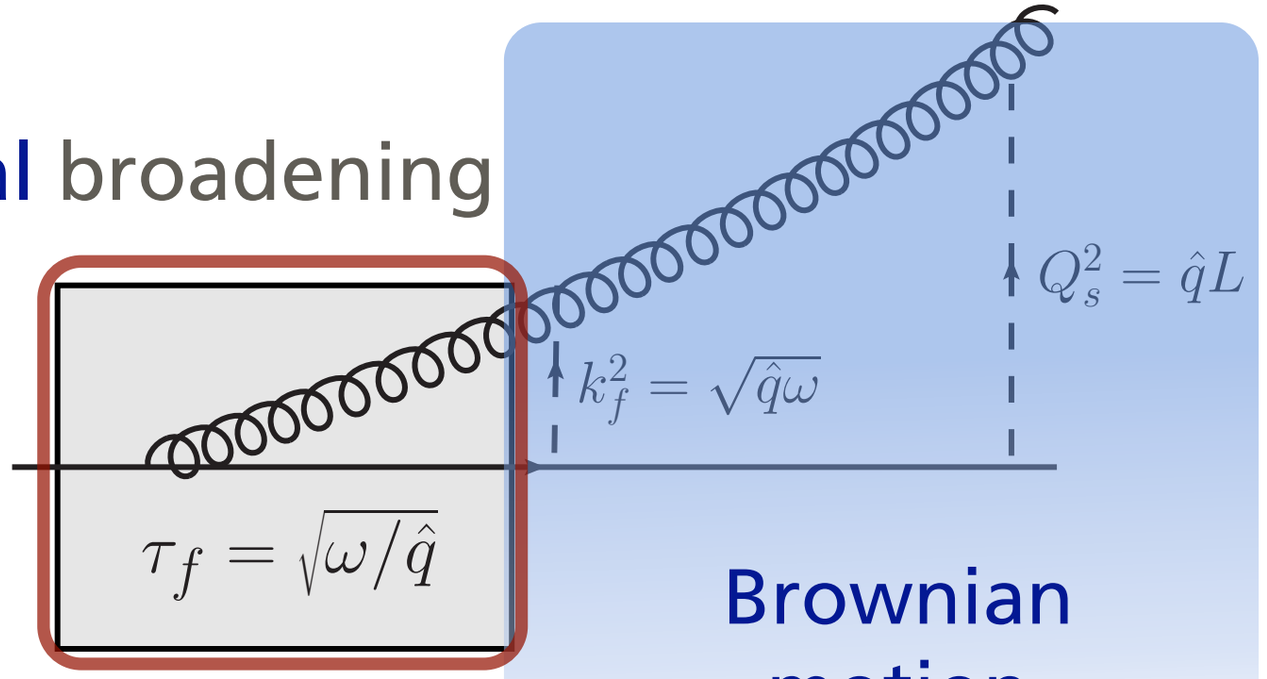

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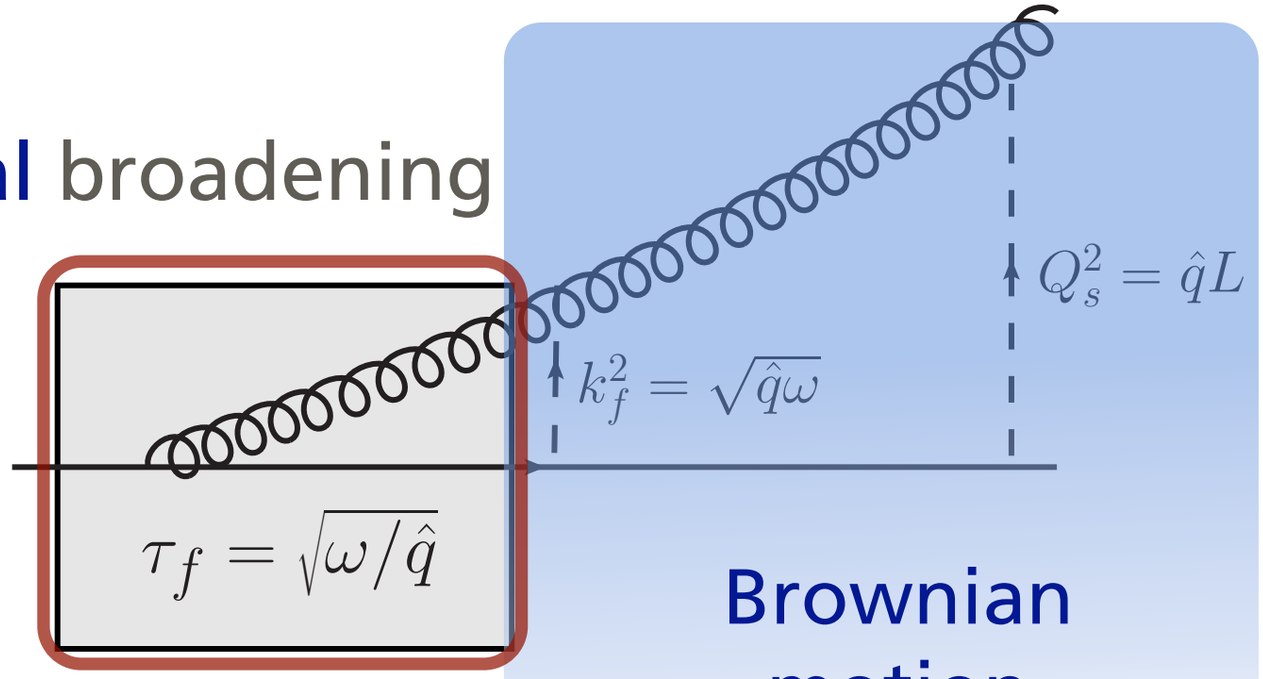
...a missing ingredient...

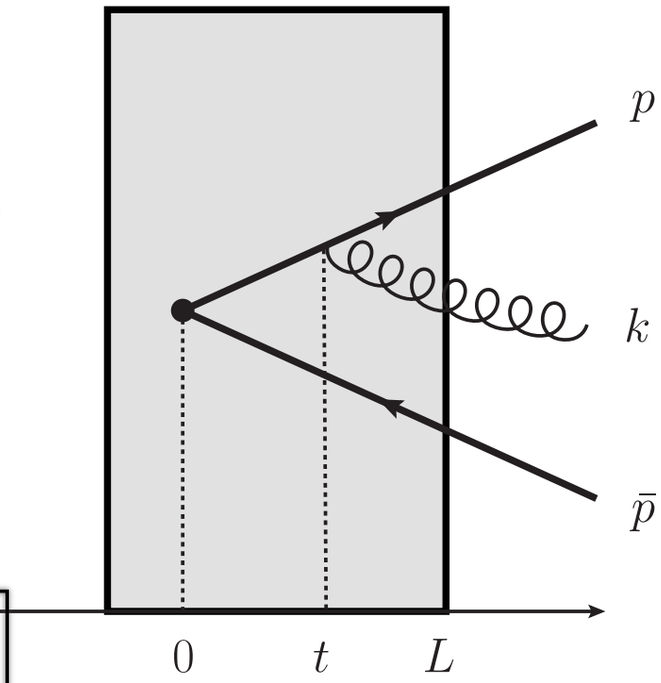


Mehtar-Tani, Salgado, KT arXiv:1205:5739

Multiple emitters in medium

Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002, PLB 707 (2011) 156, JHEP 1204 (2012) 064**
Casalderrey-Solana, Iancu **JHEP 1108 (2011) 015**
Armesto, Ma, Mehtar-Tani, Salgado, KT **JHEP 1201 (2012) 019**

- need more emitters to see coherence
- first step toward multi-gluon emissions
- calculating the interference spectrum



$$\begin{aligned}\mathcal{J} \;=\; & \mathrm{Re}\int_0^\infty dt' \int_0^{t'} dt\,\big(1-\Delta_{\mathrm{med}}(t,0)\big) \\ & \times\int d^2\boldsymbol{z}\,\exp\left[-i\bar{\boldsymbol{\kappa}}\cdot\boldsymbol{z}-\frac{1}{2}\int_{t'}^\infty d\xi\, n(\xi)\sigma(\boldsymbol{z})+i\frac{\omega}{2}\delta\boldsymbol{n}^2 t\right] \\ & \times\big(\boldsymbol{\partial}_y-i\omega\delta\boldsymbol{n}\big)\cdot\boldsymbol{\partial}_z\;\mathcal{K}(t',\boldsymbol{z};t,\boldsymbol{y}|\omega)\big|_{\boldsymbol{y}=\delta\boldsymbol{n}t}\;+\;\mathrm{sym.}\end{aligned}$$

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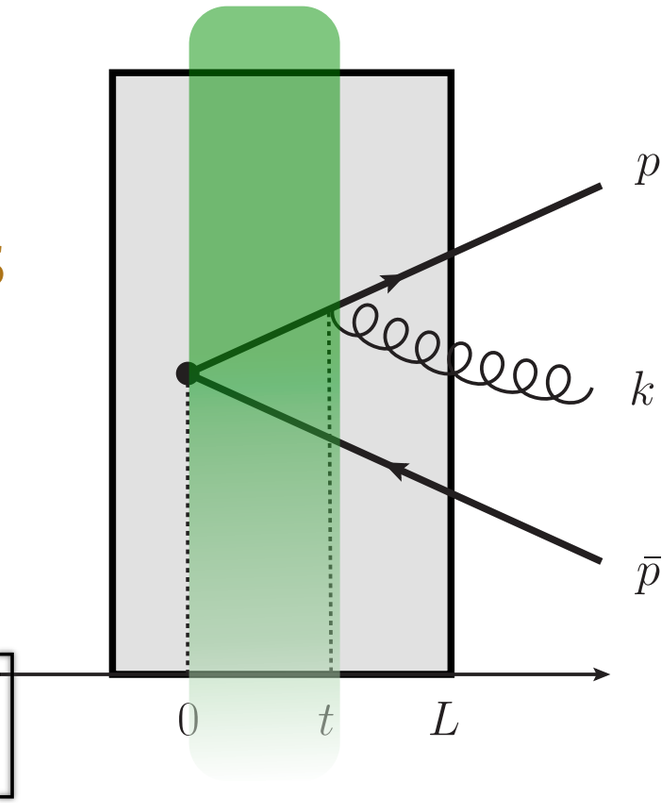

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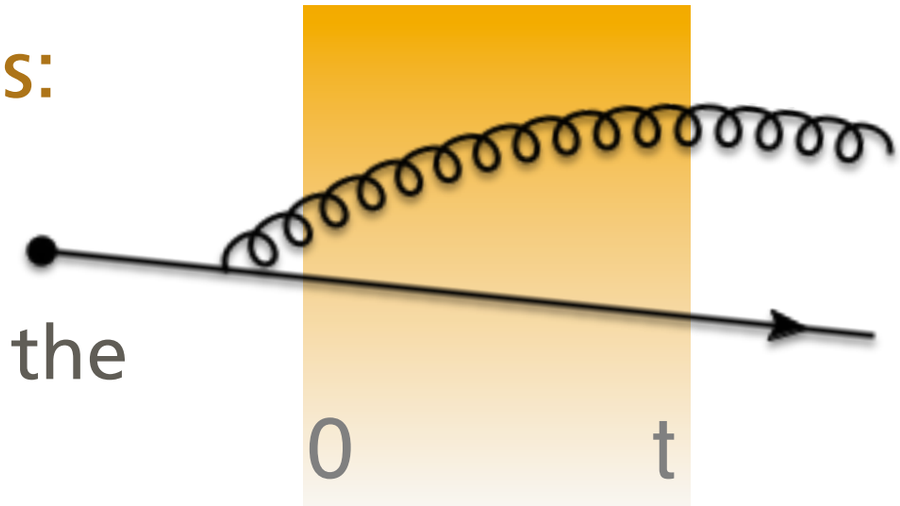
Three stage process:

- $q\bar{q}$ propagation + gluon decoherence + gluon broadening

Interferences: analysis

Importance of interferences:

- condition: color correlation between emitters
- what is the probability that the pair remains correlated?



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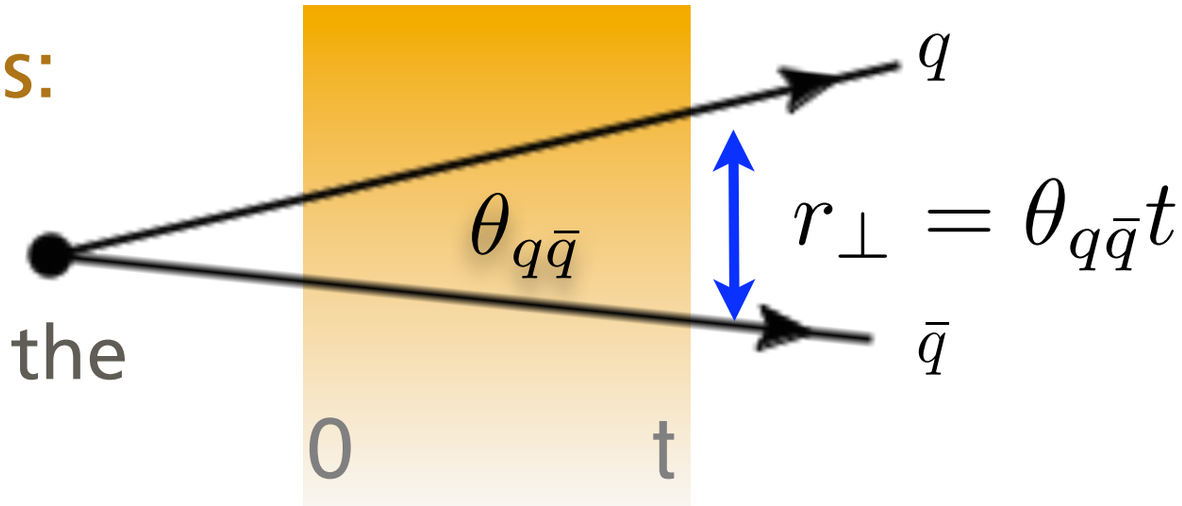

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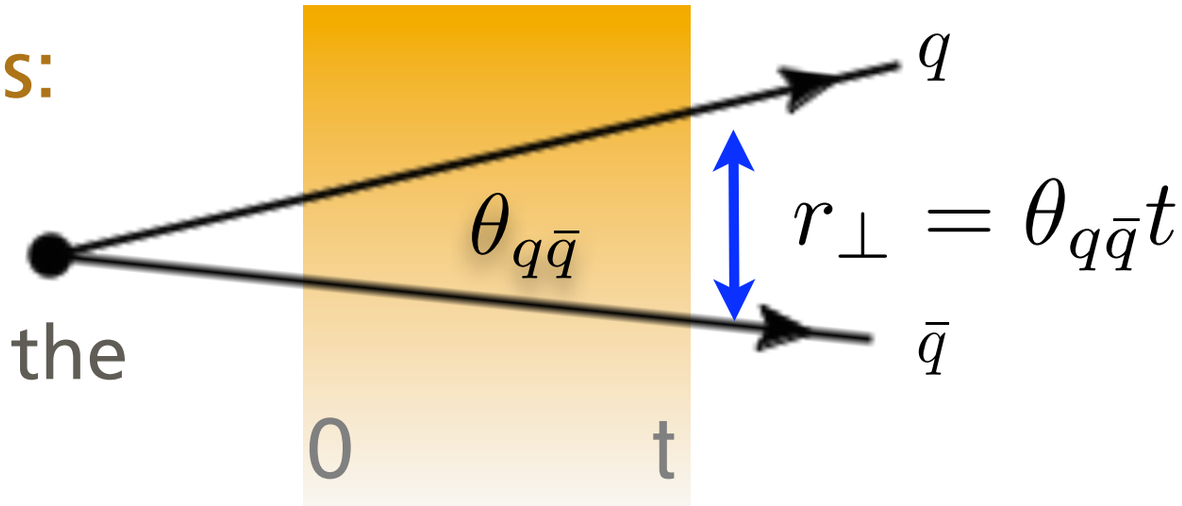

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decoherence parameter

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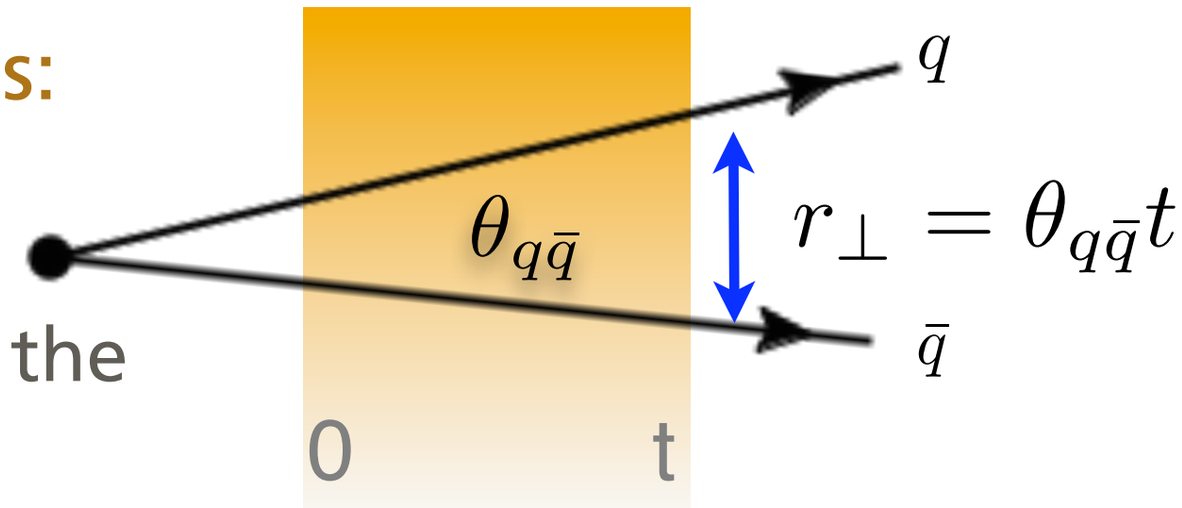

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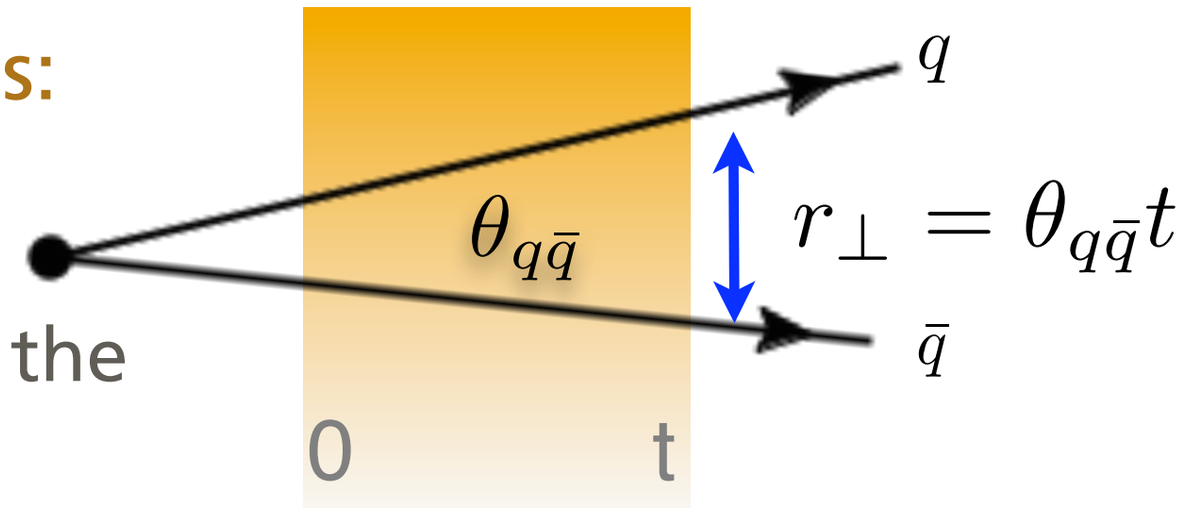

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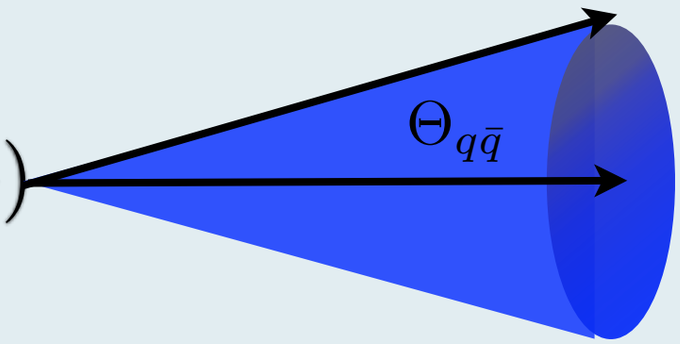
- processes at $t > \tau_d$: independent radiation
- processes at short timescales sensitive to interferences

Mehtar-Tani, Salgado, KT **JHEP 1204, 064; arXiv:1205.5739**
Casalderrey-Solana, Iancu **JHEP 1108 (2011) 015**

Vacuum: a reminder

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



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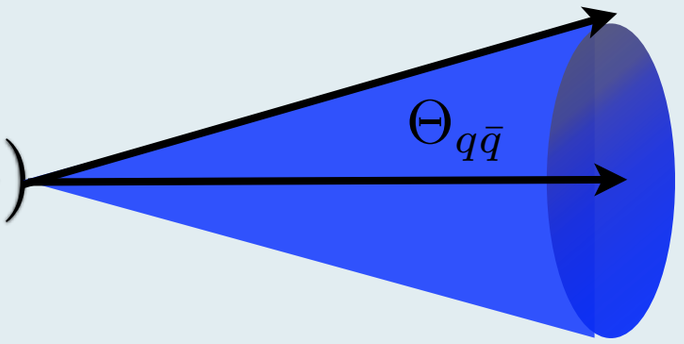
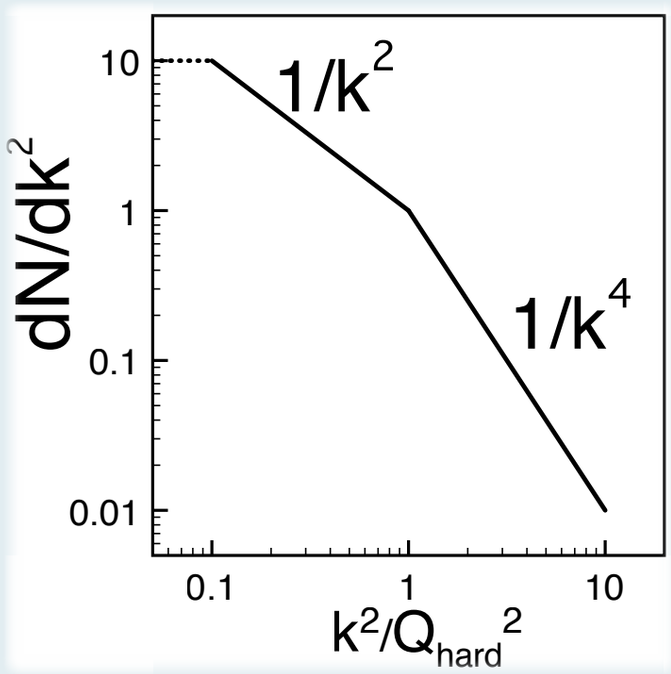


$$\omega \frac{dN_{\gamma^*}}{d^3k} = \frac{\alpha_s C_F}{\pi} \begin{cases} \frac{1}{\boldsymbol{k}^2} & \boldsymbol{k} \ll \delta\boldsymbol{k}, \text{ or } \theta \ll \theta_{q\bar{q}} \\ \frac{\delta\boldsymbol{k}^2}{\boldsymbol{k}^4} & \boldsymbol{k} \gg \delta\boldsymbol{k}, \text{ or } \theta \gg \theta_{q\bar{q}} \end{cases}$$



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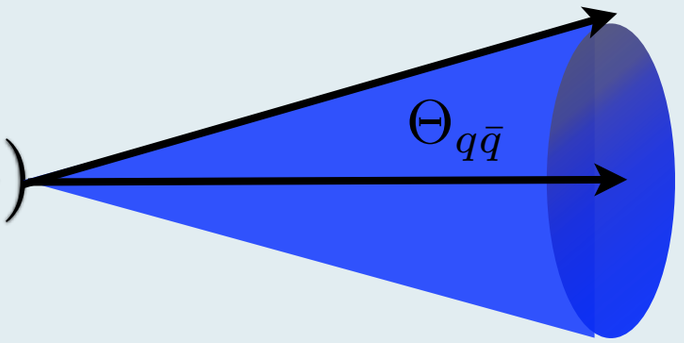

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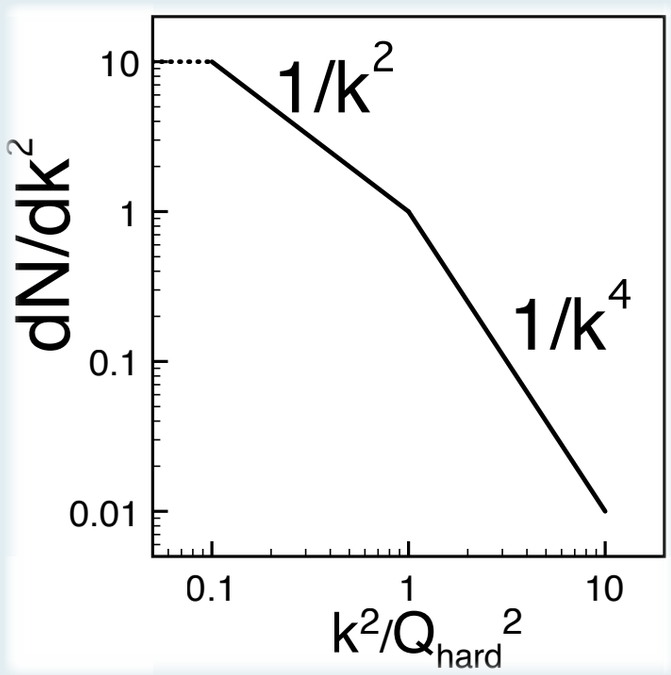

Hard scale of the problem: $|\delta\boldsymbol{k}| \simeq \omega\theta_{q\bar{q}}$

- determines the **maximal transverse momentum** of gluons

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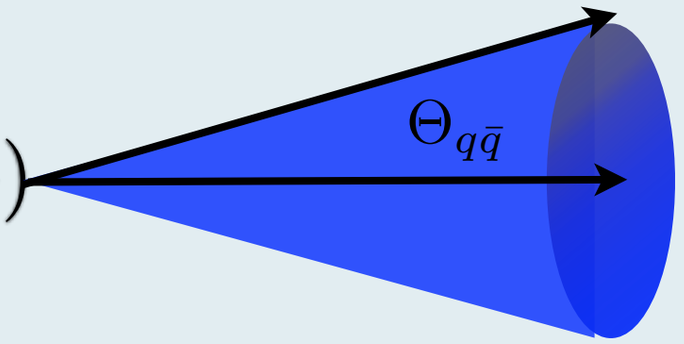

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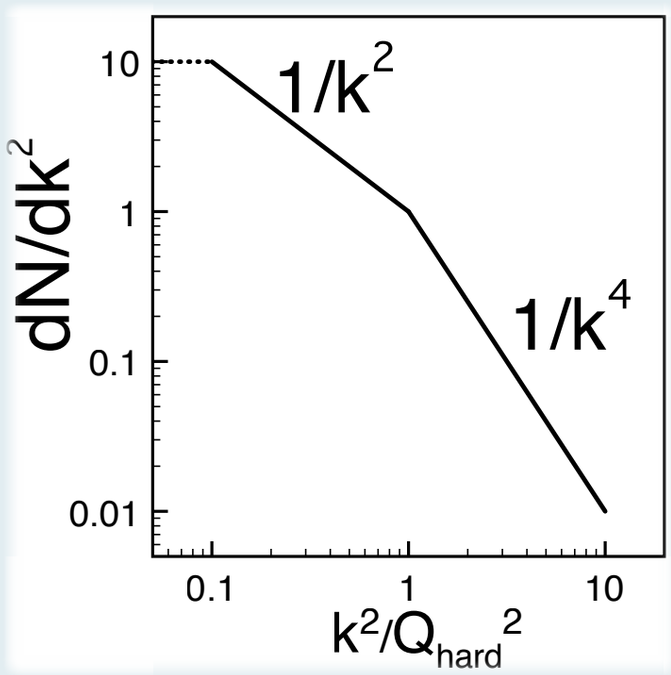


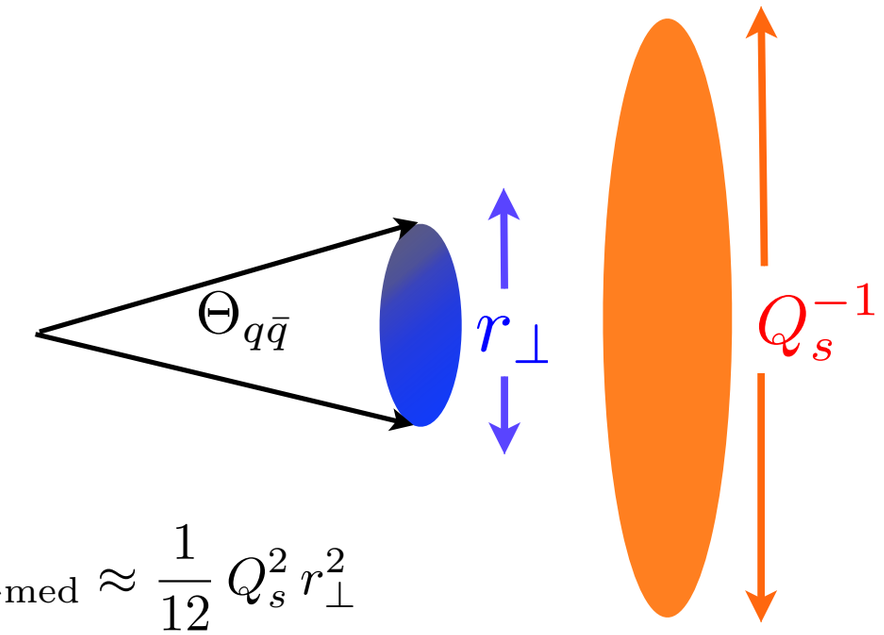
Hard scale of the problem: $|\delta\boldsymbol{k}| \simeq \omega\theta_{q\bar{q}}$

- determines the **maximal transverse momentum** of gluons

What are the relevant hard scales in the medium?

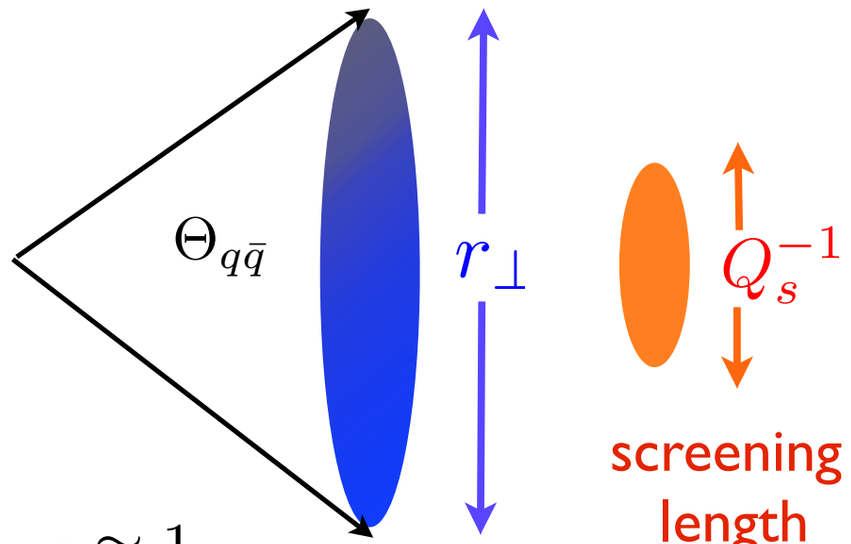
Hard scale analysis

- $r_\perp < Q_s^{-1}$ (Dipole regime)



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

- $r_\perp > Q_s^{-1}$ (Decoh. regime)



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

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

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

Q_s: characteristic momentum scale of the medium

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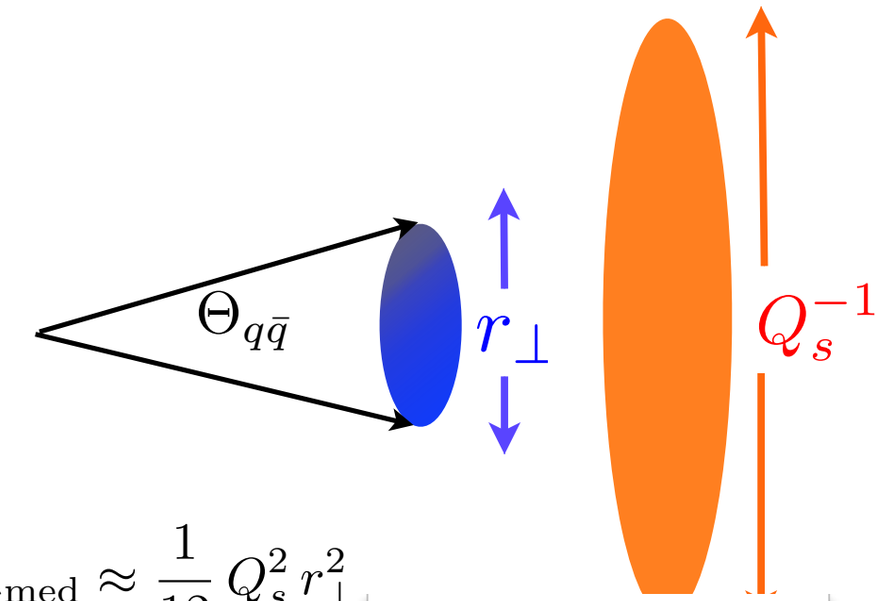
Hard scale analysis

- $r_\perp < Q_s^{-1}$ (Dipole regime)

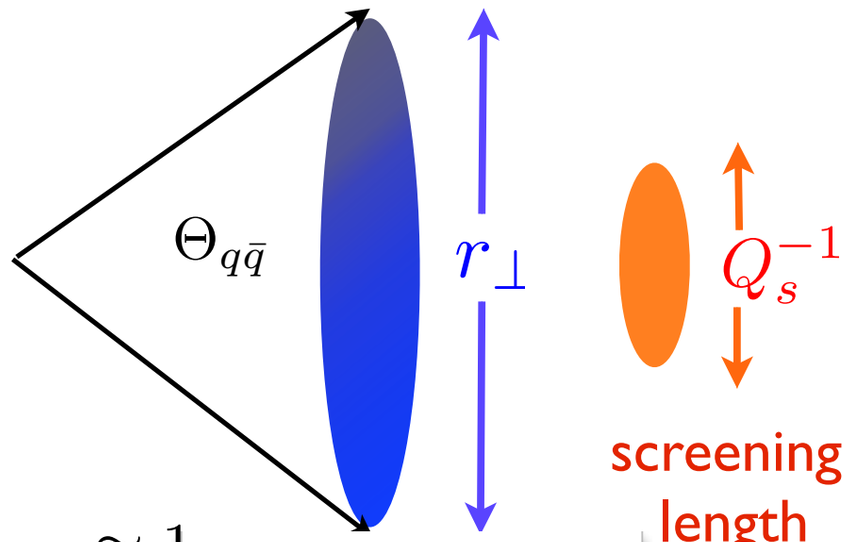


$\Delta_{\rm med} \approx \frac{1}{12} Q_s^2 r_\perp^2$

$\tau_d \gg L$

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

- $r_\perp > Q_s^{-1}$ (Decoh. regime)



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

$\tau_d \ll L$

$r_\perp =$

Q_s: characteristic momentum scale of the medium

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Finite energies

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

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

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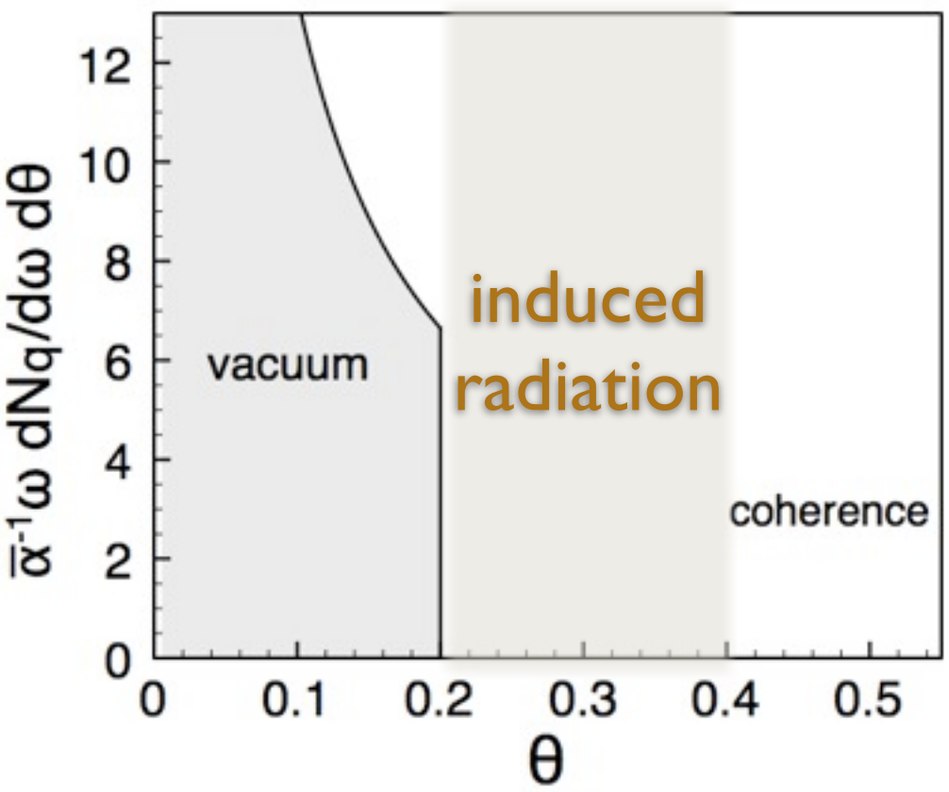
Finite energies

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

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

$\theta > Q_{hard}/\omega$: coherence!



Medium scales open phase space

- "out-of-cone" radiation
- no interferences inside

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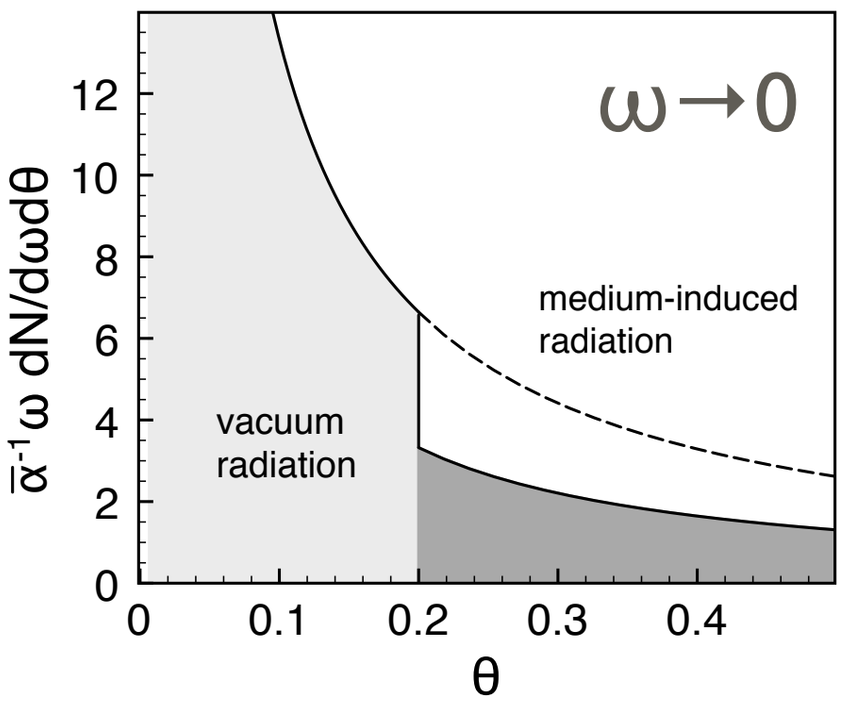
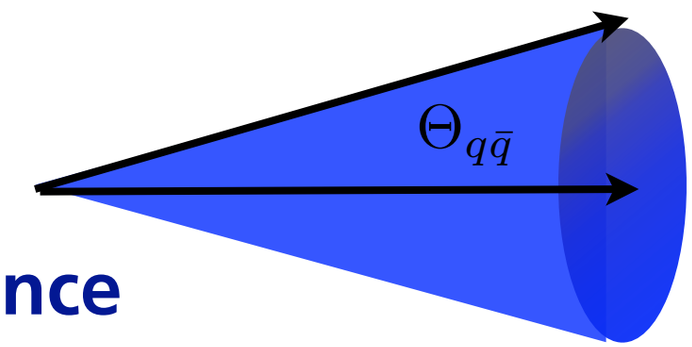
Onset of decoherence

- in the soft sector



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



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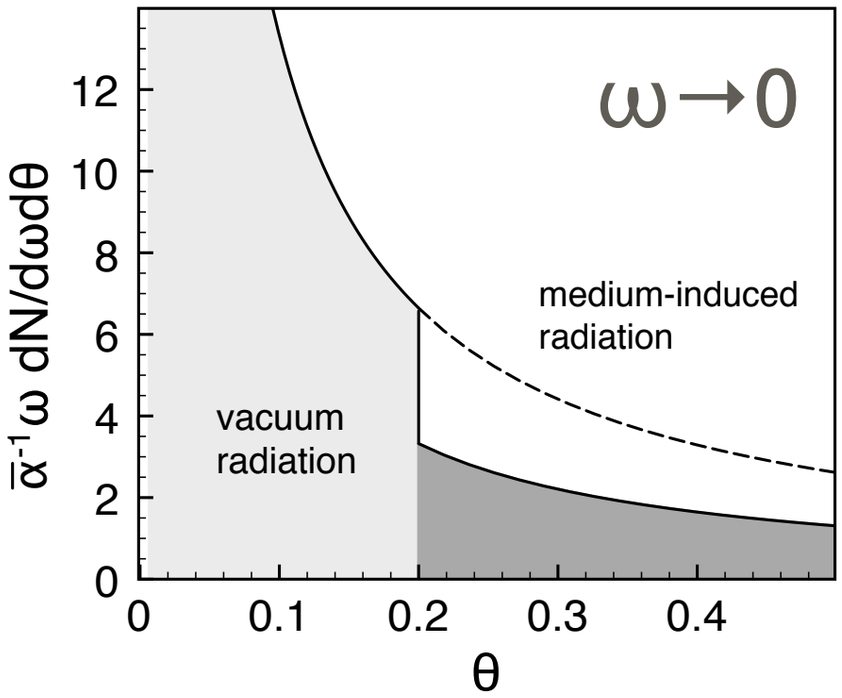
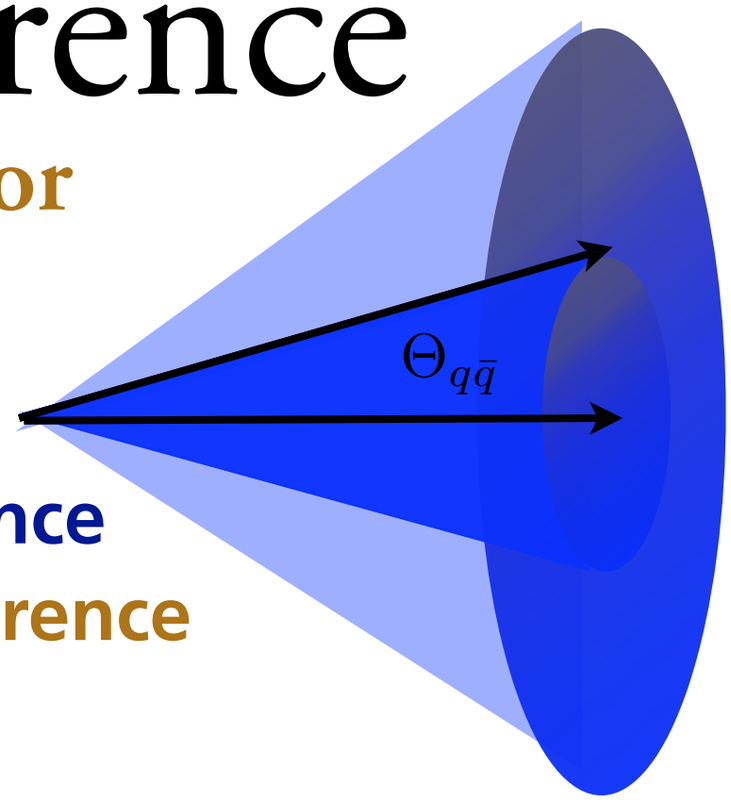


$\Delta_{\rm med} \to 0$ **Coherence**

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



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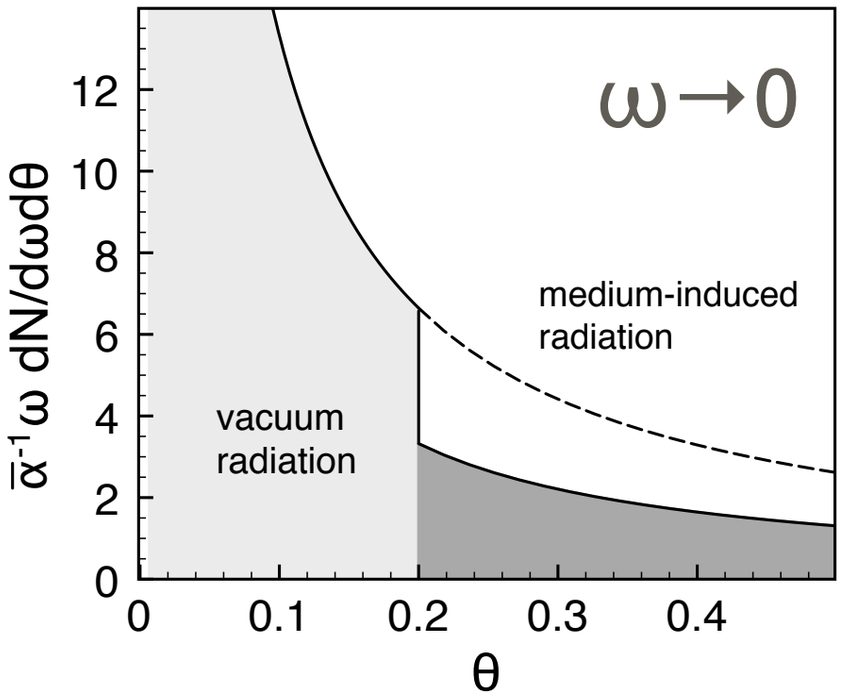

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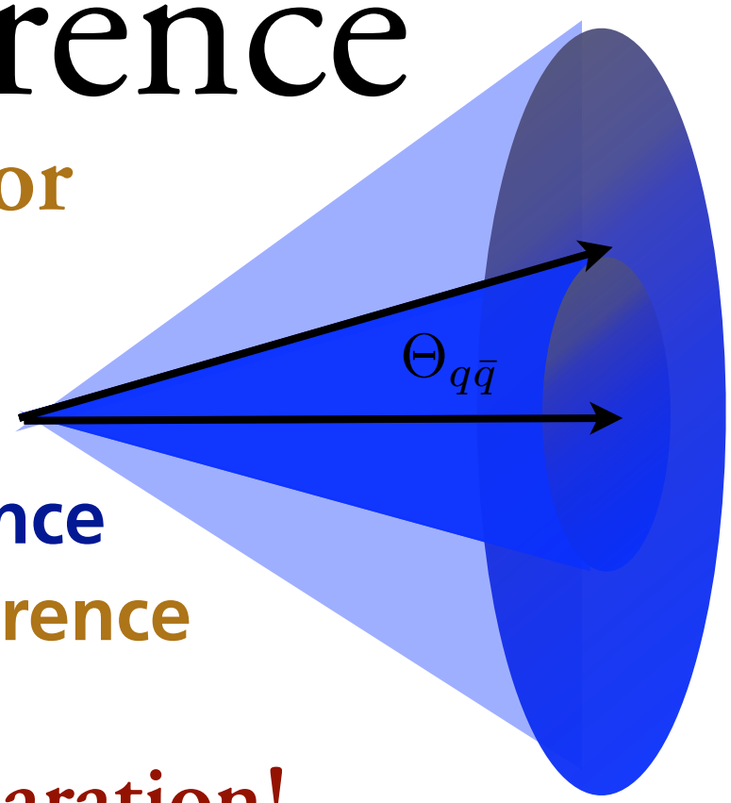

Geometrical separation!

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Onset of decoherence

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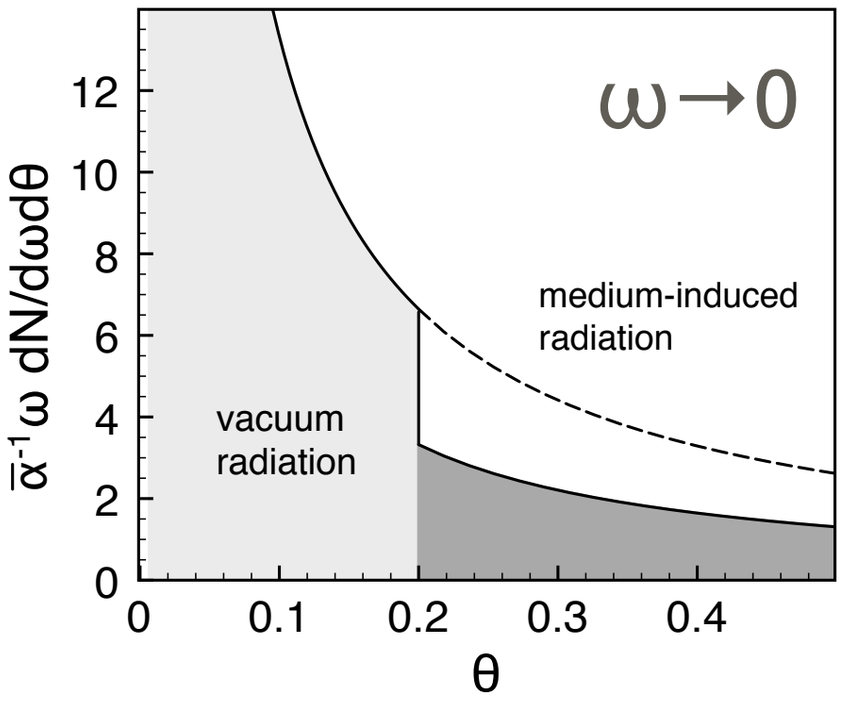

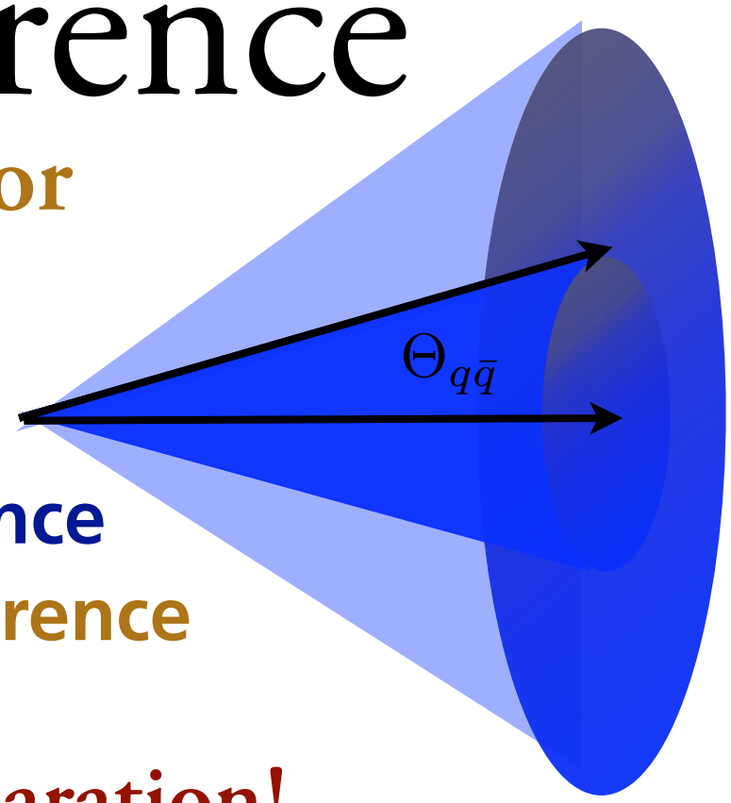

$\Delta_{\rm med} \to 0$ **Coherence**

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

Geometrical separation!

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

Soft gluons with long formation times

- particles radiate independently
- "memory loss": no color correlation to parent

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Conclusions

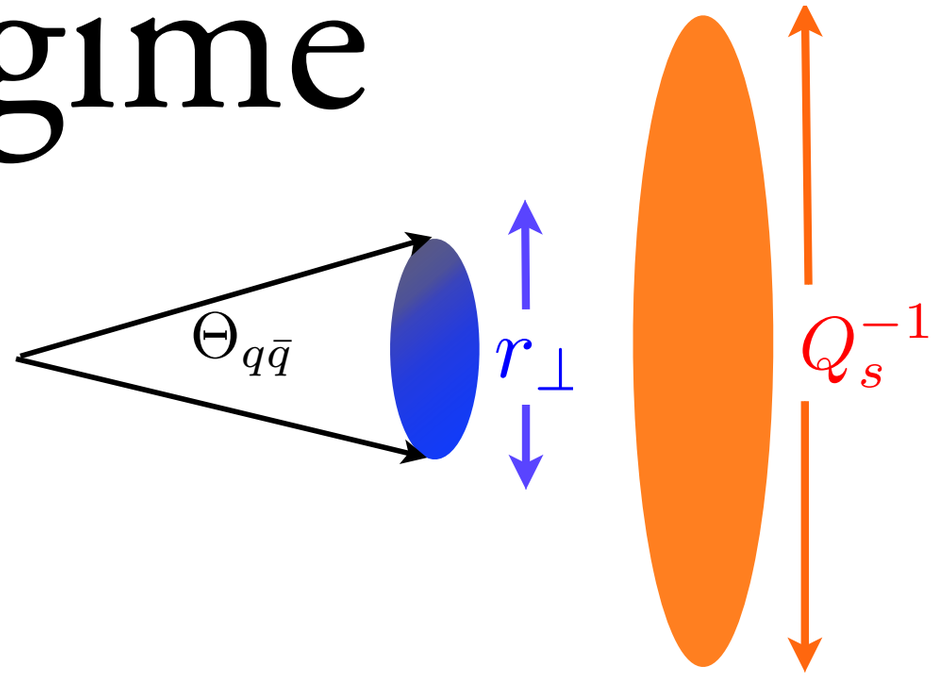
- spectrum governed by the hardest scale
- establishing a understanding of jet dynamics in medium in terms of hard scales
- developing a space-time picture of radiation inside the medium
- from multiple emitters to multiple emissions

Backup

“Dipole” regime

Color transparency

- pair remains color correlated
- radiates coherently: antiangular
- no medium-induced component!



Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002, JHEP 1204 (2012) 064**

“Dipole” regime

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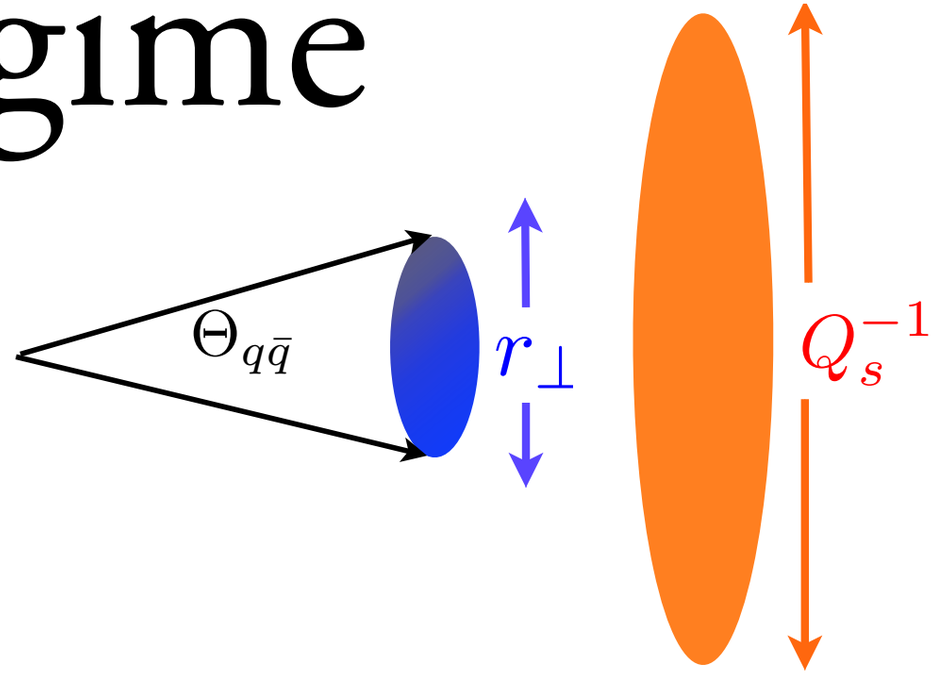

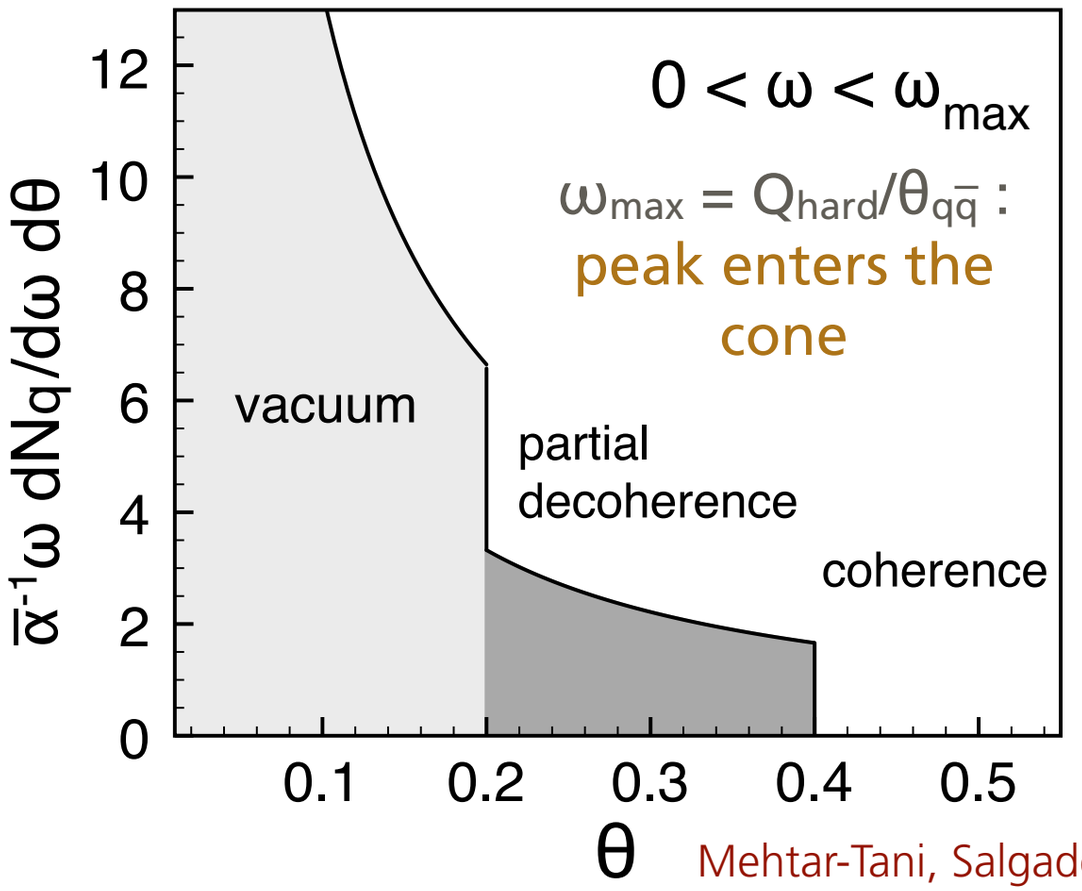

Mehtar-Tani, Salgado, KT **PRL106 (2011) 122002, JHEP 1204 (2012) 064**

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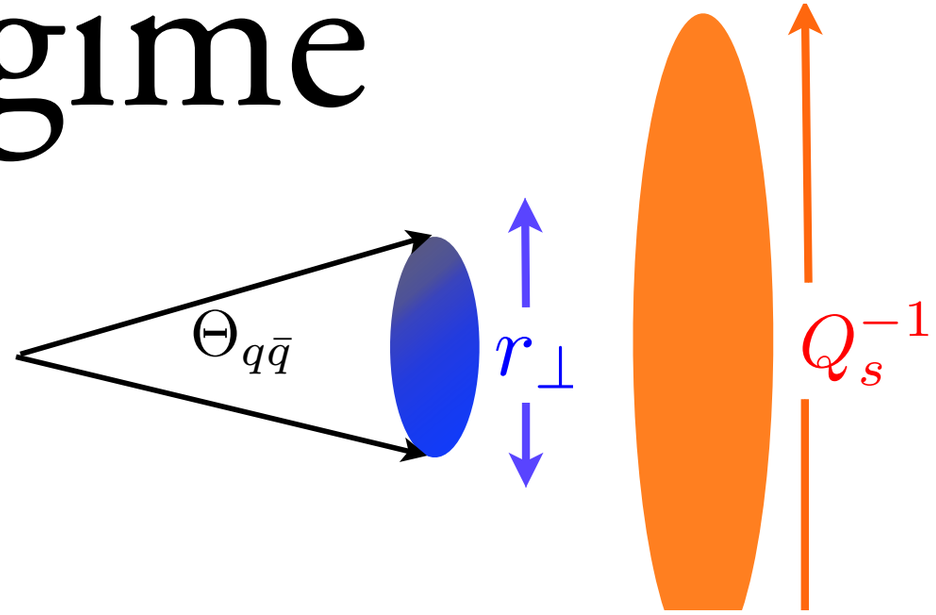
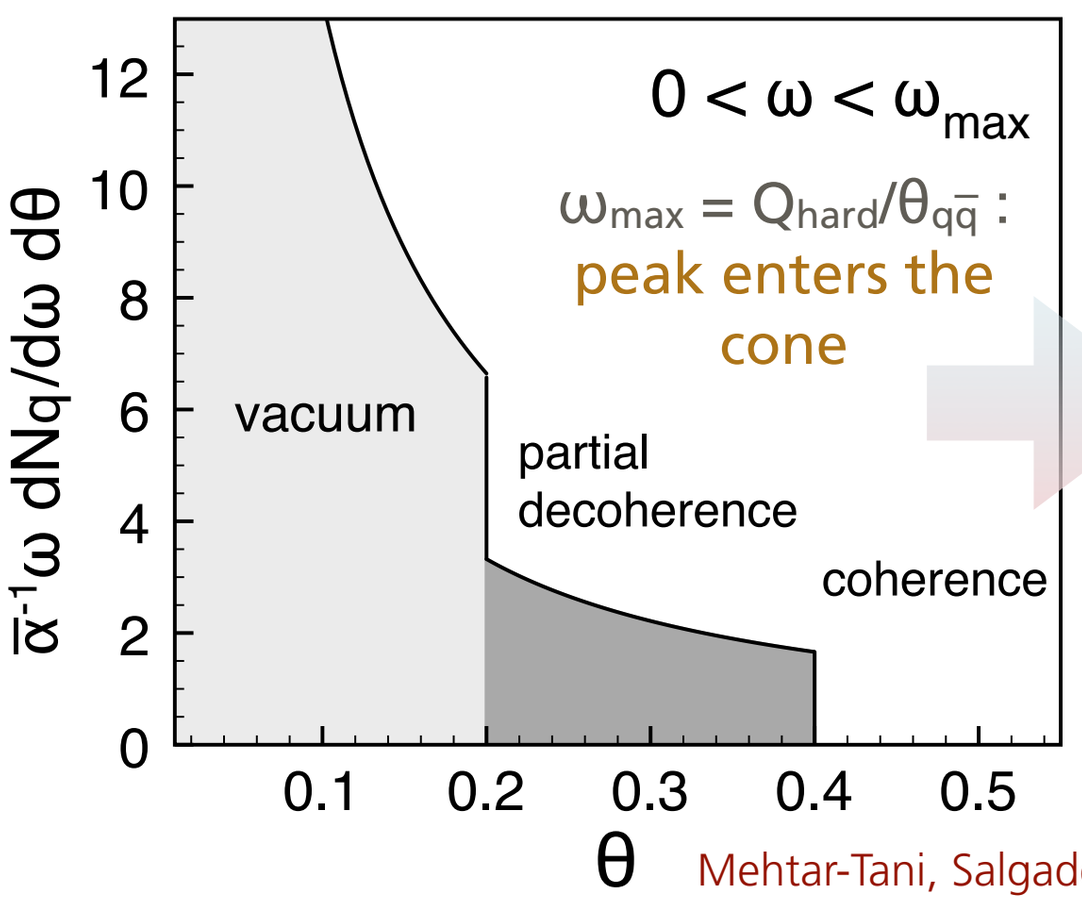
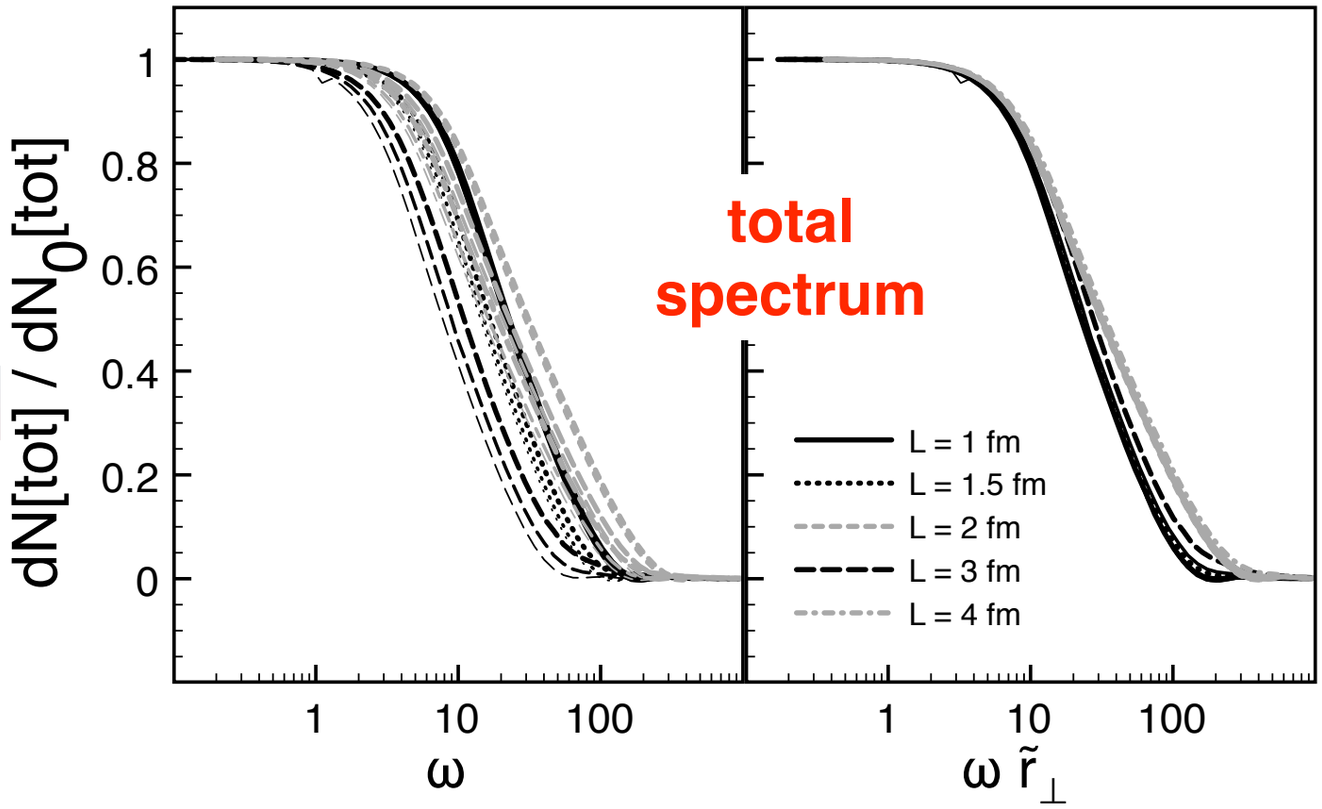




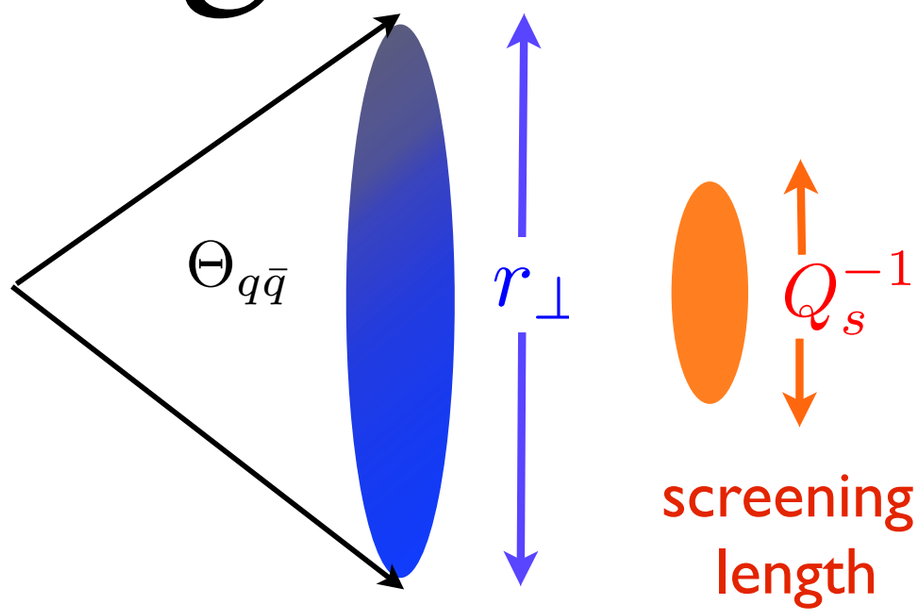


Mehtar-Tani, Salgado, KT PRL106 (2011) 122002, JHEP 1204 (2012) 064

“Decoherence” regime

Two-component spectrum

- pair decorrelates rapidly
- medium induces radiation off each of the legs independently
  - interferences scale like τ_d
- vacuum-radiation up to Q_s!



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J. Casalderrey-Solana, E. Iancu **JHEP 1108 (2011) 015**

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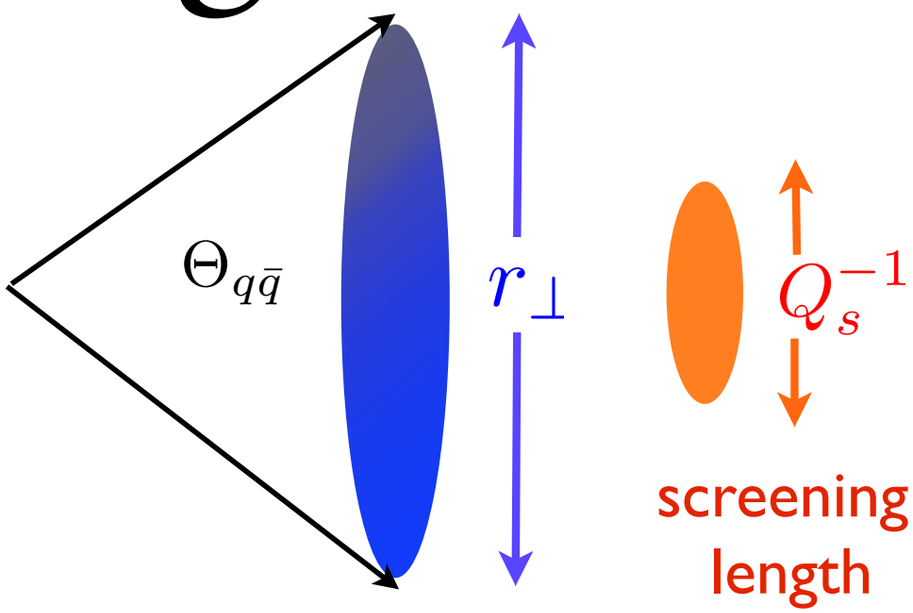

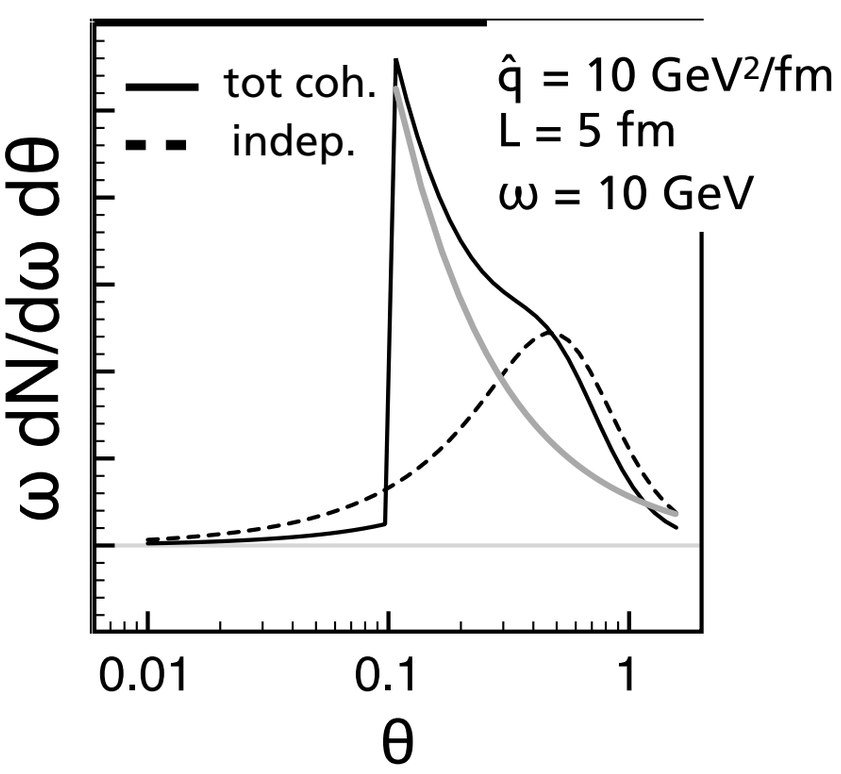

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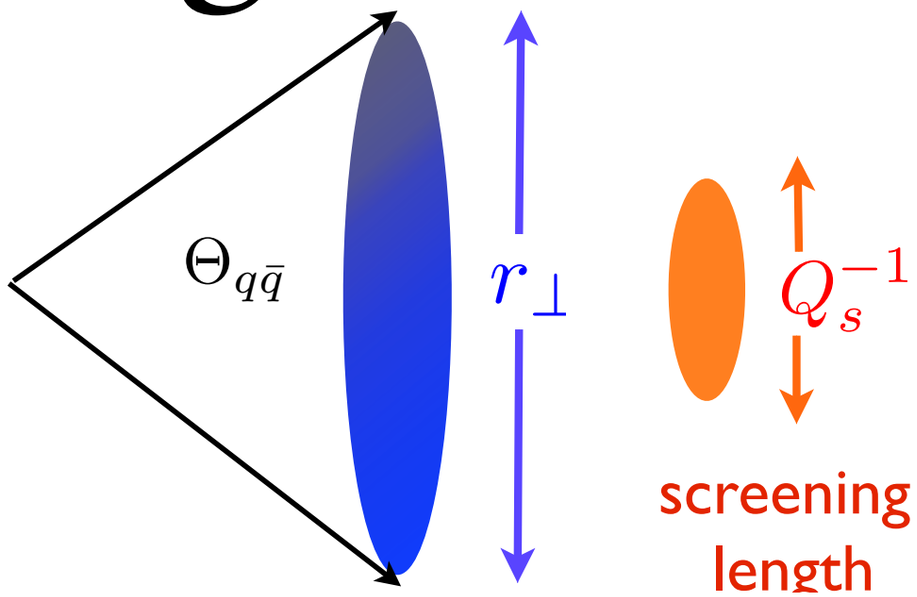
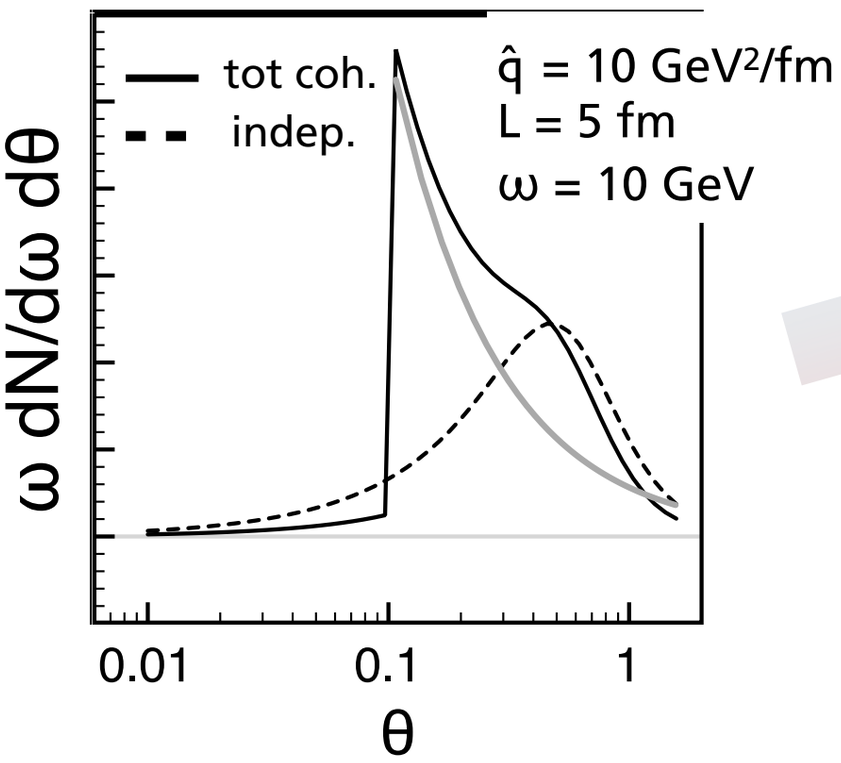
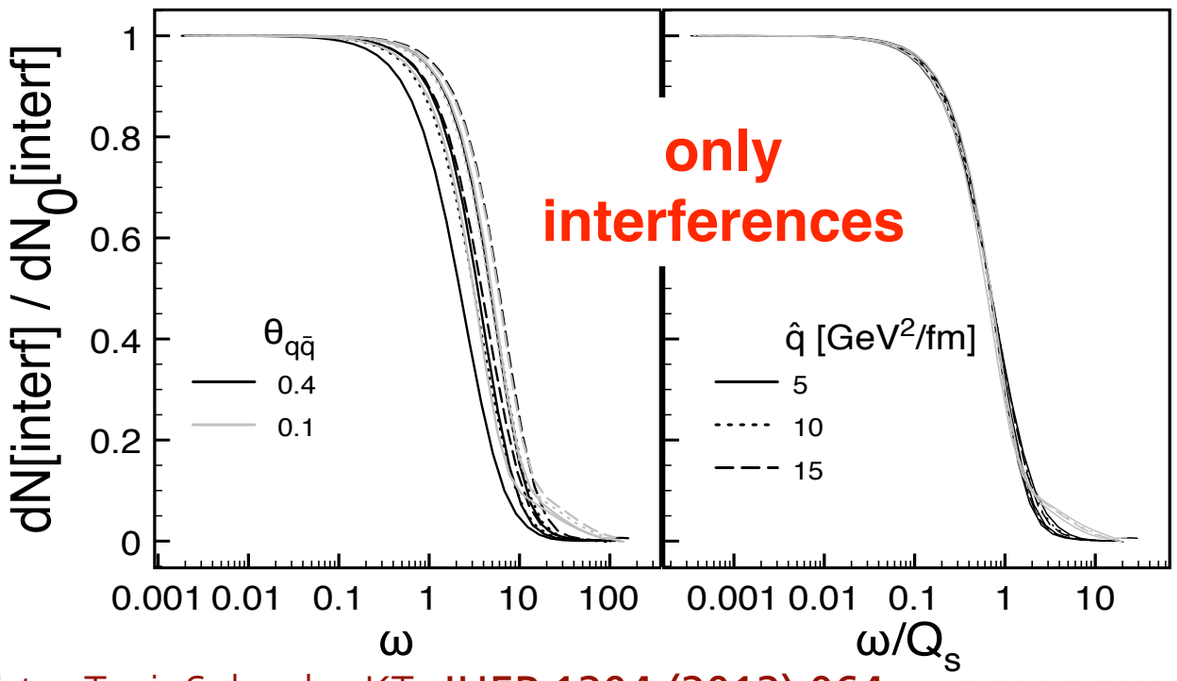
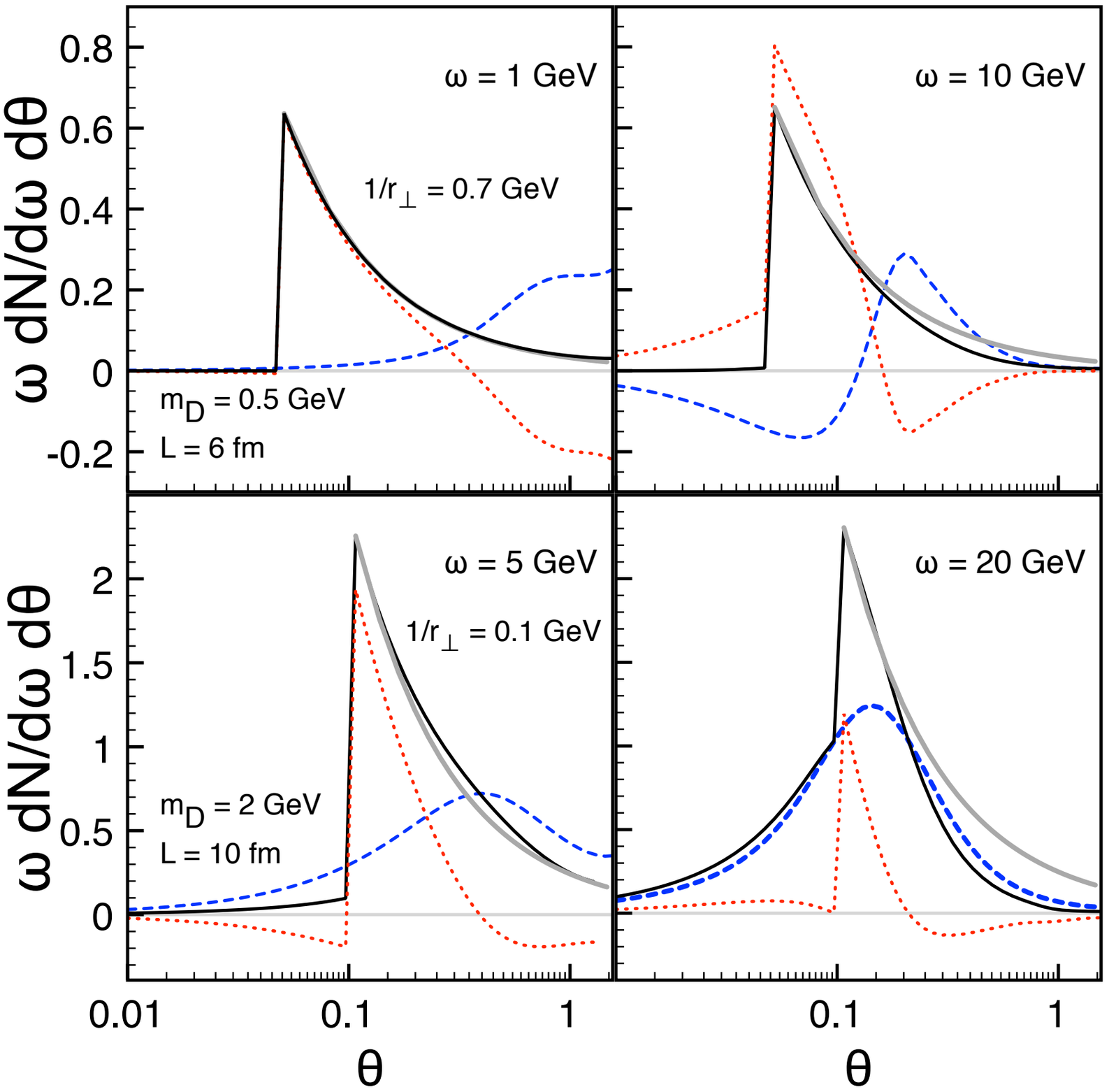






Mehtar-Tani, Salgado, KT **JHEP 1204 (2012) 064**
J. Casalderrey-Solana, E. Iancu **JHEP 1108 (2011) 015**

C.A. Salgado, Y. Mehtar-Tani, KT **JHEP 1204 (2012) 064**



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

$1/\theta$

[N=1 case]

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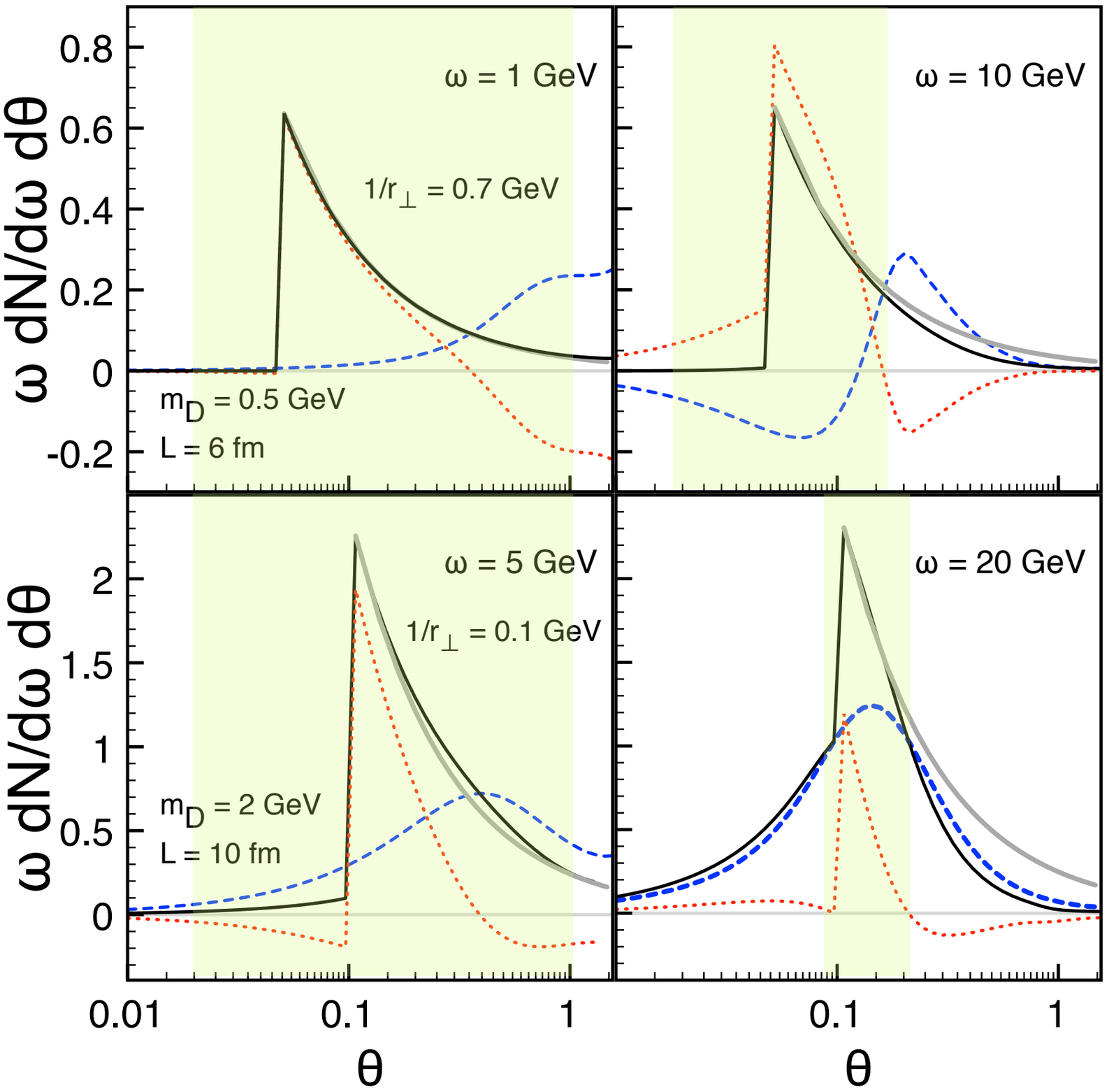

$\mathcal{R}_q^{\rm med}$ $\mathcal{J}_q^{\rm med}$

$1/\theta$

antiangular ordering

[N=1 case]

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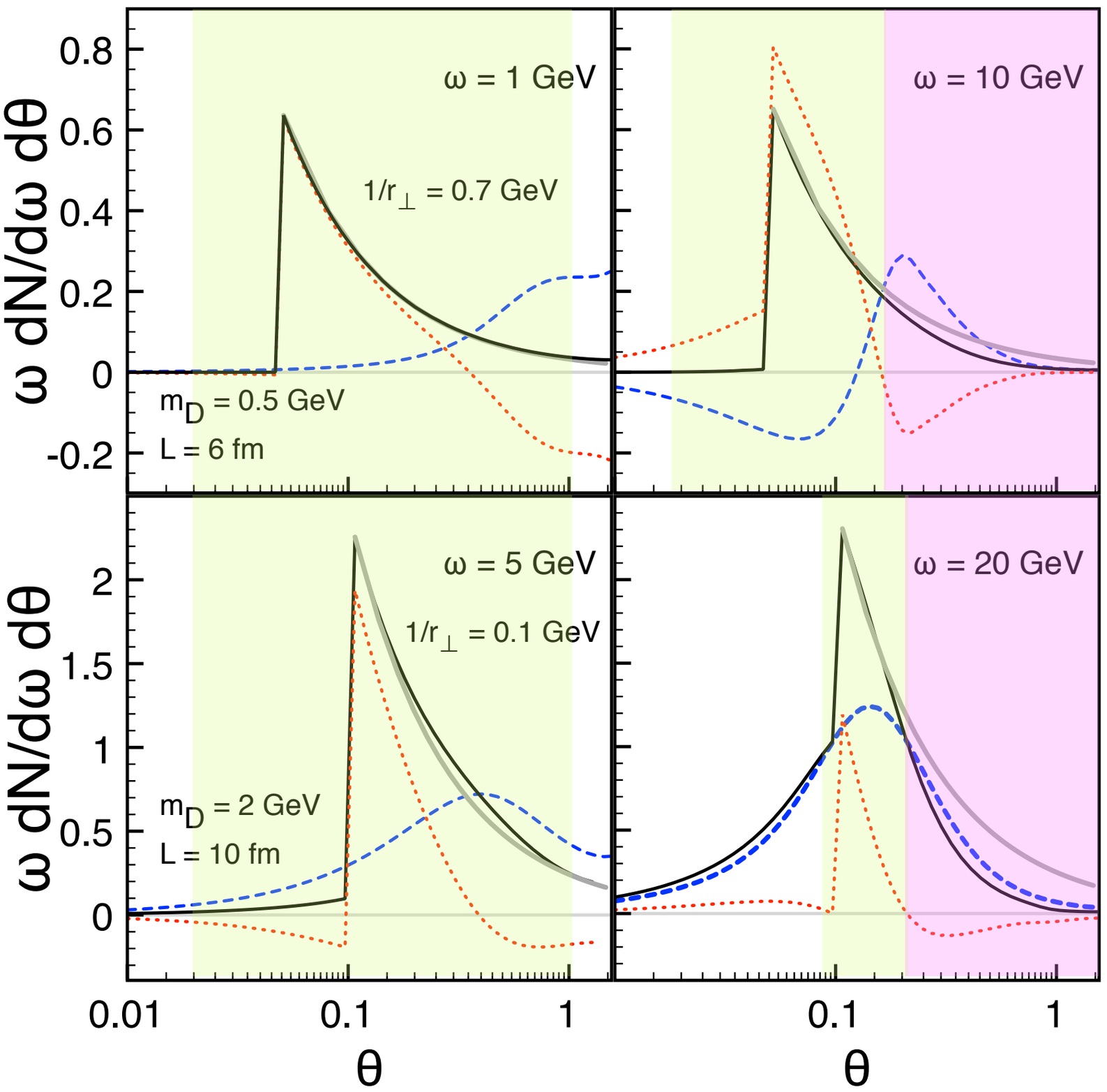


$\mathcal{R}_q^{\rm med}$ $\mathcal{J}_q^{\rm med}$

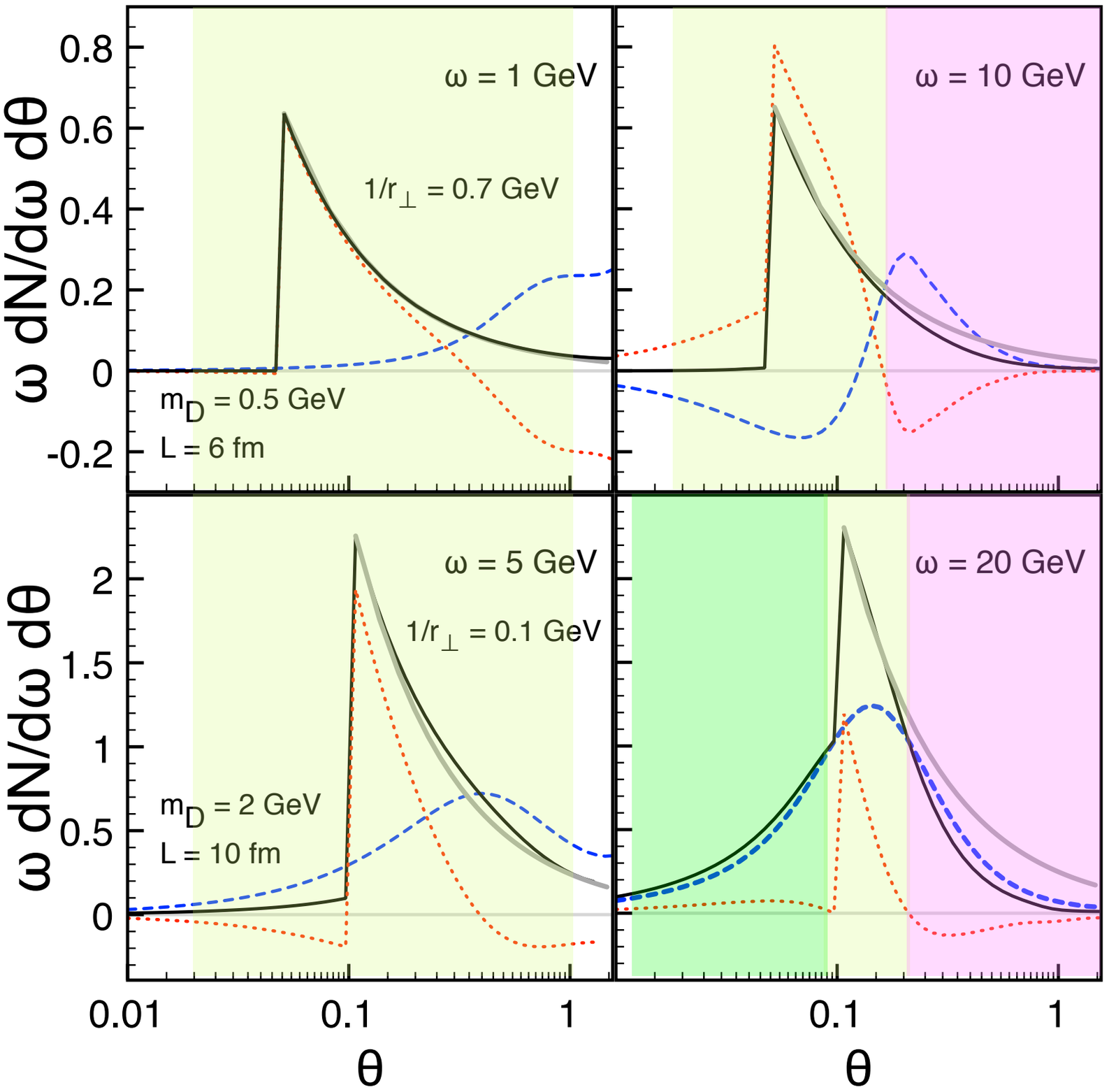
$1/\theta$

antiangular ordering

coherence

[N=1 case]

C.A. Salgado, Y. Mehtar-Tani, KT **JHEP 1204 (2012) 064**



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

$1/\theta$

antiangular ordering

coherence

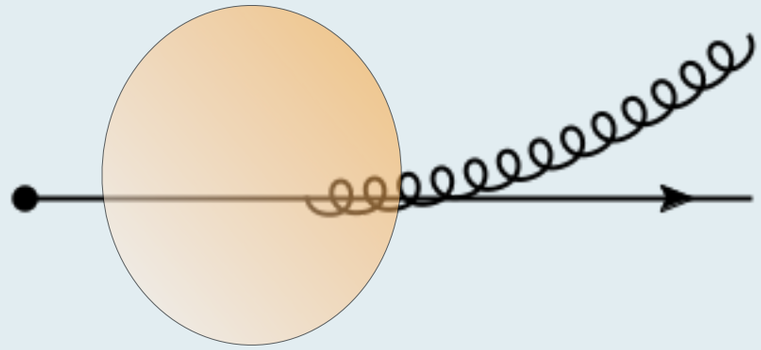
inside cone

[N=1 case]

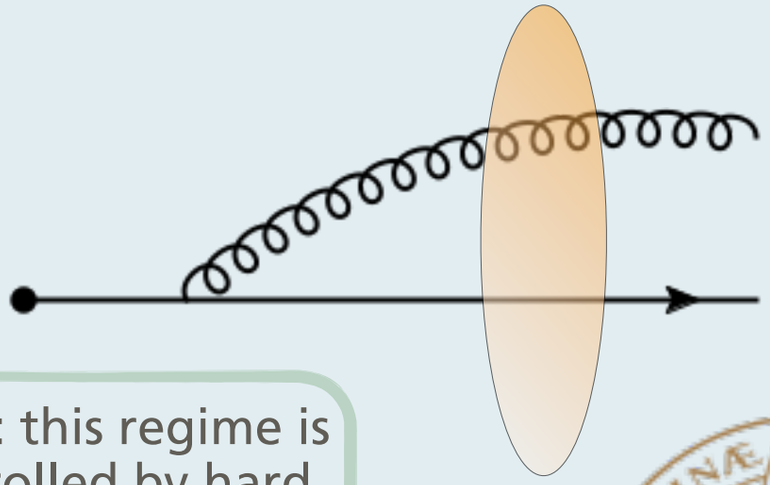
The vacuum component

Usually neglected/subtracted from medium-induced spectrum.

- bremsstrahlung off accelerated charge
  - after the medium
    - does not resolve the medium
    - soft radiation ($t_{form} > L$)

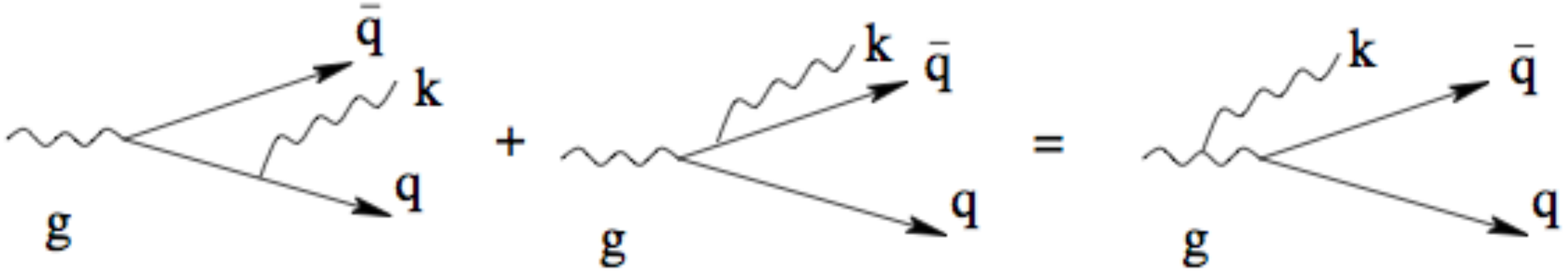


  - early in the medium
    - medium does not resolve it ($t_{form} < \lambda_{mfp}$)
    - can feel broadening



NOTE: this regime is controlled by hard medium interactions

Reshuffling of radiation



- radiation is reinstated as coming off the total charge
- in the soft limit:

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

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