On jet dynamics in the QGP

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arXiv:1009.2965 [hep-ph] (work in progress)

Universidade de Santiago de Compostela

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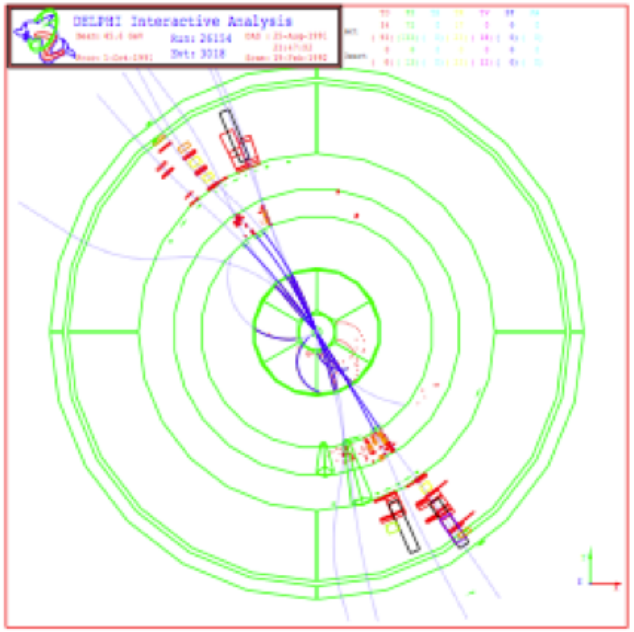
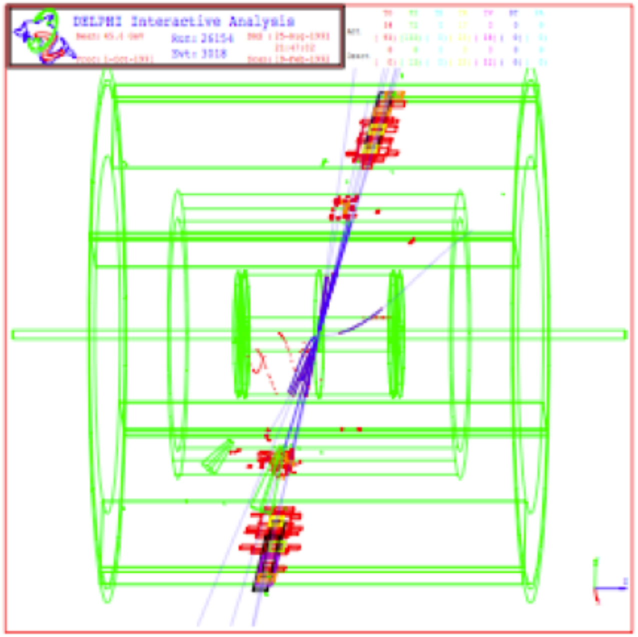
Clermont-Ferrand

What is a Jet?

"A collimated and energetic bunch of hadrons produced in a hard process"



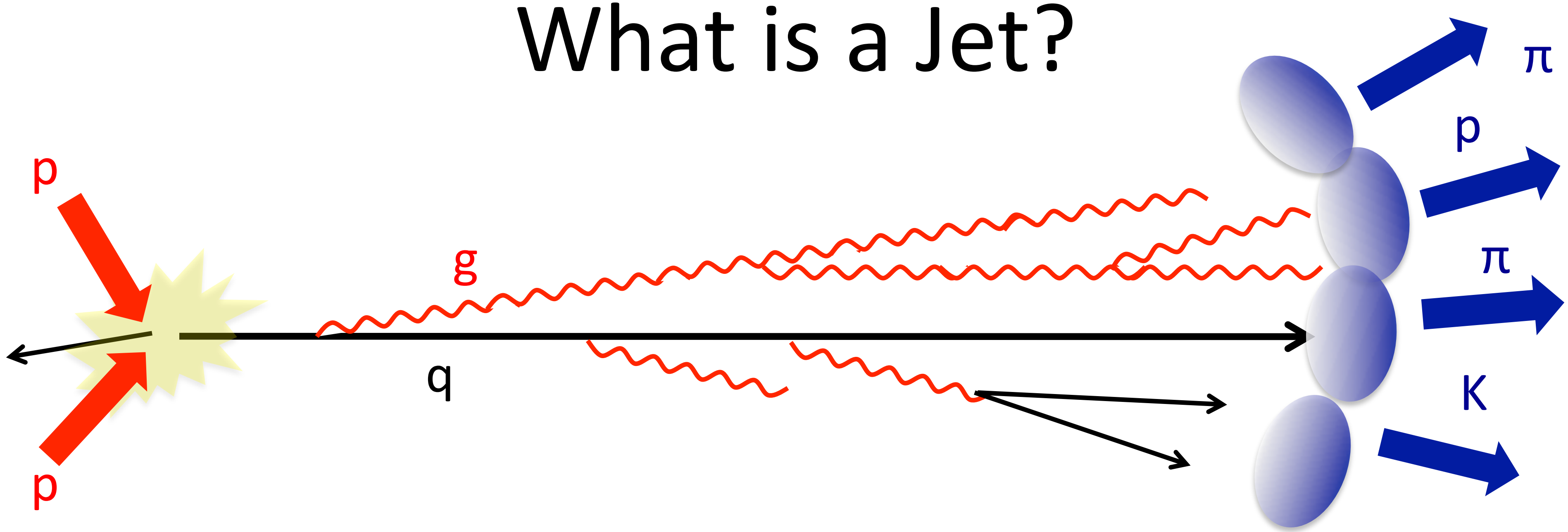
x-y plane



z-y plane

[2-jet event at LEP]

What is a Jet?



- Originally a jet is born as a hard parton (quark/gluon) which fragments into many partons when the time goes by with decreasing virtuality down to a non-perturbative scale where hadronization takes place
- Parton shower is well described within pQCD
- LPHD: Hadronization does not affect exclusive observables: Jet shape, energy distribution, etc.

How about jets in HIC?

- Jets in vacuum is a *"fine tuned technology".* Once the hard parton is produced it fragments in vacuum without any further interaction in the final state as an independent object : energy and charge conservation, etc.
- With HIC, a new chapter in jet physics is being written: Jets do not propagate in vacuum but instead traverse a hot and colored (partonic) medium produced after the collision.

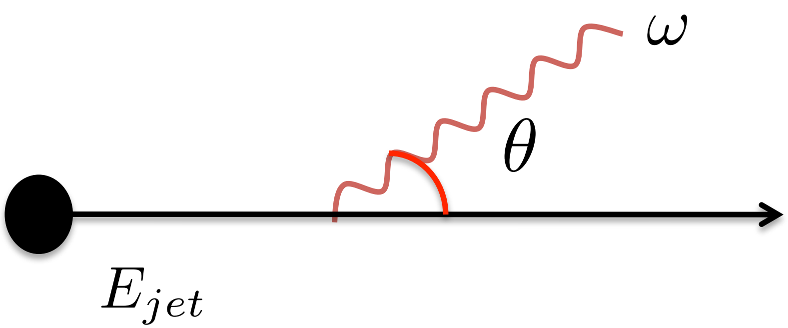
Jets in vacuum (basics)

Dynamics of an energetic parton produced in a hard collision

- QCD bremsstrahlung : an accelerated charge radiates soft gluons

Double logarithmic divergence (DLA): collinear and soft

$$\omega \ll E_{jet}$$



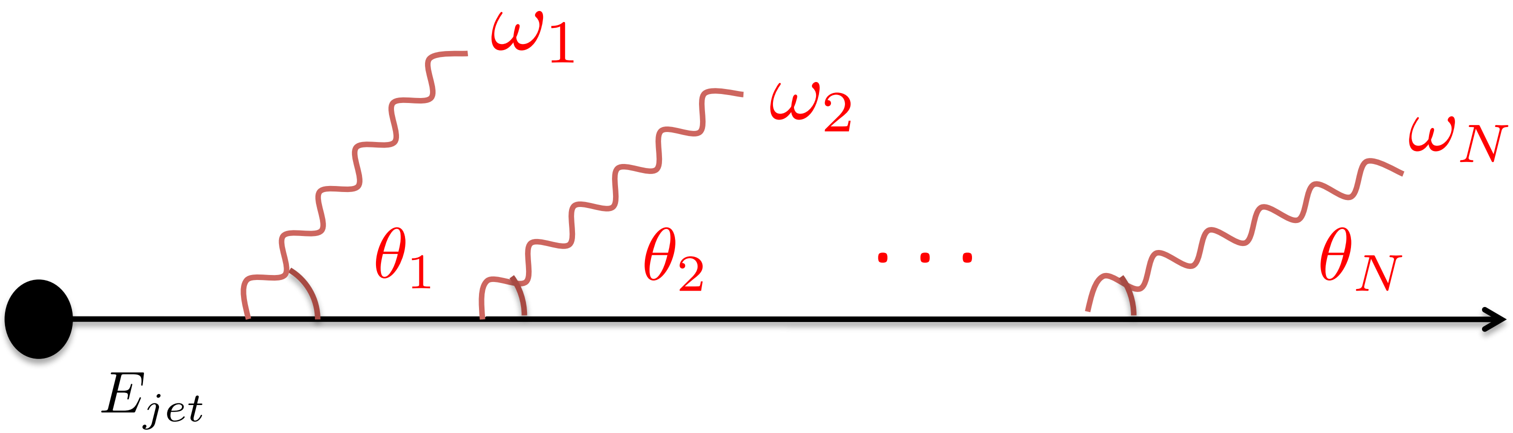
$$dN \propto \alpha_S \frac{d\omega}{\omega}\frac{d\theta}{\theta} \rightarrow \alpha_S \ln^2 E_{jet}$$

What happens when $\alpha_S \ln^2 E_{jet} \sim \mathcal{O}(1)$?

QCD coherence

- ✓ DLA: Successive gluon emissions are ordered in energies and angles

$$E_{jet} \gg \omega_1 \gg \ldots \gg \omega_N$$
$$\theta_1 \gg \theta_2 \gg \ldots \gg \theta_N$$

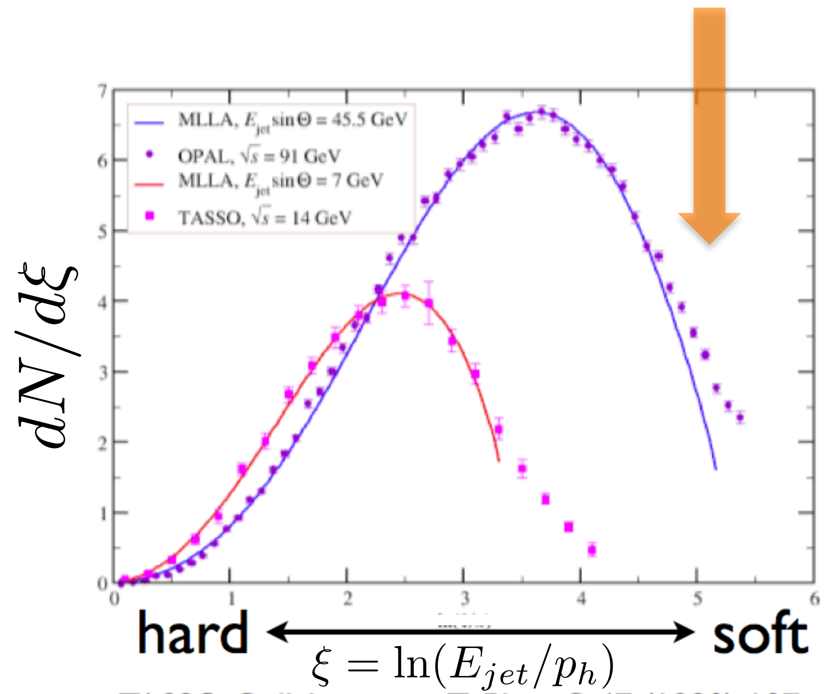


- ✓ MLLA: energy conservation, running of the coupling, etc.

A. Basseto, M. Ciafaloni, G. Marchesini, A. H. Mueller (1982) V. S. Fadin (1983)]

DLA: Let's have a closer look…

QCD coherence leads to the depletion of soft gluons!



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

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

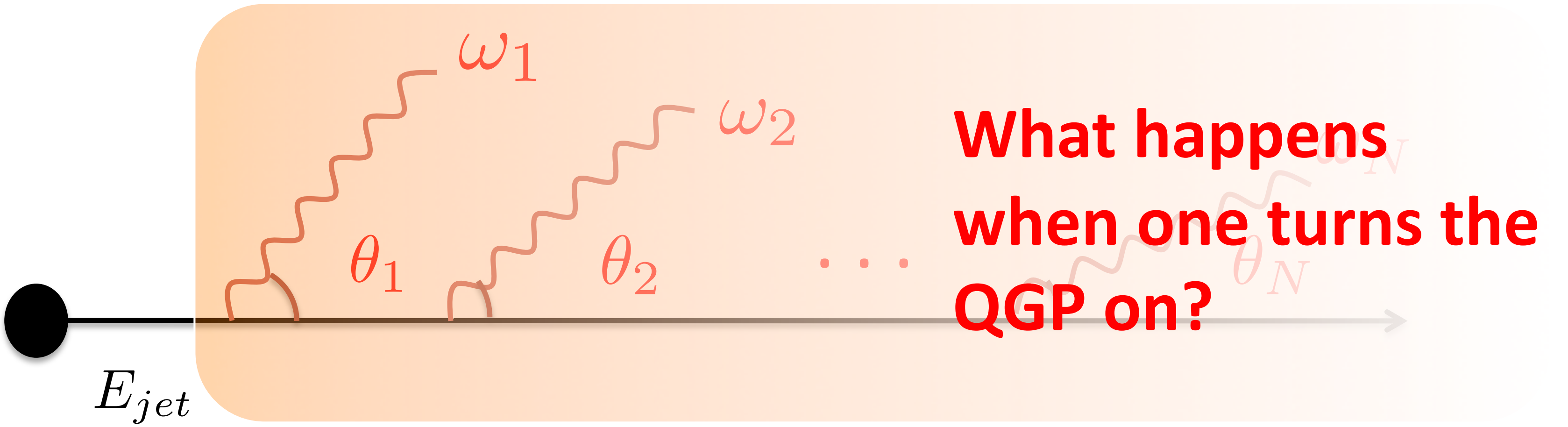
The "Hump-backed" plateau

QCD coherence

✓ Successive gluon emissions are ordered in energy and angle

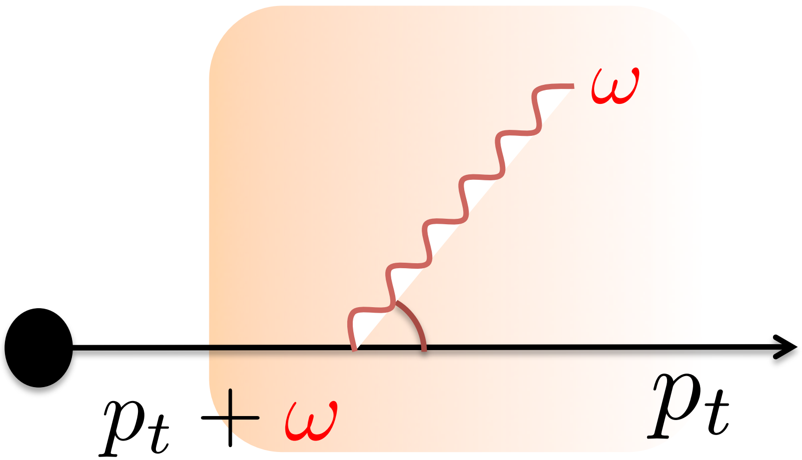
$$E_{jet} \gg \omega_1 \gg \ldots \gg \omega_N$$

$$\theta_1 \gg \theta_2 \gg \ldots \gg \theta_N$$



From Jet-Quenching to Jets?

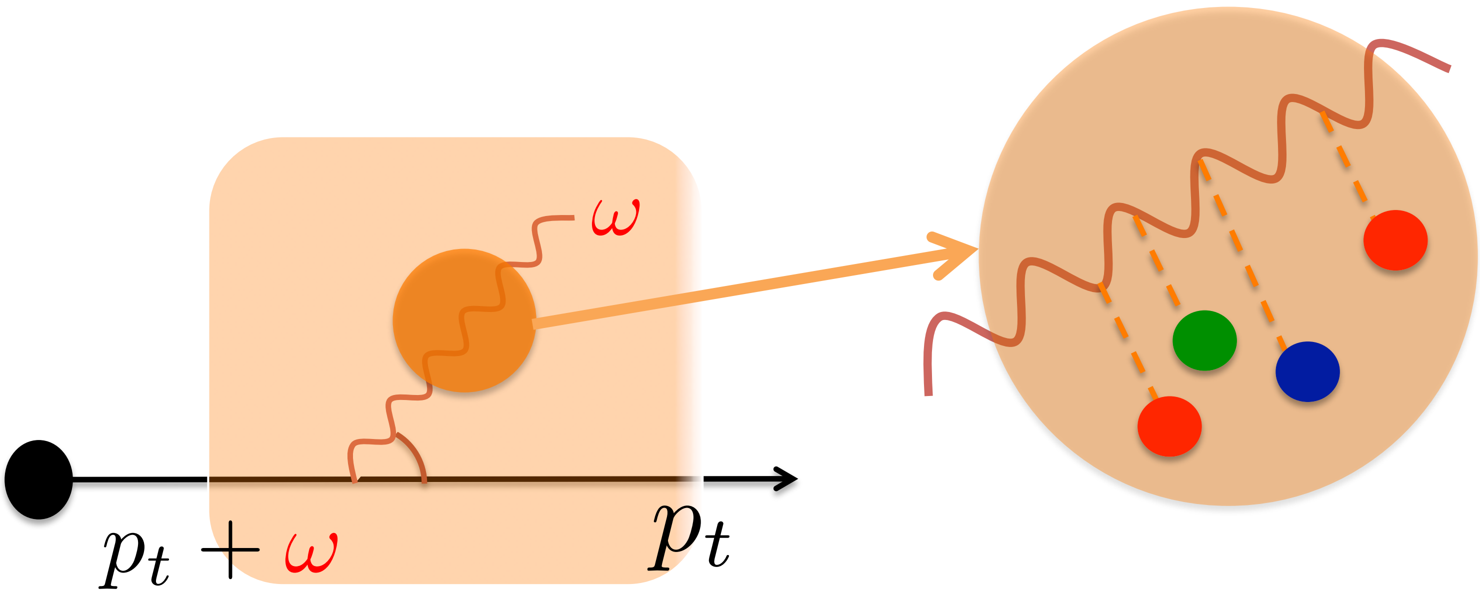
- Radiative parton energy loss: inclusive 1-gluon spectrum
- Remember! Need 2 gluon emissions to see QCD coherence (angular-ordering)



The hard quark loses energy by medium-induced gluon radiation

From Jet-Quenching to Jets?

- Radiative parton energy loss: 1-gluon inclusive spectrum.
- The emitted gluon undergoes multiple scattering in the medium (BDMPS-ZW-GLV picture (1997-2001)



Collinear and infrared finite spectrum!

QCD coherence in medium
A missing piece…

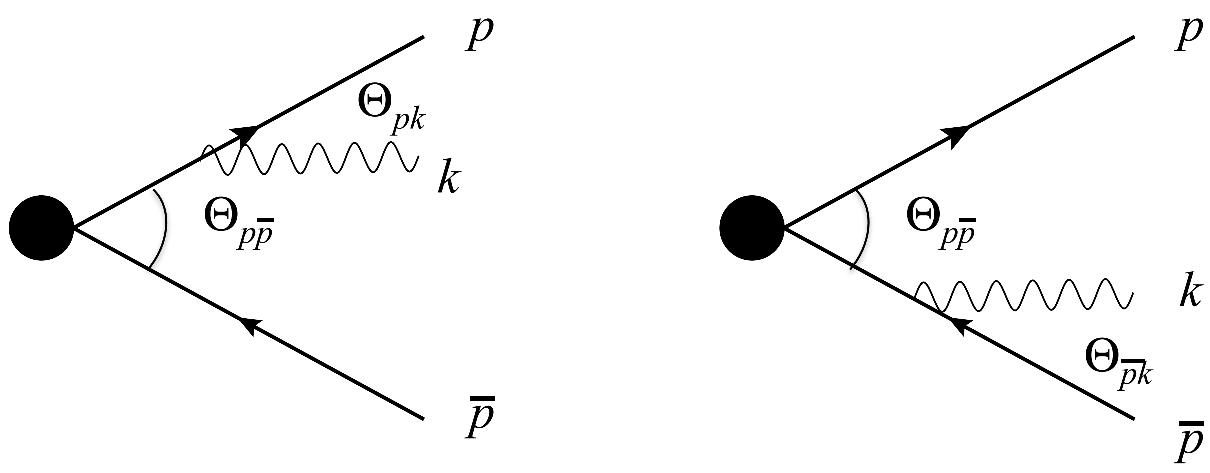
- On the market: in-medium jet calculus are performed by enhancing the vacuum emission by the BDMPS/GLV spectrum: No coherence!

[QPYTHIA, QHERWIG,JEWEL...]

- Are medium modified jets mainly determined by the BDMPS/GLV radiation pattern?

- We know from studying the gluon cascade in vacuum that the 1-gluon emission spectrum is not enough to build up the N-gluon cascade: Interferences, angular ordering, etc, play a role at higher orders

A simple exercise: QCD coherence from the quark-antiquark antenna



- Probabilistic interpretation $dN = dN_q + dN_{\bar{q}}$

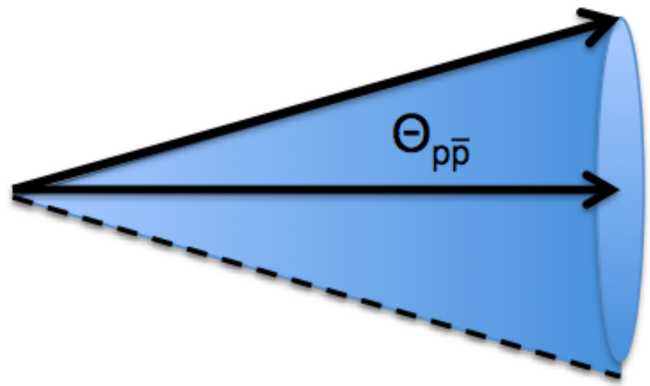
$$dN_q \propto \alpha_s \frac{d\omega}{\omega} \frac{d\theta_{pk}}{\theta_{pk}} \Theta(\theta_{p\bar{p}} - \theta_{pk}),$$

- Quantum interferences lead to a probabilistic picture!

A simple exercise: QCD coherence from the quark-antiquark antenna

- Radiation off the quark (dN_q)
- No radiation outside the cone
- Why?

gluons emitted at larger angles than the pair opening angle can not resolve the internal structure of the pair and thus are suppressed

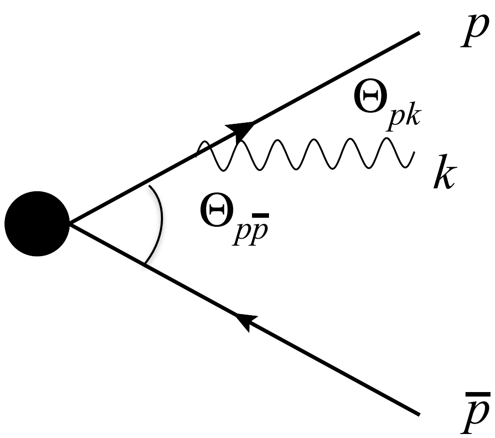


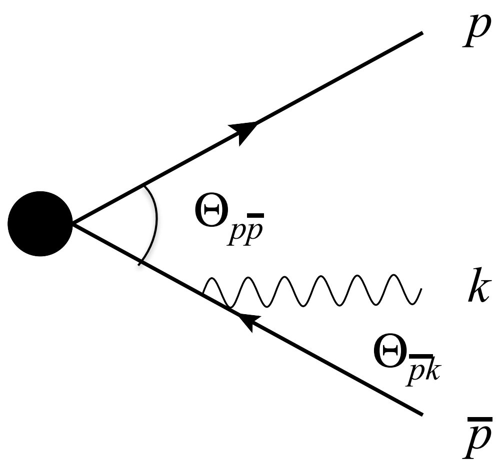
Angular ordering in vacuum

$$(t_{form} = \omega / k_\perp^2)$$

$$\lambda_\perp \sim \frac{1}{k_\perp} \sim t_{form}\theta > t_{form}\theta_{p\bar{p}} = r_\perp$$

A simple exercise: QCD coherence from the quark-antiquark antenna





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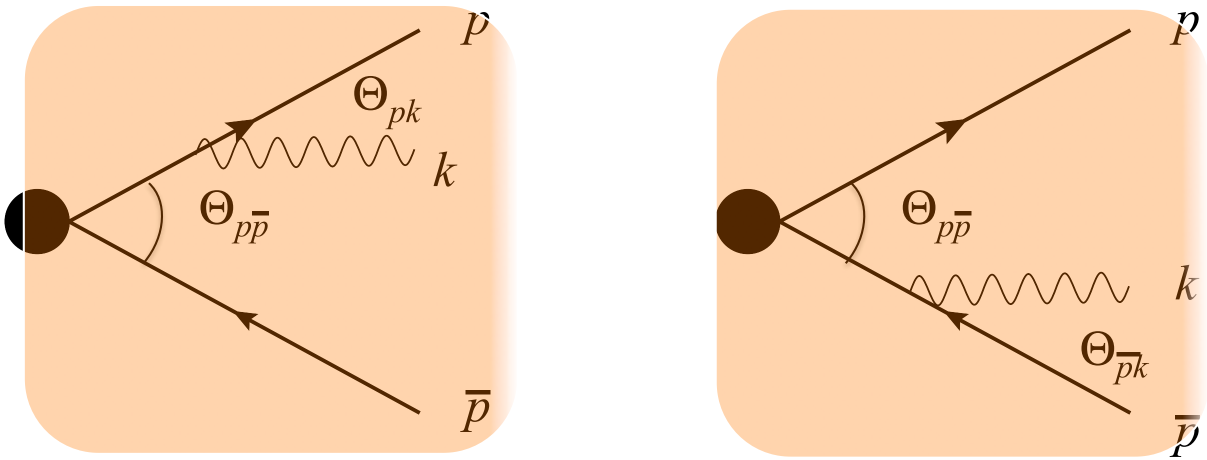

- Let’s switch on the medium

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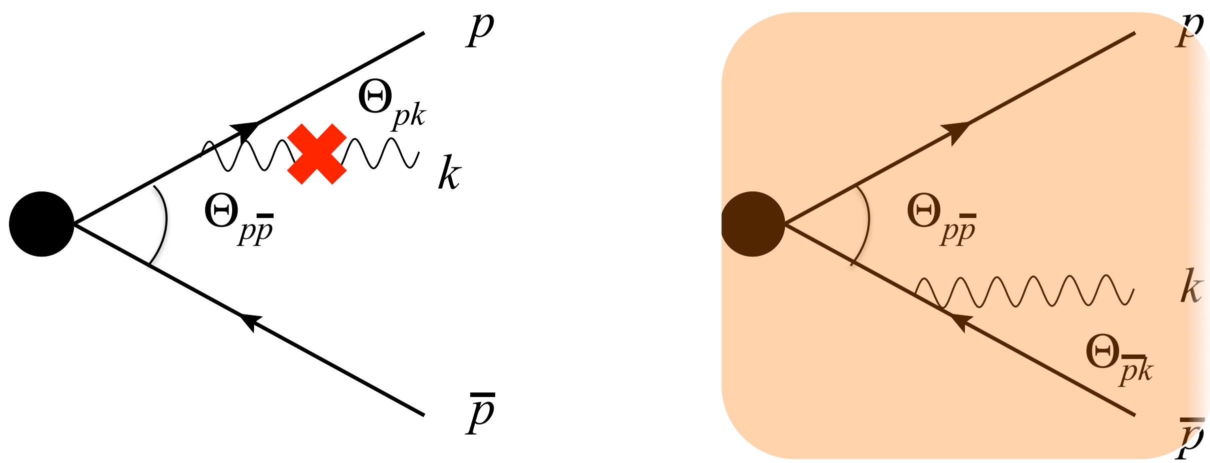

- Let's switch on the medium
- single interaction: one gluon exchange with the medium

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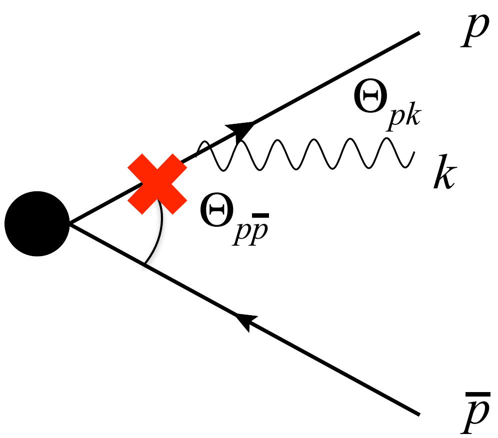

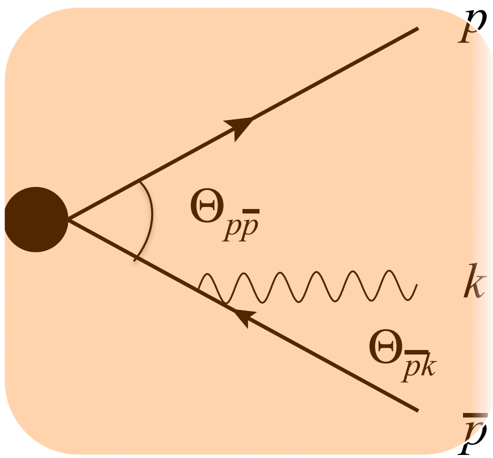

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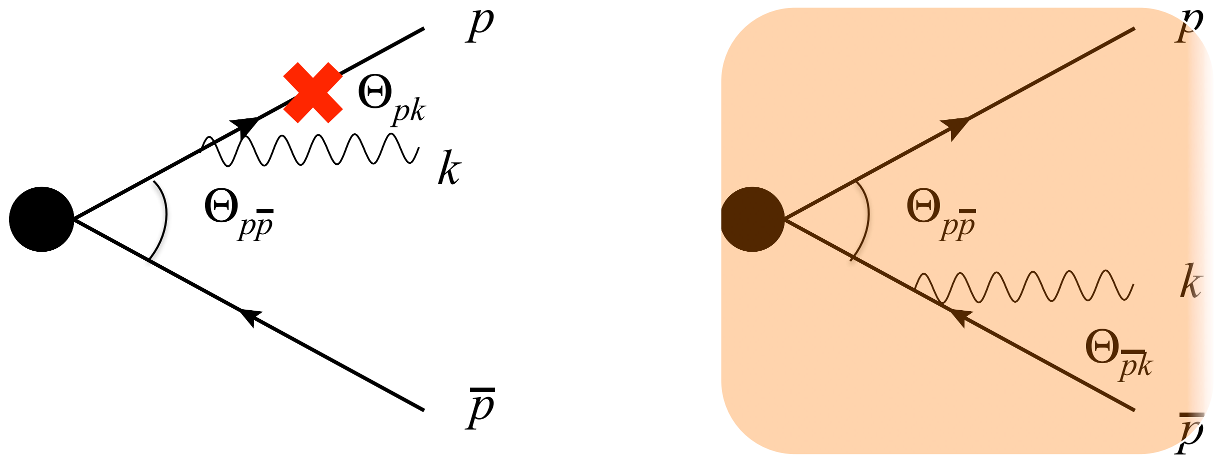

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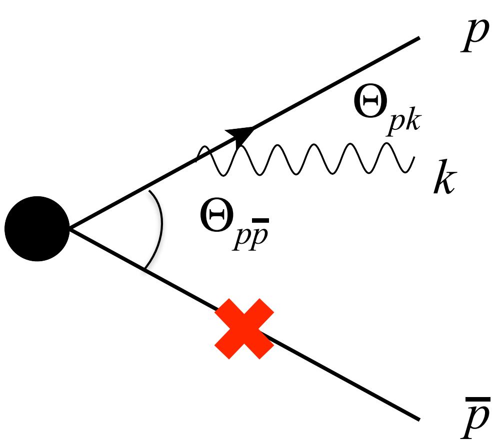

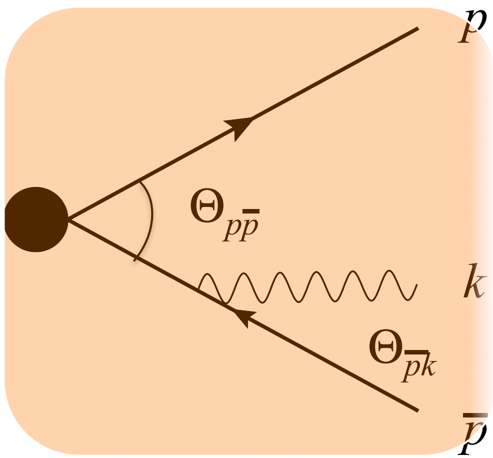

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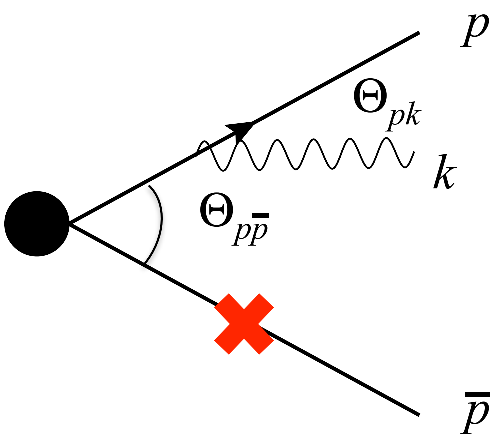

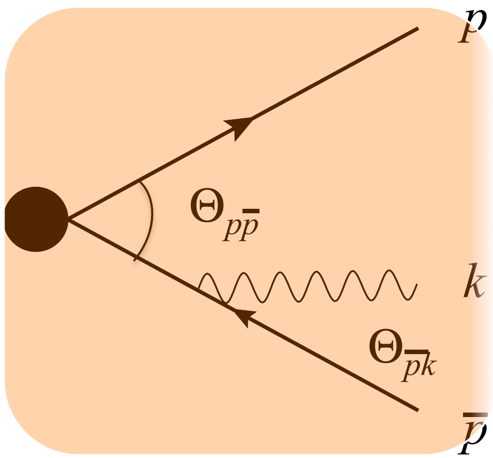

- Let's switch on the medium
- single interaction: one gluon exchange with the medium
- QGP: classical background field $A_0^\mu(\vec{x})$

Classical picture: Yang-Mills equations

- **Input:** the classical current $J_{pair} = J_q + J_{\bar{q}}$

$$J_q^\mu = g\frac{p^\mu}{E}\ \delta^{(3)}(\vec{x} - \frac{\vec{p}}{E}t)\ \Theta(t)\ \mathcal{C}^a t^a$$

- **limit:** $E \to \infty,\quad \theta_{p\bar{p}} \to 0$ **, gauge:** $A^+ = 0$
- The gluon radiation amplitude off the quark

$$\mathcal{M}^{i,a}_{1(q)} = ig^2 f^{abc}\mathcal{C}^c \int \frac{d^2q_\perp}{(2\pi)^2}\int_{t_1}^{t_2} dt\mathcal{A}^b_0(t,\boldsymbol{q}_\perp)\left[\frac{\boldsymbol{\nu}^i_\perp}{p\cdot v}\left(1 - e^{i\frac{p\cdot v}{E}t}\right) + \frac{\boldsymbol{\kappa}^i_\perp}{p\cdot k}e^{i\frac{p\cdot v}{E}t}\right]$$

$q_\perp$ Is the quark-medium momentum exchange

- where

$$\boldsymbol{\nu}_\perp = \frac{p^+}{k^+}(\boldsymbol{k} - \boldsymbol{q})_\perp - \boldsymbol{p}_\perp$$

$$v \equiv (k^+, \frac{(\boldsymbol{k} - \boldsymbol{q})^2_\perp}{2k^+}, (k-q)^i)$$

$$\boldsymbol{\kappa}_\perp = \frac{p^+}{k^+}\boldsymbol{k}_\perp - \boldsymbol{p}_\perp$$

Classical picture: Yang-Mills equations

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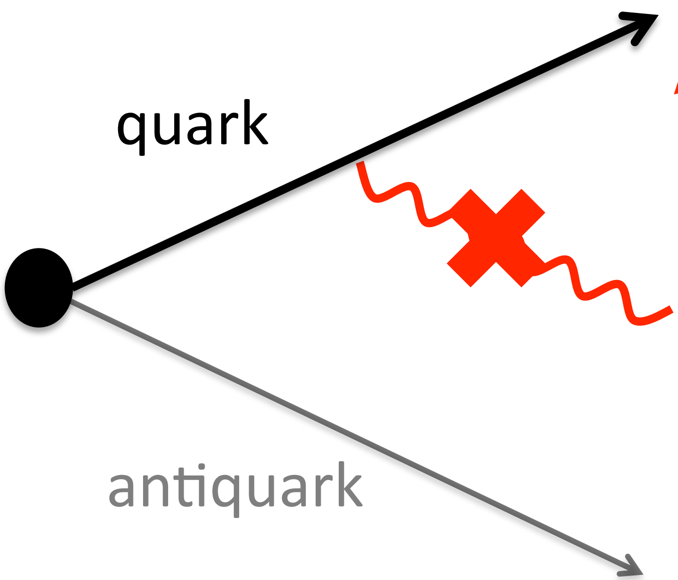
gluon interaction with the medium

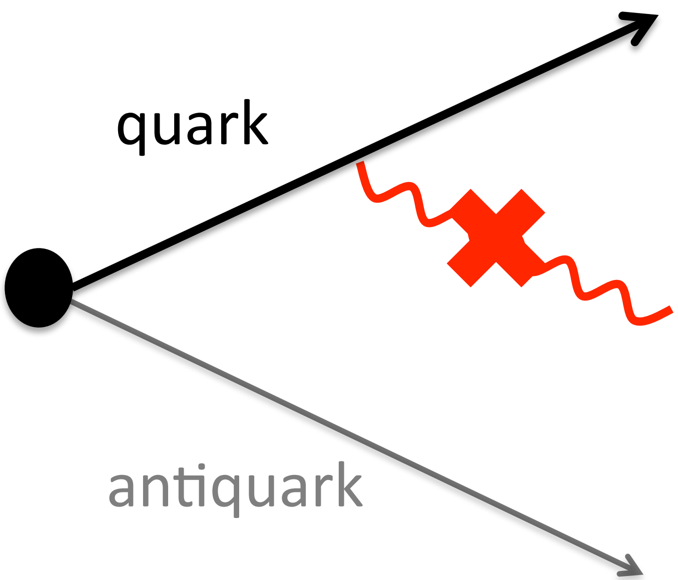


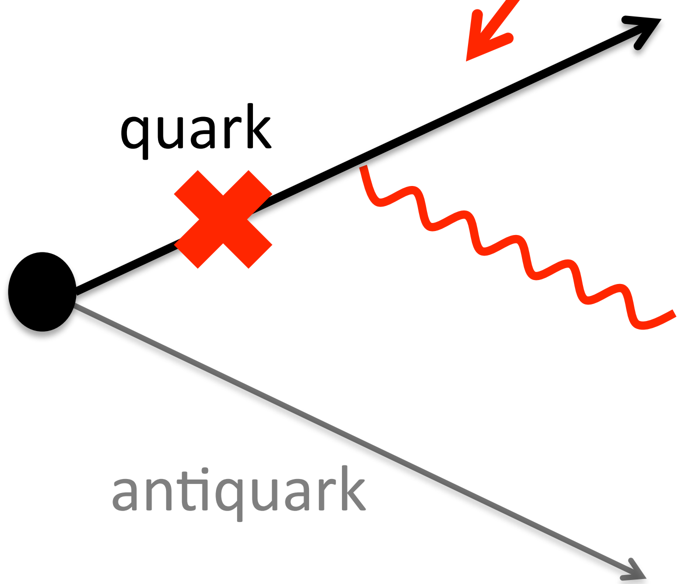
Classical picture: Yang-Mills equations

- The gluon radiation amplitude off the quark

$$\mathcal{M}^{i,a}_{1(q)} = ig^2 f^{abc}\mathcal{C}^c \int \frac{d^2 q_\perp}{(2\pi)^2} \int_{t_1}^{t_2} dt \mathcal{A}_0^b(t, \boldsymbol{q}_\perp) \left[\frac{\boldsymbol{\nu}^i_\perp}{p\cdot v}\left(1 - e^{i\frac{p\cdot v}{E}t}\right) + \frac{\boldsymbol{\kappa}^i_\perp}{p\cdot k} e^{i\frac{p\cdot v}{E}t} \right]$$

gluon bremsstrahlung





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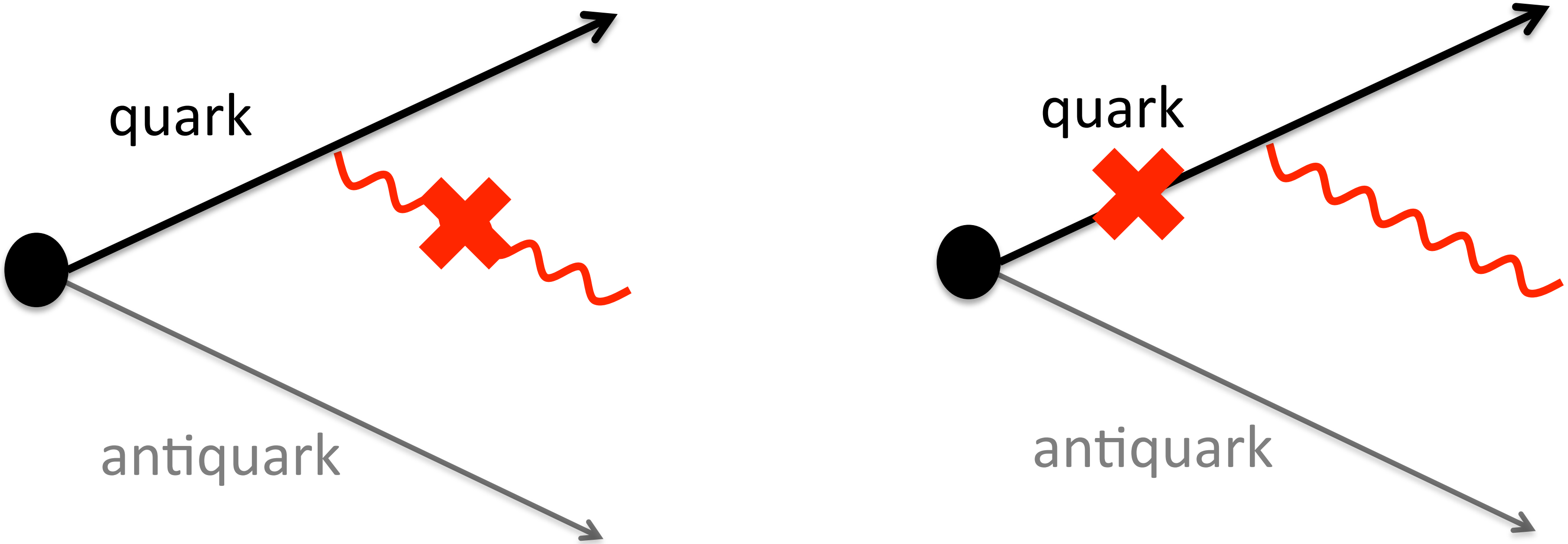
Similarly for the antiquark



Induced gluon radiation spectrum

- Squaring the amplitude

$$|\mathcal{M}|^2 \equiv |\mathcal{M}_q + \mathcal{M}_{\bar{q}}|^2 = |\mathcal{M}_q|^2 + |\mathcal{M}_{\bar{q}}|^2 + 2Re\mathcal{M}_q\mathcal{M}_{\bar{q}}^*$$

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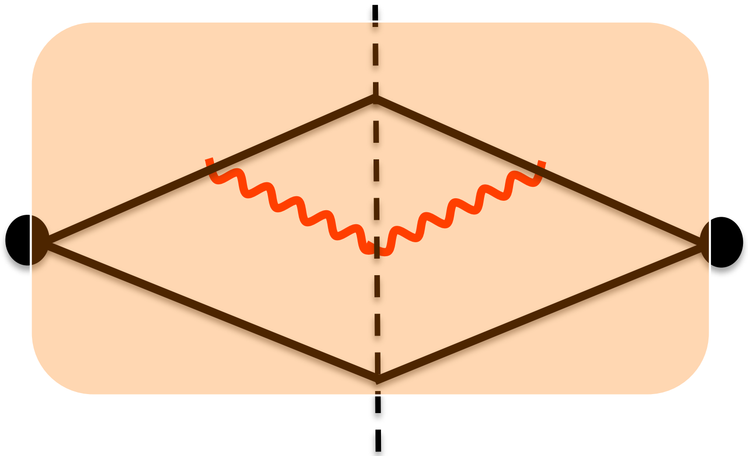
BDMPS/GLV (1-scattering)



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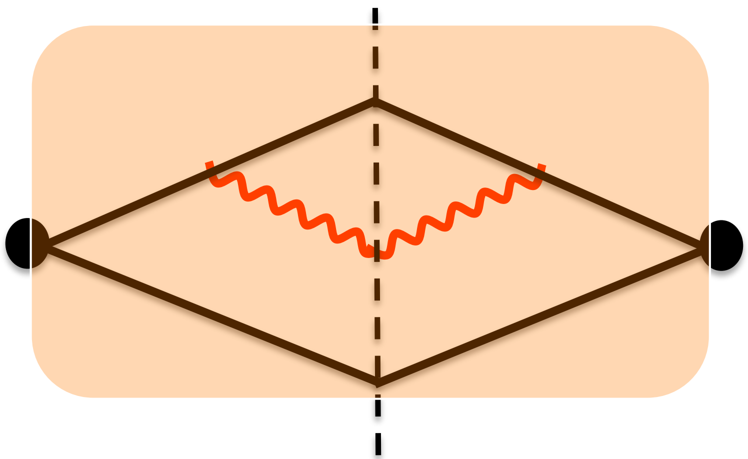
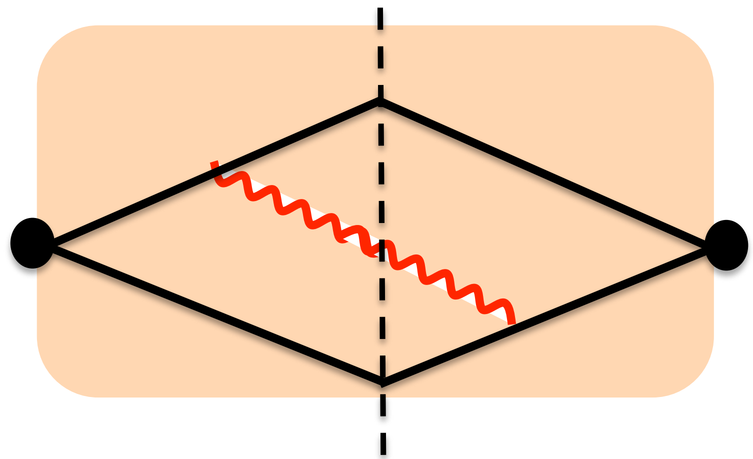


Interference term



The spectrum

$$(2\pi)^2 E\frac{dN}{d^3k} = 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2}\int_0^L dt\; n(t)\; \mathcal{V}(\boldsymbol{q}_\perp)$$

$$\left[\left(\frac{\boldsymbol{\nu}_\perp^2}{(p\cdot v)^2} - \frac{\boldsymbol{\nu}_\perp\cdot\boldsymbol{\kappa}_\perp}{(p\cdot v)(p\cdot k)}\right)(1-\cos\Omega_1 t)\right.$$

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

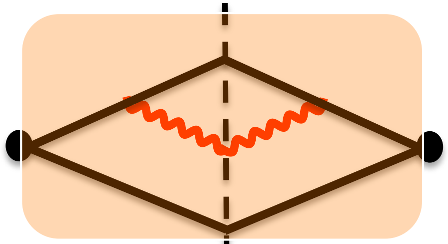
$$-\frac{\boldsymbol{\nu}_\perp\cdot\bar{\boldsymbol{\nu}}_\perp}{(p\cdot v)(\bar{p}\cdot v)}(1+\cos\Omega_{12}t-\cos\Omega_1 t-\cos\Omega_2 t)$$

$$-\frac{\boldsymbol{\nu}_\perp\cdot\bar{\boldsymbol{\kappa}}_\perp}{(p\cdot v)(\bar{p}\cdot k)}(\cos\Omega_2 t-\cos\Omega_{12}t) - \frac{\bar{\boldsymbol{\nu}}_\perp\cdot\boldsymbol{\kappa}_\perp}{(\bar{p}\cdot v)(p\cdot k)}(\cos\Omega_1 t-\cos\Omega_{12}t)$$

$$\left.-\frac{\boldsymbol{\kappa}_\perp\cdot\bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)}(\cos\Omega_{12}t-1)\right]$$

where

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



The spectrum

GLV (quark)

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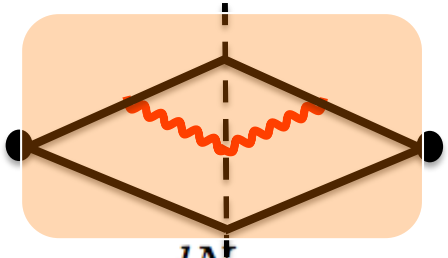

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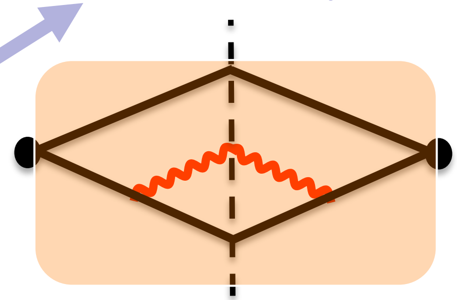
GLV (quark)

GLV (antiquark)



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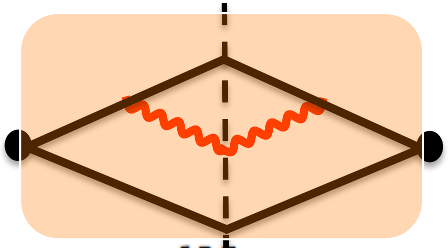
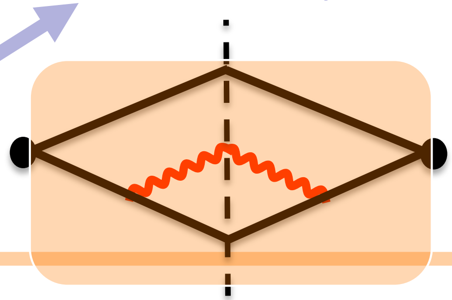
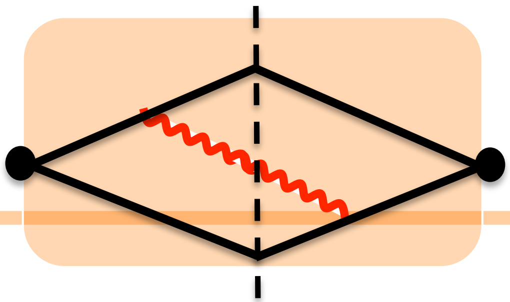


$$
\begin{aligned}
(2\pi)^2 E\frac{dN}{d^3k} = \; & 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2} \int_0^L dt\; n(t)\; \mathcal{V}(\boldsymbol{q}_\perp) \\
& \Bigg[\left(\frac{\boldsymbol{\nu}_\perp^2}{(p\cdot v)^2} - \frac{\boldsymbol{\nu}_\perp \cdot \boldsymbol{\kappa}_\perp}{(p\cdot v)(p\cdot k)} \right) (1-\cos\Omega_1 t) \\
& + \left(\frac{\bar{\boldsymbol{\nu}}_\perp^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\nu}}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right) (1-\cos\Omega_2 t) \\
& - \frac{\boldsymbol{\nu}_\perp \cdot \bar{\boldsymbol{\nu}}_\perp}{(p\cdot v)(\bar{p}\cdot v)} (1+\cos\Omega_{12} t - \cos\Omega_1 t - \cos\Omega_2 t) \\
& - \frac{\boldsymbol{\nu}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot v)(\bar{p}\cdot k)} (\cos\Omega_2 t - \cos\Omega_{12} t) - \frac{\bar{\boldsymbol{\nu}}_\perp \cdot \boldsymbol{\kappa}_\perp}{(\bar{p}\cdot v)(p\cdot k)} (\cos\Omega_1 t - \cos\Omega_{12} t) \\
& - \frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)} (\cos\Omega_{12} t - 1) \Bigg]
\end{aligned}
$$

GLV (quark)

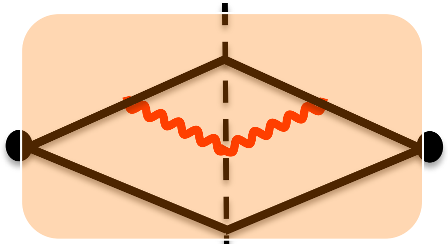
GLV (antiquark)





Interferences

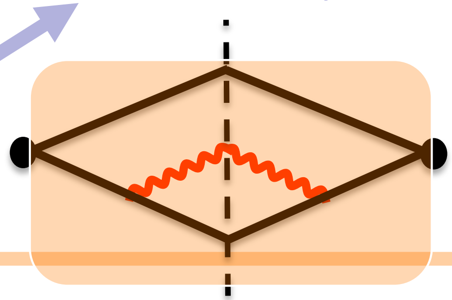
The spectrum

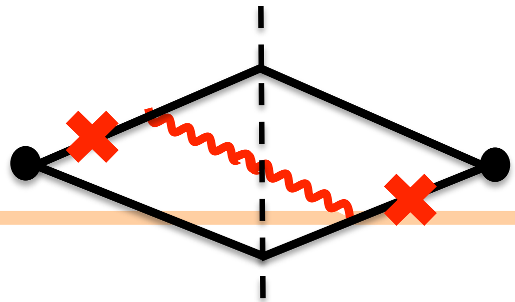


$$
\begin{aligned}
(2\pi)^2 E\frac{dN}{d^3k} = \; & 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}_\perp}{(2\pi)^2} \int_0^L dt\; n(t)\; \mathcal{V}(\boldsymbol{q}_\perp) \\
& \Bigg[\left(\frac{\boldsymbol{\nu}_\perp^2}{(p\cdot v)^2} - \frac{\boldsymbol{\nu}_\perp \cdot \boldsymbol{\kappa}_\perp}{(p\cdot v)(p\cdot k)} \right) (1-\cos\Omega_1 t) \\
& + \left(\frac{\bar{\boldsymbol{\nu}}_\perp^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\nu}}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right) (1-\cos\Omega_2 t) \\
& - \frac{\boldsymbol{\nu}_\perp \cdot \bar{\boldsymbol{\nu}}_\perp}{(p\cdot v)(\bar{p}\cdot v)} (1+\cos\Omega_{12} t - \cos\Omega_1 t - \cos\Omega_2 t) \\
& - \frac{\boldsymbol{\nu}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot v)(\bar{p}\cdot k)} (\cos\Omega_2 t - \cos\Omega_{12} t) - \frac{\bar{\boldsymbol{\nu}}_\perp \cdot \boldsymbol{\kappa}_\perp}{(\bar{p}\cdot v)(p\cdot k)} (\cos\Omega_1 t - \cos\Omega_{12} t) \\
& - \frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)} (\cos\Omega_{12} t - 1) \Bigg]
\end{aligned}
$$

GLV (quark)

GLV (antiquark)





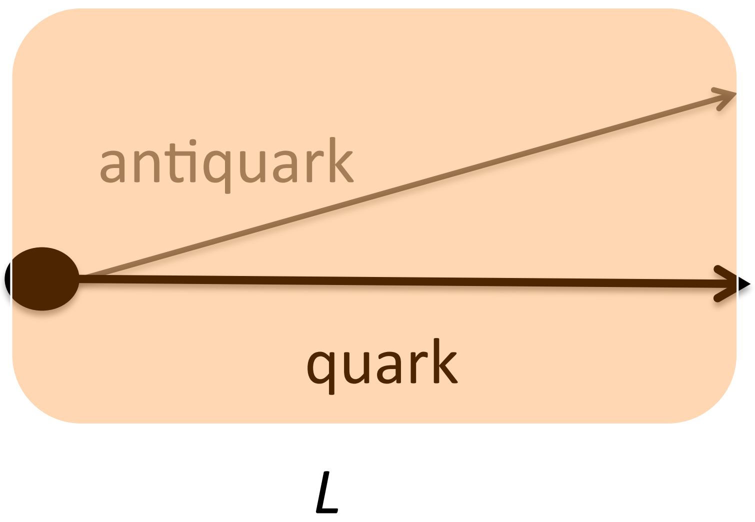
Interferences

Bremsstrahlung interference
(soft divergence)

The soft limit and anti-angular ordering

ω →0, the quark on the z axis

$$(2\pi)^2\omega\frac{dN^{\rm soft}}{d^3k} \propto \frac{\boldsymbol{\kappa}_\perp\cdot\bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)}\int_0^L dt\int\frac{d^2q_\perp}{(2\pi)^2}\,V(\boldsymbol{q}_\perp)(1-\cos\frac{\bar{\boldsymbol{p}}_\perp\cdot\boldsymbol{q}_\perp}{\bar{E}}t)$$



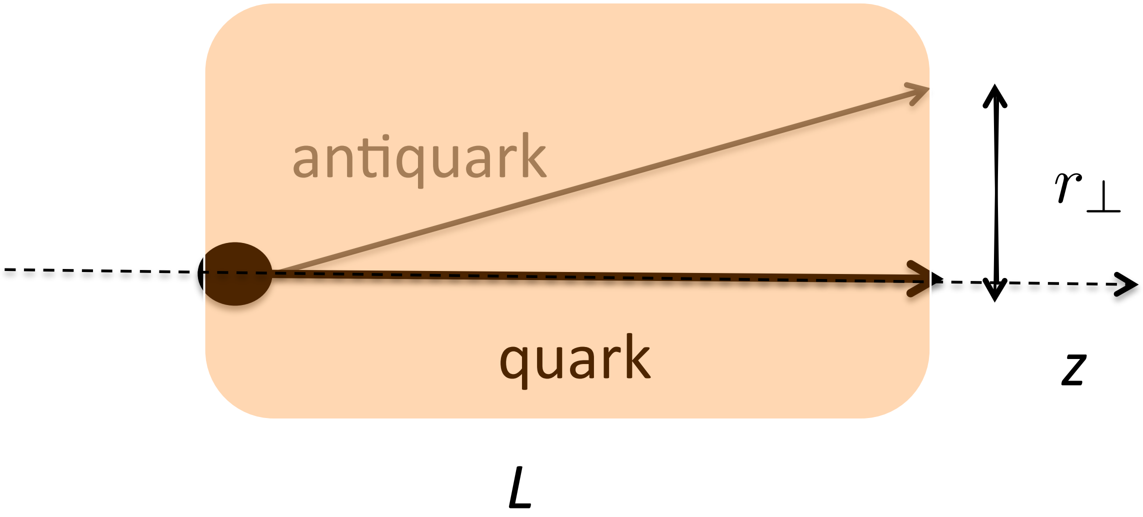
The soft limit and anti-angular ordering

$\omega \to 0$, the quark on the z axis

$$(2\pi)^2 \omega \frac{dN^{\text{soft}}}{d^3k} \propto \frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)} \int_0^L dt \int \frac{d^2 q_\perp}{(2\pi)^2} V(\boldsymbol{q}_\perp)\left(1-\cos \frac{\bar{\boldsymbol{p}}_\perp \cdot \boldsymbol{q}_\perp}{\bar{E}} t\right)$$

$$A_{\text{med}} \propto \hat{q} L\, r_\perp^2 \ln \frac{1}{r_\perp m_D}$$

→ Dipole scattering amplitude



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

The soft limit and anti-angular ordering

$\omega \to 0$, the quark on the z axis

$$(2\pi)^2 \omega \frac{dN^{\text{soft}}}{d^3k} \propto \frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)} \int_0^L dt \int \frac{d^2 q_\perp}{(2\pi)^2} V(\boldsymbol{q}_\perp)(1 - \cos \frac{\bar{\boldsymbol{p}}_\perp \cdot \boldsymbol{q}_\perp}{\bar{E}} t)$$

- Integrating over the azimuth

$$\frac{dN}{d\omega d\theta} \propto \frac{1}{\omega} \frac{\sin\theta}{1-\cos\theta} \Theta(\cos\theta_{p\bar{p}} - \cos\theta) A_{\text{med}}(\theta_{p\bar{p}})$$

The soft limit and anti-angular ordering

$\omega \to 0$, the quark on the z axis

$$(2\pi)^2 \omega \frac{dN^{\rm soft}}{d^3k} \propto \frac{\boldsymbol{\kappa}_\perp \cdot \bar{\boldsymbol{\kappa}}_\perp}{(p\cdot k)(\bar{p}\cdot k)} \int_0^L dt \int \frac{d^2 q_\perp}{(2\pi)^2} V(\boldsymbol{q}_\perp)(1 - \cos \frac{\bar{\boldsymbol{p}}_\perp \cdot \boldsymbol{q}_\perp}{\bar{E}} t)$$

- Integrating over the azimuth

$$\frac{dN}{d\omega d\theta} \propto \frac{1}{\omega} \frac{\sin\theta}{1-\cos\theta} \Theta(\cos\theta_{p\bar{p}} - \cos\theta) A_{\rm med}(\theta_{p\bar{p}})$$

→ No emissions inside the pair!

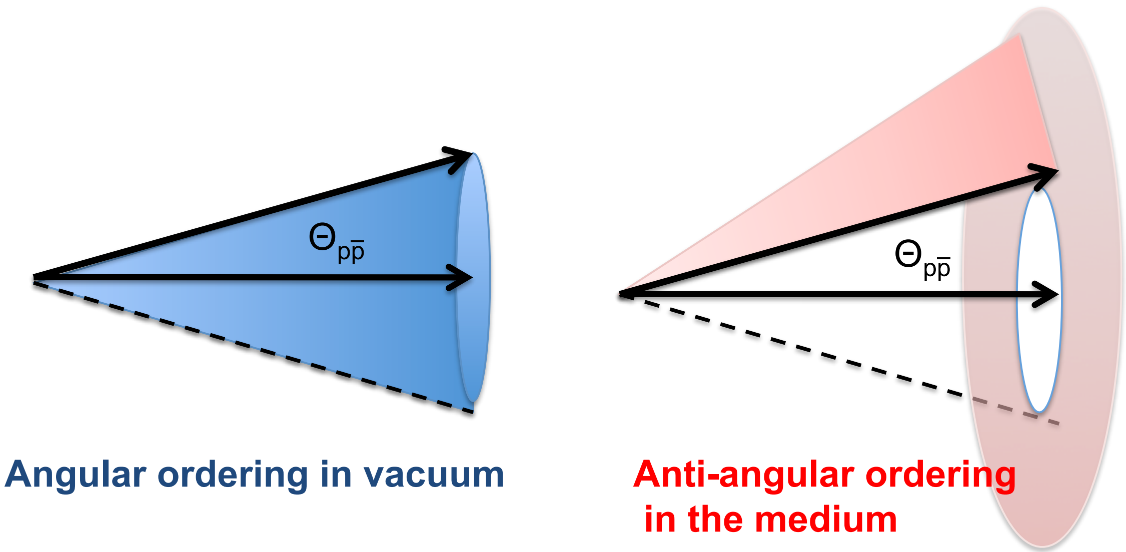
The soft limit and anti-angular ordering

- Soft divergence and anti-angular ordering
- vacuum+medium: (ω → 0)

$$dN_q = \frac{1}{2\pi}\alpha_s C_F \frac{d\omega}{\omega}\frac{\sin\theta d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{p\bar{p}}) + A_{\rm med}(\theta_{p\bar{p}})\Theta(\cos\theta_{p\bar{p}} - \cos\theta)\right]$$

Vacuum emission:
inside the cone

Medium
emissions:
outside the cone

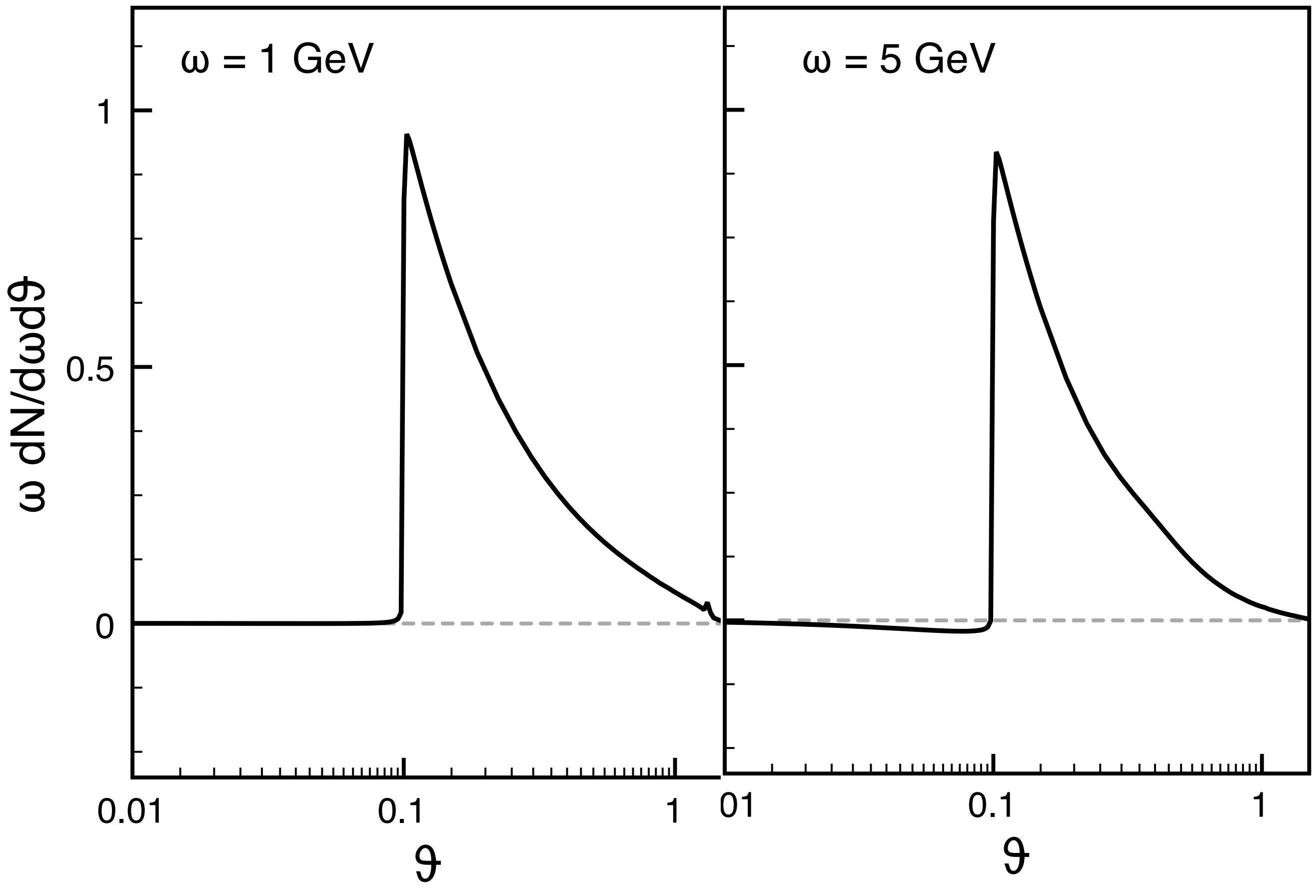


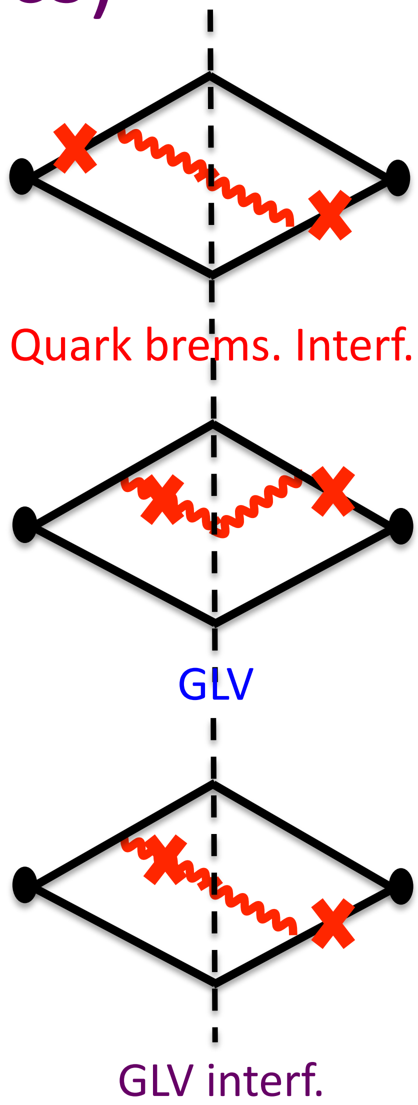
Angular ordering in vacuum

Anti-angular ordering in the medium

Full spectrum (some numerics)

L=20 GeV^{-1}= 4 fm





Toward medium modified jets?

✓ Coherence (neglected so far) plays an important role in medium-jet modification

✓ Geometrical separation between vacuum radiation and medium induced one. Total decoherence in opaque media.

✓ Logarithmic soft divergence: resummation of LL – QCD evolution eqs. in medium