Coherence and broadening in medium induced gluon radiation

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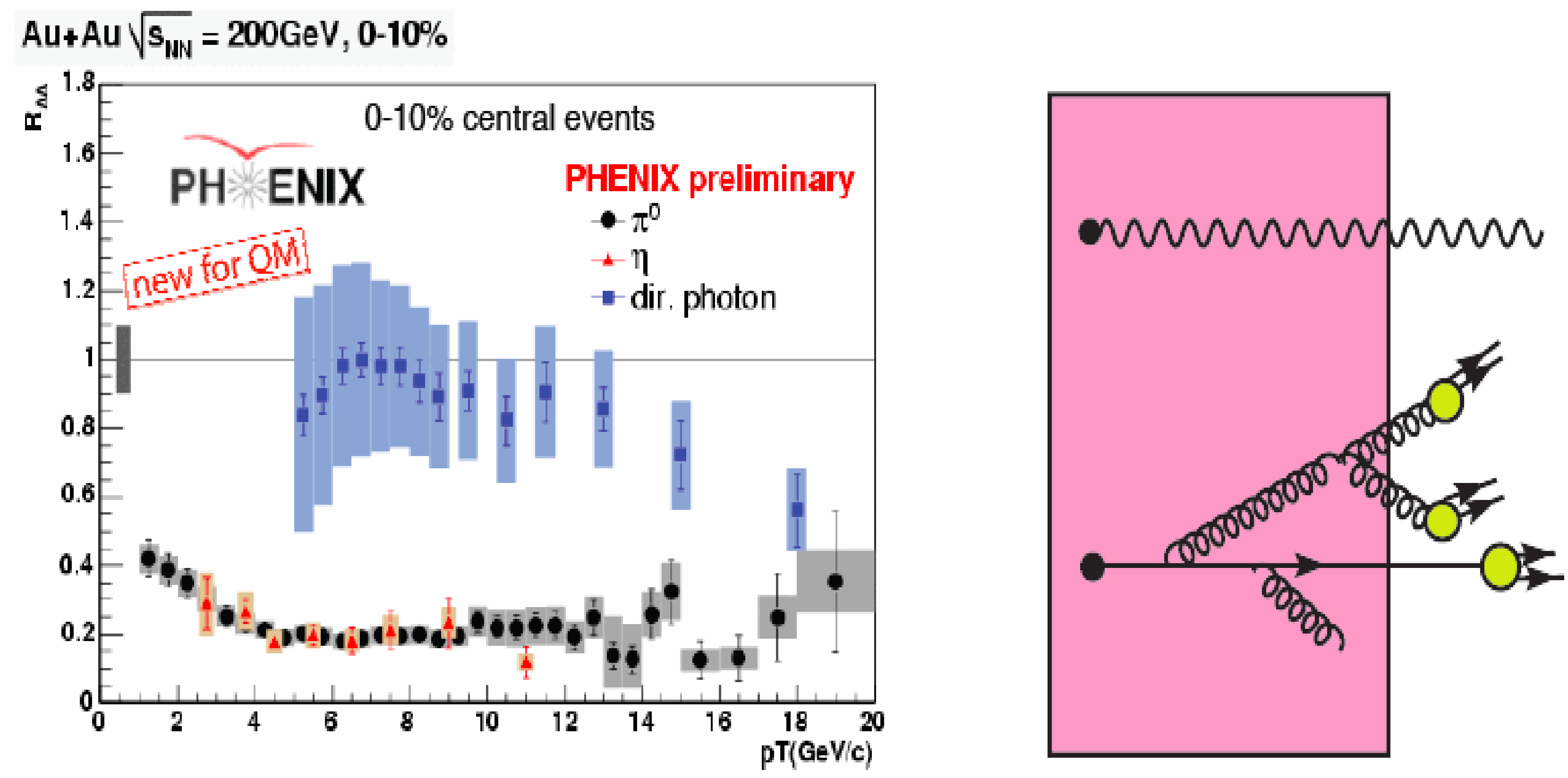
Work in progress

High P_T Physics at LHC

March 26-27 2012, Hanau, Germany

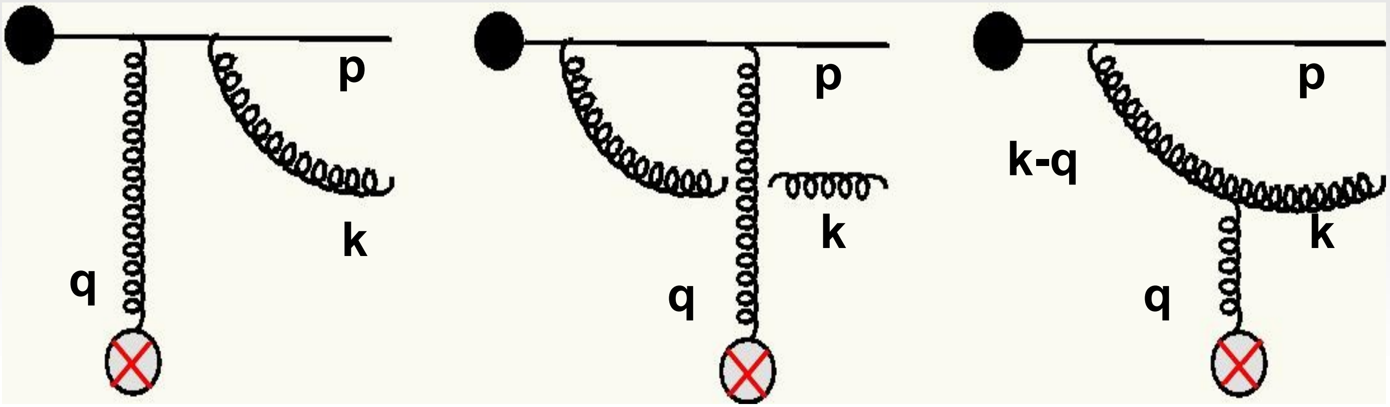
Jet quenching in Heavy Ion Collisions



- Strong suppression of leading particle spectra
- Suppression has been interpreted as a probe of the existence of a deconfined QCD medium !!!

Radiative energy loss in QCD medium: dilute regime case

Opacity expansion (Wiedemann, Gyulassy, Levai, Vitev)



- **Expansion in terms of the density of scattering centers**

$$\Rightarrow (L/\lambda)^N$$

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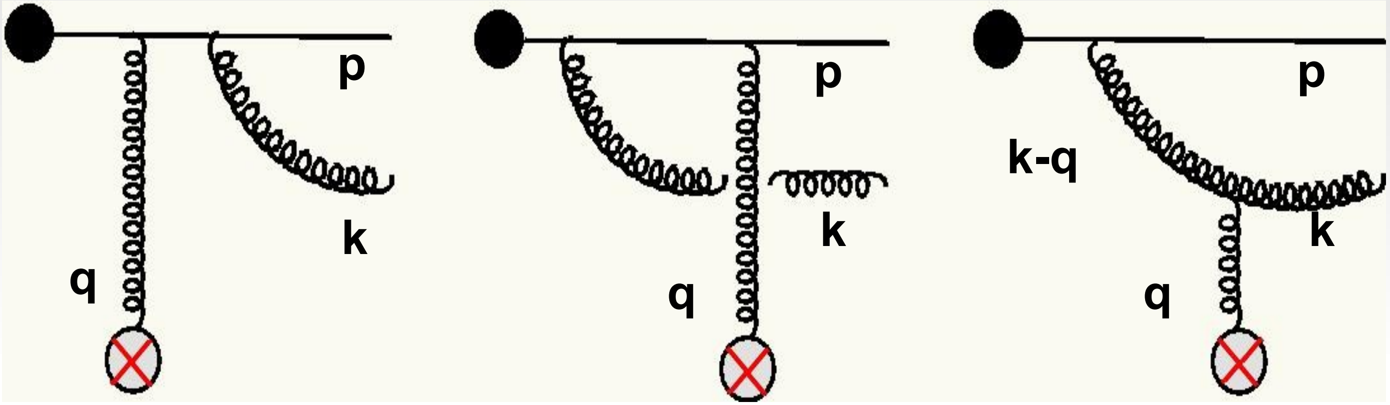

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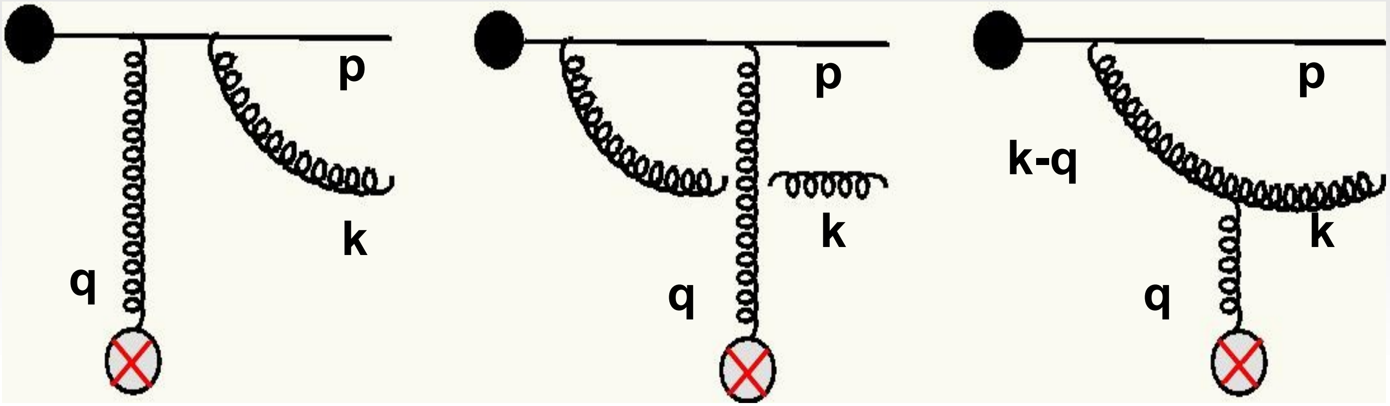

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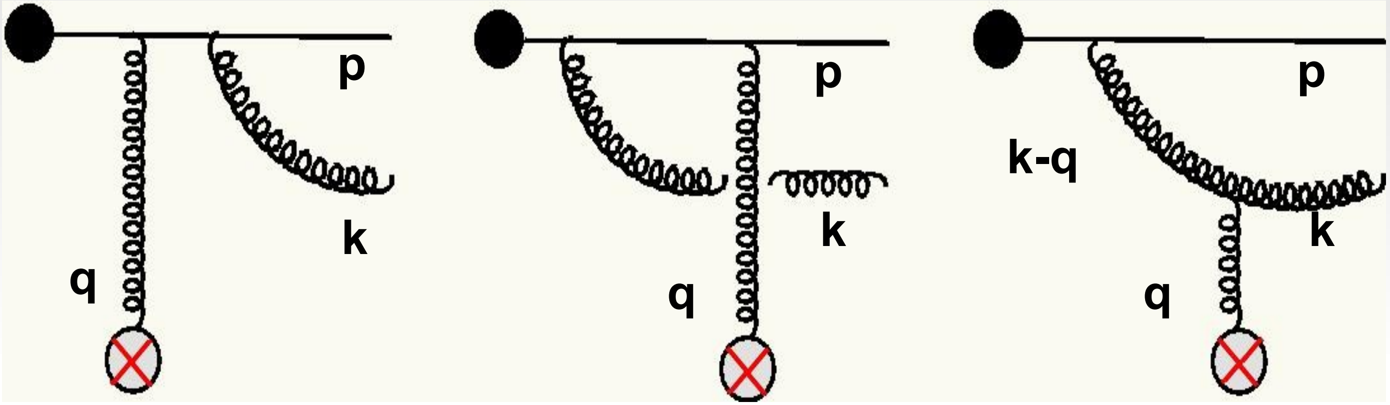

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- Spectrum off a parton created at finite time.
- No longitudinal correlations between scattering centers.
- Eikonal Approximation

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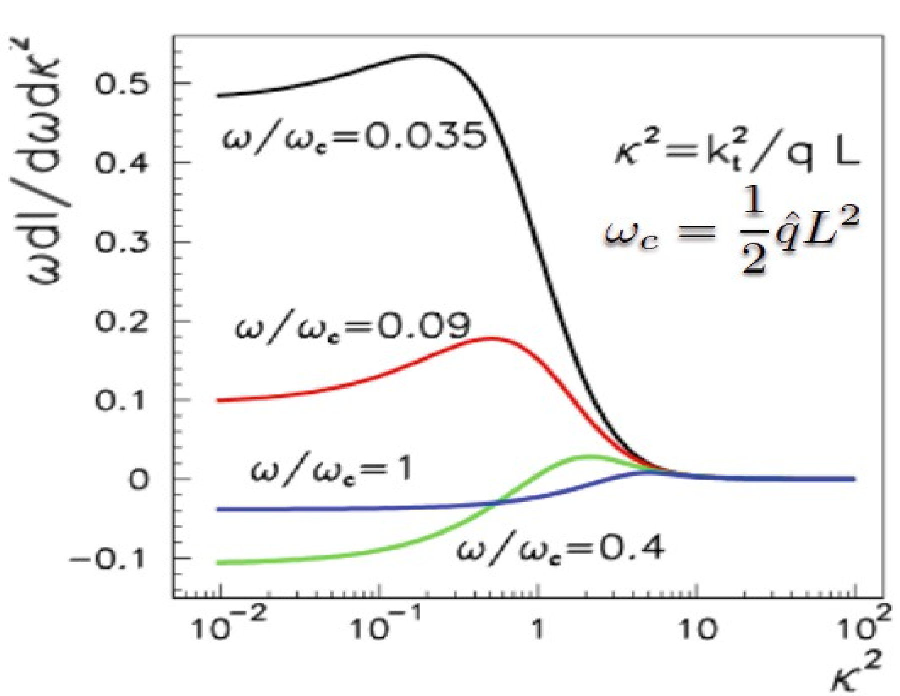
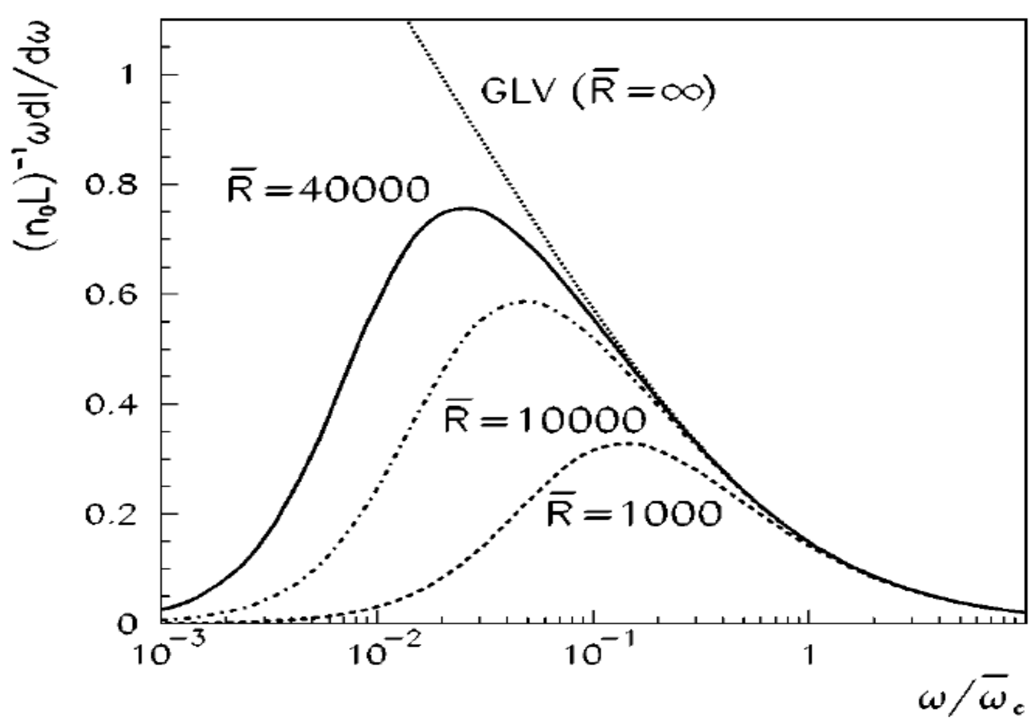
N= 1 opacity expansion: GLV spectrum

$$\omega \frac{dN_q^{\text{indep}}}{d\omega\, d^2\boldsymbol{k}} = \frac{8\,\alpha_s C_F\,\hat{q}}{\pi} \int_{\mathcal{V}(\boldsymbol{q})} \int_0^{L^+} dx^+ \left(1 - \cos\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2k^+} x^+\right) \frac{\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2}$$





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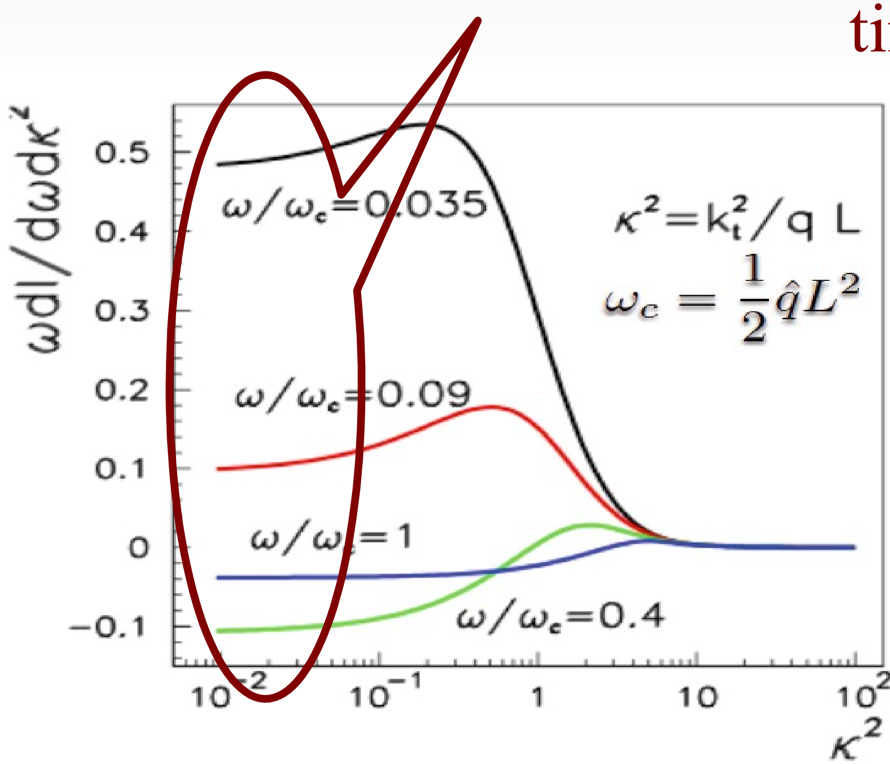
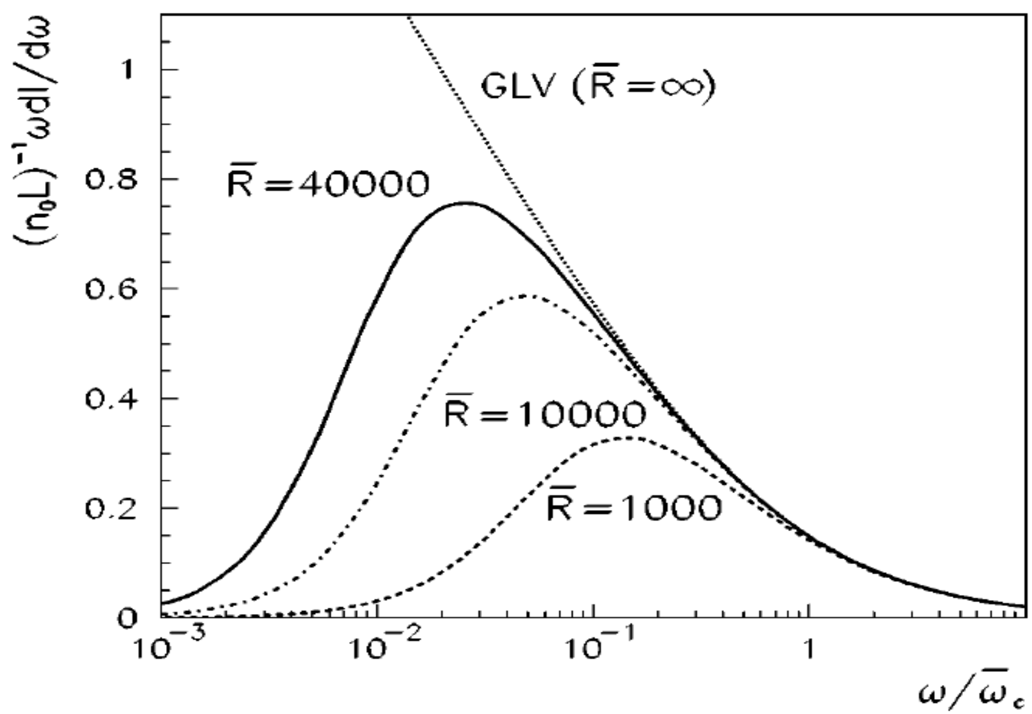
LPM suppression: Partons with large formation times are suppressed





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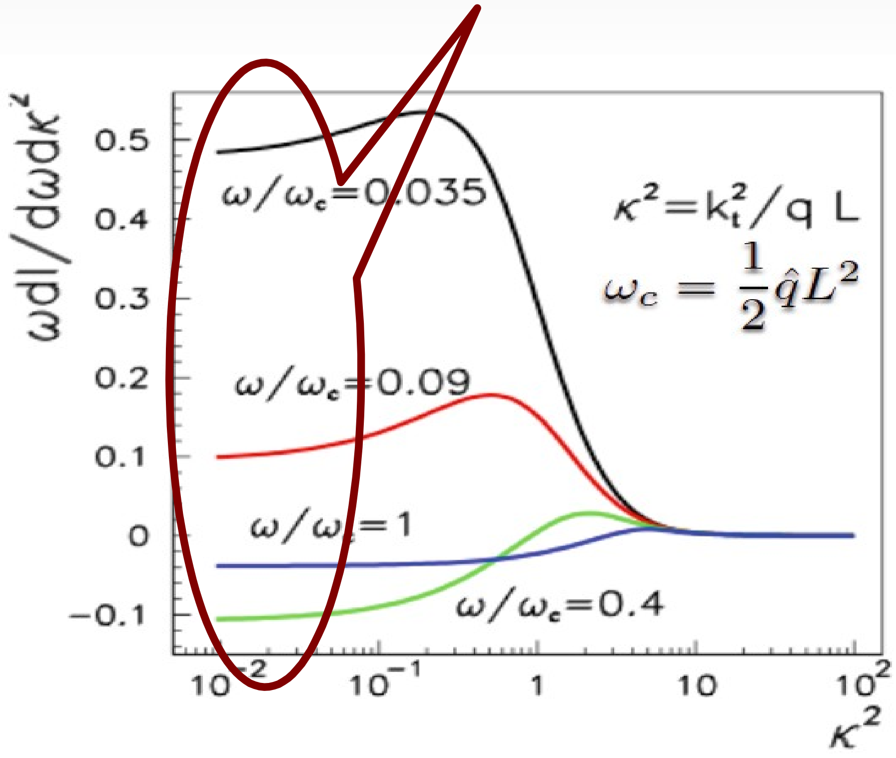
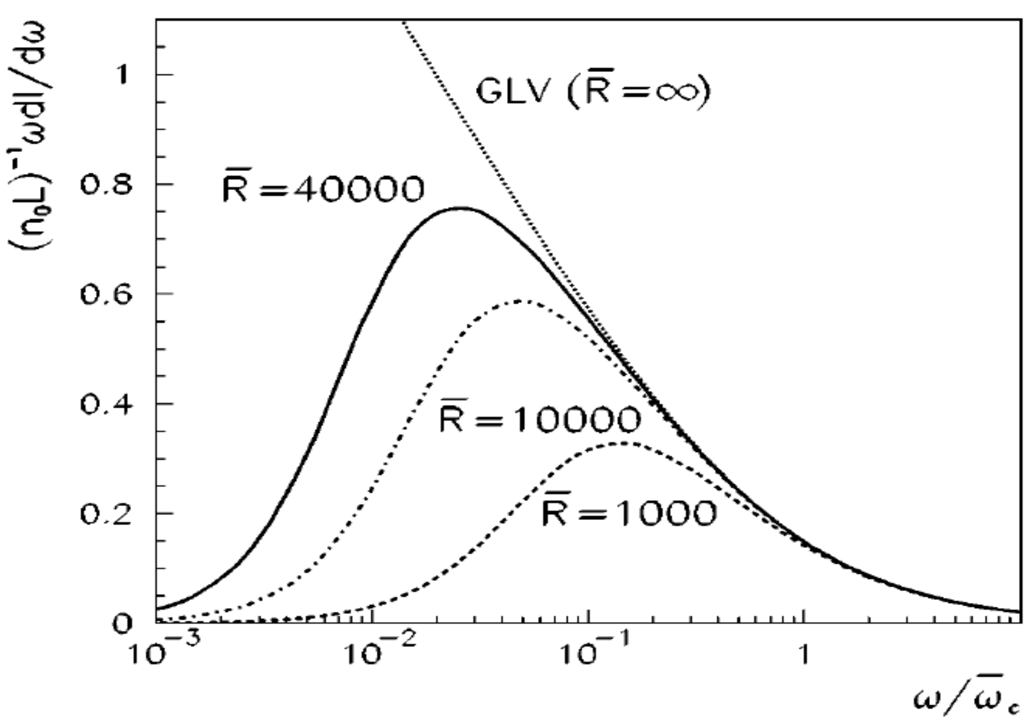


Collinear and Infrared Safe spectrum



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Incoherent Limit (L → ∞) : Probabilistic interpretation

$$\hat{q} \int_{\mathcal{V}(\boldsymbol{q})} \frac{\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2} = \frac{\hat{q}}{2} \int_{\mathcal{V}(\boldsymbol{q})} \left(-\frac{1}{\boldsymbol{k}^2} + \frac{1}{(\boldsymbol{k}-\boldsymbol{q})^2} + \boldsymbol{L}^2\right)$$

Wiedemann (2000)

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$$\lim_{L\to\infty} \sum_{m=0}^{N=1} \frac{d^3\sigma^{(nas)}(m)}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{\pi^2} N_C\, C_F \times \left[(1-w_1) H(\mathbf{k}_\perp) + n_0\, L \int_{\mathbf{q}_1} H(\mathbf{k}_\perp + \mathbf{q}_{1\perp}) + n_0\, L \int_{\mathbf{q}_1} R(\mathbf{k}_\perp, \mathbf{q}_{1\perp})\right].$$

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Hard medium independent emission by bremsstrahlung which reduces the collinear emissions

Wiedemann (2000)

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Hard Radiation emission which rescatters once in the medium

Wiedemann (2000)

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Gunion-Bertsch contribution associated with the rescattering

Wiedemann (2000)

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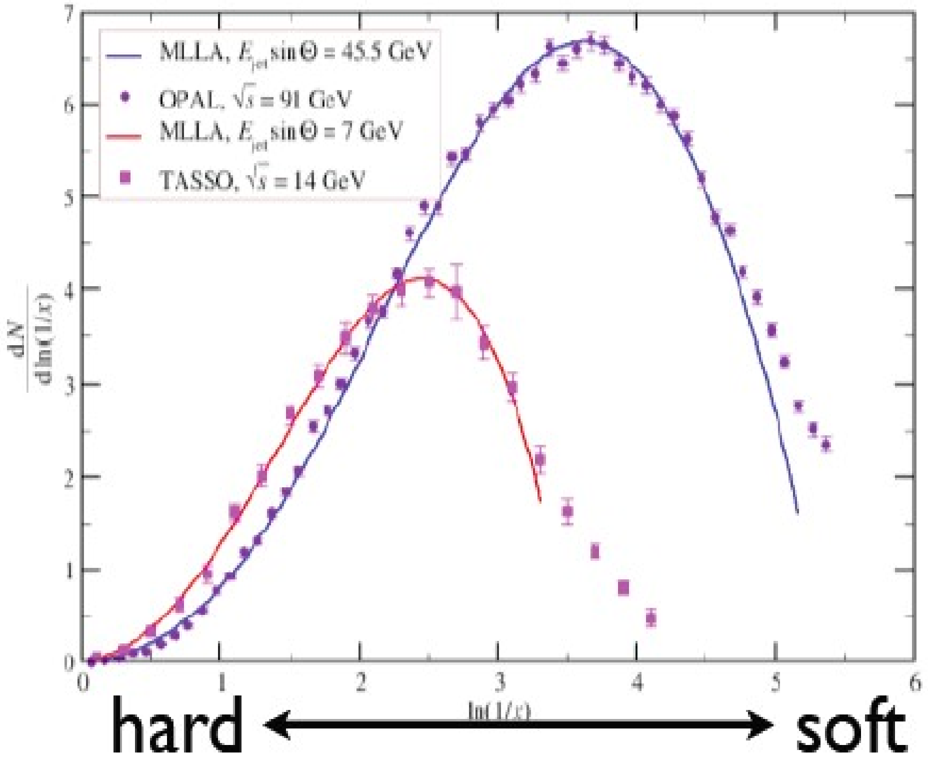
  $\Rightarrow$ **No interference** between different colored particles in the parton shower

- A missing and fundamental ingredient:

  QCD coherence in jets in vacuum

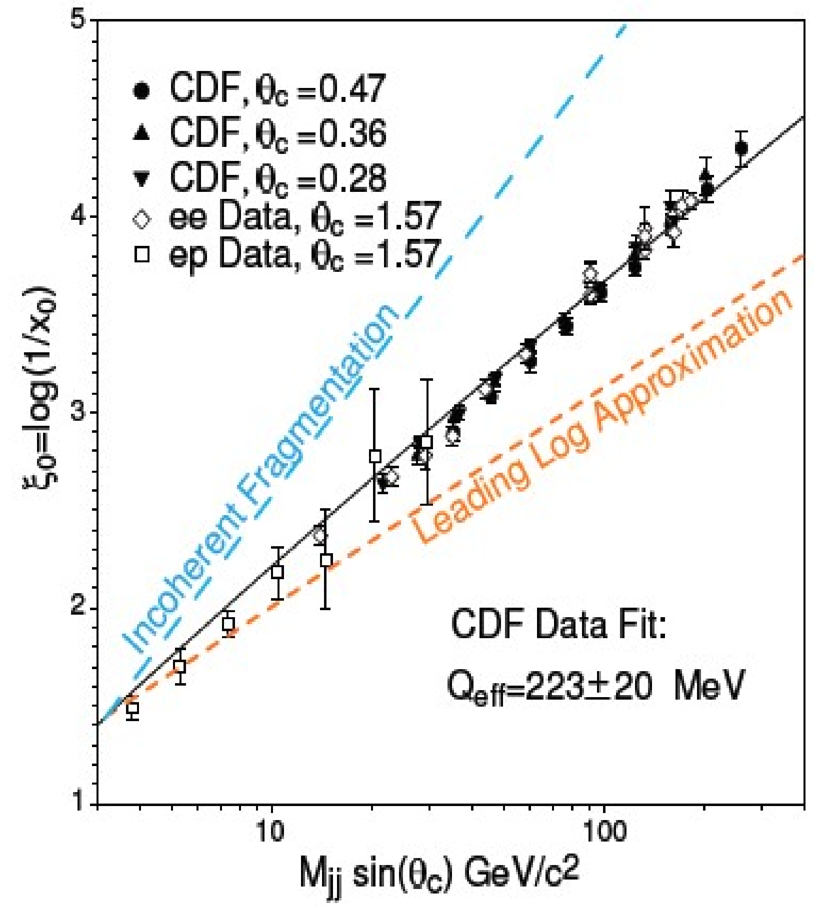
  Angular ordering in the parton shower
  Basseto, Ciafaloni, Marchesini (1982), Fadin (1983), Dokshitzer, Diakonov, Troian (1980)

QCD Coherence and Intrajet physics



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

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

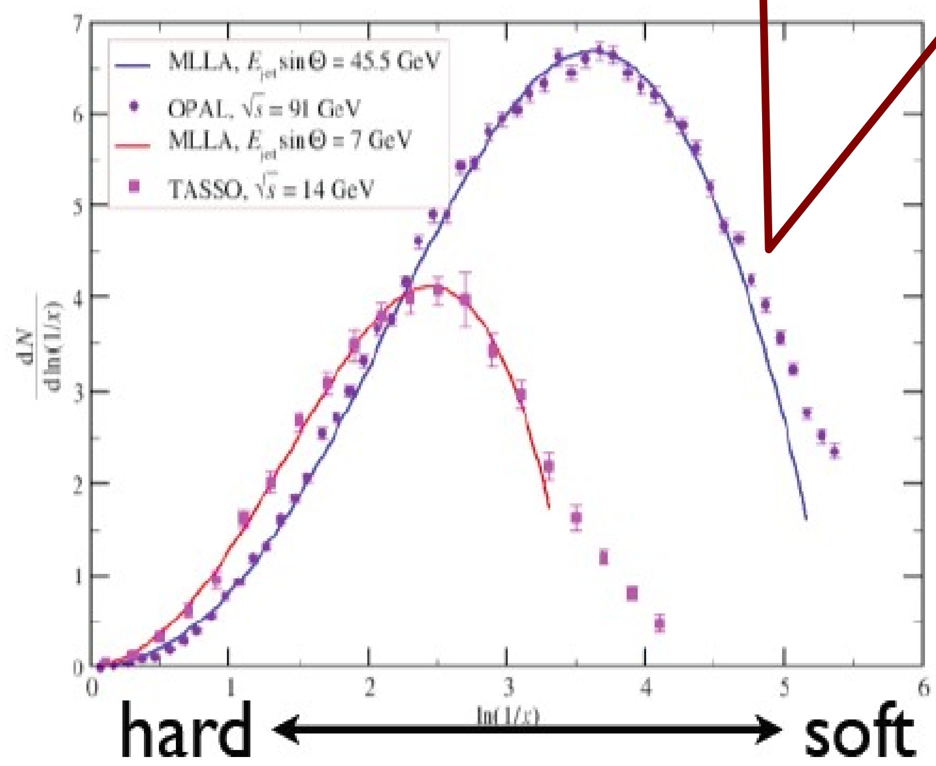


Humpbacked Plateau

Position of hump

QCD Coherence and Intrajet physics

Limiting phase space for soft gluon radiation



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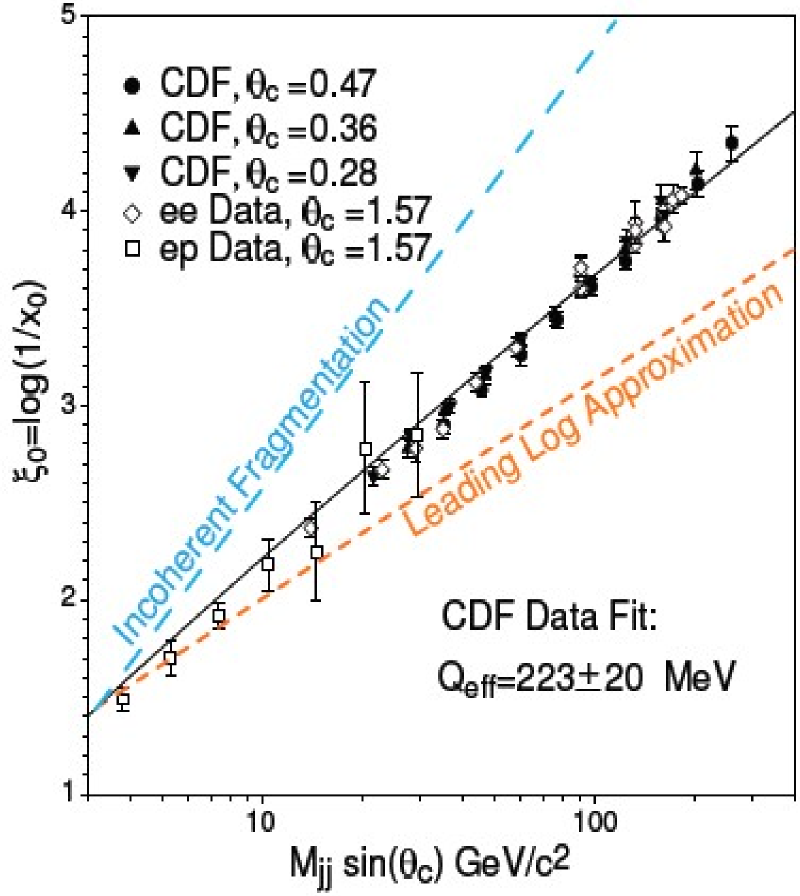
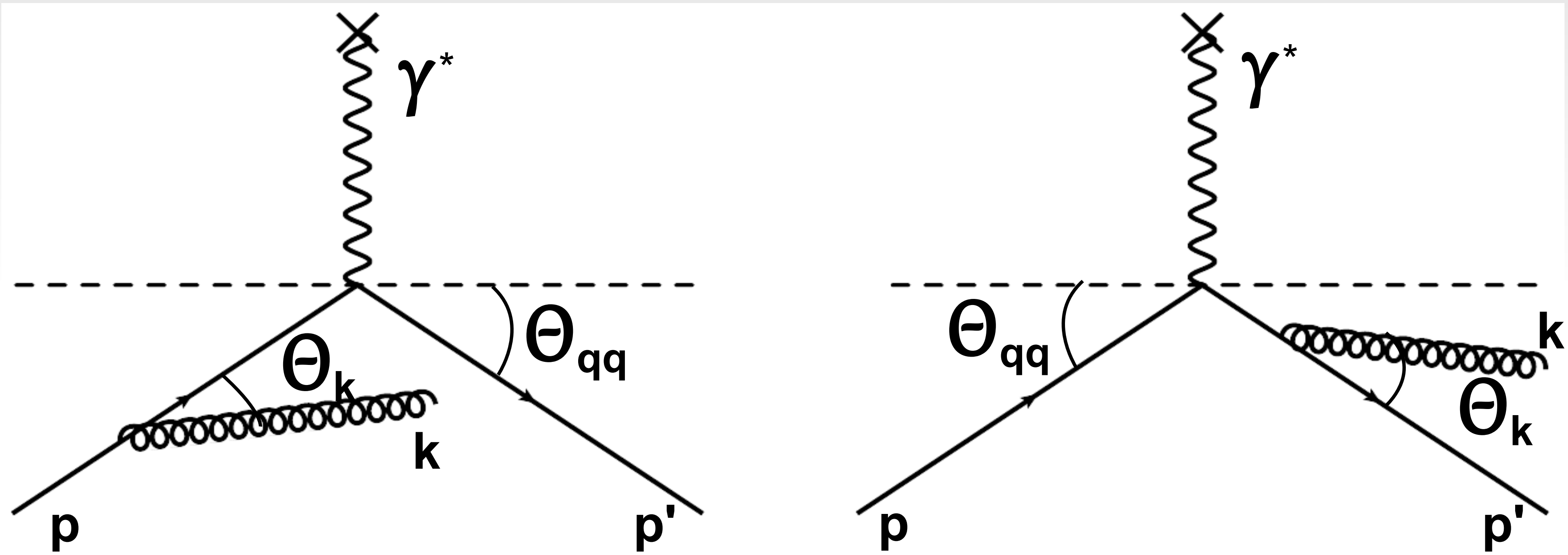


Humpbacked Plateau **Position of hump**

Angular ordering in the initial state radiation

Vacuum case: space-like cascade



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

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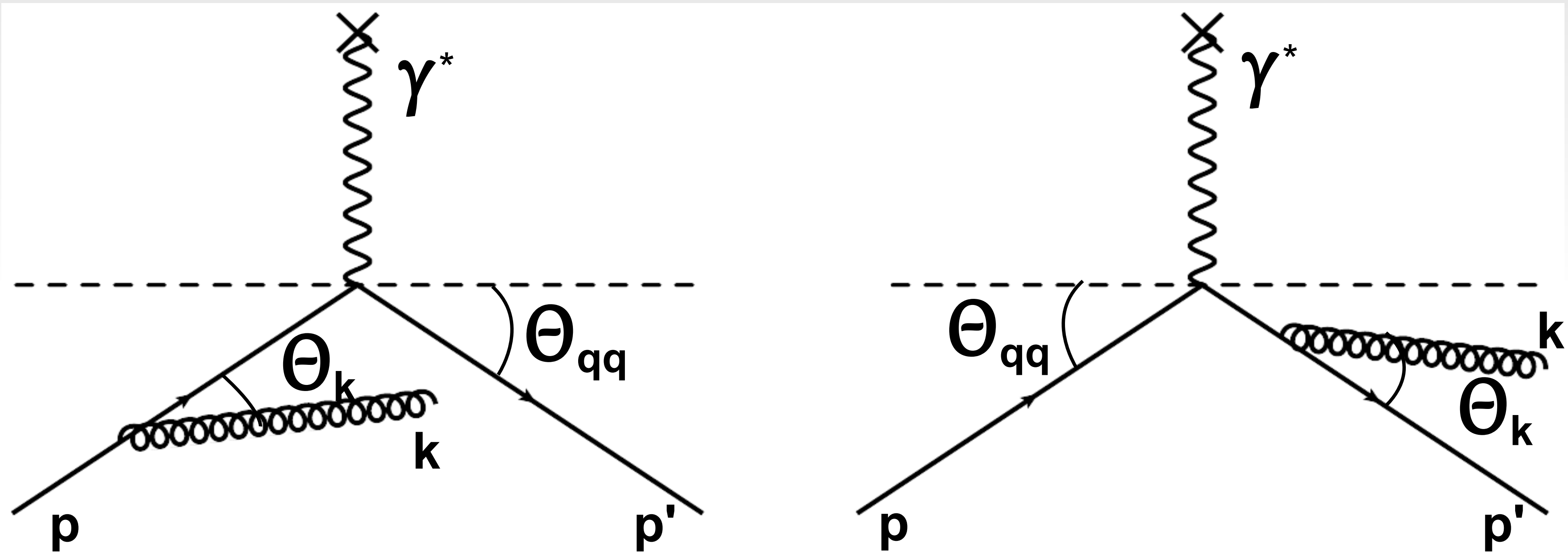

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Independent Emissions

Angular ordering in the initial state radiation

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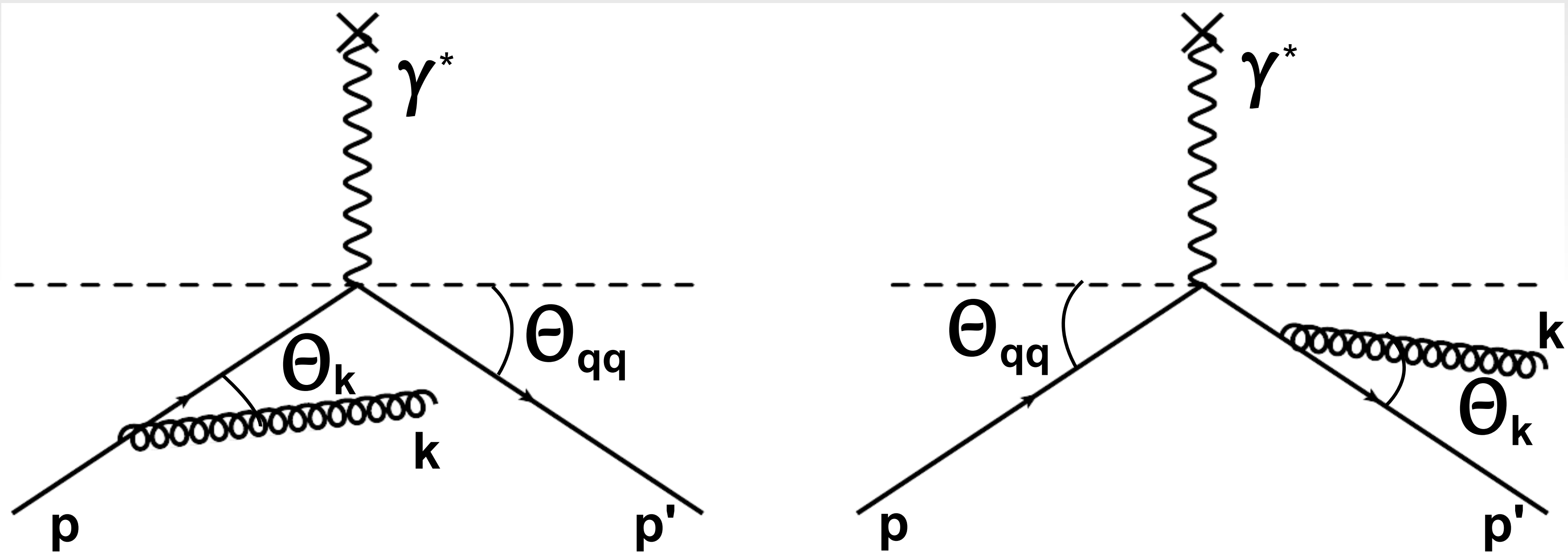

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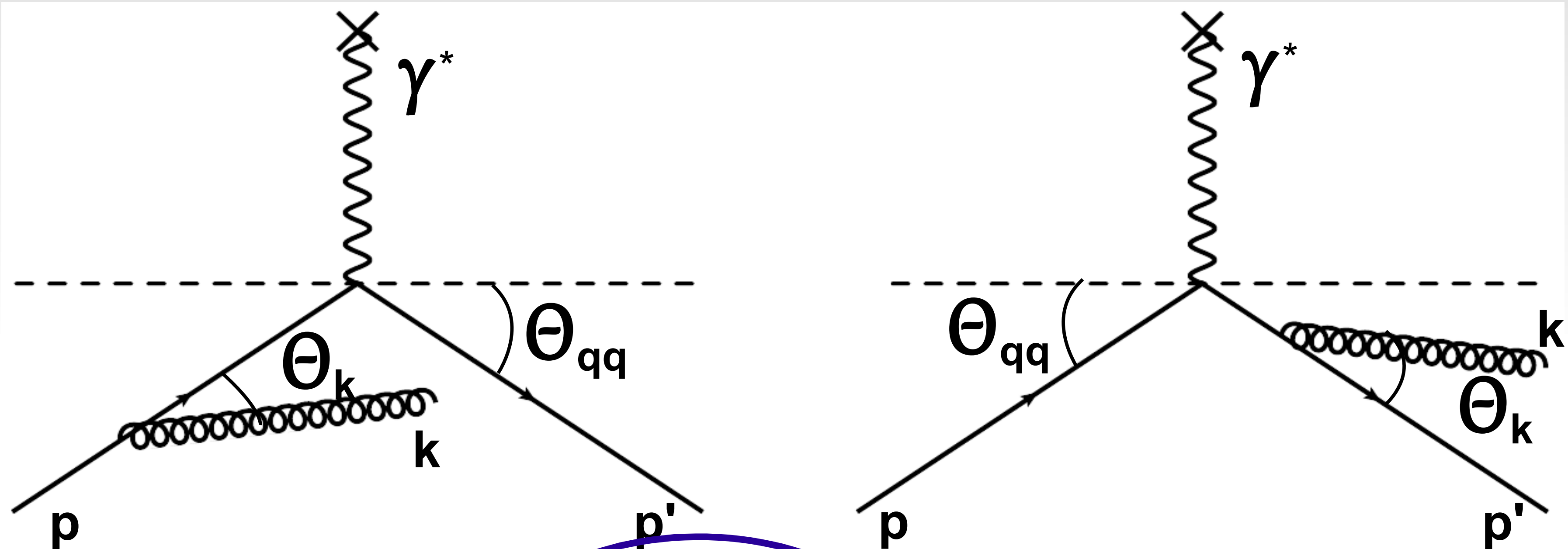
Destructive interferences

Angular ordering in the initial state radiation

Vacuum case: double leading log



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

Infrared and collinear divergence

Angular ordering in the initial state radiation

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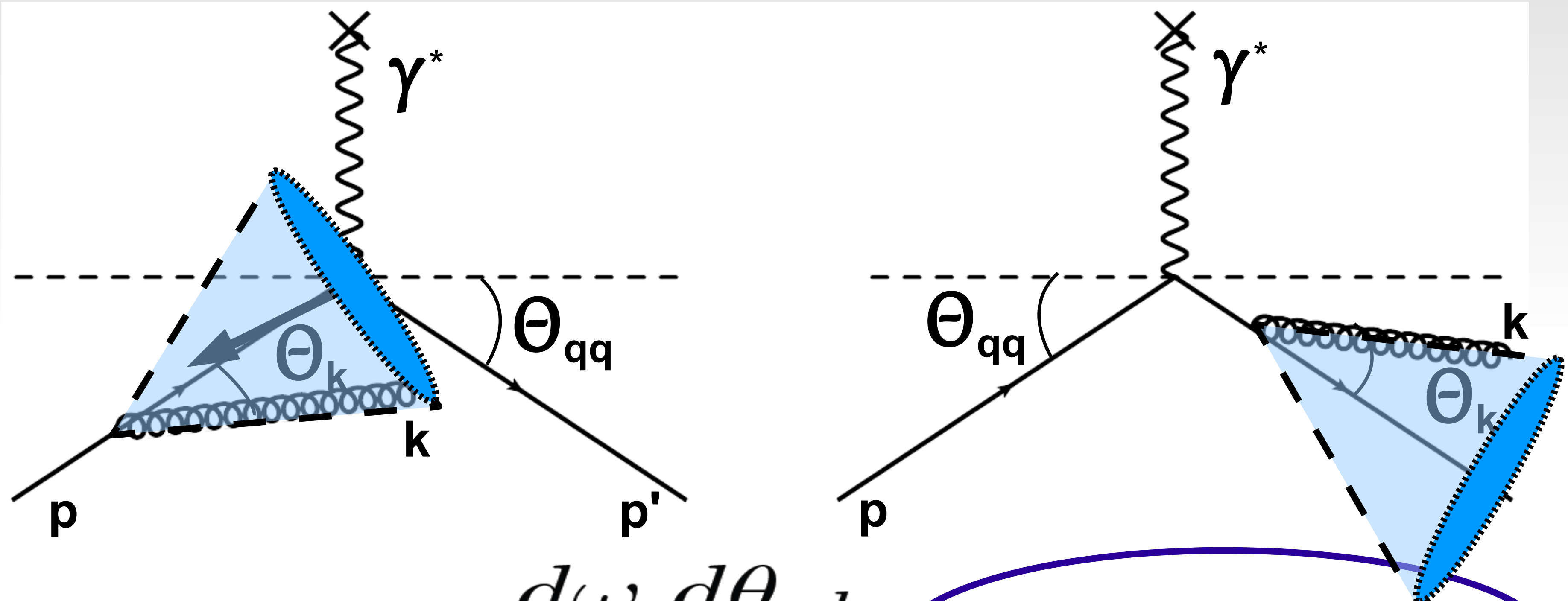

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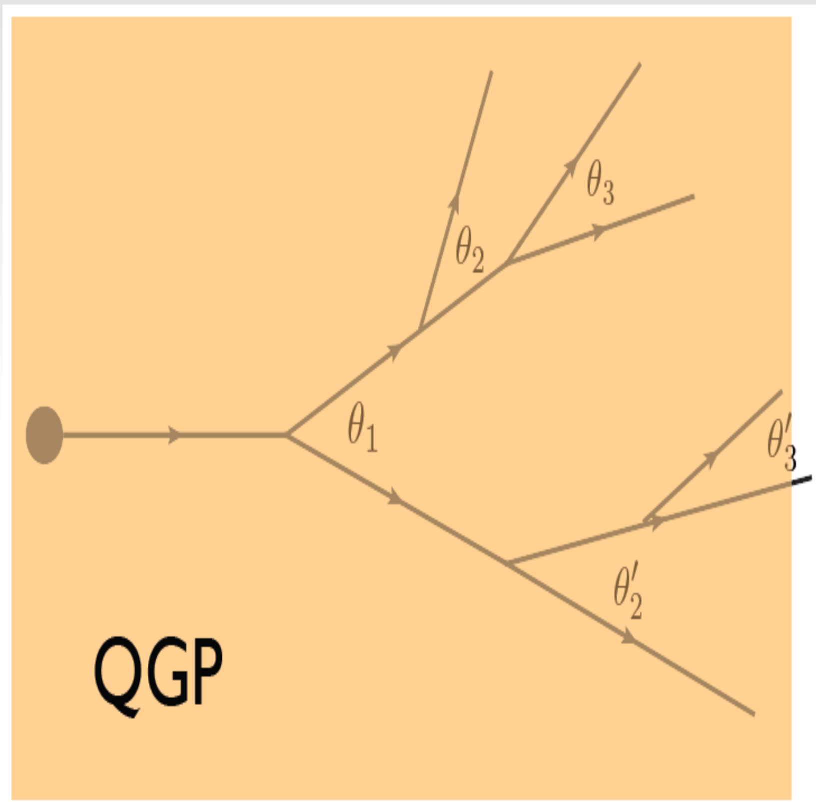
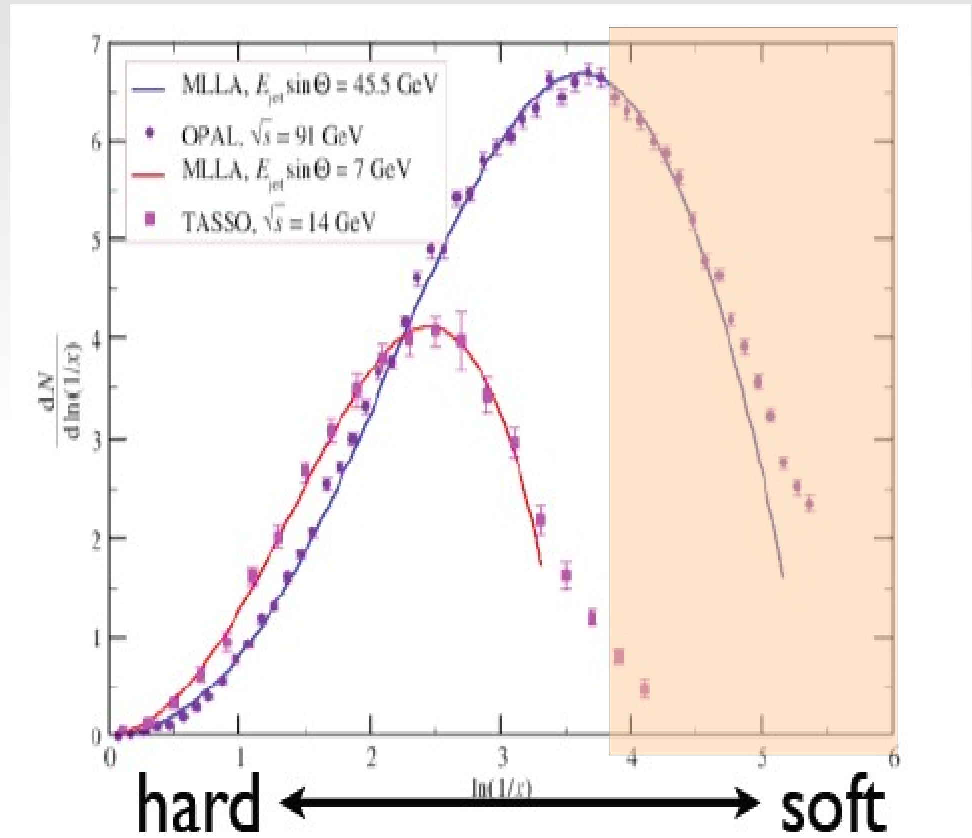
Angular ordering ➡ Large angle suppression due to interference between the emitters

How does the presence of a QCD medium affects QCD coherence in a jet?





Attempts to test coherence in the presence of a QGP: Wiedemann and Borghini, hep-ph/0506218

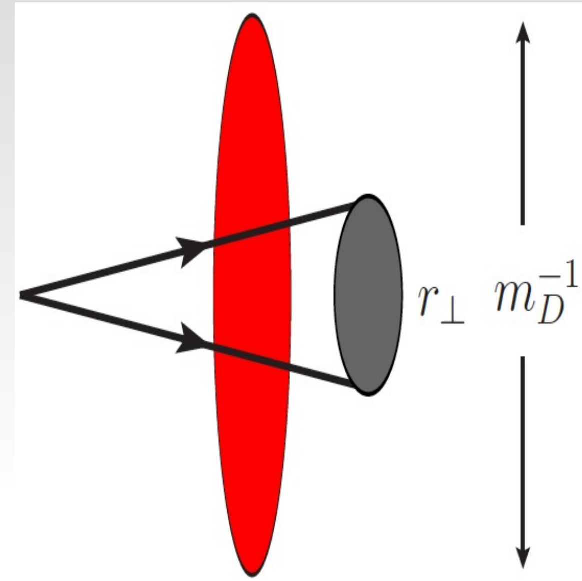
First steps towards jet calculus in medium: QCD antenna

✯ **QCD massless antenna in a dilute QGP medium:**

Y. Mehtar-Tani, C. Salgado and K. Tywoniuk,
Phys. Rev. Lett. 106 (2011), arXiv:1112.5031 .

✯ **QCD Massive antenna in a dilute QGP medium:**

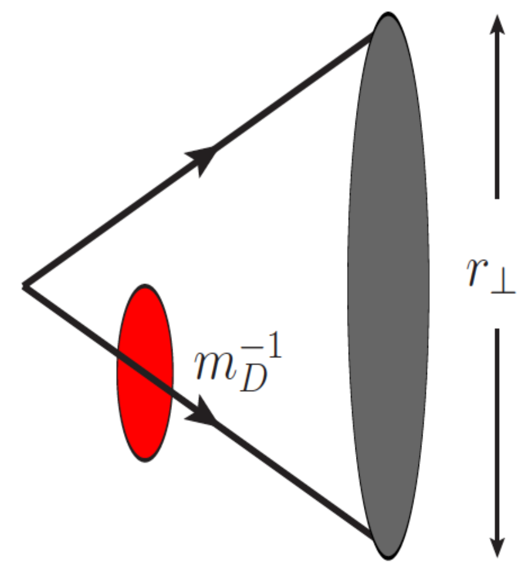
Nestor Armesto, Hao Ma, Y. Mehtai, C. Salgado and
K. Tywoniuk, JHEP 1201 (2012) 109.



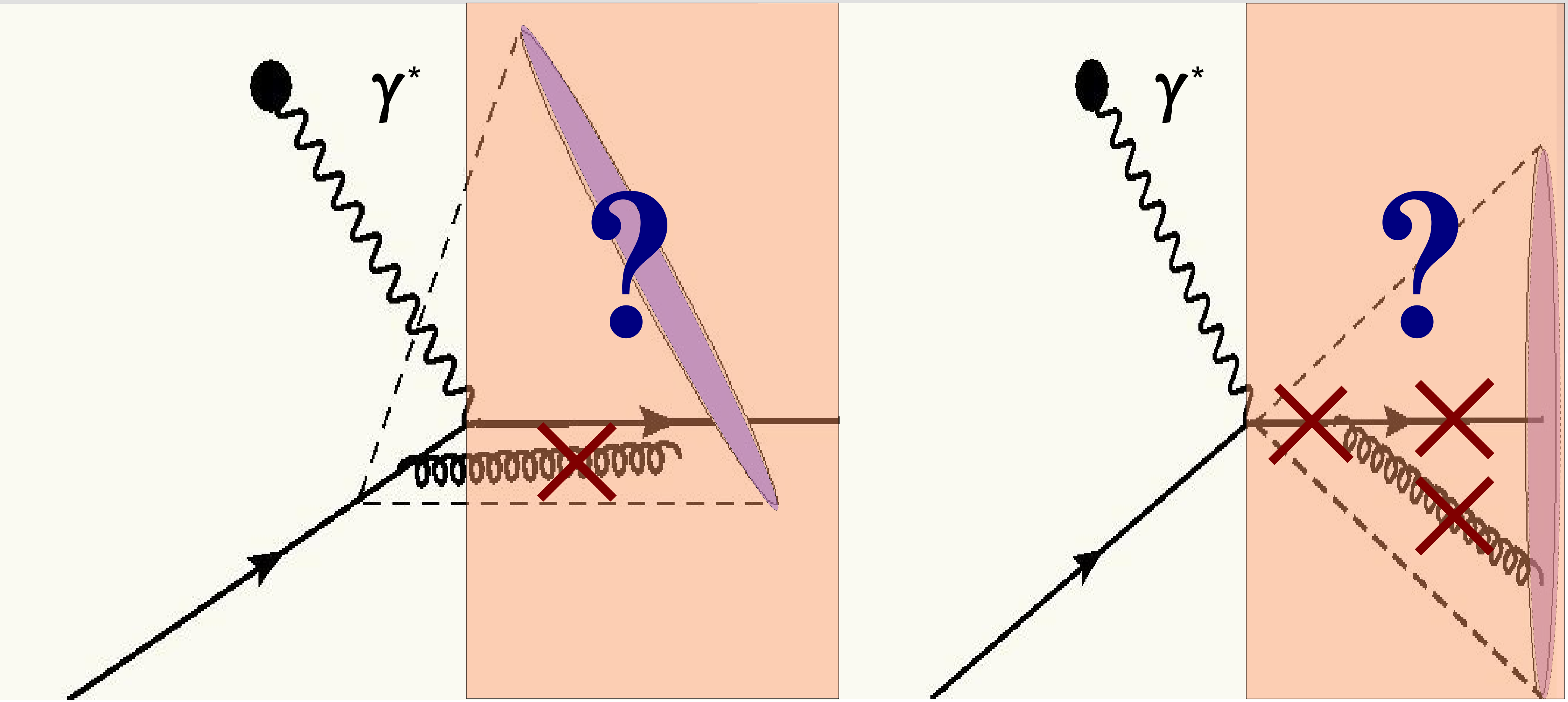
✯ **QCD massless antenna in an opaque QGP medium:**

Y. Mehtar-Tani, C. Salgado and K. Tywoniuk, Phys.
Lett. B707 (2012) 156).

Y. Mehtar-Tani and K. Tywoniuk, arXiv:1105.1346 .
J. Casalderrey and E. Iancu, JHEP 1108 (2011) .

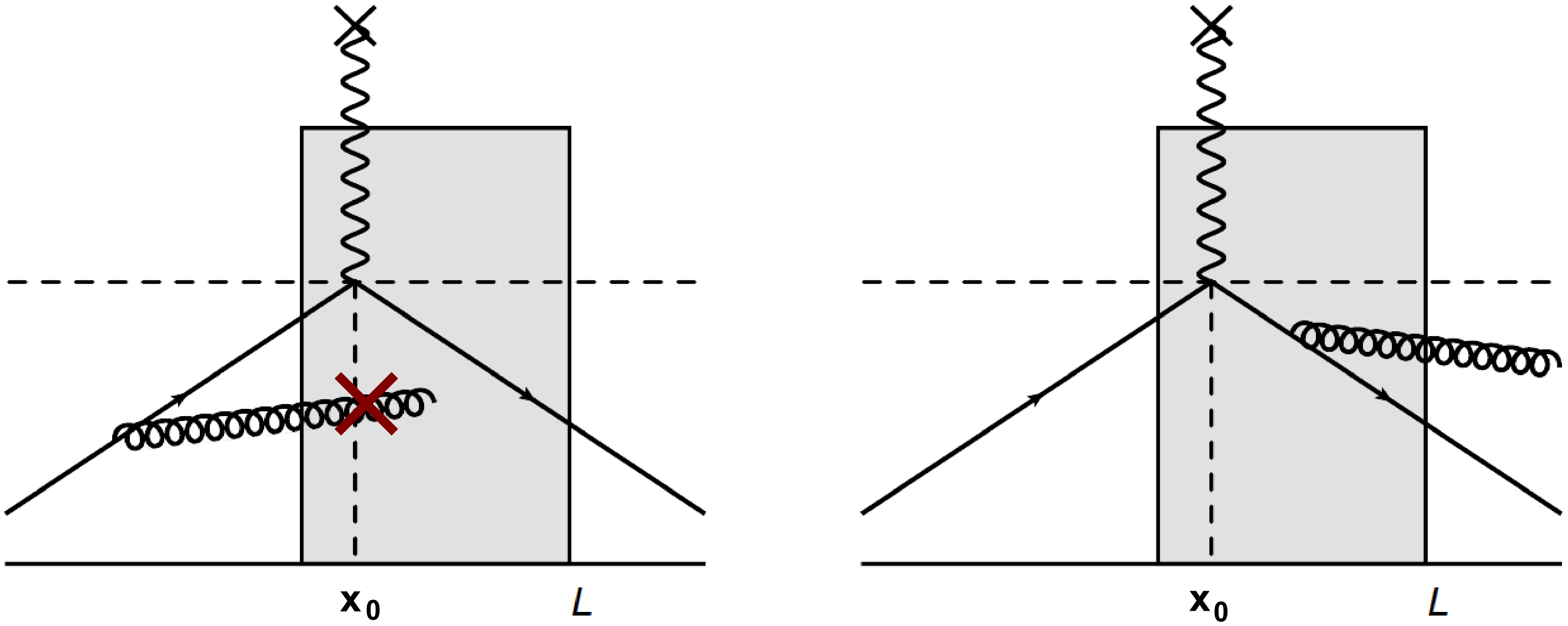


In this talk: Coherence effects on Initial State Radiation in the presence of a QCD medium



⇒ How does the presence of a thin plasma affect the interference pattern of the initial state radiation?

Setting the physical system



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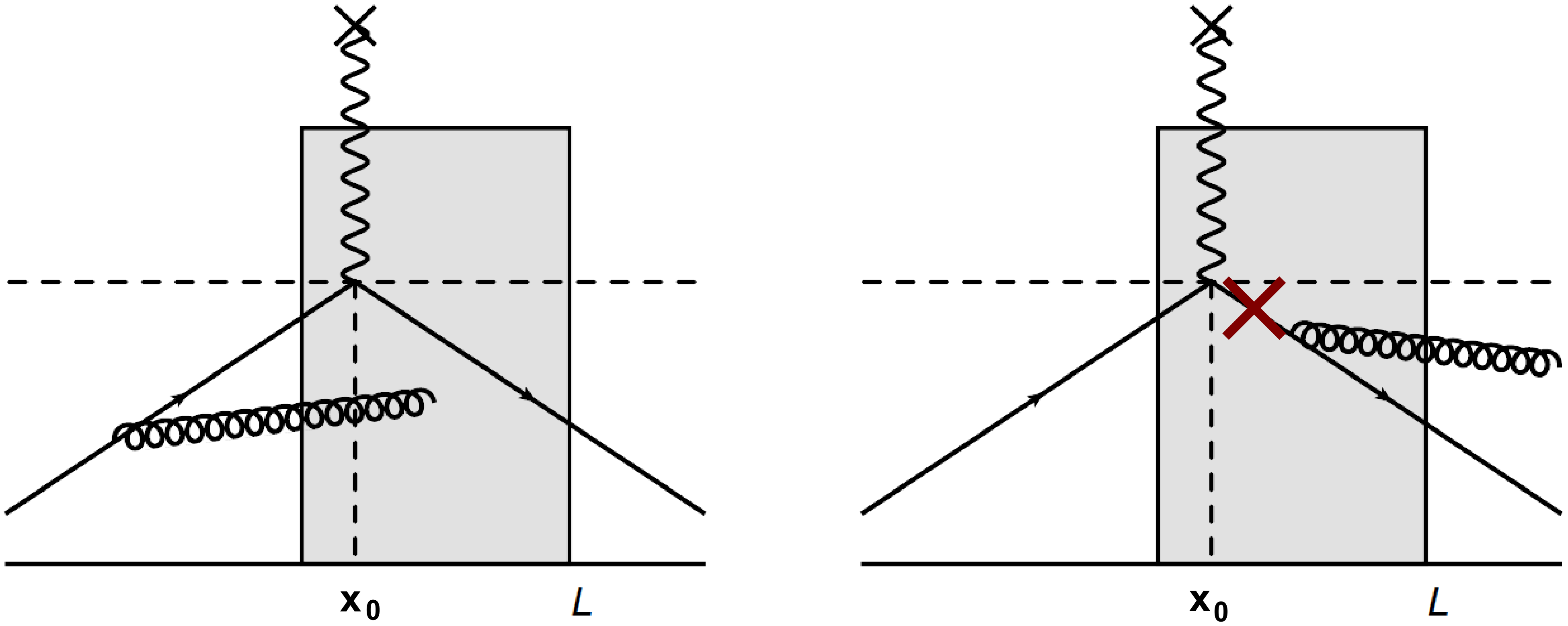

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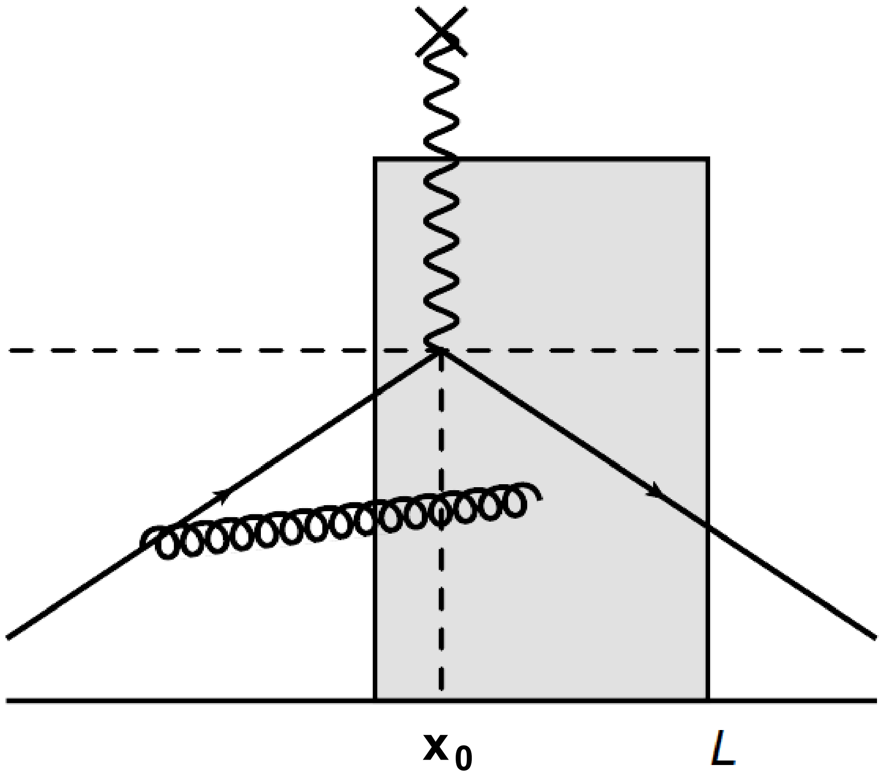

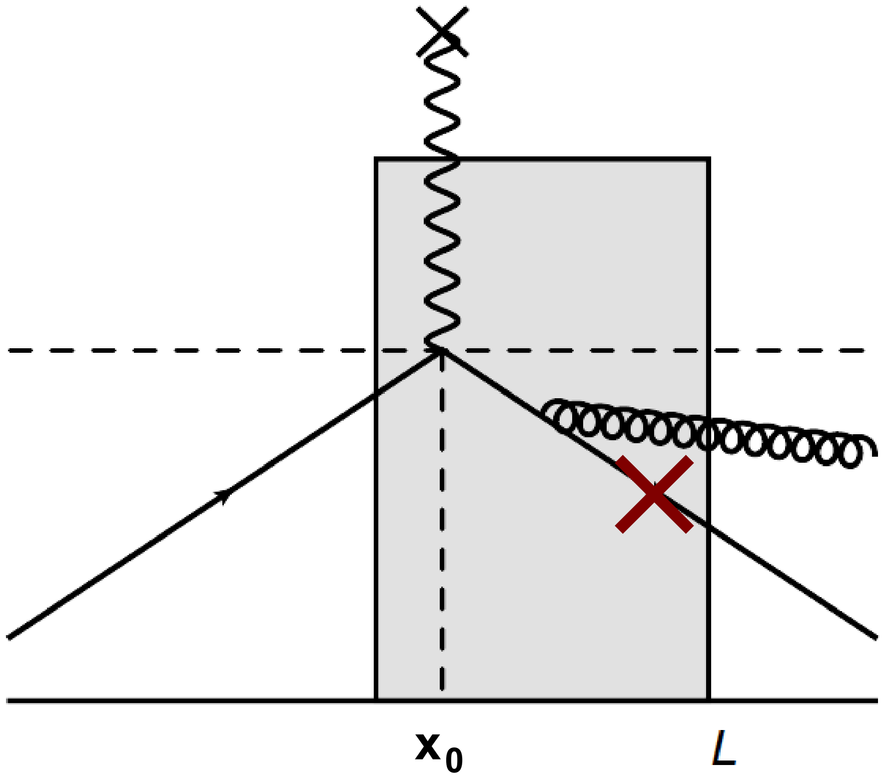

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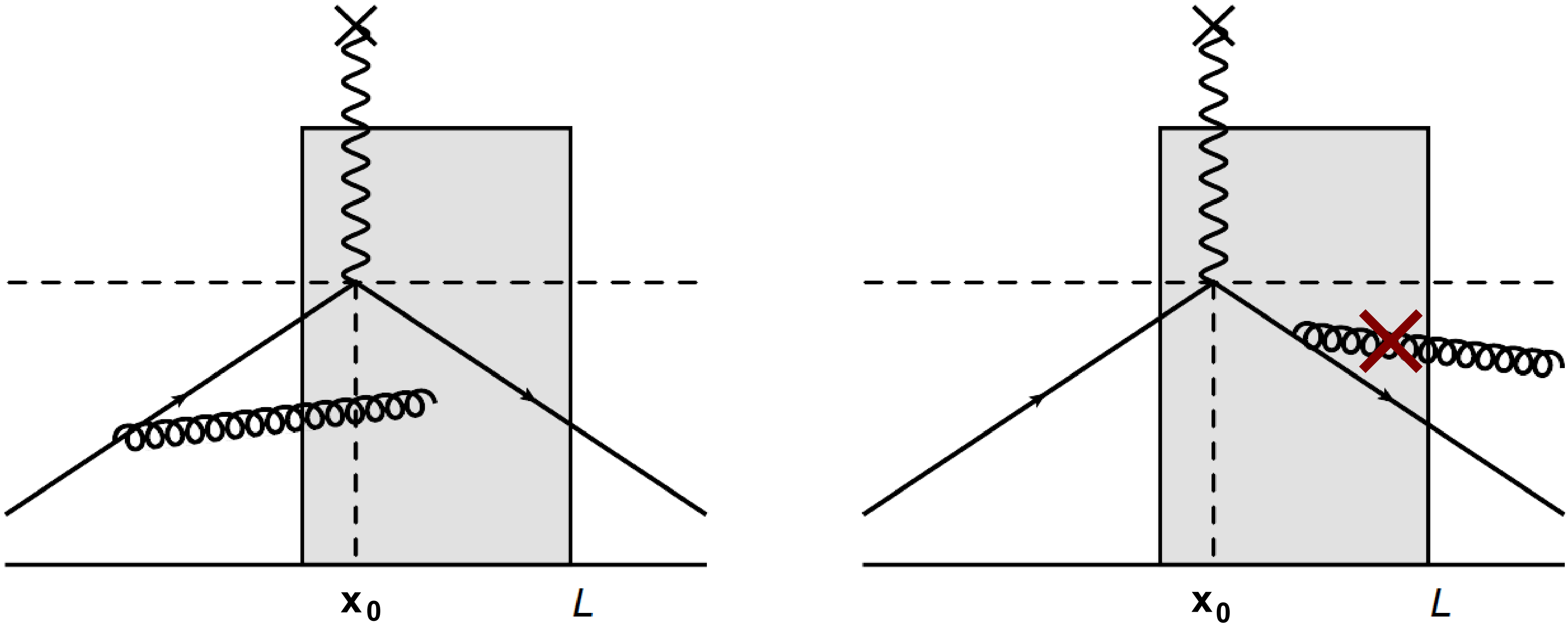

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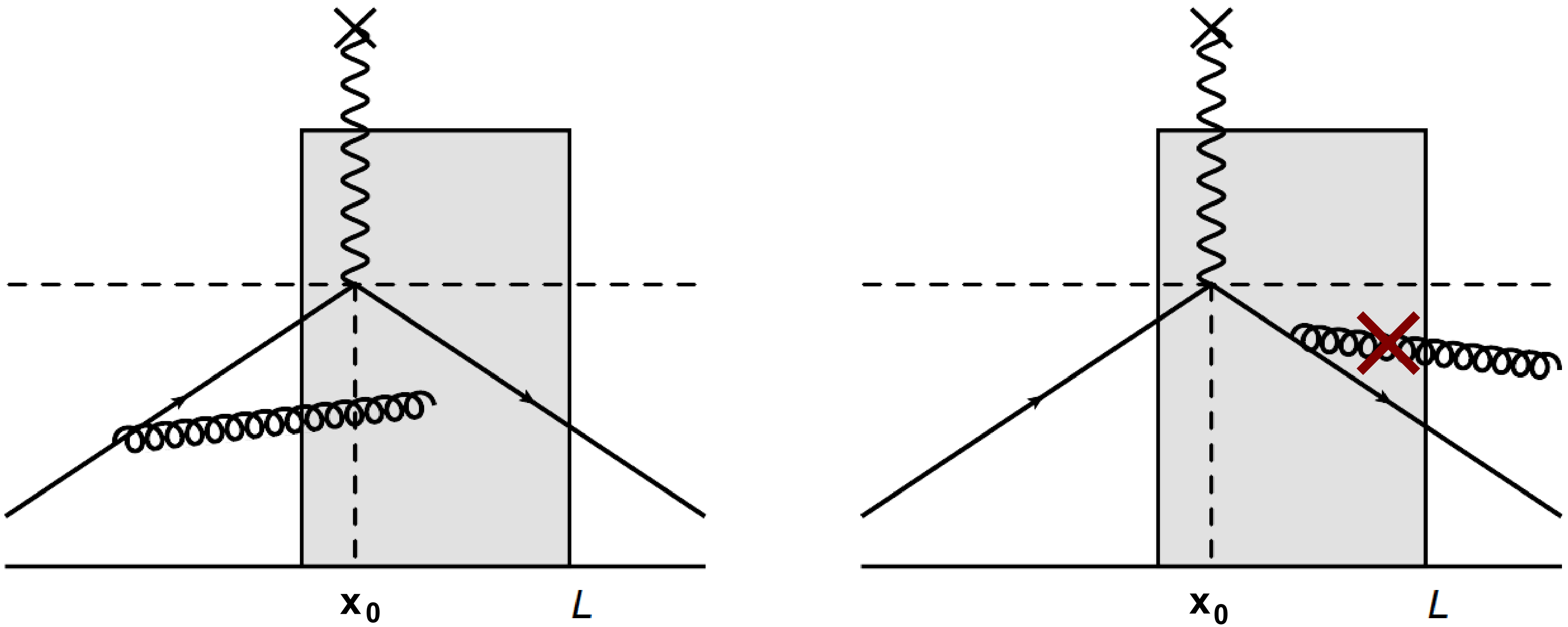
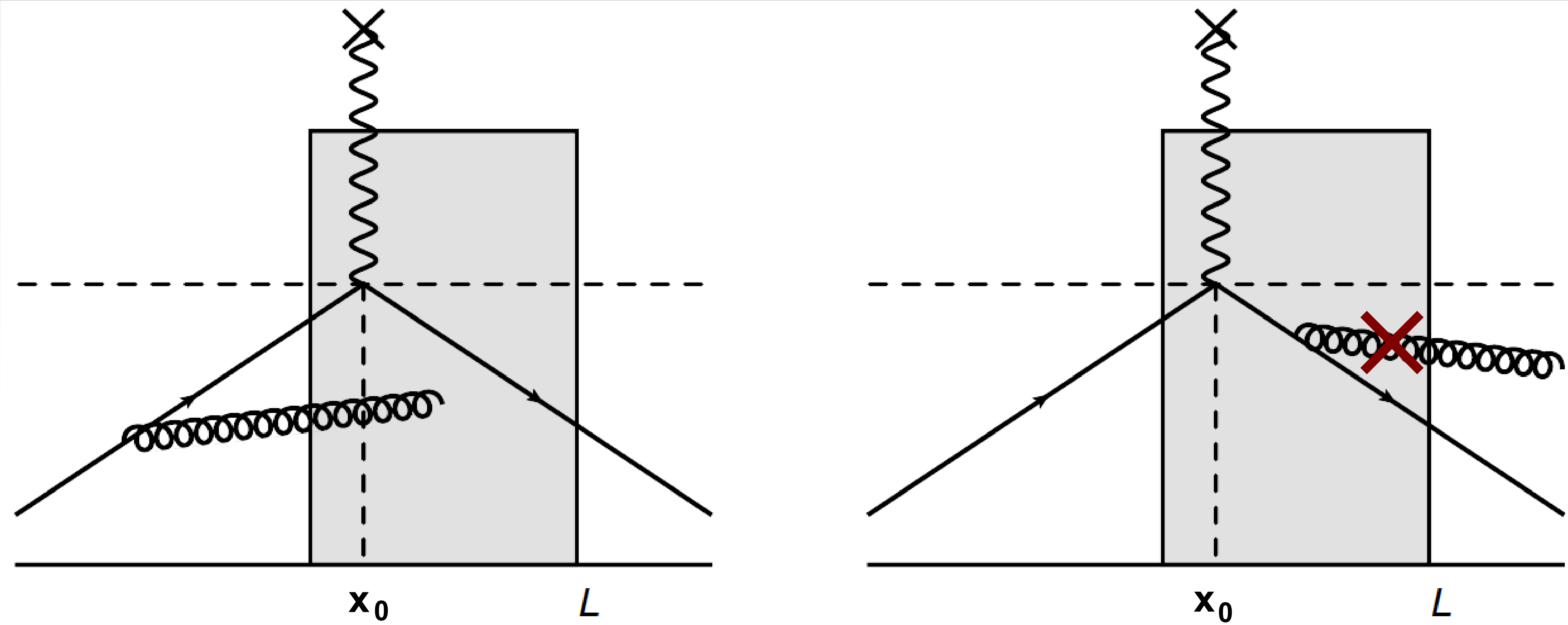


☆ **Finite angle depletion between quarks:** $\Theta_{qq} \geq 0$

Setting the physical system



- ✫ **Finite angle depletion between quarks:** $\Theta_{qq} \geq 0$
- ✫ **Eikonal approximmation:** $E >> w >> k_T$

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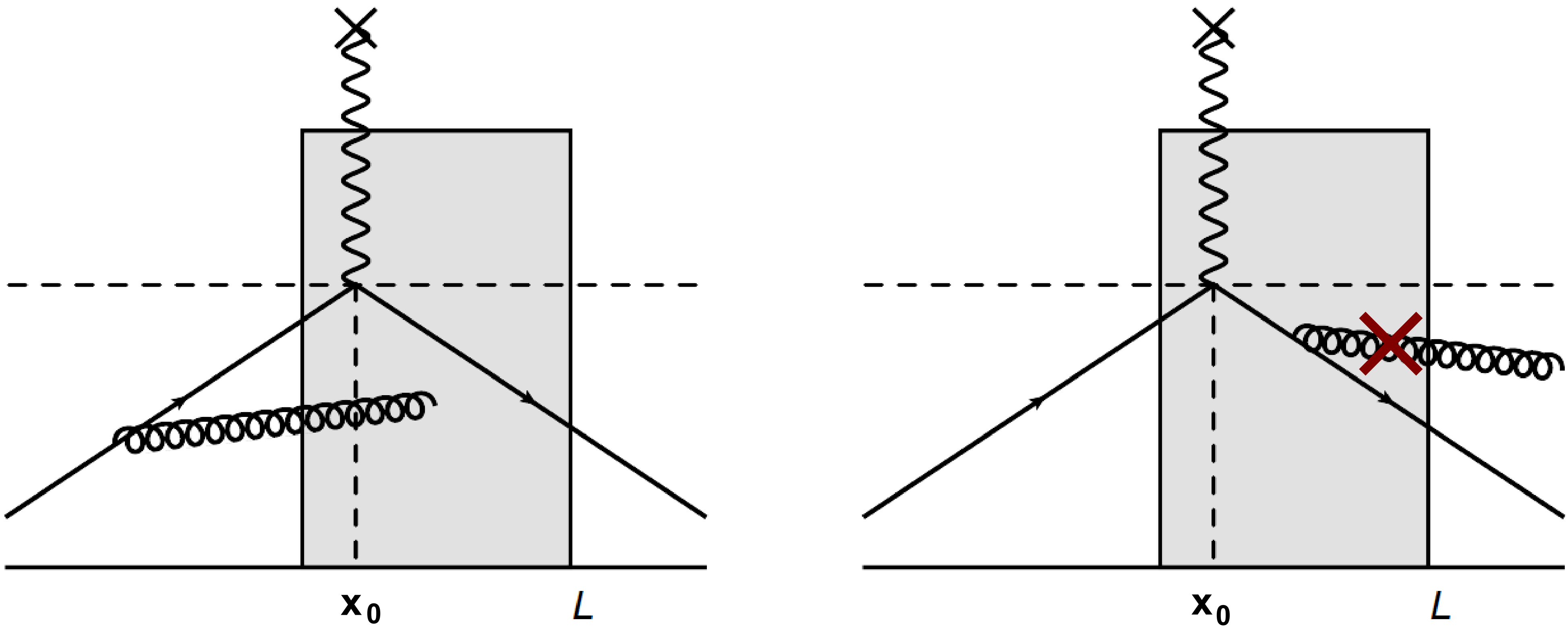
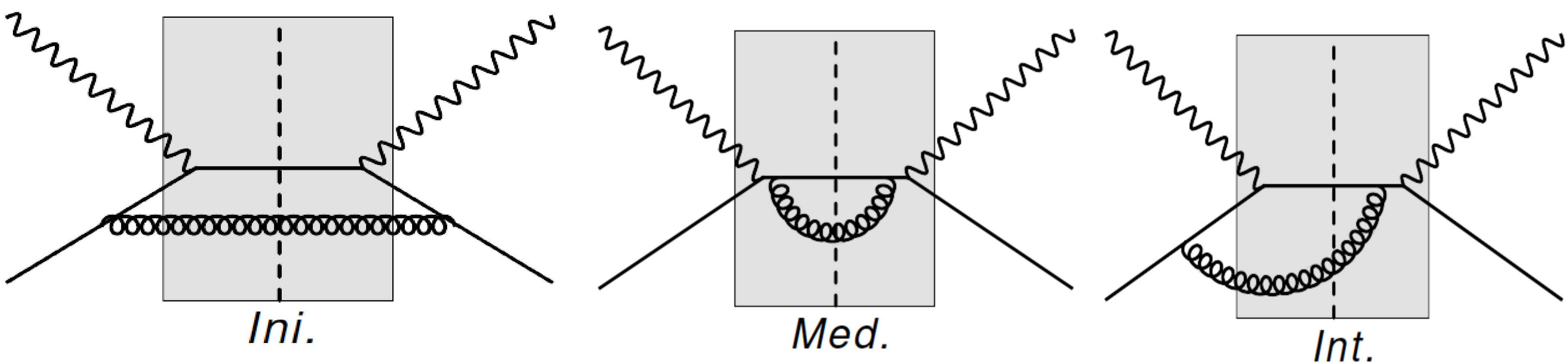


- ✯ **Finite angle depletion between quarks:** $\Theta_{qq} \geq 0$
- ✯ **Eikonal approximmation:** E >> w >> k_T
- ✯ **The scattering centers (QCD medium) are treated as a classical background field (Yukawa type potential).**

Radiative cross section

$$d\sigma_{(1)} \propto |\mathcal{M}|^2_{Total}$$

$$|\mathcal{M}|^2_{Total} = |\mathcal{M}|^2_{Ini.} + |\mathcal{M}|^2_{GLV} + |\mathcal{M}|^2_{Int.}$$



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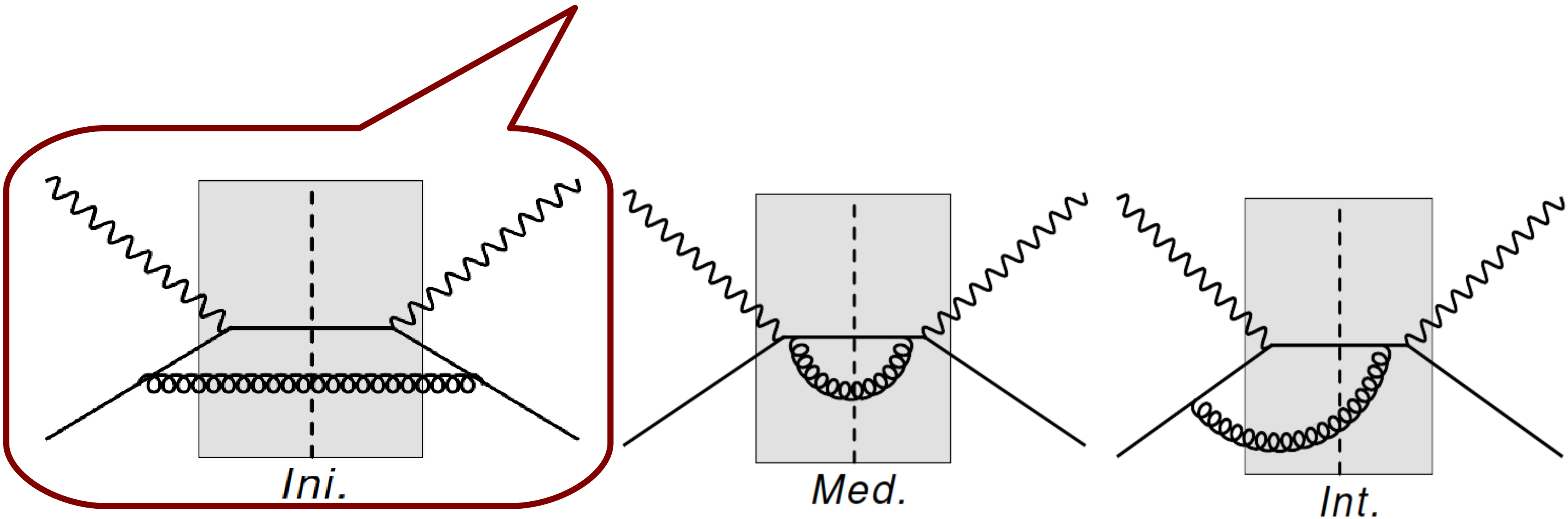

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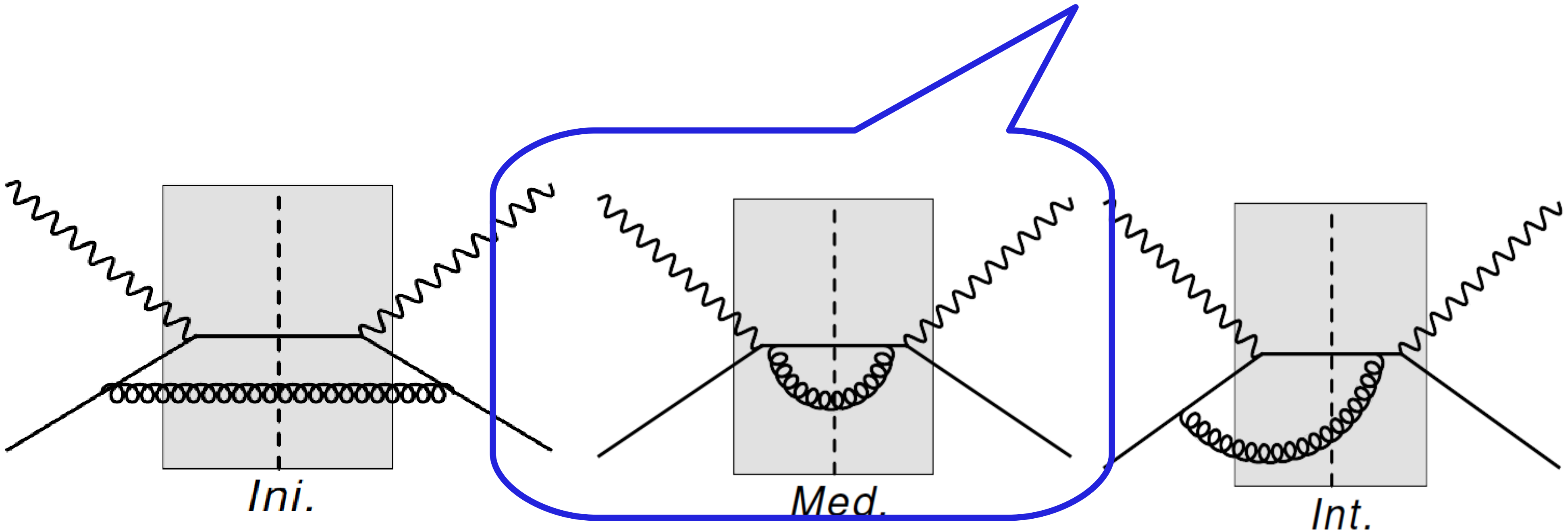
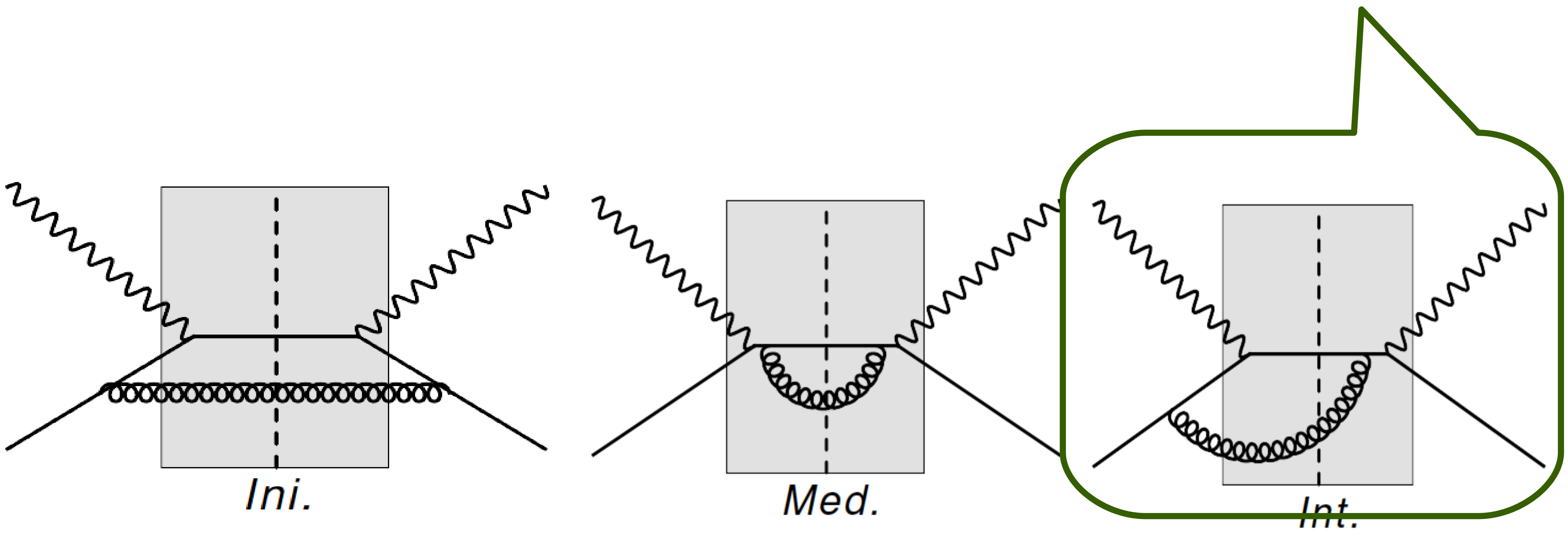


Radiative cross section

$$d\sigma_{(1)} \propto |\mathcal{M}|^2_{Total}$$

$$|\mathcal{M}|^2_{Total} = |\mathcal{M}|^2_{Ini.} + |\mathcal{M}|^2_{GLV} + |\mathcal{M}|^2_{Int.}$$



The gluon spectrum

$$(2\pi)^2 w \frac{dN}{d^3k} = 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \int_0^{L^+} dx^+ n(x+) [\mathcal{V}(\boldsymbol{q})]^2$$

$$\left[\frac{\boldsymbol{\nu}^2}{x^2\,(p\cdot v)^2} - \frac{\boldsymbol{\kappa}^2}{x^2\,(p\cdot k)^2} \right.$$

$$+ \frac{2}{\bar{x}^2} \left(\frac{\bar{\boldsymbol{\nu}}^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\kappa}}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+])$$

$$+ \frac{2}{x\,\bar{x}} \left(\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot k)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} \right.$$

$$\left. \left. + \left(\frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)\,(p\cdot v)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+]) \right) \right]$$

$$\Omega_{\bar{p}} = \frac{\bar{p}\cdot v}{\bar{p}}$$

The gluon spectrum

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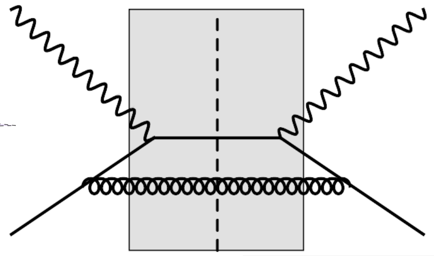


$$\Omega_{\bar{p}} = \frac{\bar{p}\cdot v}{\bar{p}}$$

$$+ \frac{2}{\bar{x}^2}\left(\frac{\bar{\boldsymbol{\nu}}^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\kappa}}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right)(1-\cos[\Omega_{\bar{p}} x_1^+])$$

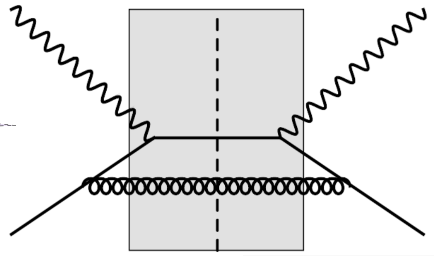
$$+ \frac{2}{x\,\bar{x}}\left(\left(\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot k)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} \right.\right.$$

$$\left.\left.\left. + \left(\frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)\,(p\cdot v)} \right)(1-\cos[\Omega_{\bar{p}} x_1^+]) \right)\right]\right.$$

The gluon spectrum

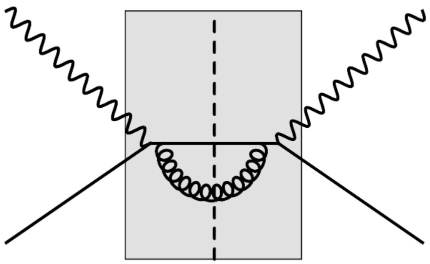
$$(2\pi)^2 w \frac{dN}{d^3k} = 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} \int_0^{L^+} dx^+ n(x+) [\mathcal{V}(\boldsymbol{q})]^2$$

$$\Bigg[\frac{\boldsymbol{\nu}^2}{x^2 (p \cdot v)^2} - \frac{\boldsymbol{\kappa}^2}{x^2 (p \cdot k)^2}$$



$$\Omega_{\bar{p}} = \frac{\bar{p} \cdot v}{\bar{p}}$$

$$+ \frac{2}{\bar{x}^2} \left(\frac{\bar{\boldsymbol{\nu}}^2}{(\bar{p} \cdot v)^2} - \frac{\bar{\boldsymbol{\kappa}} \cdot \bar{\boldsymbol{\nu}}}{(\bar{p} \cdot v)(\bar{p} \cdot k)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+])$$



$$+ \frac{2}{x\,\bar{x}} \Bigg(\frac{\boldsymbol{\kappa} \cdot \bar{\boldsymbol{\kappa}}}{(\bar{p} \cdot k)\,(p \cdot k)} - \frac{\boldsymbol{\nu} \cdot \bar{\boldsymbol{\kappa}}}{(\bar{p} \cdot k)\,(p \cdot v)}$$

$$+ \left(\frac{\boldsymbol{\nu} \cdot \bar{\boldsymbol{\kappa}}}{(\bar{p} \cdot k)\,(p \cdot v)} - \frac{\boldsymbol{\nu} \cdot \bar{\boldsymbol{\nu}}}{(\bar{p} \cdot v)\,(p \cdot v)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+]) \Bigg) \Bigg]$$

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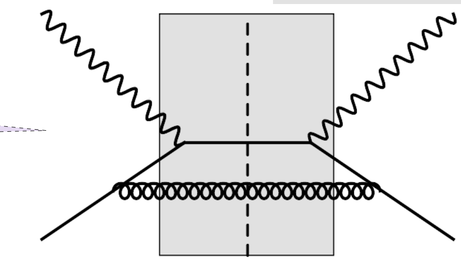
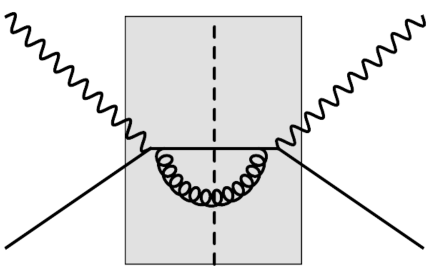


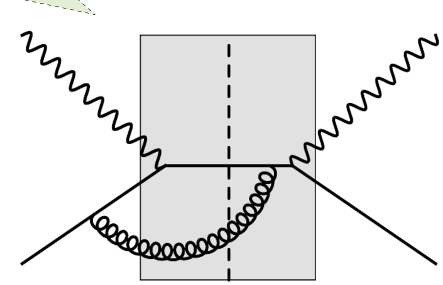
$$\Omega_{\bar{p}} = \frac{\bar{p}\cdot v}{\bar{p}}$$

$$+ \frac{2}{\bar{x}^2} \left(\frac{\bar{\boldsymbol{\nu}}^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\kappa}}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)(\bar{p}\cdot k)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+])$$



$$+ \frac{2}{x\,\bar{x}} \Bigg(\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot k)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)}$$

$$+ \left(\frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)\,(p\cdot v)} \right) (1 - \cos[\Omega_{\bar{p}} x_1^+]) \Bigg) \Bigg]$$



New Terms !!!

The gluon spectrum

$$(2\pi)^2 w\frac{dN}{d^3k} = 8\pi C_A C_F \alpha_s^2 \int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\int_0^{L^+} dx^+ n(x+)[\mathcal{V}(\boldsymbol{q})]^2$$

$$\left[\frac{\boldsymbol{\nu}^2}{x^2\,(p\cdot v)^2} - \frac{\boldsymbol{\kappa}^2}{x^2\,(p\cdot k)^2}\right.$$

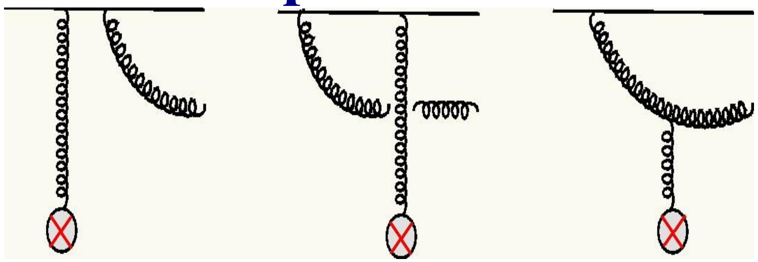
$$\Omega_{\bar{p}} = \frac{\bar{p}\cdot v}{\bar{p}}$$

$$+\frac{2}{\bar{x}^2}\left(\frac{\bar{\boldsymbol{\nu}}^2}{(\bar{p}\cdot v)^2} - \frac{\bar{\boldsymbol{\kappa}}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)(\bar{p}\cdot k)}\right)(1-\cos[\Omega_{\bar{p}} x_1^+])$$

$$+\frac{2}{x\,\bar{x}}\left(\frac{\boldsymbol{\kappa}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot k)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)}\right.$$

$$\left.\left.+\left(\frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\kappa}}}{(\bar{p}\cdot k)\,(p\cdot v)} - \frac{\boldsymbol{\nu}\cdot\bar{\boldsymbol{\nu}}}{(\bar{p}\cdot v)\,(p\cdot v)}\right)(1-\cos[\Omega_{\bar{p}} x_1^+])\right)\right]$$

- ⋆ **In the limit when $\Theta_{qq} \to 0$, one recovers the spectrum of an asymptotic parton (GB).**



Soft limit: $\mathbf{w} \to \mathbf{0}$

$$w \frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k} \right)\bigg|_{w\to 0}$$

Soft limit: $\mathbf{w \rightarrow 0}$

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k}\right)\bigg|_{w\to 0}$$

Vacuum

Soft limit: $\mathbf{w \rightarrow 0}$

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k} \right)\bigg|_{w\to 0}$$

Vacuum

Medium induced radiation

Soft limit: $\mathbf{w \longrightarrow 0}$

$$w \frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k} \right)\bigg|_{w\to 0}$$

$$w\frac{dN^{N=0}}{d^3k} \propto 2\frac{p\cdot\bar{p}}{(p\cdot k)(\bar{p}\cdot k)}$$ $\Longrightarrow$ **Vacuum: Angular ordered**

Soft limit: w $\longrightarrow$ 0

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k} \right)\bigg|_{w\to 0}$$

$$w\frac{dN^{N=0}}{d^3k} \propto 2\frac{p\cdot\bar{p}}{(p\cdot k)(\bar{p}\cdot k)}$$ $\Longrightarrow$ **Vacuum: Angular ordered**

$$w\frac{dN^{N=1}}{d^3k} \propto \frac{\hat{q}\,L^+}{m_D^2}\left(2\frac{\kappa\cdot\bar{\kappa}}{\kappa^2\,\bar{\kappa}^2} - \frac{1}{\kappa^2} \right)$$ $\Longrightarrow$ **Medium induced**

Soft limit: w $\longrightarrow$ 0

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k}\right)\bigg|_{w\to 0}$$

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$$\frac{L}{\lambda} \ll 1$$

Soft limit: w $\longrightarrow$ 0

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \left(w\frac{dN^{N=0}}{d^3k} + w\frac{dN^{N=1}}{d^3k}\right)\bigg|_{w\to 0}$$

$$w\frac{dN^{N=0}}{d^3k} \propto 2\frac{p\cdot\bar{p}}{(p\cdot k)(\bar{p}\cdot k)}$$

$\Longrightarrow$ **Vacuum: Angular ordered**

$$w\frac{dN^{N=1}}{d^3k} \propto \frac{\hat{q}\,L^+}{m_D^2}\left(2\frac{\kappa\cdot\bar{\kappa}}{\kappa^2\,\bar{\kappa}^2} - \frac{1}{\kappa^2}\right)$$

$\Longrightarrow$ **Medium induced**

$$\frac{L}{\lambda} \ll 1$$

Antiangular ordered: depletion of soft radiation to large angles !!!

Soft limit: w $\longrightarrow$ 0

$$w \frac{dN}{d^3k}\bigg|_{w\to 0} = \frac{1}{\kappa^2}(1-\Delta_s) - 2\frac{\kappa\cdot\bar{\kappa}}{\kappa^2\,\bar{\kappa}^2}(1-\Delta_s) + \frac{1}{\bar{\kappa}^2}, \qquad \Delta_s = \frac{\hat{q}\,L^+}{m_D^2}$$

Hard medium independent radiation reduced by the probability Δ_s that one interaction of the projectile occurs in the medium

Soft limit: w $\longrightarrow$ 0

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \frac{1}{\kappa^2}(1-\Delta_s) - 2\frac{\kappa\cdot\bar{\kappa}}{\kappa^2\,\bar{\kappa}^2}(1-\Delta_s) + \frac{1}{\bar{\kappa}^2}\,, \qquad \Delta_s = \frac{\hat{q}\,L^+}{m_D^2}$$

Quark-Quark Interference reduced by the probability Δ_s after the interaction of the projectile inside the medium

Soft limit: w $\longrightarrow$ 0

$$w\frac{dN}{d^3k}\bigg|_{w\to 0} = \frac{1}{\kappa^2}(1-\Delta_s) - 2\frac{\kappa\cdot\bar{\kappa}}{\kappa^2\,\bar{\kappa}^2}(1-\Delta_s) + \frac{1}{\bar{\kappa}^2}\,, \qquad \Delta_s = \frac{\hat{q}\,L^+}{m_D^2}$$

In the presence of a QGP, partons with small x are reduced in the Initial State Radiation

$\Rightarrow$ **In agreement with expectations from CGC**

$\Rightarrow$ **Phenomenological implications for observables sensitive to the initial state radiation**

Conclusions

- We study coherence effects for medium induced gluon radiation in the N=1 opacity expansion.
- In the soft limit we found a very rich structure of the medium induced radiation which provides a very intuitive probabilistic interpretation.
- Future work (stay tuned) :

  ☆ Numerical results for the N=1 opacity

  ☆ Multiple soft scattering and numerical studies

  ☆ Using modifications of initial state radiation due to QCD medium for phenomenology...
- First steps towards in medium jet calculus and medium evolution equations.