Recent developments in jet quenching theory

Liliana Apolinário

Universidade de Santiago de Compostela

CENTRA-IST

Special thanks to : Nestor Armesto, Guilherme Milhano and Carlos Salgado

July 19th, 2013

EPS-HEP, Stockholm, Sweden

For recent developments in lattice, see Panero's talk
(Saturday, Non-perturbative QCD session)

(Some) Recent developments in jet quenching theory

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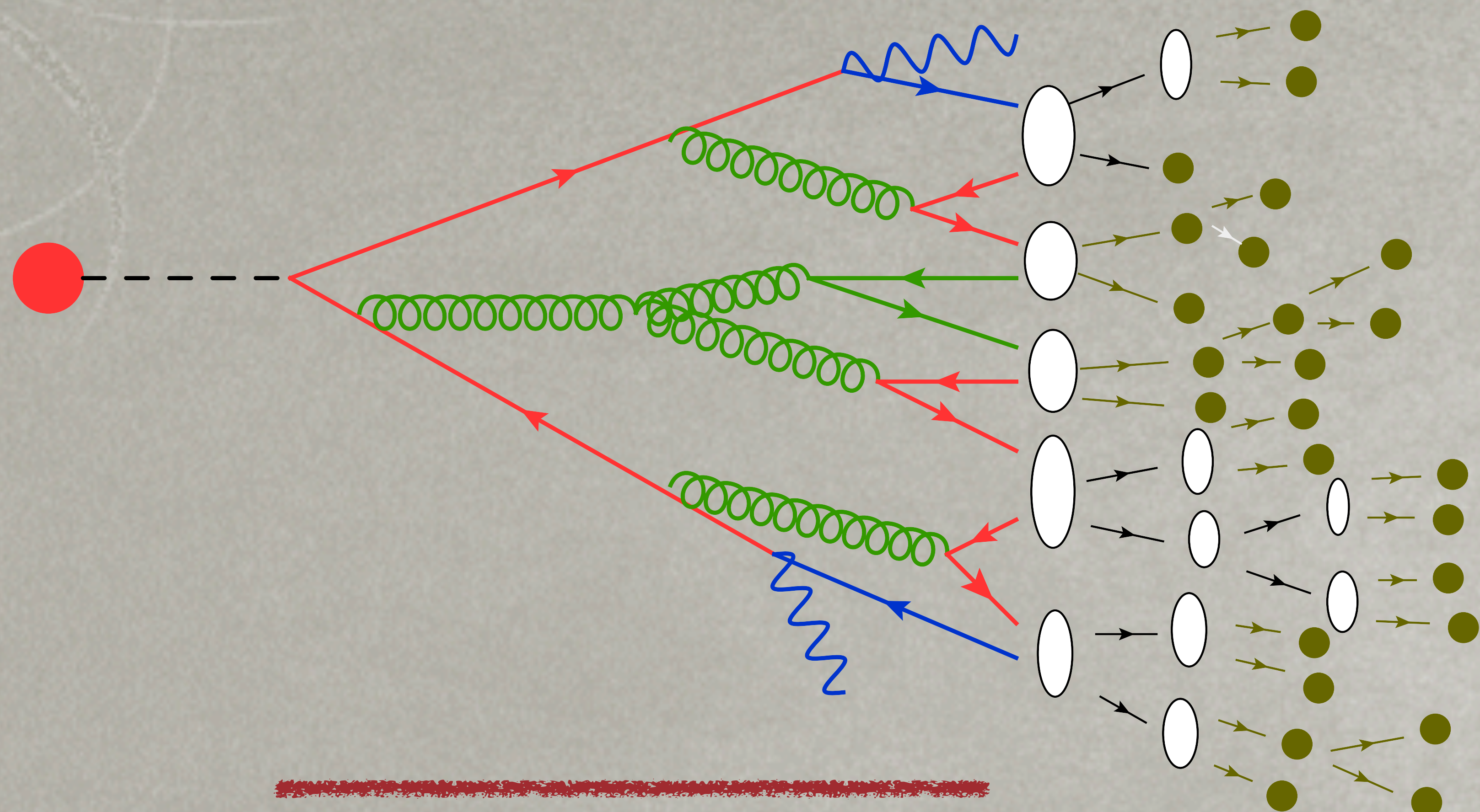
Introduction

- Parton Branching:

Introduction

- Parton Branching:

Hard Scattering (matrix element)



Hadrons (measured)

Parton showering:
- Calculable through pQCD
- Known in vacuum

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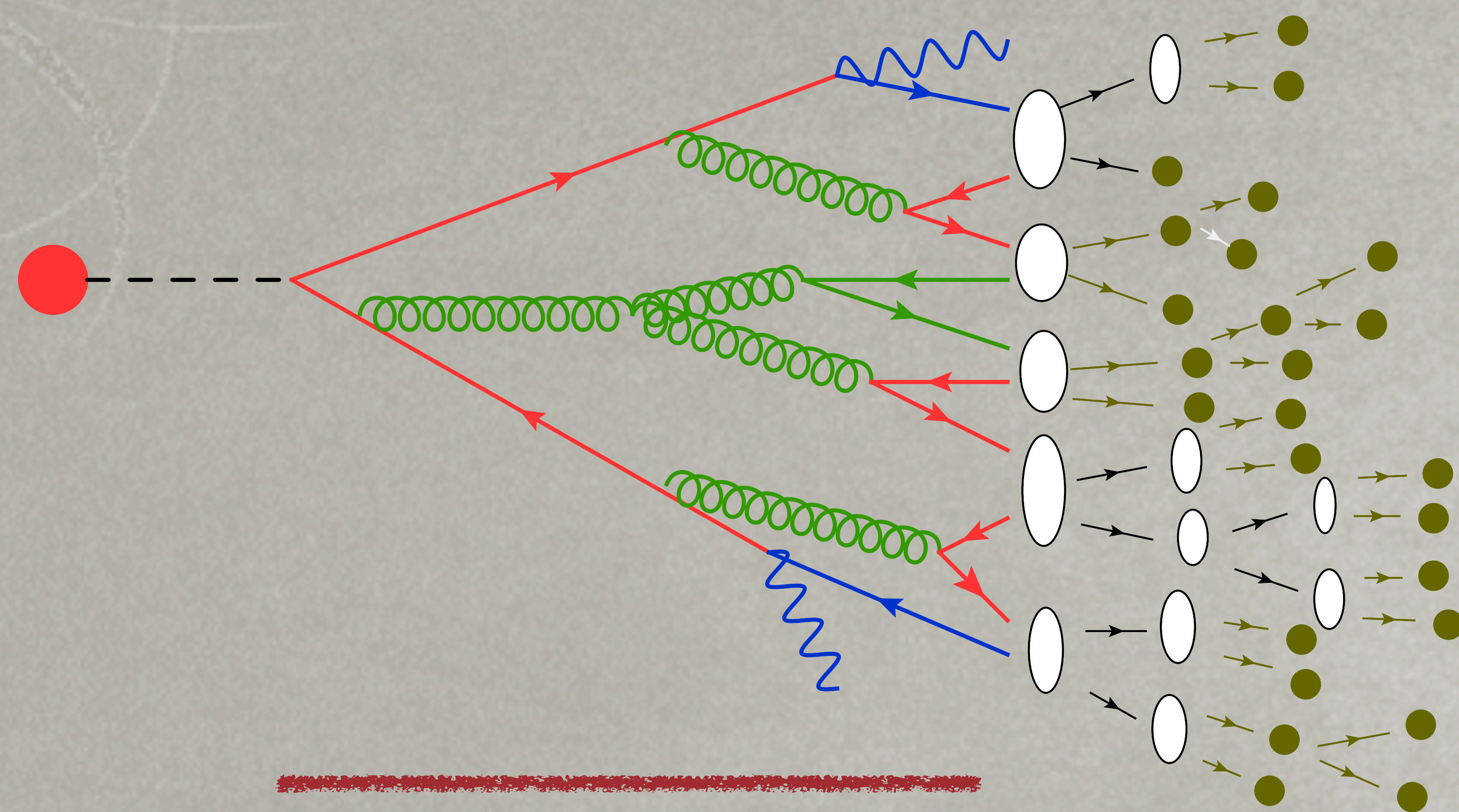

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Hadronization
- Universal/process independent
- Not described by pQCD

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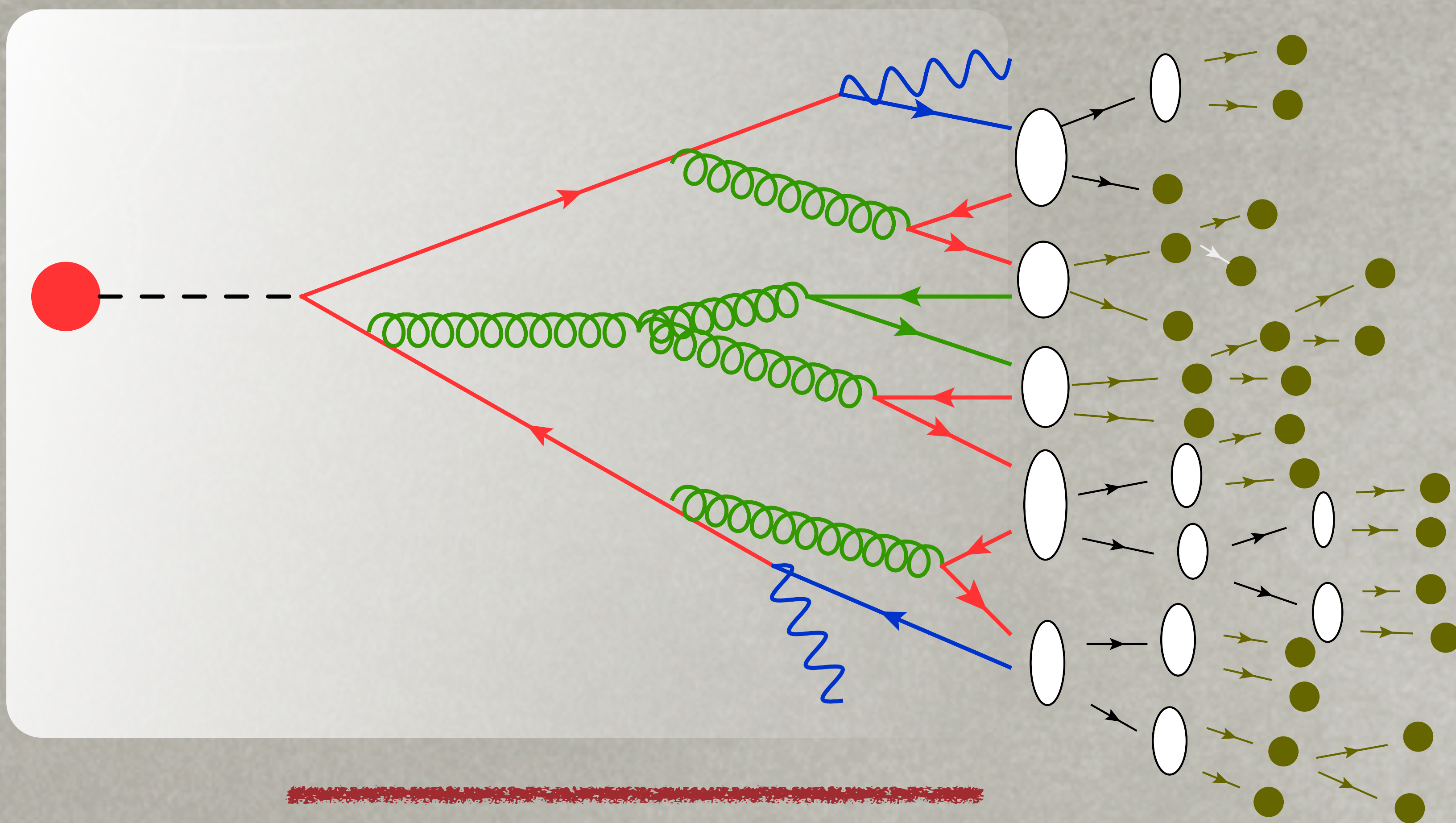


Hadrons (measured)

Medium

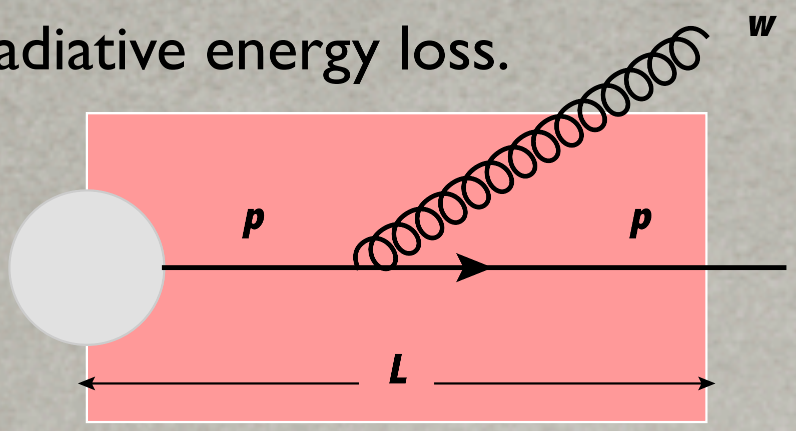
What are the main mechanisms of in-medium energy loss?

Parton showering:
- Calculable through pQCD
- Known in vacuum
- Medium?

Hadronization
- Universal/process independent
- Not described by pQCD

Jet Quenching "before LHC"

- Standard jet quenching models: description in terms of radiative energy loss.
  - Four classes of formalisms based on pQCD:
    - Baier-Dokshitzer-Mueller-Peigné-Schiff–Zakharov and Armesto-Salgado-Wiedemann (BDMPS-Z/ASW)
    - Gyulassy-Levai-Vitev (GLV)
    - Arnold-Moore-Yaffe (AMY)
    - Higher-Twist (HT)



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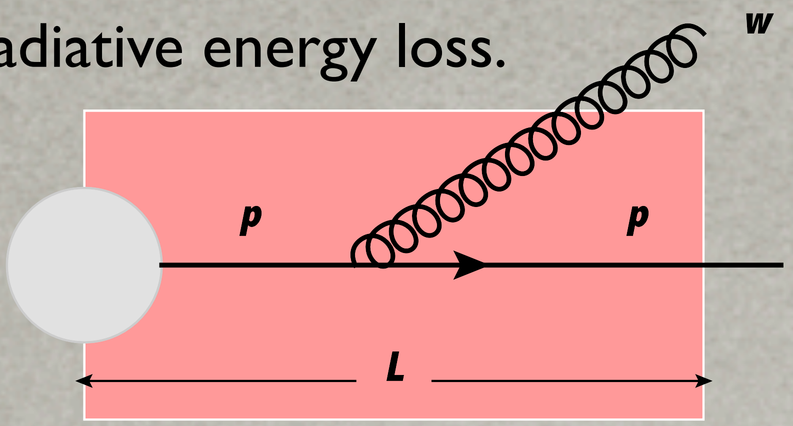

  - Usual characteristics:
    - Neglect recoil (elastic energy loss not included);
    - Work in the limit of soft ($x \to 0$) (except AMY) and collinear ($k_T << \omega$) gluon emissions;
    - Assume multiple gluon emissions as a factorization of single gluon emissions.

Jet Quenching "before LHC"

- Problems/limitations of jet quenching models:
  - Phenomenological extension into large x and large angle domain:
    - Extensions beyond the formalism domain lead to large discrepancies [1106.1106].

      ⇒ Calculation of single emission process in a more general kinematic range

      Several efforts within the path-integral formalism and SCET

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  - Shower evolution based on multi-gluon radiation:
    - Problem of color coherence between different emitters.

      ⇒ Propagation of color correlated sources inside a colored medium

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  - Hadronization unmodified by the presence of a medium;
    - Color (de)coherence can induce modifications independently of where hadronization takes place.

      ⇒ Extension of medium-induced gluon radiation to the study of color-differential case

      Study of medium-modified color connections

Jet Quenching "before LHC"

"Outline" of this talk

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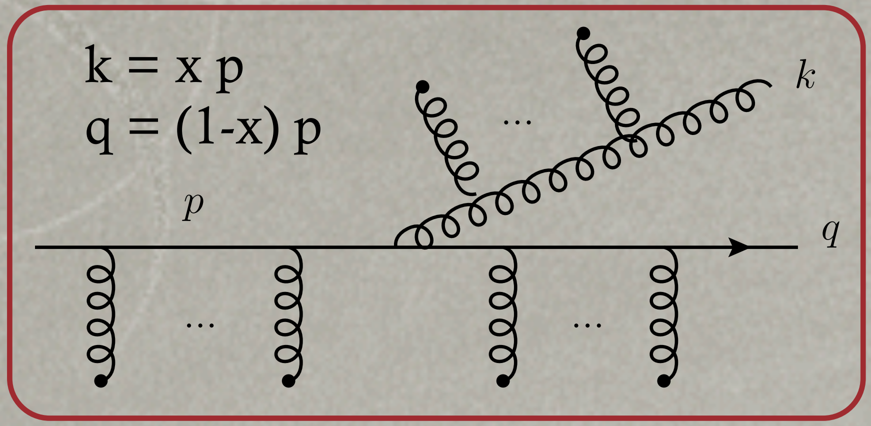
⇒ Extension of medium-induced gluon radiation to the study of color-differential case

Study of medium-modified color connections

Medium-induced radiation

- Radiative energy loss assumed to be the dominant process:
  - Particle propagation inside a medium:



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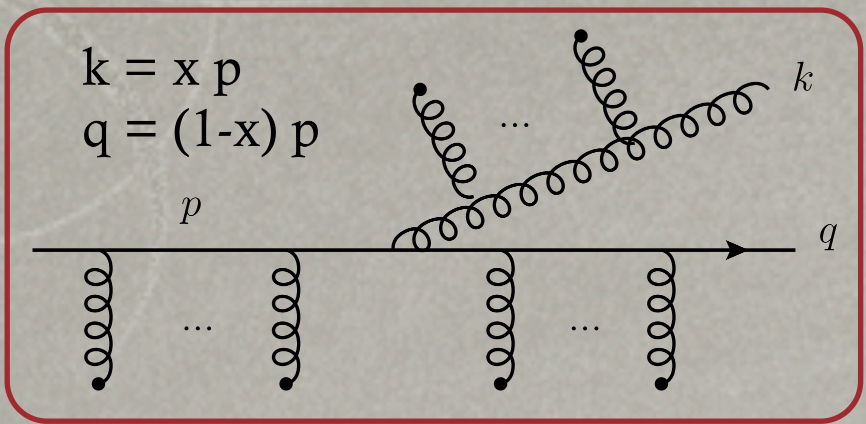
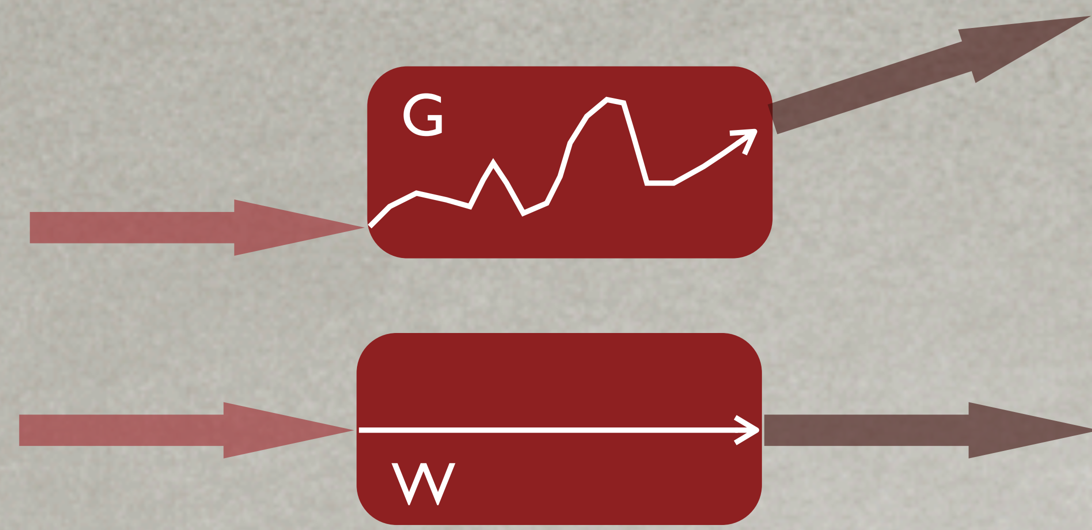




  - Highly energetic partons described by a Wilson Line:

$$W(x_{0+}, L_+; \mathbf{x}_\perp) = \mathcal{P} \exp \left\{ ig \int_{x_{0+}}^{L_+} dx_+ A_-(x_+, \mathbf{x}_\perp) \right\}$$

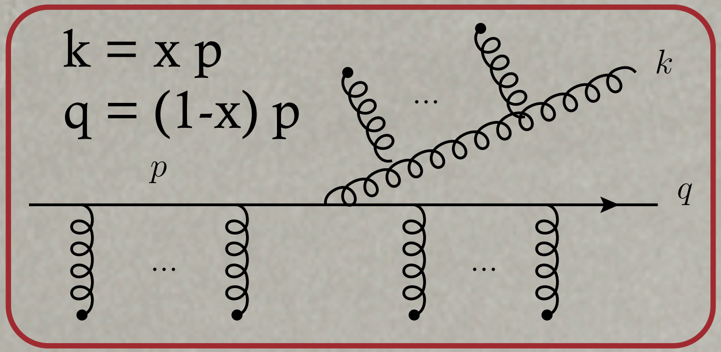
  - Less energetic particles described by a Green's Function:

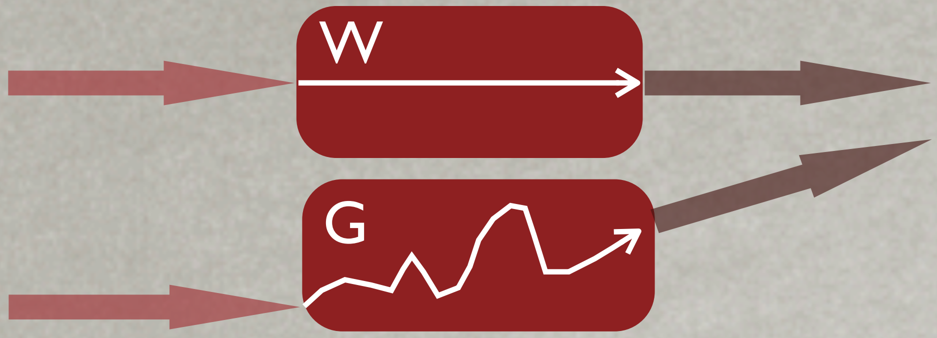
$$G(x_{0+}, \mathbf{x_0}_\perp; L_+, \mathbf{x}_\perp | p_+) = \int_{\mathbf{r}_\perp(x_{0+})=\mathbf{x_0}_\perp}^{\mathbf{r}_\perp(L_+)=\mathbf{x}_\perp} \mathcal{D}\mathbf{r}_\perp(\xi) \exp \left\{ \frac{ip_+}{2} \int_{x_{0+}}^{L_+} d\xi \left(\frac{d\mathbf{r}_\perp}{d\xi} \right)^2 \right\} \times W(x_{0+}, L_+; \mathbf{r}_\perp(\xi)),$$

Medium-induced radiation

LA, Armesto and Salgado [1204.2929]

- Radiative energy loss assumed to be the dominant process:
  - Particle propagation inside a medium:
    - Contribution in the opposite limit allows to find an interpolation function between the two limits:





    - Numerical results:

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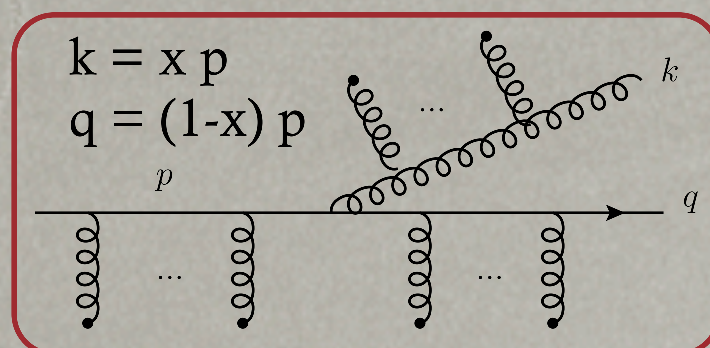

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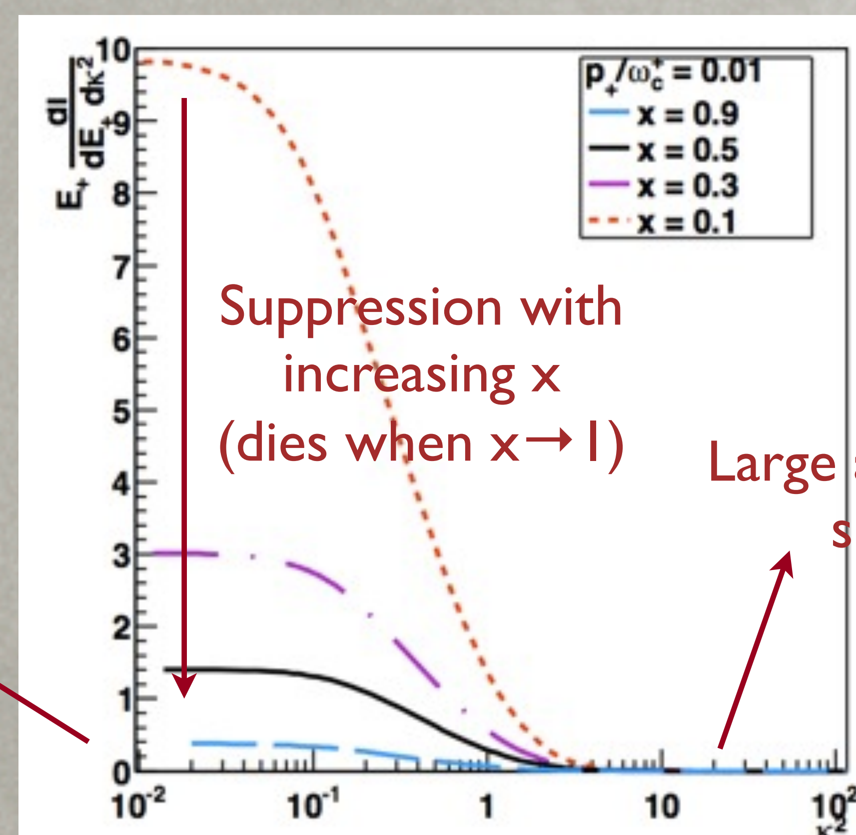
Dimensionless variables

Energy:

$$\frac{p_+}{\omega_c^+} = \frac{2p_+}{\hat{q}_A L_+^2}$$

Transverse momentum:

$$\kappa^2 = \frac{q_\perp^2}{\hat{q}_A L_+}$$



No collinear divergency

Medium information encoded in:
L_+: Medium length
q_A: Transport coefficient

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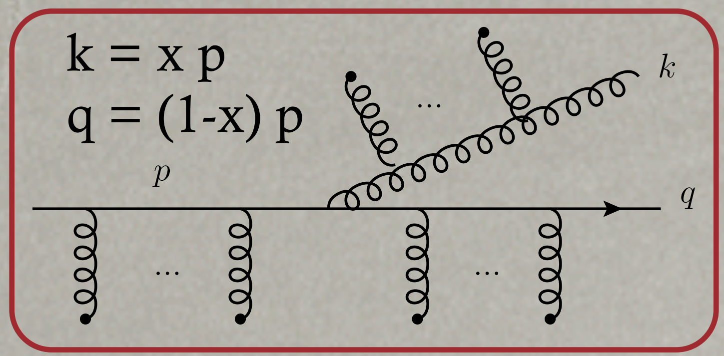

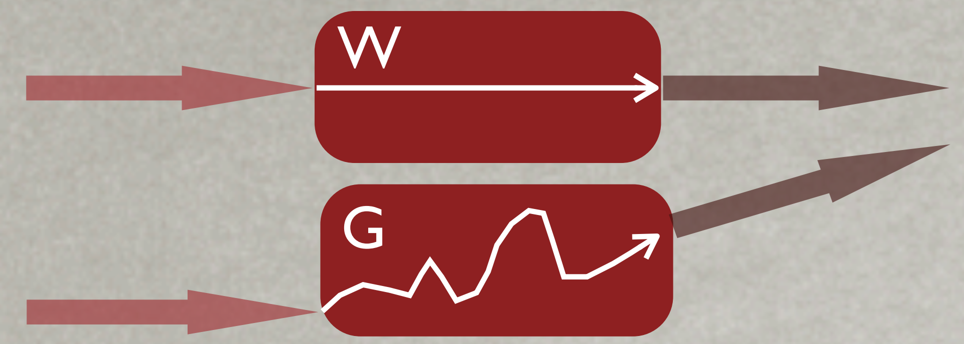

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Decreasing ω_c:

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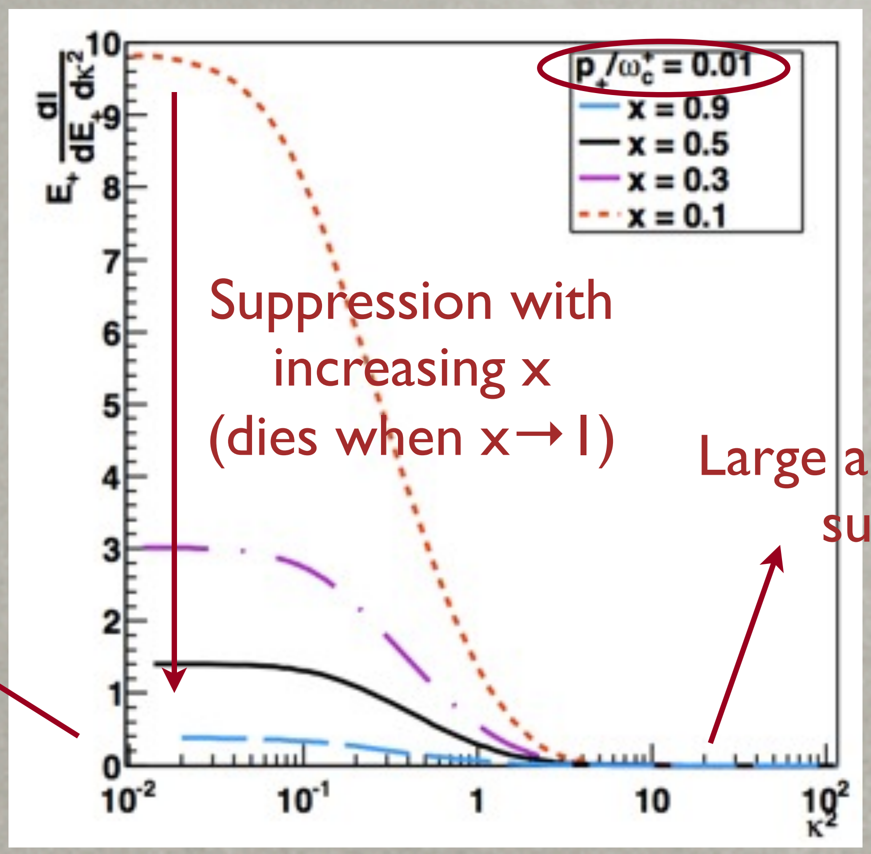

Large angle emissions suppressed

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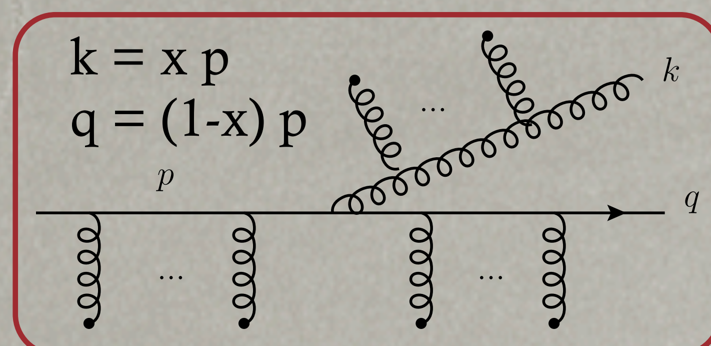

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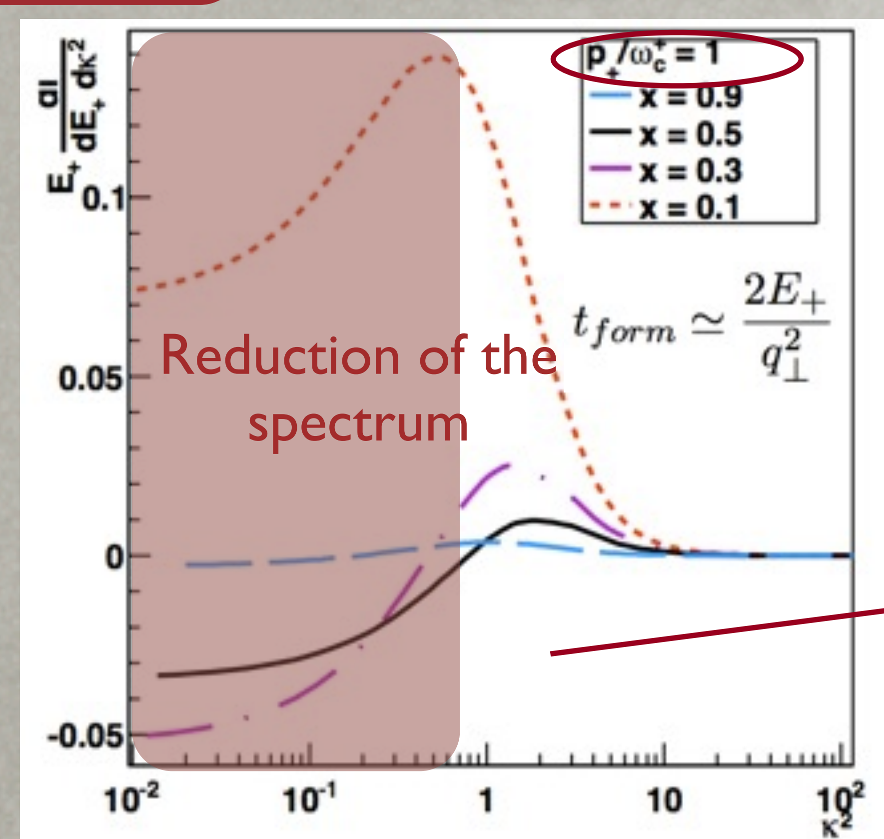

Medium information encoded in:
L_+: Medium length
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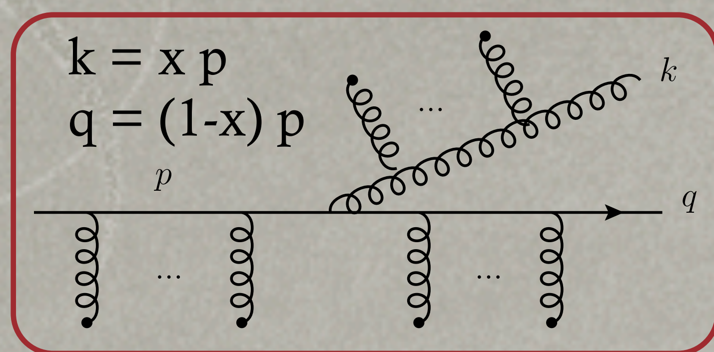
If $t_{form} >> L$, whole medium act as a single scattering center (LPM effect in QCD)

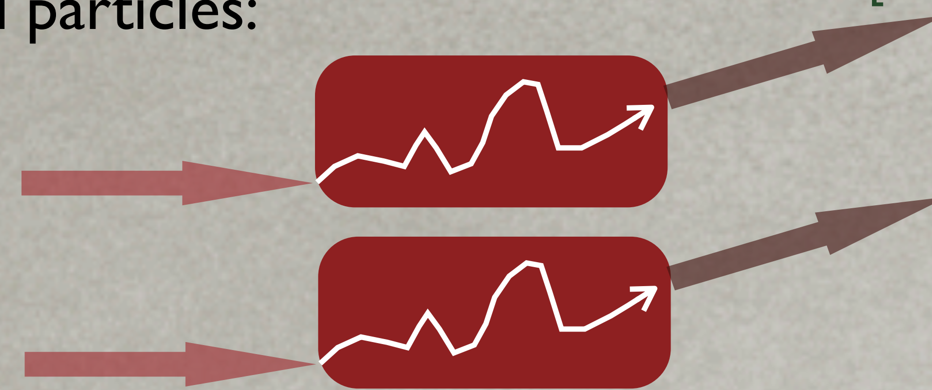
Medium-induced radiation

Blaizot, Dominguez, Iancu, Mehtar-Tani
[1209.4585]

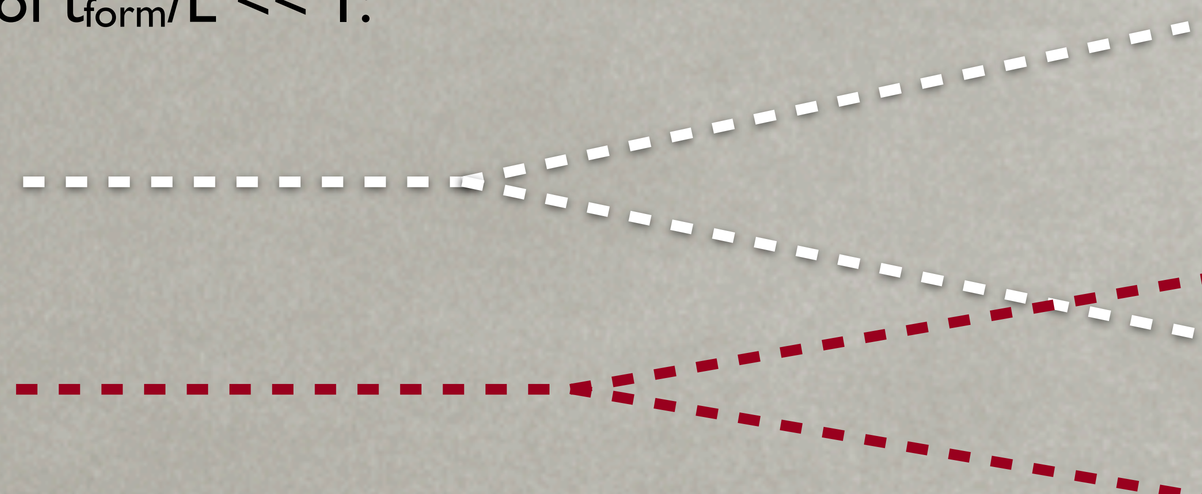
Extension beyond small t_{form}:
LA, Armesto, Milhano and Salgado
[in prep]

- Gluon branching process:
  - Free the transverse motion of all particles:





  - Limit of $t_{form}/L << 1$:



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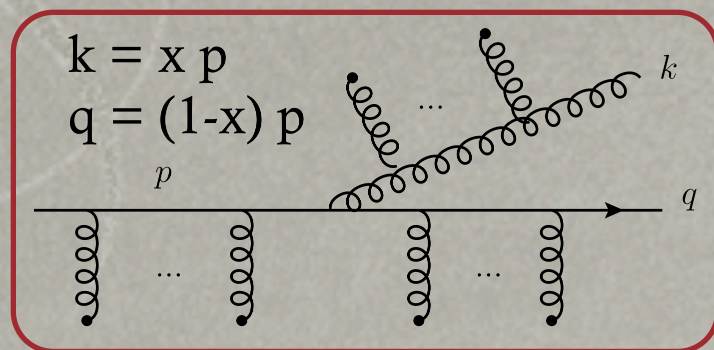
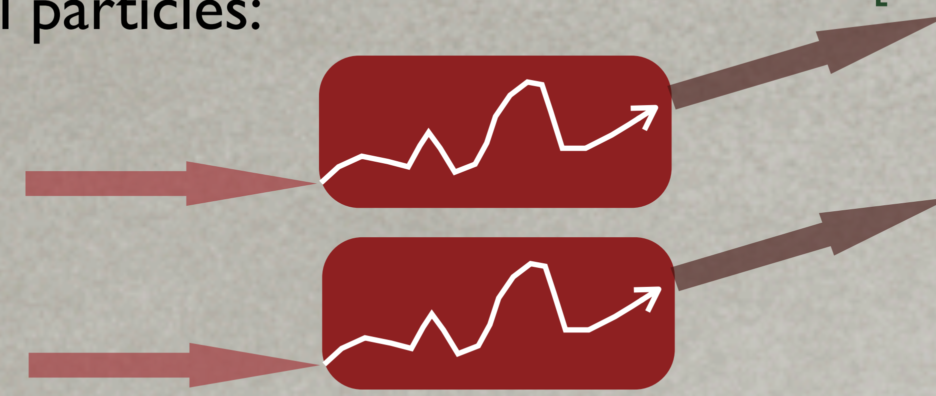
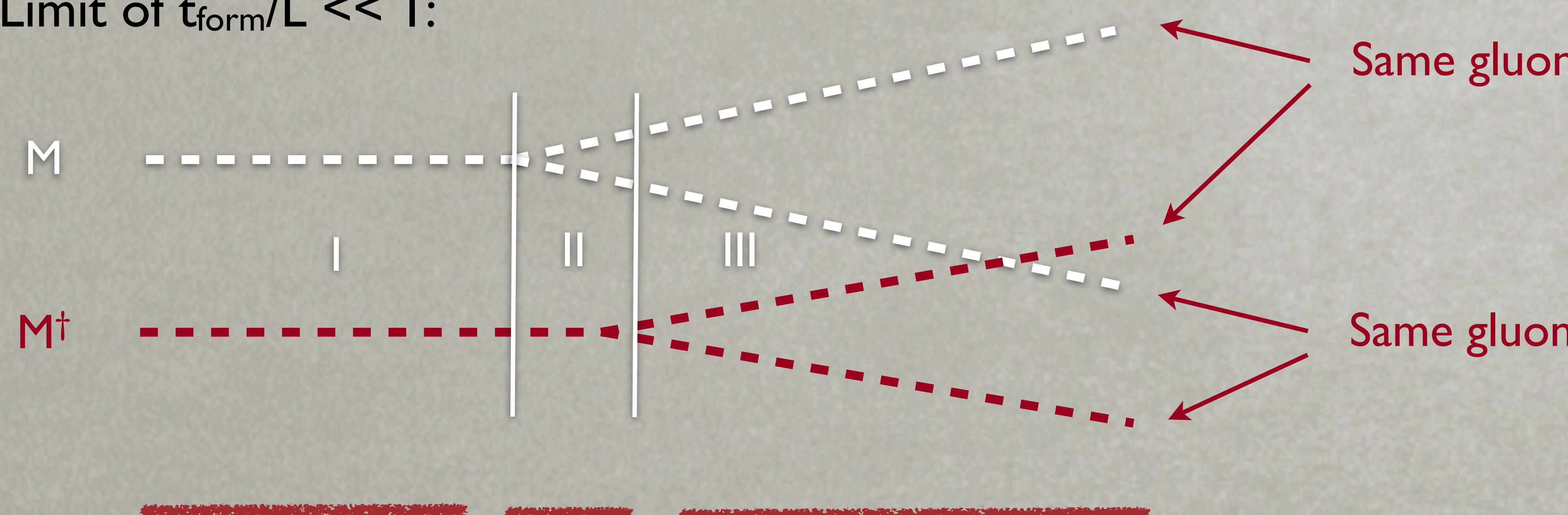




  - Limit of $t_{form}/L \ll 1$:



Random walk of initial parton

t_{form} (Parametrically goes to 0)

Decoherence of final gluons

Medium-induced radiation

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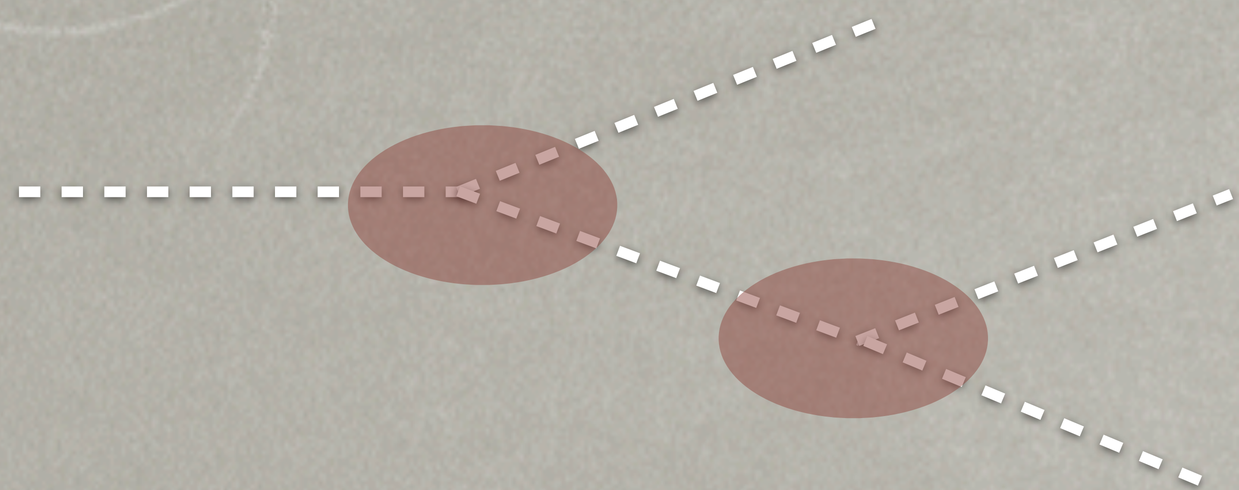
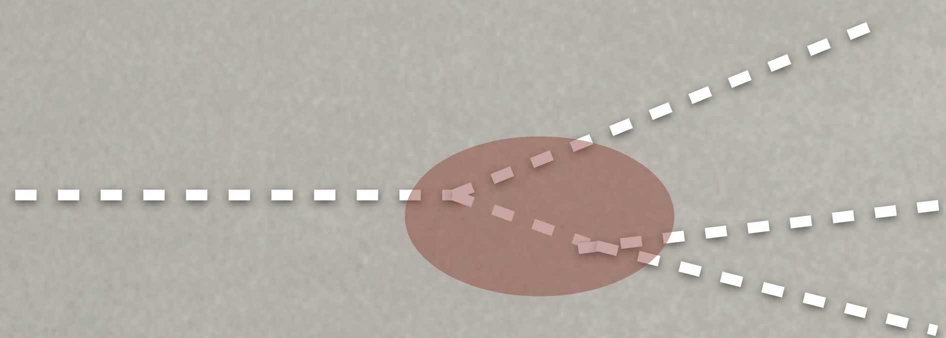
Extension beyond small t_{form}: LA, Armesto, Milhano and Salgado [in prep]

- Gluon branching process:
  - Limit of $t_{form}/L << 1$:
    - Decoherence of final gluons can provide a probabilistic picture



$$\sim \left(\alpha_s \frac{L}{t_f}\right)^2$$

Independent emissions are enhanced within the considered limit



$$\sim \alpha_s^2 \frac{L}{t_f}$$

Showering can be understood as a factorization of single gluon emissions for $t_{form} << L$

Momentum broadening

Original works:
Idilbi, Majumder [0808.1087]

- Soft Collinear Effective Theory (SCET):
  - Other framework to describe dynamics of highly energetic quarks and gluons (radiative and collisional energy loss);
  - Based on a scale separation: Q >> l_T >> T $\Rightarrow \lambda \equiv \frac{T}{Q} \ll 1$

Hard parton energy

Soft scale characteristic of the medium

Transverse momentum of radiated gluon

D'Eramo, Liu, Rajagopal
[1010.0890, 1006.1367]
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    Hard parton energy

    Transverse momentum of radiated gluon

    Soft scale characteristic of the medium
  - Setup:
    - High energy parton with $p_0 = (0, Q, 0)$ that exchanges Glauber gluons $p_G \sim Q\ (\lambda^2, \lambda^2, \lambda)$ with the medium.
    - After interaction, $p_0 \rightarrow p_c \sim Q\ (\lambda^2, 1, \lambda)$
    - Continuous kicks to hard parton result in significant transverse momentum broadening (Brownian motion)
  - Lagrangian degrees of freedom: p_G, p_c and $p_s \sim (\lambda^2, \lambda^2, \lambda^2)$ (subset of Glauber gluons)
    - Feynman rules $\Rightarrow$ Medium-induced splitting kernels

D'Eramo, Liu, Rajagopal
[1010.0890, 1006.1367]
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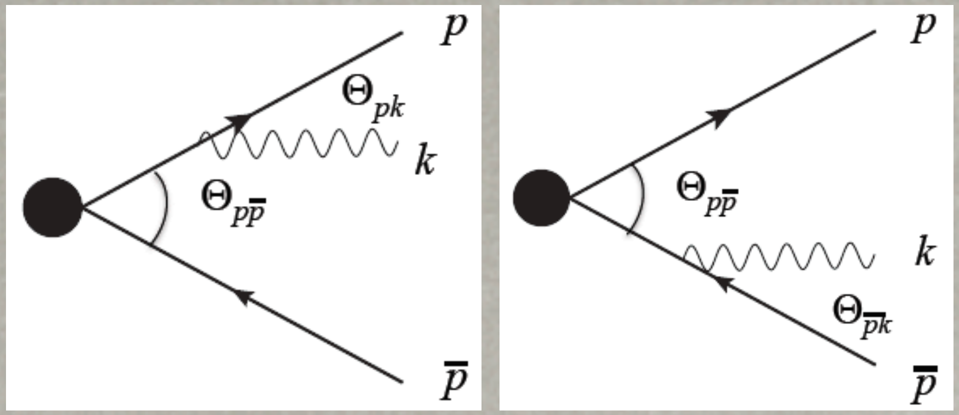
[1103.1074, 1109.5619]

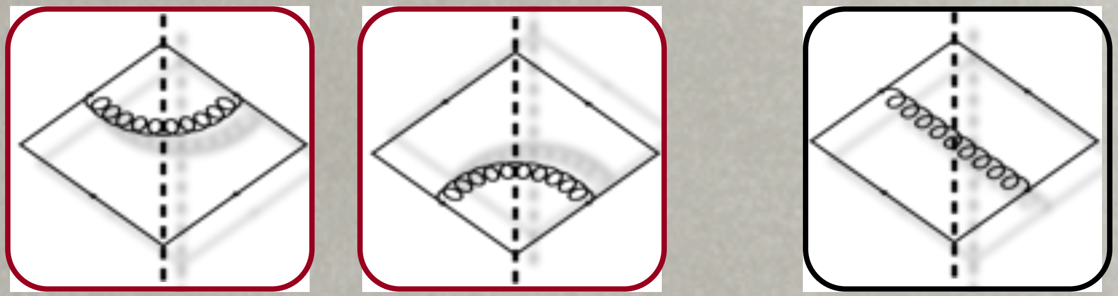
Color (de)coherence

- Vacuum angular ordering property determined in the antenna setup:
  - Diagrams:



  - Radiation spectrum contributions:

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



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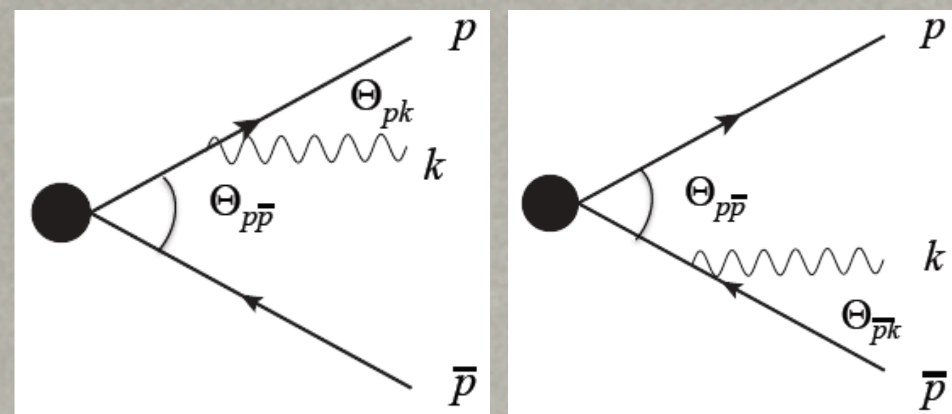

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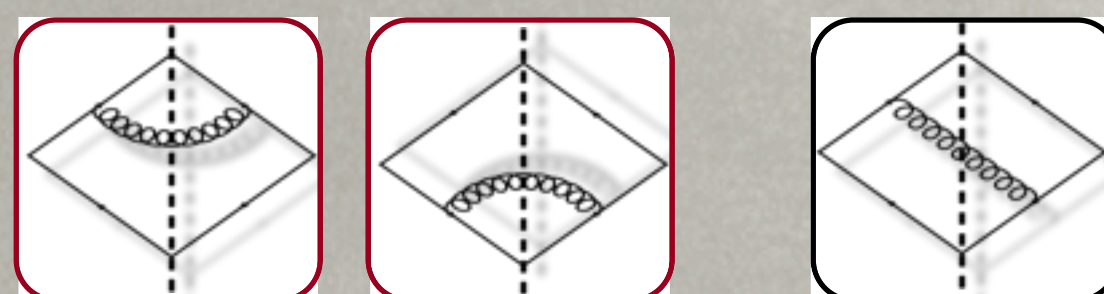
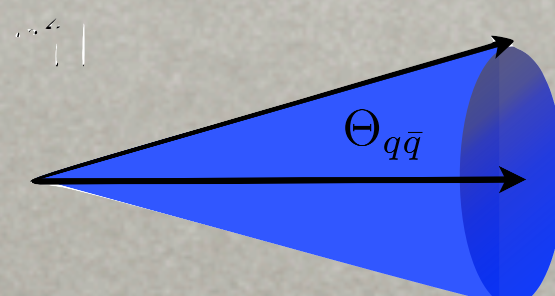


Destructive interferences suppress large angle emission

- Coherent radiation spectrum off a quark (same for anti-quark):

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

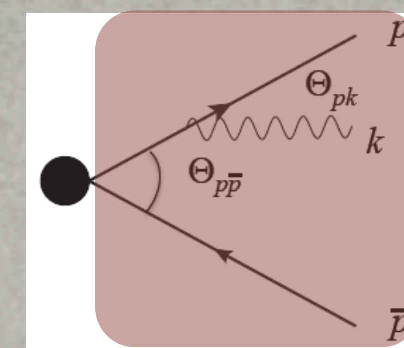
IRC divergent   Angular Ordering



Color (de)coherence

Mehtar-Tani, Salgado and Tywoniuk
[1009.2965, 1102.4317, 1112.5031]

- Ordering properties within in-medium antenna setup:
  - Same contributions to radiation spectrum:



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Casalderrey-Solana and Iancu
[1105.1760]

Massive antenna:
Armesto, Ma, Mehtar-Tani,
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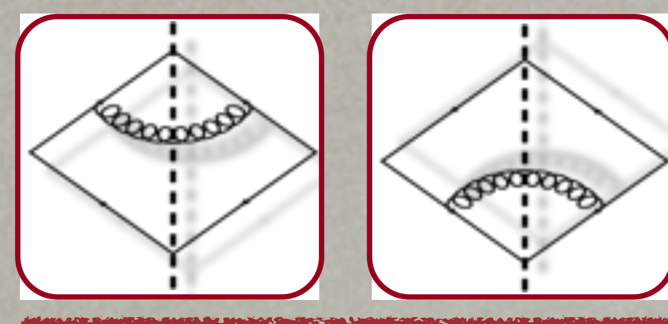

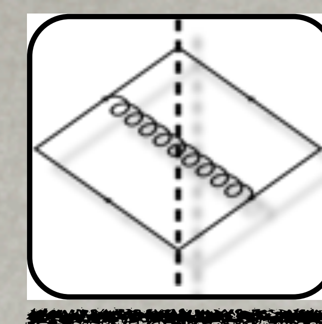

BDMPS-Z/GLV independent spectrum:
- IRC safe;
- LPM interference;
- Broad angular structure;

Interference spectrum:
- Vacuum-like radiation (IR divergent and collinear safe)
- In-cone radiation suppressed;

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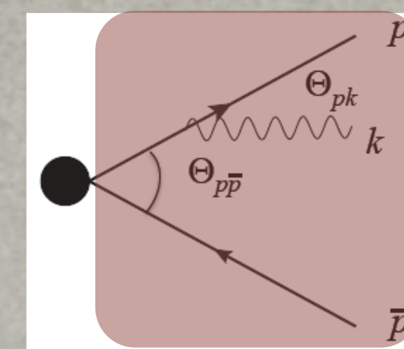

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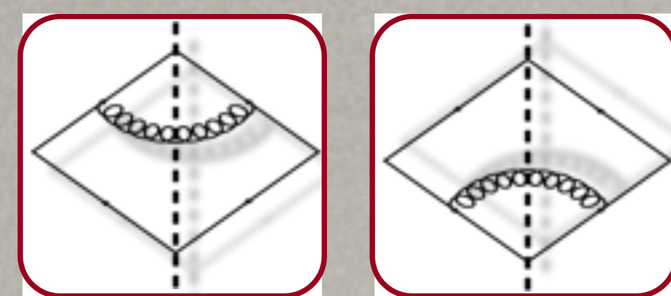

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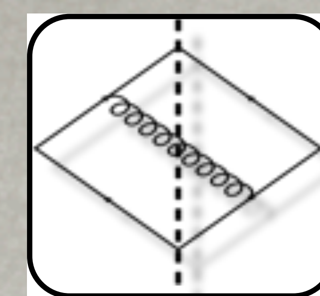
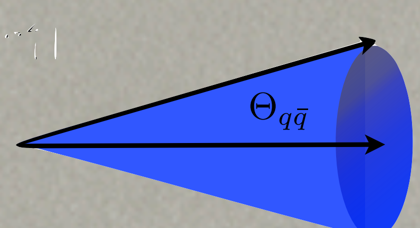


Interference spectrum:
- Vacuum-like radiation (IR divergent and collinear safe)
- In-cone radiation suppressed;

- Total gluon spectrum off an antenna in the soft limit (vacuum + medium):

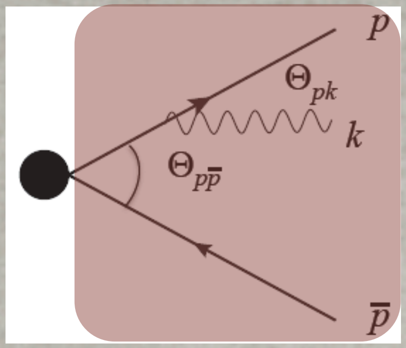


$$dN_q^{\rm tot}\big|_{\omega\to 0} = \frac{\alpha_s C_F}{\pi}\,\frac{d\omega}{\omega}\,\frac{\sin\theta\ d\theta}{1-\cos\theta}\Big[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\Big]$$

Angular ordering

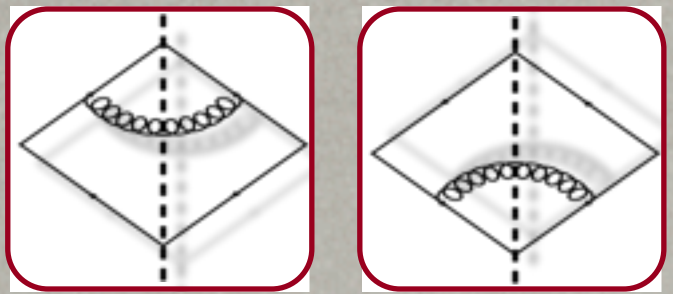
Color (de)coherence

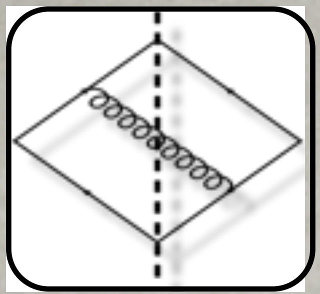
Mehtar-Tani, Salgado and Tywoniuk
[1009.2965, 1102.4317, 1112.5031]



- Ordering properties within in-medium antenna setup:
  - Same contributions to radiation spectrum:

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





Casalderrey-Solana and Iancu
[1105.1760]

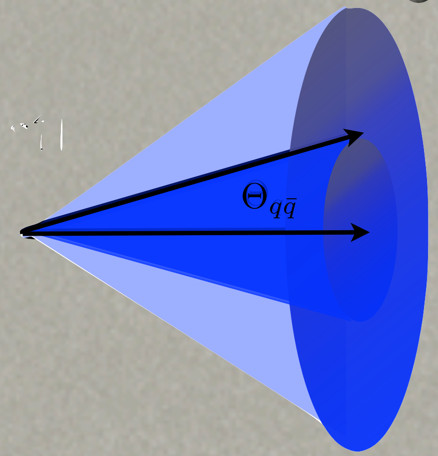
Massive antenna:
Armesto, Ma, Mehtar-Tani, Salgado and Tywoniuk
[1110.4343]

BDMPS-Z/GLV independent spectrum:
- IRC safe;
- LPM interference;
- Broad angular structure;

Interference spectrum:
- Vacuum-like radiation (IR divergent and collinear safe)
- In-cone radiation suppressed;

- Total gluon spectrum off an antenna in the soft limit (vacuum + medium):

$$dN_q^{\mathrm{tot}}\Big|_{\omega\to 0} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\, d\theta}{1-\cos\theta}\Big[\underbrace{\Theta(\cos\theta - \cos\theta_{q\bar{q}})}_{\text{Angular ordering}} + \underbrace{\Delta_{\mathrm{med}}\Theta(\cos\theta_{q\bar{q}} - \cos\theta)}_{\text{Antiangular ordering}}\Big]$$



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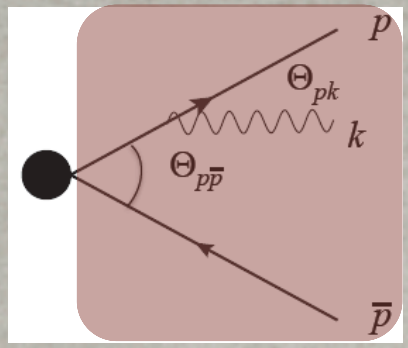

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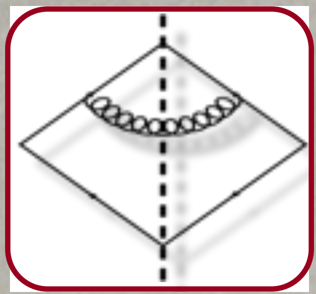
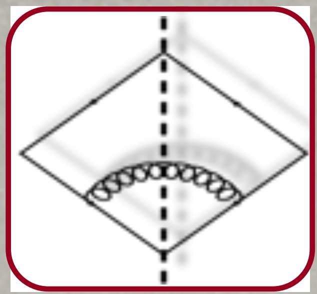
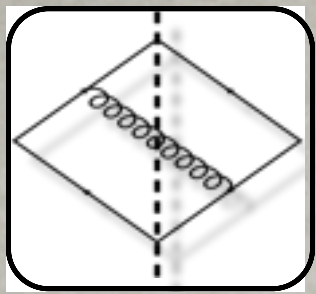
Δ_{med} = 0: No medium effects
Δ_{med} = 1: Complete decorrelation of emitters







Casalderrey-Solana and Iancu [1105.1760]

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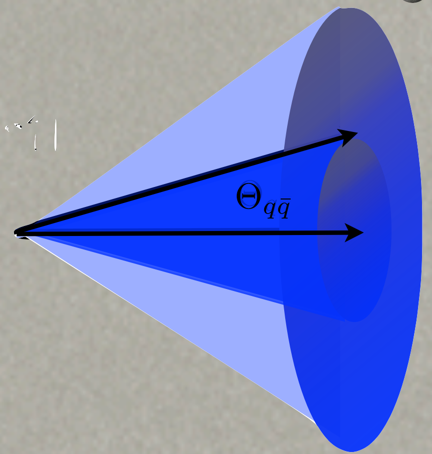

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Angular ordering

Antiangular ordering

Interference effects open up radiation phase space

Color Flow

- Final state of a parton shower needs to be interfaced with an hadronization prescription:
  - Lund Model (implemented in PYTHIA): color connection through a string between a quark-antiquark pair, with gluons as kinks.
  - Singlet clusters (implemented in HERWIG): clusters color singlet objects, where gluons are split into quark-antiquark pairs.

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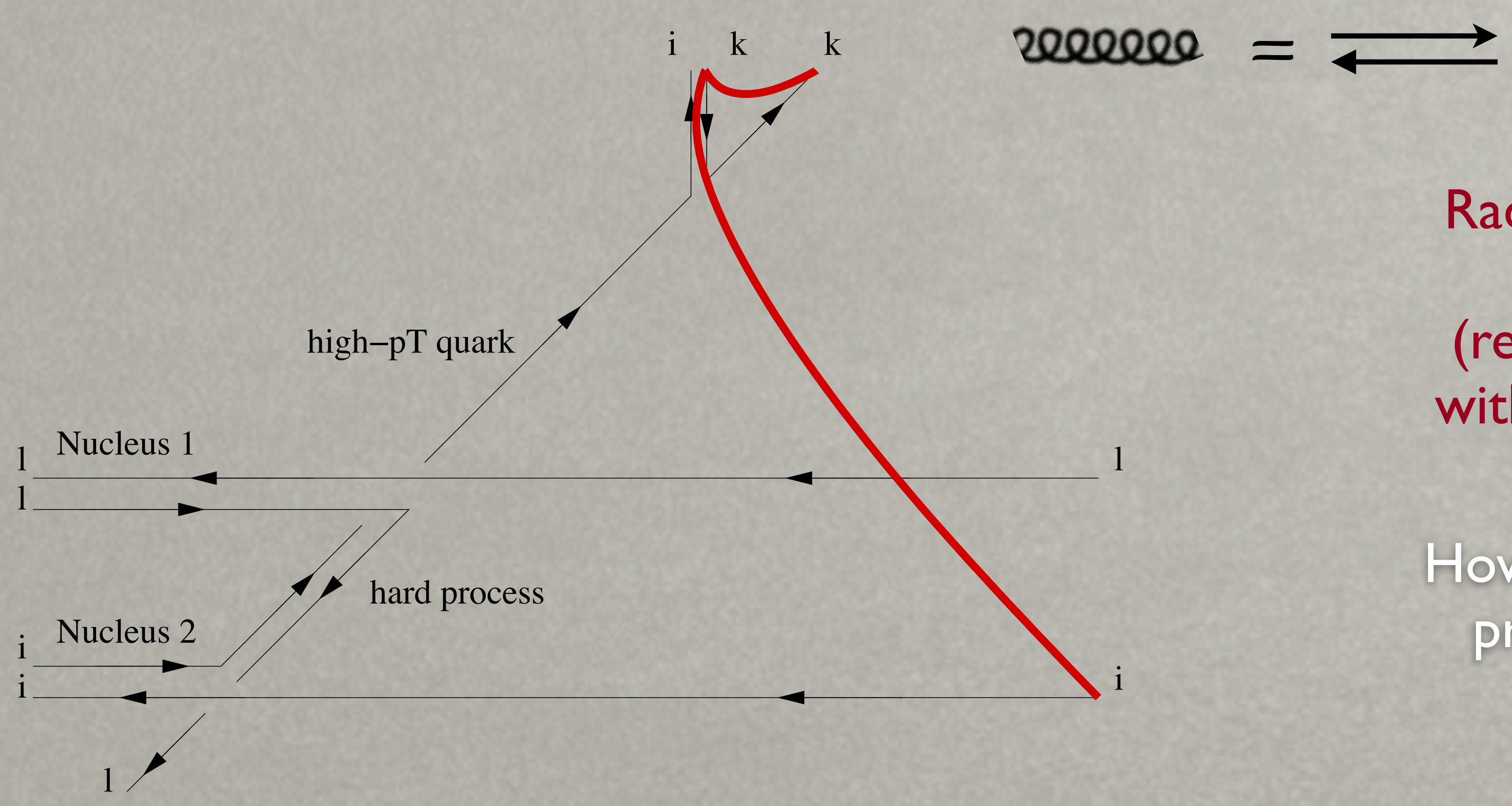
  - Singlet clusters (implemented in HERWIG): clusters color singlet objects, where gluons are split into quark-antiquark pairs.
- Vacuum color connections, in the large N_c limit, as:



Radiated gluons is part of the same string (remain color connected with the leading fragment)

How is this modified in the presence of a medium?

Color Flow

Beraudo, Milhano and Wiedemann [1109.5025, 1204.4342]
Aurenche, Zakharov [1109.6819]

- Color flows in the presence of a medium, within Lund string model (first order in opacity expansion:
  - Two possible situations:
    - No medium interaction after emission:
    - Medium interaction after emission:

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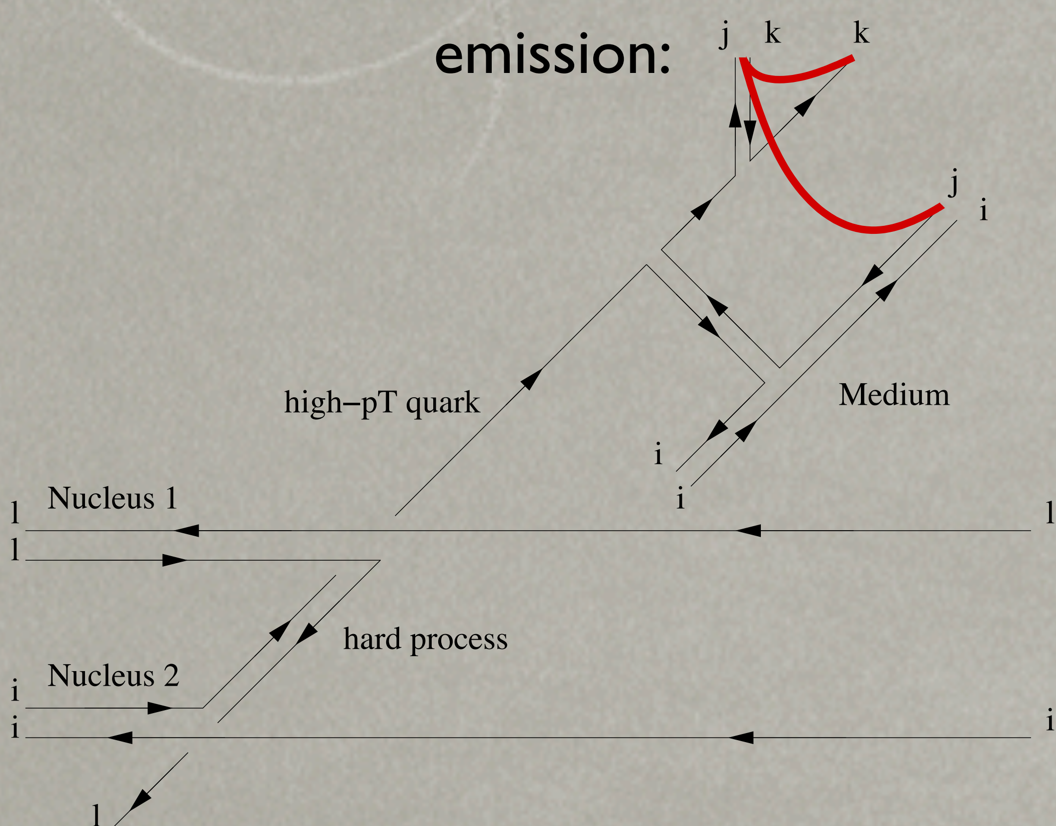
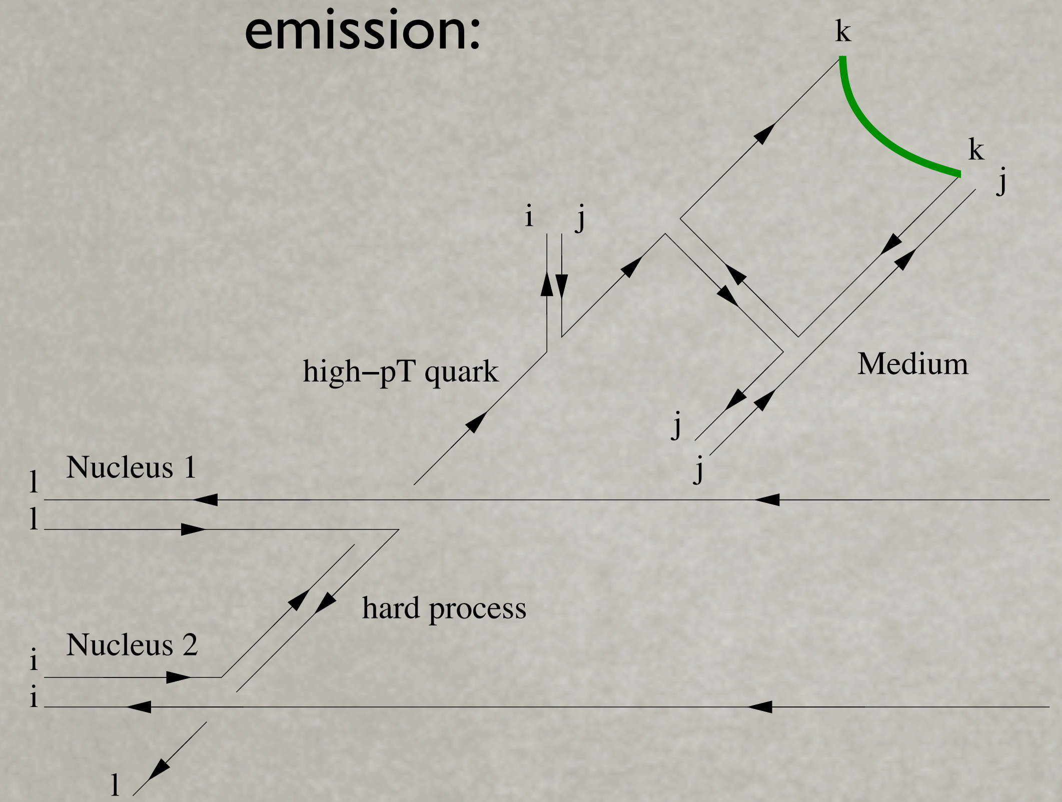


Gluon belongs to the string that will form leading fragment (as in vacuum)



Gluon decohered from the leading string ⇒ Energy is lost

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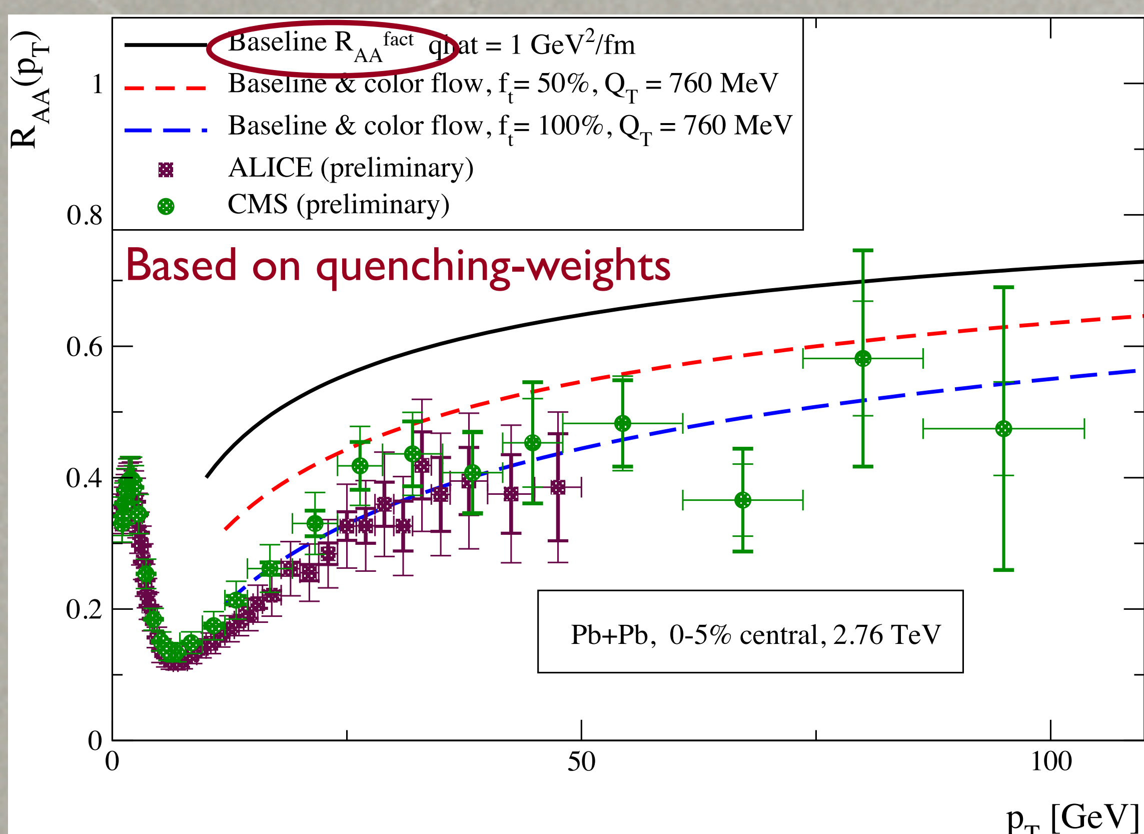
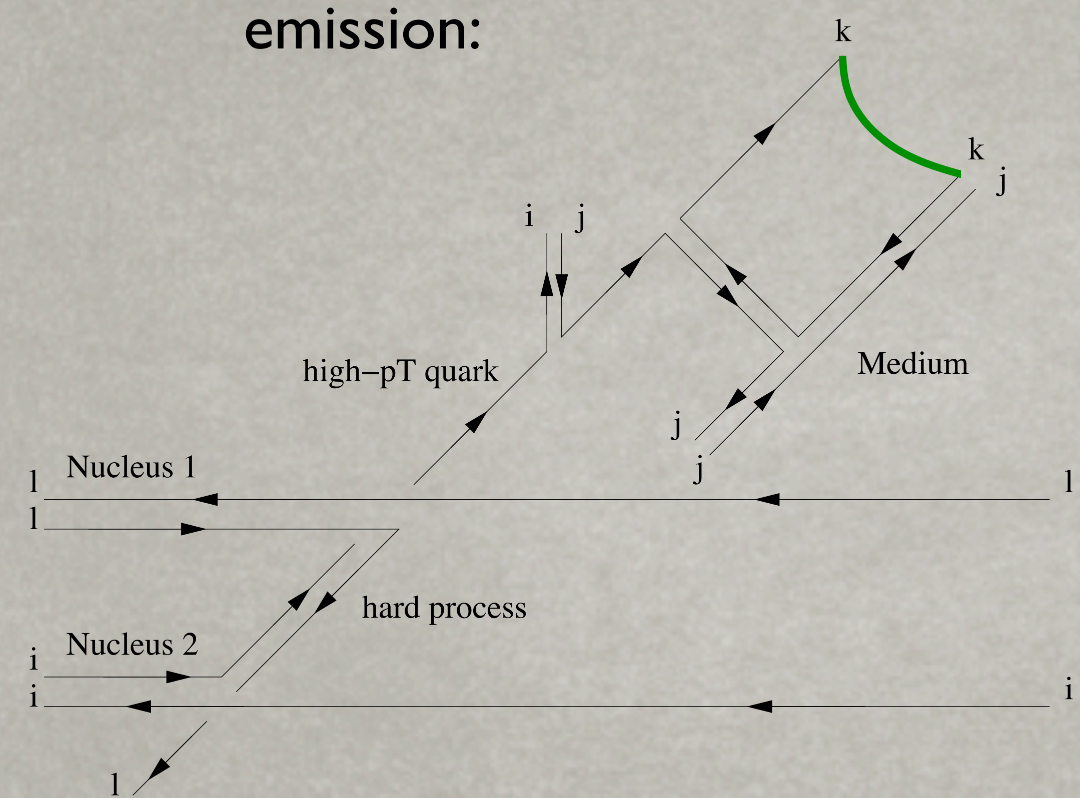
[1109.5025]



Induces an extra amount of energy loss
⇒ Same qhat but a larger effect in the R_{AA}

- Medium interaction after emission:



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Summary

- There has been several developments in the jet quenching theory, to build a complete picture of the shower branching in the medium.
  - Improvements in the kinematics:
    - Relaxation of approximations to account for finite energy loss, instead of soft and collinear radiation;
      - Several works within the path-integral and SCET formalisms.
  - Improvements in the parton shower evolution:
    - Identification of a probabilistic picture for $L \gg t_{form}$;
    - Developments in the angular structure of color correlated pairs, with a clear identification of the relevant scales that allow for a geometrical separation of the radiation;
    - Study of the modification of color connections inside a hot and dense medium;

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Relevant for particle and jet observables @ AA
Phenomenological use of these new theoretical ingredients is under development!

Thanks!

Backup slides

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Casalderrey-Solana and Iancu
[1105.1760]

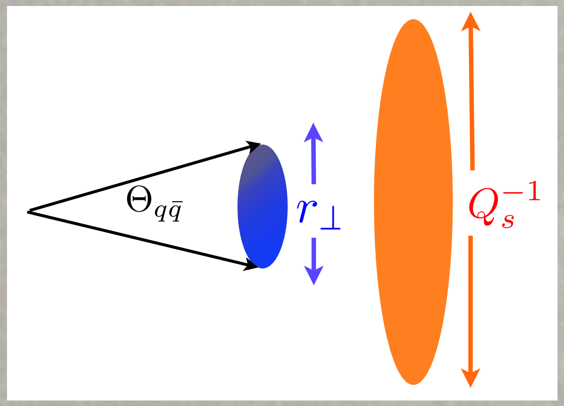
- Total gluon spectrum off an antenna in the soft limit:
  - Dominated by interference effects:

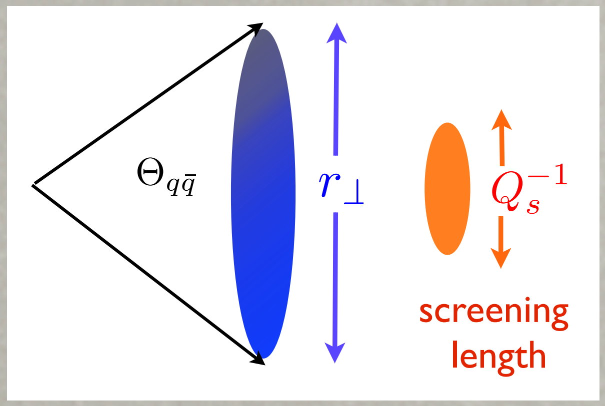
$$dN_q^{\mathrm{tot}}\big|_{\omega\to 0} = \frac{\alpha_s C_F}{\pi}\,\frac{d\omega}{\omega}\,\frac{\sin\theta\;d\theta}{1-\cos\theta}\Big[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\mathrm{med}}\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\Big]$$

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

  - Characteristic scale of the medium: $Q_s^2 = \hat{q}\,L$
  - Transverse resolution of the antenna inside the medium: $r_\perp = \theta_{q\bar{q}}\,L$
  - Two possible situations:

$\Delta_{\mathrm{med}} \sim Q_s^2\, r_T^2$
Medium probes the pair as a singlet. Gluon spectrum not much affected by the medium





$\Delta_{\mathrm{med}} = 1$
Pair lose color coherence and radiation becomes independent (radiation out-of-cone)

- For the non-soft limit (large ω), spectrum dominated by BDMPS-Z

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