Radiation Spectrum of a Massive Quark-Gluon Antenna in a QCD Medium

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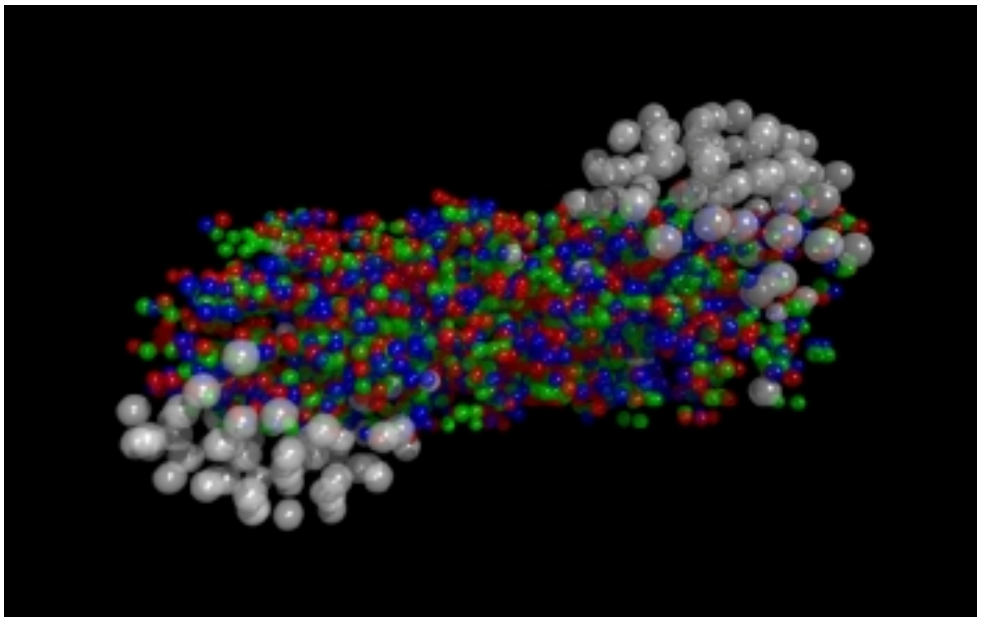
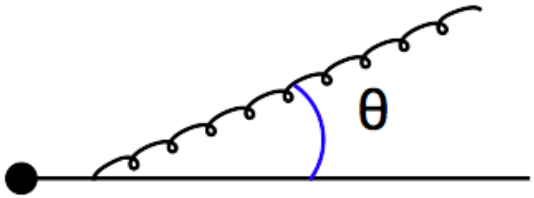
Motivation



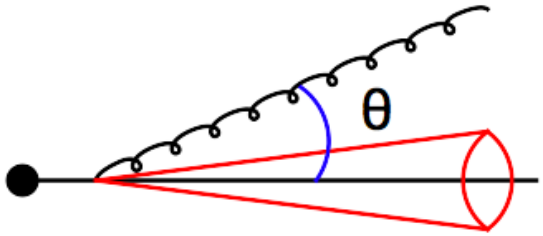
- A state of deconfined coloured particles (QGP) is formed in heavy ion collisions.
- One of the most striking effects of QGP is the energy loss of high energy partons in heavy ion collisions.
- Is this energy loss the same for heavy quarks than for massless quarks?

Dead Cone Effect

- In vacuum, the presence of a mass leads to a suppression of gluon radiation inside the so-called dead cone.



$m = 0$



$m \neq 0$

Dead cone angle: $\theta_0 = m/E$

Massive BDMPS Spectrum

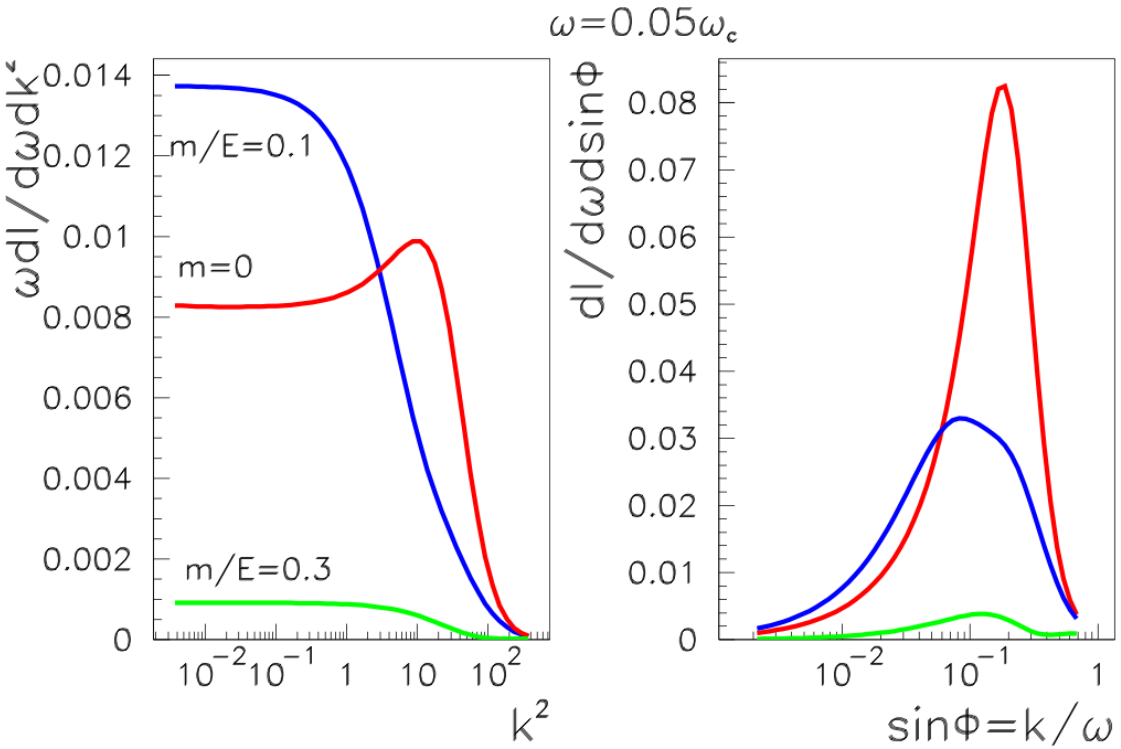
- In a medium, there is also a suppression due to mass effects.

$$k^+ \frac{\mathrm{d}N}{\mathrm{d}k^+ \mathrm{d}^2\mathbf{k}} = \frac{\alpha_s C_F}{(2\pi)^2 (k^+)^2} 2\mathrm{Re} \int_0^\infty \mathrm{d}y'^+ \int_0^{y'^+} \mathrm{d}y^+ \times \exp\left[i \frac{k^+}{2} \theta^2_{DC} (y^+ - y'^+) \right] \int \mathrm{d}^2\mathbf{z} \exp\Bigg[- i\mathbf{k}\cdot\mathbf{z} - \frac{1}{2} \int_{y'^+}^\infty \mathrm{d}\xi \, n(\xi)\sigma(\mathbf{z}) \Bigg] \boldsymbol{\partial}_y \cdot \boldsymbol{\partial}_z \mathcal{K}(y'^+, \mathbf{z}; y^+, \mathbf{y})\big|_{\mathbf{y}=\mathbf{0}}$$

(Armesto, Salgado, Wiedemann; Dokshitzer, Karzeev; Zhang, Wang, Wang; Djordjevic, Gyulassy, ...)

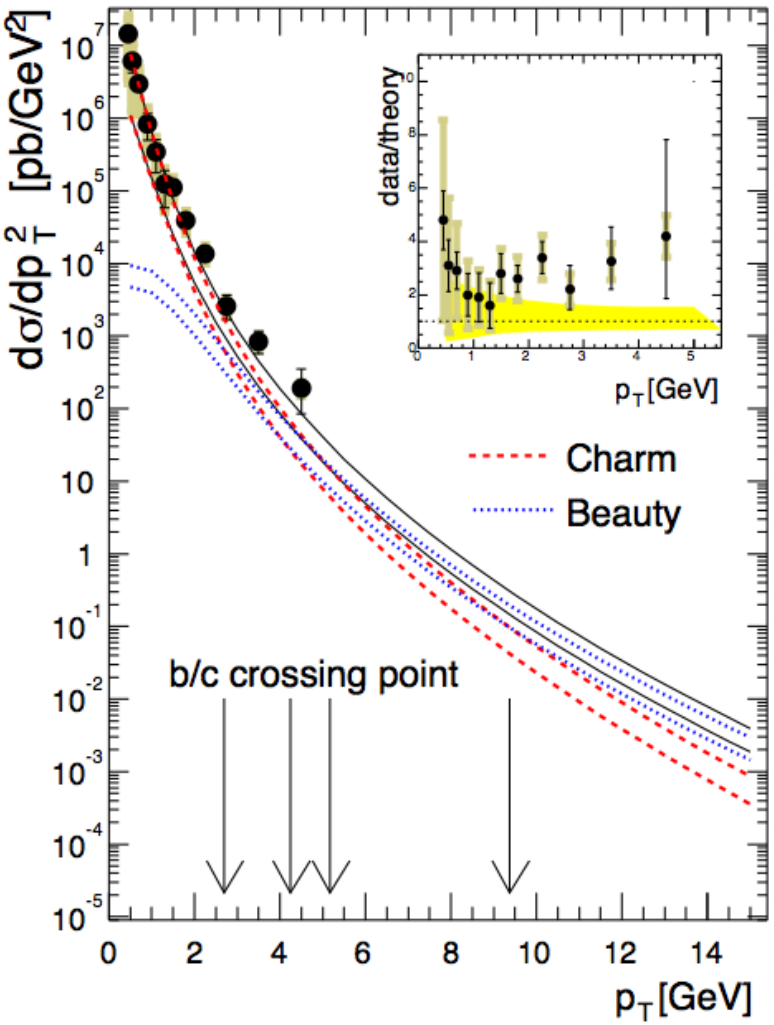
Massive BDMPS

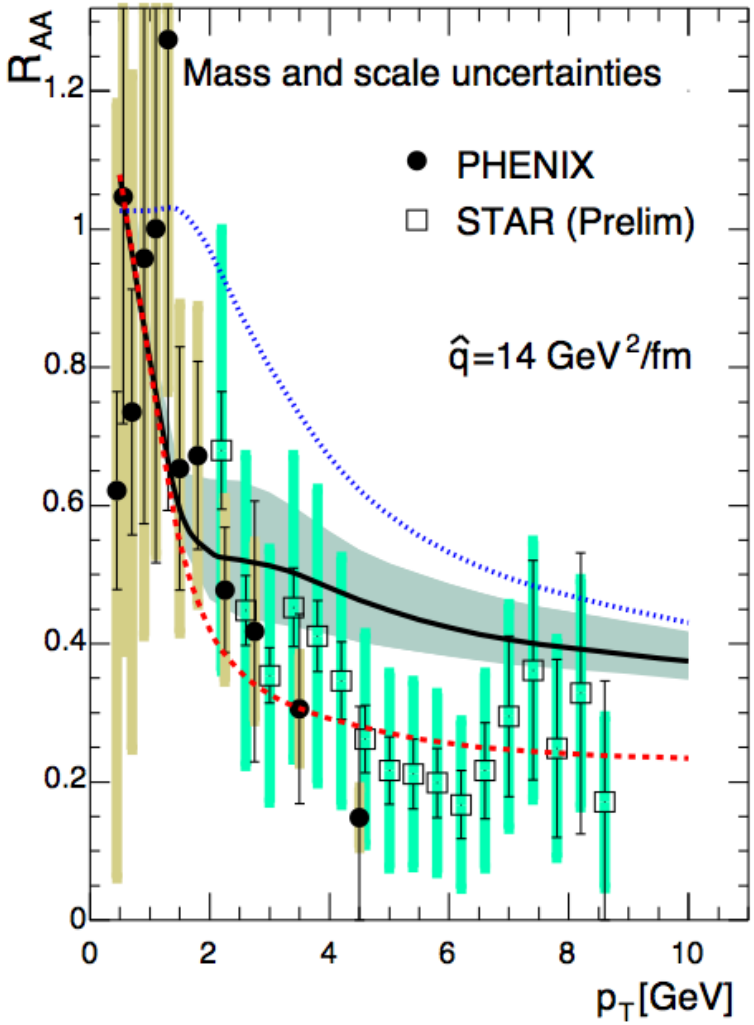
- Smaller energy loss in the massive case (dead cone).



(Armesto, Salgado, Wiedemann)

Trouble with RHIC data





Armesto, Cacciari, Dainese, Salgado, Wiedemann

- RHIC data remains a puzzle.

Radiative Antenna (Massless case)

- The BDMPS spectrum does not deal with interference effects between emitters.
- We can consider an antenna composed of two partons to study the role of these interferences

$$dN = \frac{\alpha_s}{(2\pi)^2}\left[C_F\mathcal{R}_q + C_A\mathcal{R}_g - C_A\mathcal{J}\right]\frac{d^3k}{(k^+)^3}$$

- For massless partons, the result is known:

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

Antenna Parameters

- Decoherence parameter:

$$\Delta_{\mathrm{med}}(y^+,0) \equiv 1 - \exp\left\{-\frac{1}{2}\int_0^{y^+} \mathrm{d}\xi\, n(\xi)\sigma(\delta\mathbf{n}\xi)\right\}$$

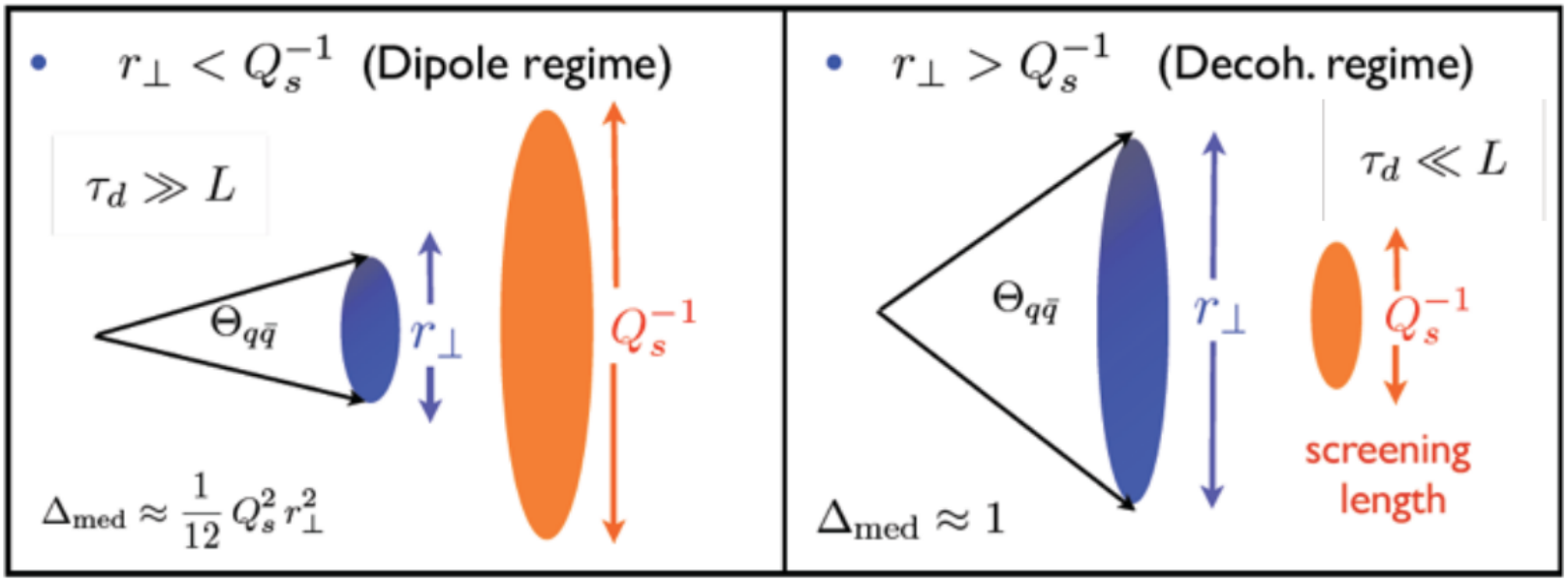
- Opening angle:

$$\delta\mathbf{n} \equiv \frac{\mathbf{p}_q}{p_q^+} - \frac{\mathbf{p}_g}{p_g^+} \to |\delta\mathbf{n}| \equiv \sin\theta_{qg} \sim \theta_{qg}$$

- $\sigma(\mathbf{r})$ is the dipole cross-section.
- Harmonical approximation: $n(\xi)\sigma(\mathbf{r}) \approx \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$
  $\hat{q}$ is the medium transport coefficient.

Antenna Scales

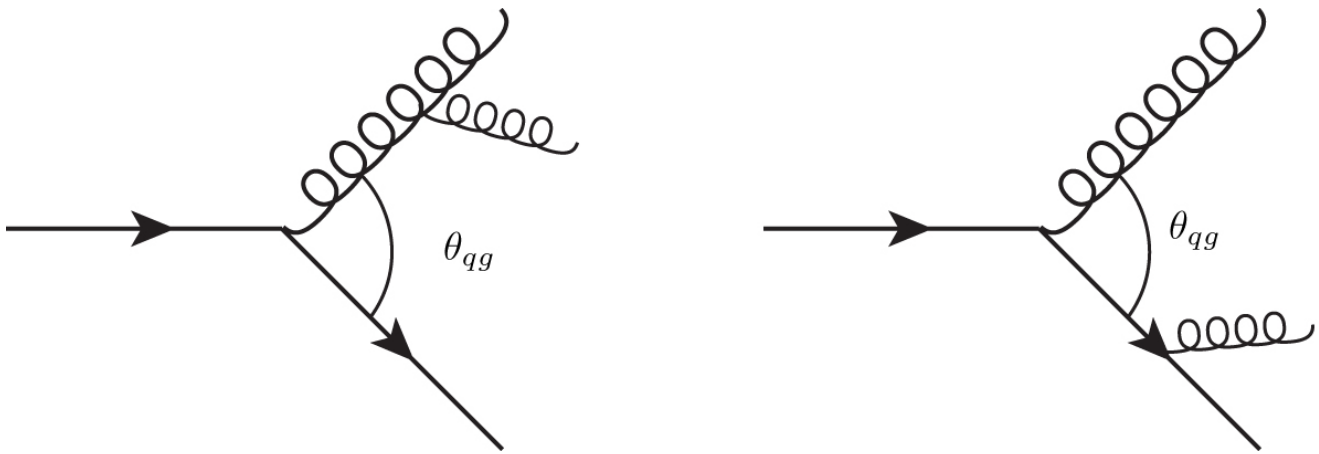
- What is the role of the parton mass in the picture below?



(Mehtar-Tani, Tywoniuk, Salgado, Casalderrey, Iancu)

Massive Antennae

- The case of a massive quark-antiquark antenna has been studied before. (Armesto, Ma, Mehtar-Tani, Salgado, Tywoniuk)
- Here we focus in the case of a massive quark-gluon antenna, more relevant for high-energy jets.



Framework Set-up

- BDMPS and interference spectra are calculated by solving the Classical Yang-Mills (CYM) equations

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

with the help of the continuity equation

$$[D_\mu, J^\mu] = 0$$

- Light-cone gauge ($A^+ = 0$) + linearized CYM equations.

$$\Box A^i - 2ig[A^-_{\text{med}}, \partial^+ A^i] = -\frac{\partial^i}{\partial^+} J^+ + J^i$$

Amplitude / Mass efect

- Applying the usual reduction formula to compute amplitudes, we get for the massive quark-gluon antenna:

$$\mathcal{M}_\lambda(\vec{k}) = \frac{g}{k^+} \int_{x^+=+\infty} \mathrm{d}^2\mathbf{x}\, e^{ik^- x^+} e^{-i\mathbf{k}\cdot\mathbf{x}} \int_0^{+\infty} \mathrm{d}y^+ \, e^{ik^+ \frac{p^-}{p^+} y^+}$$
$$\times \epsilon_\lambda(k) \cdot (i\partial_y + k^+ \mathbf{n})\, \mathcal{G}(x^+, \mathbf{x}; y^+, \mathbf{y}|k^+)\Big|_{\mathbf{y}=\mathbf{n}y^+} U_p(y^+, 0) Q$$

- The difference between the massive and massless cases comes from the dispersion relation:

$$2p^+p^- - \mathbf{p}^2 = M^2$$

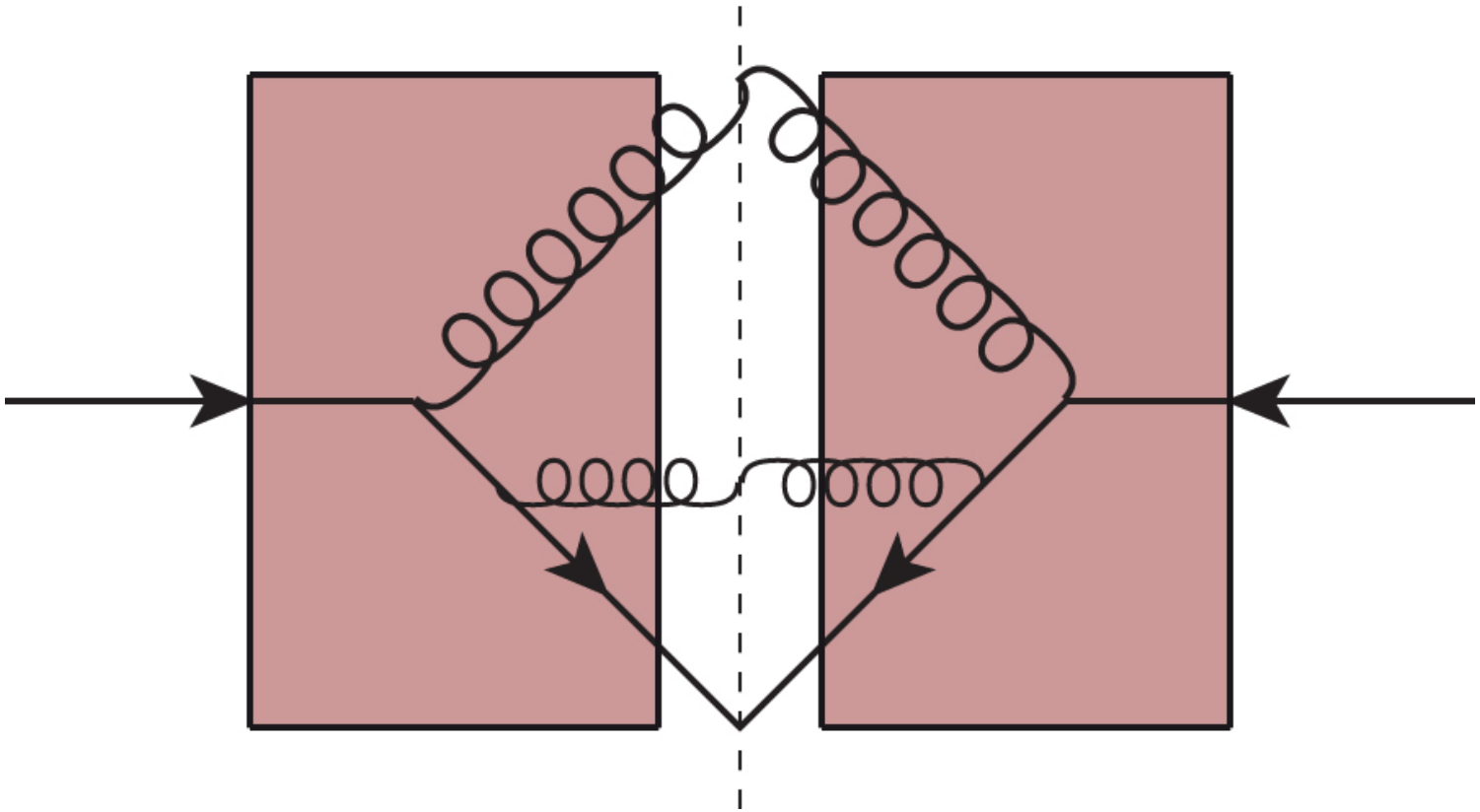
- This leads to the appearence of a new phase:

$$\exp\left(ik^+ \frac{p^-}{p^+} y^+\right) = \exp\left(i\frac{k^+}{2}\theta^2_{DC} y^+\right) \exp\left(i\frac{k^+}{2}\mathbf{n}^2 y^+\right)$$

BDMPS $\mathcal{R}_q$

$$dN = \frac{\alpha_s}{(2\pi)^2}\left[C_F\mathcal{R}_q + C_A\mathcal{R}_g - C_A\mathcal{J}\right]\frac{d^3k}{(k^+)^3}$$

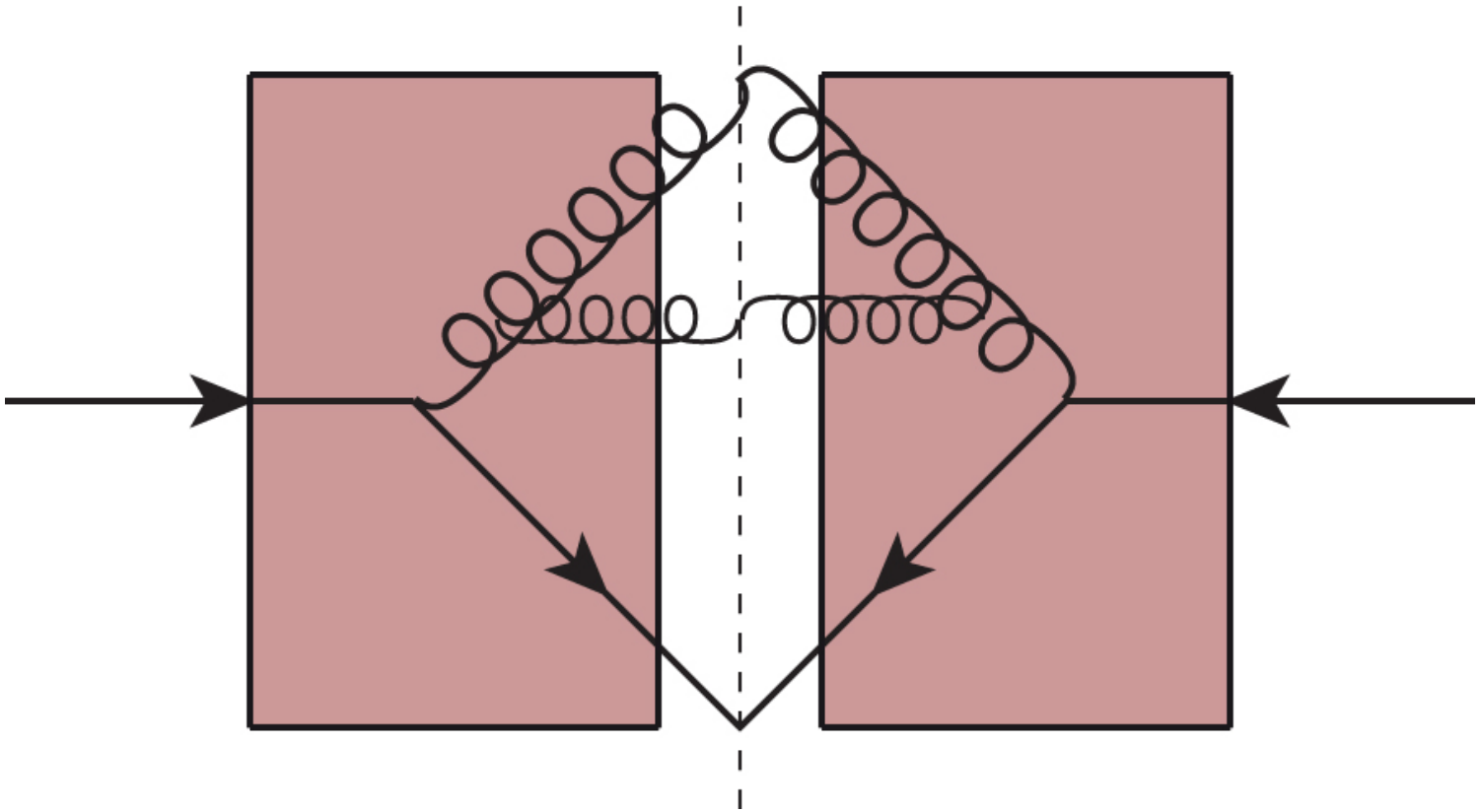
$$C_F\mathcal{R}_q = (k^+)^2\langle|\mathcal{M}_q|^2\rangle$$



BDMPS $\mathcal{R}_g$

$$dN = \frac{\alpha_s}{(2\pi)^2}\left[C_F\mathcal{R}_q + C_A\mathcal{R}_g - C_A\mathcal{J}\right]\frac{d^3k}{(k^+)^3}$$

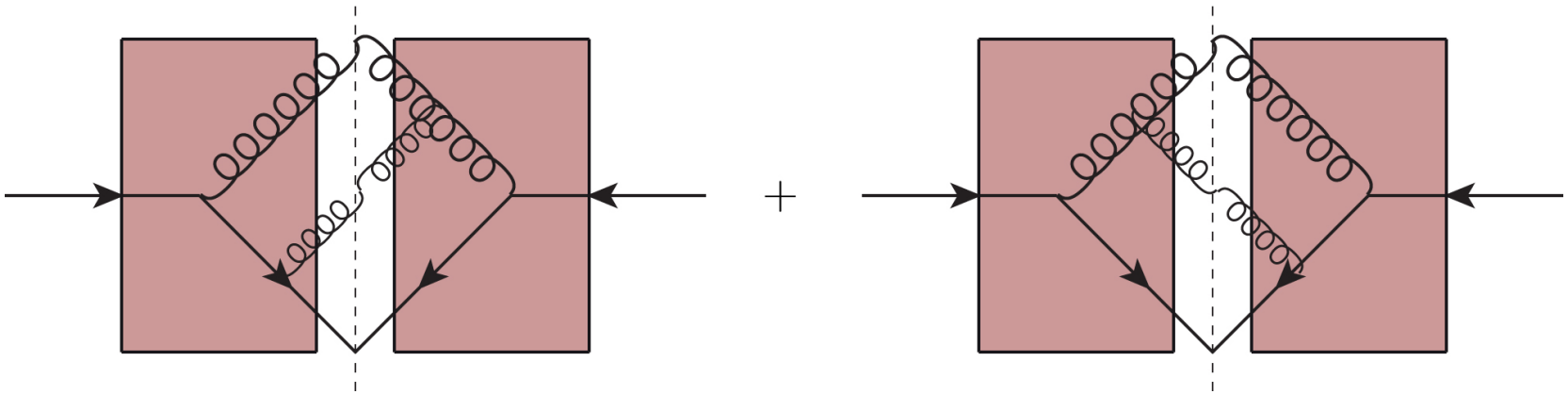
$$C_A\mathcal{R}_g = (k^+)^2\langle|\mathcal{M}_g|^2\rangle$$



Interference $\mathcal{J}$

$$dN = \frac{\alpha_s}{(2\pi)^2}\left[C_F\mathcal{R}_q + C_A\mathcal{R}_g - C_A\mathcal{J}\right]\frac{d^3k}{(k^+)^3}$$

$$-C_A\mathcal{J} = (k^+)^2\,\mathrm{Re}\langle\mathcal{M}_q\mathcal{M}_g^\dagger\rangle$$



Interference Spectrum

- The interference spectrum for the massive quark-gluon antenna:

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

- Same result as in the massless case... except for the mass phase!

Discussion

- $\exp\left(i\frac{k^+}{2}\theta^2_{DC}y^+\right)$ is a quickly oscillating exponencial if the mass is big enough:

$$\theta^2_{DC} \gg \frac{2}{k^+ L}$$

- Different mass phases for massive quark-gluon antenna and BDMPS/massive quark-antiquark antenna.
  - qg antenna:

$$\exp\left(i\frac{k^+}{2}\theta^2_{DC}y^+\right)$$

  - $q\bar{q}$ antenna:

$$\exp\left(i\frac{k^+}{2}\theta^2_{DC}(y^+ - y'^+)\right)$$

Discussion

- The effect of the mass will suppress the interferences, thus losing coherence more easily than in the massless antenna.
- Interference in the massive qg antenna will dissappear faster than in the massive $q\bar{q}$ one.
- The loss of coherence implies a larger energy loss.
- Phenomenological relevance to be investigated.

Summary

- Energy loss of heavy quarks is a remaining puzzle.
- Dead cone effect makes the energy loss smaller.
- Role of interferences in in-medium jets has been investigated in recent years.
- Here we compute the interferences for a heavy quark-gluon antenna.
- Coherence more easily lost for heavy quarks implies enhanced energy loss.