Coherence and resolution in jet formation inside a dense medium

Fabio Dominguez
Universidade de Santiago de Compostela

Hard Probes 2016

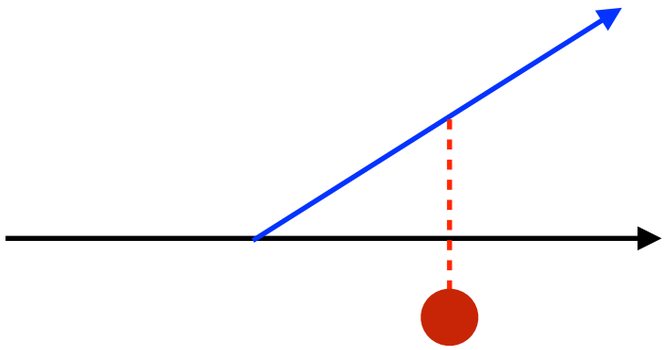
Wuhan, China

September 25th, 2016

Medium modification of jets: a very difficult problem

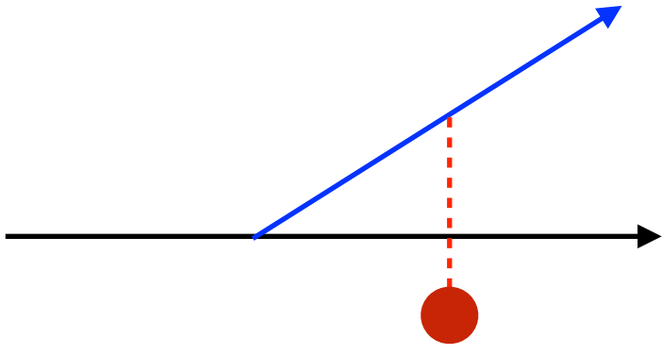
Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton

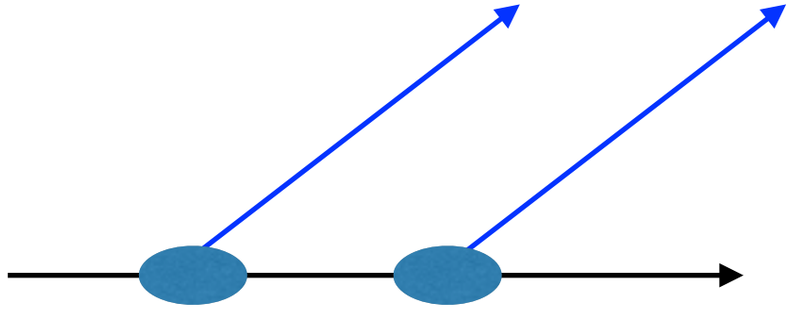


Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton

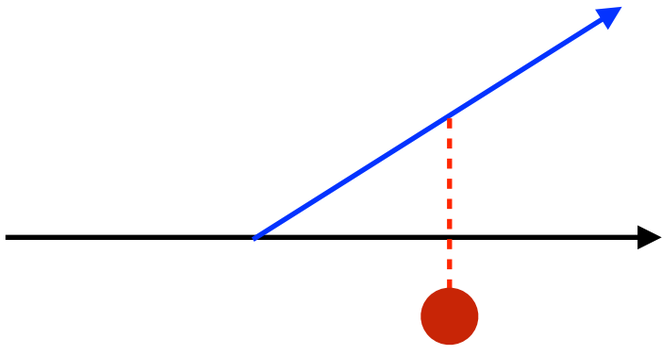


- What about multiple emissions? Is it safe to assume they are independent?

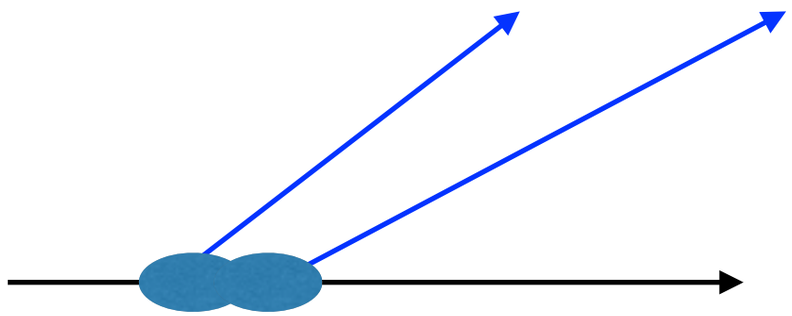


Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton

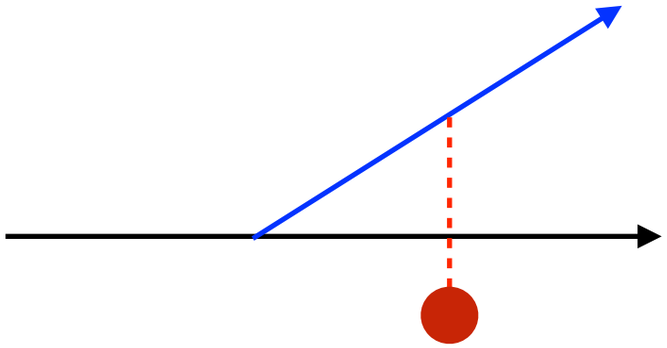


- What about multiple emissions? Is it safe to assume they are independent?

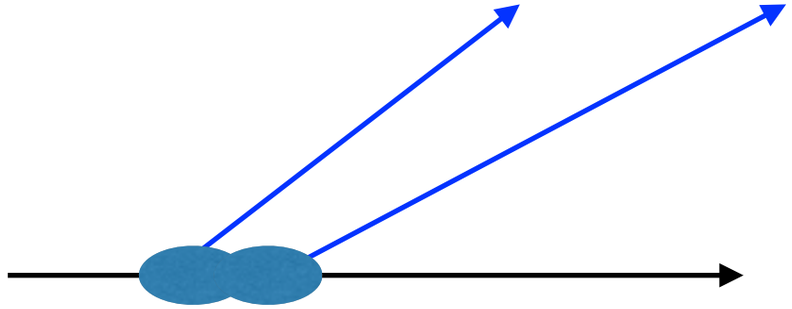


Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton



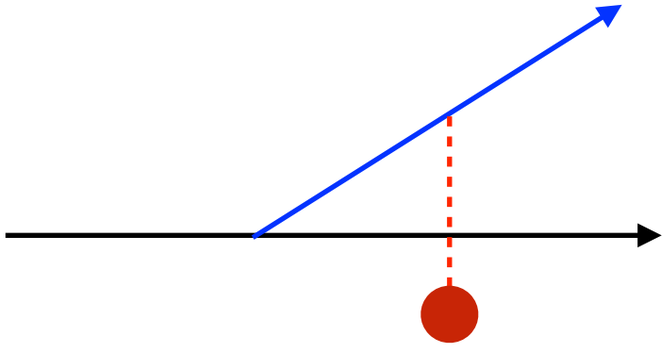
- What about multiple emissions? Is it safe to assume they are independent?

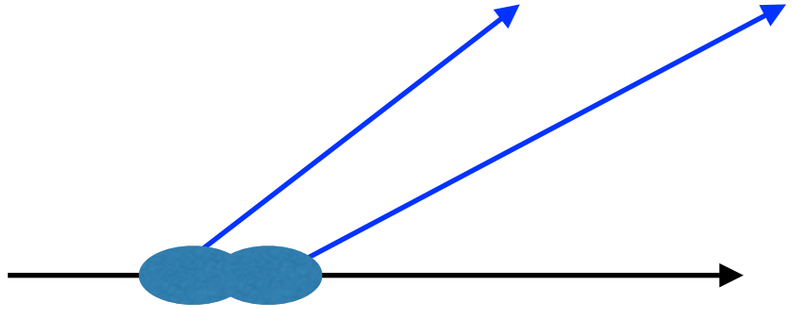


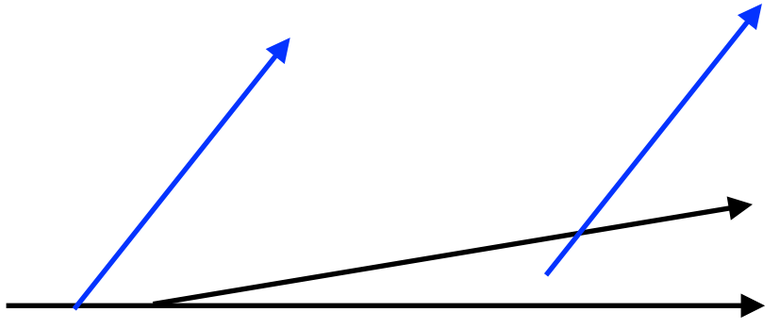
- Is a jet a good proxy for a parton? How many sources inside a jet for medium-induced emissions?

Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton
- What about multiple emissions? Is it safe to assume they are independent?
- Is a jet a good proxy for a parton? How many sources inside a jet for medium-induced emissions?

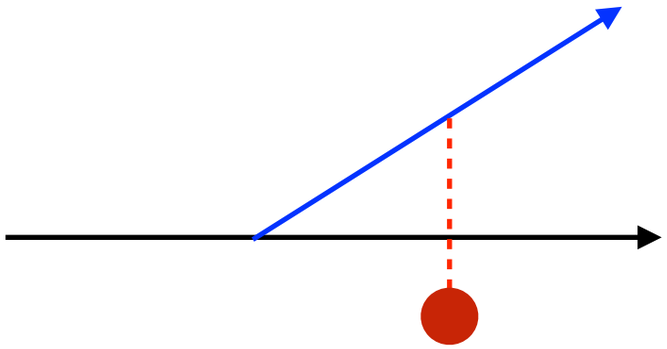


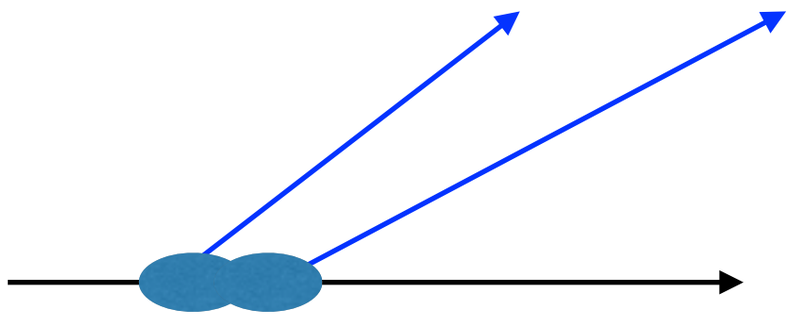


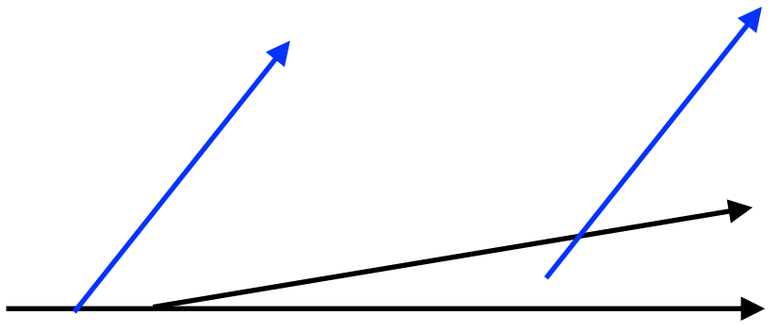


Medium modification of jets: a very difficult problem

- First, calculate single soft gluon emission from very hard parton
- What about multiple emissions? Is it safe to assume they are independent?
- Is a jet a good proxy for a parton? How many sources inside a jet for medium-induced emissions?
- Two gluon emission needed







Two-gluon emission in a medium

- Opacity 1:
  - 1 to 3 splitting functions in a medium (SCET)

    Fickinger, Ovanesyan, Vitev 1304.3497
  - Jet formation in dilute media

    Casalderrey-Solana, Pablos, Tywoniuk 1512.07561
- Multiple scatterings:
  - Two-gluon emission from hard on-shell quark (no vacuum radiation)

    Arnold, Iqbal 1501.04964
    Arnold, Chang, Iqbal 1605.07624
    Arnold, Chang, Iqbal 1606.08853
    Arnold, Chang, Iqbal 1608.05718

Very complicated results.
Some insight when relevant approximations are taken

Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

Antennas and resolution

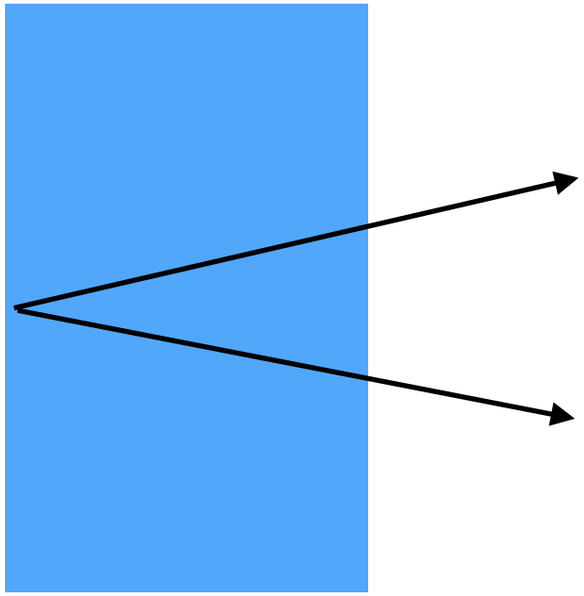
Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation

Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

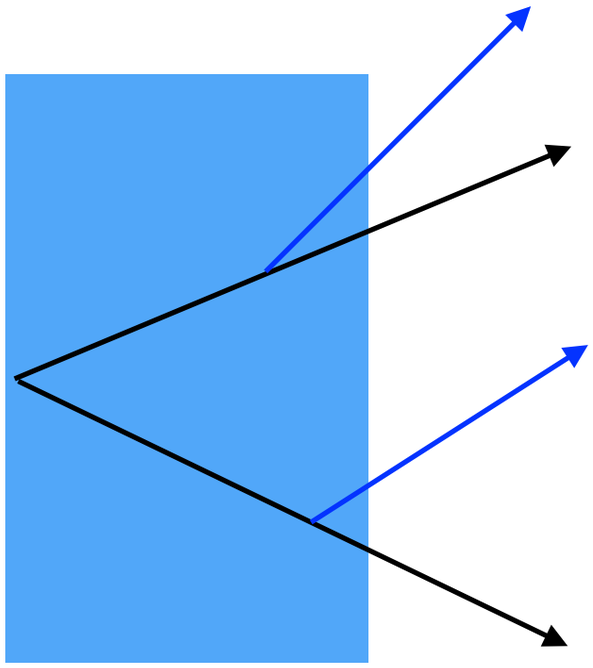
- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation
  - Eikonal (very hard) quark-antiquark pair going through the medium with a fixed angle



Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation
  - Eikonal (very hard) quark-antiquark pair going through the medium with a fixed angle
  - At large angles coherence is broken

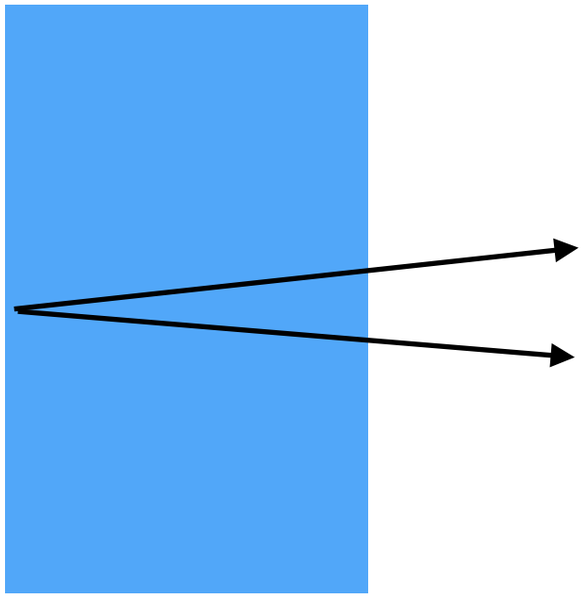


Independent emissions

Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation
  - Eikonal (very hard) quark-antiquark pair going through the medium with a fixed angle
  - At large angles coherence is broken
  - Very narrow systems of partons radiate as a single source

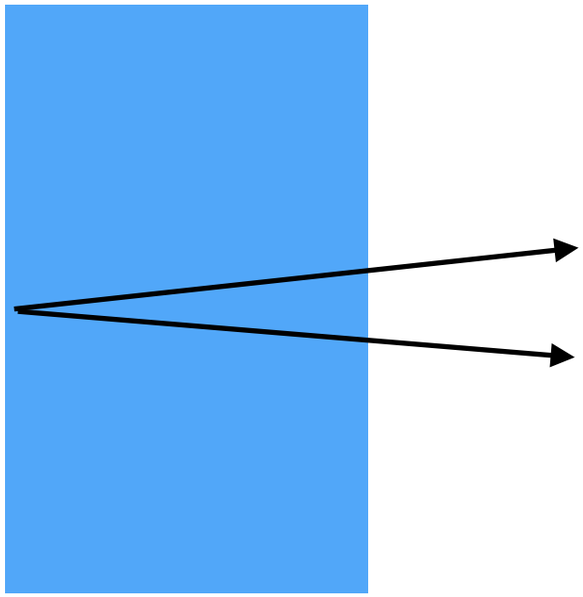


Emissions suppressed

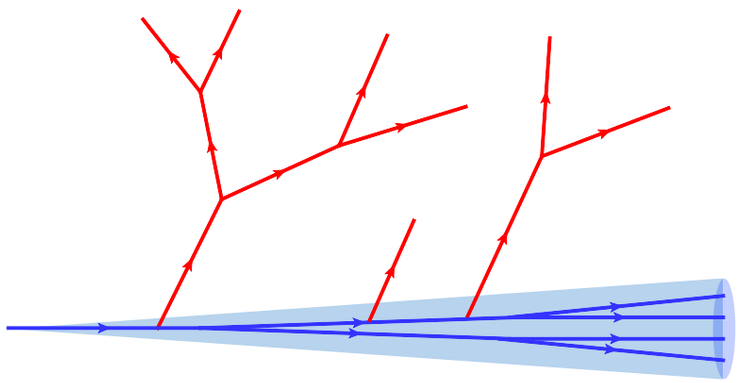
Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation
  - Eikonal (very hard) quark-antiquark pair going through the medium with a fixed angle
  - At large angles coherence is broken
  - Very narrow systems of partons radiate as a single source
- Leads to a picture where subjets radiate as a single particle



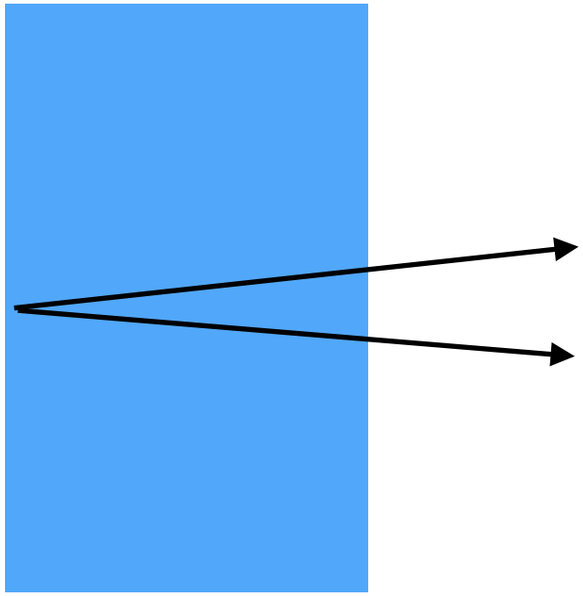
Emissions suppressed



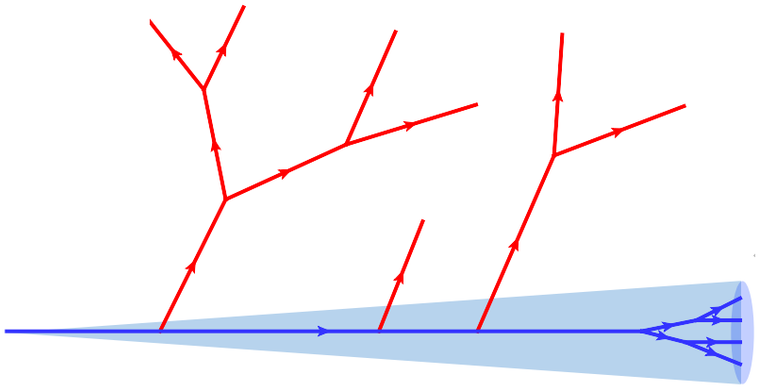
Antennas and resolution

Mehtar-Tani, Salgado, Tywoniuk
Iancu, Casalderrey-Solana

- Most of what we know about coherence of a parton system inside a medium comes from the antenna calculation
  - Eikonal (very hard) quark-antiquark pair going through the medium with a fixed angle
  - At large angles coherence is broken
  - Very narrow systems of partons radiate as a single source
- Leads to a picture where subjets radiate as a single particle



Emissions suppressed



Caveats

- Rigid antenna picture is too simplistic
- Coherent picture assumes vacuum-like shower forms independently of the medium and then it is imbedded into it
- Including finite formation times for the hard shower can vary the coherent picture
- Transverse momentum broadening of hard partons is ignored

Dynamical antennas

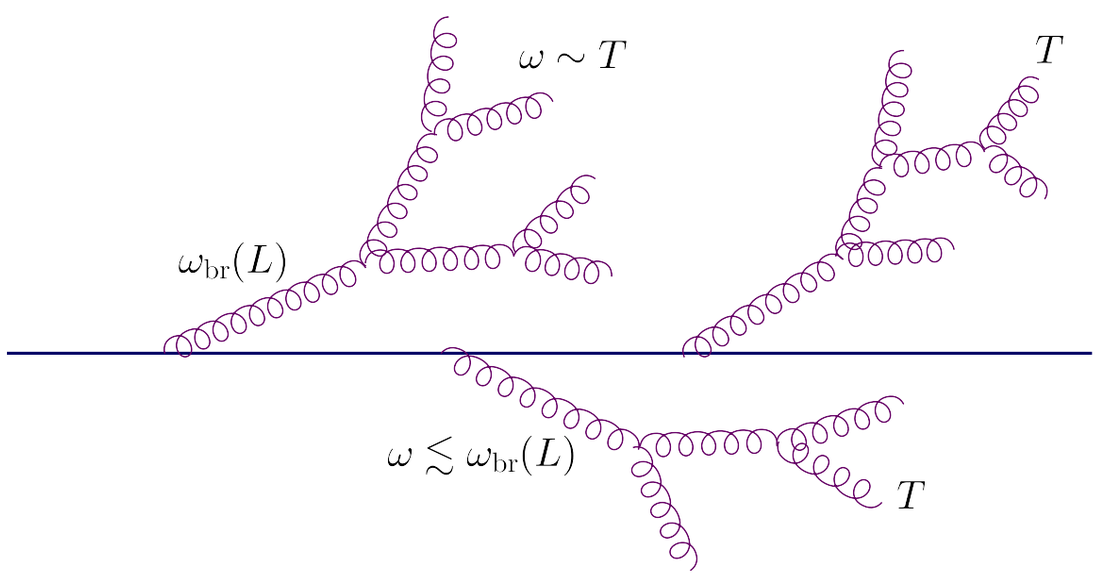
- Make antennas less rigid and allow its legs to diffuse in transverse coordinate space
- This modification can possibly account for momentum-broadening effects
- Full calculation is too difficult so results are only available for instantaneous formation of the antenna, in which case the totally incoherent picture is recovered

Liliana Apolinario's Talk

Fully decorrelated case

Blaizot, Dominguez, Iancu, Mehtar-Tani

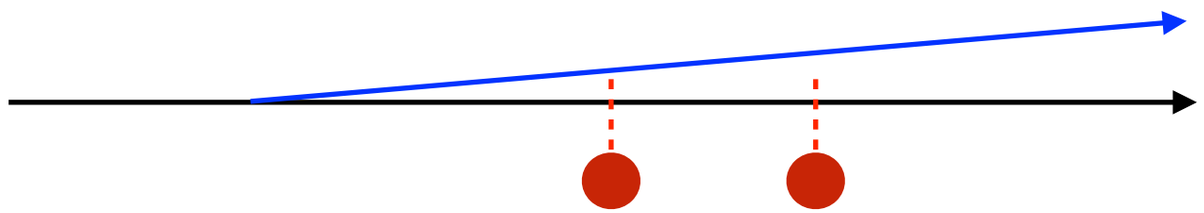
- Soft gluons at large angle have a very short formation time
- After such time they propagate independently of the parent parton
- This independent propagation has been taken as confirmation that multiple emissions in this regime are independent
- Energy flow to the plasma scale and multiple particle correlations have been calculated in this limit



Miguel Escobedo's Talk

Collinear emissions and narrow antennas

- Consider the opposite limit where emissions stay close to the parent parton
- The eikonal limit is too strong, gluons emitted at zero angle can not be measured
- A systematic expansion around the eikonal limit is needed for these hard collinear emissions



Next-to-eikonal expansion

Altinoluk, Armesto, Beuf, Martinez, Salgado 1404.2219

Originally developed in a CGC context, where multiple interactions are always taken in the full eikonal limit

$$\mathcal{G}^{ab}_{p^+}(x,y) = \int_{y_\perp}^{x_\perp} \mathcal{D}r_\perp \exp\left\{\frac{ip^+}{2}\int_{y^+}^{x^+} dt\, \dot{r}_\perp^2(t)\right\}\mathcal{U}^{ab}(x^+,y^+;[r_\perp])$$
$$= \mathcal{G}_{0,p^+}(x,y)\mathcal{R}^{ab}_{p^+}(x,y)$$

Eikonal limit $p^+ \to \infty$

$$\mathcal{G}_{0,p^+}(x,y) \to \delta^{(2)}(x_\perp - y_\perp)$$

Fourier transform,
then expand around zero angle

$$\mathcal{R}^{ab}_{p^+}(x,y) \to \mathcal{U}^{ab}(x^+,y^+;[r^{cl}_\perp])$$

Expand around classical trajectory

Next-to-eikonal expansion

$$\int d^2x_\perp\, e^{-ik_\perp\cdot x_\perp}\mathcal{G}^{ab}_{k^+}(x,y) \simeq \theta(x^+-y^+)e^{-ik_\perp\cdot y_\perp}\left\{\left(1-i\frac{x^+-y^+}{2k^+}k_\perp^2\right)\mathcal{U}(x^+,y^+,y_\perp)\right.$$
$$\left.+\frac{x^+-y^+}{k^+}k_\perp^i\mathcal{U}^i_{(1)}(x^+,y^+,y_\perp)+i\frac{x^+-y^+}{2k^+}\mathcal{U}_{(2)}(x^+,y^+,y_\perp)\right\}^{ab}$$

Where the decorated Wilson lines are:

$$\mathcal{U}^{i,ab}_{(1)}(x^+,y^+,y_\perp)=\int_{y^+}^{x^+}dz^+\frac{1}{(x^+-y^+)}\left\{\left[\partial_{y^i}\mathcal{U}(x^+,z^+,y_\perp)\right]\mathcal{U}(z^+,y^+,y_\perp)\right\}^{ab}$$

$$\mathcal{U}^{ab}_{(2)}(x^+,y^+,y_\perp)=\int_{y^+}^{x^+}dz^+\frac{1}{(x^+-y^+)}\left\{\left[\partial^2_{y}\mathcal{U}(x^+,z^+,y_\perp)\right]\mathcal{U}(z^+,y^+,y_\perp)\right\}^{ab}$$

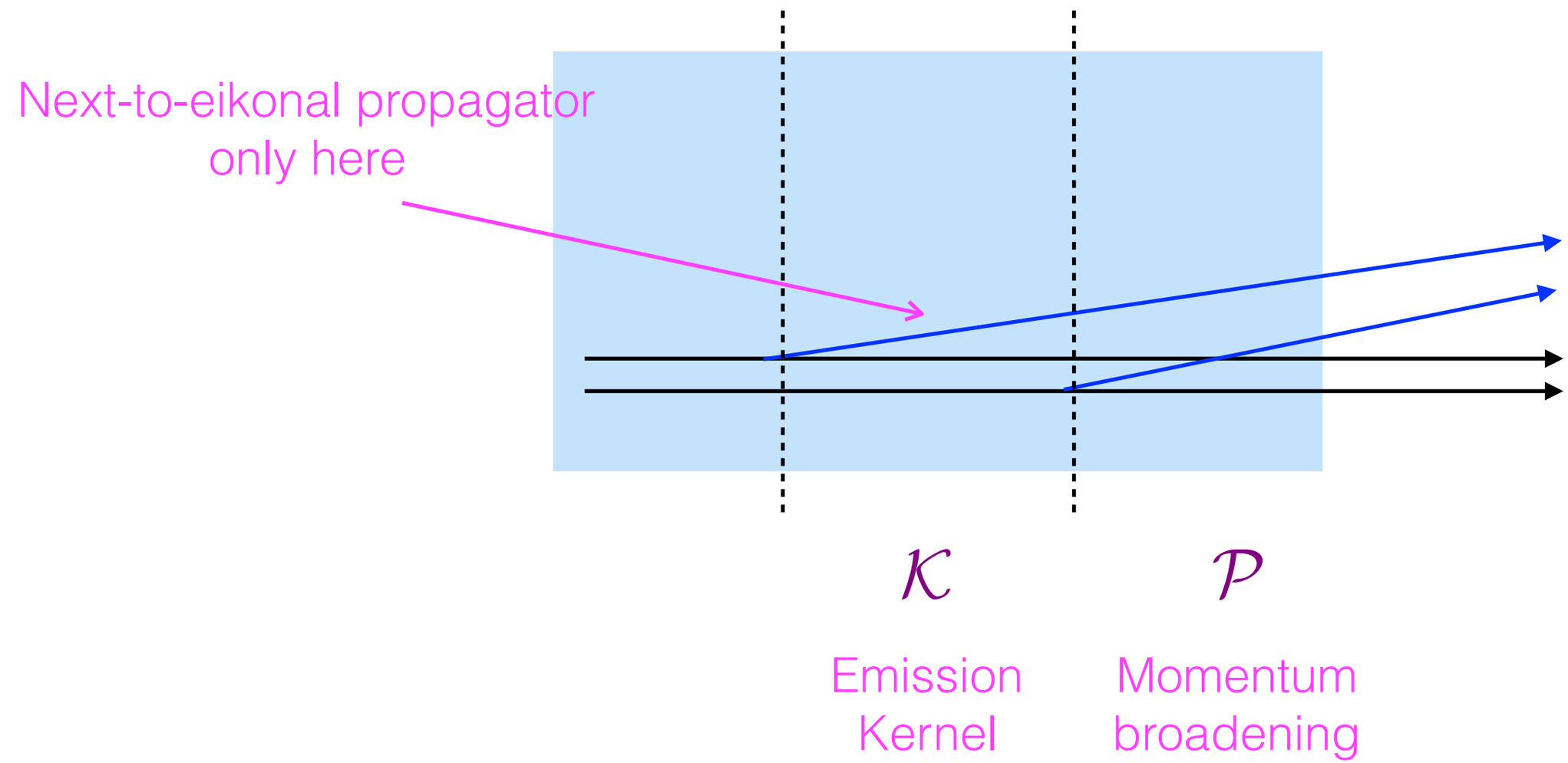
$$\frac{L}{k^+}k_\perp^2,\ \frac{L}{k^+}\hat{q}L$$ Must be small

Next-to-next-to-eikonal propagator has also been calculated

Altinoluk, Armesto, Beuf,Moscoso 1505.01400

Collinear BDMPS

- Not for energy loss purposes
- Think about it as the formation of a semi-eikonal antenna



Collinear BDMPS

- Instead of calculating path integrals we only need to calculate medium averages of combinations of Wilson lines and decorated Wilson lines

- One can easily find the contributions to the in-in and in-out terms

$$k^+ \frac{dI^{\text{in-in}}}{dk^+ d^2k_\perp} = \frac{\alpha_s C_F}{2\pi^2}\left[\frac{k_\perp^2}{2k^{+2}}L^{+2} + \frac{\hat{q}}{6k^{+2}}L^{+3}\right]$$

$$k^+ \frac{dI^{\text{in-out}}}{dk^+ d^2k_\perp} = -\frac{\alpha_s C_F}{2\pi^2}\left[\frac{k_\perp^2}{2k^{+2}}L^{+2} + \frac{\hat{q}}{3k^{+2}}L^{+3}\right]$$

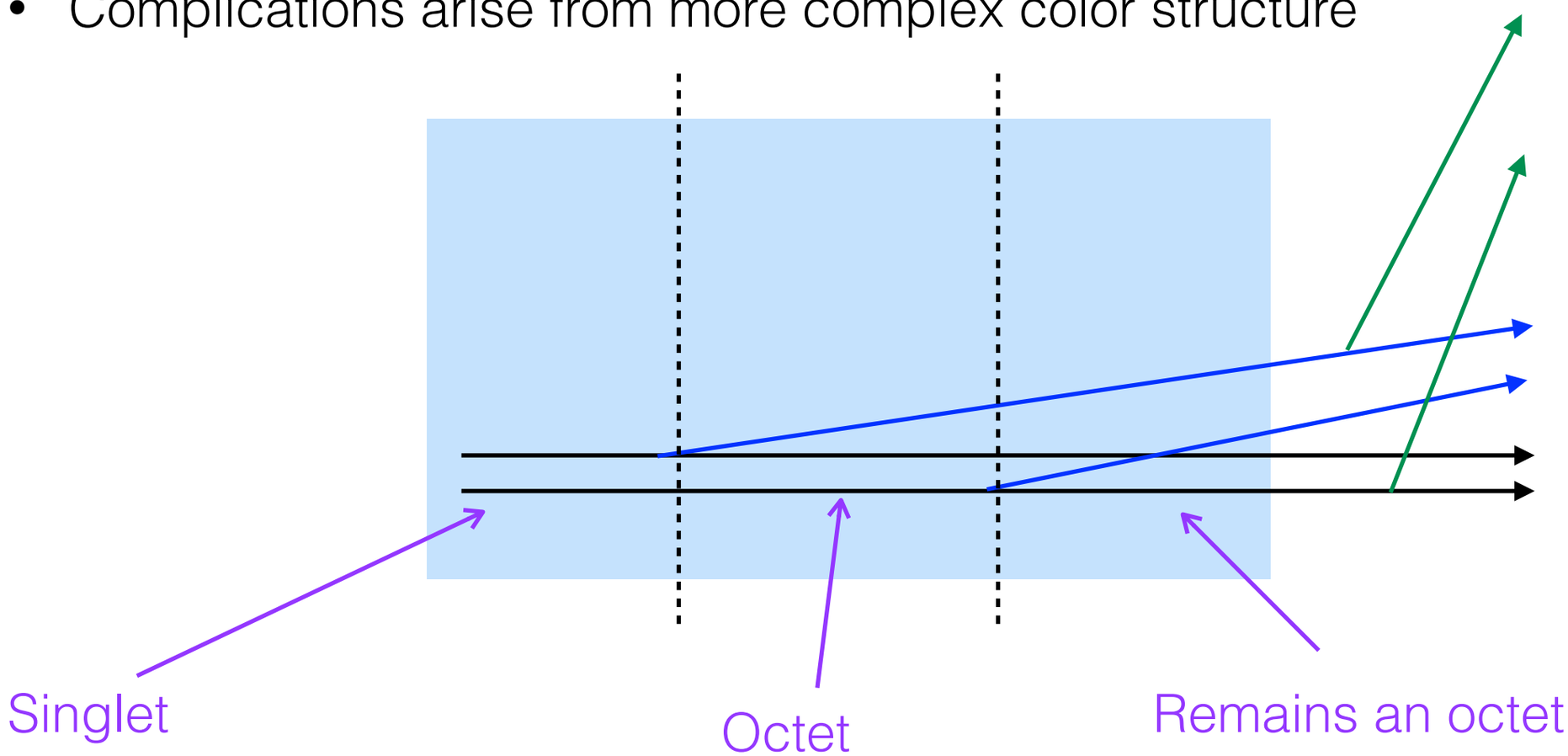
$$k^+ \frac{dI}{dk^+ d^2k_\perp} = -\frac{\alpha_s C_F \hat{q} L^{+3}}{12\pi^2 k^{+2}}$$

Corresponds to known large energy limit of BDMPS spectrum

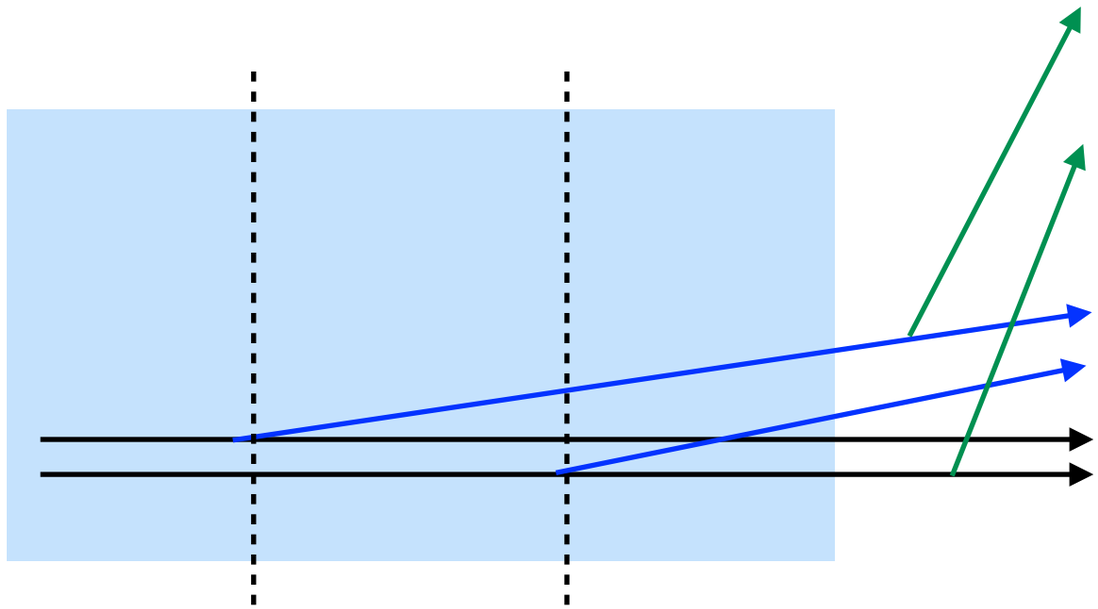
Wiedemann 2001

Additional soft emission

- In order to look at the coherence of the composite state, consider an extra soft emission outside the medium
  - Has been done for other coherence studies (eikonal antenna, non-eikonal antenna)
- Complications arise from more complex color structure



Additional soft emission



- Full expression in multiple scattering approach involves 3 path integrals convoluted through time integrations which cannot be computed analytically

- For short formation time of the first emission one can show that the fully decorrelated limit is recovered and the interference diagram is not important

- Using next-to eikonal approximation for the hard gluon this contribution has been explicitly evaluated

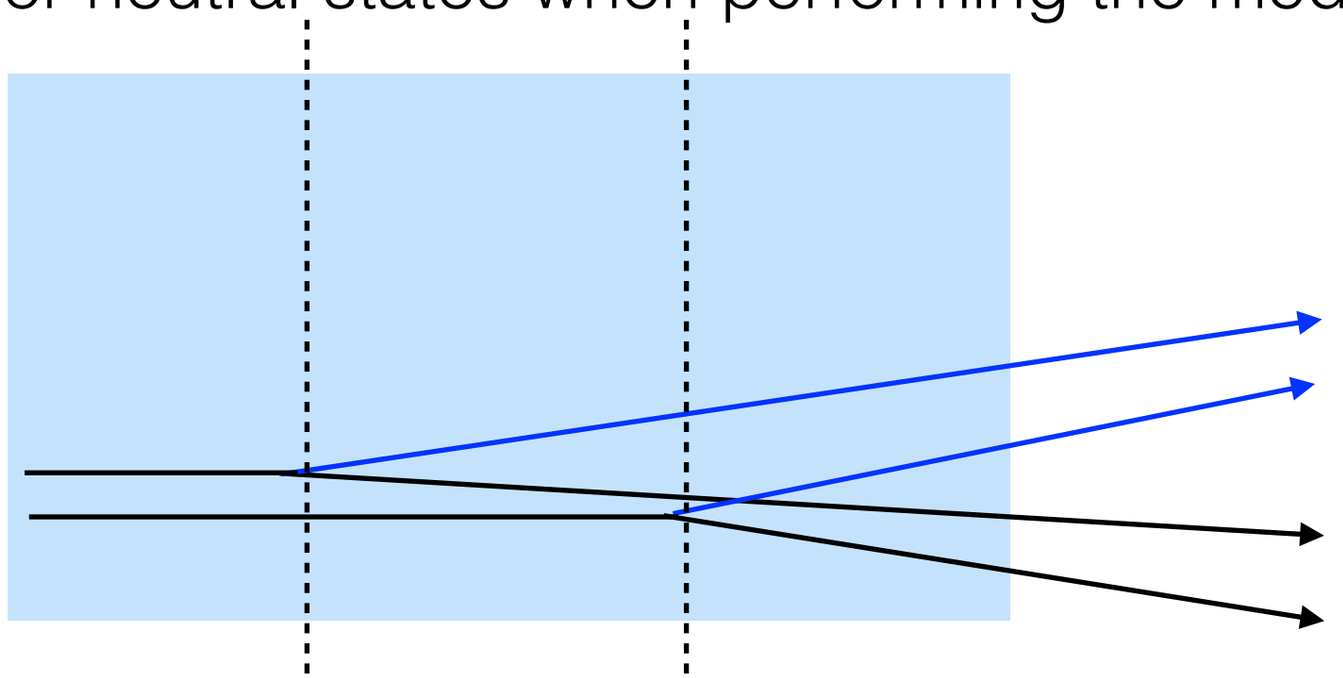
- Though, this is not enough since the formation time of the soft gluon is shorter than the formation time of the hard gluon and therefore diagrams where the soft emission occurs first are important (work in progress)

Non-eikonal vertex

- One can also consider the parent quark as non-eikonal, the corresponding splitting can be seen as the formation of a very narrow (non-eikonal) antenna

- This can also be calculated in the next-to-eikonal approximation

- The color structure is more interesting than the previous cases since the next-to-eikonal terms allow transitions between differerent color neutral states when performing the medium averages



Conclusions

- Collinear emission are very important to understand the interplay between the vacuum-like shower and the medium-induced radiation

- A systematic expansion is developed to consistently calculate such collinear emissions in a simplified setup

- Clear path towards a more rigorous understanding of coherence phenomena in jet formation inside a medium

- Initial results look promising, further calculations currently in progress