Color-coherence in the weakly coupled picture

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Introduction

What is perturbative in the medium?
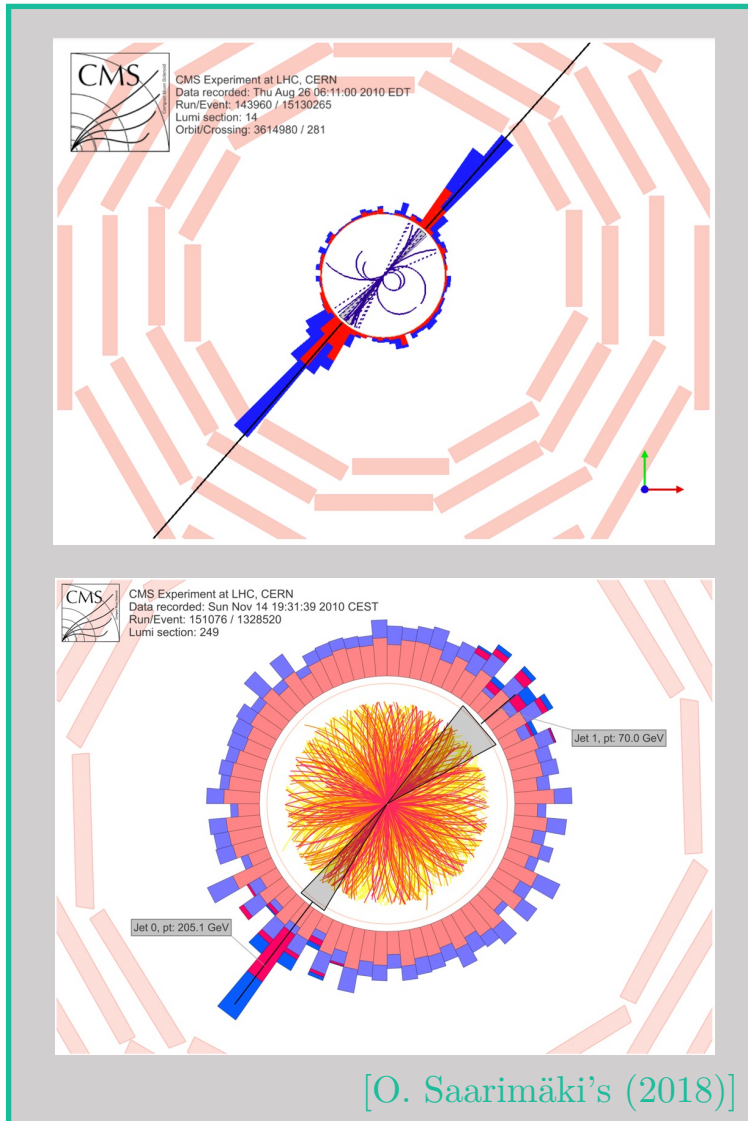
pp

AA

[O. Saarimäki's (2018)]

It is perturbative!

- pQCD is valid:

$$Q_{jet} \gg \Lambda_{QCD}$$

- jet-medium int. is perturbative:

$$Q_{jet} \gg Q_{med}$$

(medium bkg. is removable)

Is weakly coupled?

- medium is perturbative:

$$Q_{med} \; ? \gg ? \; \Lambda_{QCD}$$

What is perturbative in the medium?

pp

AA

[O. Saarimäki's (2018)]

It is perturbative!

- pQCD is valid:

$$Q_{jet} \gg \Lambda_{QCD}$$

- jet-medium int. is perturbative:
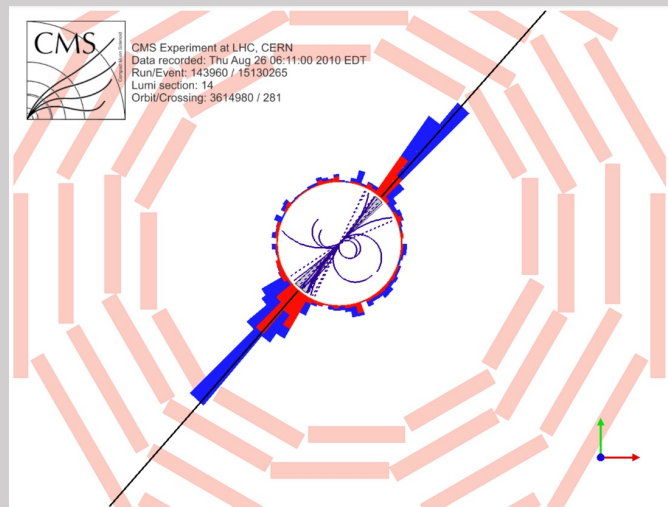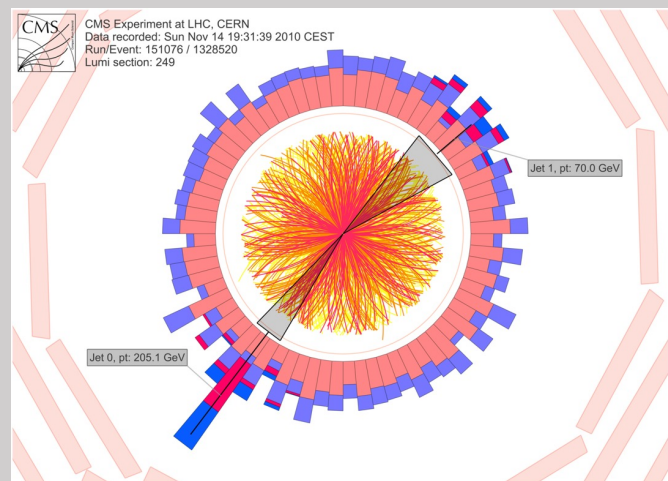
$$Q_{jet} \gg Q_{med}$$

(medium bkg. is removable)
[see talks from Daniel Pablos and Carlota Andres]

Is weakly coupled?

- medium is perturbative:
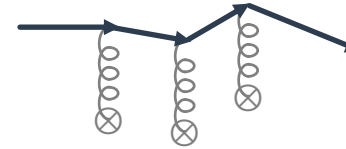
$$Q_{med} \, ? \gg ? \, \Lambda_{QCD}$$

QCD in the QGP medium
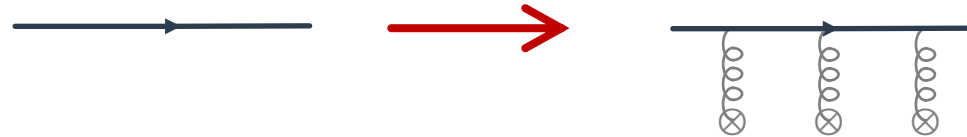
QCD with a colored background

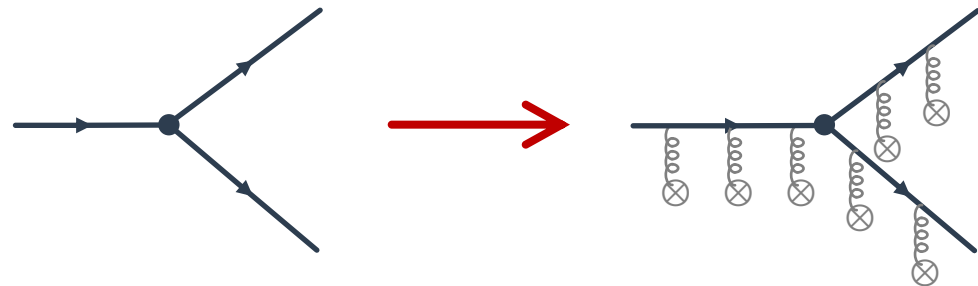QCD with color bkg: $\mathcal{A}(x) + \mathcal{A}_0(t, \boldsymbol{x})$
- Multiple scatterings

Medium Feynman rules:
- medium propagator:

- medium vertex:

- Medium average:
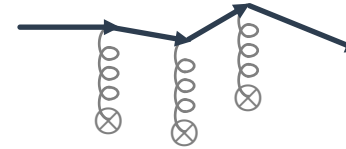$$\langle \mathcal{A}_0^-(t, \boldsymbol{x}) \mathcal{A}_0^-(t', \boldsymbol{x}') \rangle_{med}$$

  - Weakly coupled plasma ($T \gg \Lambda_{QCD}$): AMY
  - Random fields: BDMPSZ
  - recently: idk will evaluate later
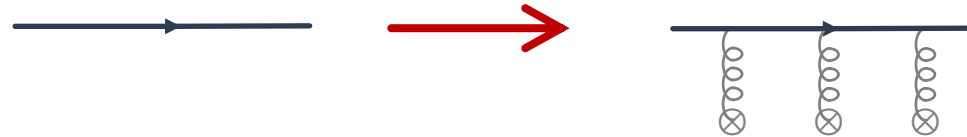
6

QCD with a colored background

QCD with color bkg: $\mathcal{A}(x) + \mathcal{A}_0(t, \boldsymbol{x})$
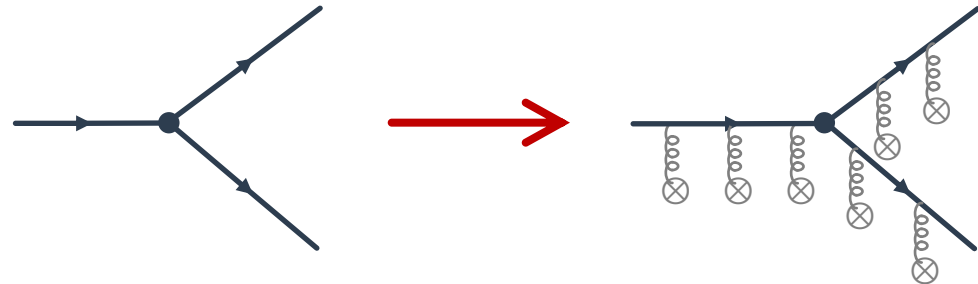
- Multiple scatterings

Medium Feynman rules:

- medium propagator:

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- Medium average:

$$\langle \mathcal{A}_0^-(t, \boldsymbol{x}) \mathcal{A}_0^-(t', \boldsymbol{x}') \rangle_{med}$$

  - o Weakly coupled plasma $(T \gg \Lambda_{QCD})$: AMY
  - o Random fields: BDMPSZ
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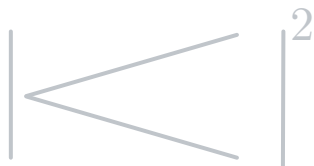
7

Color-coherence in medium

Vacuum

Emission:

$$\Rightarrow \quad \frac{dI_i^{vac}}{dz d\vartheta} \approx \frac{\alpha_s}{\pi} \frac{2C_i}{z} \frac{1}{\vartheta}$$

soft & collinear divergence!
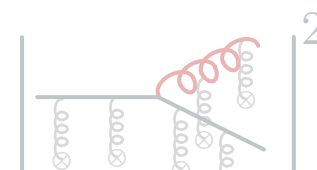
Color-conservation:

Color-coherence:

$$\Rightarrow \quad \approx \left(\frac{dI_q^{vac}}{dz d\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dz d\vartheta} \right)$$

$$\times \; \Theta(\vartheta_{q\bar{q}} > \vartheta_g)$$

angular-ordering!

Medium

Medium-induced emission:

$$\Rightarrow \quad \frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi} \frac{Q_{med}}{E} \frac{2C_i}{\sqrt{z^3}}$$
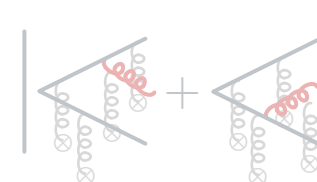
soft divergence!

Decoherence time:

$$\Rightarrow \quad \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

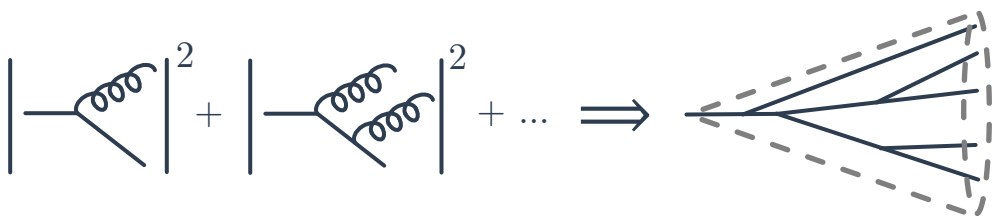$$\Rightarrow \quad \approx \left(\frac{dI_q^{med}}{dz d\vartheta} + \frac{dI_{\bar{q}}^{med}}{dz d\vartheta} \right)$$

$$\times \; \Theta(t_f > t_d)$$

Color-coherence in medium

Vacuum

Resumming many emissions: collinear jet

$$\left|\underset{}{\bigtriangleup}\right|^2 + \left|\underset{}{\bigtriangleup}\right|^2 + ... \implies \underset{}{\blacktriangleleft}$$

Color-conservation:

$$\left|\blacktriangleleft\right|^2$$

Color-coherence:

$$\left|\blacktriangleleft + \blacktriangleleft\right|^2 \implies \approx \left(\frac{dI_q^{vac}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dzd\vartheta}\right)$$

$$\times \; \Theta\big(\vartheta_{q\bar{q}} > \vartheta_g\big)$$

angular-ordering!

Medium

Medium-induced emission:

$$\left|\blacktriangleleft\right|^2 \implies \frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi} \frac{Q_{med}}{E} \frac{2C_i}{\sqrt{z^3}}$$

soft divergence!

Decoherence time:

$$\left|\blacktriangleleft\right|^2 \implies \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

$$\left|\blacktriangleleft + \blacktriangleleft\right|^2 \implies \approx \left(\frac{dI_q^{med}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{med}}{dzd\vartheta}\right)$$
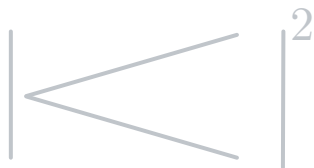
$$\times \; \Theta(t_f > t_d)$$

Color-coherence in medium

Vacuum

Resumming many emissions: collinear jet

$$\left| \raisebox{-0.5em}{\includegraphics{}} \right|^2 + \left| \raisebox{-0.5em}{\includegraphics{}} \right|^2 + ... \implies$$

Color-conservation:

$$\left| \raisebox{-0.5em}{\includegraphics{}} \right|^2$$

Color-coherence:

$$\left| \raisebox{-0.5em}{} + \raisebox{-0.5em}{} \right|^2 \implies \approx \left(\frac{dI_q^{vac}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dzd\vartheta} \right)$$

$$\times \; \Theta\!\left(\vartheta_{q\bar{q}} > \vartheta_g\right)$$

angular-ordering!

Medium

Medium-induced emission:

$$\left| \raisebox{-0.5em}{\includegraphics{}} \right|^2 \implies \frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi} \frac{Q_{med}}{E} \frac{2C_i}{\sqrt{z^3}}$$

soft divergence!

Decoherence time:

$$\left| \raisebox{-0.5em}{\includegraphics{}} \right|^2 \implies \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

$$\left| \raisebox{-0.5em}{} + \raisebox{-0.5em}{} \right|^2 \implies \approx \left(\frac{dI_q^{med}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{med}}{dzd\vartheta} \right)$$

$$\times \; \Theta\!\left(t_f > t_d\right)$$
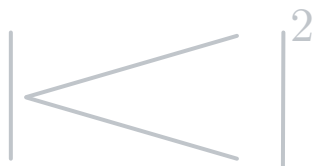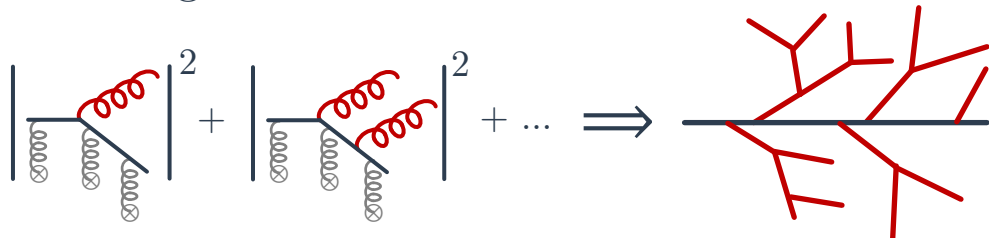
Color-coherence in medium

Vacuum	Medium
Resumming many emissions: collinear jet	wide-angle medium cascade

Color-conservation:

$$\left|\ \underset{}{\prec}\ \right|^2$$

Color-coherence:

$$\left|\ \prec\!\!\!\!\!\!_{0000} + \prec\!\!\!\!\!\!_{0000}\ \right|^2 \implies \approx \left(\frac{dI_q^{vac}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dzd\vartheta}\right)$$

$$\times\ \Theta\!\left(\vartheta_{q\bar{q}} > \vartheta_g\right)$$

angular-ordering!

Decoherence time:

$$\left|\ \underset{}{\prec}\ \right|^2 \implies \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

$$\left|\ \prec + \prec\ \right|^2 \implies \approx \left(\frac{dI_q^{med}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{med}}{dzd\vartheta}\right)$$

$$\times\ \Theta\!\left(t_f > t_d\right)$$

Color-coherence in medium

Vacuum

Resumming many emissions: collinear jet

Color-conservation:
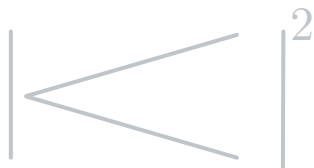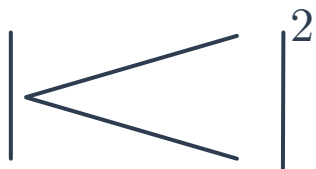
Color-coherence:

$$\left| \begin{array}{c} \end{array} \right|^2 \implies \approx \left(\frac{dI_q^{vac}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dzd\vartheta} \right)$$

$$\times \; \Theta(\vartheta_{q\bar{q}} > \vartheta_g)$$

angular-ordering!

Medium
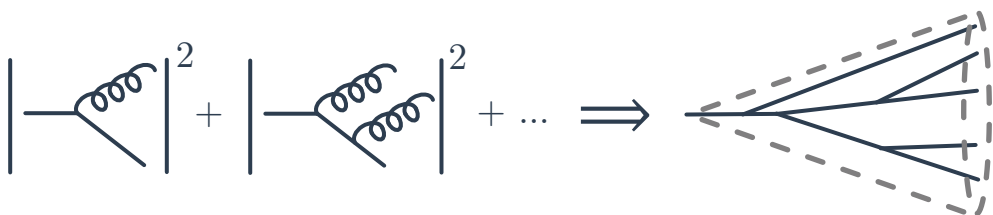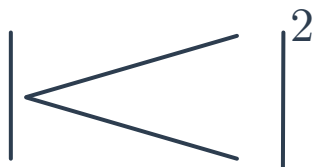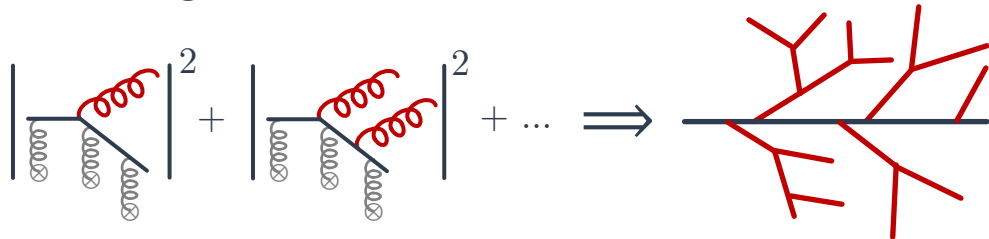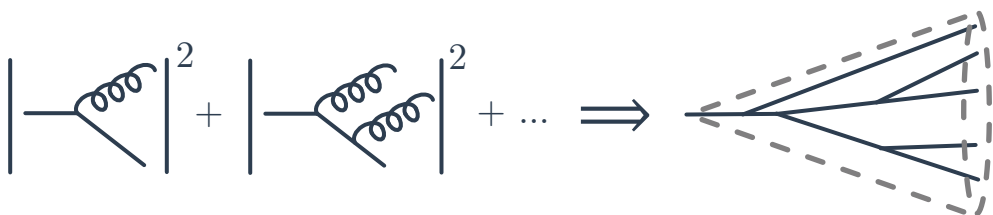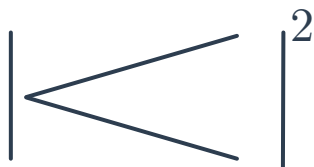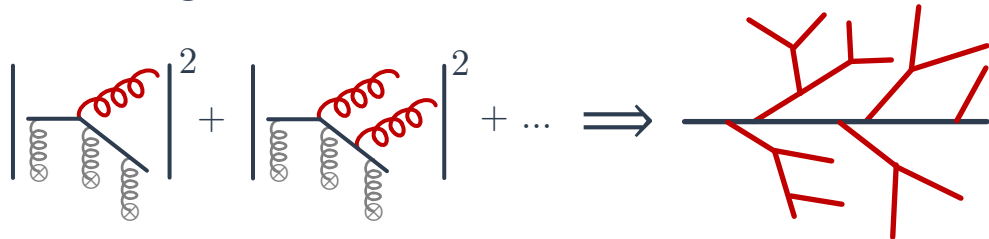
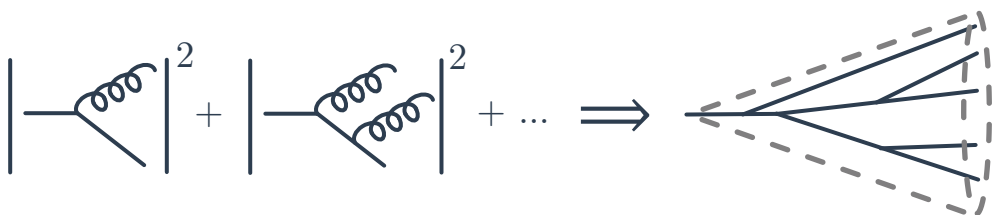wide-angle medium cascade

Decoherence time:

$$\left| \begin{array}{c} \end{array} \right|^2 \implies \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

$$\left| \begin{array}{c} \end{array} \right|^2 \implies \approx \left(\frac{dI_q^{med}}{dzd\vartheta} + \frac{dI_{\bar{q}}^{med}}{dzd\vartheta} \right)$$

$$\times \; \Theta(t_f > t_d)$$

Color-coherence in medium

Vacuum	Medium
Resumming many emissions: collinear jet	wide-angle medium cascade

Color-conservation:

Decoherence time:

$$\Longrightarrow \quad \Theta(t_d > t)$$

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Color-coherence:

$$\Longrightarrow \quad \approx \left(\frac{dI_q^{vac}}{dz d\vartheta} + \frac{dI_{\bar{q}}^{vac}}{dz d\vartheta} \right)$$

$$\times \ \Theta\left(\vartheta_{q\bar{q}} > \vartheta_g\right)$$

angular-ordering!

Medium resolution:

$$\Longrightarrow \quad \approx \left(\frac{dI_q^{med}}{dz d\vartheta} + \frac{dI_{\bar{q}}^{med}}{dz d\vartheta} \right)$$
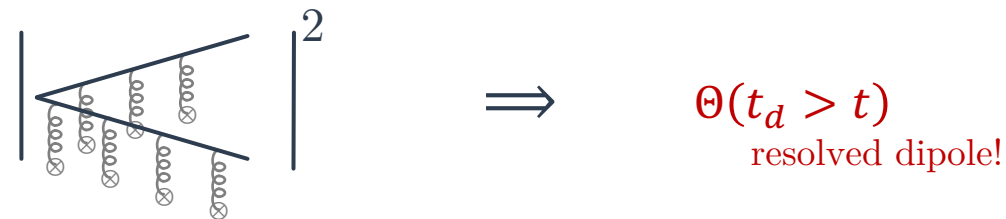
$$\times \ \Theta\left(t_f > t_d\right)$$

Color-coherence in medium

Color-coherence in medium

Vacuum

Medium

wide-angle medium cascade

$$\left| \begin{array}{c} \end{array} \right|^2 + \left| \begin{array}{c} \end{array} \right|^2 + ... \implies$$

Decoherence time:

$$\left| \begin{array}{c} \end{array} \right|^2 \implies \Theta(t_d > t)$$

resolved dipole!

Medium resolution:

$$\left| \begin{array}{c} \end{array} + \begin{array}{c} \end{array} \right|^2 \implies \approx \left(\frac{dI_q^{med}}{dz d\vartheta} + \frac{dI_{\bar{q}}^{med}}{dz d\vartheta} \right)$$

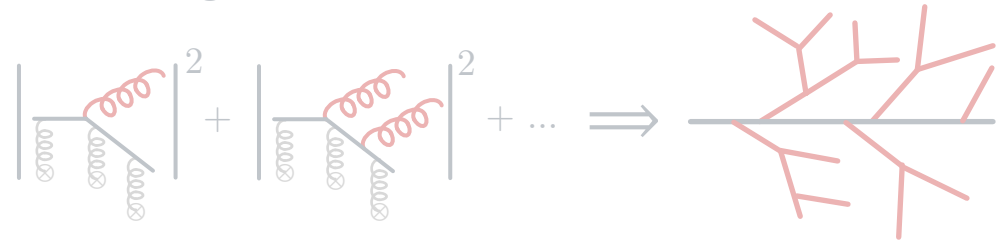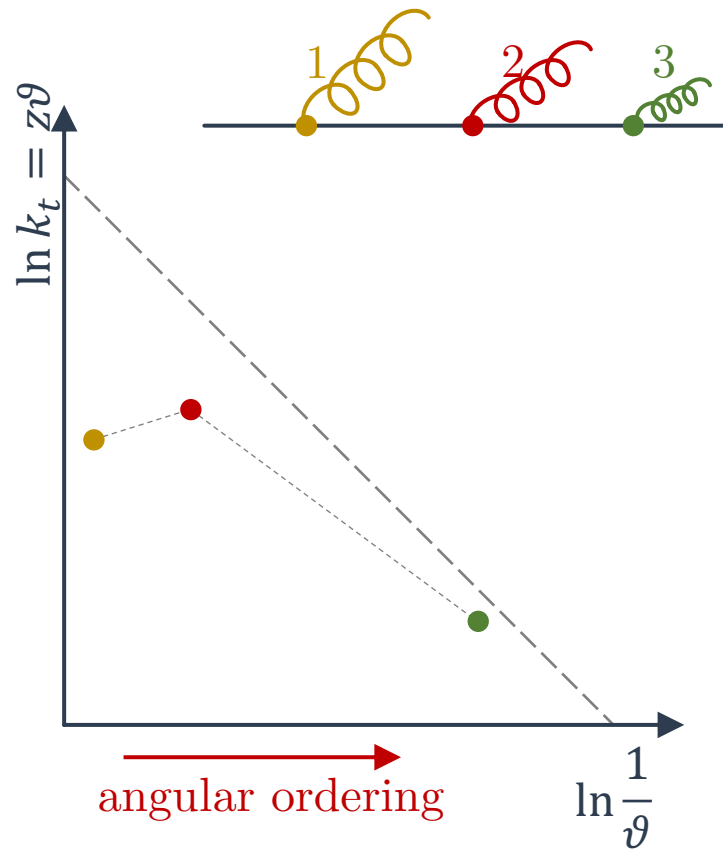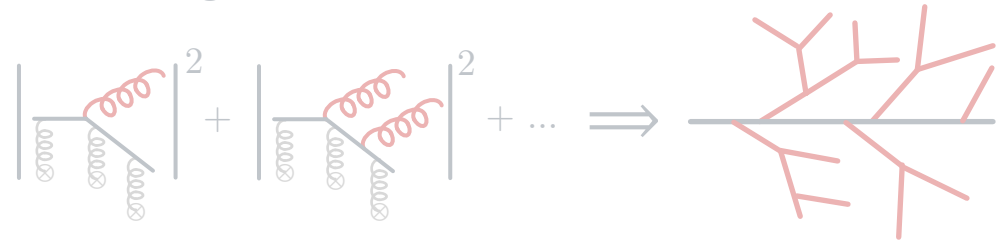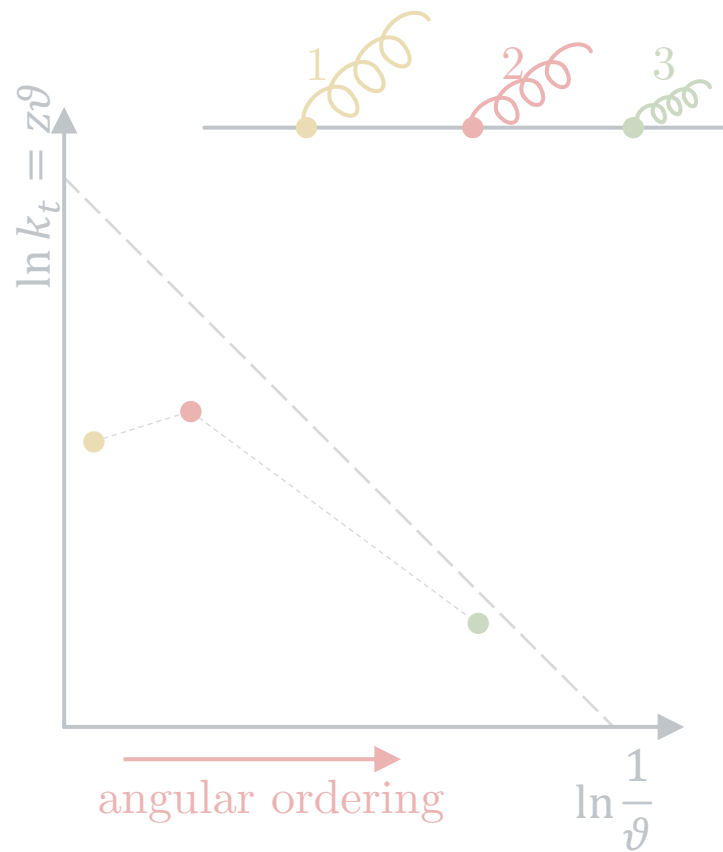$$\times \ \Theta(t_f > t_d)$$

Color-coherence in medium
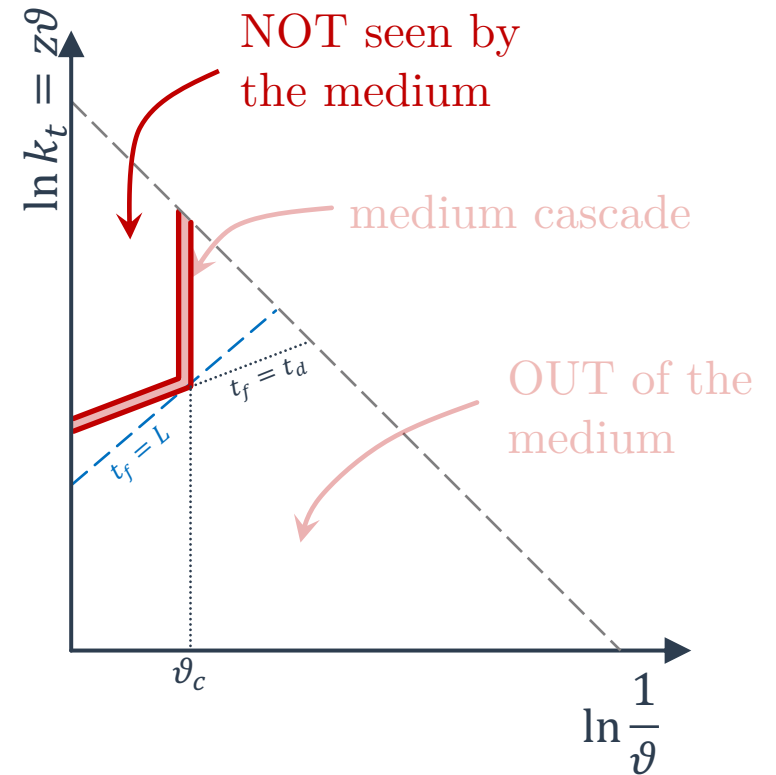
QCD Challenges from pp to AA collisions

Color-coherence in medium

Vacuum

Medium

Factorized picture of jet evolution in medium

[Blaizot,Dominguez,Iancu,Mehtar-Tani]
[Mehtar-Tani,Salgado,Tywoniuk]
[Caucal,Iancu,Mueller,Soyez]

1. Hard scattering is unaffected[*]

2. Vacuum parton shower is unaffected

3. Switching at: $L > t_d = t_f$

4. Cascade of medium-induced emissions

5. Vacuum parton shower is unaffected[#]

Adam Takacs   QCD Challenges from pp to AA collisions
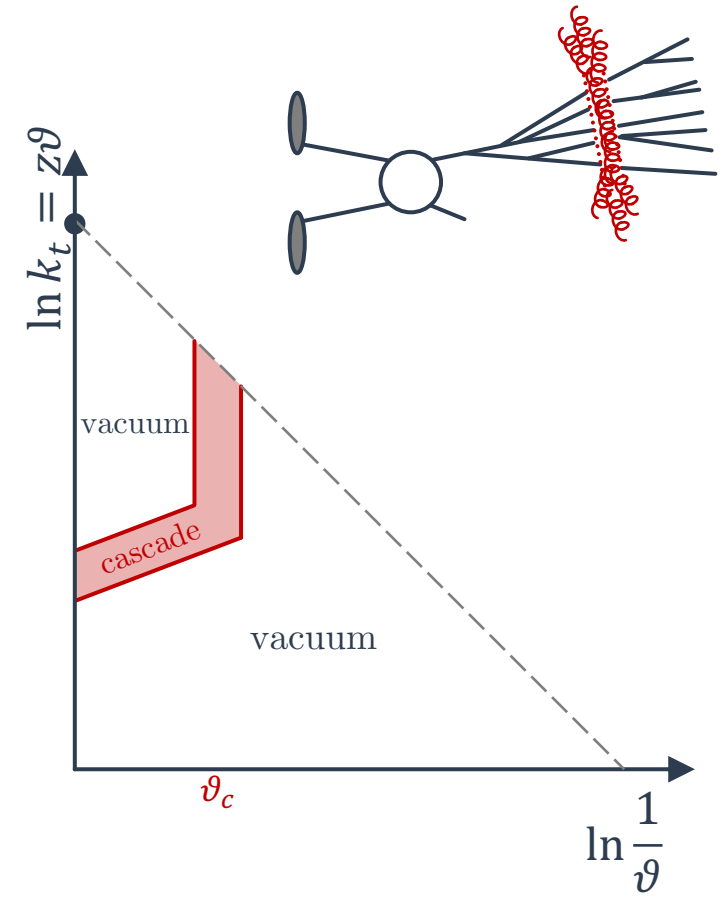
Testing color-coherence

and the factorized picture

How to test color-coherence?

R_{AA} measurements (with bkg subtraction!):

- small R - dependence of R_{AA}

- high p_T - dependence of R_{AA}

- big centrality (L) dependence of R_{AA}

Jet substructure:

- **Dynamical grooming**, SoftDrop

- R_{AA} vs. substructure

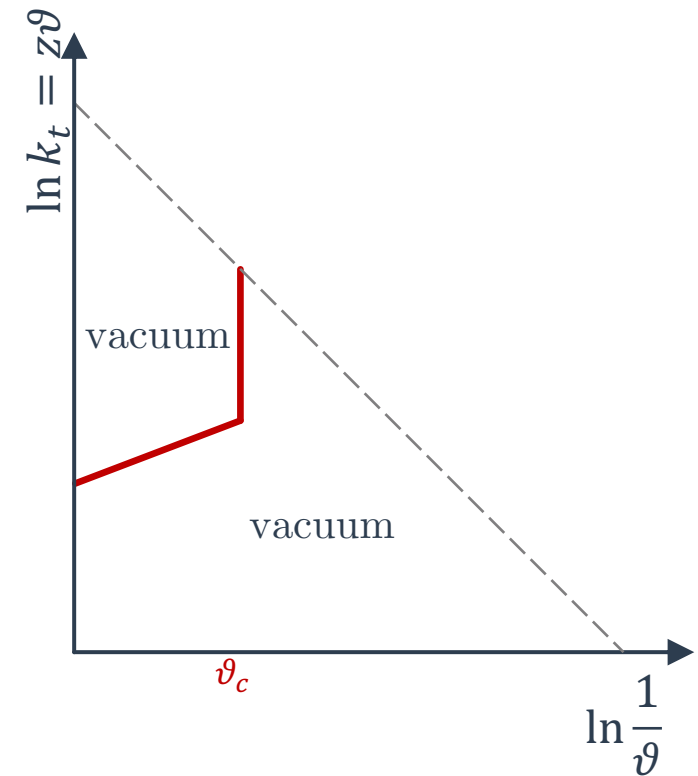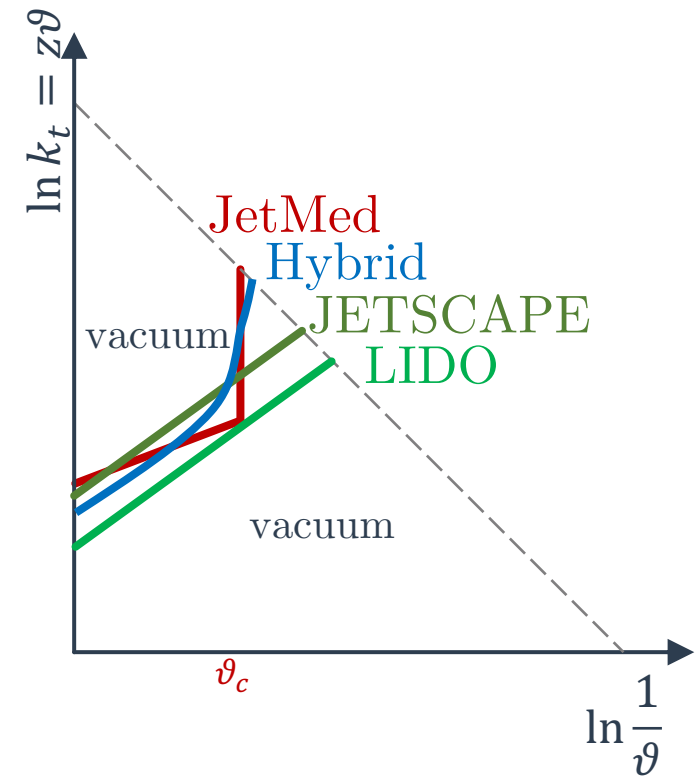Adam Takacs   QCD Challenges from pp to AA collisions

How to test color-coherence?

R_{AA} measurements (with bkg subtraction!):

- small R - dependence of R_{AA}

- high p_T - dependence of R_{AA}

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Jet substructure:

- **Dynamical grooming**, SoftDrop

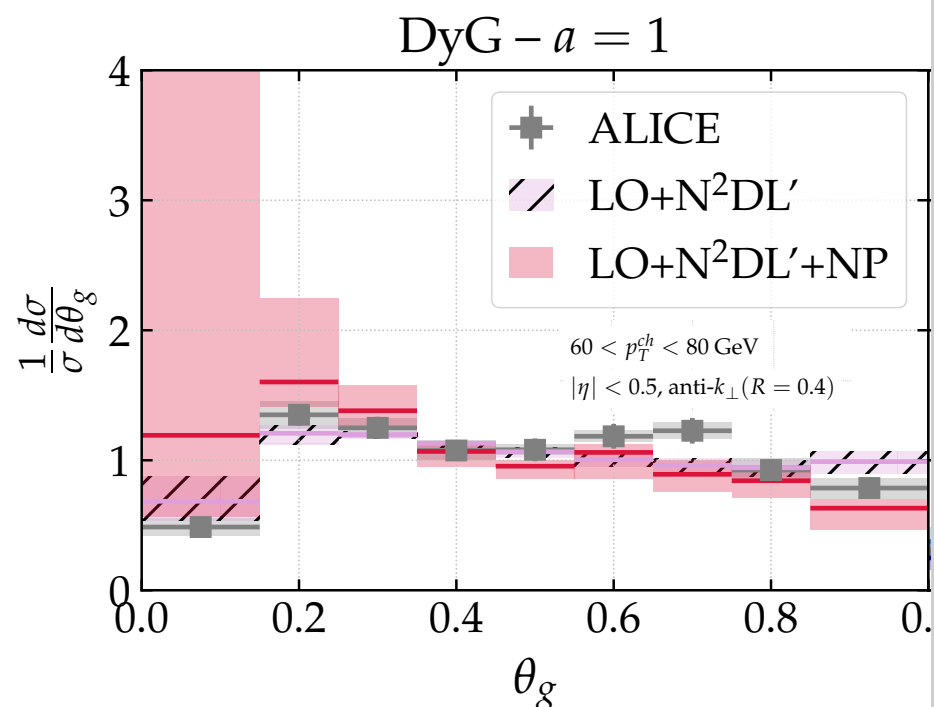- R_{AA} vs. substructure

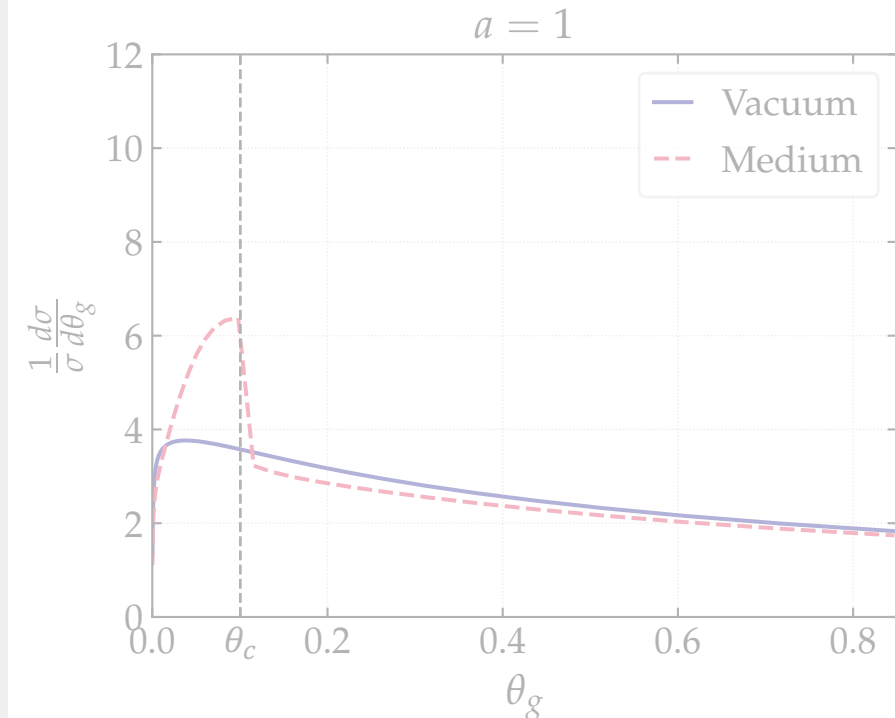Adam Takacs   QCD Challenges from pp to AA collisions

Angle of the hardest branching

Precise pQCD calculation in pp
[arXiv:2103.06566]

Changes in AA
[arXiv:2111.14768]
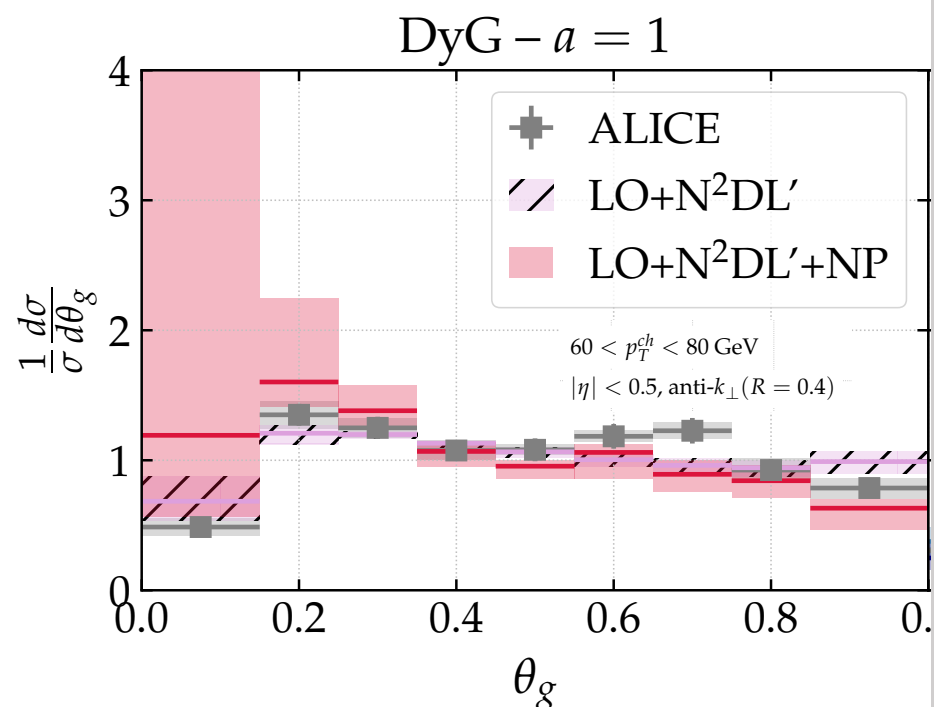

[ALICE 2204.10246]

[Caucal,Soto-Ontoso,Takacs]

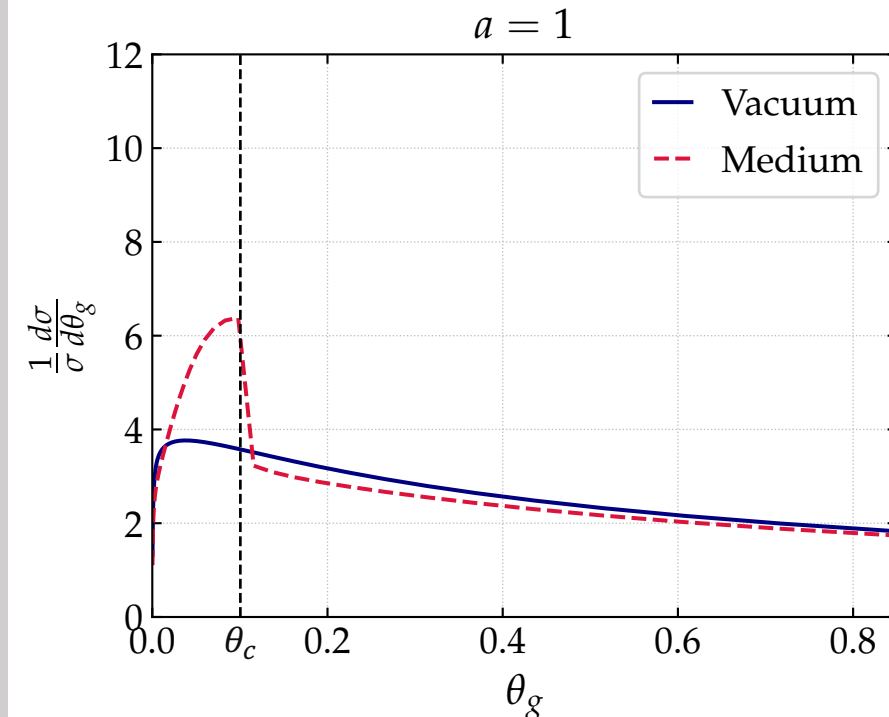huge enhancement around ϑ_c!

Angle of the hardest branching

Precise pQCD calculation in pp
[arXiv:2103.06566]

Changes in AA
[arXiv:2111.14768]

[ALICE 2204.10246]

huge enhancement around ϑ_c!

Is ϑ_c really measurable?

- HI event generator study:

  JetMed [Caucal,Iancu,Soyez]

  Jewel [Zapp,Krauss,Wiedemann]

  Hybrid [Casalderrey-S,Milhano,Pablos,Rajagopal]

- Non-perturbative physics:

  - Fluctuating background

  - Medium response

  - Hadronization

Enhancement remains!
Best chance to measure ϑ_c:
- $R = 0.2$, DyG $a = 0.2$

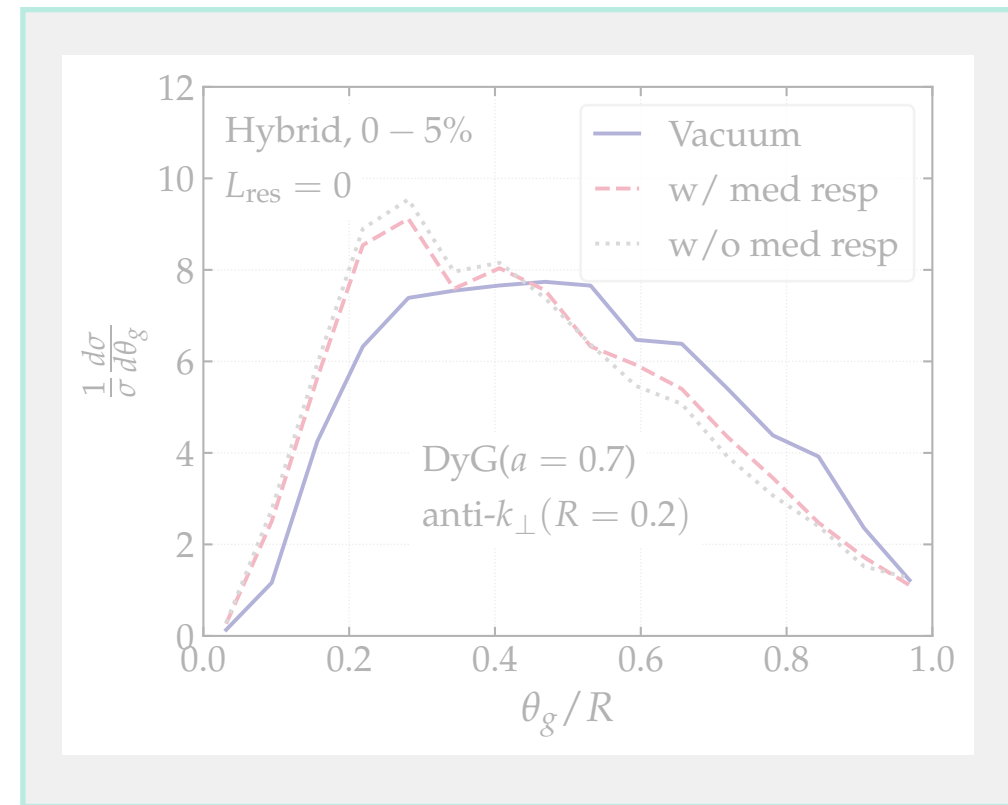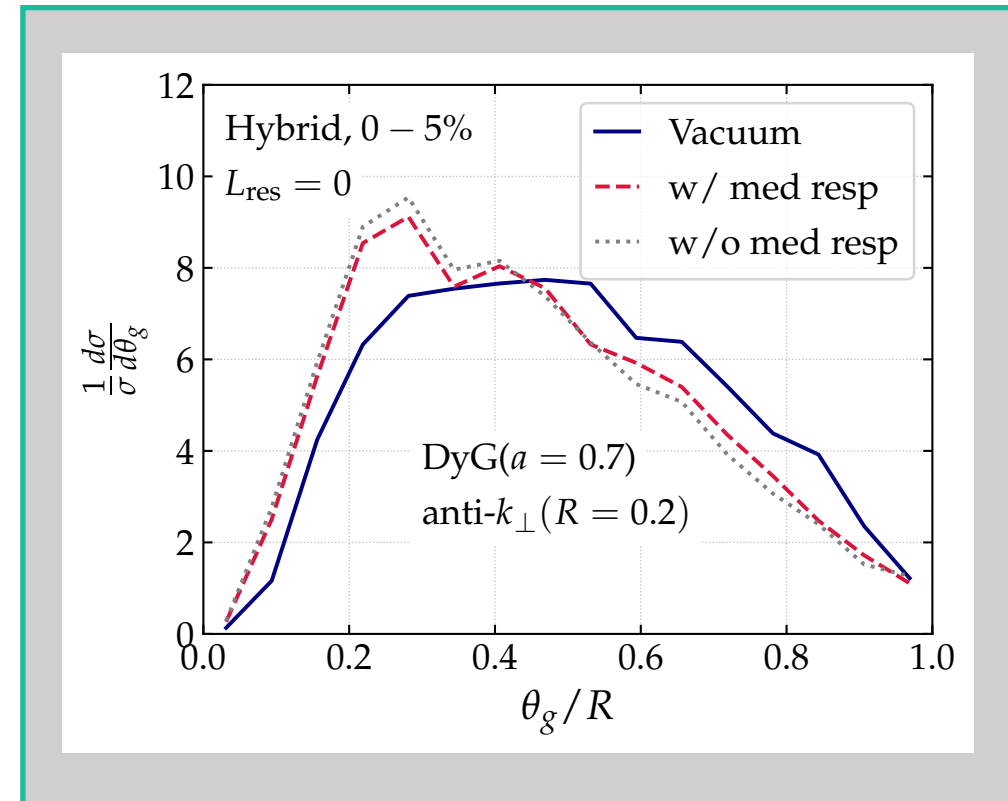# Is ϑ_c really measurable?

- HI event generator study:

  JetMed [Caucal,Iancu,Soyez]

  Jewel [Zapp,Krauss,Wiedemann]

  Hybrid [Casalderrey-S,Milhano,Pablos,Rajagopal]

- Non-perturbative physics:
  - Fluctuating background
  - Medium response
  - Hadronization

Enhancement remains!
Best chance to measure ϑ_c:
- $R = 0.2$, DyG $a = 0.2$

Summary

Summary

- What is **perturbative**, and what is **weakly coupled**.

- **Color-coherence** results in **angular ordering** in vacuum.

- In medium, color-connections gets **resolved** and **decohere**

$$\Rightarrow \textbf{Factorized picture} \text{ of jet energy loss}$$

- Testing the factorized picture

- **Dynamical grooming to measure** ϑ_c

Adam Takacs QCD Challenges from pp to AA collisions
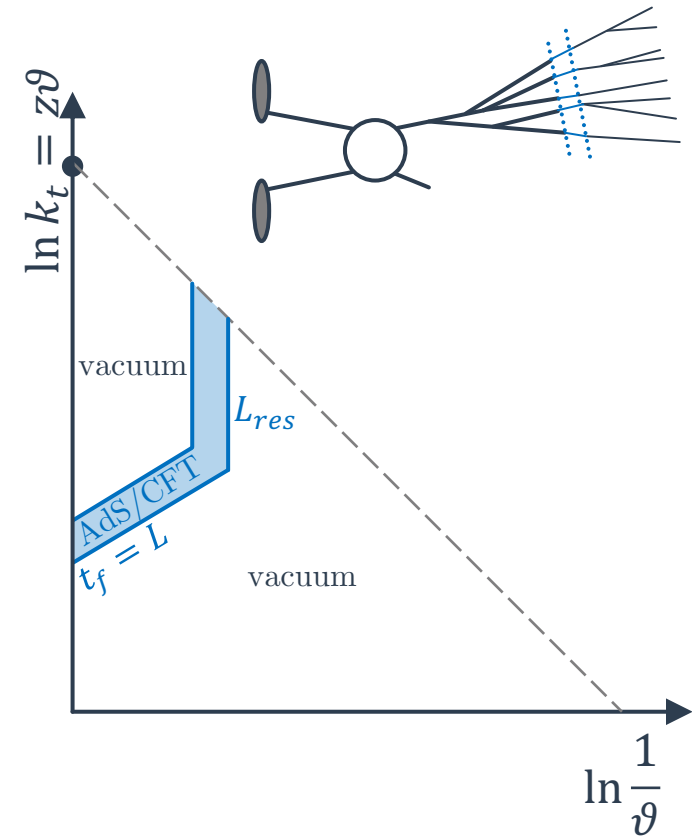
Thank you for the attention!

Other models and recent progression

# Color-coherence in Hybrid

[Casalderrey-S,Milhano,Pablos,Rajagopal]

1. Hard scattering from Pythia8

2. Vacuum parton shower is unaffected

3. Switching scale: formation time & dipole size

4. Ads/CFT energy-loss

5. Vacuum parton shower the rest

Color-coherence in LIDO

1. Hard scattering from Pythia8

2. Vacuum parton shower is unaffected

3. Switching scale in virtuality

4. LIDO/LBT (LO QCD 2→2, and 1→2 higher-twist)

5. Vacuum parton shower the rest
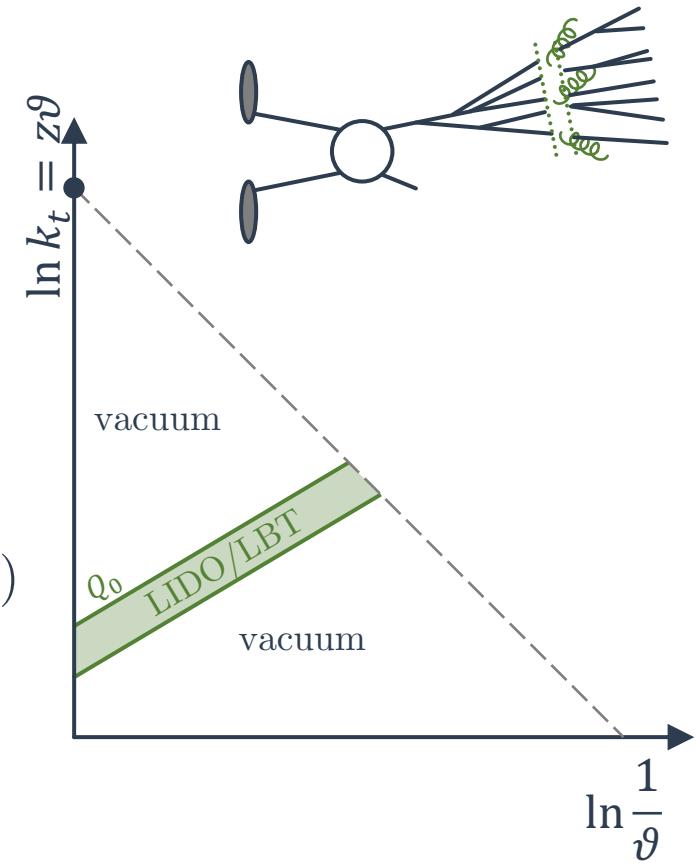
Recent improvements: soft + hard scatterings
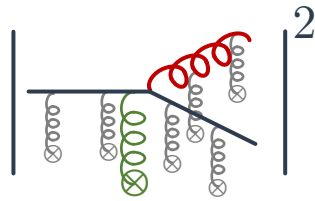
Emission in medium:

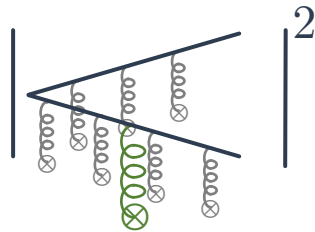 $\implies$ $\frac{dI_i^{med}}{dz} = \int d\vartheta \frac{dI}{dzd\vartheta} \approx \frac{\alpha_s}{\pi} \sqrt{\frac{\hat{q}L^2}{4E}} \frac{2C_i}{\sqrt{z^3}} [1 + \mathcal{O}(1^{st} \text{ opacity})]$

small modification of the cascade!
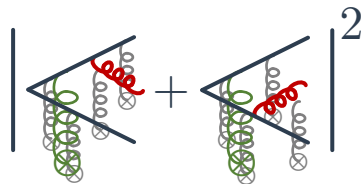
Decoherence time (destroying color-connections):

 $\implies$ $\Delta^{med}(t) = \Theta(t_d > t)[1 + \mathcal{O}(1^{st} \text{ opacity})]$

modification of coherence!

Angular ordering:

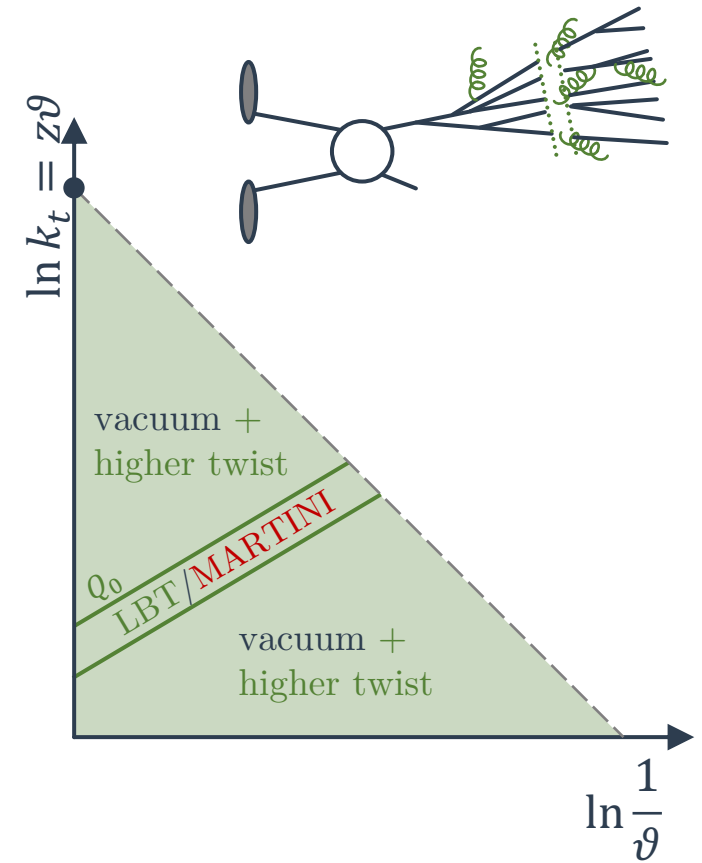 $\implies$ $\frac{dI_{q\bar{q}}^{med}}{dzd\vartheta} \approx ?$ work in progress!

Color-coherence in OLD JETSCAPE

1. Hard scattering from Pythia8

2. MATTER (vacuum + higher-twist splittings)

3. Switching scale in virtuality

4. LBT (LO QCD 2→2, and 1→2 higher-twist)

    MARTINI (LO HTL 2→2, and 1→2 splittings)

5. MATTER (vacuum + higher-twist splittings)

Color-coherence in NEW JETSCAPE

1. Hard scattering from Pythia8

2. MATTER (vacuum + ~~higher-twist~~ splittings)

3. Switching scale in virtuality

4. LBT (LO QCD 2→2, and 1→2 higher-twist)

   MARTINI (LO HTL 2→2, and 1→2 splittings)

5. MATTER (vacuum + higher-twist splittings)