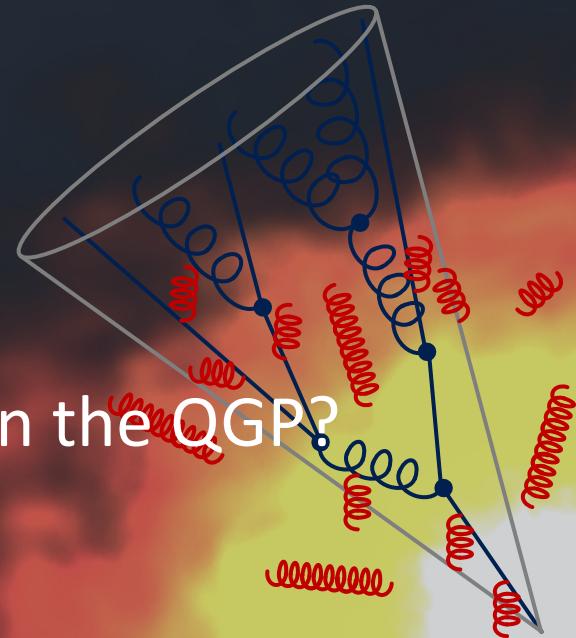


# Jet evolution & substructure modification within the QGP

Adam Takacs  
Heidelberg University

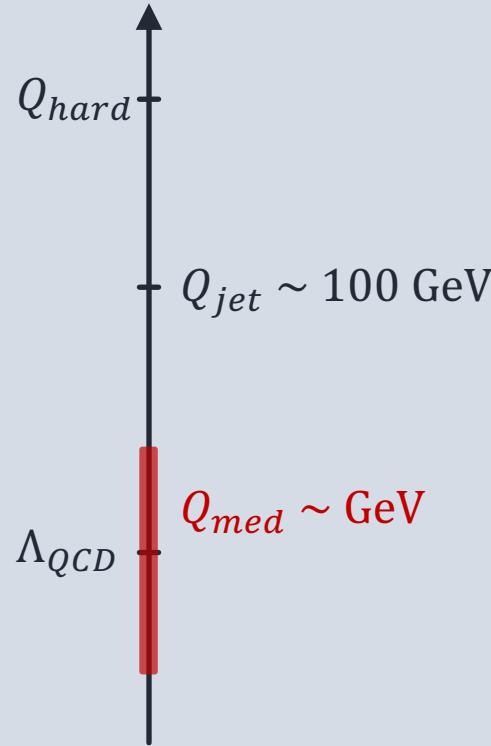


UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386



What is jet modification in the QGP?

# Introduction



- pQCD and factorization:

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

- Jet-medium interaction:

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

← This talk!

- Weakly or strongly coupled medium?

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

← Talk by Go,  
Almaalol, Li

\*There can be several medium scales and they can depend on the observable.

# Introduction

- Separate hard and background fields ( $q = q_h + \mathbf{q}_0, A = A_h + \mathbf{A}_0$ )

$$\begin{aligned}\mathcal{L}_{QCD}(q, A) &= \mathcal{L}(q_h, A_h) + \mathcal{L}(\mathbf{q}_0, \mathbf{A}_0) + \mathcal{L}_{int}(q_h, A_h, \mathbf{q}_0, \mathbf{A}_0) \\ &\approx \mathcal{L}(q_h, A_h) + g\bar{q}_h \langle J \rangle q_h + gA_h \langle J \rangle A_h\end{aligned}$$

- Dressed propagators:

$$\begin{aligned}\text{---} &= \text{---} + \text{---} \otimes \text{---} + \text{---} \otimes \text{---} \otimes \text{---} + \dots \\ \text{---} &= \text{---} + \text{---} \otimes \text{---} + \text{---} \otimes \text{---} \otimes \text{---} + \dots\end{aligned}$$

- Models for the background  $\langle J(x^\mu) \rangle$ :

- High-temperature plasma ( $T \gg \Lambda_{QCD}$ )
- Random color-fields
- Non-perturbative “function”

# Introduction

- Separate hard and background fields ( $q = q_h + \mathbf{q}_0, A = A_h + \mathbf{A}_0$ )

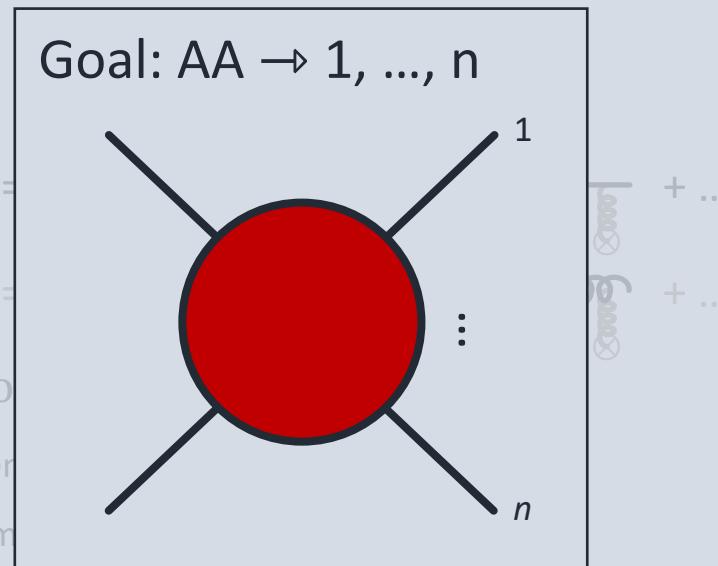
$$\mathcal{L}_{QCD}(q, A) = \mathcal{L}(q_h, A_h) + \mathcal{L}(\mathbf{q}_0, \mathbf{A}_0) + \mathcal{L}_{int}(q_h, A_h, \mathbf{q}_0, \mathbf{A}_0)$$

- Dressed propagators:



- Models for the background

- High-temperature
- Random
- Non-perturbative “function”

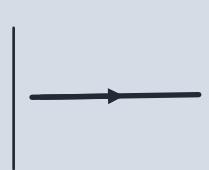


\*This talk focuses on  $i \rightarrow 1, \dots, n$ .

# Jet modification: medium-induced emissions

## Vacuum

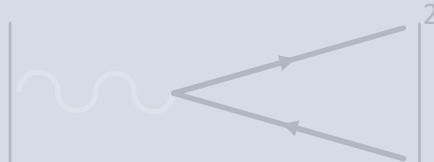
- Fixed path:


$$\left| \begin{array}{c} \text{---} \\ \text{---} \end{array} \right| \approx \delta_{ij} \delta(p' - p)$$

A horizontal line with an arrow pointing right, enclosed in vertical brackets. The right bracket has a superscript  $2$ .

The expression  $\delta_{ij} \delta(p' - p)$  is shown to the right of the brackets.

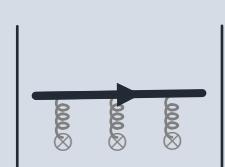
- Color conservation:


$$\left| \begin{array}{c} \text{---} \\ \text{---} \end{array} \right|^2$$

A horizontal line with an arrow pointing right, followed by a wavy line that splits into two paths forming a triangle. The right bracket has a superscript  $2$ .

## Medium

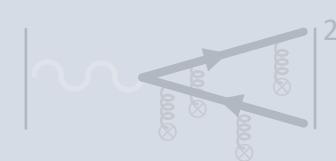
- Broadening:


$$\left| \begin{array}{c} \text{---} \\ \text{---} \end{array} \right|^2 \approx \mathcal{G}_{ij}(p', p)$$

A horizontal line with an arrow pointing right, followed by three small circles with crossed lines, enclosed in vertical brackets. The right bracket has a superscript  $2$ .

The expression  $\mathcal{G}_{ij}(p', p)$  is shown to the right of the brackets.

- Color decoherence:


$$\approx \left| \begin{array}{c} \text{---} \\ \text{---} \end{array} \right|^2$$

The diagram shows the broadening process from the previous slide, followed by a dotted line and a colored triangle (red, yellow, green) at the end of the paths, representing color decoherence. The right bracket has a superscript  $2$ .

The text "color decoherence" is written in red at the bottom right.

# Jet modification: medium-induced emissions

## Vacuum

- Fixed path:

$$\left| \begin{array}{c} \rightarrow \\ \hline \end{array} \right| \approx \delta_{ij} \delta(p' - p)$$

- Color conservation:

$$\left| \begin{array}{c} \text{wavy line} \\ \swarrow \searrow \\ \hline \end{array} \right|^2$$

## Medium

- Broadening:

$$\left| \begin{array}{c} \rightarrow \\ \otimes \otimes \otimes \\ \hline \end{array} \right|^2 \approx \mathcal{G}_{ij}(p', p)$$

- Color decoherence:

$$\left| \begin{array}{c} \text{wavy line} \\ \swarrow \searrow \\ \otimes \otimes \otimes \\ \hline \end{array} \right|^2 \approx \left| \begin{array}{c} \text{wavy line} \\ \swarrow \searrow \\ \text{color decoherence} \\ \hline \end{array} \right|^2$$

color decoherence

# Jet modification: medium-induced emissions

## Vacuum

- Emission:

$$\left| \frac{dI_i^{vac}}{dz d\vartheta} \right|^2 \approx \frac{\alpha_s}{\pi} \frac{2C_i}{z} \frac{1}{\vartheta}$$

soft & collinear poles!

- Resumming emissions: collinear jet



## Medium

- Vacuum + medium-induced emissions:

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

soft pole!

$m \ll Q_{med}$   
 $z \ll Q_{med}/E$

- Wide-angle medium-induced cascade:



# Jet modification: medium-induced emissions

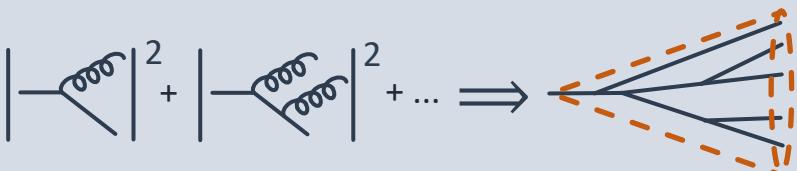
## Vacuum

- Emission:

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

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- Resumming emissions: collinear jet



## Medium

- Vacuum + medium-induced emissions:

$$\frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi} \sqrt{\frac{Q_{med}}{E}} \frac{C_i}{\sqrt{z^3}}$$

soft pole!  
 $m < Q_{med}$   
 $z \ll Q_{med}/E$

- Wide-angle medium-induced cascade:



# Jet modification: medium-induced emissions

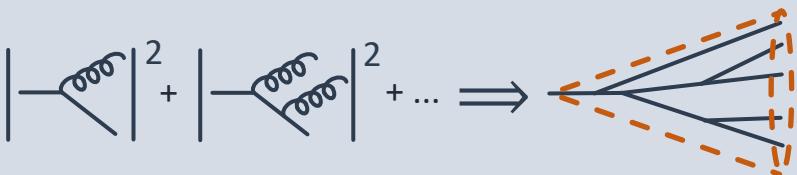
## Vacuum

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# Jet modification: medium-induced emissions

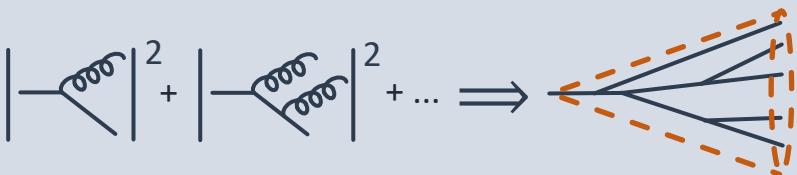
## Vacuum

- Emission:

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soft & collinear poles!

- Resumming emissions: collinear jet



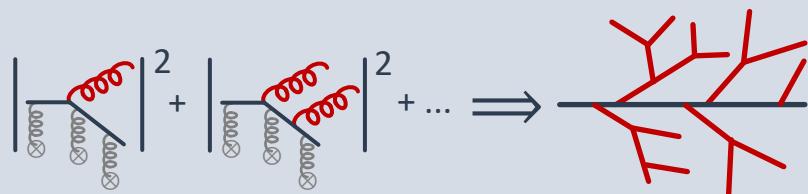
## Medium

- Vacuum + medium-induced emissions:

$$\frac{dI_i^{med}}{dz} \approx \frac{\alpha_s}{\pi} \sqrt{\frac{Q_{med}}{E}} \frac{C_i}{\sqrt{z^3}}$$

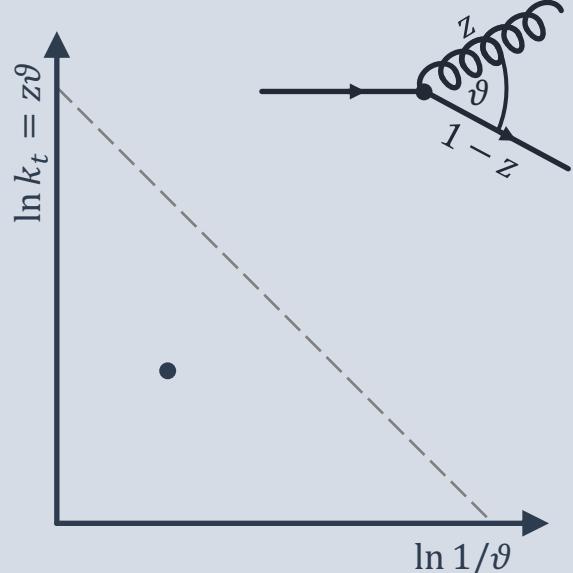
soft pole!

- Wide-angle medium-induced cascade:



# Jet evolution: factorized picture

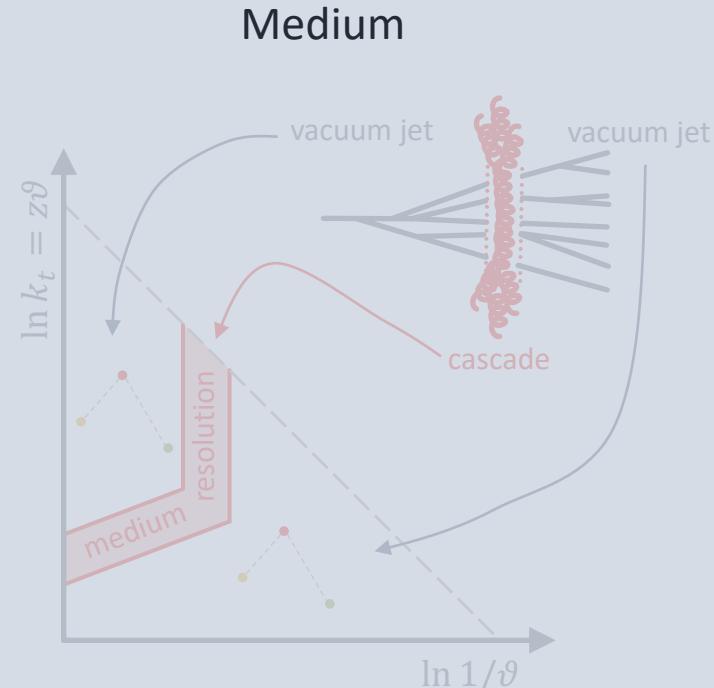
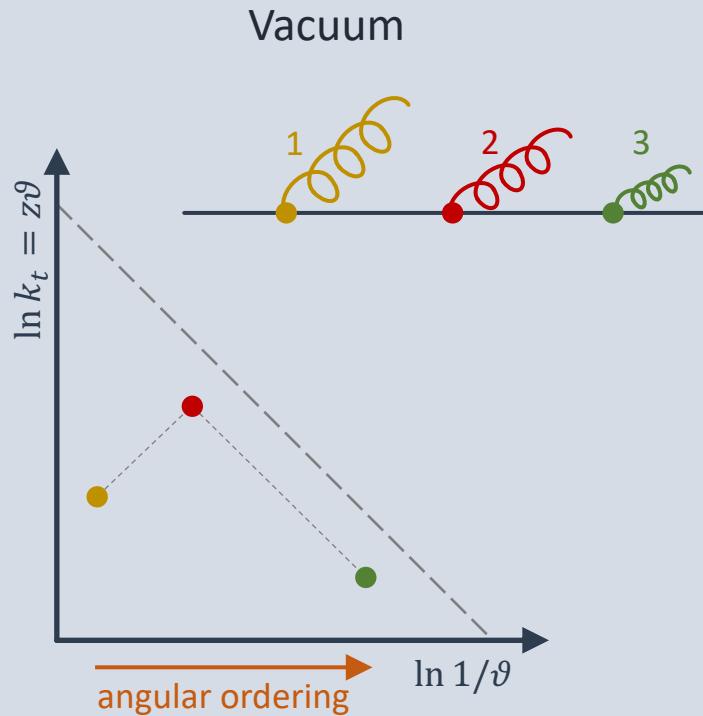
[Mehtar-Tani, Tywoniuk, Salgado]  
[Caucal, Iancu, Mueller, Soyez]



Medium

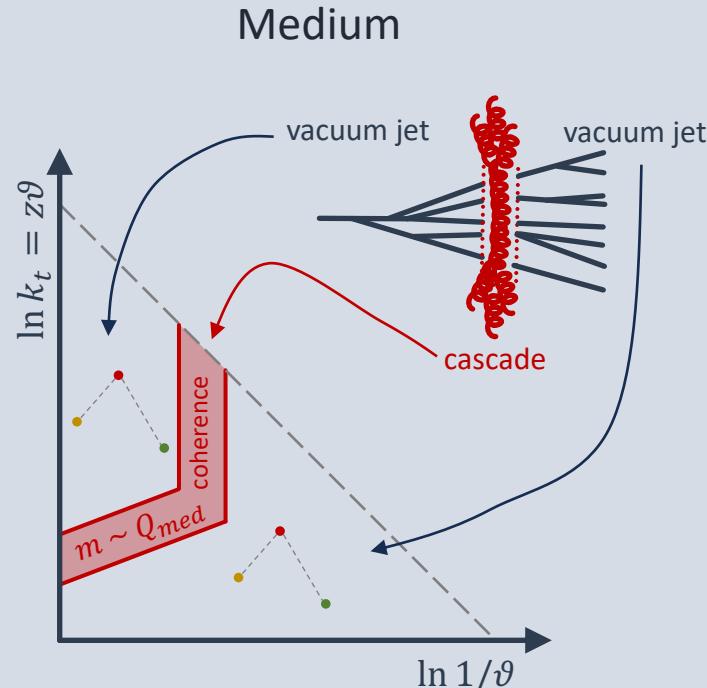
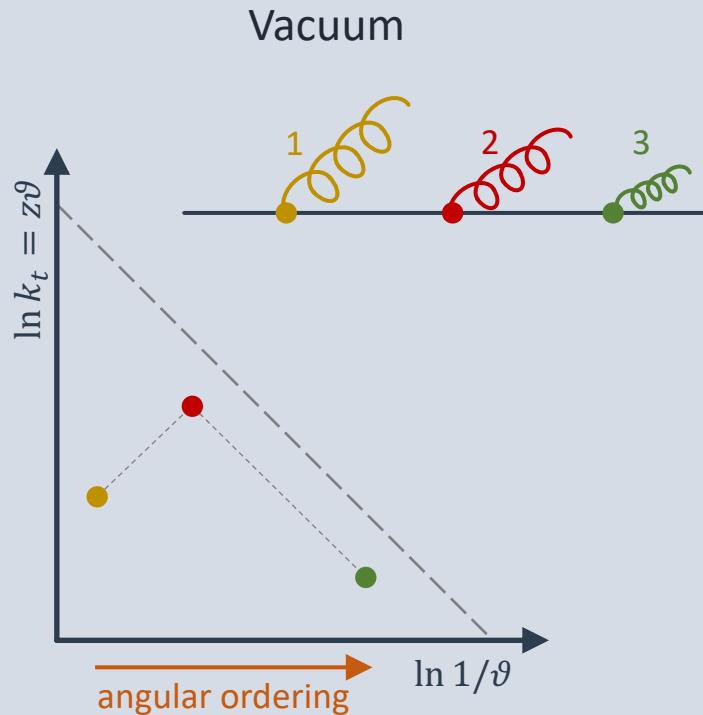
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[Mehtar-Tani, Tywoniuk, Salgado]  
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# Jet evolution: factorized picture

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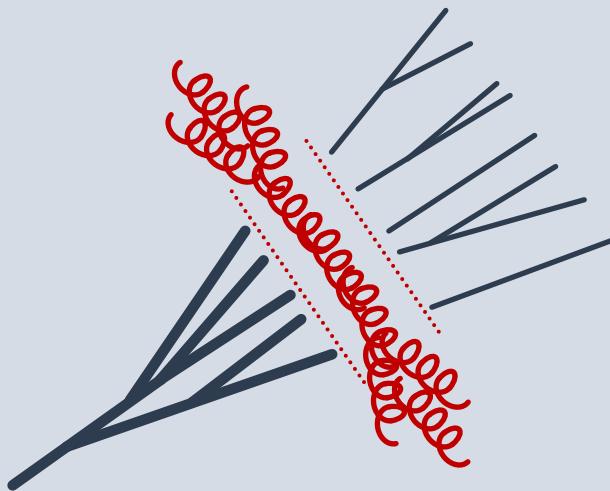
# Experimental test of the factorized picture

Talks by: Barata, Rothman, Jacobs, Go, Ehlers, Andres  
See also in my backup.

# How to improve this picture?

# Improvements

Factorized picture:



## Ingredients:

- vacuum evolution:  
- jet creation ( $\text{LO} \rightarrow \text{NLO}$ ), jet evolution ( $\text{DLA} \rightarrow \text{NLL}$ )  
Talks by  
Caletti, Roloff, Chahrour, Hoppe
- cascade evolution:  
- beyond soft&collinear limit ( $\text{NLO}_{\text{med}}$ ,  $\text{NLL}_{\text{med}}$ )  
[Ghiglieri, Teaney]  
- finite sized medium  
[Caron-Huot, Gale]  
[Isaksen, Takacs, Tywoniuk]
- medium scales:  
- resolution, coherence, orderings  
[Arnold 2023]
- +1 medium modeling:  
- homogeneous/static  $\rightarrow$  dynamical medium  
[Sadofyev et al]  
- medium response / jet thermalization  
Talks by  
Go, Almaalol, Li

# Jet modification: correlated emissions

## Vacuum

- Two gluon emission:

$$\left| \text{Diagram} \right|^2 = \left| \text{Diagram with two gluons} + \text{Diagram with one gluon} \right|^2$$

$$\approx \frac{dI_q^{vac}}{dz_1 d\vartheta_1} \frac{dI_g^{vac}}{dz_2 d\vartheta_2} \times \Theta(\vartheta_1 > \vartheta_2)$$

angular-ordering!

## Medium

- Two gluon emission:

- (anti-)Angular ordering:  
[Mehtar-Tani, Tywoniuk, Salgado]  
[Caucal, Iancu, Mueller, Soyez]



- Medium coherence:  
[Mehtar-Tani, Tywoniuk, Salgado]  
[Casalderrey-Solana, Iancu]



- In-medium ordering:  
[Blaizot, Dominguez, Mehtar-Tani]  
[Arnold 2015-]



# Jet modification: correlated emissions

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



- In-medium ordering:  
[Blaizot, Dominguez, Mehtar-Tani]  
[Arnold 2015-]



# Summary:

- Jets modify in the QGP → extract QGP features ( $T, n, \varepsilon, \dots$ )
- (Semi-) perturbative treatment
  - scattering amplitudes  $\leftrightarrow$  jet observable
- State of the art picture of jet modification:
  - good agreement with data!
  - improvements in the doorstep!

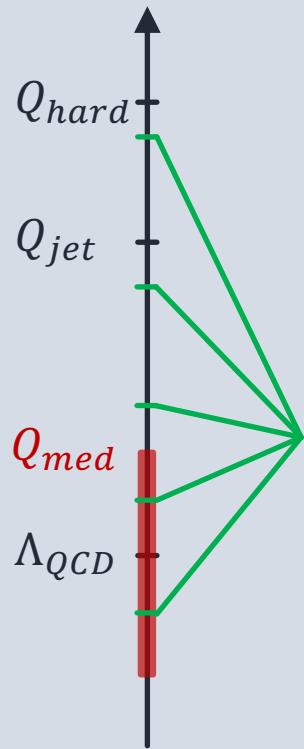
ask me about it!

Thank you for your attention!

# Experimental test of the factorized picture

# Experimental tests

Talks by: Barata, Rothman, Jacobs, Go, Ehlers, Andres

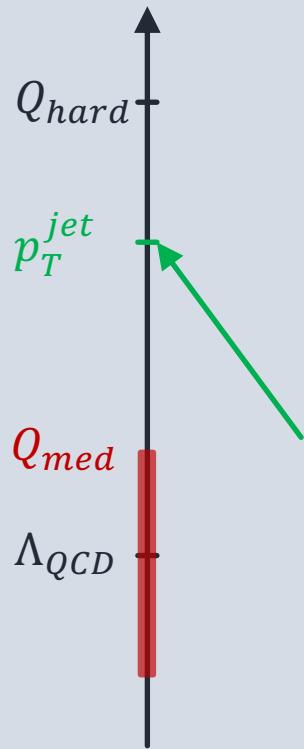


## Observables:

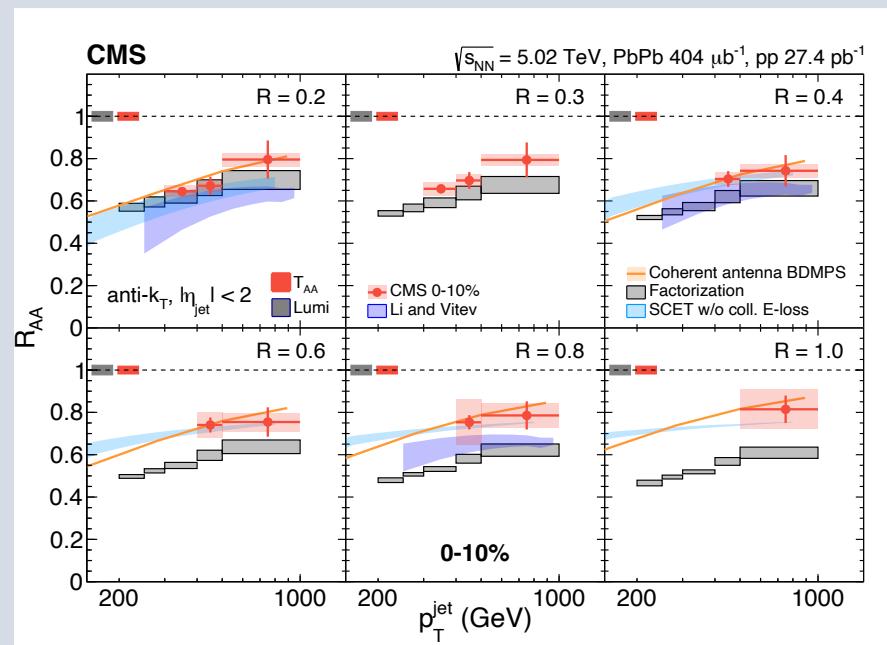
- event shapes
- jet substructure
- energy correlators
- etc.

# Experimental tests

Talks by: Barata, Rothman, Jacobs, Go, Ehlers, Andres



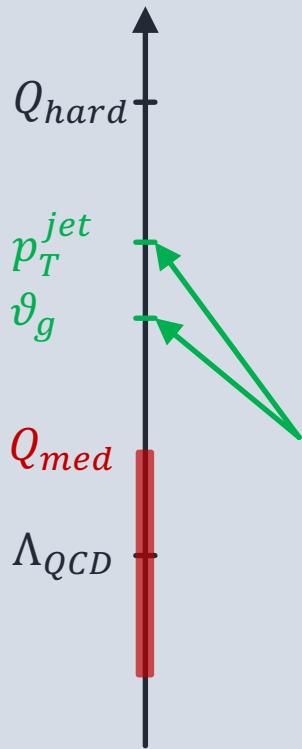
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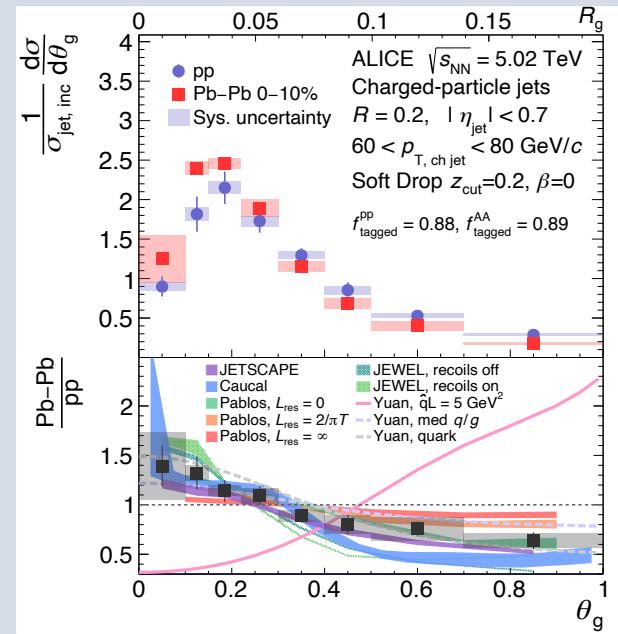
[CMS JHEP05(2021)]

# Experimental tests

Talks by: Barata, Rothman, Jacobs, Go, Ehlers, Andres



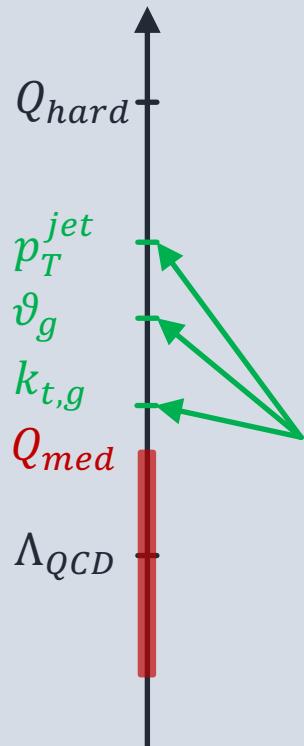
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[ALICE PRL128(2022)]

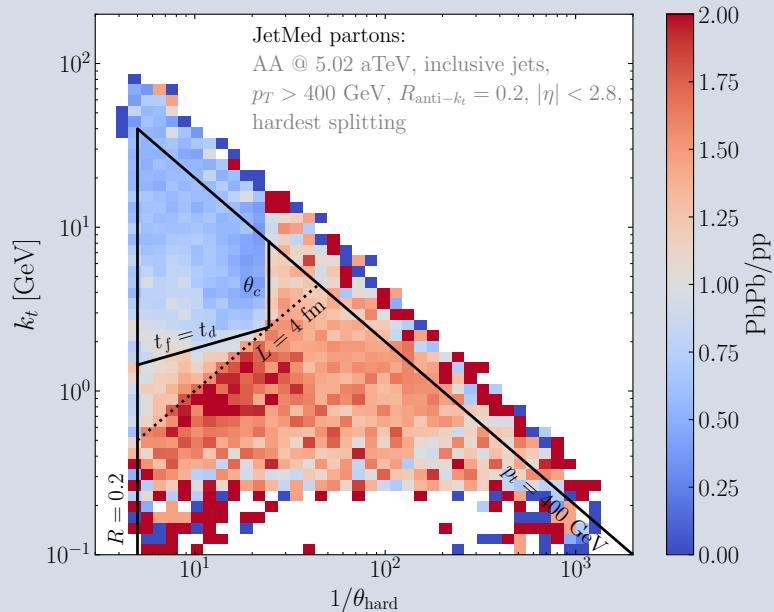
# Experimental tests

Talks by: Barata, Rothman, Jacobs, Go, Ehlers, Andres



## Observables:

- event shapes
- jet substructure
- energy correlators
- etc.



[Cunqueiro, Pablos, Soto-Ontoso, Spousta, Takacs, Verweij 2023]