

# Medium enhancement and parton formation times in the $g \rightarrow c\bar{c}$ splitting

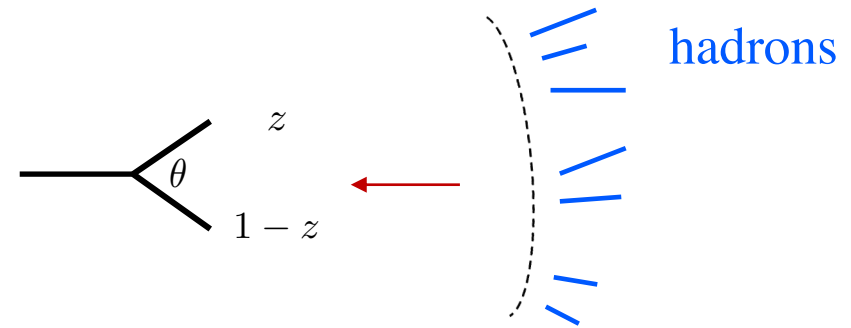
Jasmine Brewer



In collaboration with Maximilian Attems, Gian Michele Innocenti, Aleksas Mazeliauskas, Sohyun Park, Wilke van der Schee, Gregory Soyez, and Urs Wiedemann

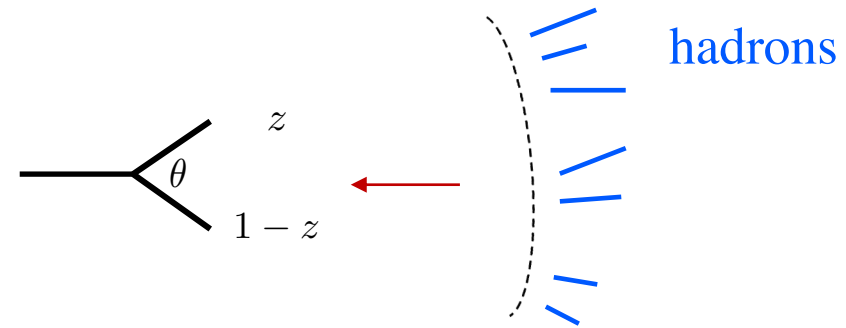
# Building up a picture of a medium-modified jet from phenomenology

- **Hadrons to splittings**



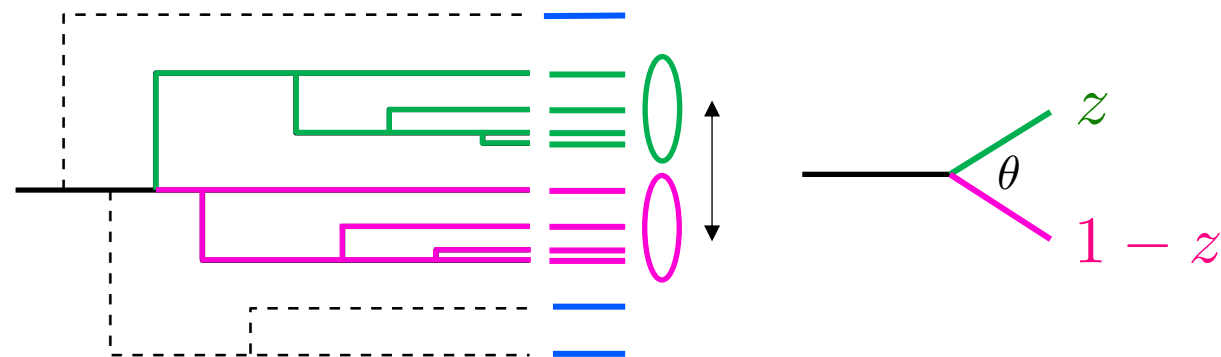
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- **Hadrons to splittings**



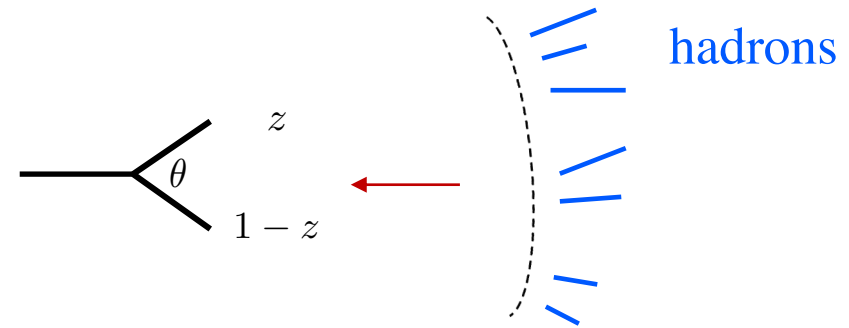
## Jet substructure:

Use angular ordering of QCD to reconstruct emission history of shower from hadrons

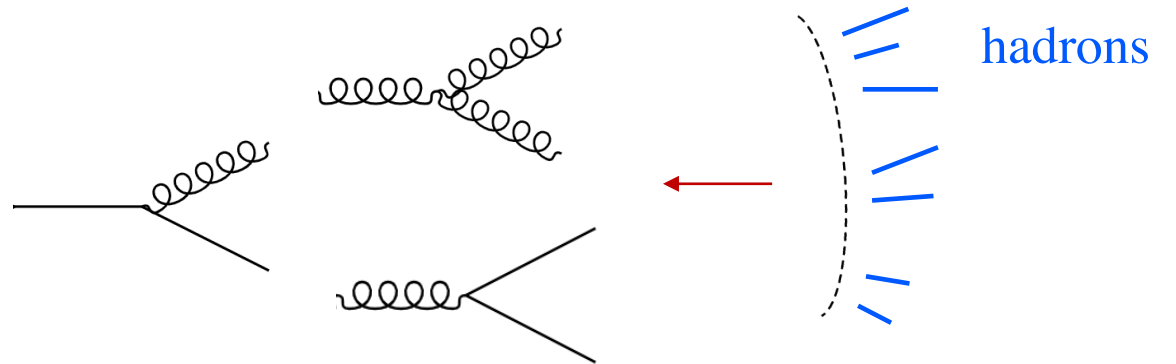


# Building up a picture of a medium-modified jet from phenomenology

- Hadrons to splittings

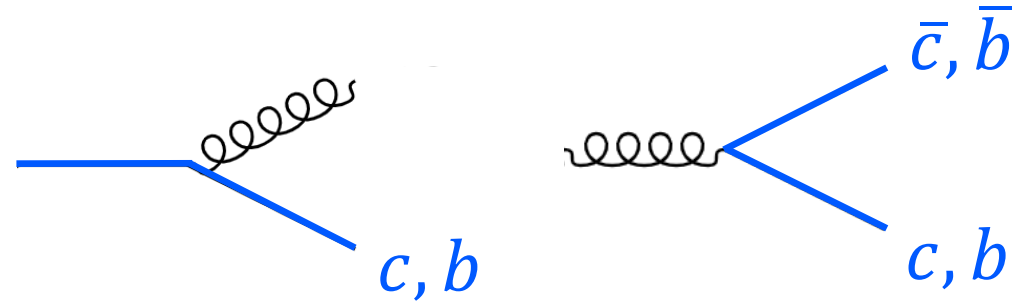


- Flavor-dependence of splittings



# Accessing heavy flavor splitting functions

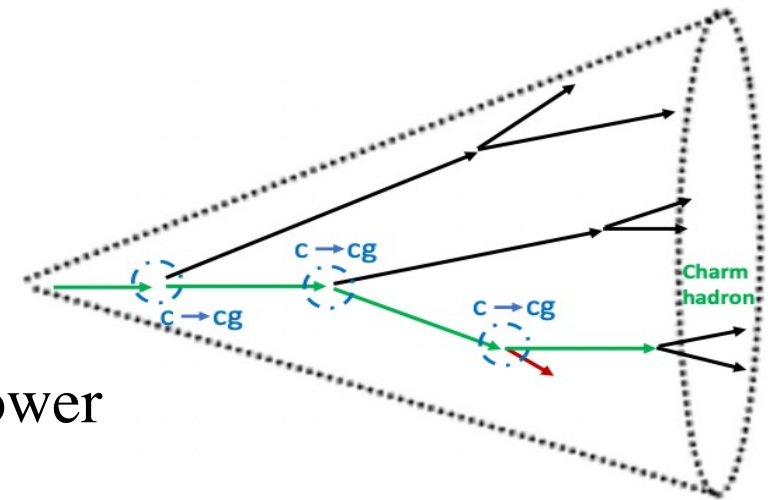
Heavy flavor splittings:



Advantages:

- Heavy flavor is preserved in the shower and not produced at hadronization
- Access late (more modified) splittings in the shower
- At high energies, access light flavor splittings

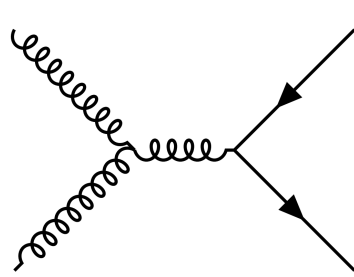
Used in ALICE [2106.05713]



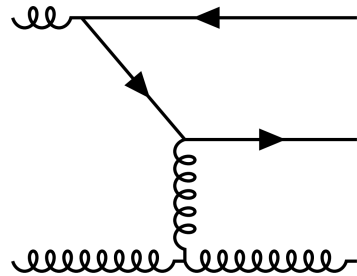
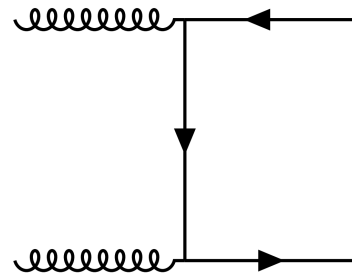
Focus of this talk: phenomenology of  $g \rightarrow c\bar{c}$

# Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets

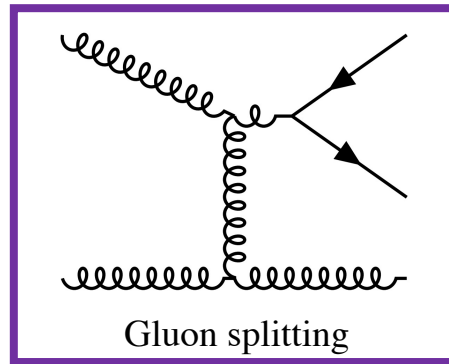
## Leading processes for heavy quark production



Flavor creation

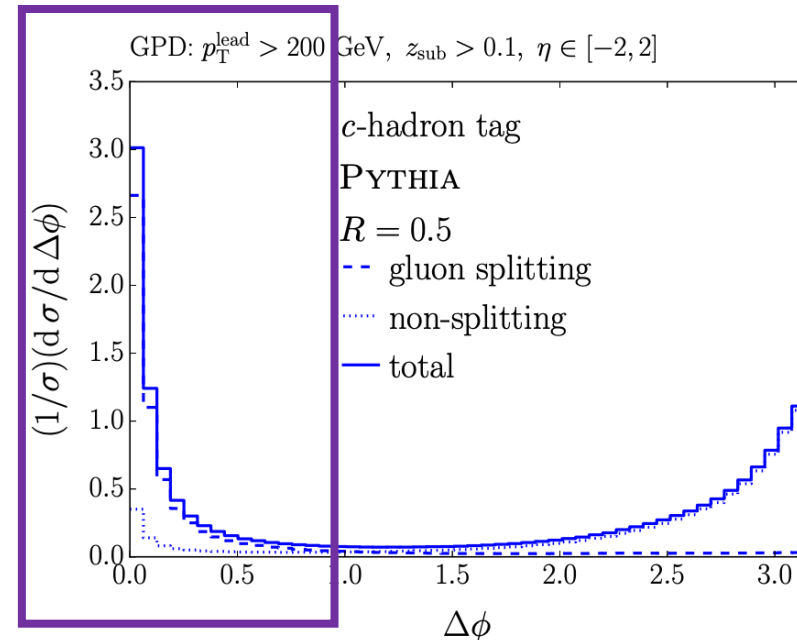
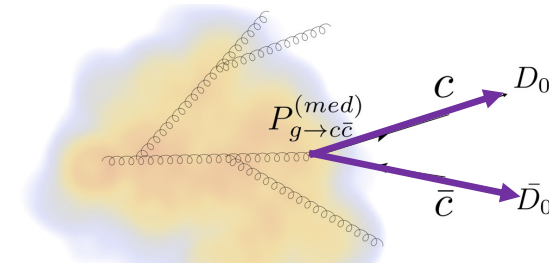


Flavor excitation



Gluon splitting

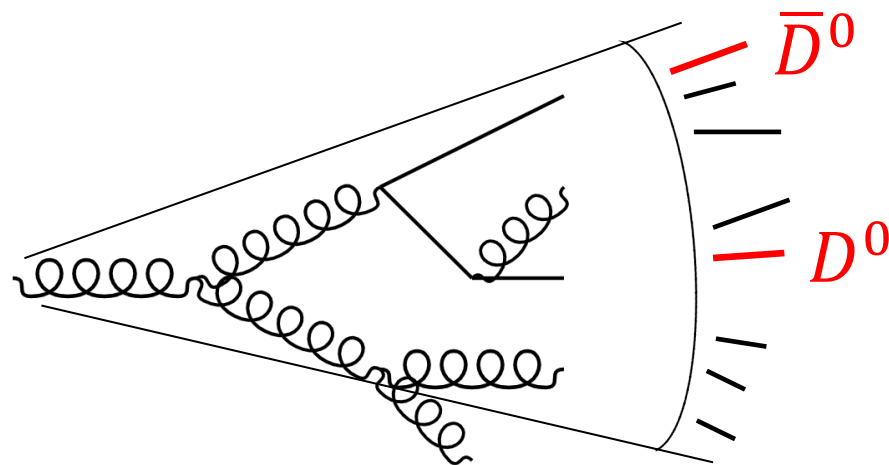
(approximately) collinear



Gluon splitting

Non-gluon-splitting

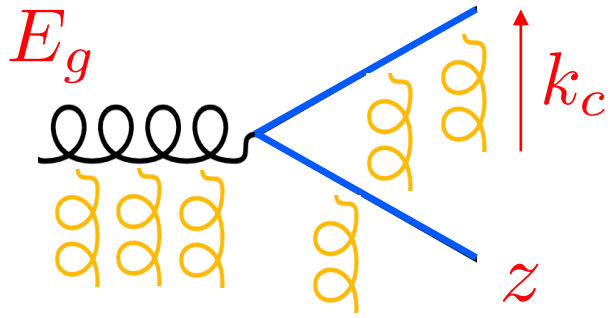
# Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets



Sample of showers including  $g \rightarrow c\bar{c}$   
splitting with high purity ( $>99\%$ )

Expected experimental sensitivity already in Run 3/4

# Modification of the $g \rightarrow c\bar{c}$ splitting function

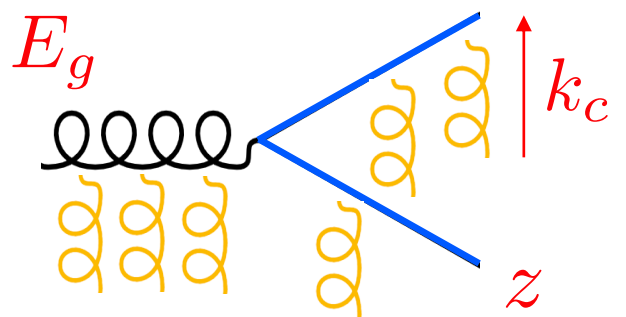


$$P_{g \rightarrow c\bar{c}}(E_g, k_c^2, z) = P_{g \rightarrow c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g \rightarrow c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

Resum arbitrarily-many soft gluon interactions with a medium of length  $L$



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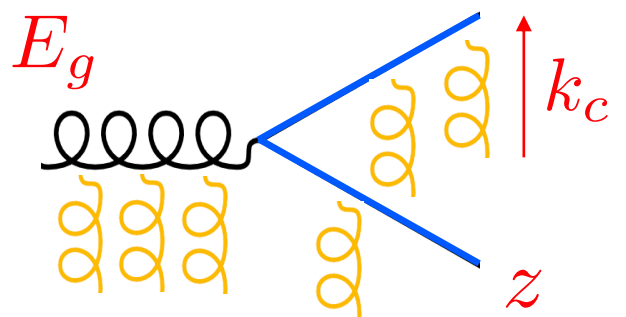
Resum arbitrarily-many soft gluon interactions with a medium of length L

## Results of the calculation:

- Depletion at small  $k_c^2$

**broadening**

# Modification of the $g \rightarrow c\bar{c}$ splitting function



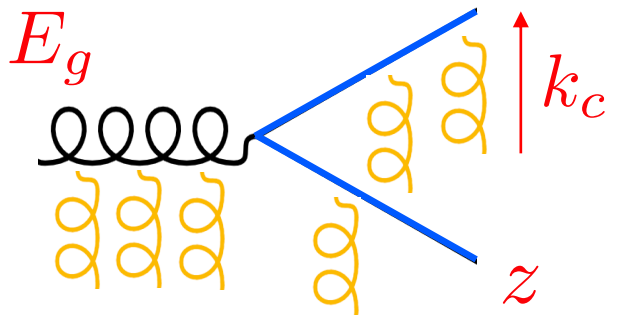
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- Less modification with increasing  $E_g$  formation-time dependence

# Modification of the $g \rightarrow c\bar{c}$ splitting function



$$P_{g \rightarrow c\bar{c}}(E_g, k_c^2, z) = P_{g \rightarrow c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g \rightarrow c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

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## Results of the calculation:

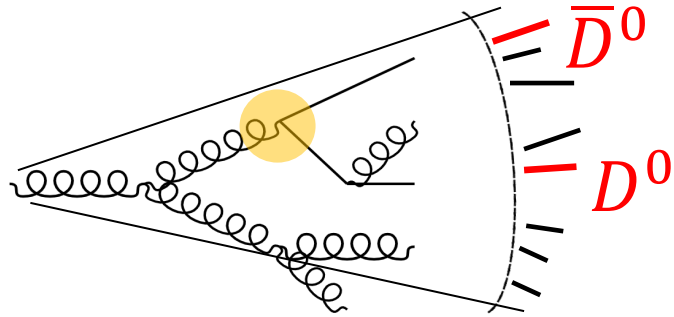
- Depletion at small  $k_c^2$  broadening
- Less modification with increasing  $E_g$  formation-time dependence
- Medium-enhanced rate of  $c\bar{c}$  production! gluons promoted above threshold

# Observing $g \rightarrow c\bar{c}$ enhancement in jets

## Computational strategies

- “Reweighting” Pythia shower with  $k_c$ -differential modified splitting function }
  - Only modifies  $g \rightarrow c\bar{c}$  splitting (no energy loss)
  - $k_c$ -differential  $g \rightarrow c\bar{c}$  splitting function
  - hadron level
- Modify all splitting functions in simple dipole shower (“Q-Pythia style”) }
  - All splittings modified (accurate energy loss)
  - $k_c$ -integrated  $g \rightarrow c\bar{c}$  splitting
  - parton level
- JetMed Monte Carlo simulations

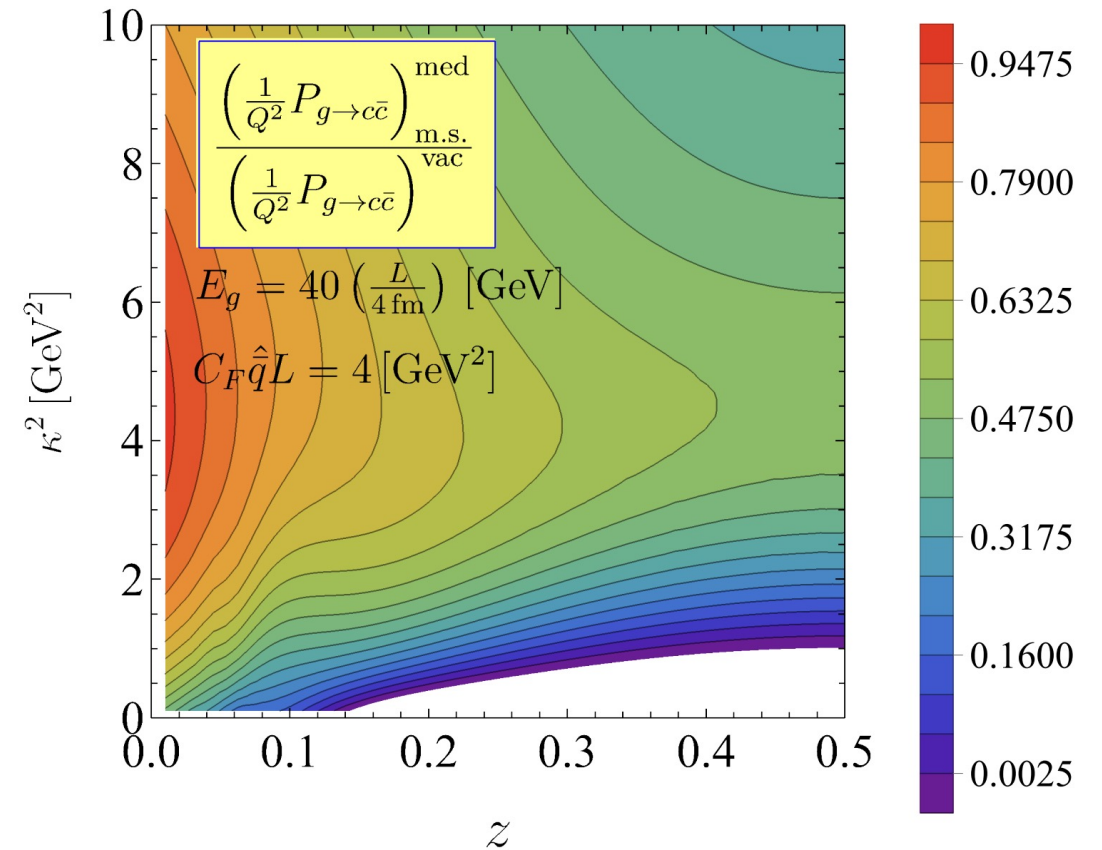
# Observing $g \rightarrow c\bar{c}$ enhancement in jets



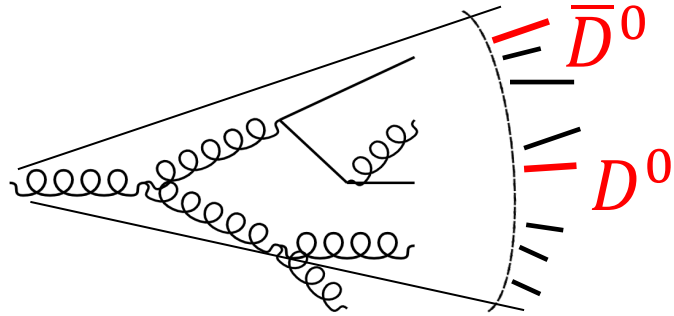
Get kinematics of  $g \rightarrow c\bar{c}$

Reweight each splitting by

$$w_{g \rightarrow c\bar{c}}^{med}(E_g, k_c^2, z) = 1 + \frac{\left(\frac{1}{Q^2} P_{g \rightarrow c\bar{c}}\right)^{med}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2} P_{g \rightarrow c\bar{c}}\right)^{vac}(k_c^2, z)}$$



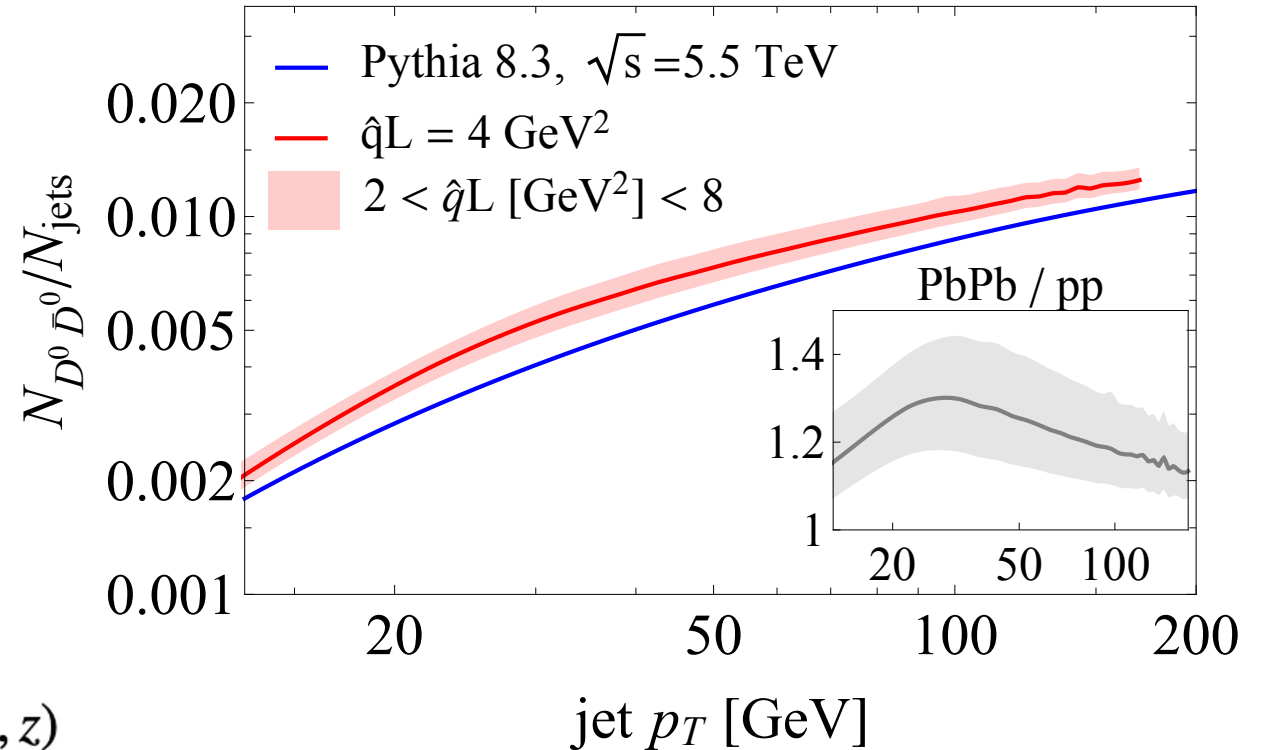
# Observing $g \rightarrow c\bar{c}$ enhancement in jets



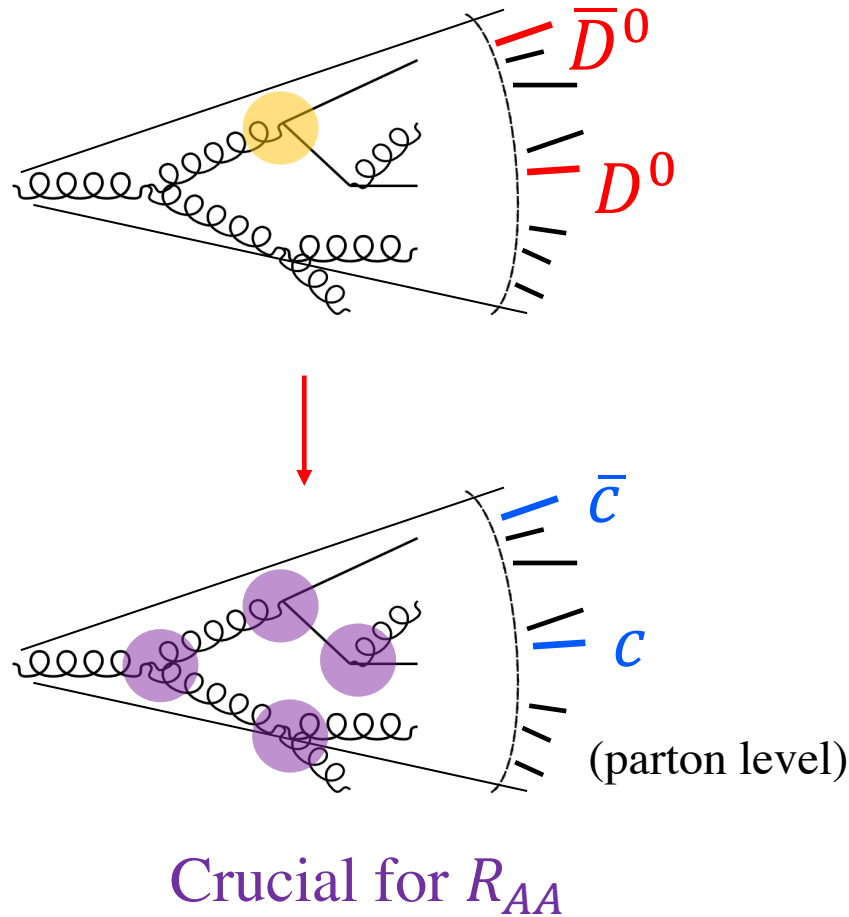
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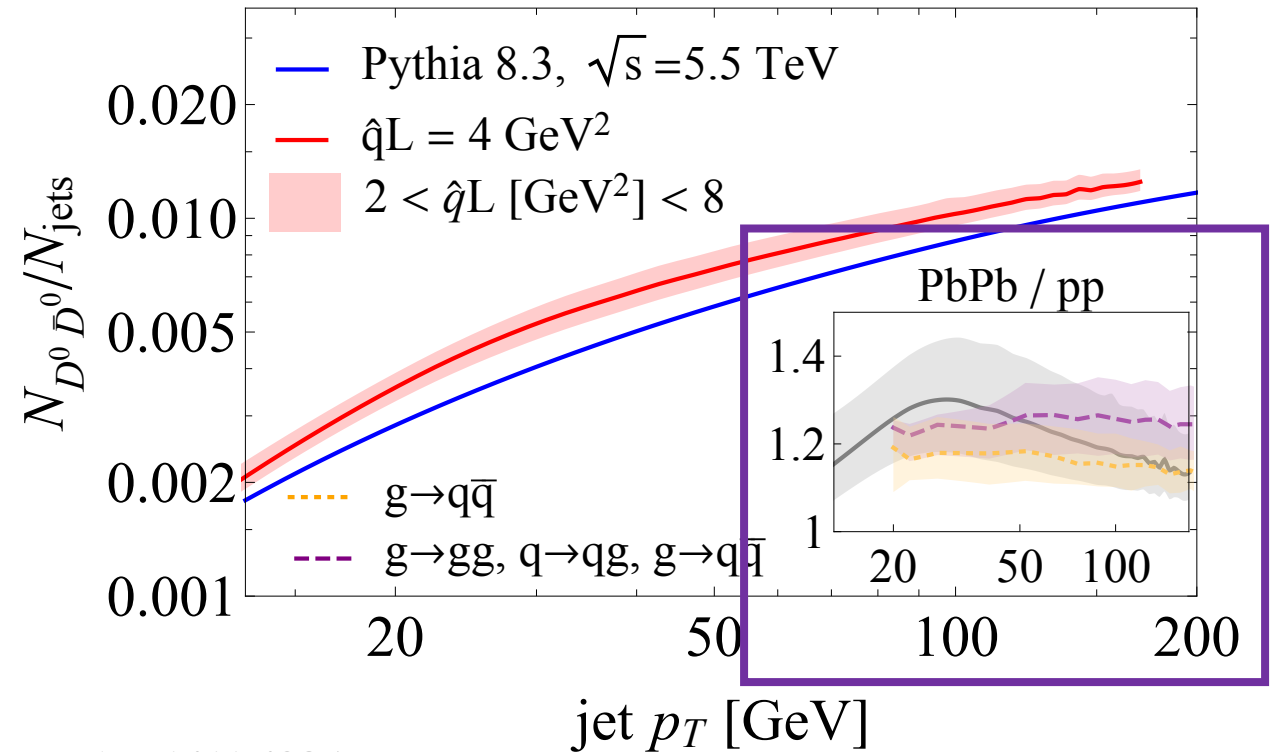
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$N_{D\bar{D}}/N_{\text{jets}}$  is dominantly sensitive to enhancement of  $g \rightarrow c\bar{c}$  splittings



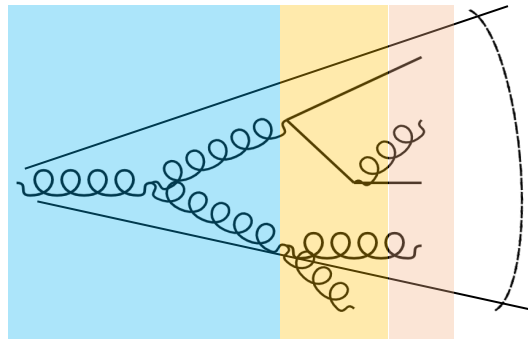
Enhancement of  $N_{D\bar{D}}/N_{\text{jets}}$  is generated by modification of  $g \rightarrow c\bar{c}$



Modified all splittings in simple dipole shower Hoeche [1411.4085]

# $g \rightarrow c\bar{c}$ enhancement in JetMed Monte Carlo simulations

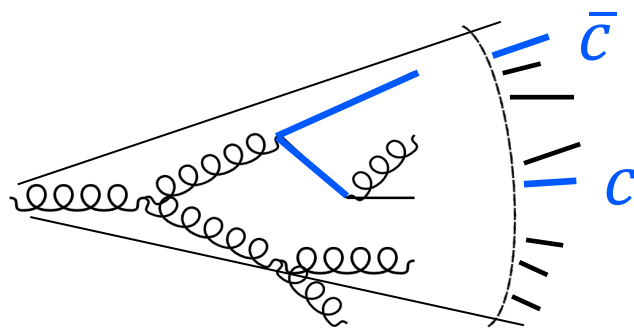
## Jet quenching in JetMed



Caucal, Iancu, Soyez  
[1907.04866]

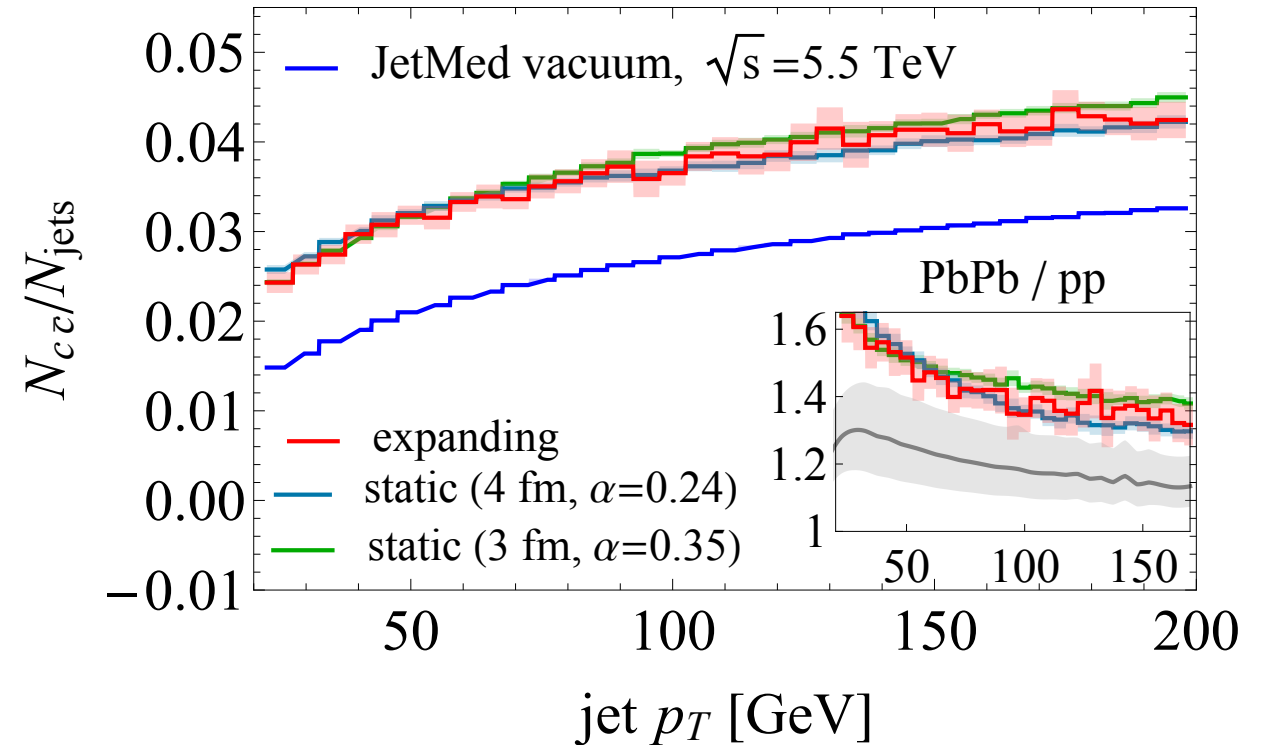
(parton level)

Vacuum-like Medium-induced Outside medium



Charm mass threshold applied after broadening

Medium-induced charm enhancement in JetMed  
moderately larger than by reweighting

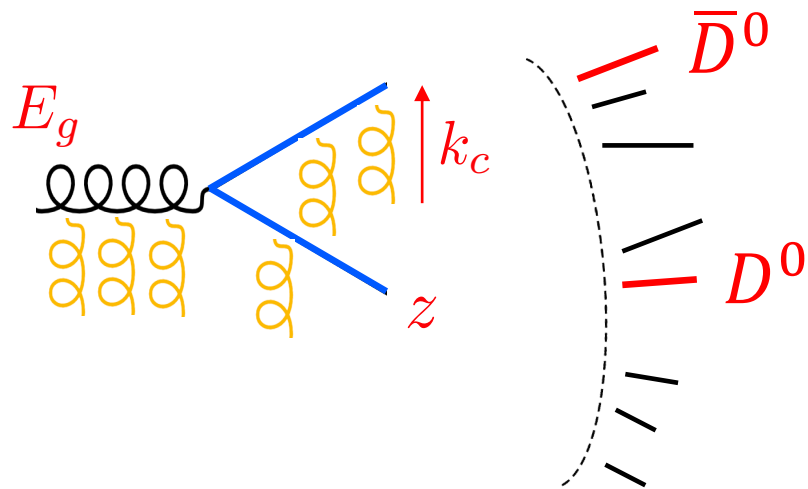


w/ Gregory Soyez



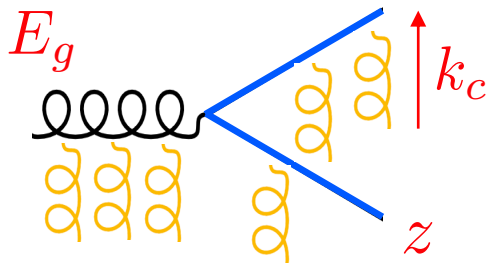
# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings

A uniquely clean phenomenological signature of medium modification



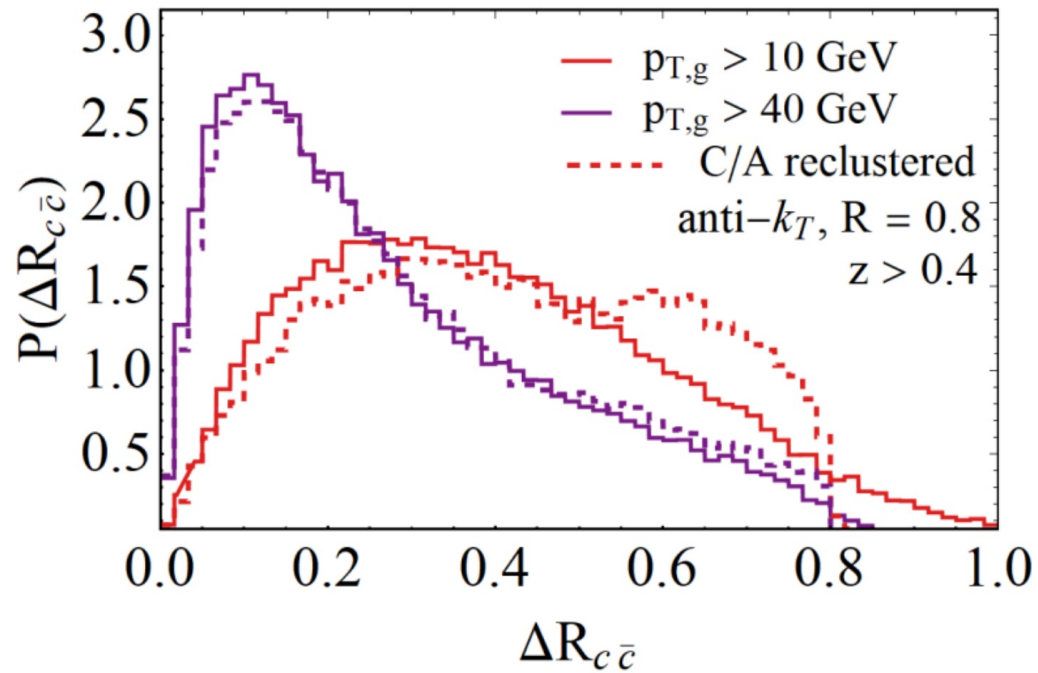
- Isolate individual type of splitting (not quark and gluon mixture) at any stage of the shower
- Splitting can be identified at hadron level from  $D$  and  $\bar{D}$  in reclustering history
- Splitting kinematics from reclustering history

# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings

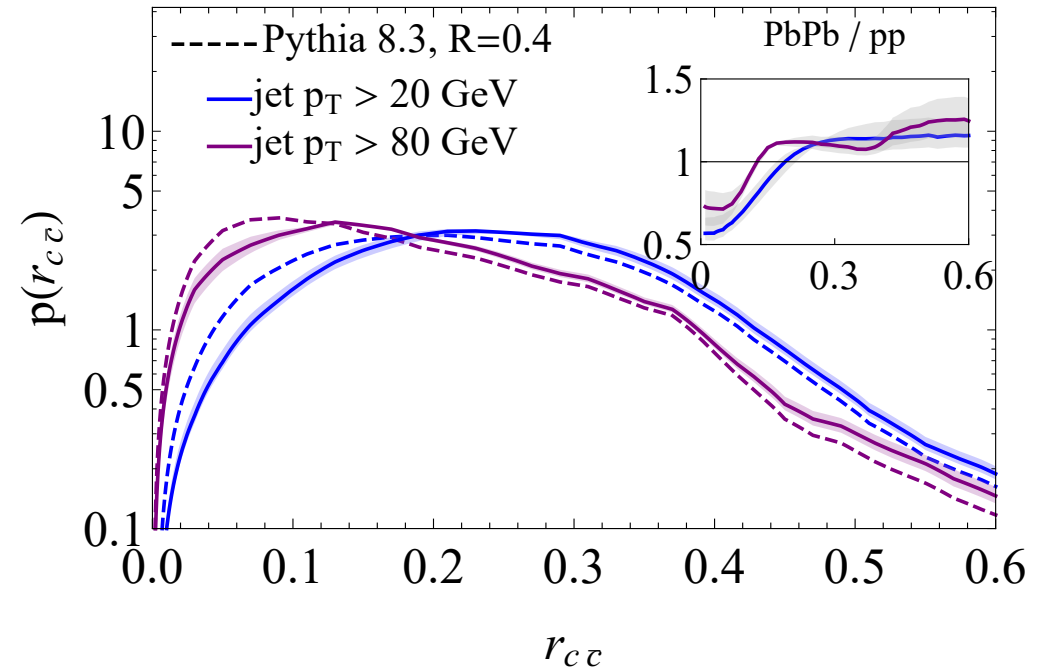


- **Broadening:** momentum broadening of  $c\bar{c}$  pair

parton vs. hadron level

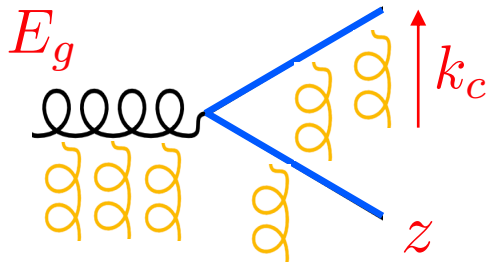


unmodified vs. modified



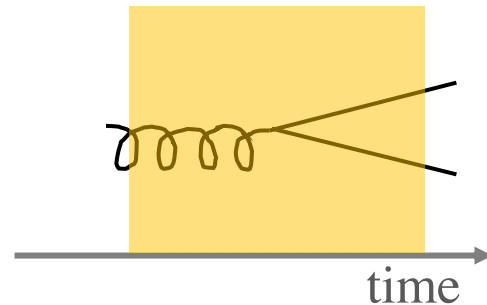
Can use jet substructure to access broadening at hadron-level

# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings

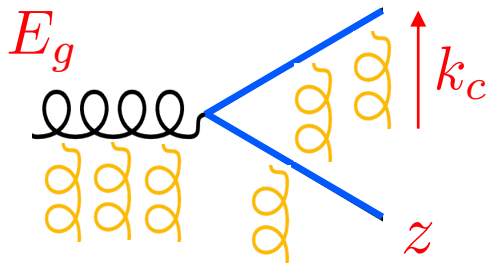


- **Formation time dependence** of broadening

Gluons have a “lifetime”  $\tau_f \sim \frac{2E_g}{Q^2}$  depending on their energy



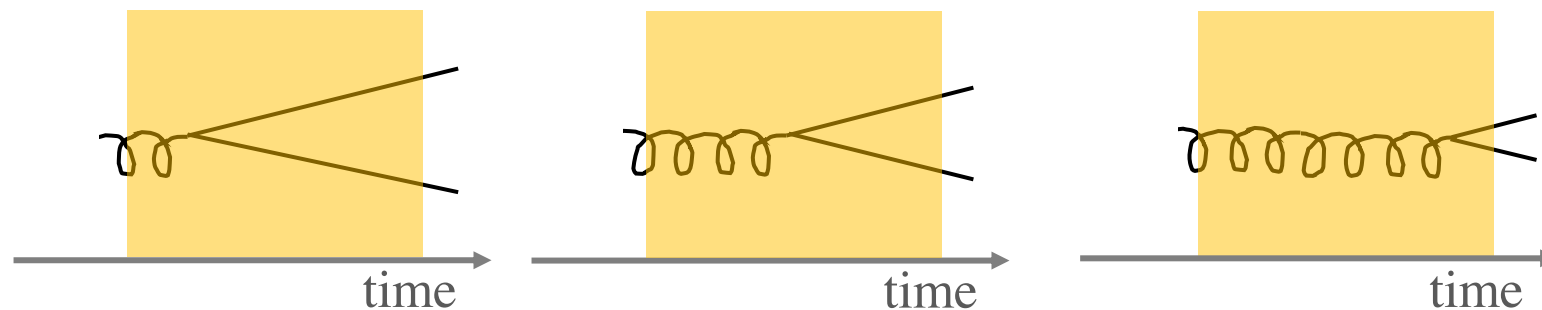
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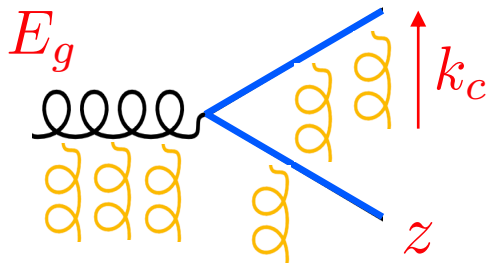
- Access modification of  $c\bar{c}$  pair at later times in the QGP



$\sim 1 - 6$  fm delay for  
20 – 100 GeV gluons

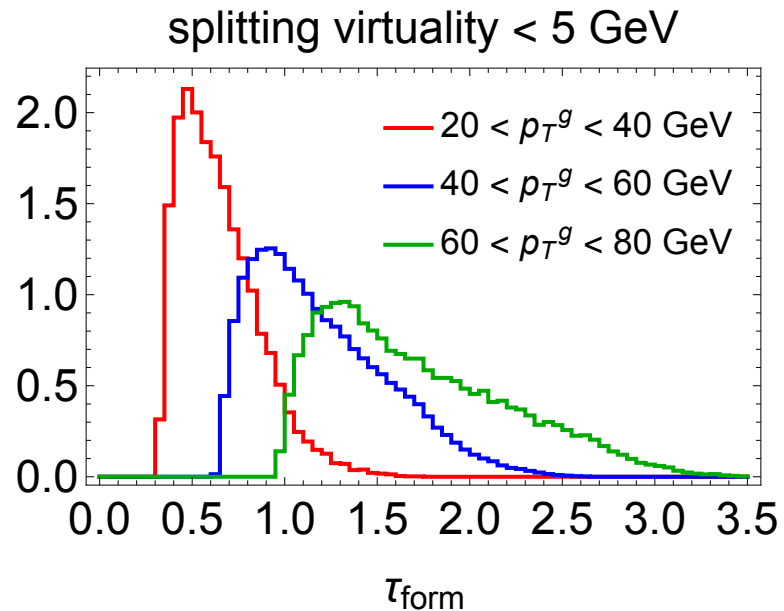
Increasing gluon energy

# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings

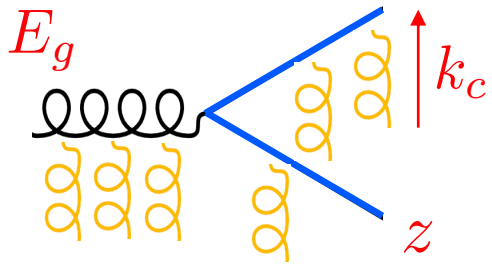


- **Formation time dependence** of broadening

Near mass threshold  $Q^2 \sim m_c^2$ , formation time grows with energy  $\tau_f \sim \frac{2E_g}{Q^2}$

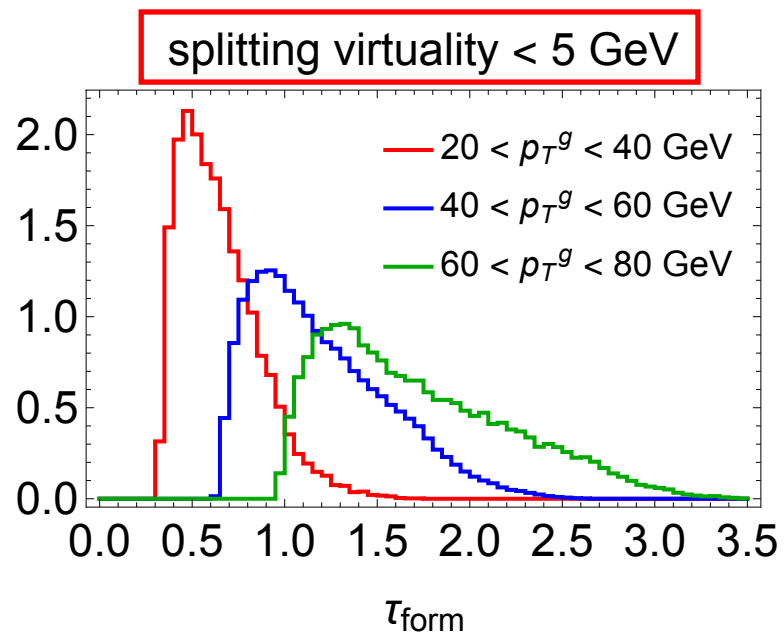


# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings



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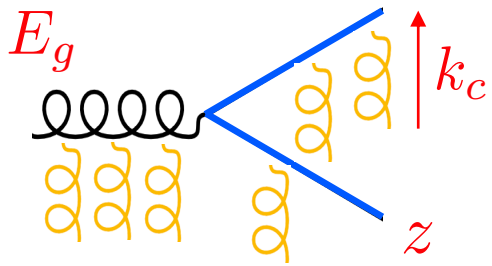


**Caution:**

virtuality depends explicitly on the relative momentum of the splitting

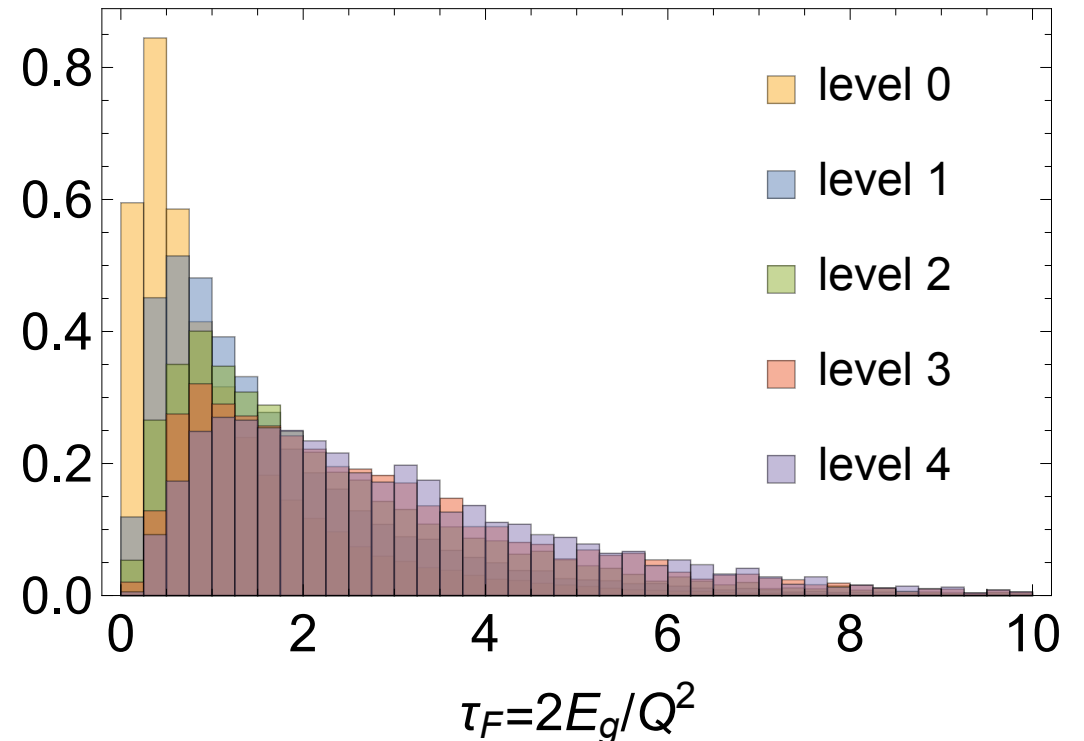
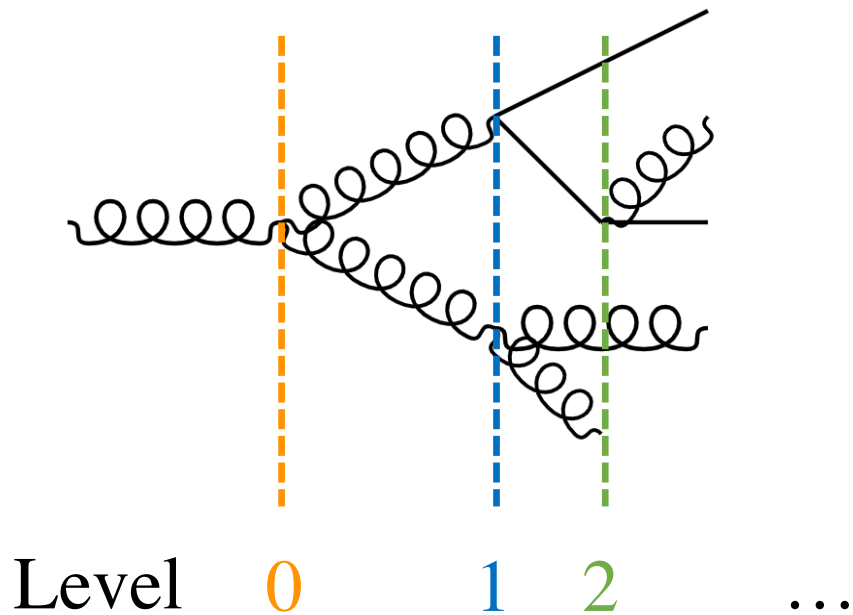
This cut vetoes pairs that have broadened!

# Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings



- **Formation time dependence** of broadening

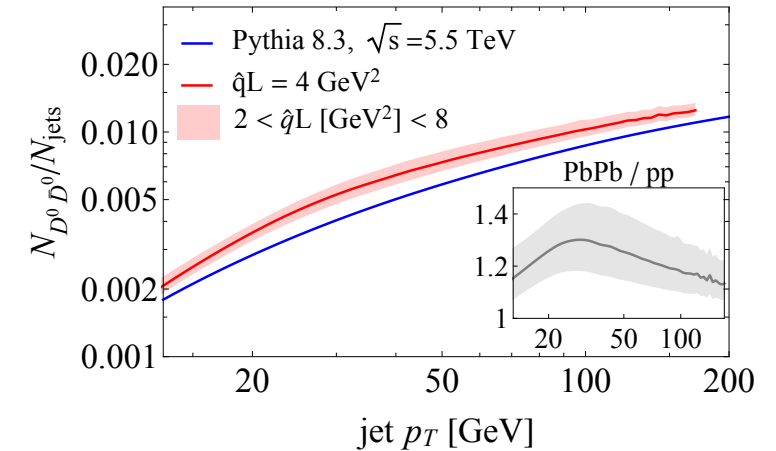
The level of the  $g \rightarrow c\bar{c}$  splitting in the shower is correlated with formation time



# A process with many exciting future avenues!

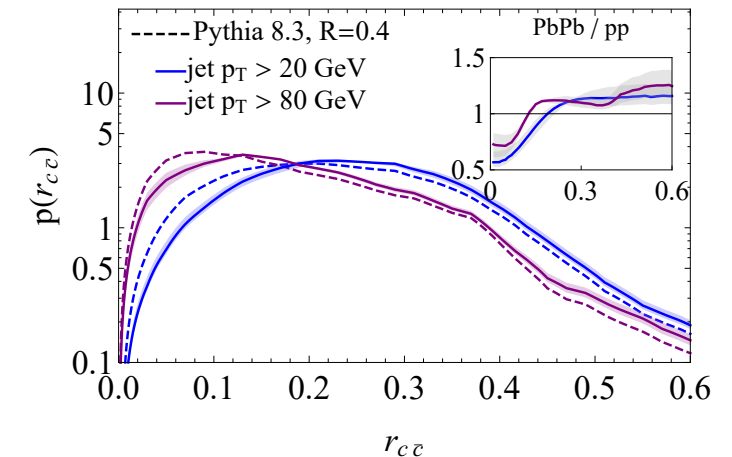
So far..

- Medium-enhanced rate of  $c\bar{c}$  production



Outlook

- Broadening of  $c\bar{c}$  pair from hadron level
- Formation time dependence of modification



Clean process with a lot of exciting physics opportunities!