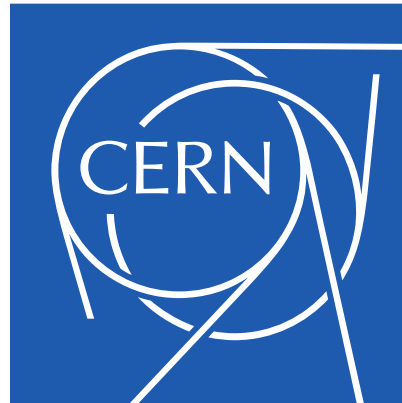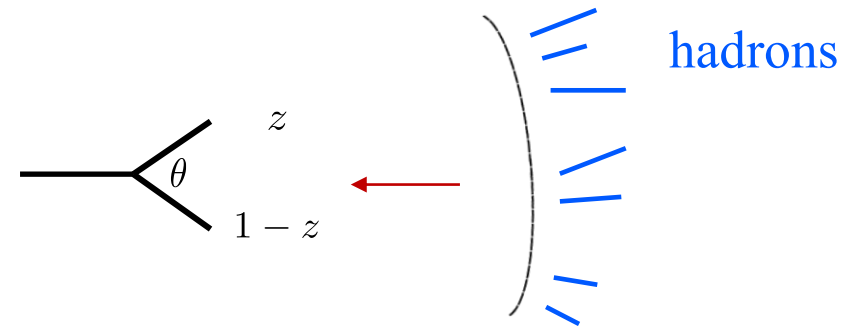# Medium-enhanced $c\bar{c}$ radiation

Jasmine Brewer



In collaboration with Maximilian Attems, Gian Michele Innocenti, Aleksas Mazeliauskas, Sohyun Park, Wilke van der Schee, and Urs Wiedemann
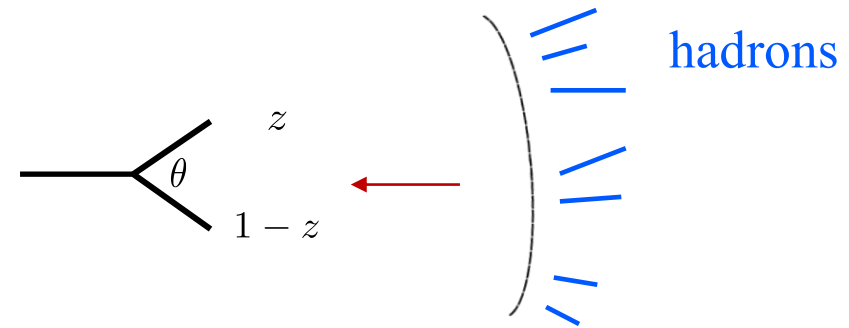
[2203.11241], [2209.13600], and ongoing work

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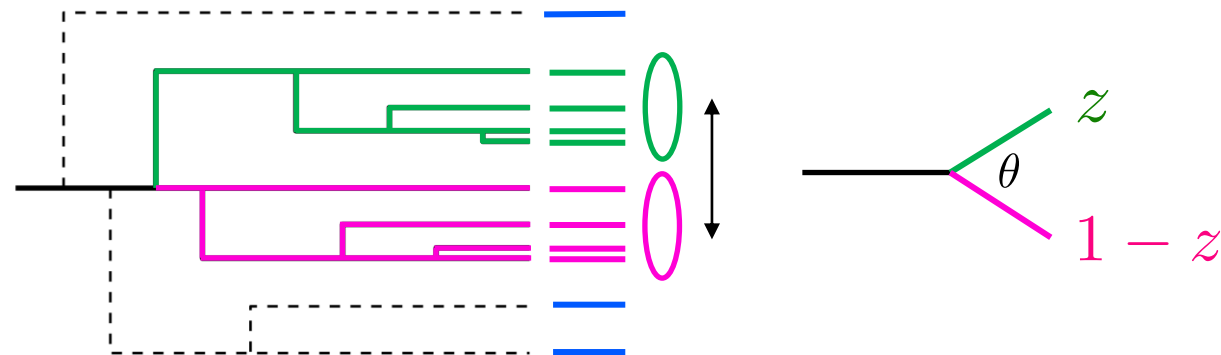
- Hadrons to splittings

# Building up a picture of a medium-modified jet from phenomenology
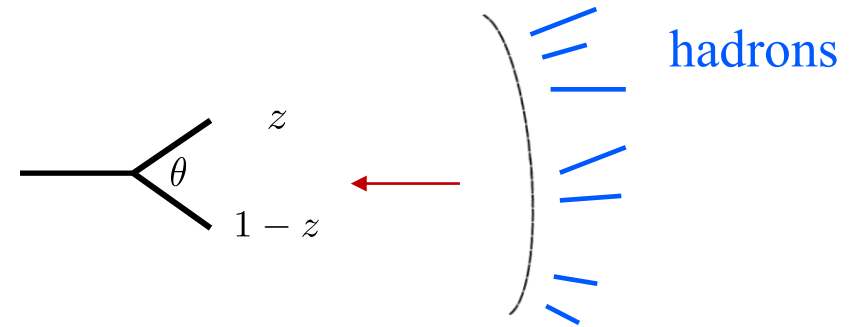
- **Hadrons to splittings**



**Jet substructure:**

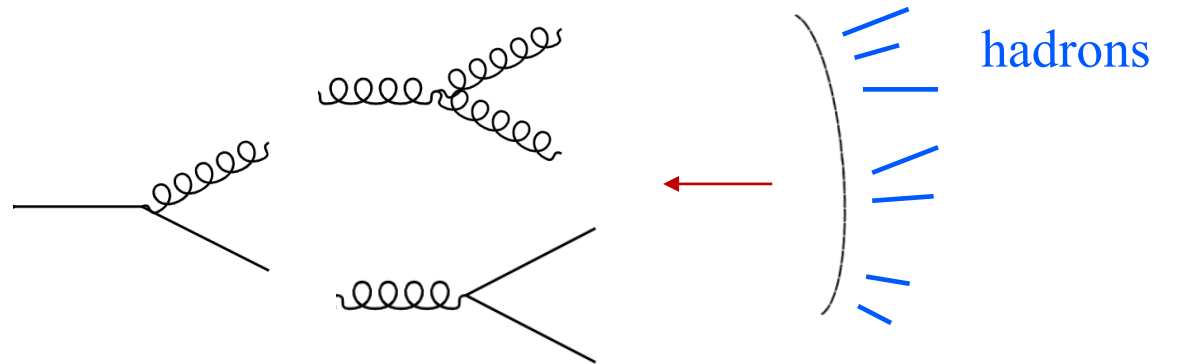Use angular ordering of QCD to reconstruct emission history of shower from hadrons

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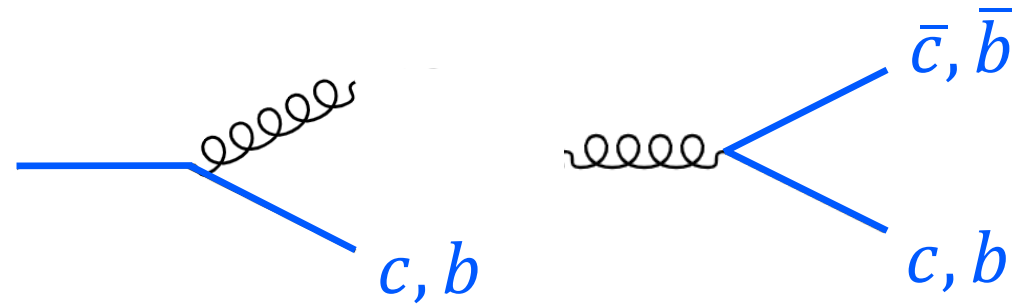
- ## Hadrons to splittings



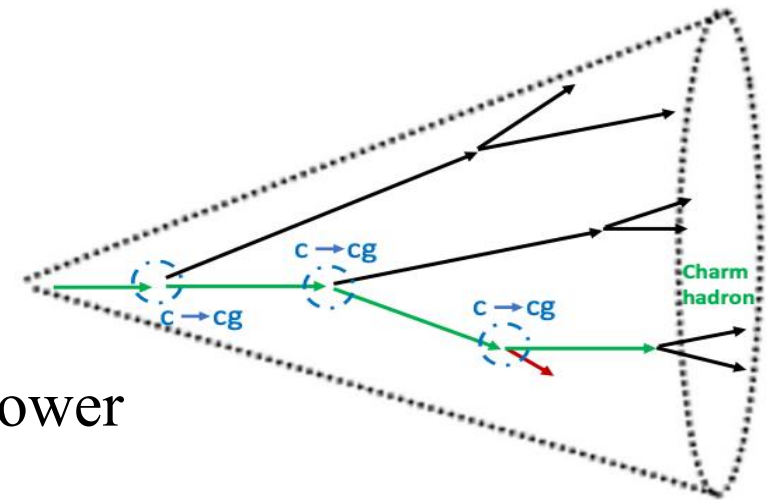- ## Flavor-dependence of splittings

# Accessing heavy flavor splitting functions

Heavy flavor splittings:



## Advantages:

- Heavy flavor is preserved in the shower and not produced at hadronization

  Used in ALICE [2106.05713]



- Access later (more modified) splittings in the shower
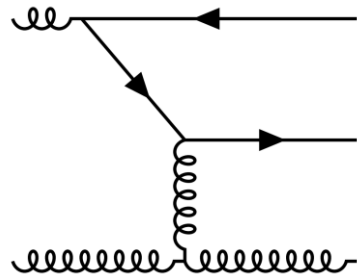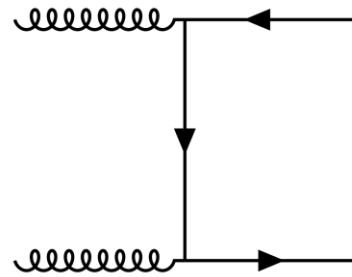
- At high energies, access light flavor splittings

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

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

## Leading processes for heavy quark production
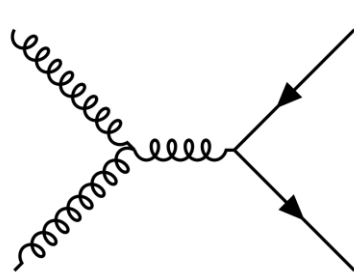


Flavor creation

Flavor excitation
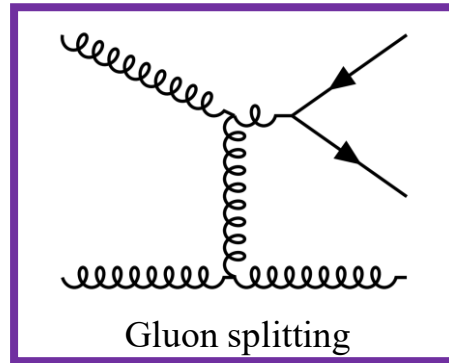
Gluon splitting

(approximately) collinear

$P_{g \to c\bar{c}}^{(med)}$

$c \quad D_0$

$\bar{c} \quad \bar{D}_0$

GPD: $p_T^{lead} > 200$ GeV, $z_{sub} > 0.1$, $\eta \in [-2, 2]$

$c$-hadron tag

PYTHIA

$R = 0.5$

-- gluon splitting

···· non-splitting

— total

$(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}\,\Delta\phi)$

$\Delta\phi$
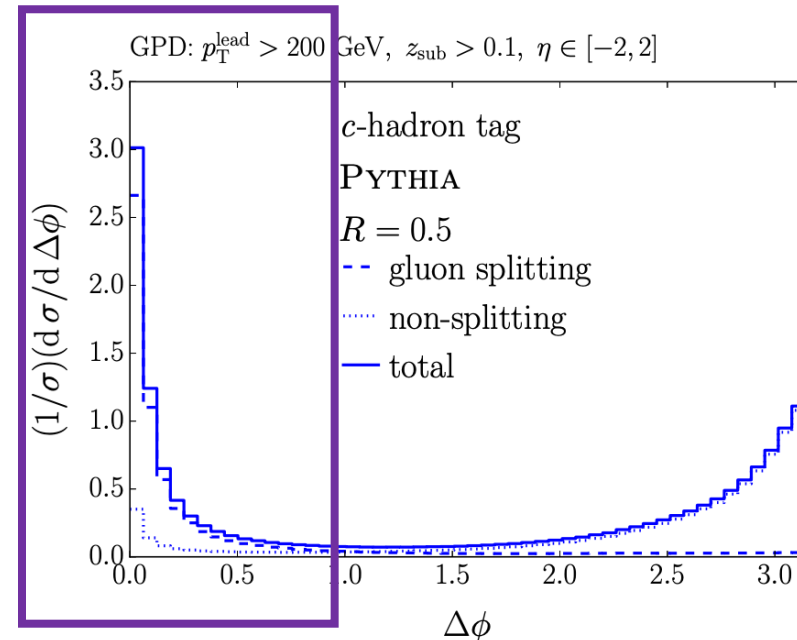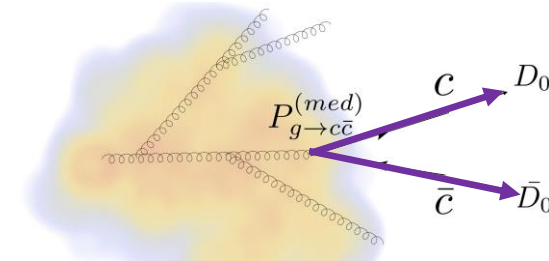
<span style="color:red">Gluon splitting</span>

Non-gluon-splitting

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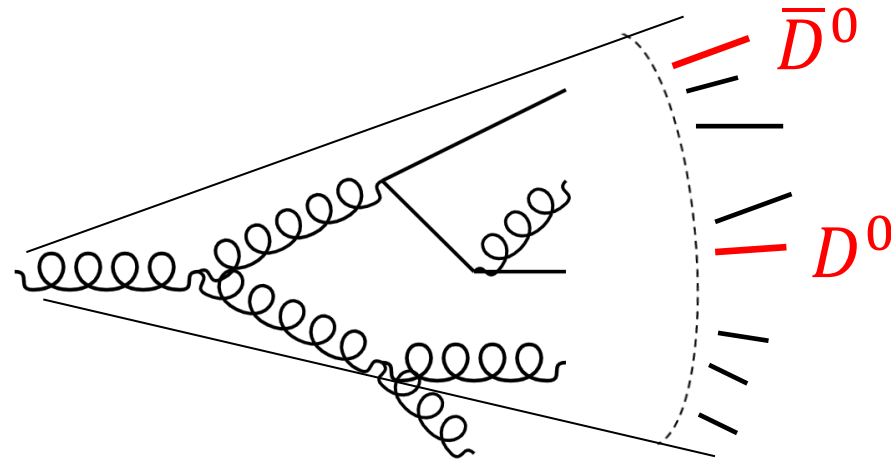


Sample of showers including $g \to c\bar{c}$
splitting with high purity (>99%)

Expected experimental sensitivity already in Run 3/4

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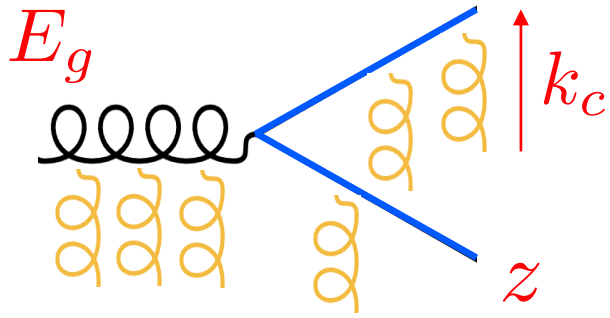


$$P_{g\to c\bar{c}}(E_g, k_c^2, z) = P_{g\to c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g\to c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

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

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

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

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 $g \to c\bar{c}$ splitting function
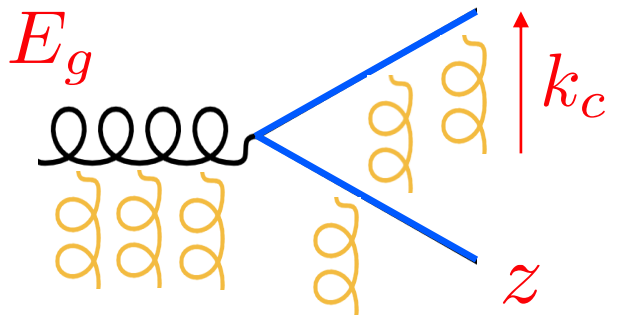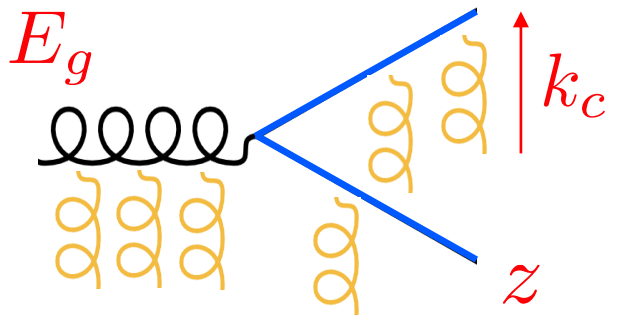


$$P_{g \to c\bar{c}}(E_g, k_c^2, z) = P_{g \to c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g \to c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

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

Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann [2203.11241]

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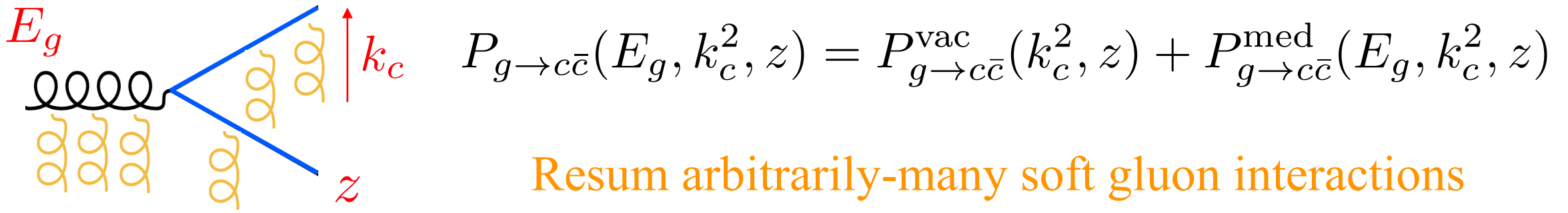


$$P_{g \to c\bar{c}}(E_g, k_c^2, z) = P_{g \to c\bar{c}}^{\mathrm{vac}}(k_c^2, z) + P_{g \to c\bar{c}}^{\mathrm{med}}(E_g, k_c^2, z)$$
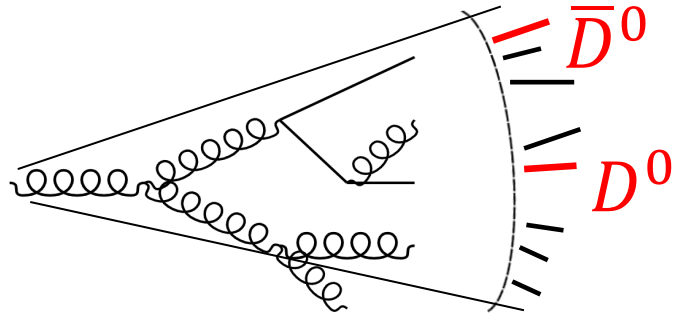
Resum arbitrarily-many soft gluon interactions with a medium of length L

## Results of the calculation:

- Depletion at small $k_c^2$       broadening

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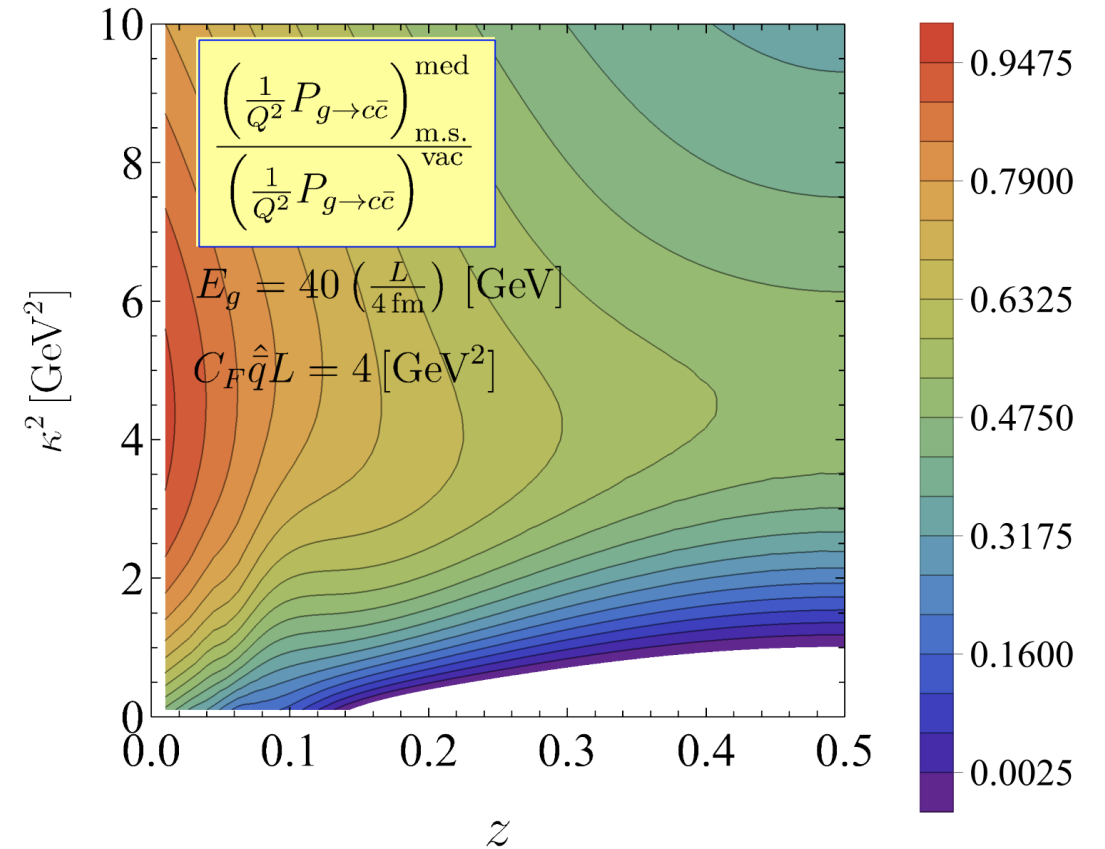- Medium-enhanced rate of $c\bar{c}$ production!       gluons promoted above threshold

Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann [2203.11241]

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



Get kinematics of g → $c\bar{c}$

Reweight each splitting by

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



$$\frac{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{med}_{m.s.}}{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{vac}}$$

$$E_g = 40\left(\frac{L}{4\,\mathrm{fm}}\right)\,[\mathrm{GeV}]$$

$$C_F\hat{\bar{q}}L = 4\,[\mathrm{GeV}^2]$$

Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann [2209.13600]

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



$\bar{D}^0$

$D^0$

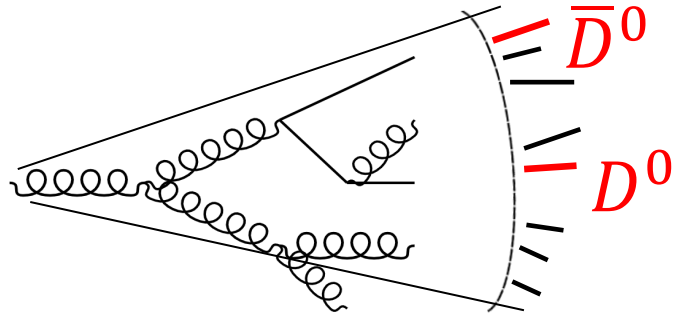Get kinematics of g → $c\bar{c}$

Reweight each splitting by

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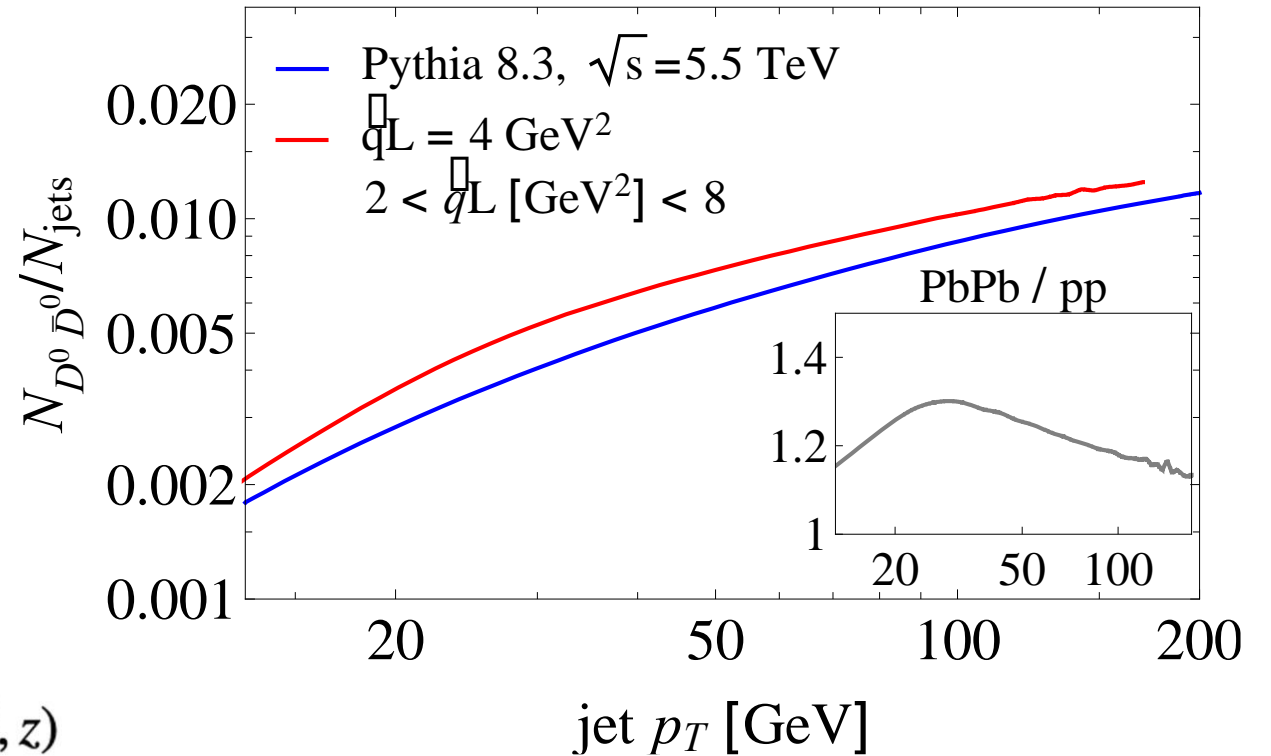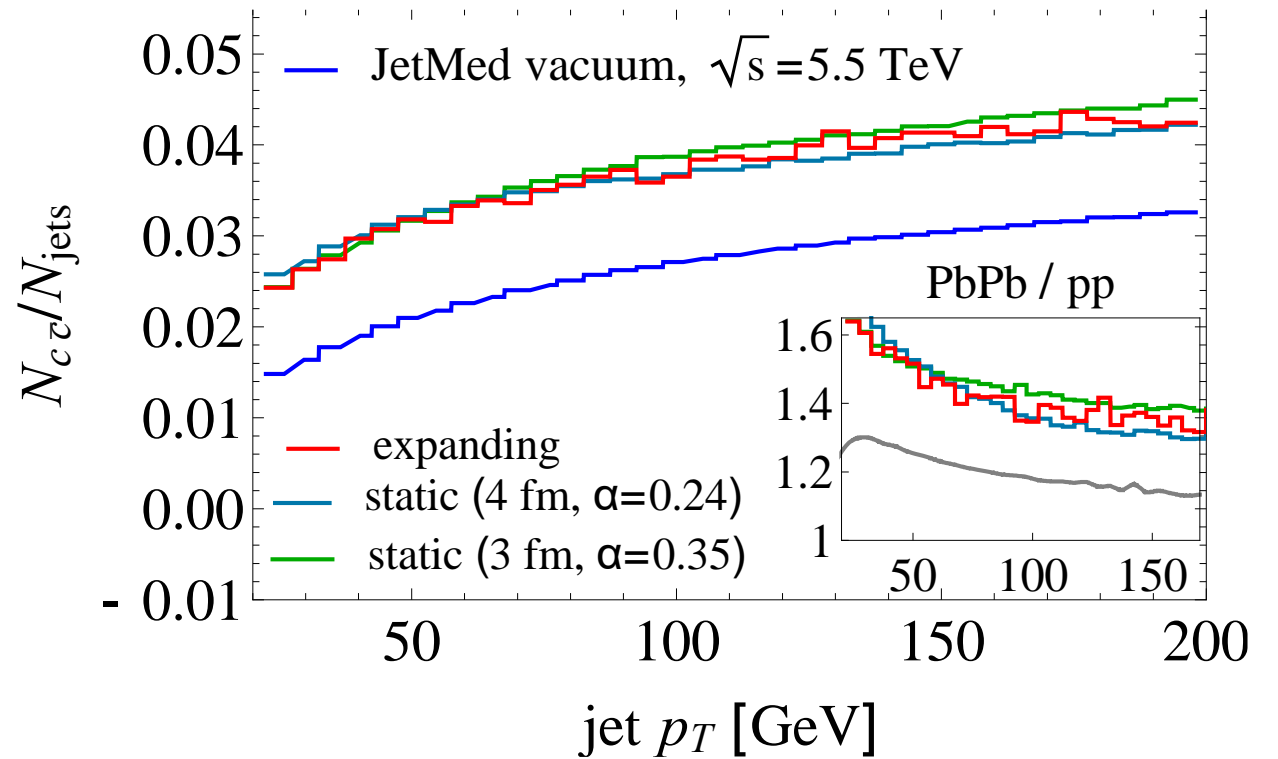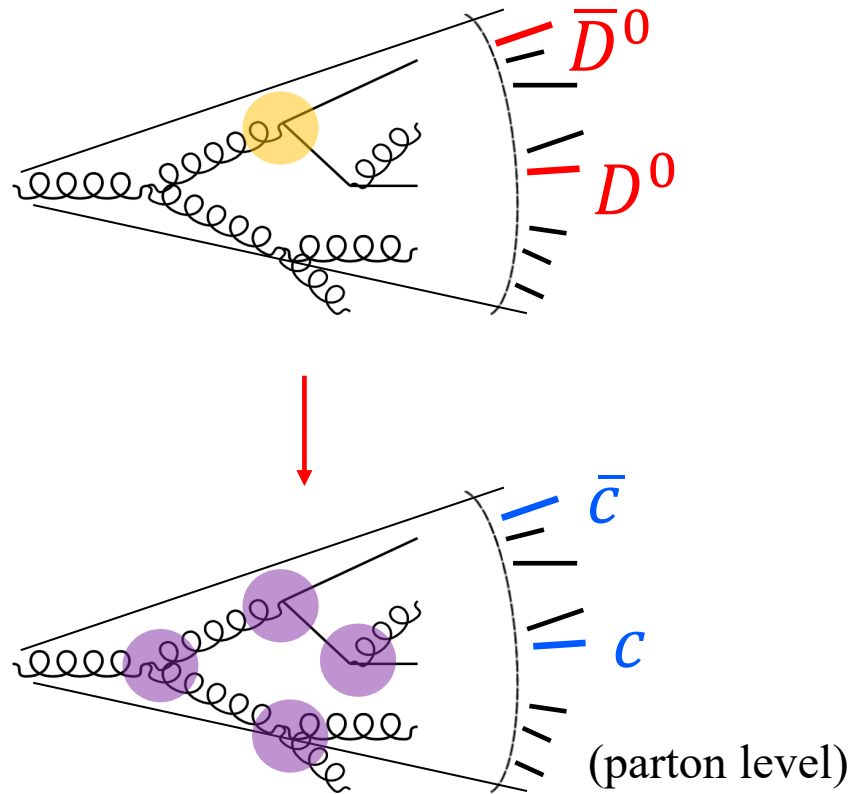


Pythia 8.3, $\sqrt{s}$ =5.5 TeV

$\hat{q}$L = 4 GeV²

2 < $\hat{q}$L [GeV²] < 8

$N_{D^0\bar{D}^0}/N_{jets}$

PbPb / pp

jet $p_T$ [GeV]

# $g \to c\bar{c}$ enhancement in state-of-the-art Monte Carlo simulations



$\overline{D}^0$

$D^0$

$\bar{c}$

$c$

(parton level)

JetMed vacuum, $\sqrt{s} = 5.5$ TeV

expanding
static (4 fm, α=0.24)
static (3 fm, α=0.35)

$N_{c\bar{c}}/N_{\text{jets}}$

jet $p_T$ [GeV]

PbPb / pp
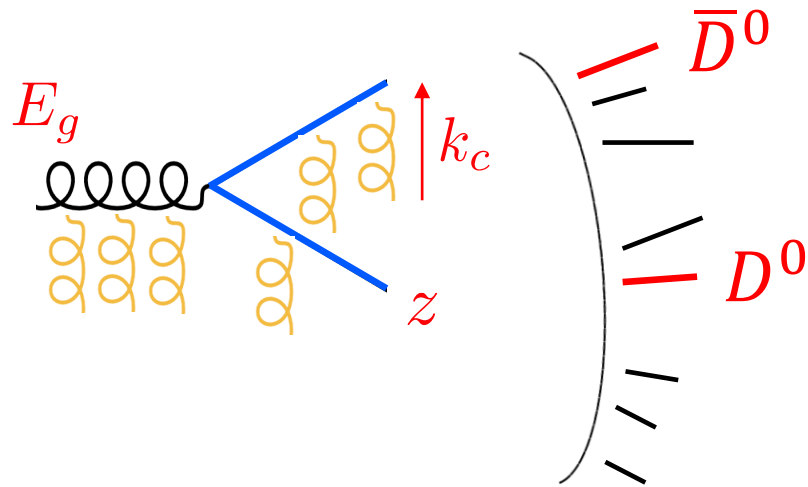
w/ Gregory Soyez

Jet quenching in JetMed: factorization of vacuum-like and medium-induced emissions

Caucal, Iancu, Soyez
[1907.04866]

Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann [2209.13600]

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

A uniquely clean phenomenological signature of medium modification
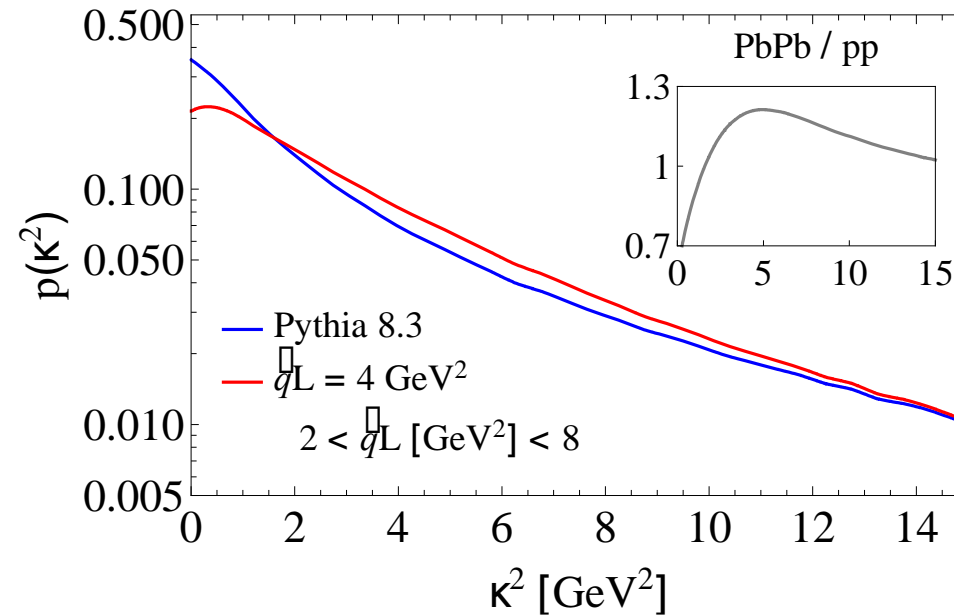


- Isolate individual type of splitting (not quark and gluon mixture) at any stage of the shower

- Splitting can be identified at hadron level from $D$ and $\bar{D}$ in reclustering history

- Splitting kinematics from reclustering history

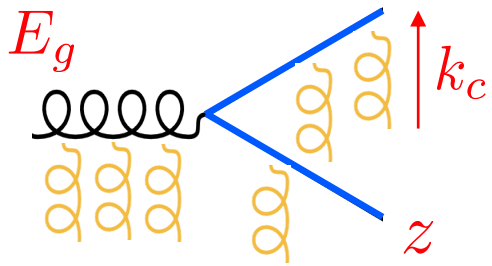# Beyond enhancement: unique phenomenology of $g \to c\bar{c}$ splittings
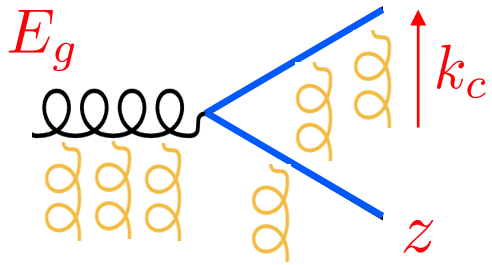


- **Broadening:** momentum broadening of $c\bar{c}$ pair



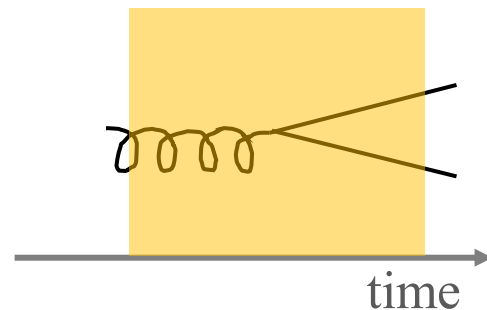Can use jet substructure to access broadening at hadron-level

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

$E_g$
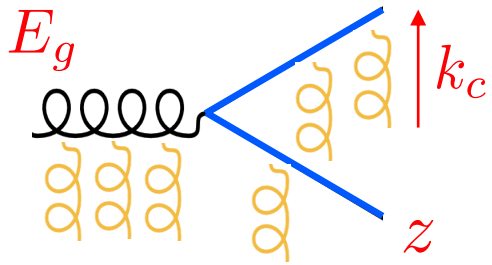
$k_c$

$z$

- **Formation time dependence** of broadening

Gluons have a "lifetime" $\tau_f \sim \dfrac{2E_g}{Q^2}$ depending on their energy

time

Another time-delayed probe: Apolinario, Milhano, Salam, Salgado [1711.03105]

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



- **Formation time dependence** of broadening

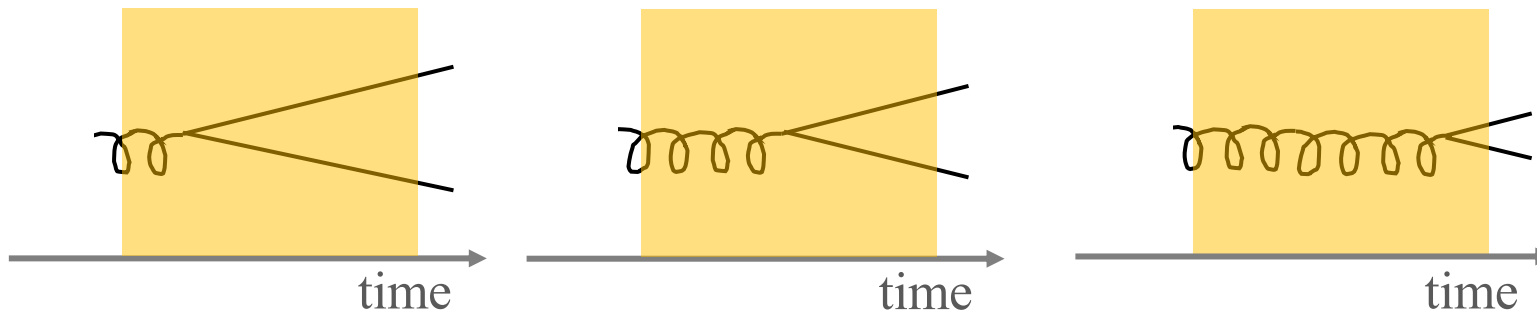Gluons have a "lifetime" $\tau_f \sim \dfrac{2E_g}{Q^2}$ depending on their energy
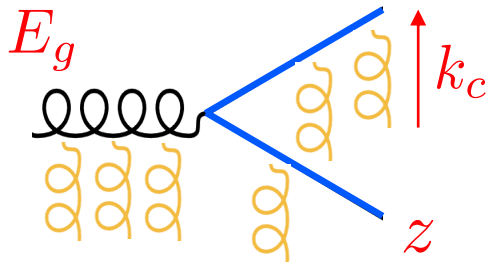
- Access modification of $c\bar{c}$ pair at later times in the QGP
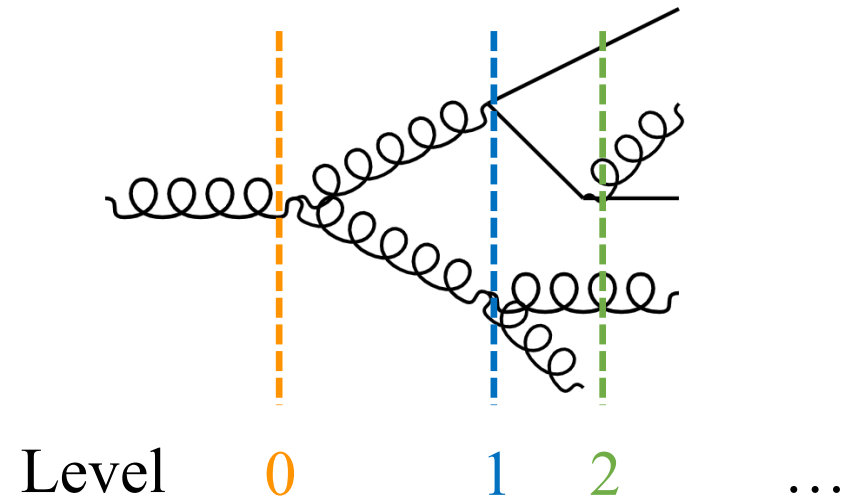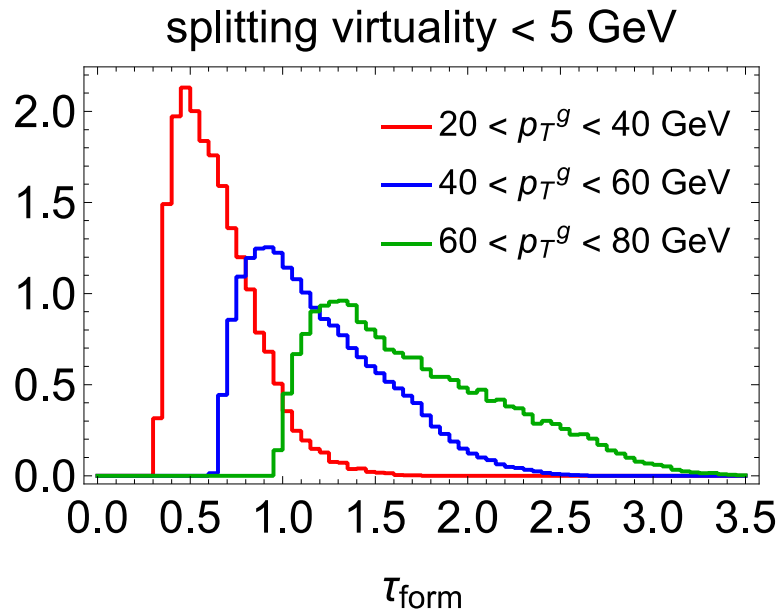


$\sim 1 - 6$ fm delay for $20 - 100$ GeV gluons

Increasing gluon energy

Another time-delayed probe: Apolinario, Milhano, Salam, Salgado [1711.03105]

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



$E_g$    $k_c$    $z$

- ## Formation time dependence of broadening

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



splitting virtuality < 5 GeV

$20 < p_T{}^g < 40$ GeV
$40 < p_T{}^g < 60$ GeV
$60 < p_T{}^g < 80$ GeV

$\tau_{\text{form}}$

Level    0    1    2    ...

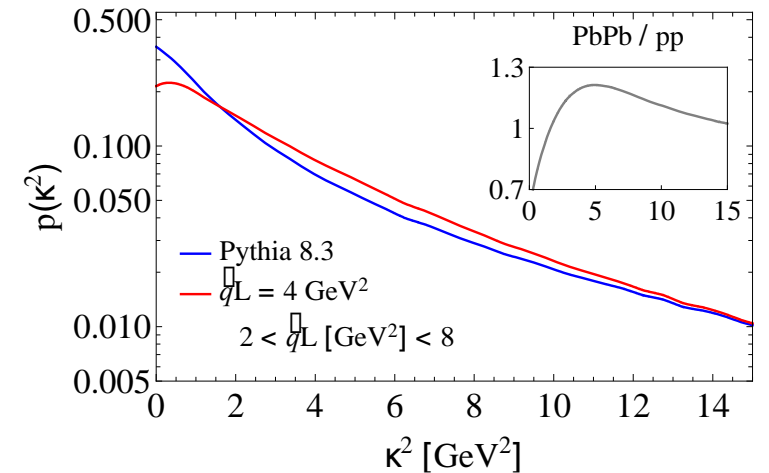# A process with many exciting future avenues!

## So far..

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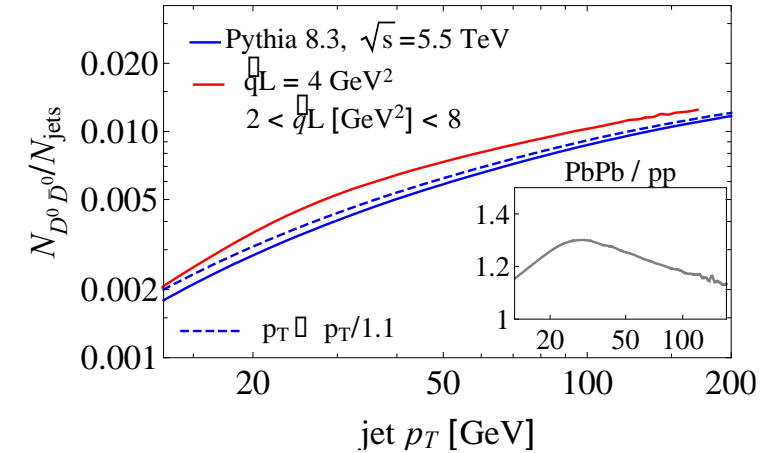
## Outlook

- Broadening of $c\bar{c}$ pair from hadron level

- Formation time dependence of modification



**Clean process with a lot of exciting physics opportunities!**