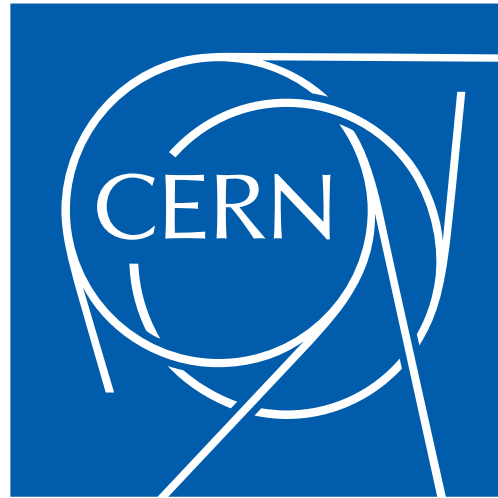


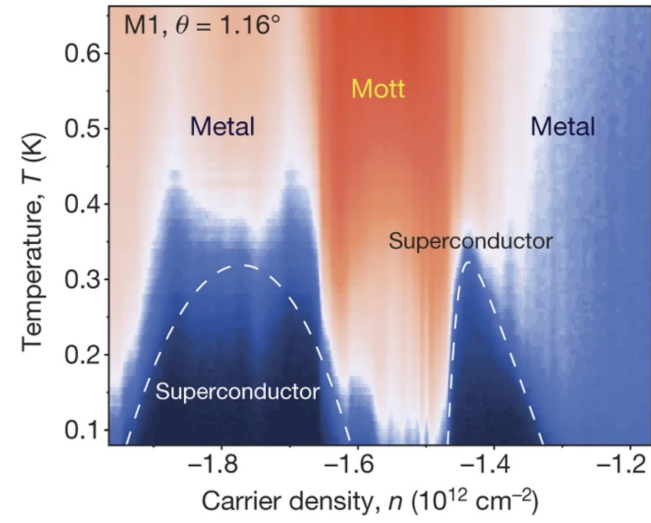
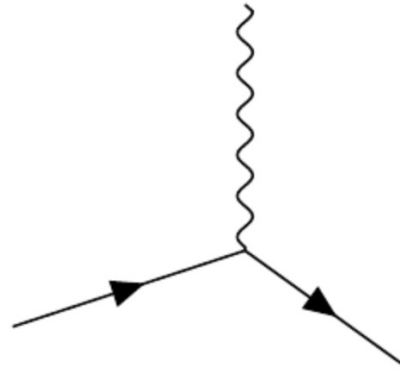
# Jets as a probe of the quark-gluon plasma

Jasmine Brewer



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

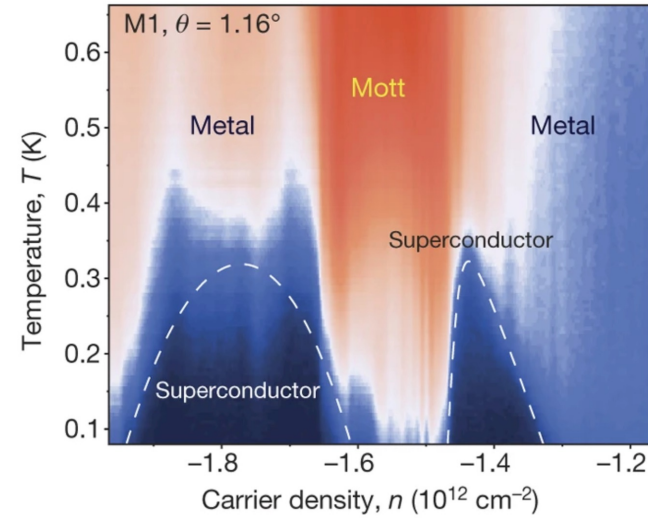
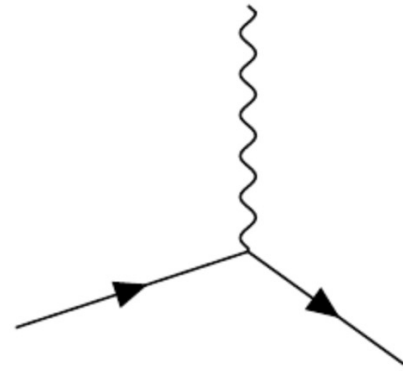
# QED



## Magic angle graphene

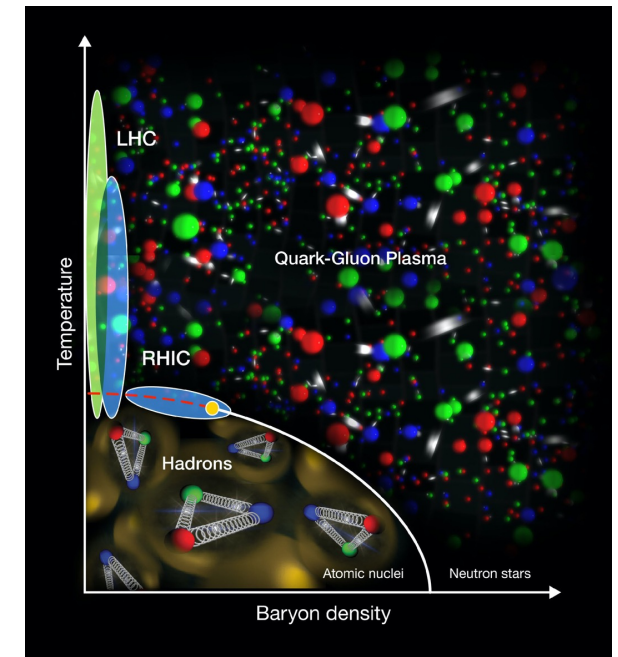
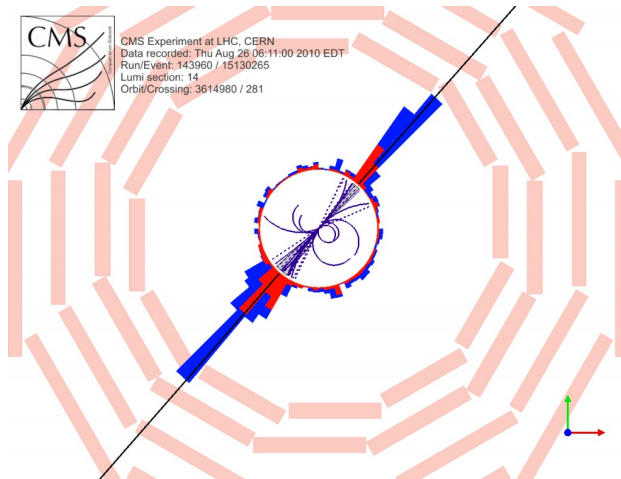
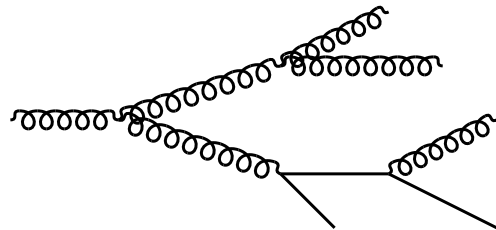
Cao et. al. *Nature* **556**, 43–50 (2018)

QED



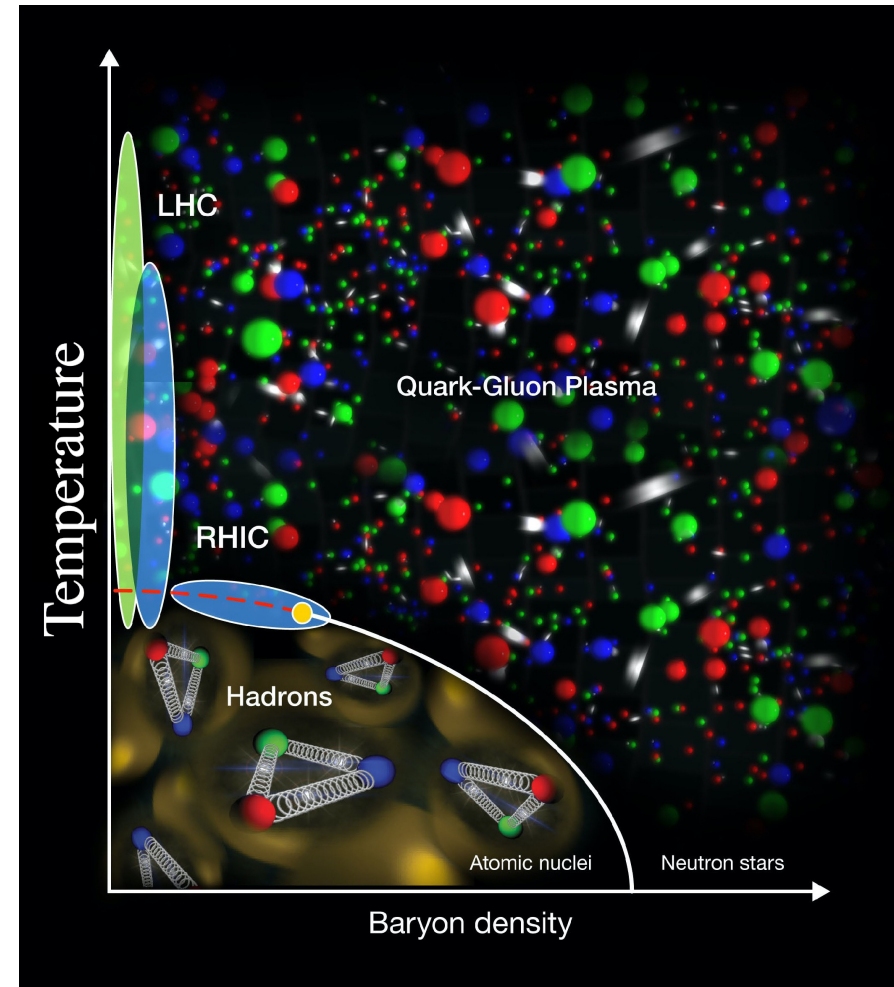
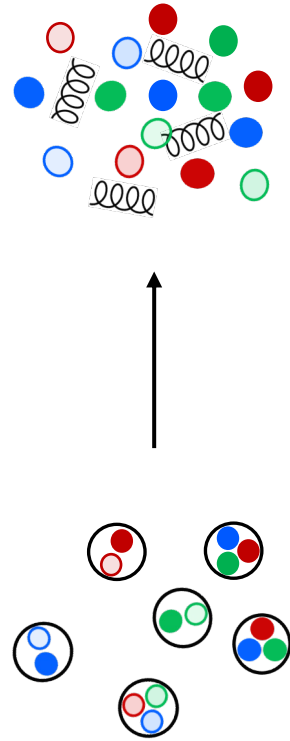
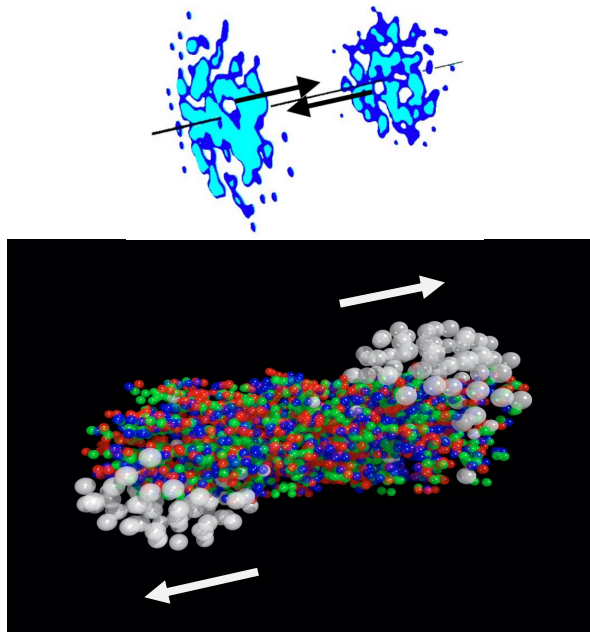
Magic angle graphene  
Cao et. al. *Nature* **556**, 43–50 (2018)

QCD



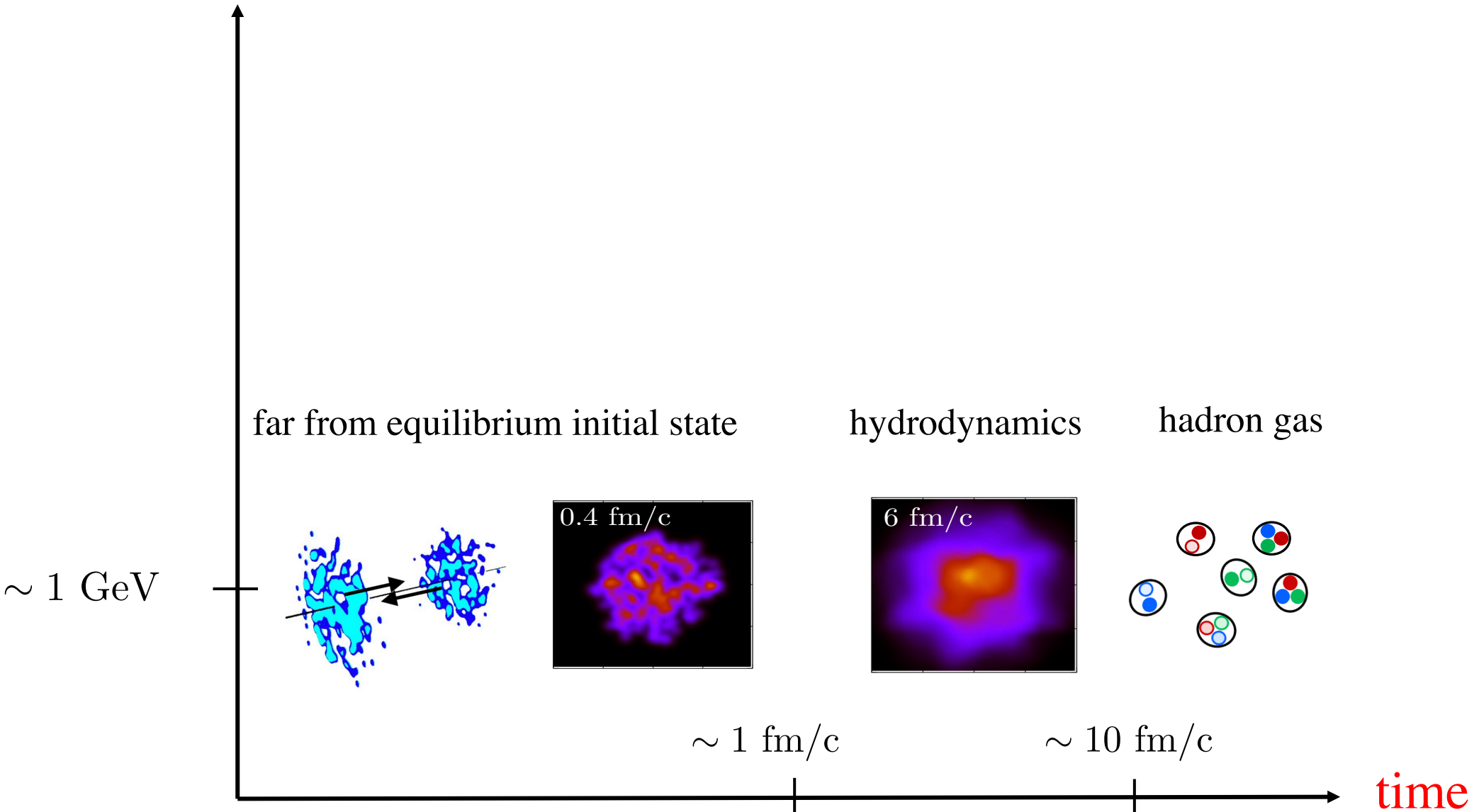
Understanding the fundamental interactions is just the beginning!

# Heavy-ion collisions and quark-gluon plasma



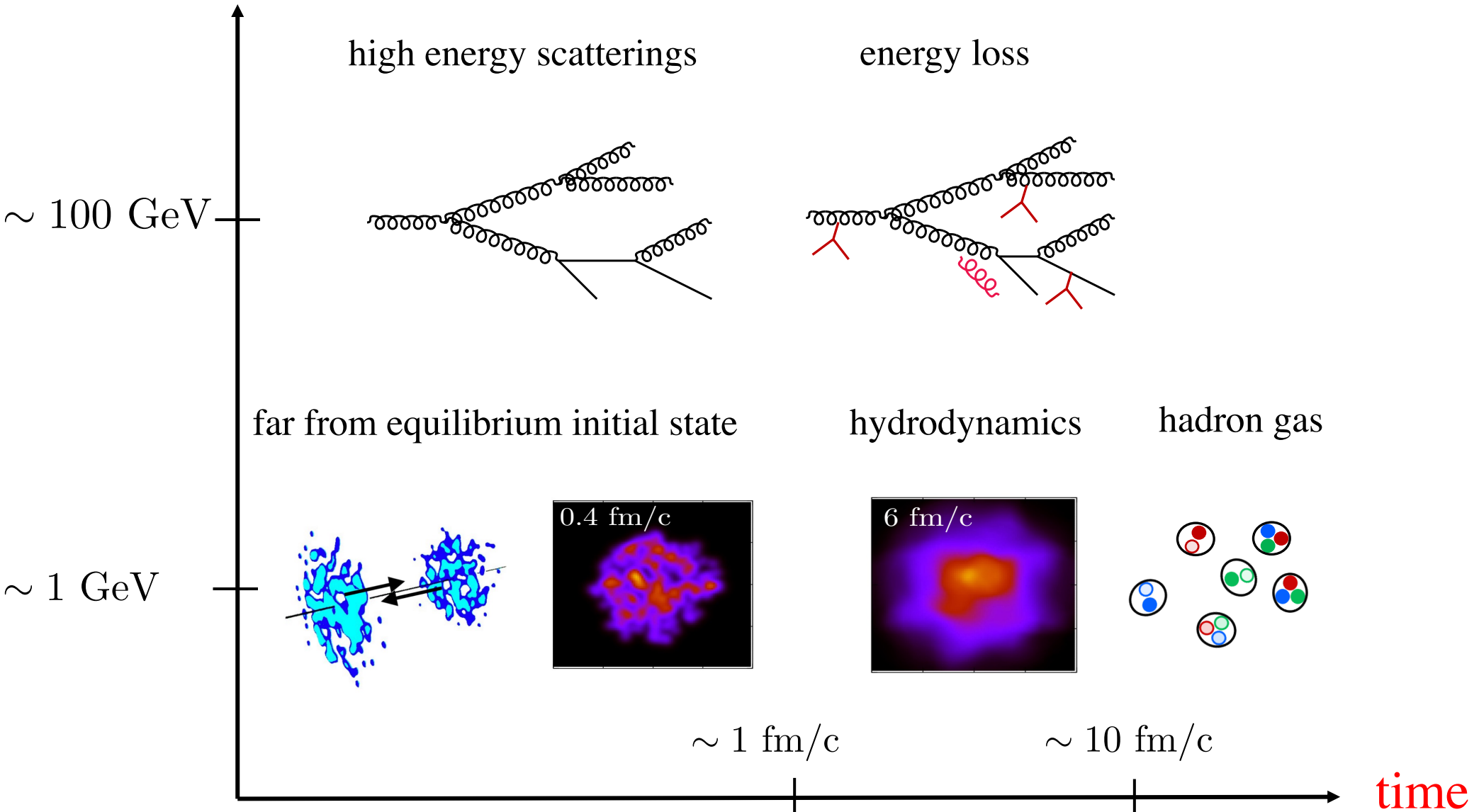
# Heavy-ion collisions

energy

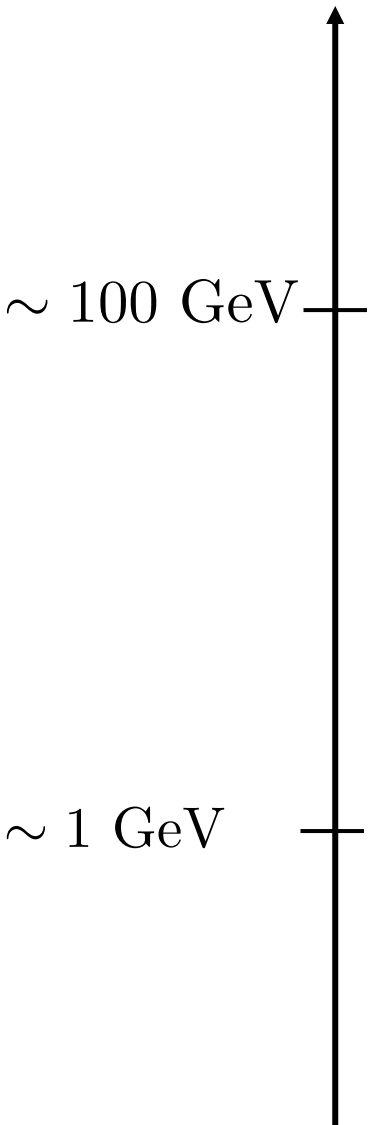


# Heavy-ion collisions

energy

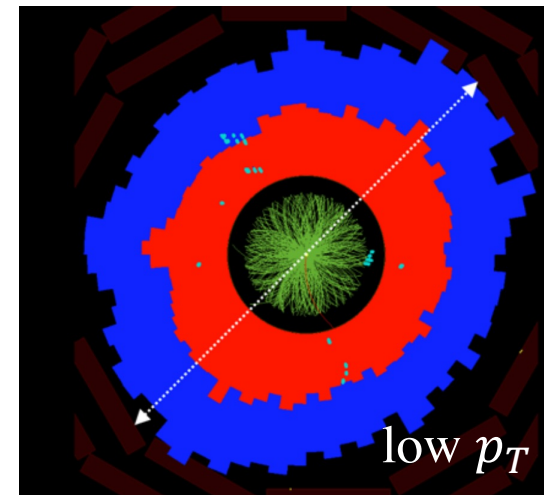
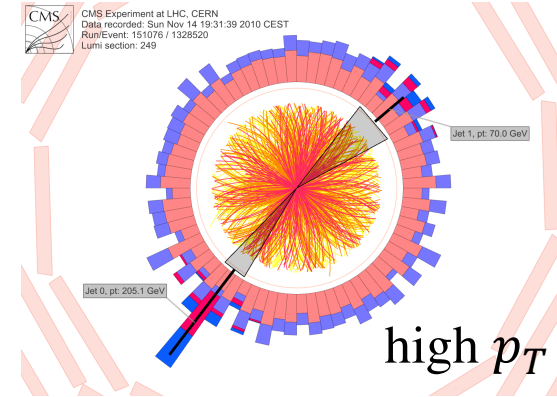


# Studying the dense QCD medium

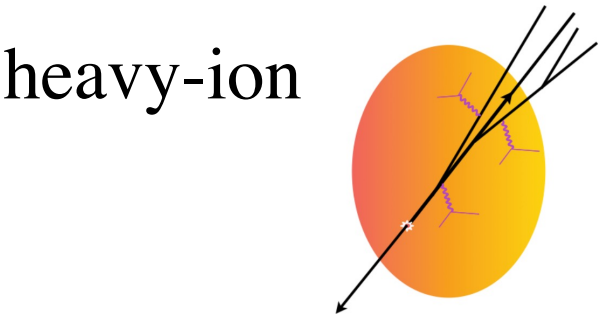
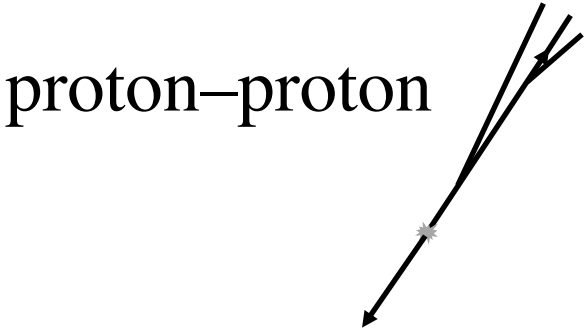


Modification of  
high-energy probes  
(hadrons, jets,  
heavy flavor, ..)

Collective behavior  
of low- $p_T$  particles

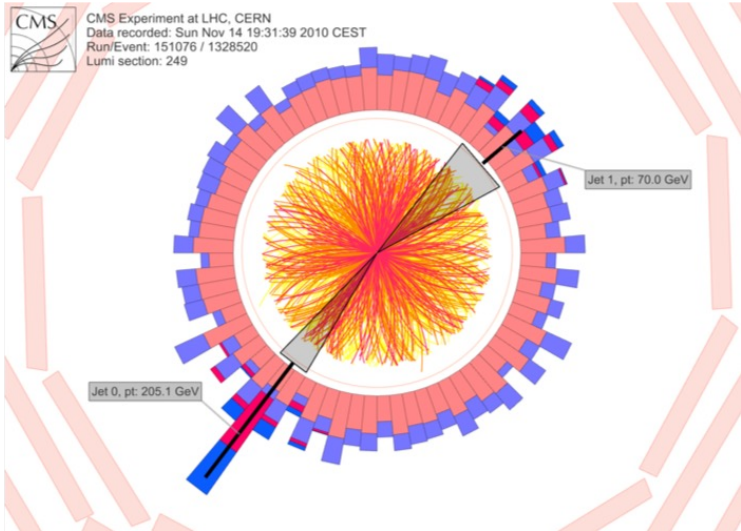
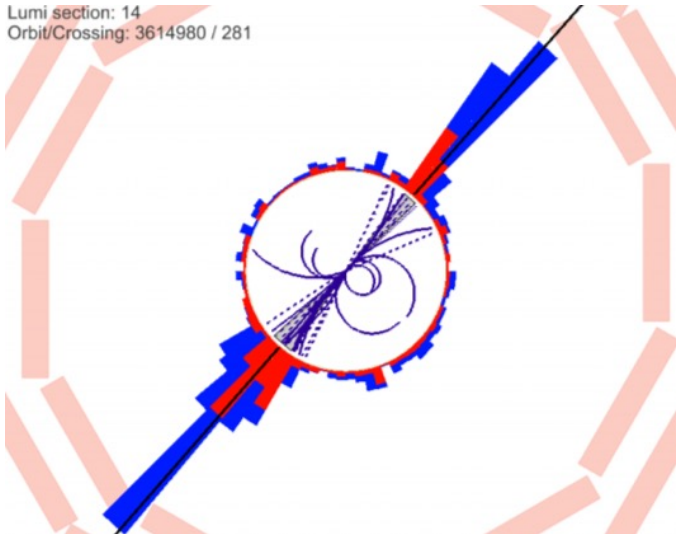


# Modification of jets as a probe of quark-gluon plasma



Large effect:

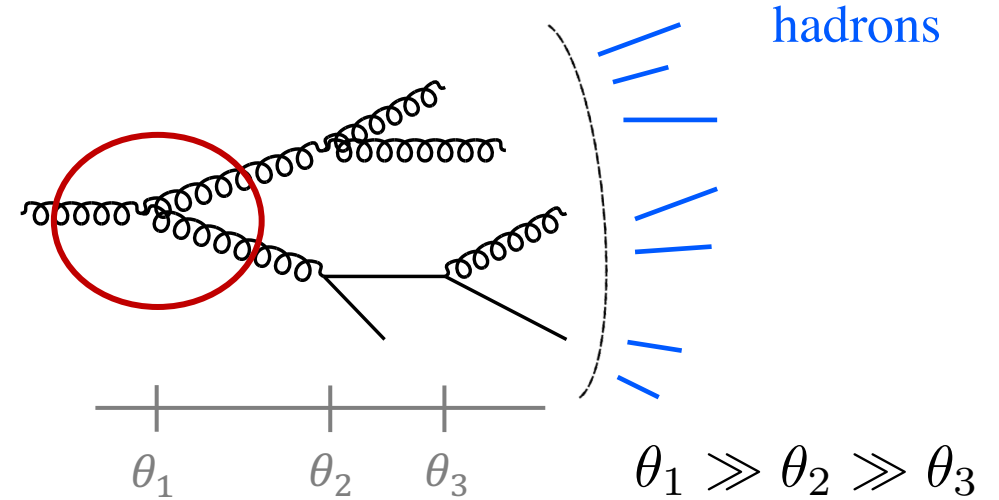
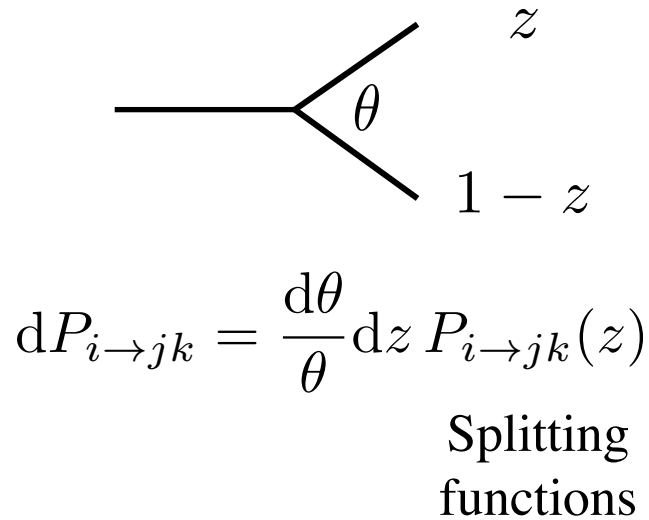
- Half as many jets per  $p_T$  in heavy-ion collisions
- Enhanced asymmetry of back-to-back jets
- ...



“baseline” jet properties



# Parton splittings in vacuum



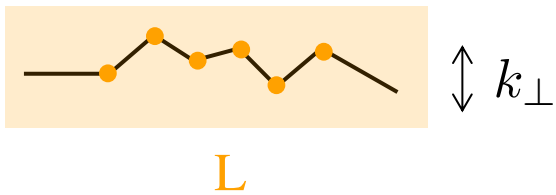
Iteratively apply splitting functions, descending in angle, virtuality

Parton showers connect perturbative QCD to hadronic world



# A single high-energy parton in finite-temperature QCD

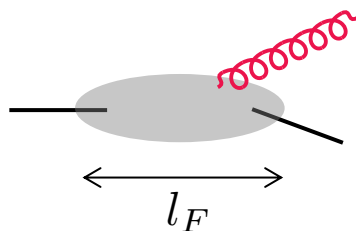
Parton undergoes transverse momentum diffusion



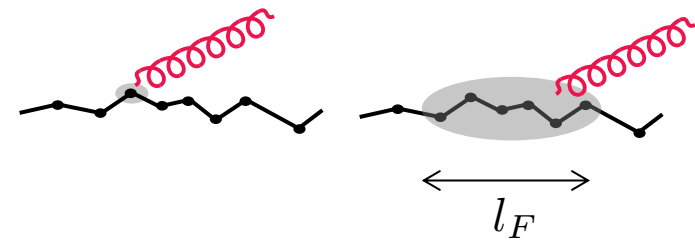
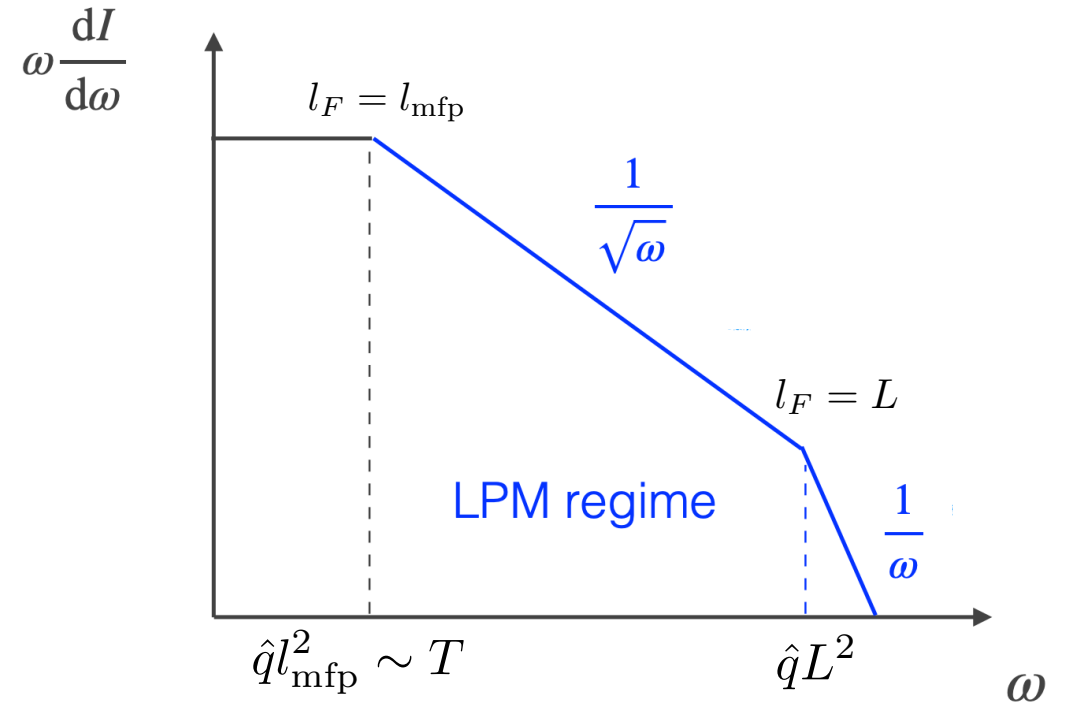
$$\hat{q} \equiv \frac{d\langle k_{\perp}^2 \rangle}{dt}$$

Kicks occasionally induce gluon radiation

Radiation can't be resolved instantaneously



$$l_F \propto \sqrt{\omega}$$

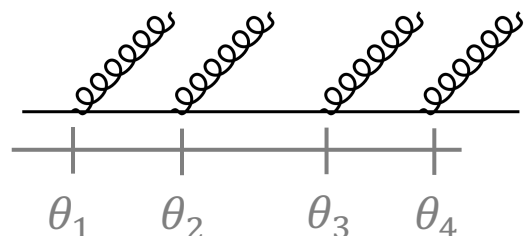


Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1996)  
Arnold, Moore, Yaffe (2003)

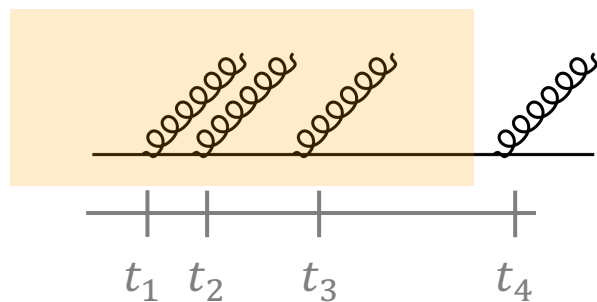
# A high-energy parton fragments even in vacuum

## Detailed interplay of vacuum physics and medium modification

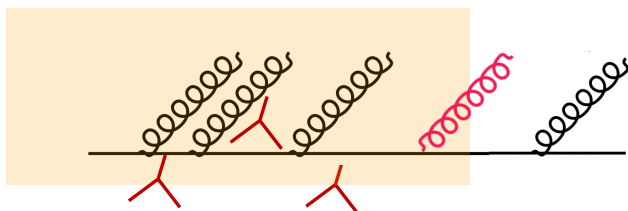
vacuum shower



vacuum shower  
in medium



medium shower



## Improved theory

- Improved parton radiation spectrum

Mehtar-Tani, Tywoniuk, Andres, Dominguez, Salgado, ...

- Parton showers in medium

Caucal, Iancu, Mueller, Soyez, Wiedemann, Zapp, ...

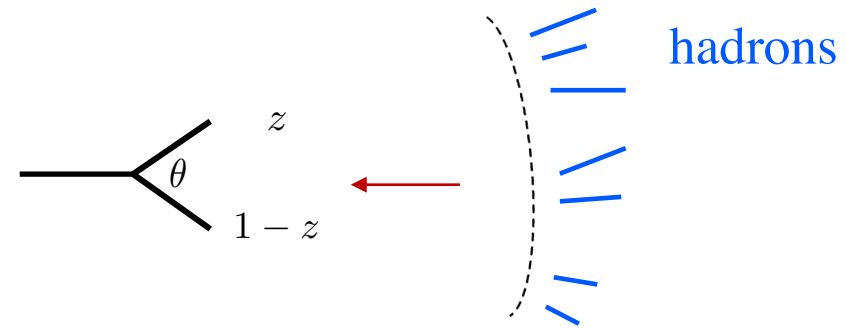
No current theories capture full complexity

## Improved phenomenology

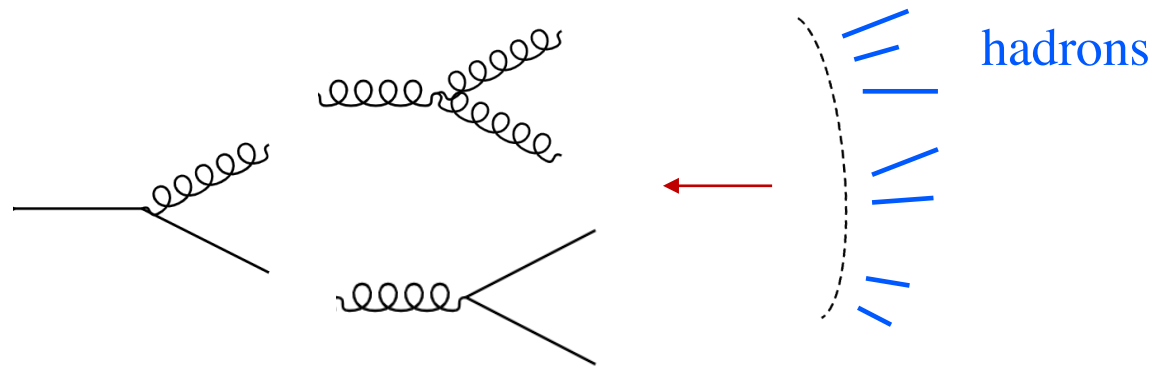
- Deconstructing a jet to access individual splittings

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

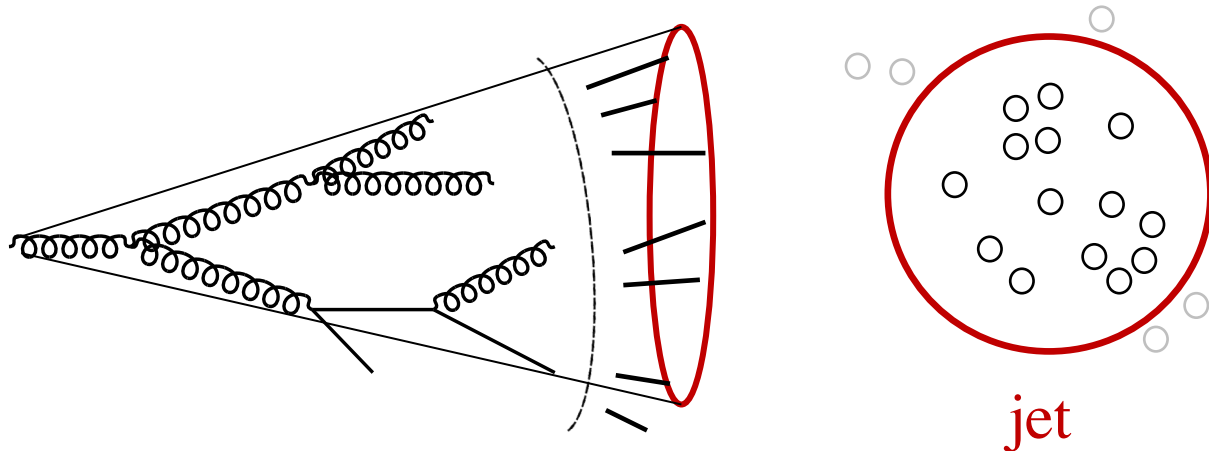
- Hadrons to splittings



- Flavor-dependence of splittings

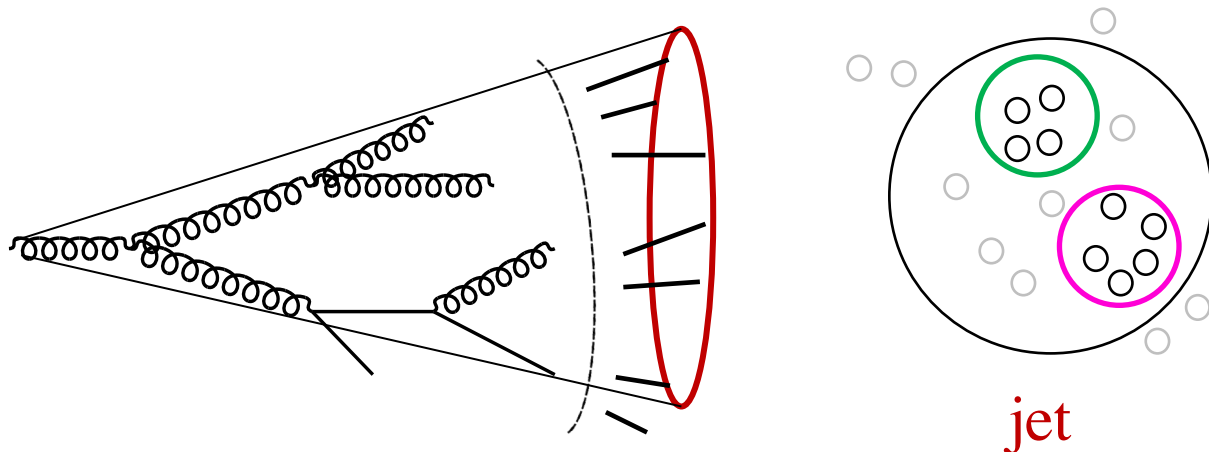


# Accessing splitting functions from jet substructure



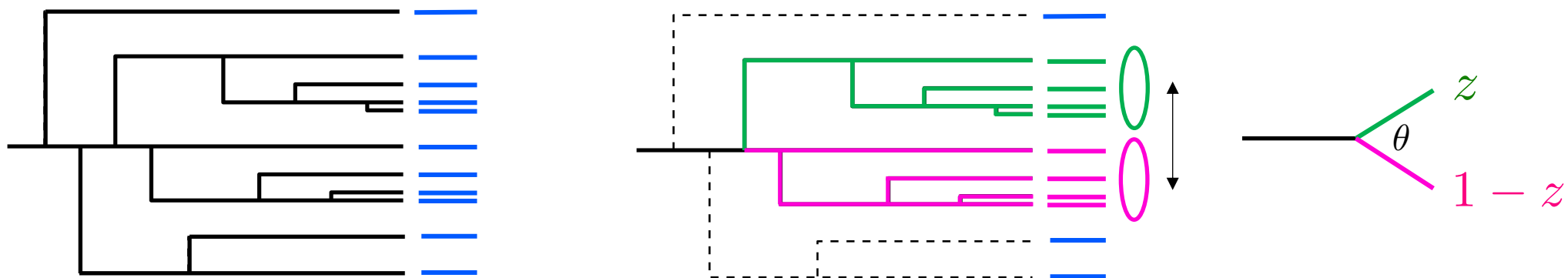
Access kinematics of gluon that initiated the shower ( $p_T, Q^2, \dots$ )

# Accessing splitting functions from jet substructure

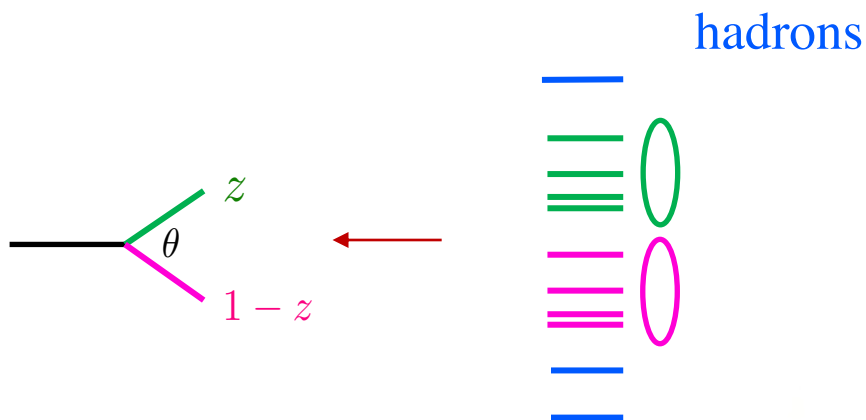


Access kinematics of gluon that initiated the shower ( $p_T, Q^2, \dots$ )

Use angular ordering of QCD to reconstruct emission history of shower from hadron level



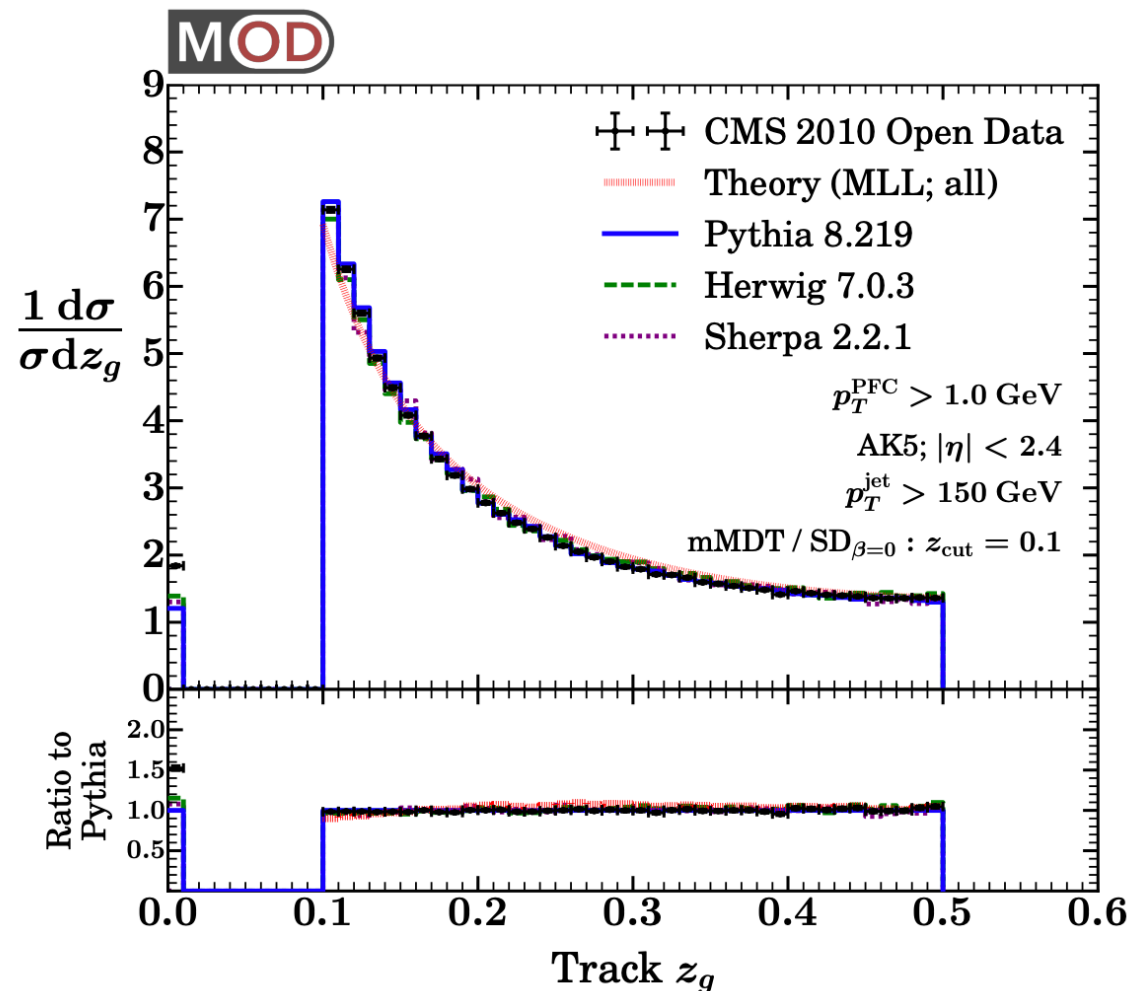
# Accessing splitting functions from jet substructure



- Adapted for heavy ions: splittings with shortest formation time, highest  $k_t$ , ...

Mehtar-Tani, Soto-Ontoso, Tywoniuk [1911.00375];  
 Caucal, Soto-Ontoso, Takacs [2111.14768]  
 (see also Apolinario, Cordeiro, Zapp [2012.02199])

## QCD splitting function from jets

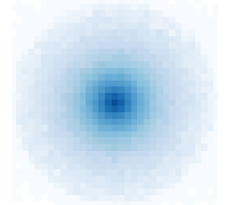
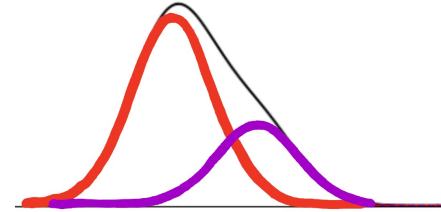
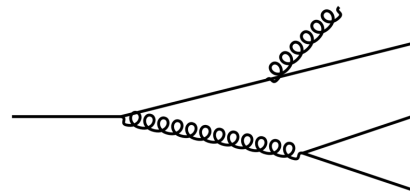
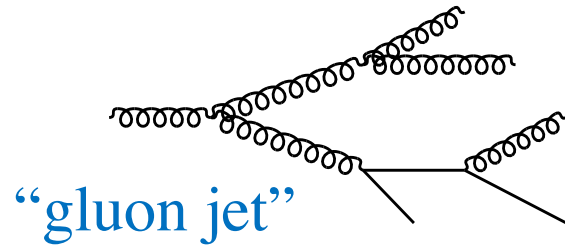


Larkoski, Marzani, Thaler [1502.01719]

Larkoski, Marzani, Thaler, Tripathy, Xue [1704.05066]

# Accessing light flavor splitting functions

- In vacuum

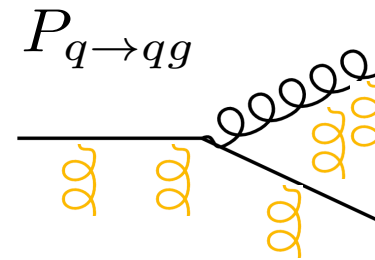
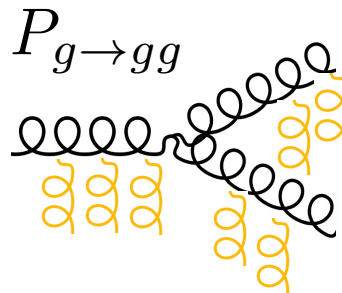


Observable-based, machine learning approaches

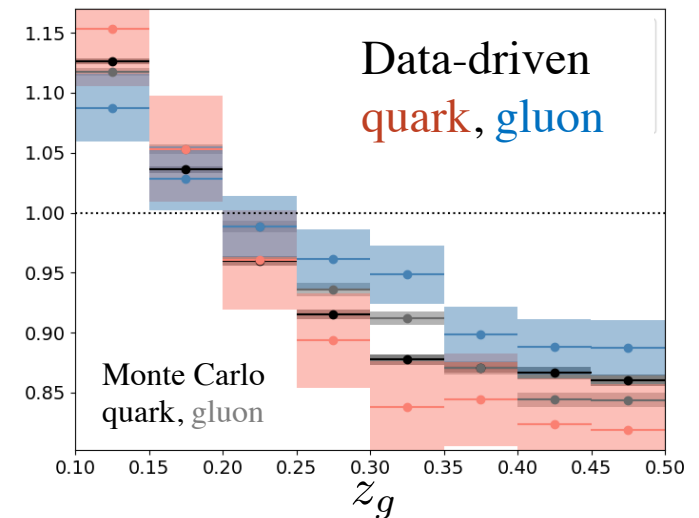
Thaler, Metodiev, Komiske, Schwartz, Dreyer, Soyez, Takacs, Larkoski, many others...

- In medium

Flavor-dependent modification



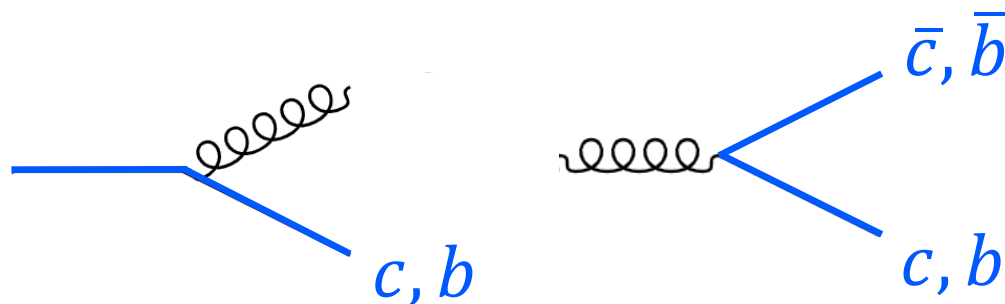
Modified q,g splitting functions





# Accessing heavy flavor splitting functions

Heavy flavor splittings:

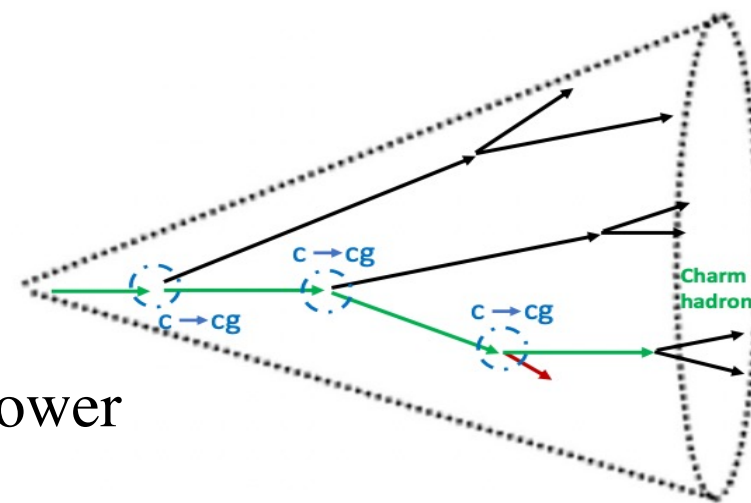


Advantages:

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

Used in ALICE [2106.05713]

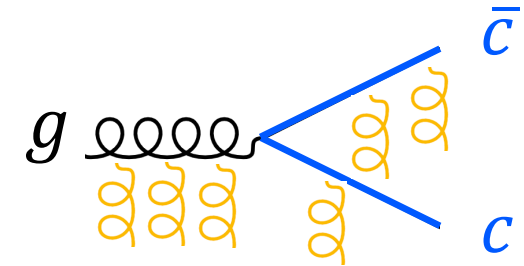
- Access later (more modified) splittings in the shower
- At high energies, access light flavor splittings



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

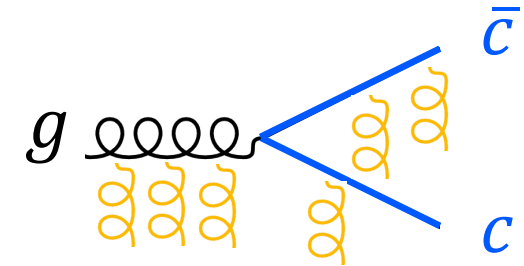
# Unique features of the modification of $g \rightarrow c\bar{c}$

Signature of momentum broadening of  $c\bar{c}$  pair

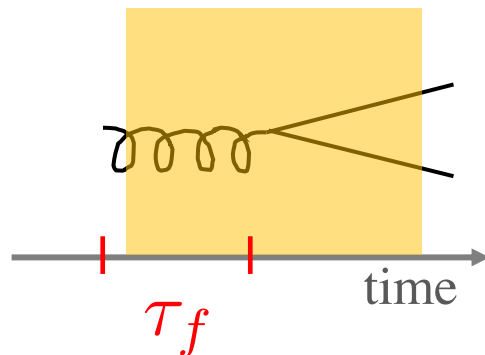


# Unique features of the modification of $g \rightarrow c\bar{c}$

Signature of momentum broadening of  $c\bar{c}$  pair

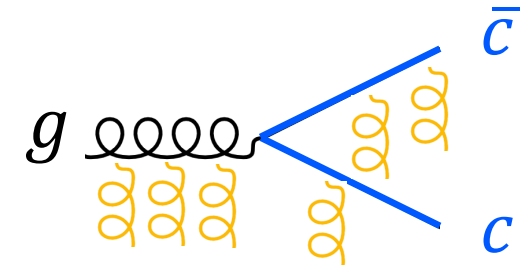


Gluons have a “lifetime”  $\tau_f \sim \frac{2E_g}{Q^2}$  depending on their energy



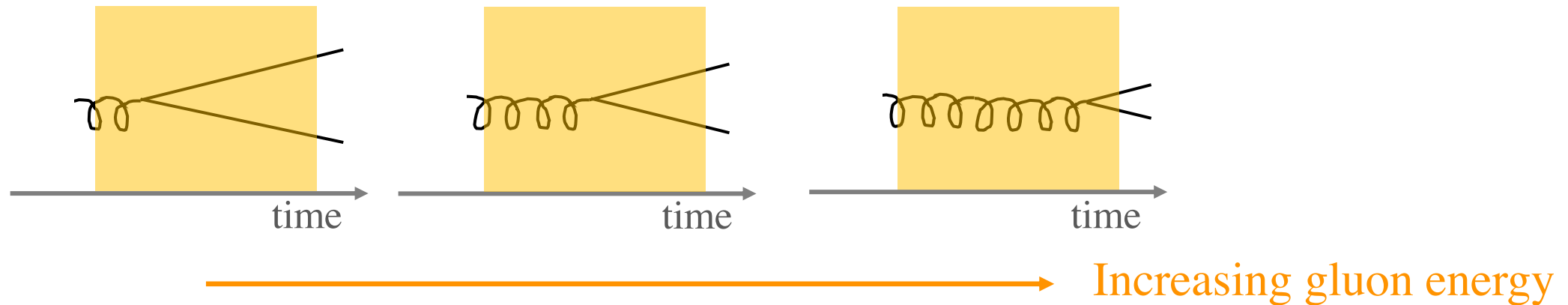
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Signature of momentum broadening of  $c\bar{c}$  pair



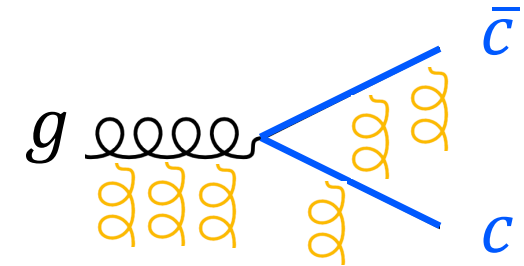
Gluons have a “lifetime”  $\tau_f \sim \frac{2E_g}{Q^2}$  depending on their energy

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



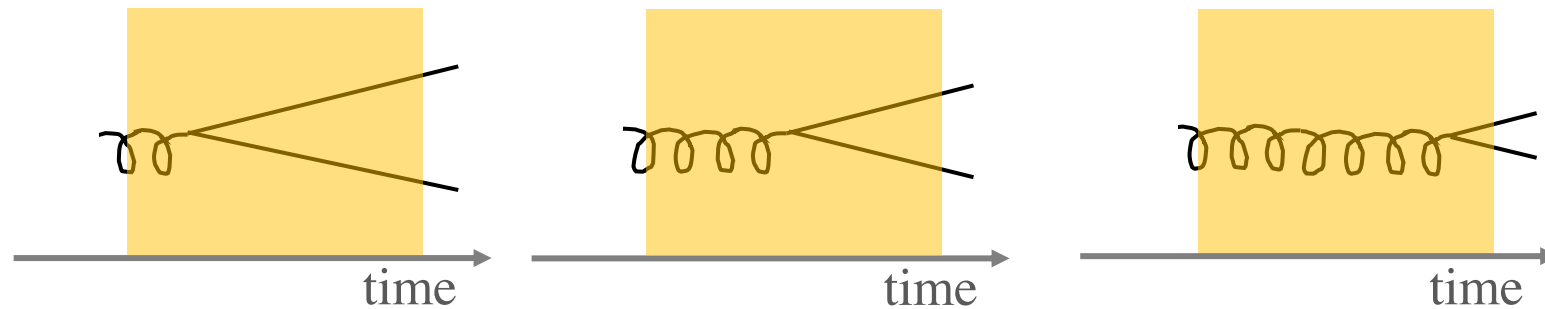
# Unique features of the modification of $g \rightarrow c\bar{c}$

Signature of momentum broadening of  $c\bar{c}$  pair



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

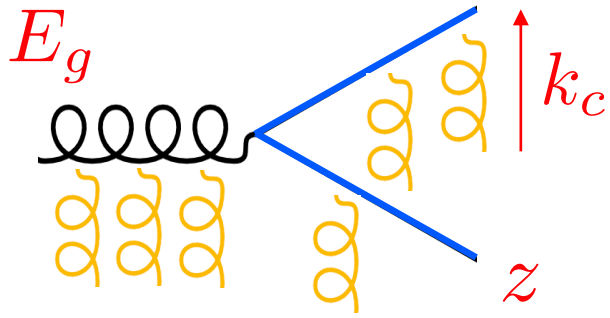
- Access modification of  $c\bar{c}$  pair at later times in the QGP



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

Increasing gluon energy

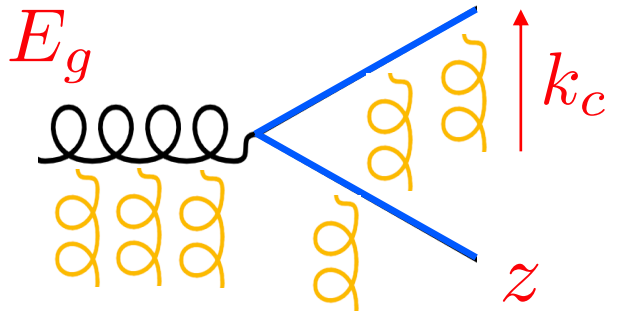
# Modification of the $g \rightarrow c\bar{c}$ splitting function



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

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

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



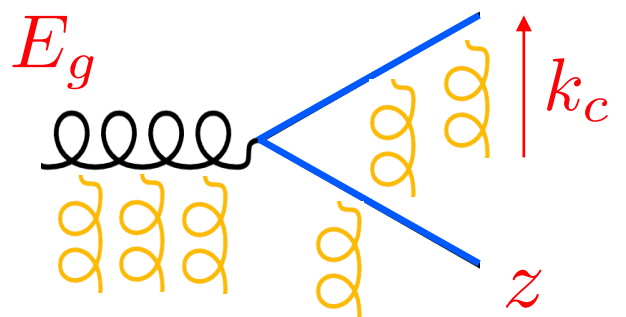
$$P_{g \rightarrow c\bar{c}}(E_g, k_c^2, z) = P_{g \rightarrow c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g \rightarrow c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

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

## Results of the calculation:

- Depletion at small  $k_c^2$  **broadening**

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



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

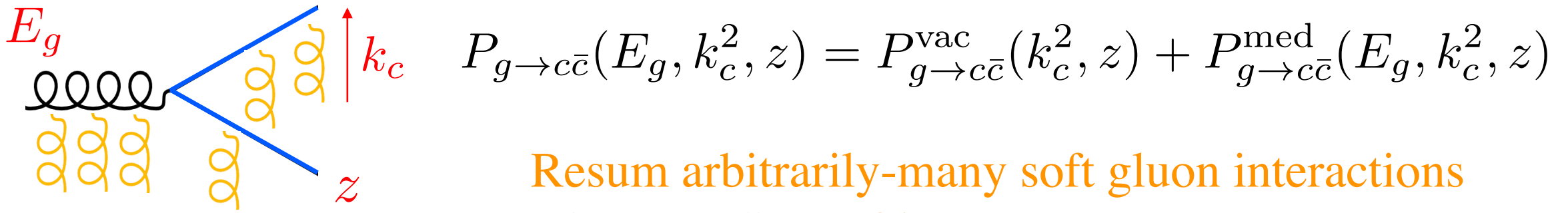
Resum arbitrarily-many soft gluon interactions with a medium of length L

## Results of the calculation:

- Depletion at small  $k_c^2$  broadening
- Less modification with increasing  $E_g$  formation-time dependence



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



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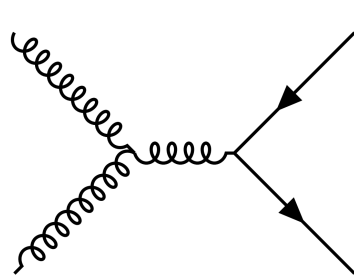
Resum arbitrarily-many soft gluon interactions with a medium of length  $L$

## Results of the calculation:

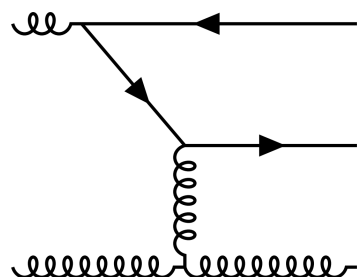
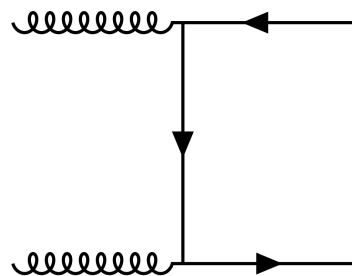
- Depletion at small  $k_c^2$  broadening
- Less modification with increasing  $E_g$  formation-time dependence
- Medium-enhanced rate of  $c\bar{c}$  production! gluons promoted above threshold

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

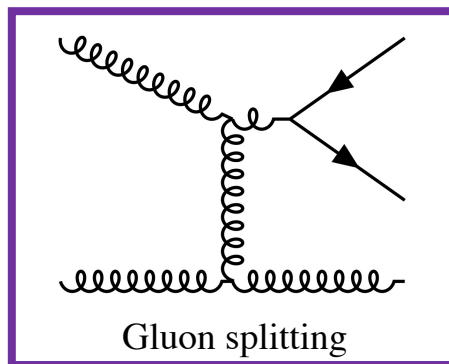
## Leading processes for heavy quark production



Flavor creation

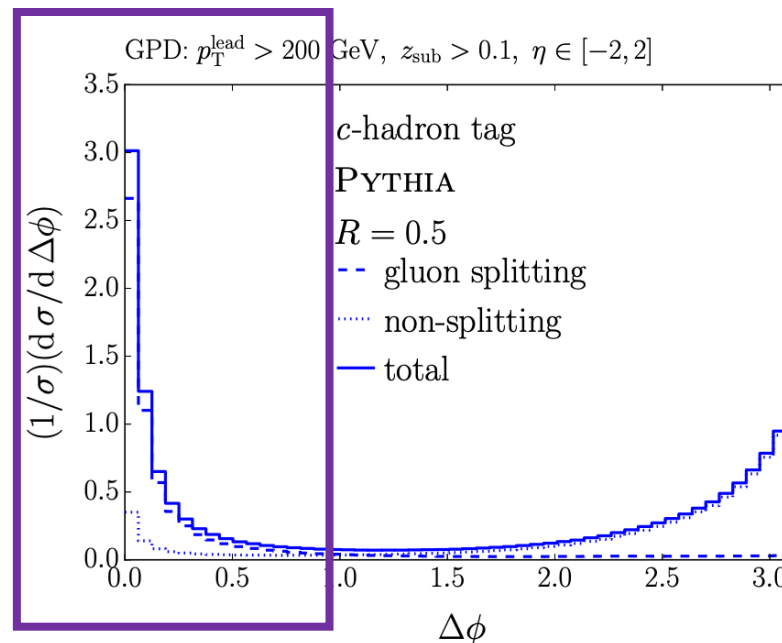
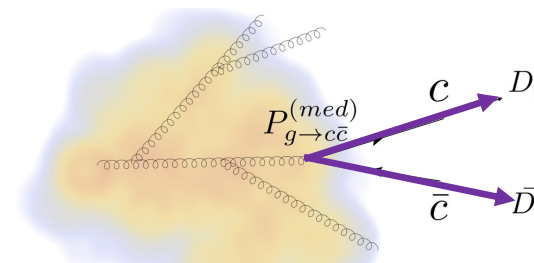


Flavor excitation



Gluon splitting

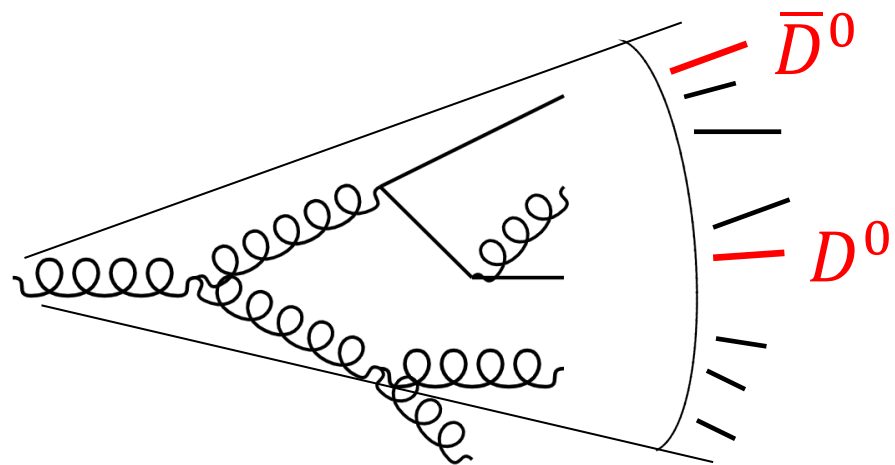
(approximately) collinear



Gluon splitting

Non-gluon-splitting

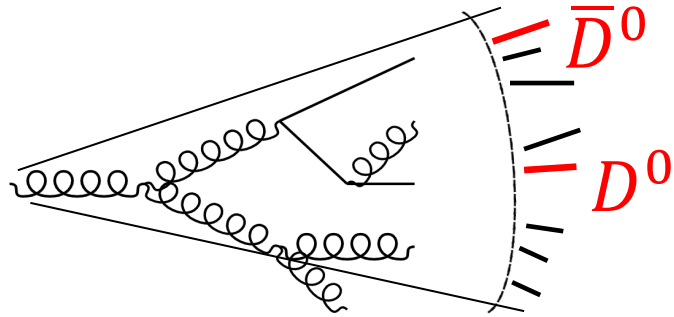
# Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets



High-purity sample of showers  
including  $g \rightarrow c\bar{c}$  splitting

Expected experimental sensitivity in Run 3/4

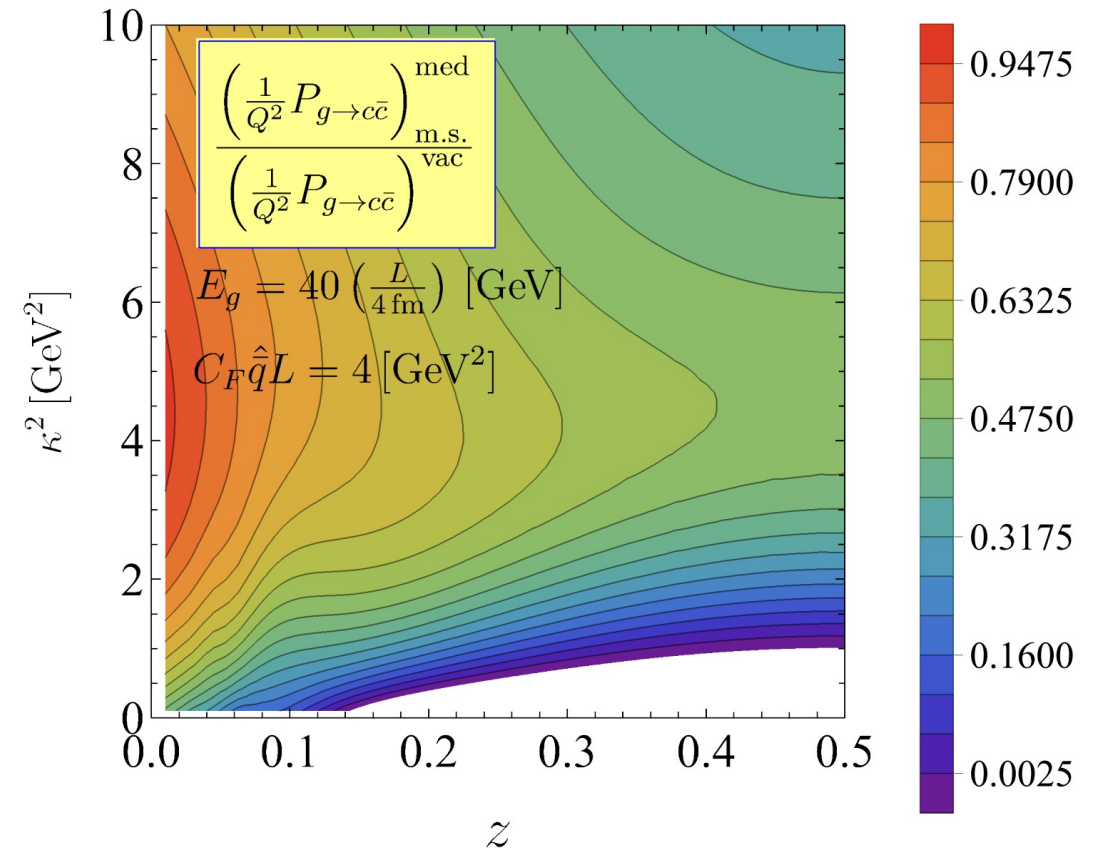
# Observing $g \rightarrow c\bar{c}$ enhancement in jets



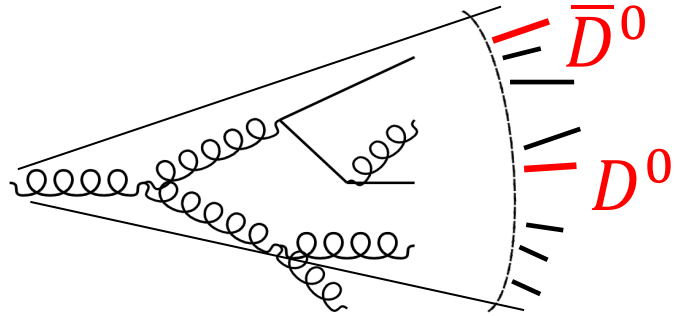
Get kinematics of  $g \rightarrow c\bar{c}$

Reweight each splitting by

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



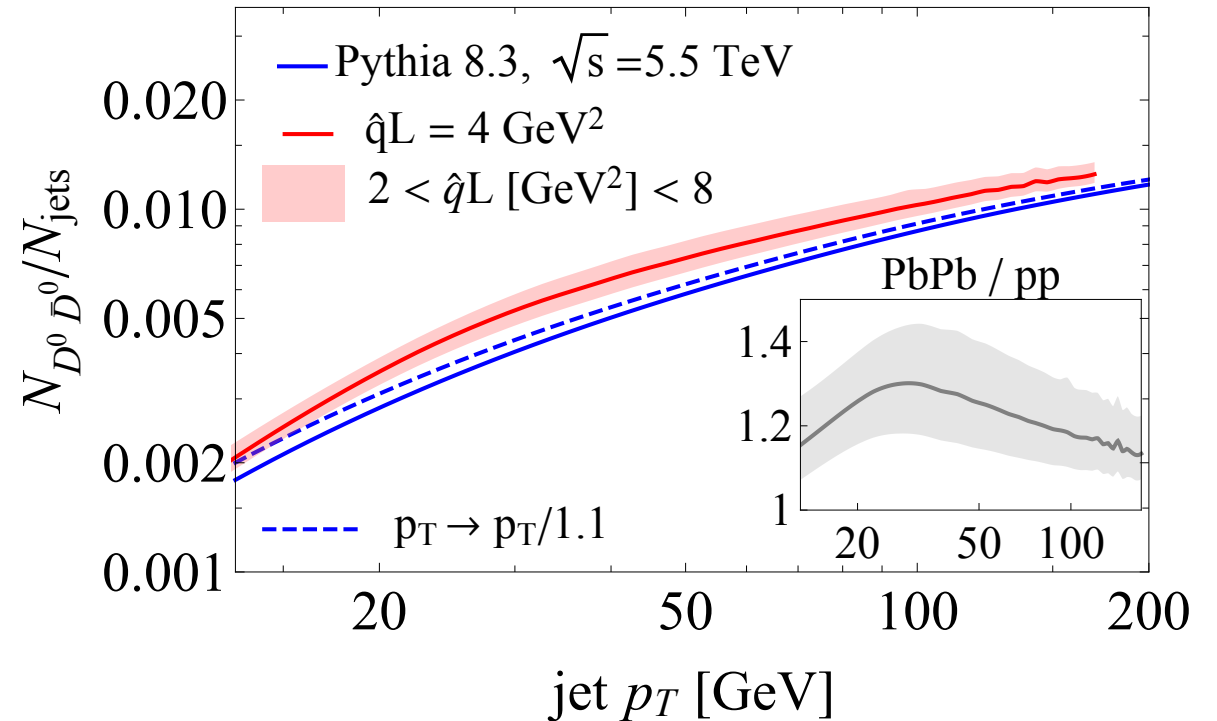
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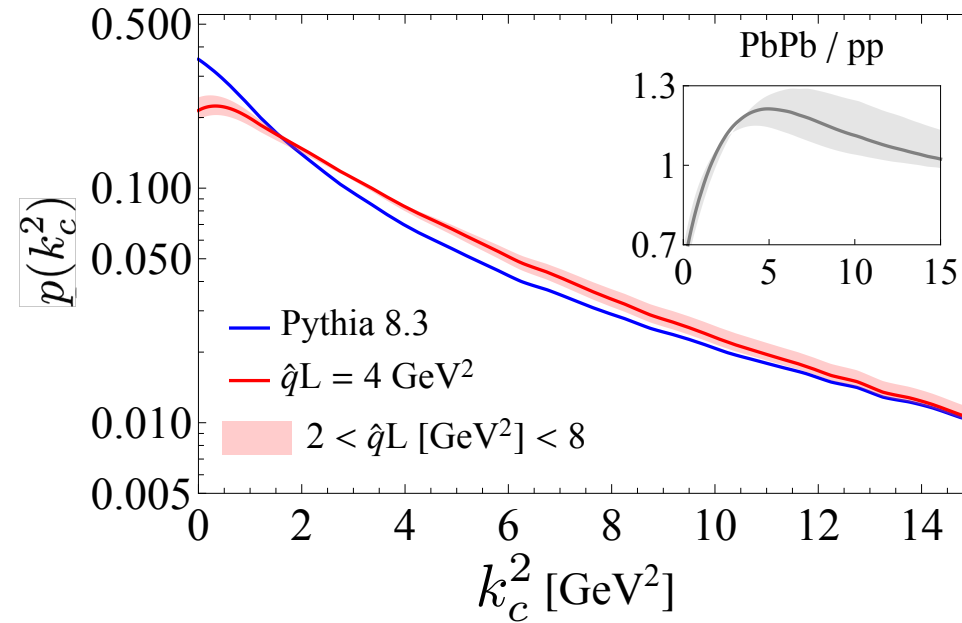
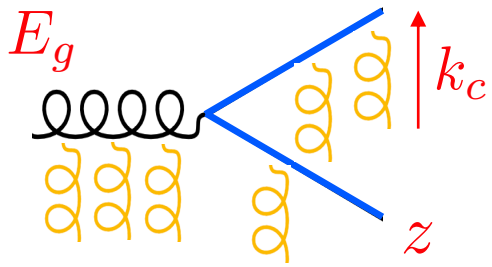
Get kinematics of  $g \rightarrow c\bar{c}$

Reweight each splitting by

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

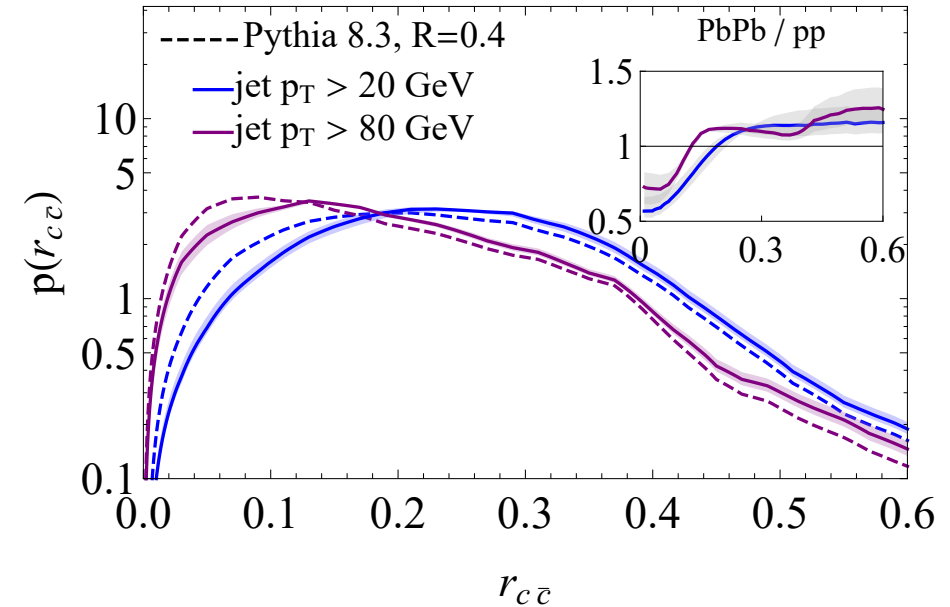
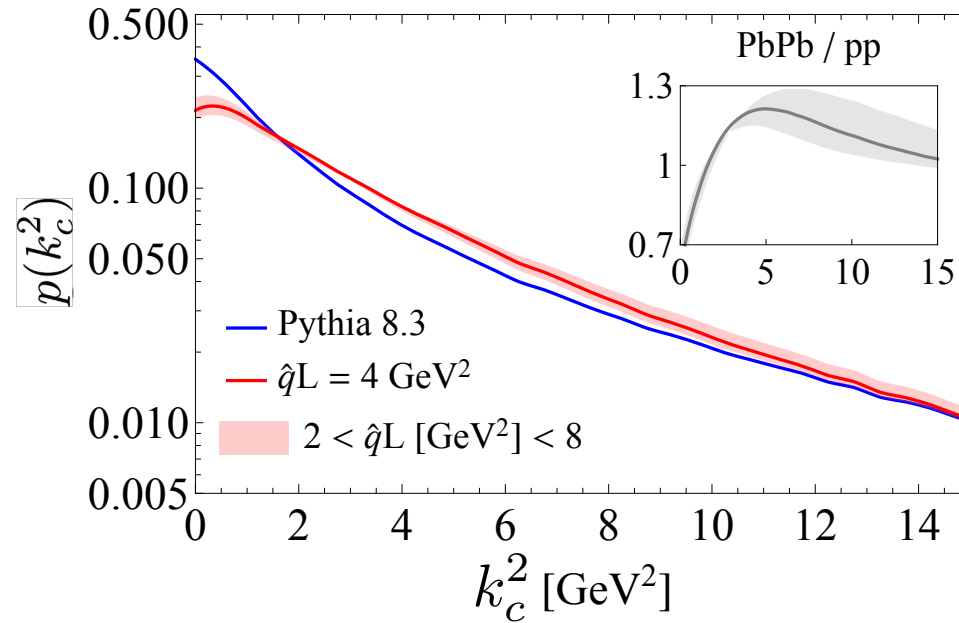
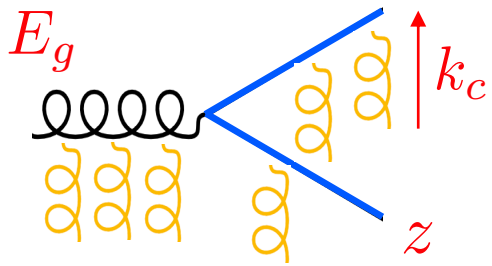


# Going forward: other unique signatures



Can use jet substructure to access broadening at hadron-level

# Going forward: other unique signatures



Can use jet substructure to access broadening at hadron-level

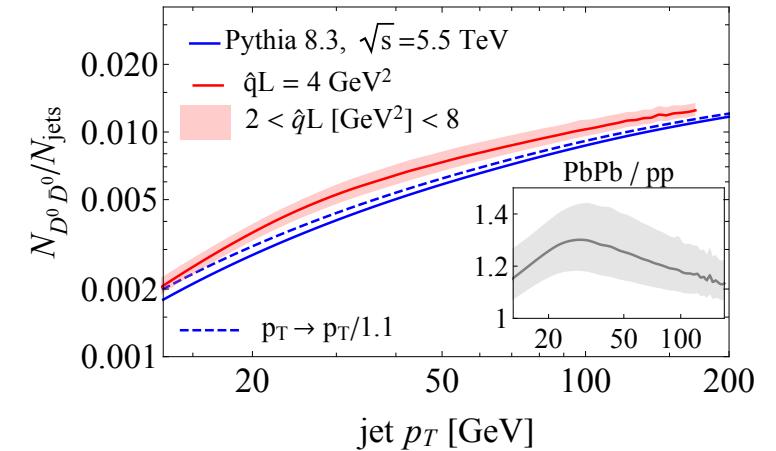
Ongoing: how to quantify modification differential in  $E_g$ ?

- Access delayed probe of QGP

# A process with many exciting future avenues!

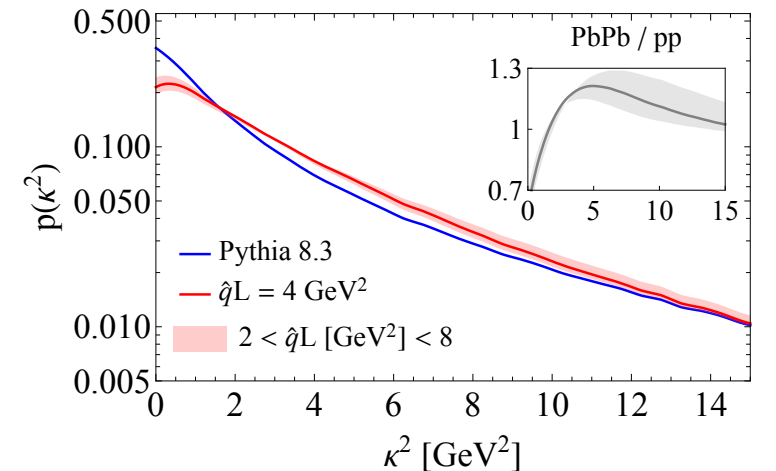
So far..

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



Outlook

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

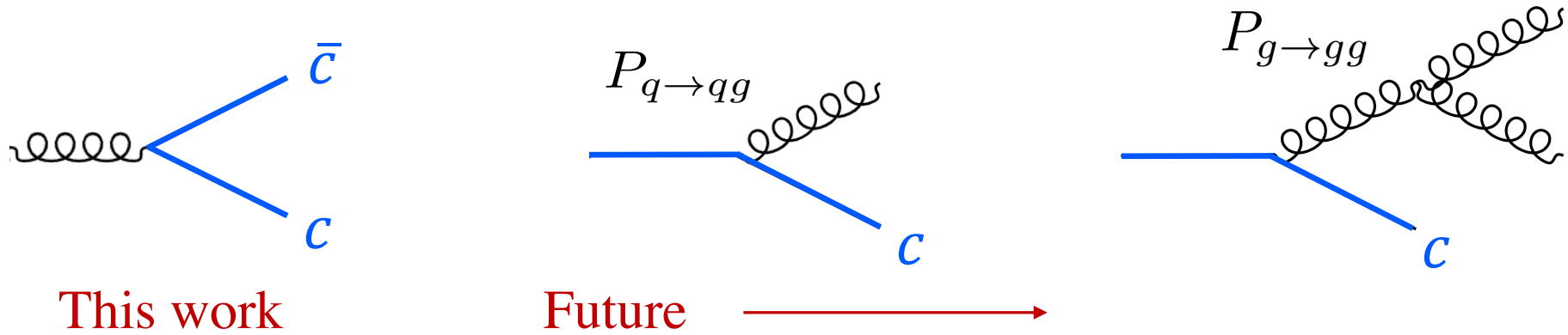


Clean process with a lot of exciting physics opportunities!



# Outlook

## Phenomenology of heavy-flavor tagged jets



## Constructing a picture of modified jets from phenomenology

