

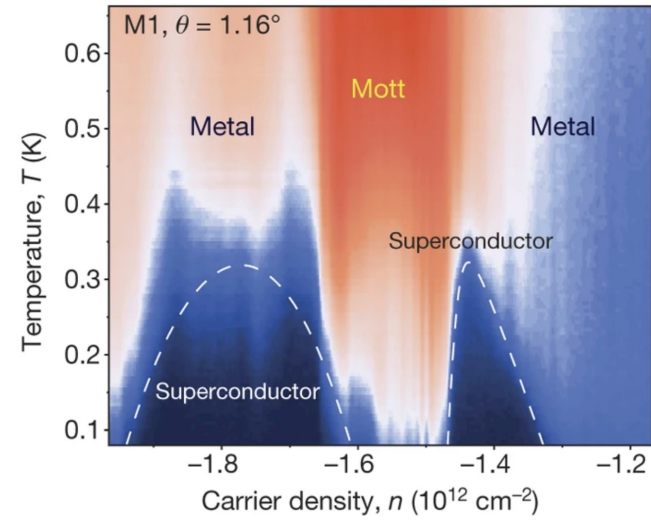
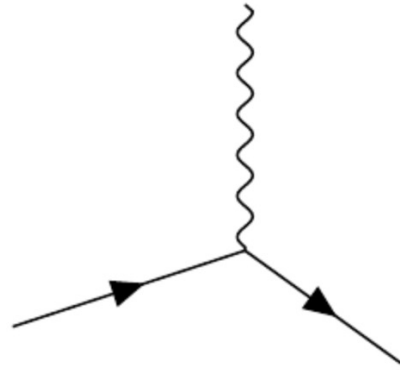
Medium-enhanced production of charm quark pairs in jets

Jasmine Brewer



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

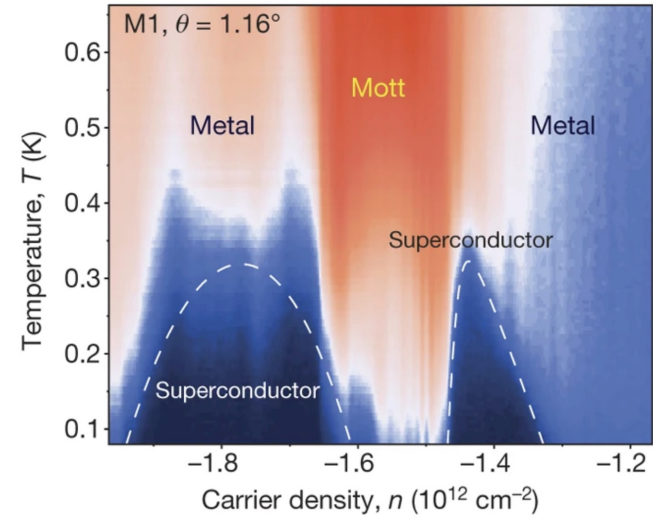
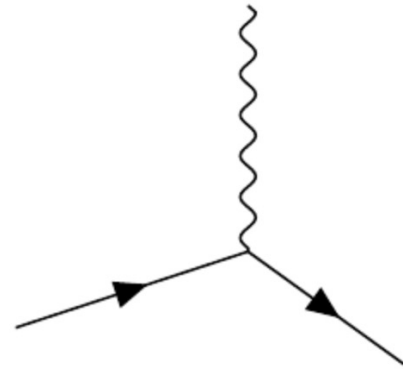
QED



Magic angle graphene

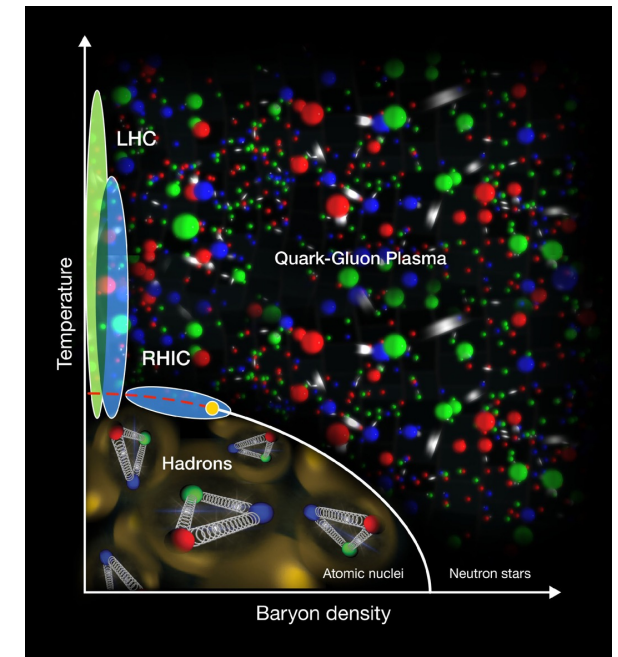
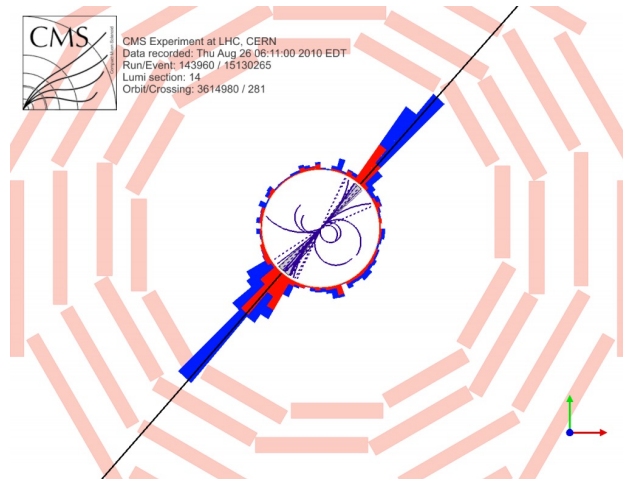
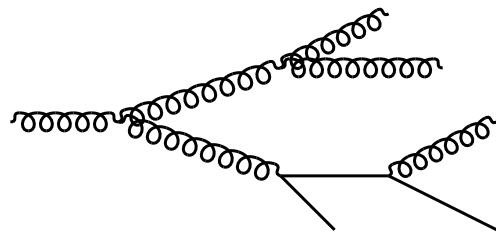
Cao et. al. *Nature* **556**, 43–50 (2018)

QED



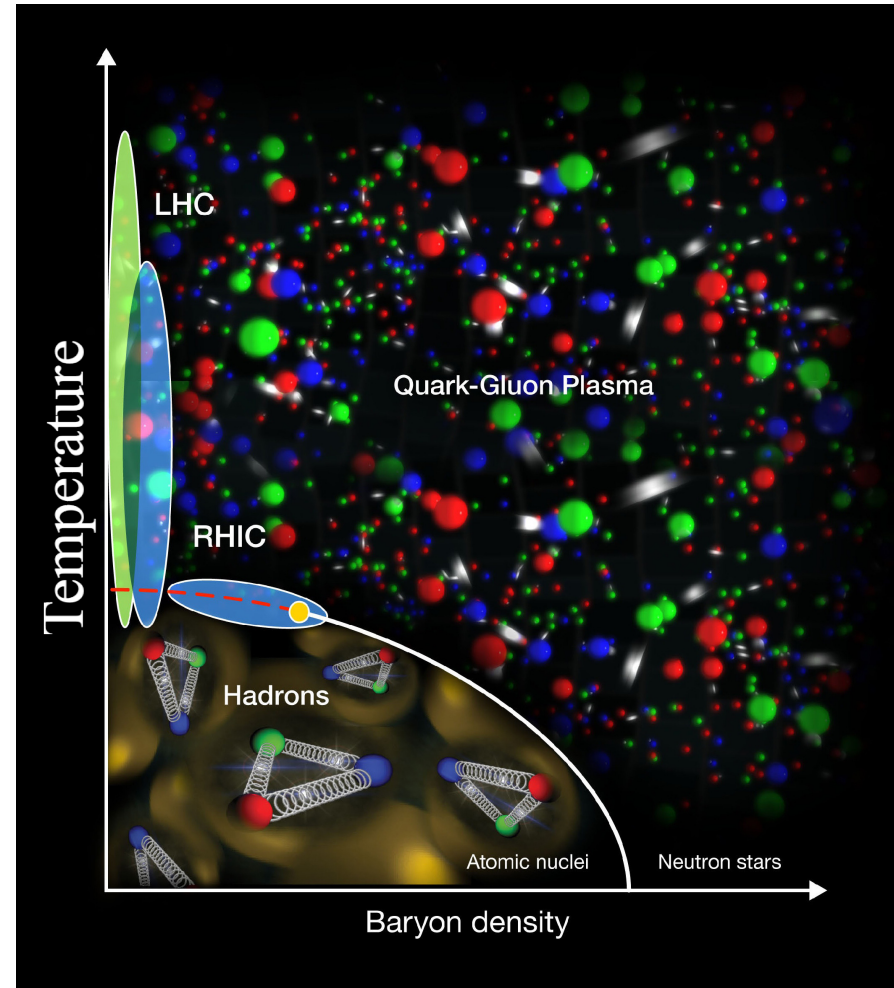
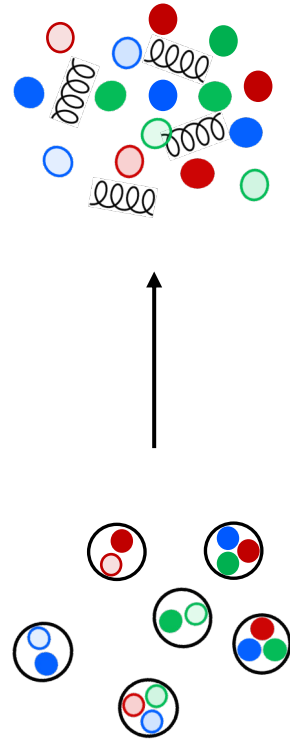
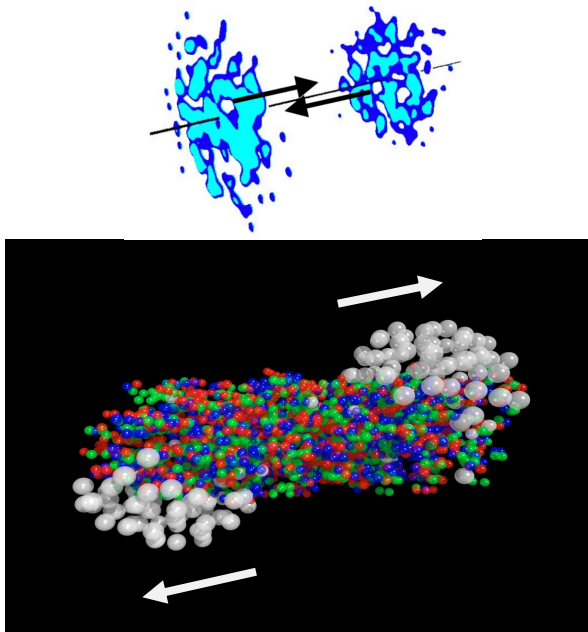
Magic angle graphene
Cao et. al. *Nature* **556**, 43–50 (2018)

QCD



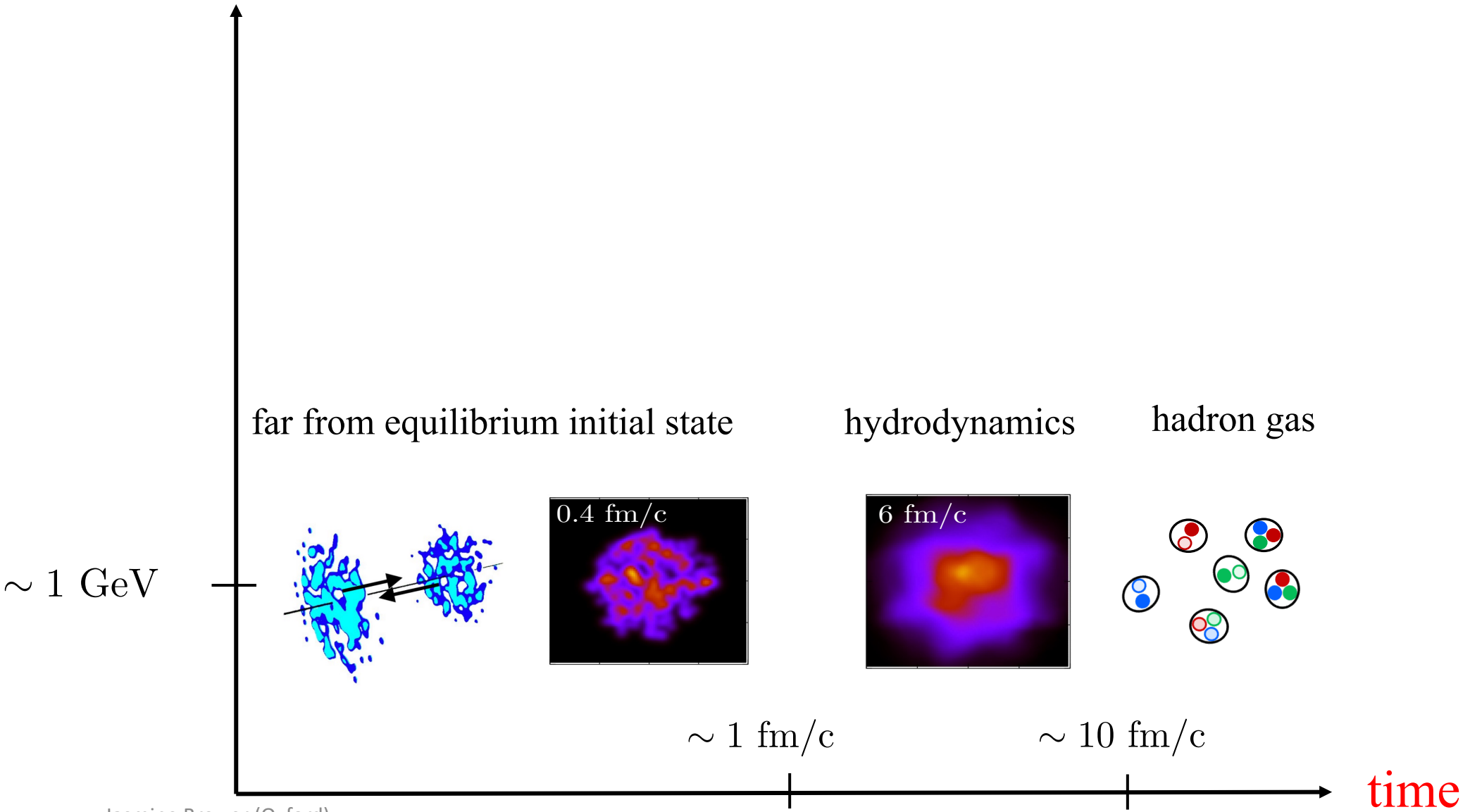
Understanding the fundamental interactions is just the beginning!

Heavy-ion collisions and quark-gluon plasma



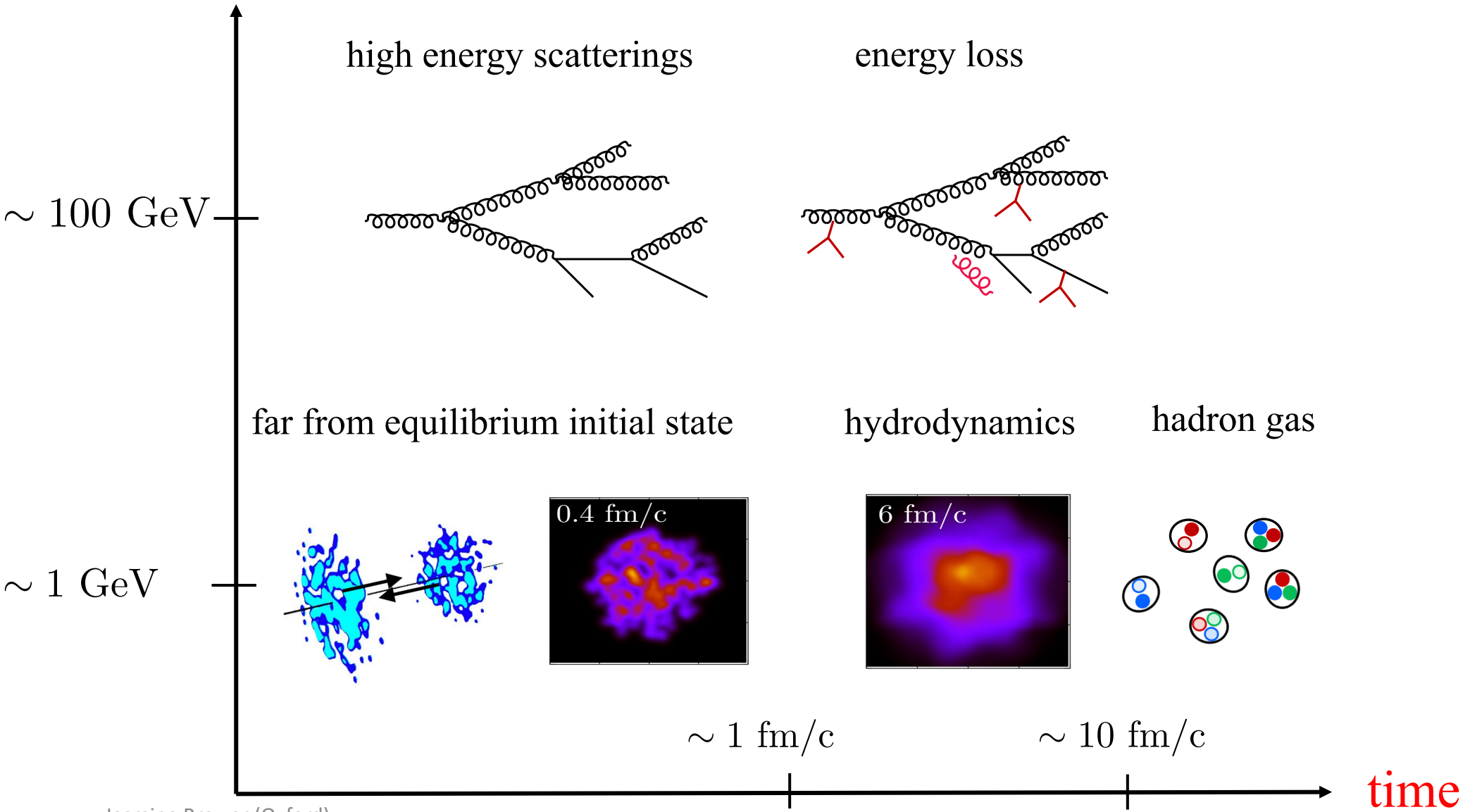
Heavy-ion collisions

energy

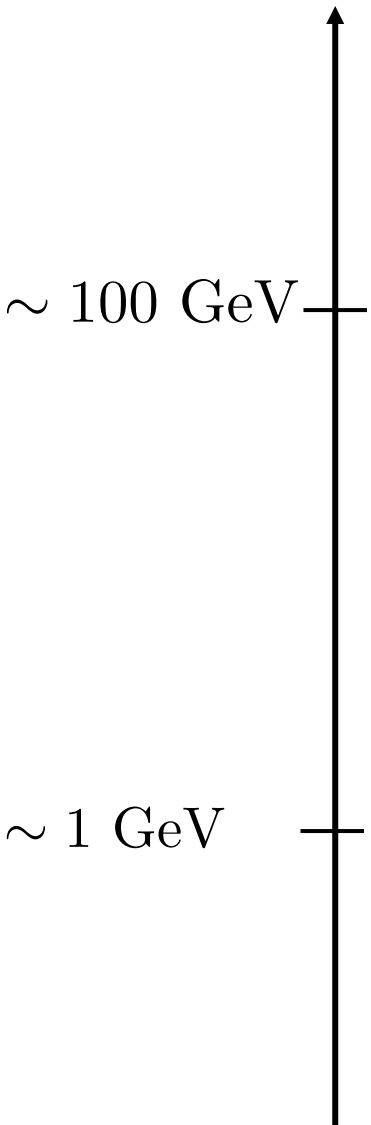


Heavy-ion collisions

energy

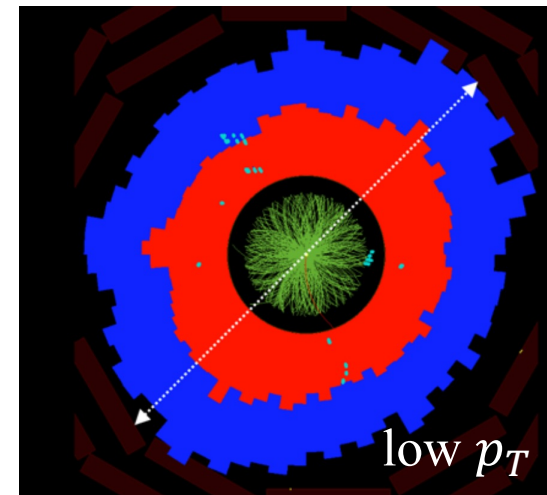
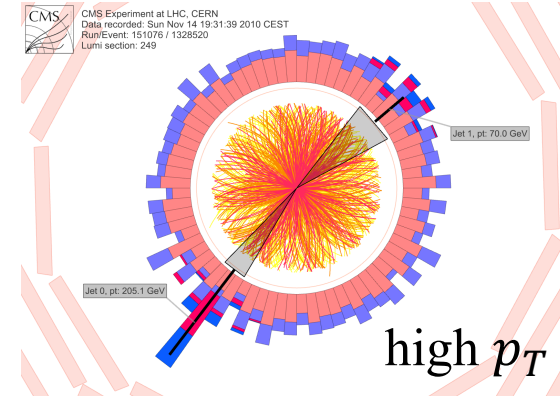


Studying the dense QCD medium

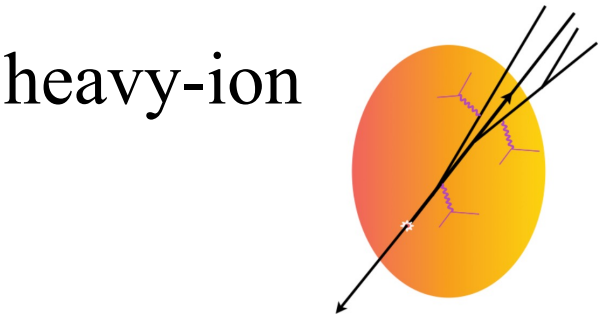
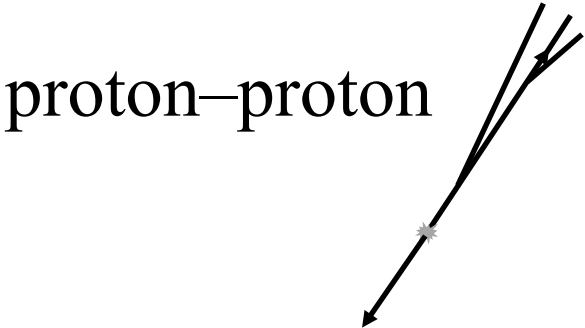


Modification of
high-energy probes
(hadrons, jets,
heavy flavor, ..)

Collective behavior
of low- p_T particles

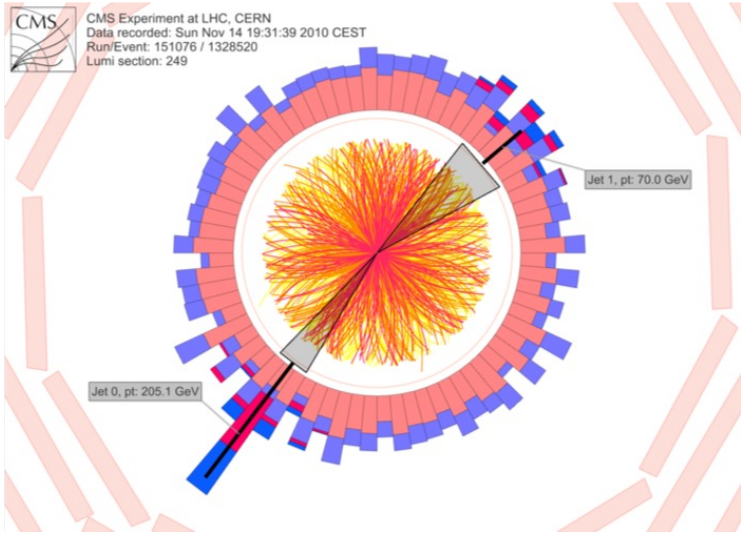
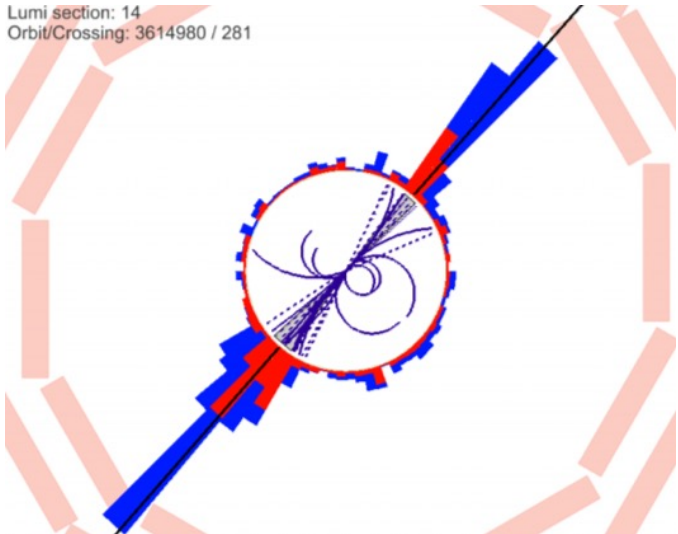


Modification of jets as a probe of quark-gluon plasma



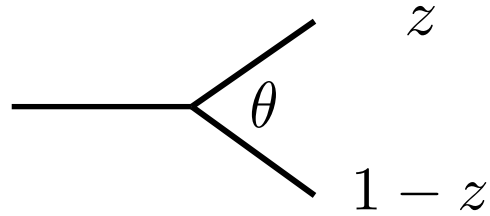
Large effect:

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



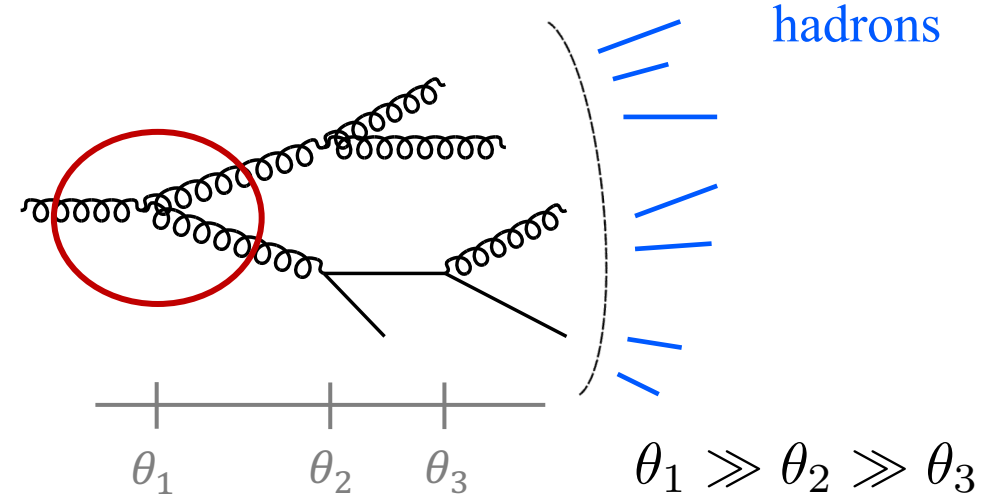
“baseline” jet properties

Parton splittings in vacuum



$$dP_{i \rightarrow jk} = \frac{d\theta}{\theta} dz P_{i \rightarrow jk}(z)$$

Splitting functions



Iteratively apply splitting functions, descending in angle, virtuality

Parton showers connect perturbative QCD to hadronic world

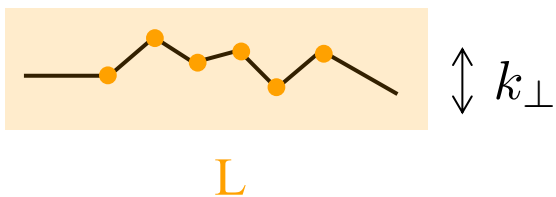
Going to higher accuracy

Parton showers

Next-to-leading log calculations
 \longleftrightarrow
 $\alpha_s \rightarrow 0$

A single high-energy parton in finite-temperature QCD

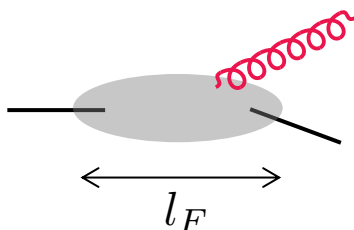
Parton undergoes transverse momentum diffusion



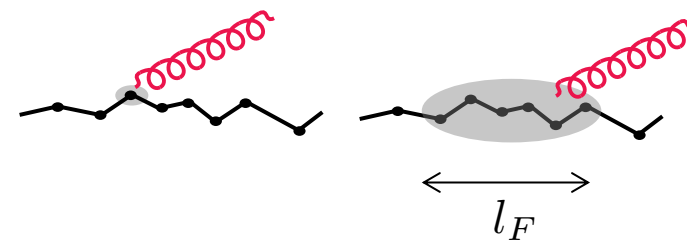
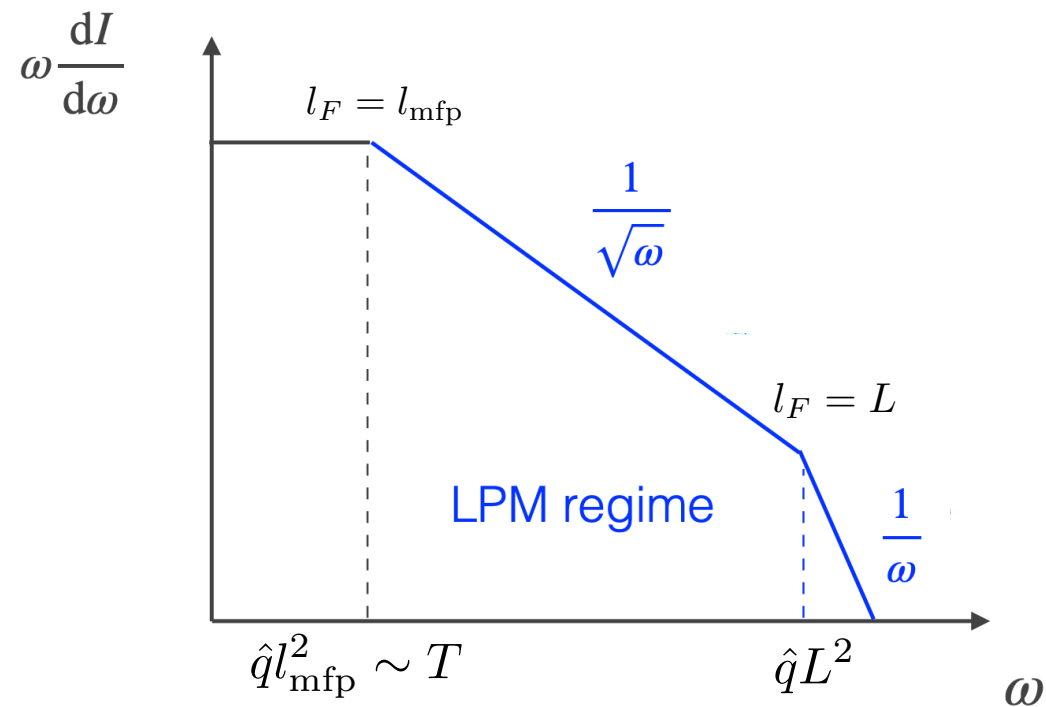
$$\hat{q} \equiv \frac{d\langle k_{\perp}^2 \rangle}{dt}$$

Kicks occasionally induce gluon radiation

Radiation can't be resolved instantaneously



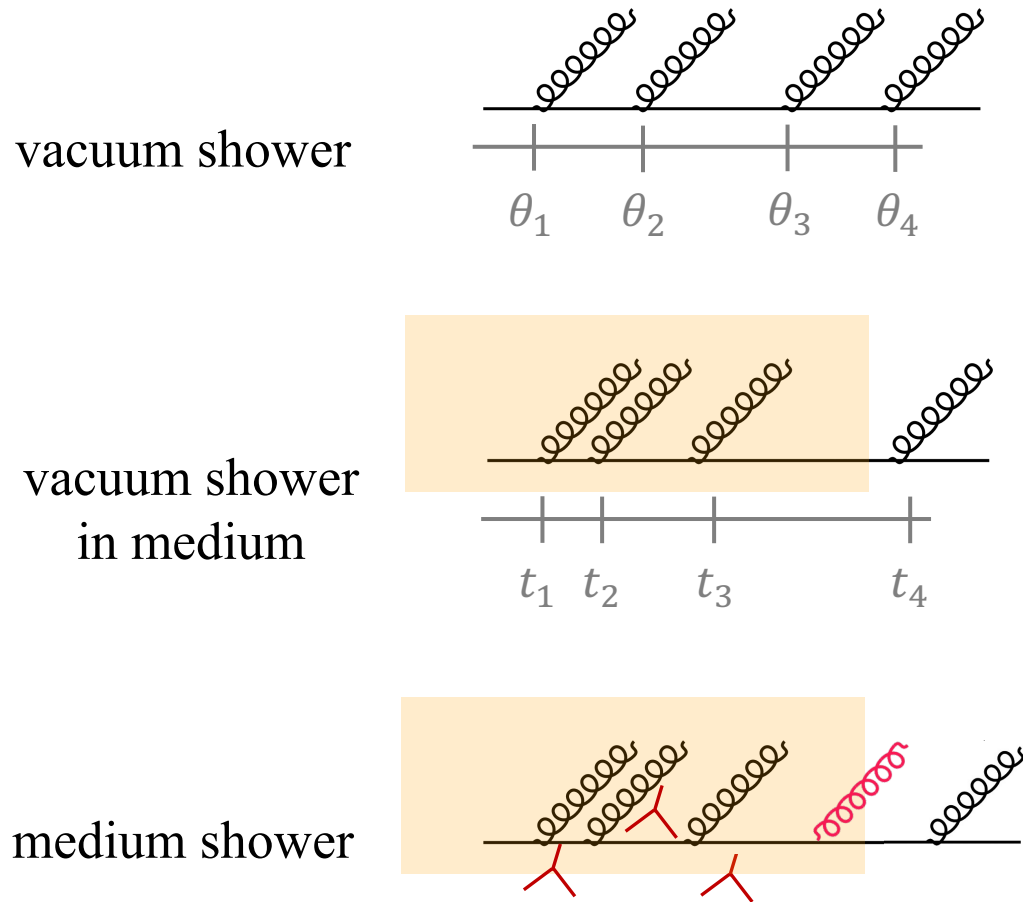
$$l_F \propto \sqrt{\omega}$$



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



Improved theory

- Improved parton radiation spectrum

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

- Parton showers in medium

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

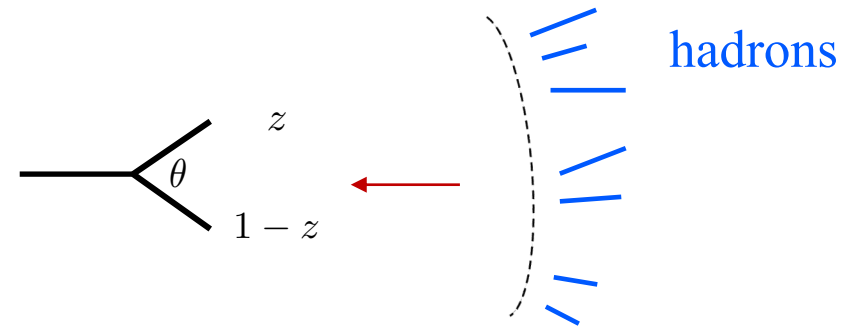
No current theories capture full complexity

Improved phenomenology

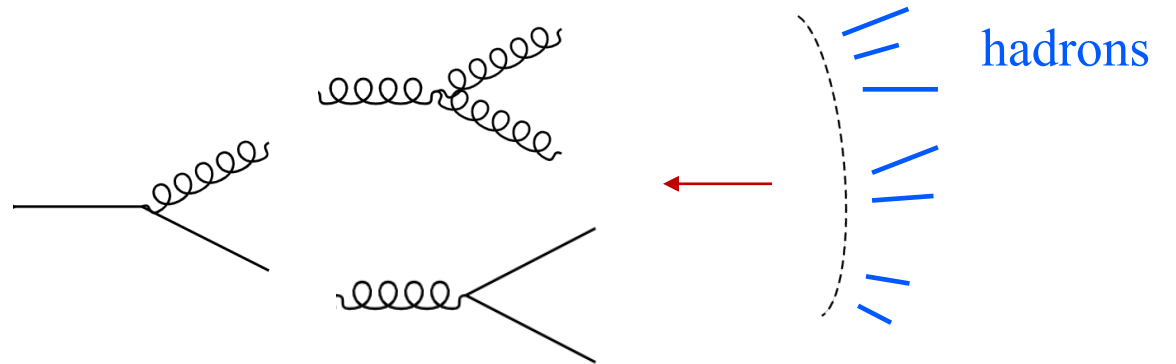
- Deconstructing a jet to access individual splittings

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

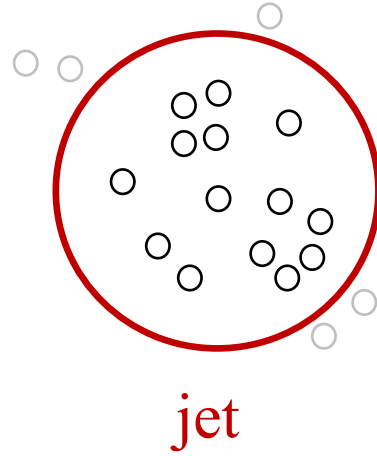
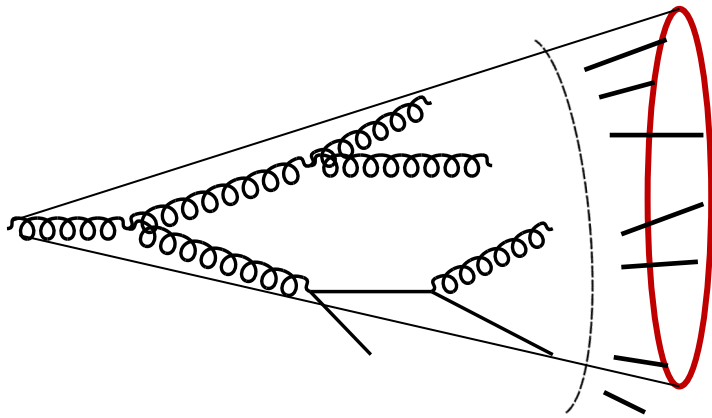
- **Hadrons to splittings**



- **Flavor-dependence of splittings**

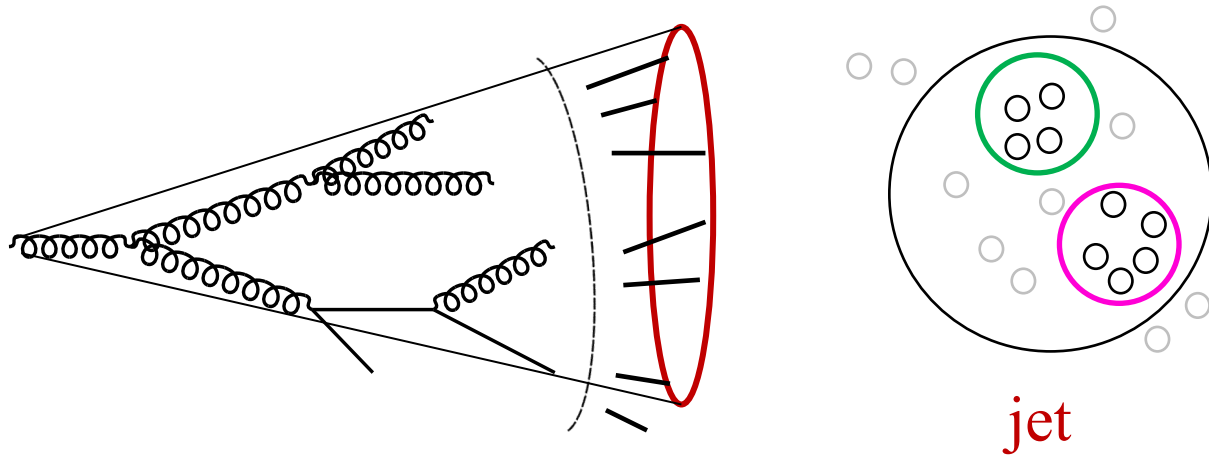


Accessing splitting functions from jet substructure



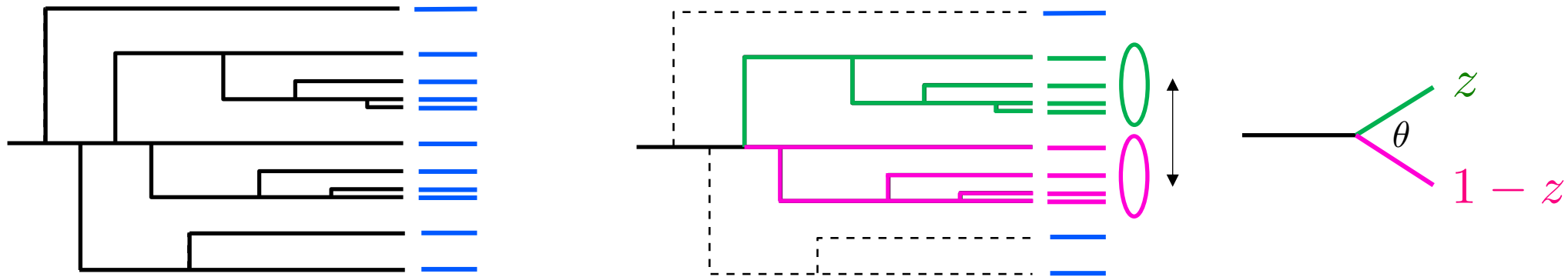
Access kinematics of gluon that initiated the shower (p_T, Q^2, \dots)

Accessing splitting functions from jet substructure

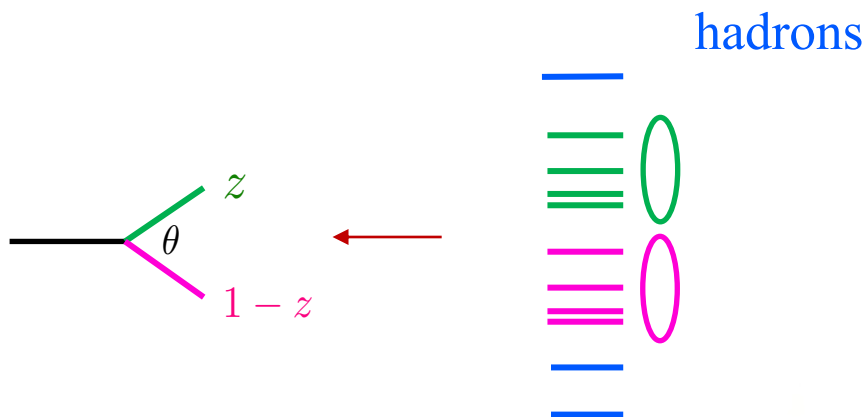


Access kinematics of gluon that initiated the shower (p_T, Q^2, \dots)

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



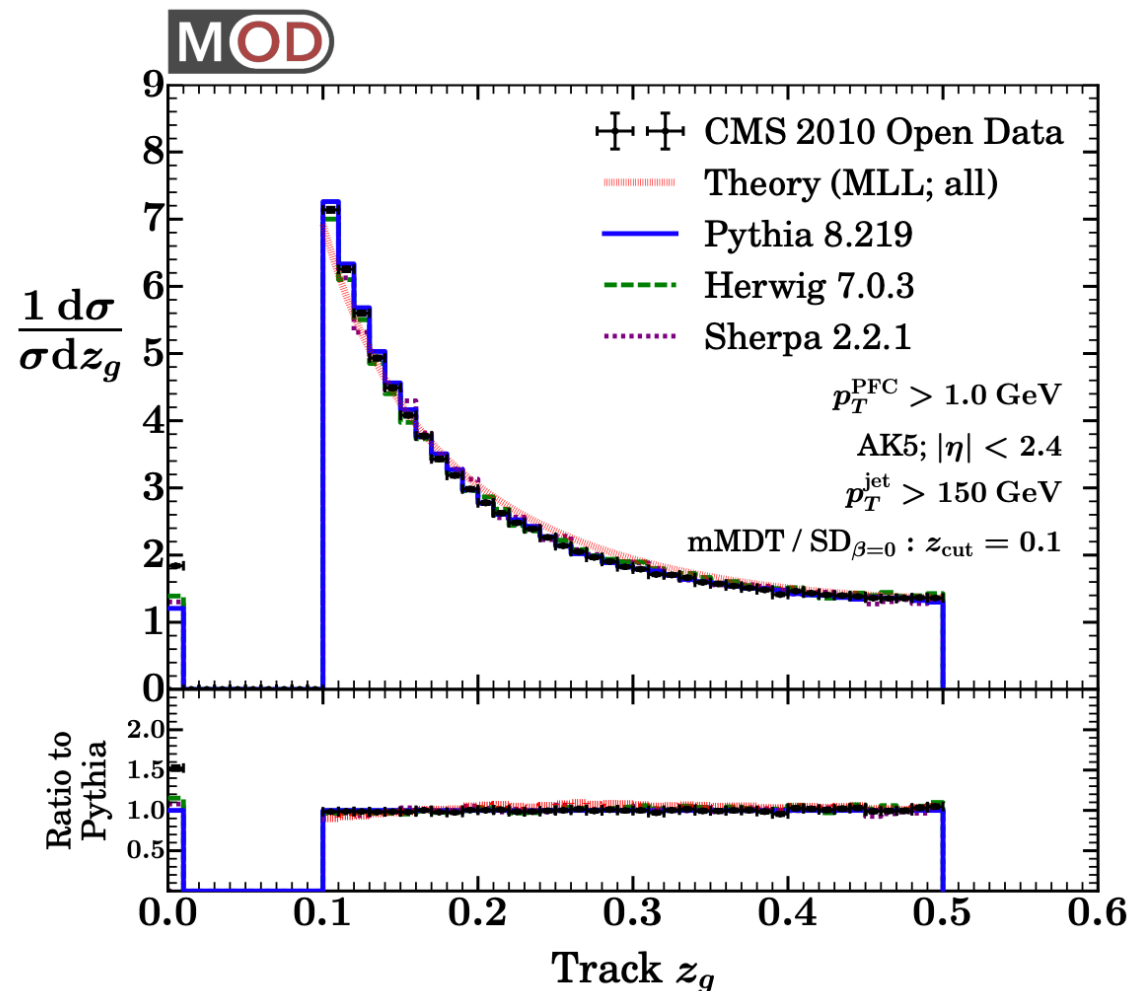
Accessing splitting functions from jet substructure



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

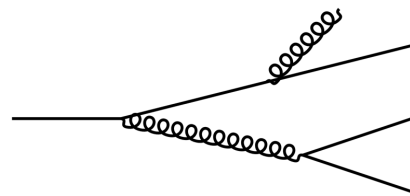
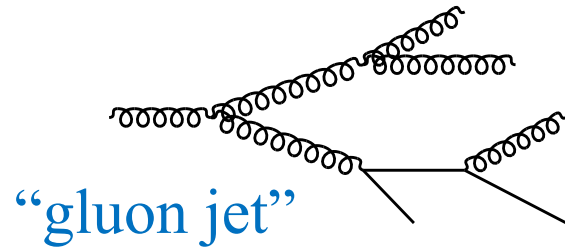
Mehtar-Tani, Soto-Ontoso, Tywoniuk [1911.00375];
 Caucal, Soto-Ontoso, Takacs [2111.14768]
 (see also Apolinario, Cordeiro, Zapp [2012.02199])

QCD splitting function from jets



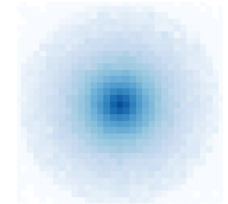
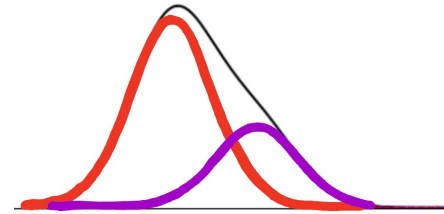
Accessing light flavor splitting functions

- In vacuum



Challenging to define beyond leading order

Banfi, Salam, Zanderighi [0601139]; Czakon, Mitov, Poncelet [2205.11879]; Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler [2306.07314]

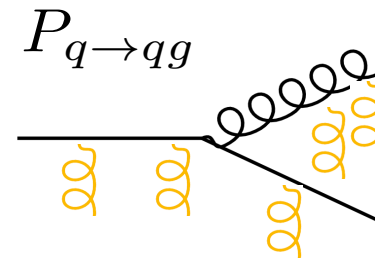
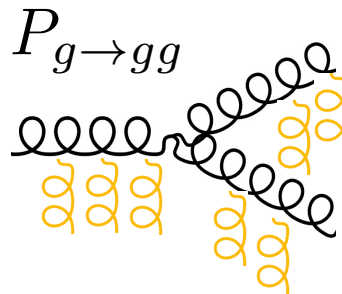


Observable-based, machine learning approaches

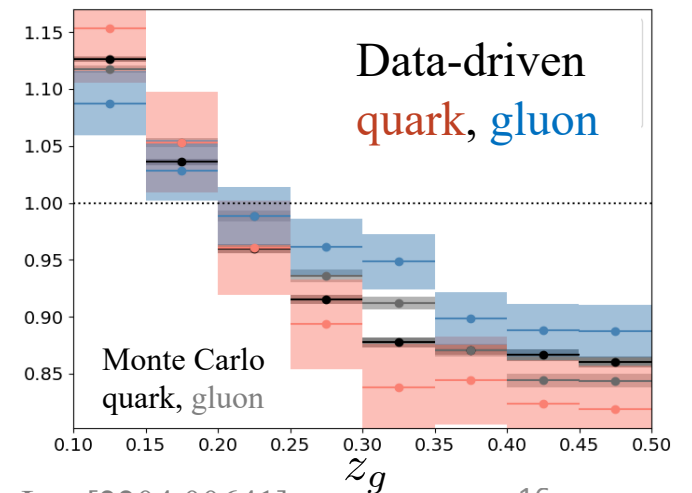
Thaler, Metodiev, Komiske, Schwartz, Dreyer, Soyez, Takacs, Larkoski, ...

- In medium

Flavor-dependent modification

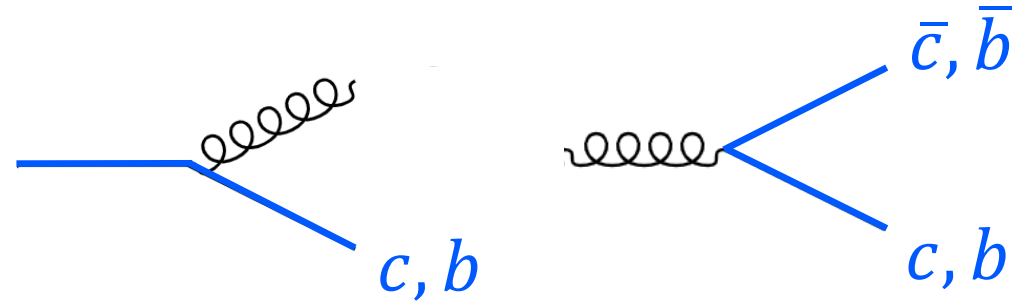


Modified q,g splitting functions



Accessing heavy flavor splitting functions

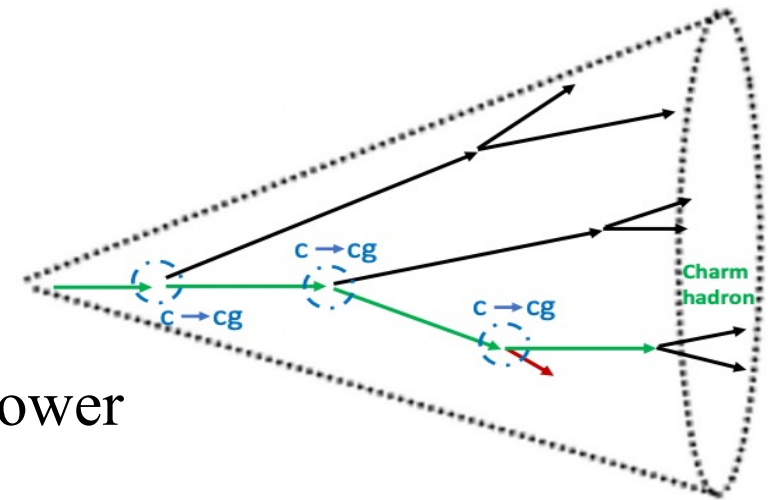
Heavy flavor splittings:



Advantages:

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

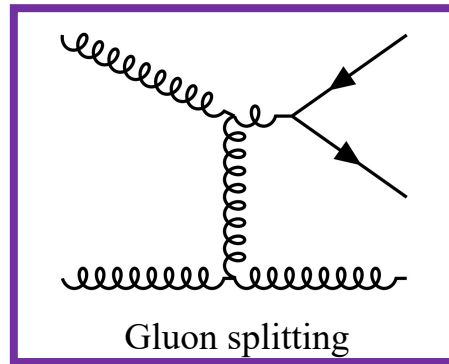
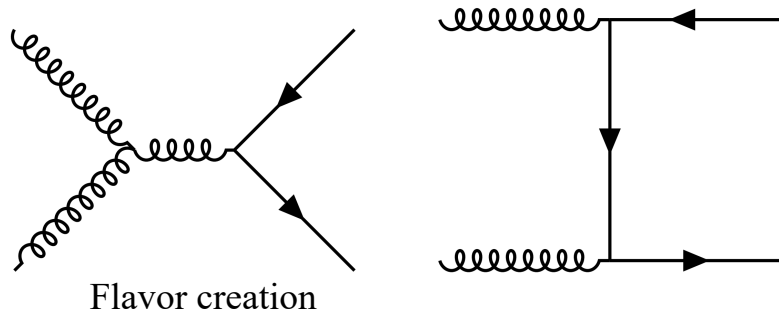
Used in ALICE [2106.05713]



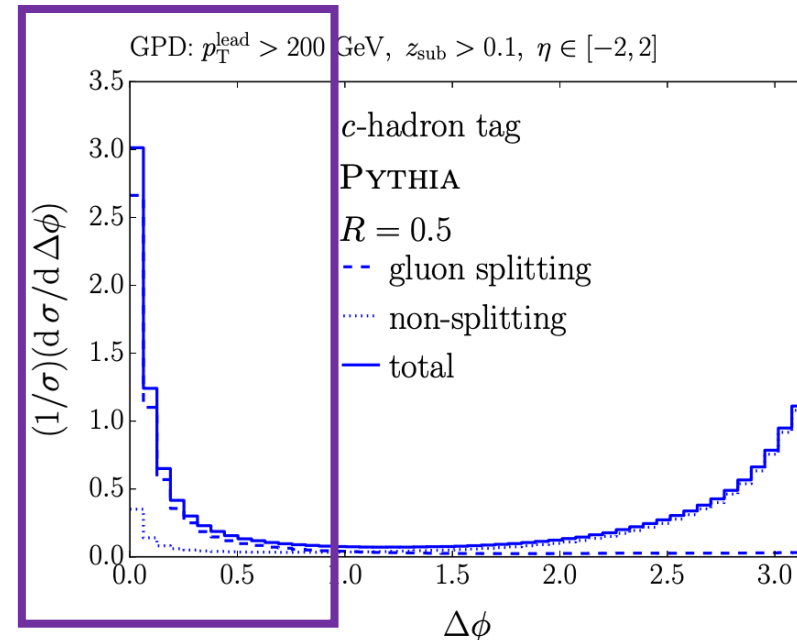
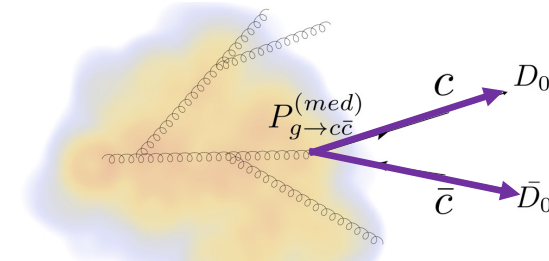
Focus of this talk: phenomenology of $g \rightarrow c\bar{c}$

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

Leading processes for heavy quark production



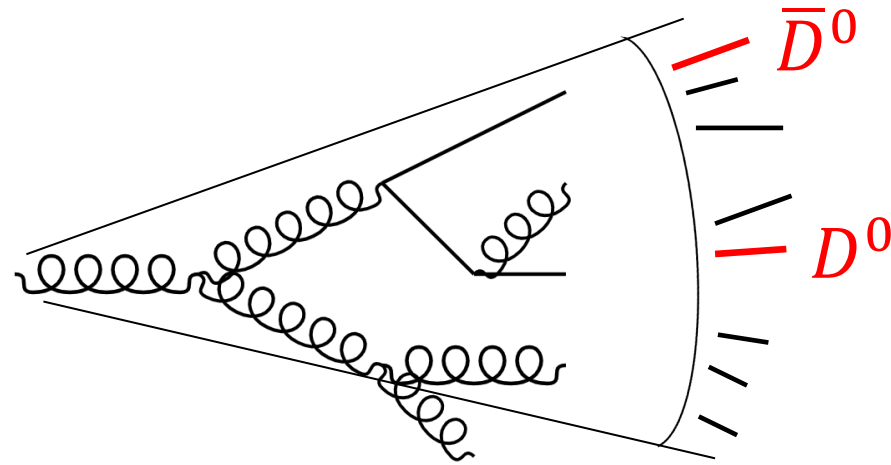
(approximately) collinear



Gluon splitting

Non-gluon-splitting

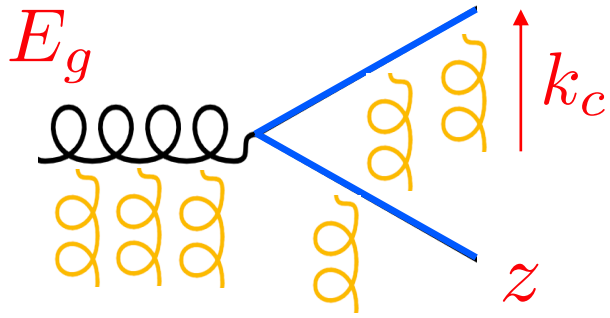
Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets



Sample of showers including $g \rightarrow c\bar{c}$
splitting with high purity

Expected experimental sensitivity already in Run 3/4

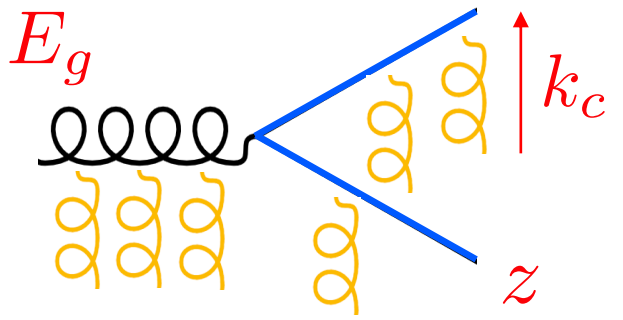
Modification of the $g \rightarrow c\bar{c}$ splitting function



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

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

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


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

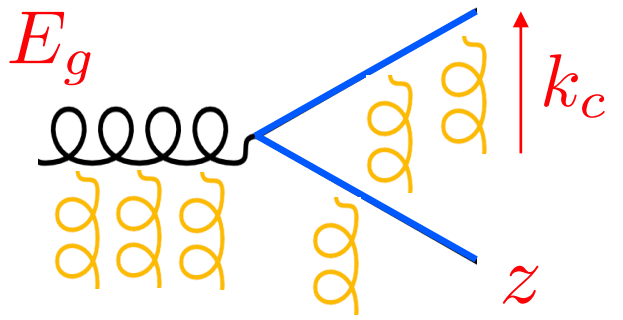
Resum arbitrarily-many soft gluon interactions with a medium of length L

Results of the calculation:

- Depletion at small k_c^2

broadening

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



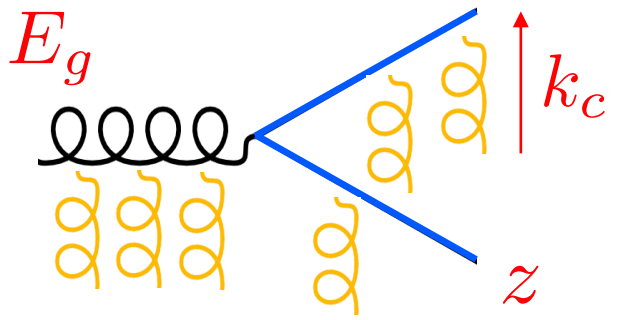
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Resum arbitrarily-many soft gluon interactions with a medium of length L

Results of the calculation:

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

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



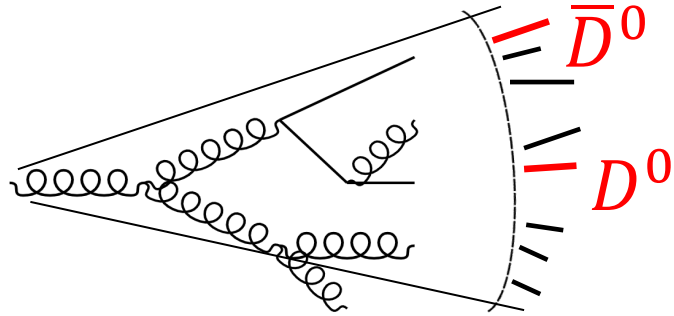
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Resum arbitrarily-many soft gluon interactions with a medium of length L

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

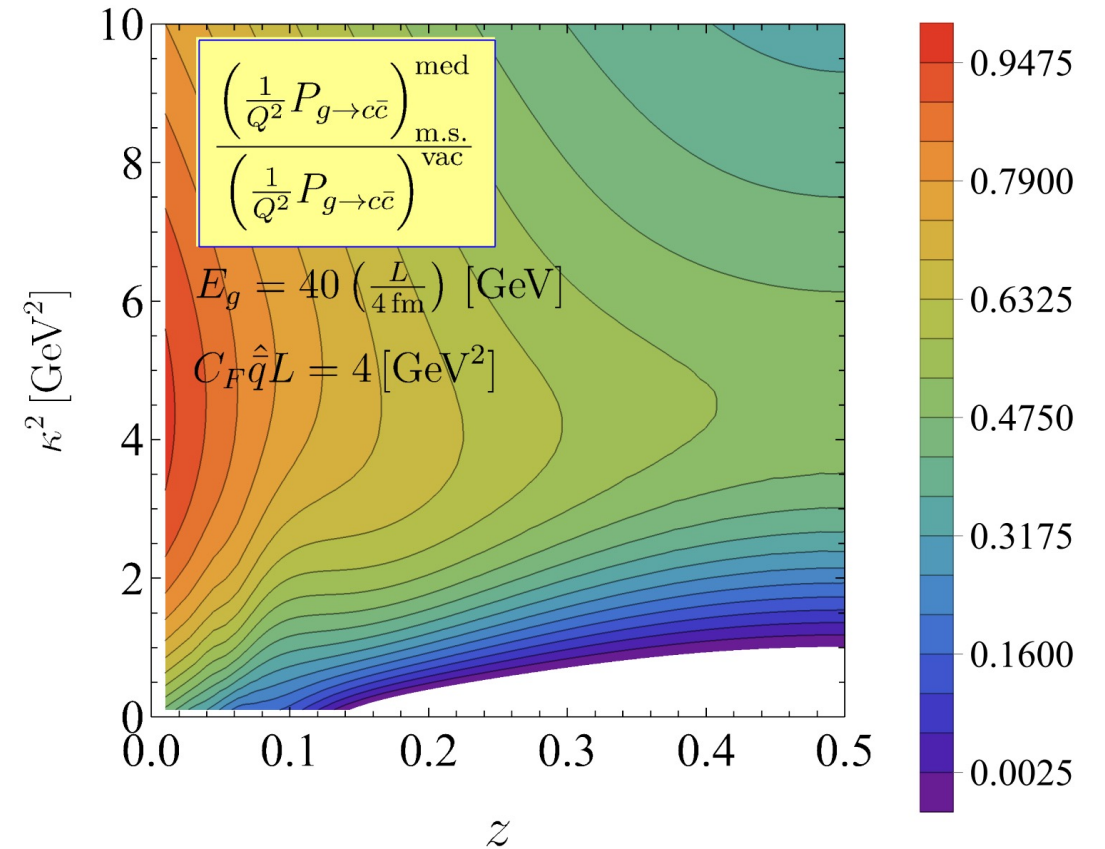
Observing $g \rightarrow c\bar{c}$ enhancement in jets



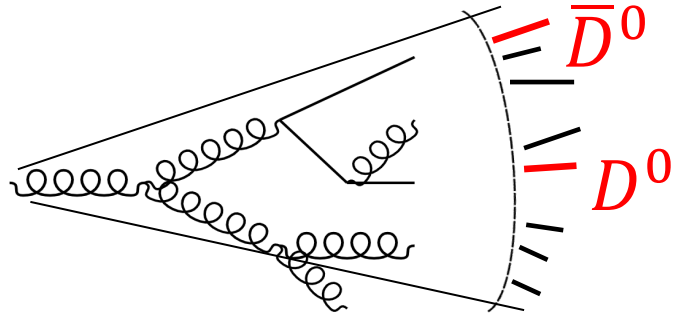
Get kinematics of $g \rightarrow c\bar{c}$

Reweight each splitting by

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



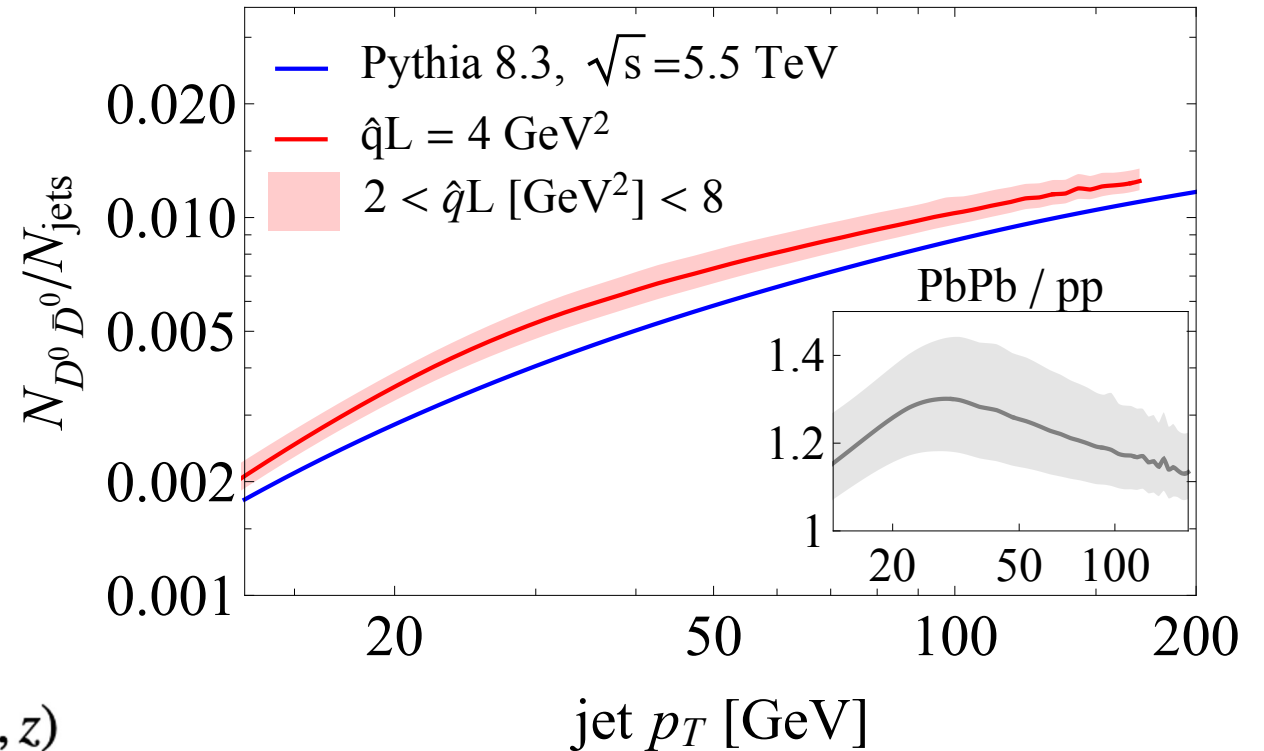
Observing $g \rightarrow c\bar{c}$ enhancement in jets



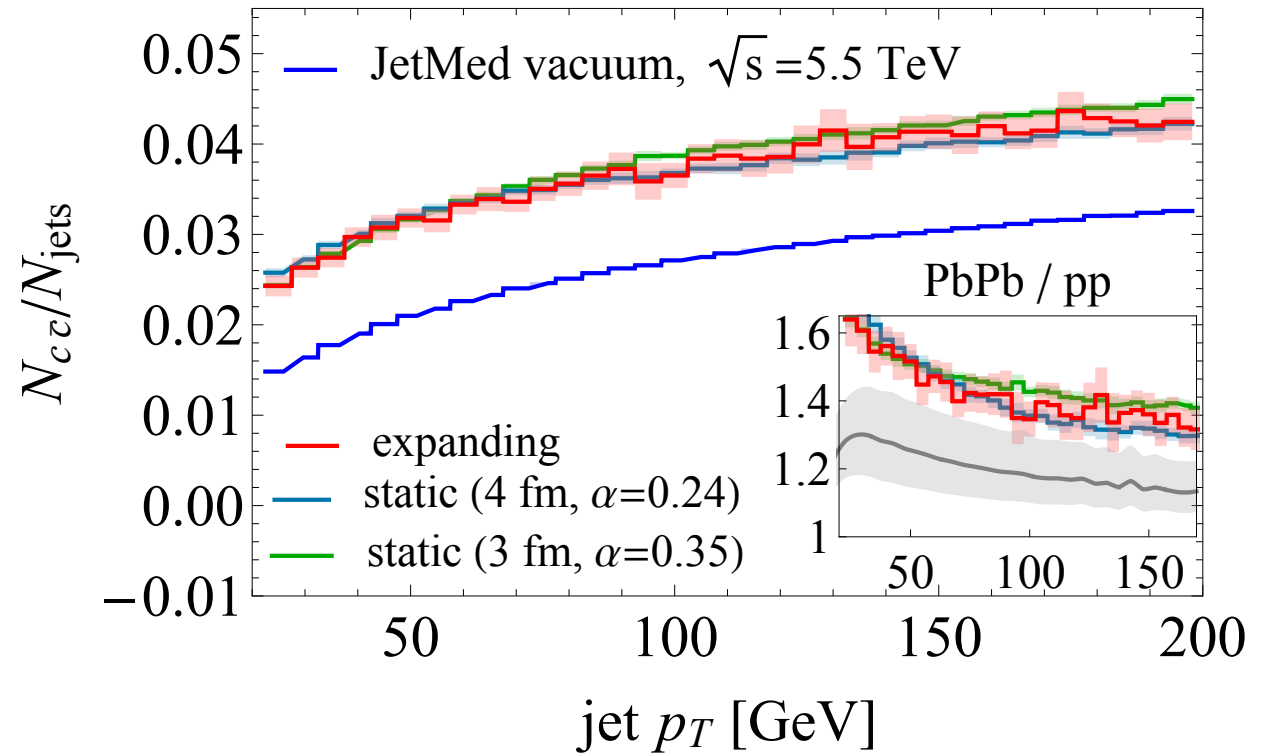
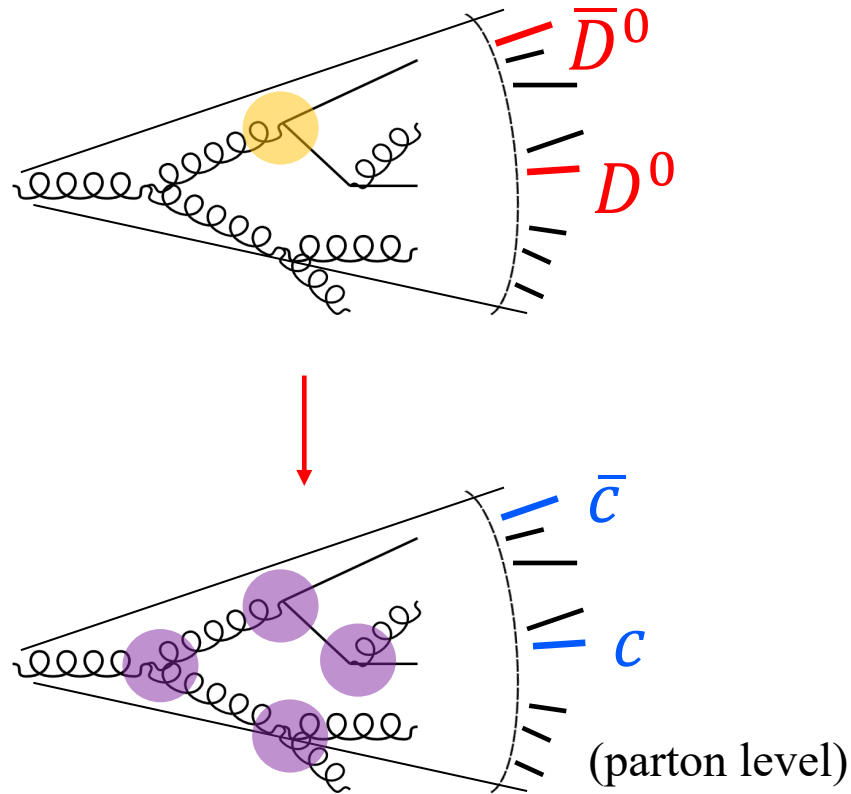
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$g \rightarrow c\bar{c}$ enhancement in state-of-the-art Monte Carlo simulations



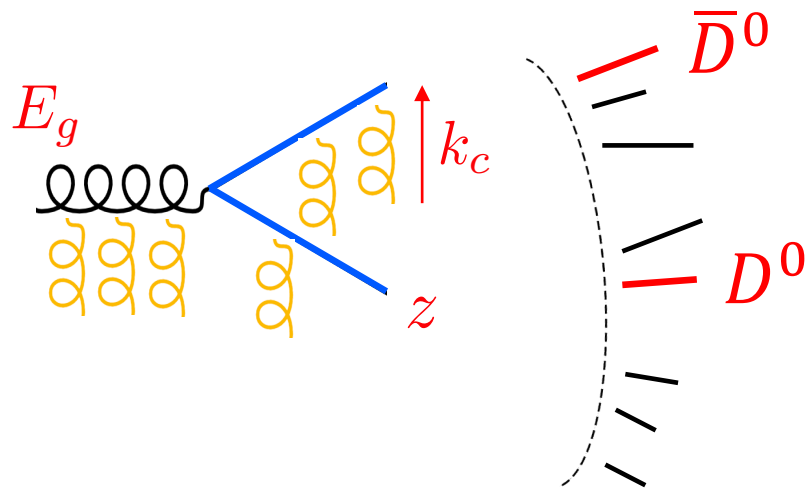
w/ Gregory Soyez

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

Caucal, Iancu, Soyez
[1907.04866]

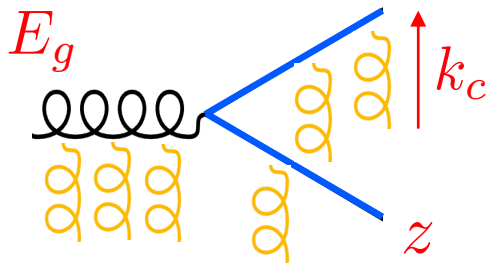
Beyond enhancement: unique phenomenology of $g \rightarrow c\bar{c}$ splittings

A uniquely clean phenomenological signature of medium modification

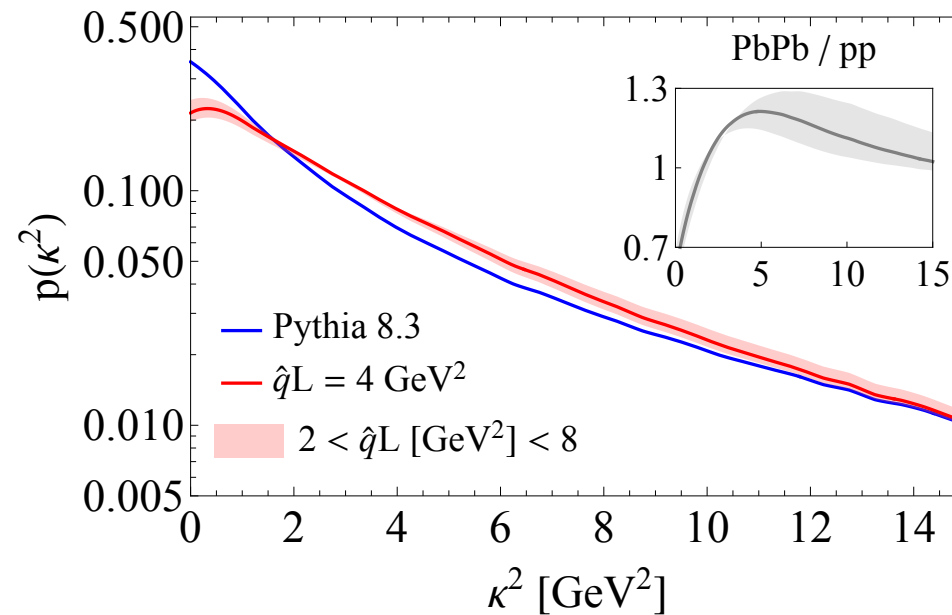


- Isolate individual type of splitting (not quark and gluon mixture) at any stage of the shower
- Splitting can be identified at hadron level from D and \bar{D} in reclustering history
- Splitting kinematics from reclustering history

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

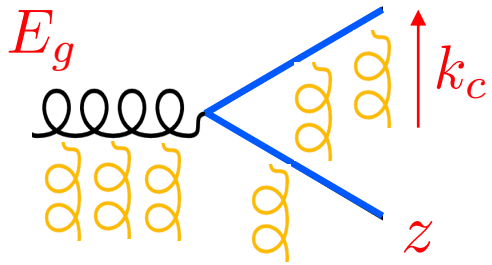


- **Broadening:** momentum broadening of $c\bar{c}$ pair



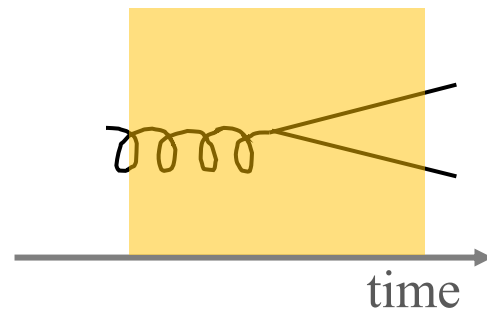
Can use jet substructure to access broadening at hadron-level

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

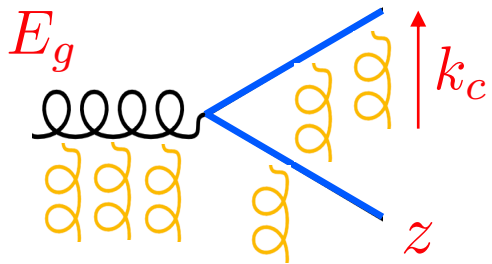


- Formation time dependence of broadening

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



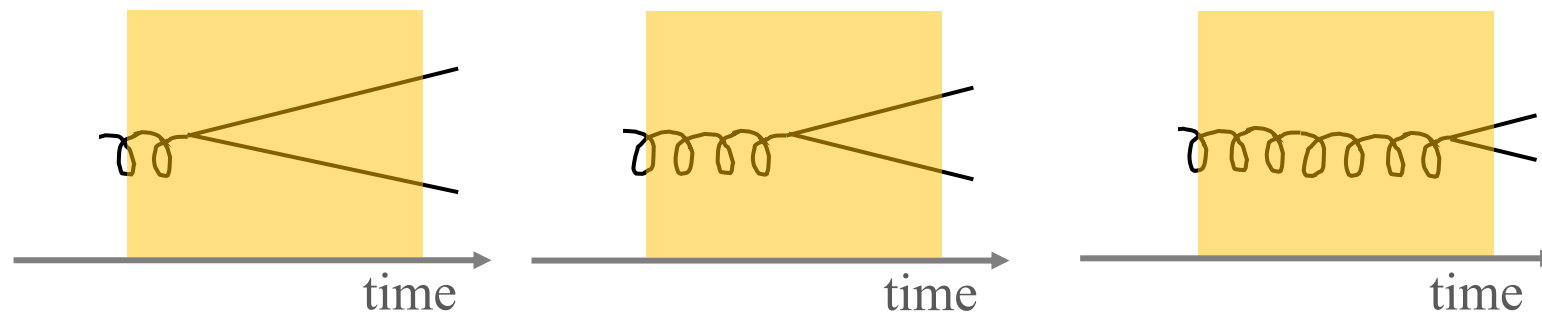
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- Formation time dependence of broadening

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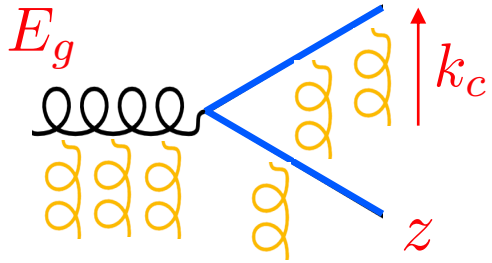
- Access modification of $c\bar{c}$ pair at later times in the QGP



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

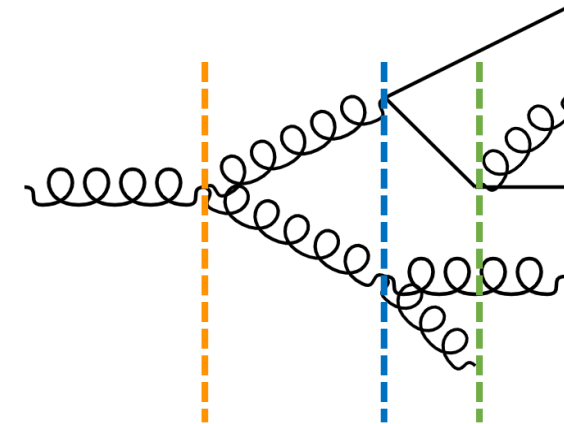
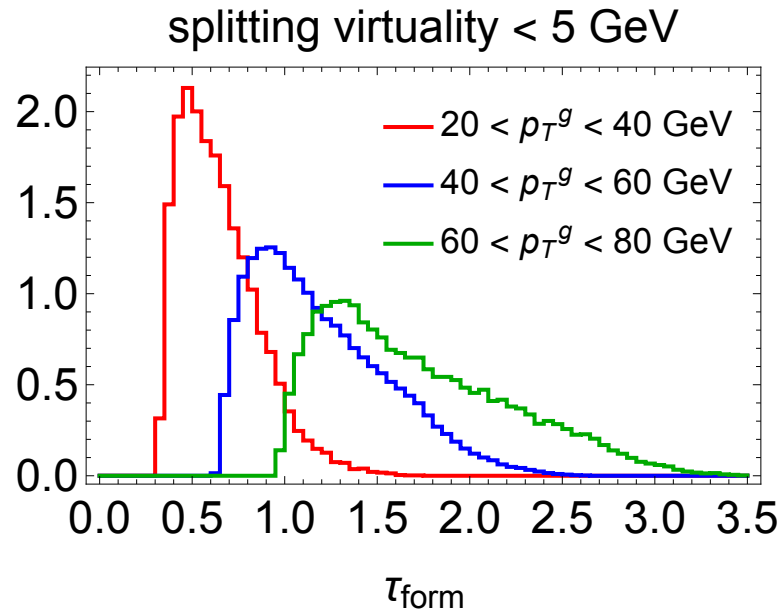
—————> Increasing gluon energy

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 $\tau_f \sim \frac{2E_g}{Q^2}$

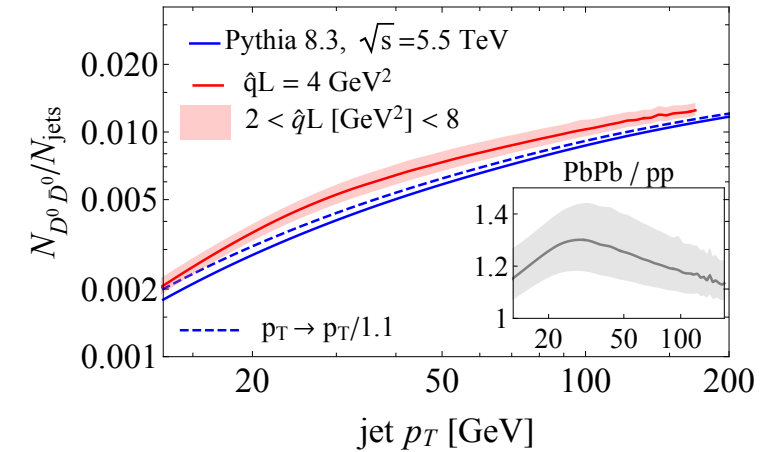


Level 0 1 2 ...

A process with many exciting future avenues!

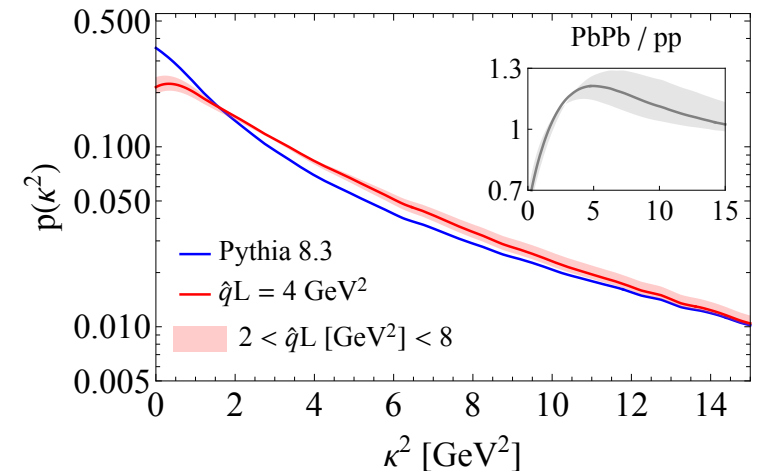
So far..

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



Outlook

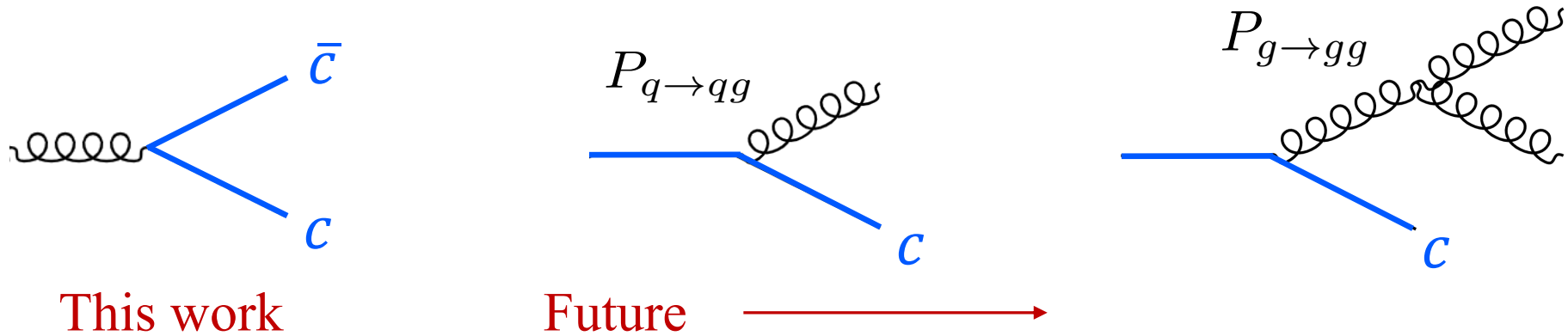
- Broadening of $c\bar{c}$ pair from hadron level
- Formation time dependence of modification



Clean process with a lot of exciting physics opportunities!

Outlook

Phenomenology of heavy-flavor tagged jets



Constructing a picture of modified jets from phenomenology

