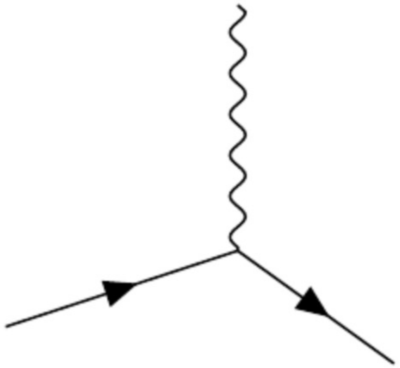
Medium-modification of $c\bar{c}$ pairs in jets

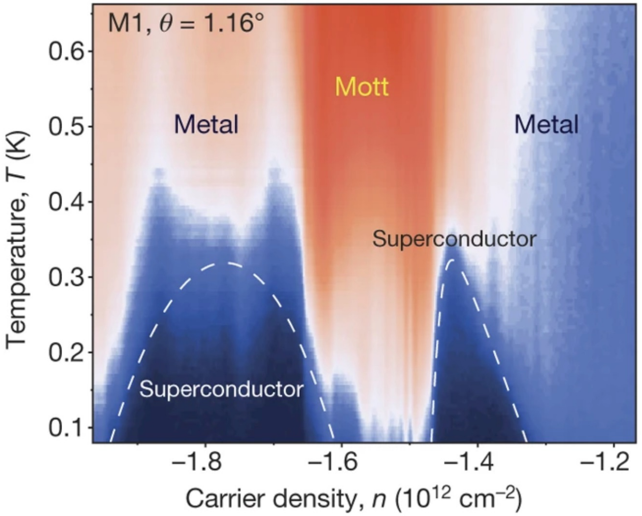
Jasmine Brewer

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

Based on [2203.11241, 2209.13600] and ongoing work

QED

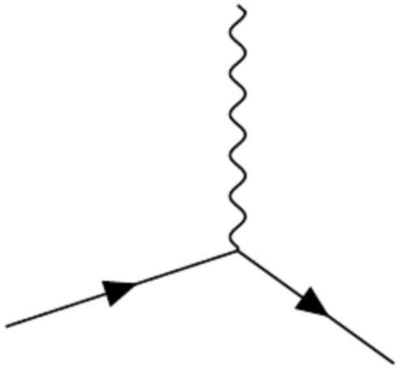


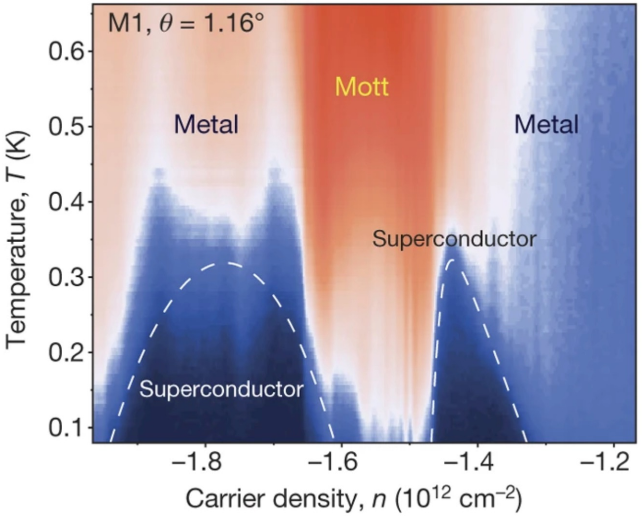


Magic angle graphene

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

QED





Magic angle graphene

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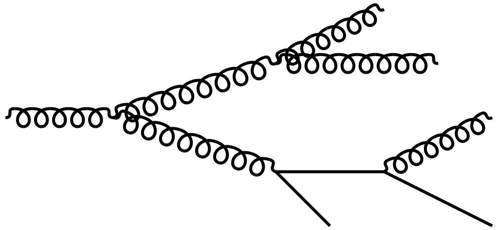
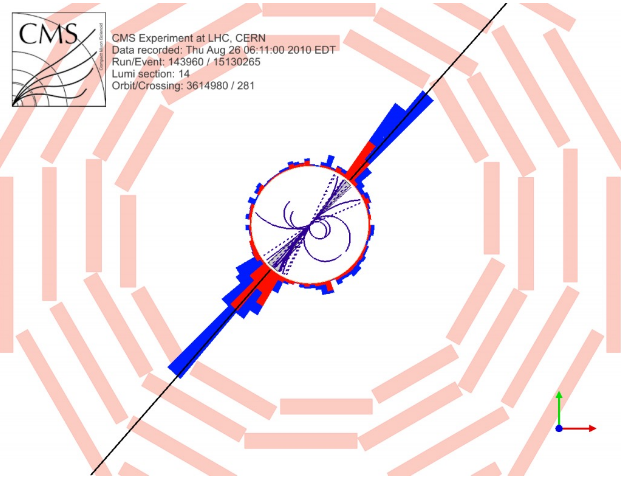
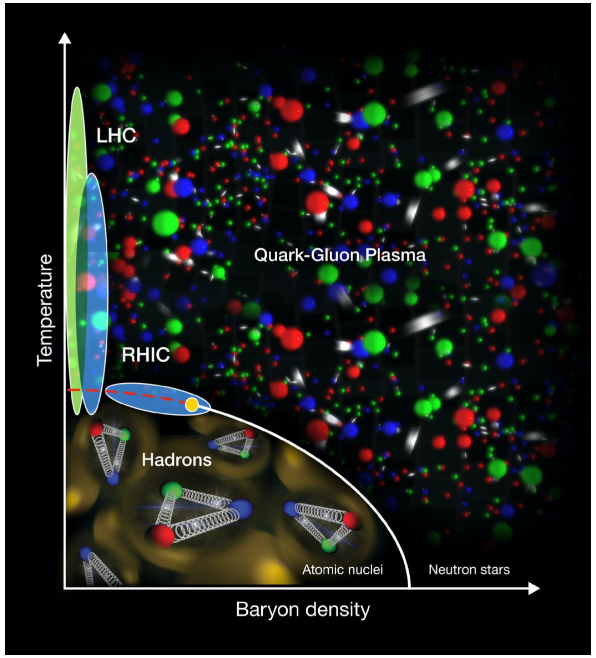
QCD

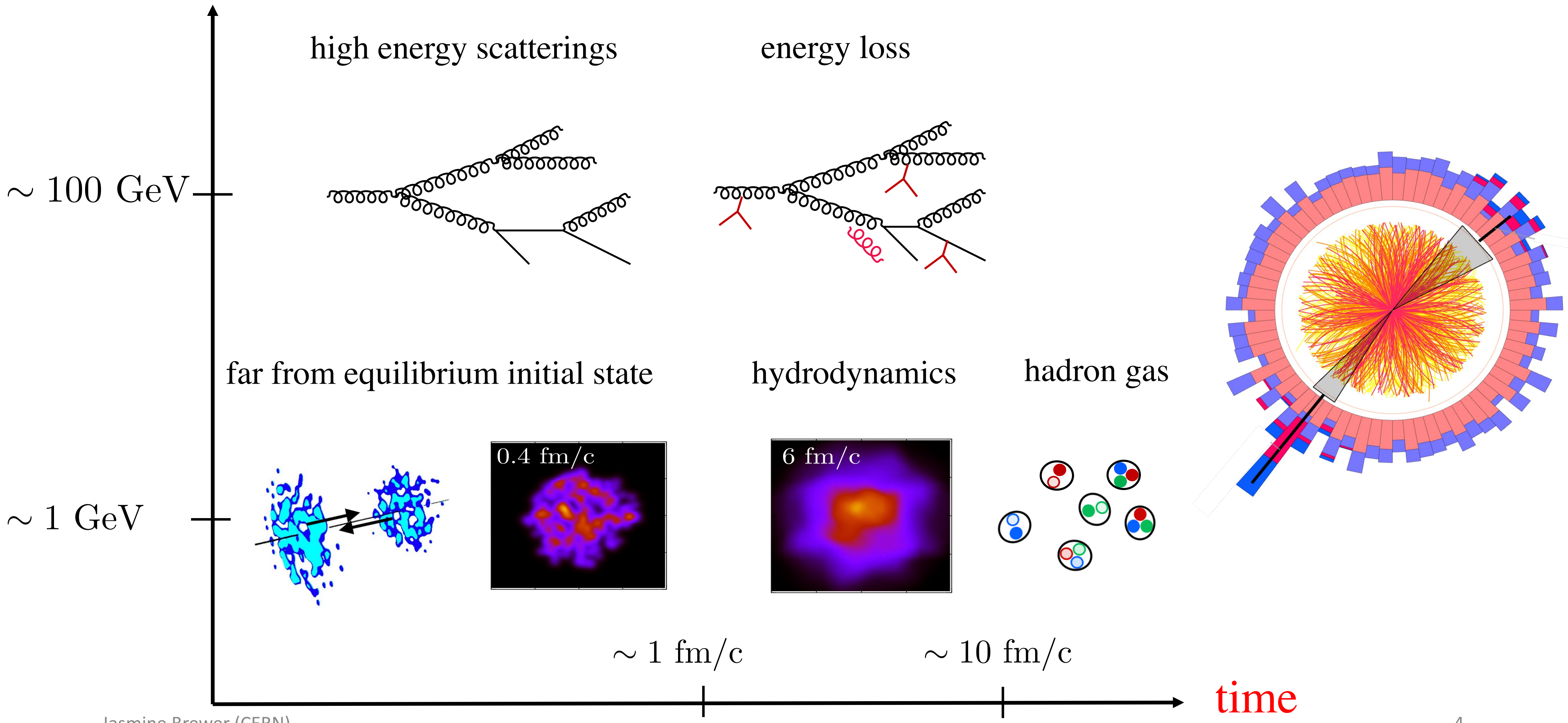






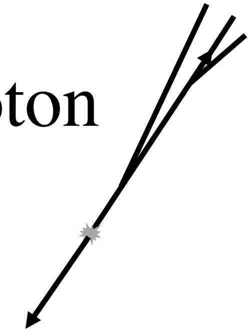
Understanding the fundamental interactions is just the beginning!

Heavy-ion collisions

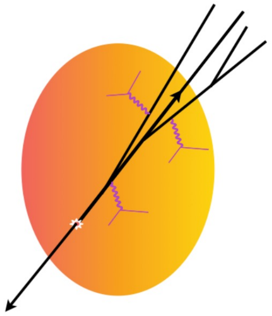


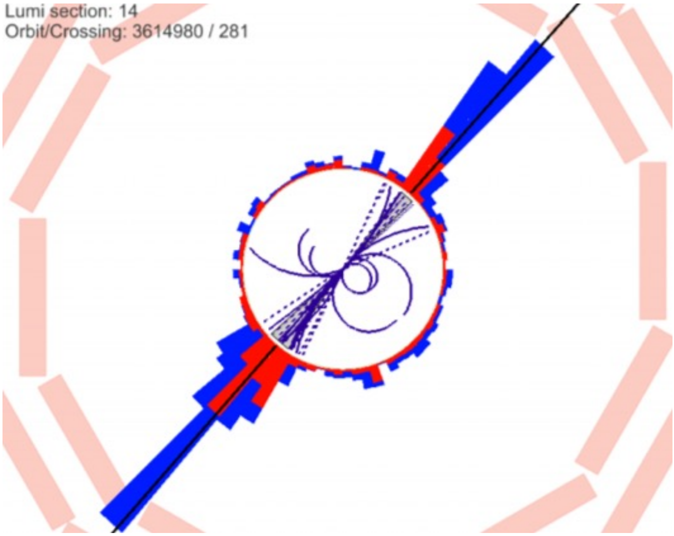
Modification of jets as a probe of quark-gluon plasma

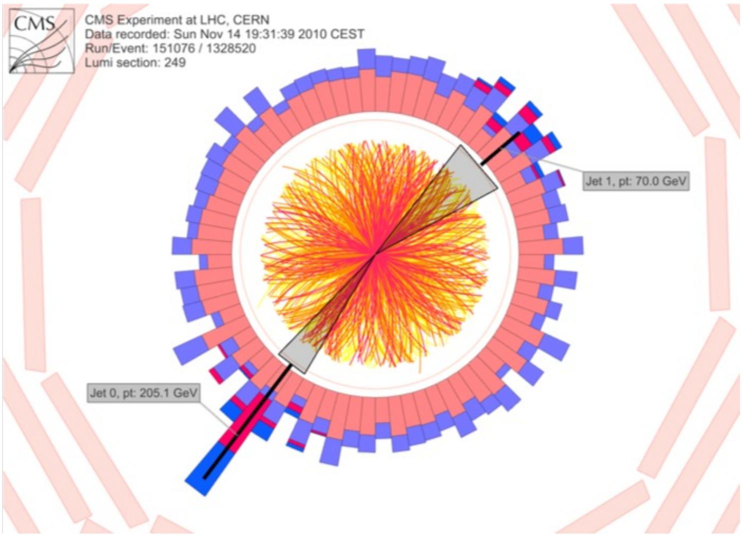
proton–proton



heavy-ion

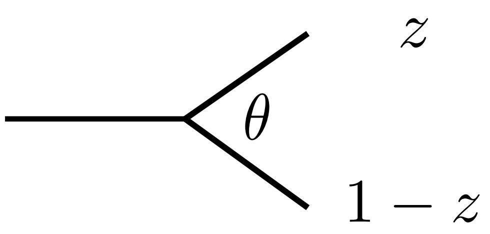






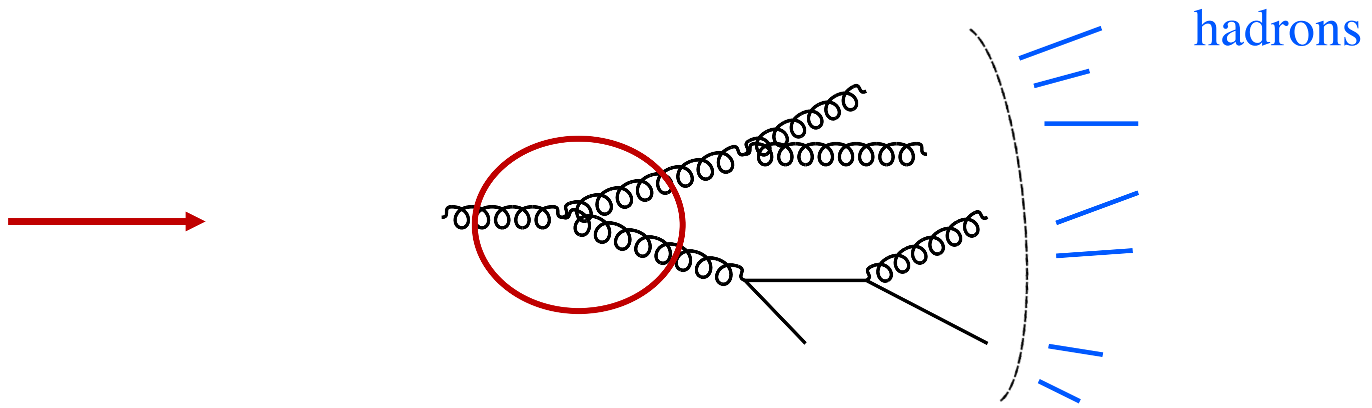
“baseline” jet properties

Successive QCD splittings form jets in vacuum

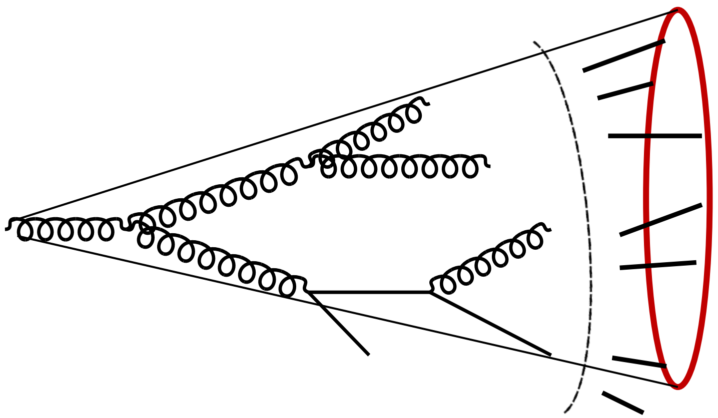


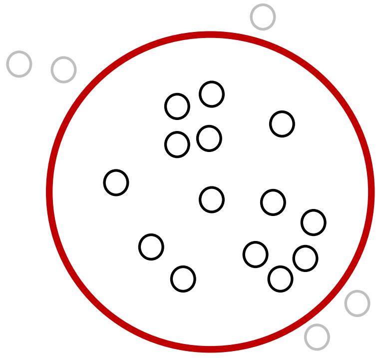
$$\mathrm{d}P_{i\to jk} = \frac{\mathrm{d}\theta}{\theta}\mathrm{d}z\, P_{i\to jk}(z)$$

Splitting functions



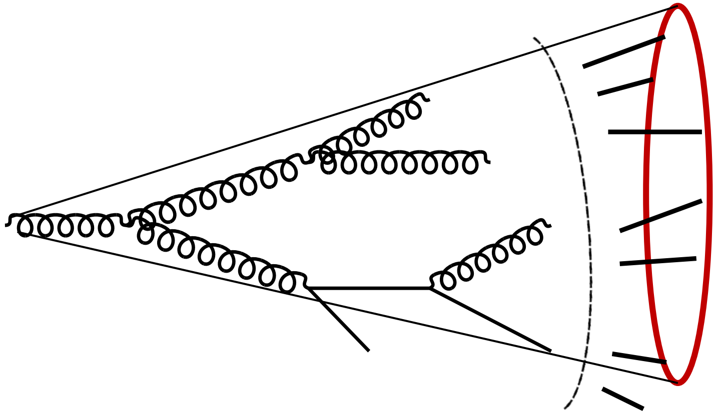
Accessing splitting functions from jet substructure

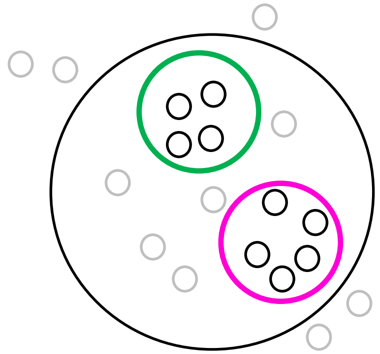




Access kinematics of gluon that initiated the shower $(p_T, Q^2, \ldots)$

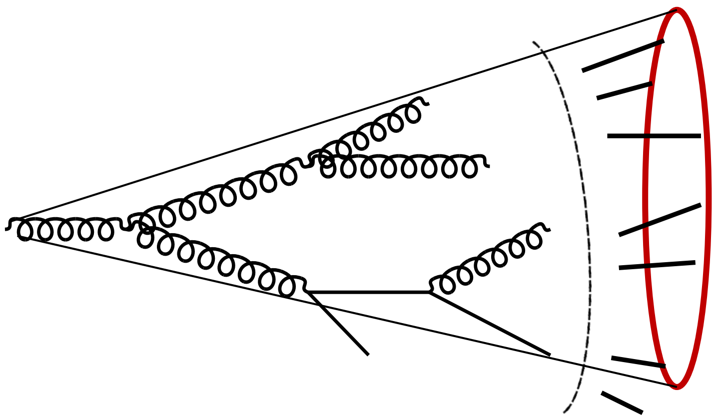
Accessing splitting functions from jet substructure

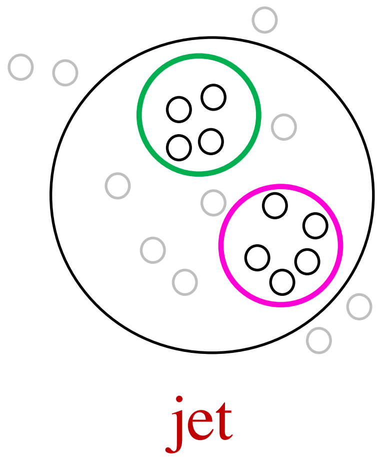




Access kinematics of gluon that initiated the shower (p_T, Q^2,…)

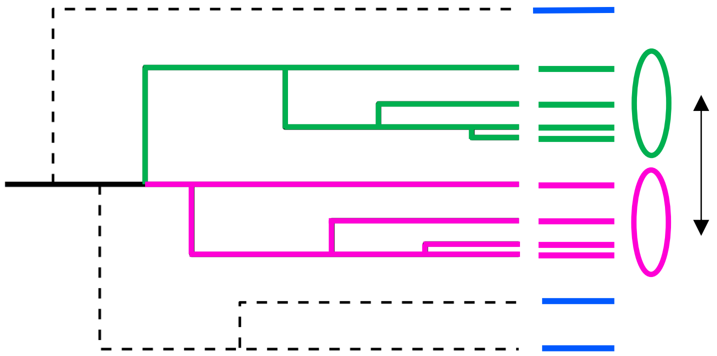
Accessing splitting functions from jet substructure

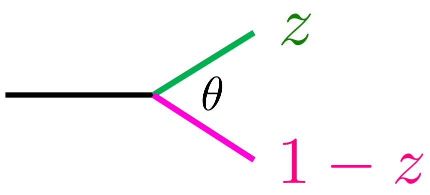




Access kinematics of gluon that initiated the shower (p_T, Q^2,…)

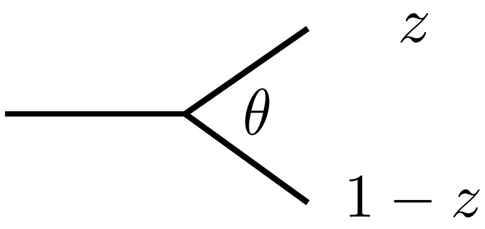
Use angular ordering of QCD to reconstruct emission history of shower from hadron level





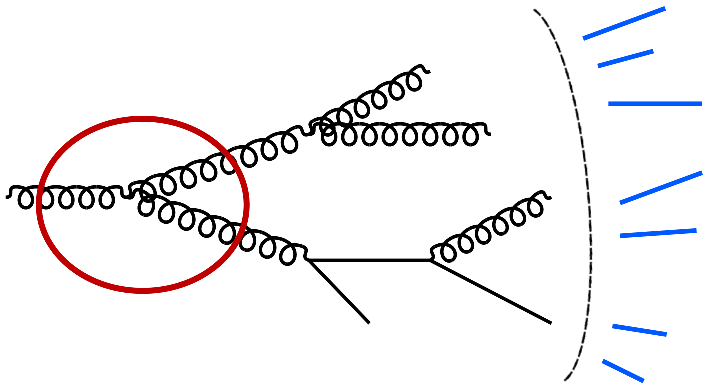
Access kinematics of splittings from jet substructure

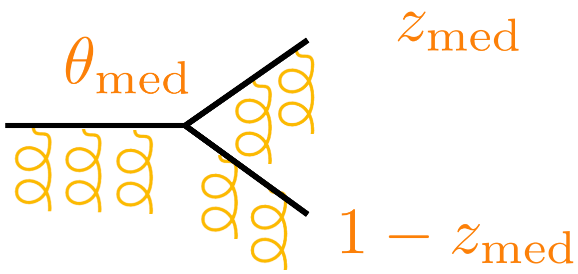
Successive QCD splittings form jets in vacuum



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

Splitting functions

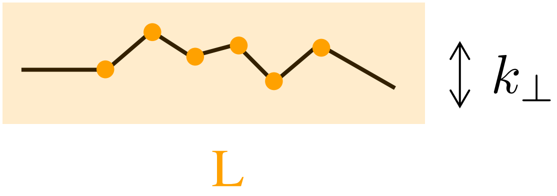




Modification of splitting functions important probe of medium

Partons and splittings in finite-temperature QCD

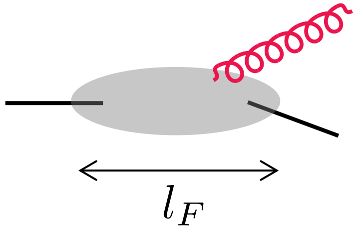
Parton undergoes transverse momentum diffusion



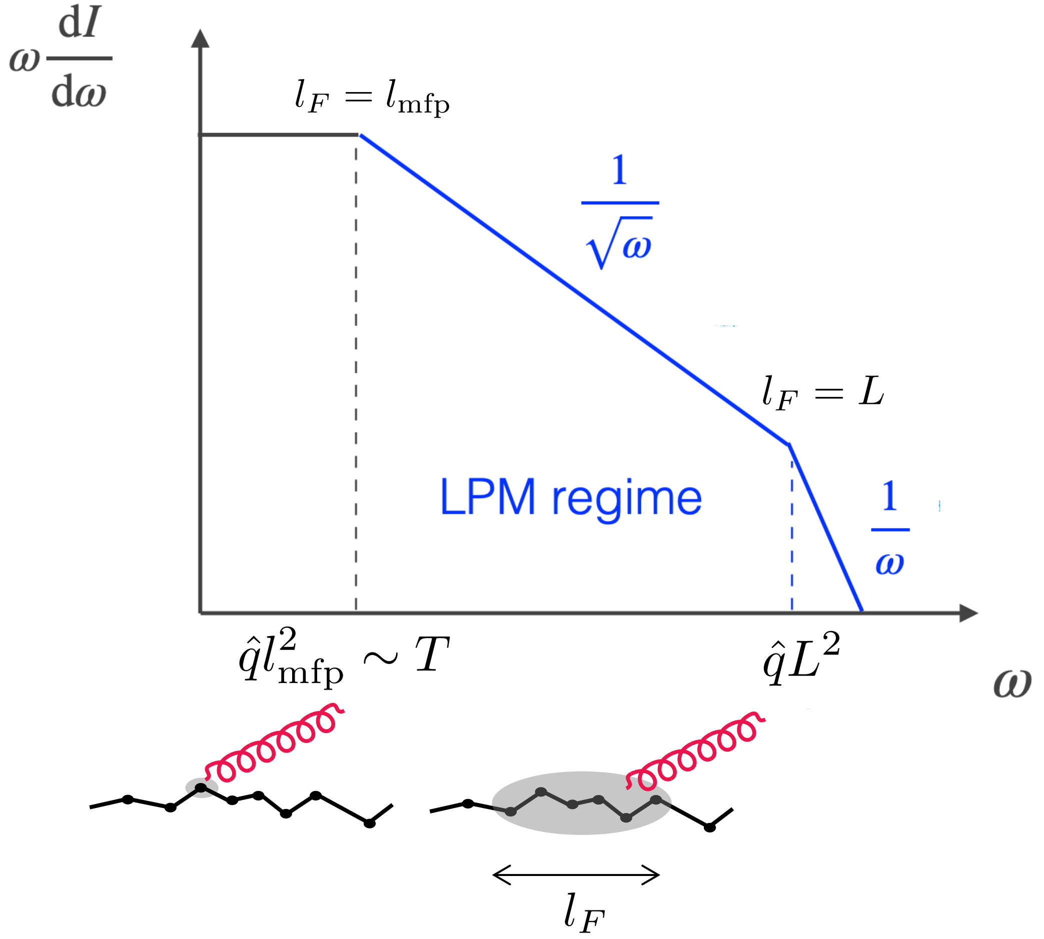
$$\hat{q} \equiv \frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t}$$

Kicks occasionally induce gluon radiation

Radiation can’t be resolved instantaneously



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

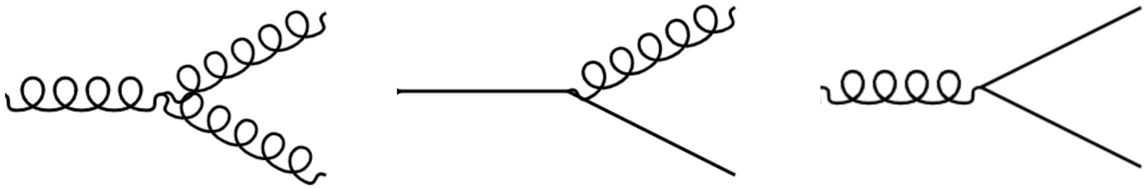


Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1996)
Arnold, Moore, Yaffe (2003)

Fig: adapted from Yacine Mehtar-Tani QM’19

Accessing modification of light flavor splitting functions

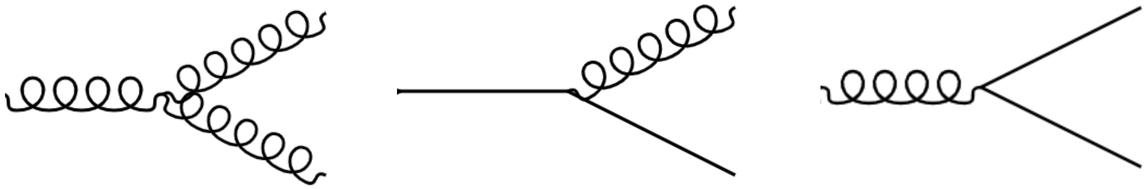
Light flavor splittings:



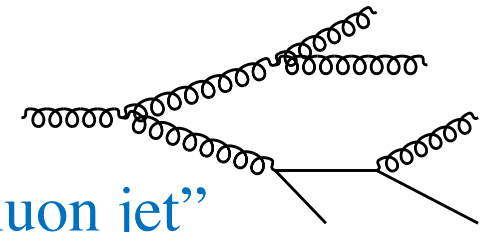
Jets are mixture of light flavor splittings.

Accessing modification of light flavor splitting functions

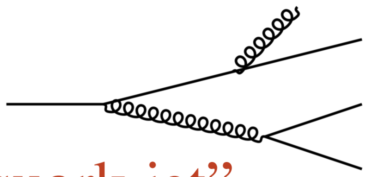
Light flavor splittings:



- Different vacuum fragmentation



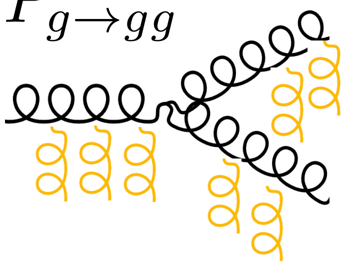
“gluon jet”



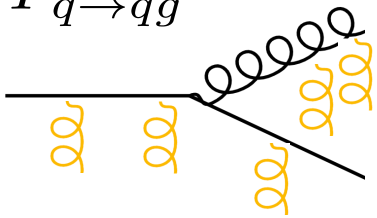
“quark jet”

- Different medium modification

$P_{g\to gg}$



$P_{q\to qg}$



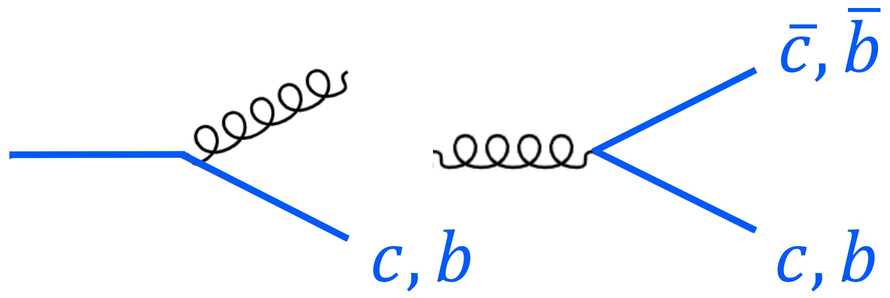
Jets are mixture of light flavor splittings.

Challenge: study their modification separately

JB, Jesse Thaler, Andrew Patrick Turner [2008.08596]; Ying, JB, Chen, Lee [2204.00641]

Accessing modification of light flavor splitting functions

Heavy flavor splittings:



Advantages:

- Follow heavy-flavor through the shower for clean access to splittings

ALICE [2106.05713]

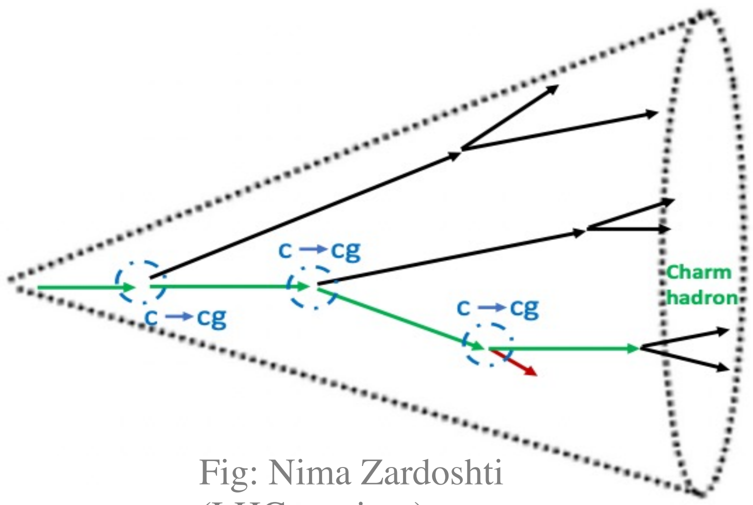


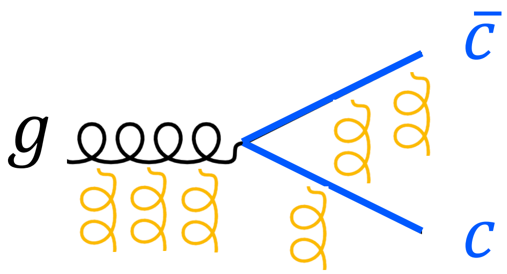
Fig: Nima Zardoshti (LHC seminar)

- At high energies, access light flavor splittings

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

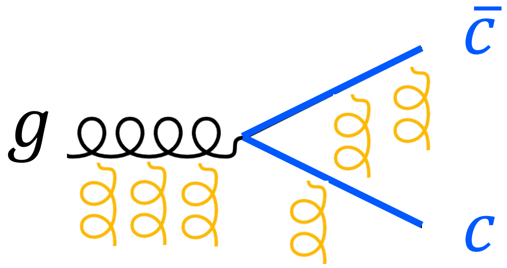
Unique features of the modification of $g \to c\bar{c}$

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

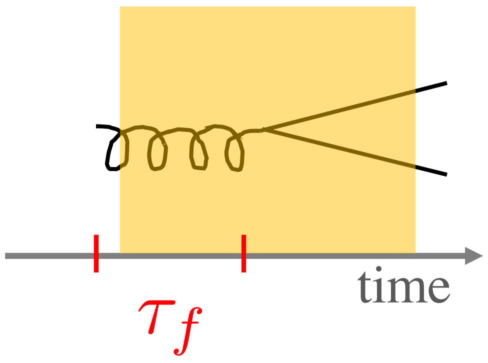


Unique features of the modification of $g \to c\bar{c}$

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



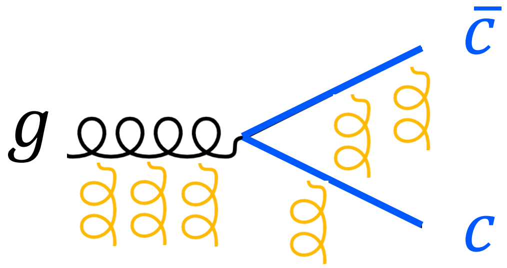
Gluons have a "lifetime" $\tau_f \sim \dfrac{2E_g}{Q^2}$ depending on their energy



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

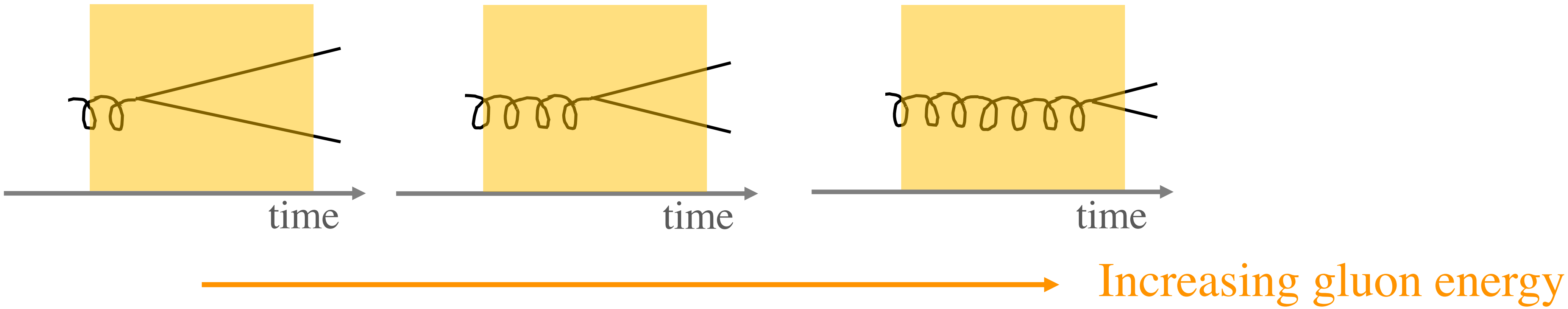
Unique features of the modification of $g \to c\bar{c}$

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



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



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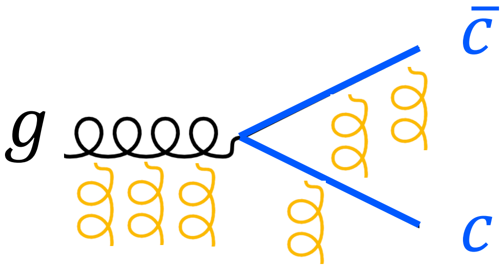
Unique features of the modification of $g \to c\bar{c}$

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



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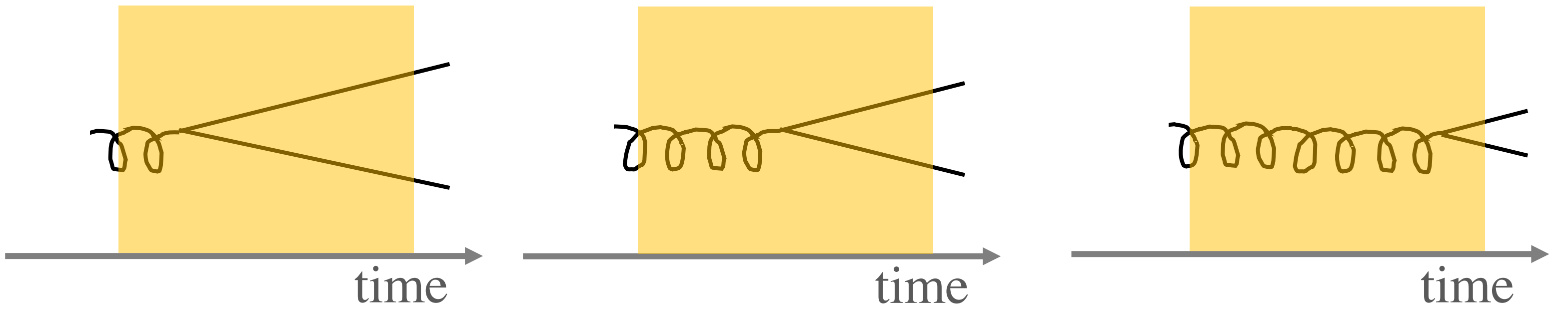
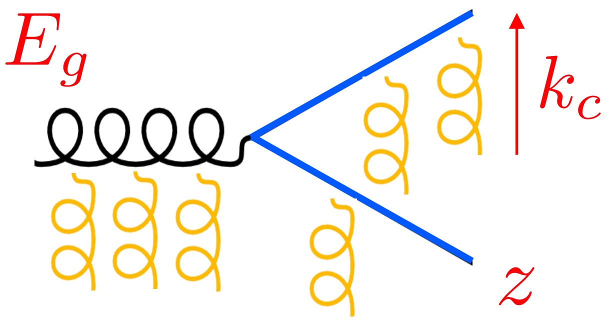


$\sim 1 - 6$ fm delay for $20 - 100$ GeV gluons

Increasing gluon energy

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

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

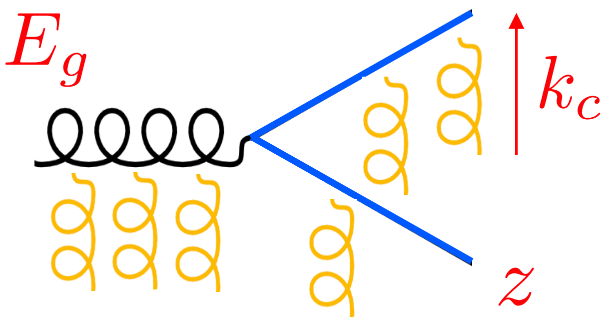


$$P_{g\to c\bar{c}}(E_g, k_c^2, z) = P^{\text{vac}}_{g\to c\bar{c}}(k_c^2, z) + P^{\text{med}}_{g\to c\bar{c}}(E_g, k_c^2, z)$$

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

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

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



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

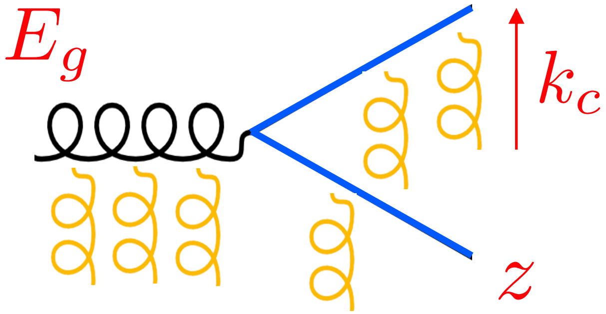
Results of the calculation:

- Depletion at small k_c^2

broadening

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

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



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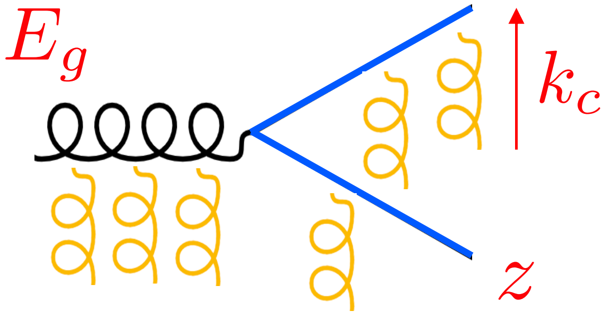
Resum arbitrarily-many soft gluon interactions with a medium of length L

Results of the calculation:

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

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

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



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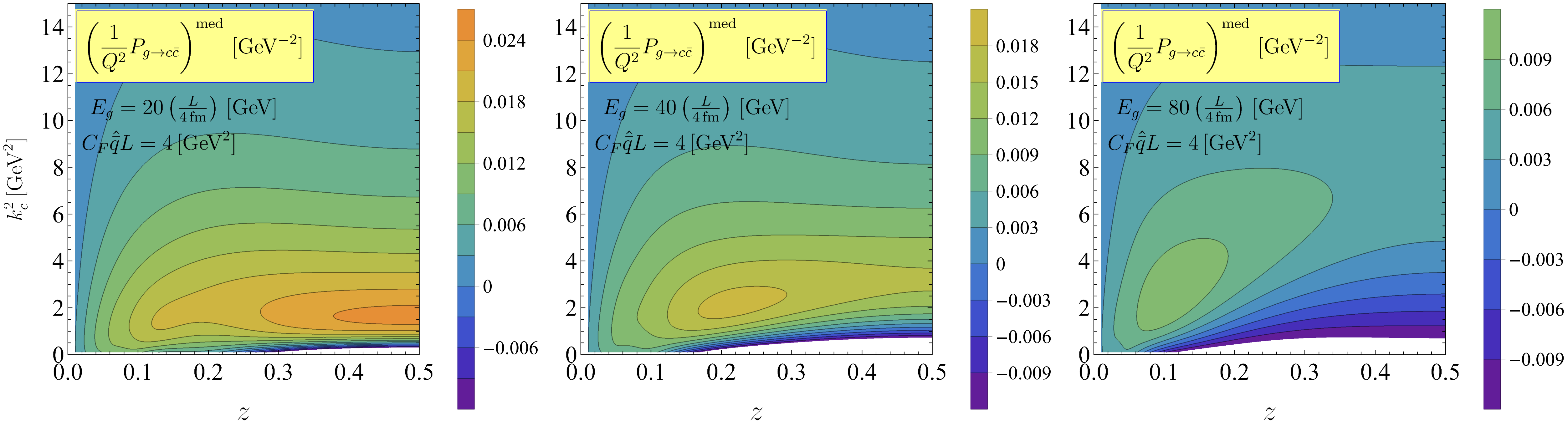
Resum arbitrarily-many soft gluon interactions with a medium of length L

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

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

Modification of the splitting function



Increasing gluon energy

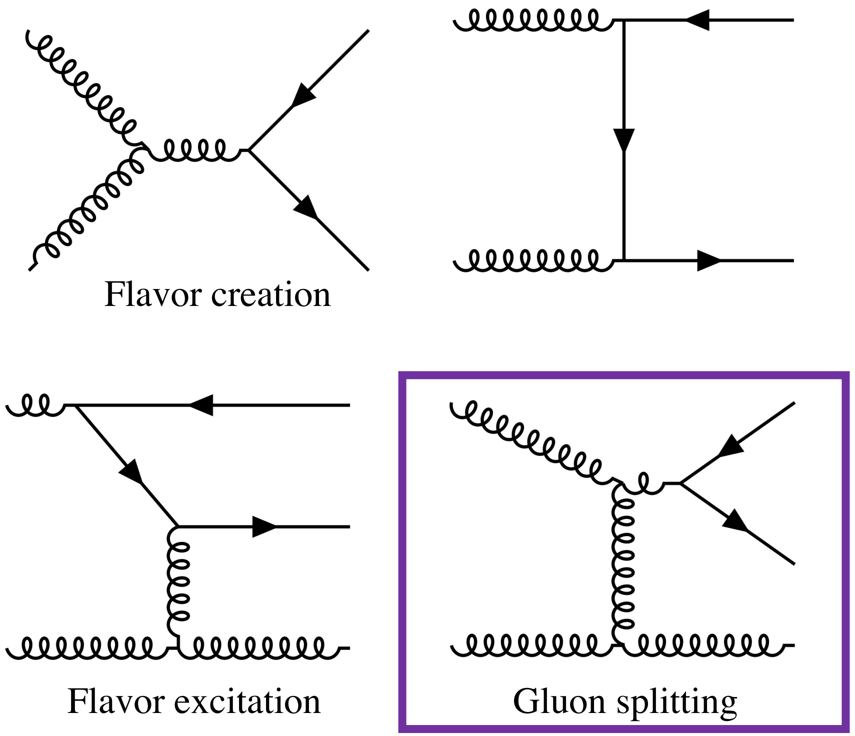
Depletion at low k_c^2

Less modification with increasing E_g

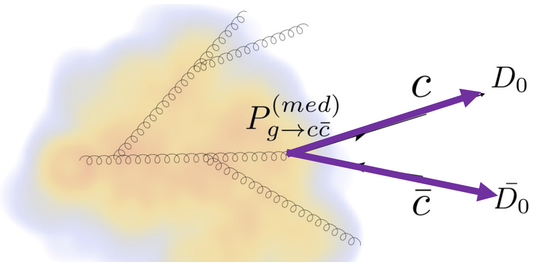
More $c\bar{c}$ pairs produced overall in the presence of medium

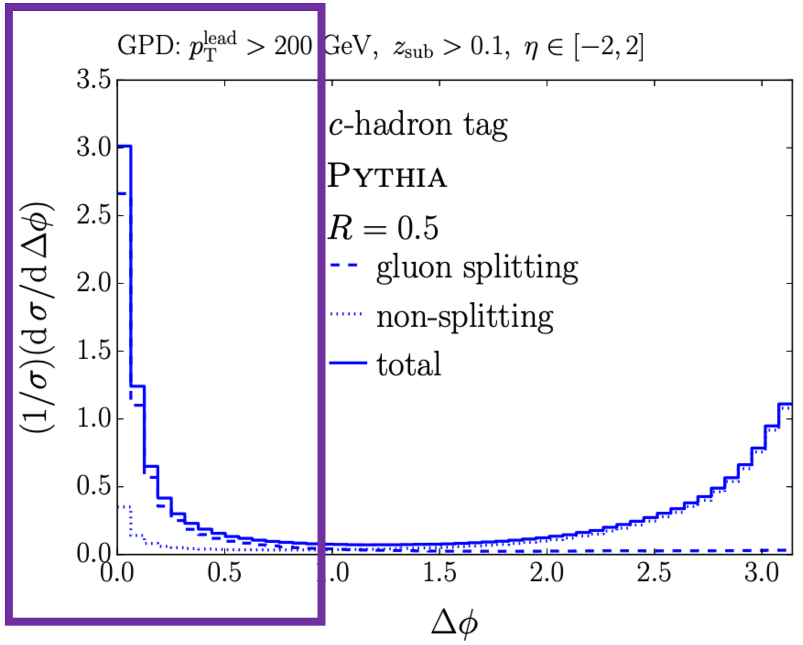
Accessing the $g \to c\bar{c}$ splitting in jets

Leading processes for heavy quark production



(approximately) collinear



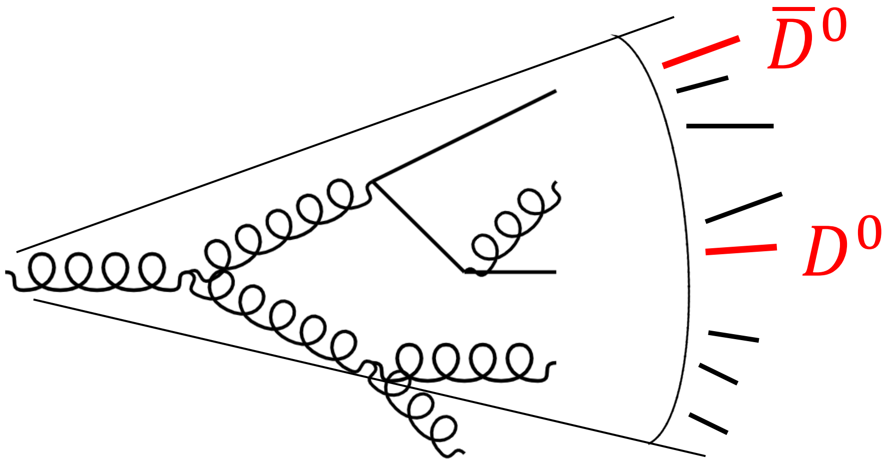


Gluon splitting

Non-gluon-splitting

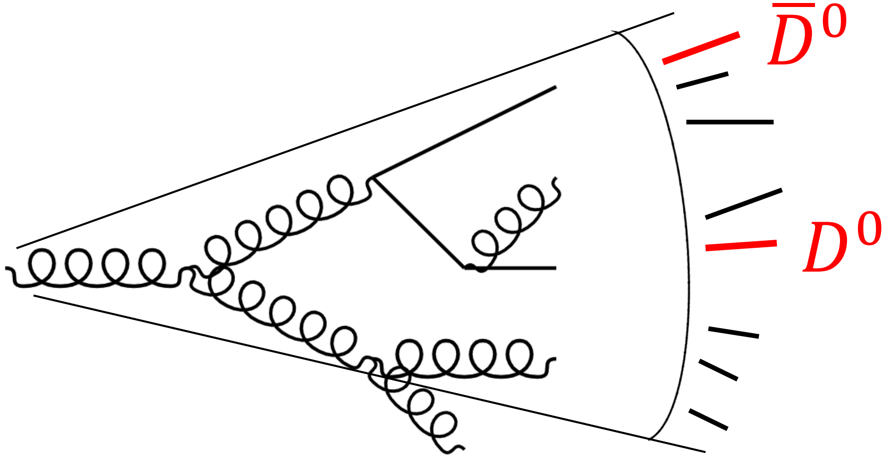
Ilten, Rodd, Thaler, Williams [1702.02947]

Accessing the $g \to c\bar{c}$ splitting in jets

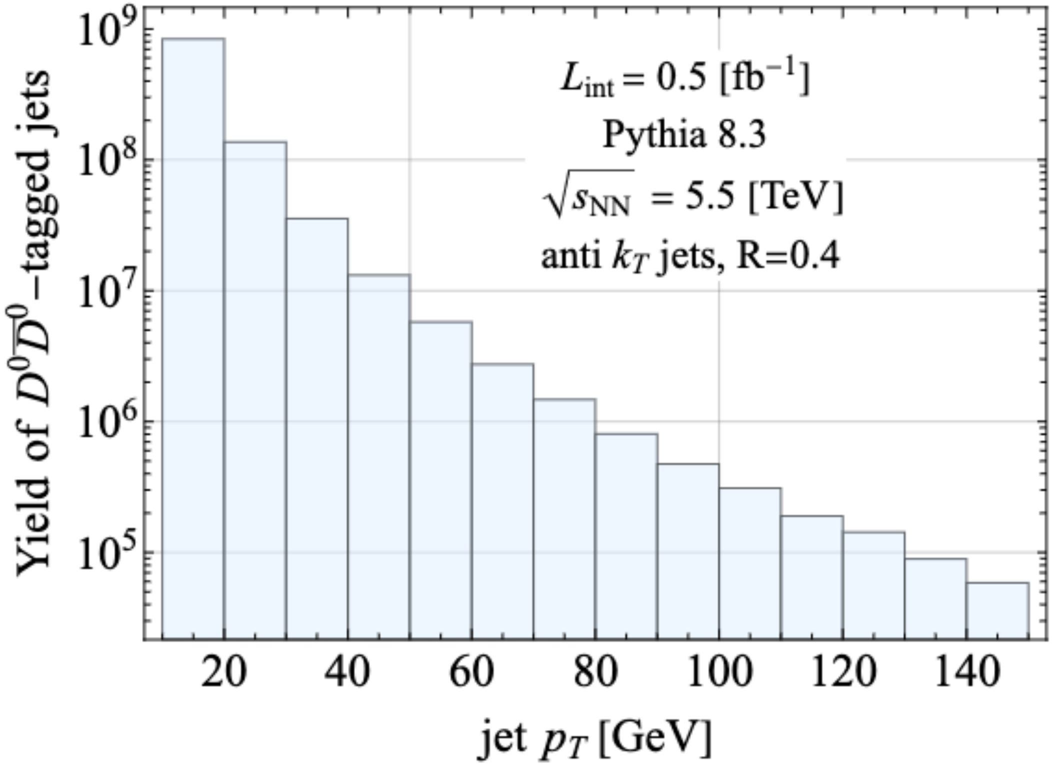


High-purity sample of showers including $g \to c\bar{c}$ splitting

Baseline: jets containing a $D^0\bar{D}^0$ pair



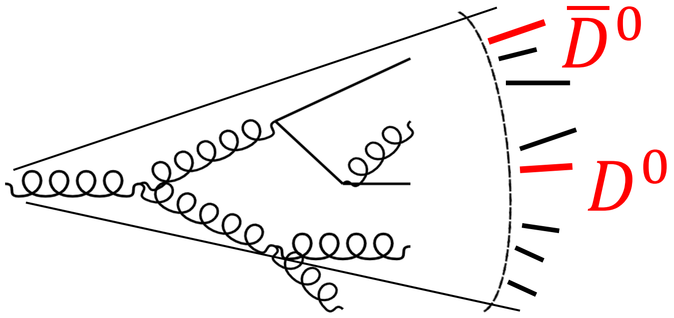
High-purity sample of showers including $g \to c\bar{c}$ splitting



Expect experimental sensitivity in Run 3/4

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

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



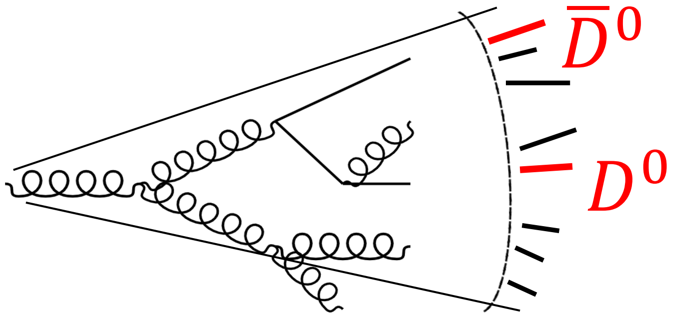
Get kinematics of g → $c\bar{c}$

Reweight each splitting by

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

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

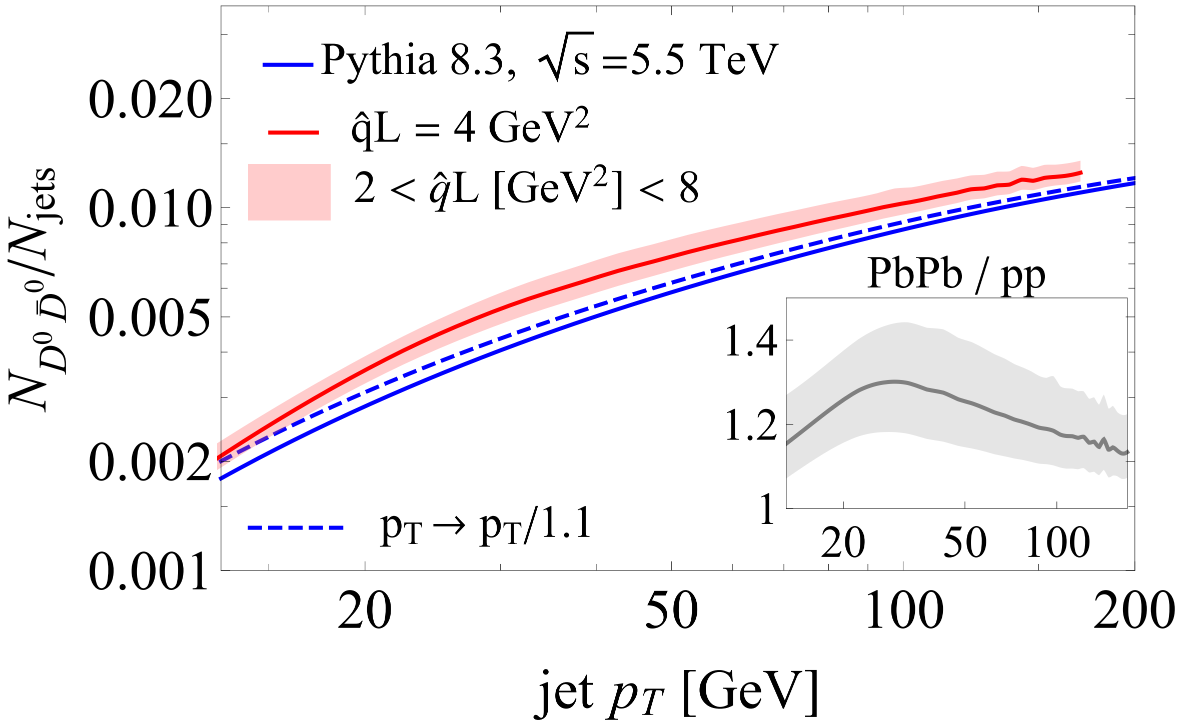
Observing $g \to c\bar{c}$ enhancement in jets



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

Reweight each splitting by

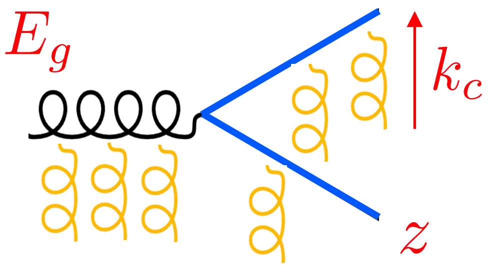
$$w^{med}_{g\to c\bar{c}}(E_g, k_c^2, z) = 1 + \frac{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{med}}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\text{vac}}(k_c^2, z)}$$

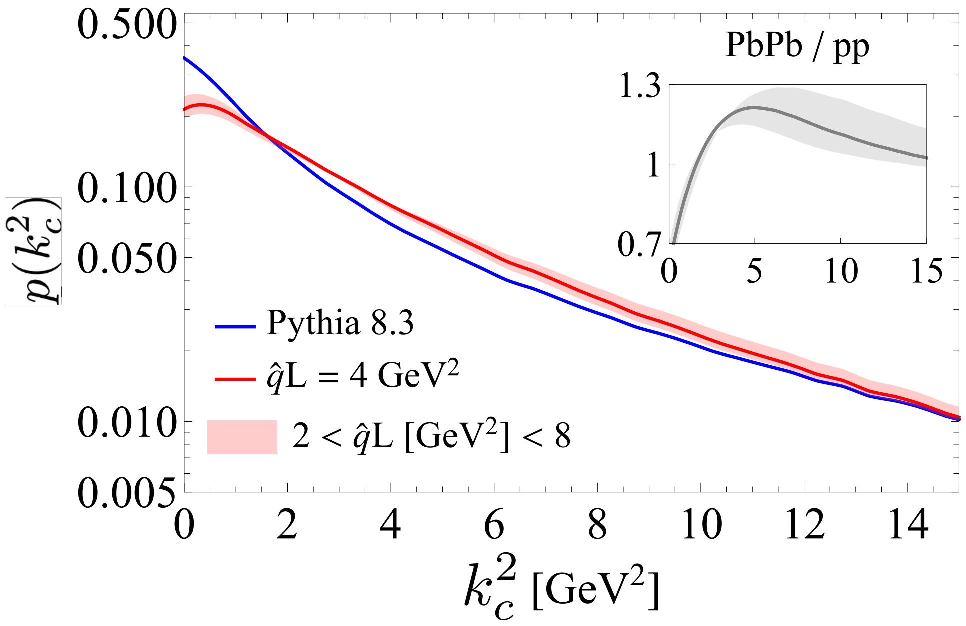


* Also verified in toy shower with all modified splittings

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

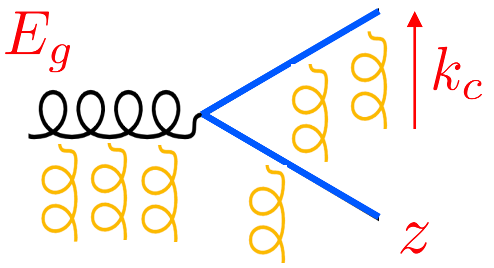
Going forward: more differential observables

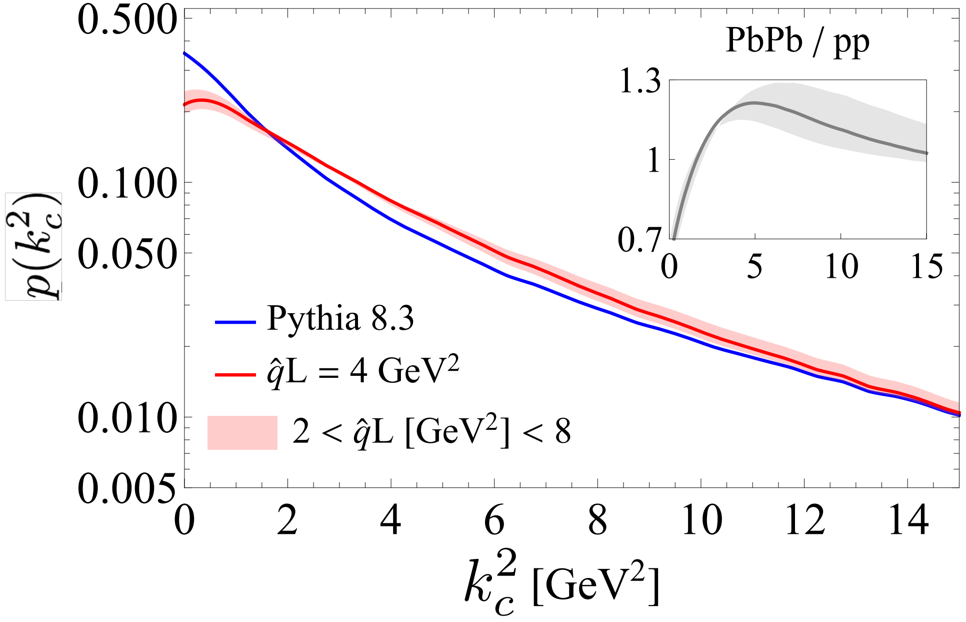


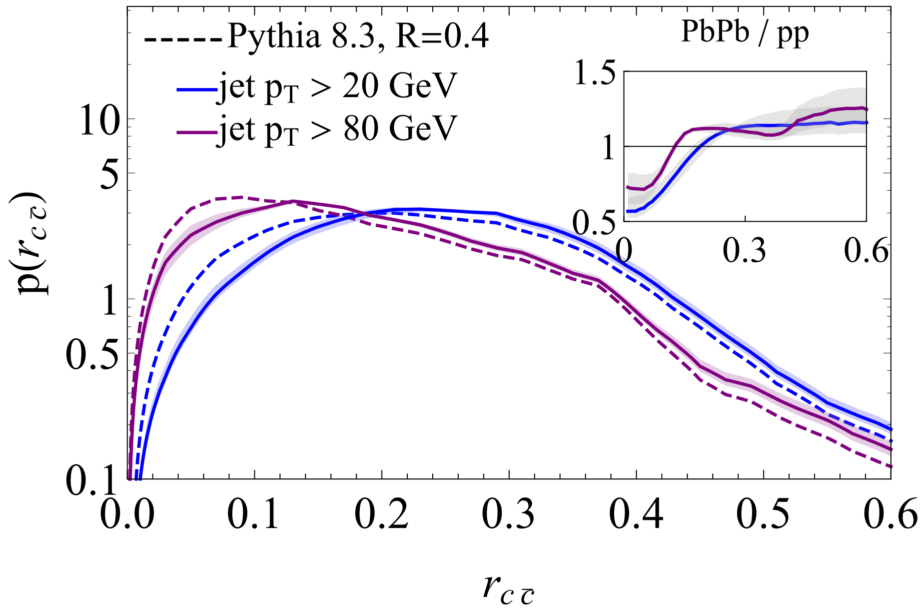


Can use jet substructure to access broadening at hadron-level

Going forward: more differential observables







Can use jet substructure to access broadening at hadron-level

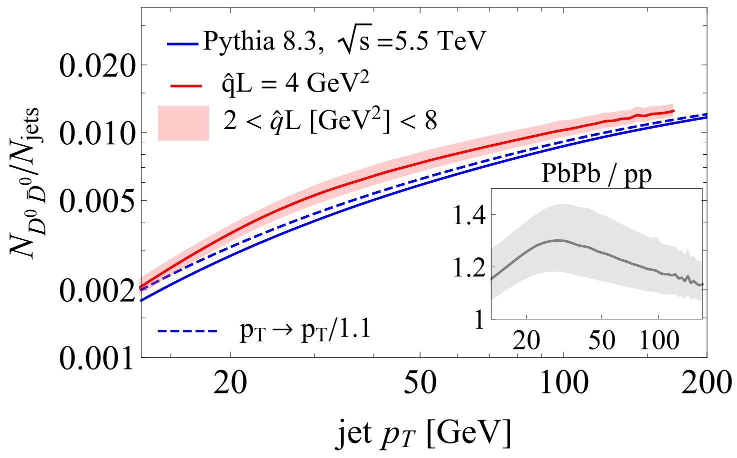
Ongoing: how to quantify modification differential in E_g?

- Access delayed probe of QGP

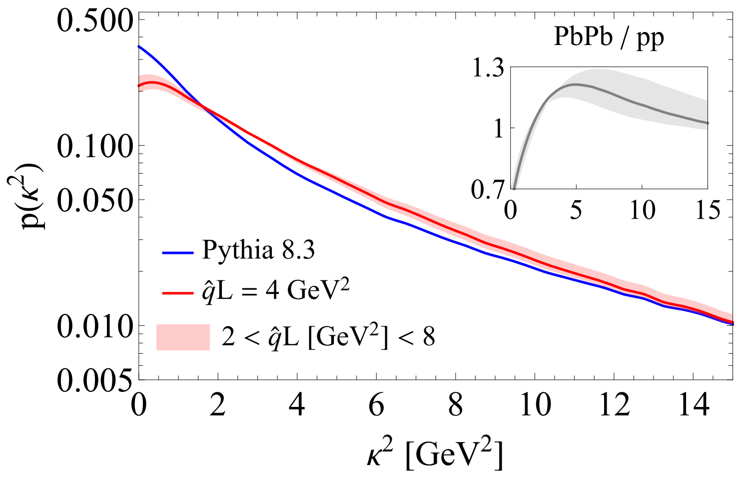
A process with many exciting future avenues!

So far..

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



- Medium-induced broadening of charm quark



Outlook

- Formation time dependence of modification

Clean process with a lot of exciting physics opportunities!