Energy correlators of the gluon splitting to heavy quarks

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THE ROYAL SOCIETY

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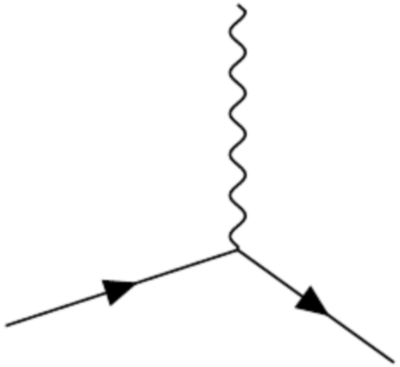
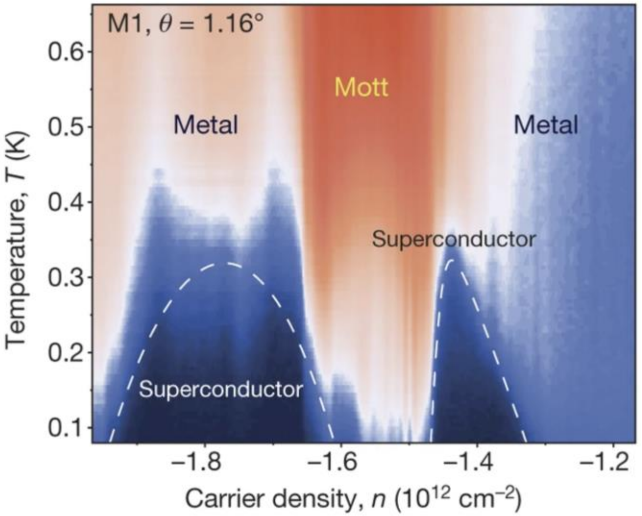
QED

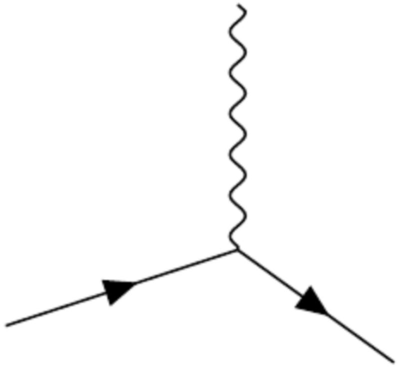


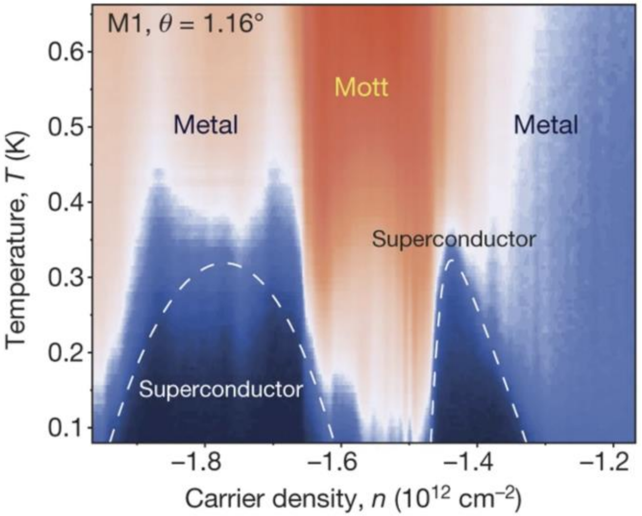


Magic angle graphene

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

QED





Magic angle graphene
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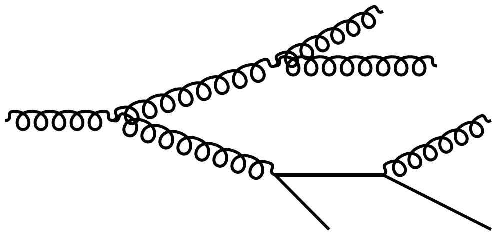
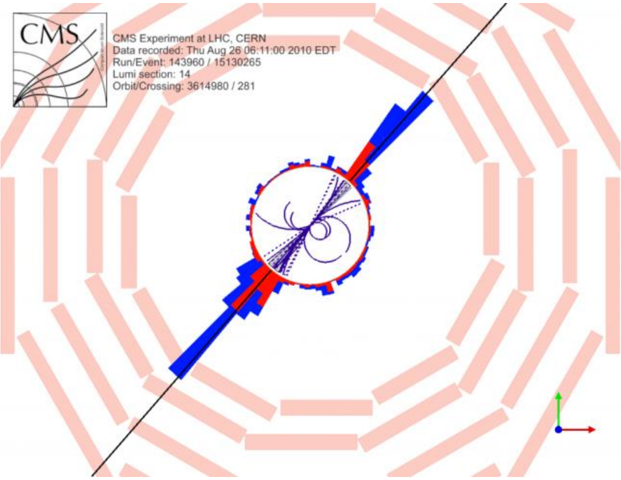
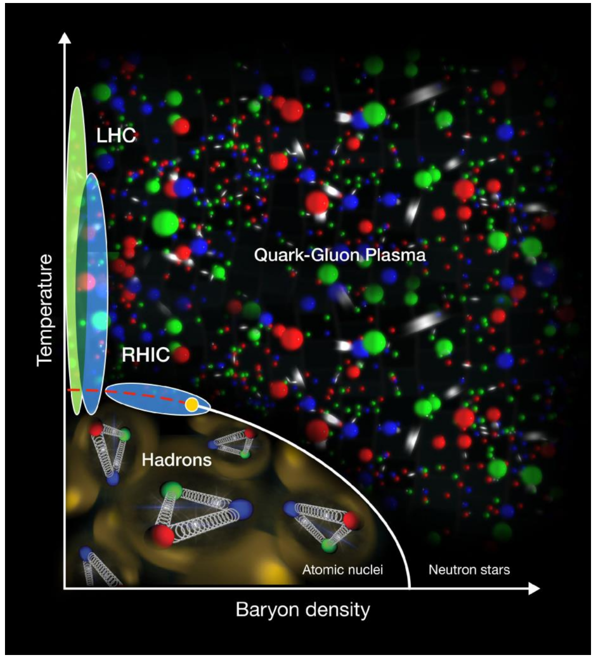
QCD

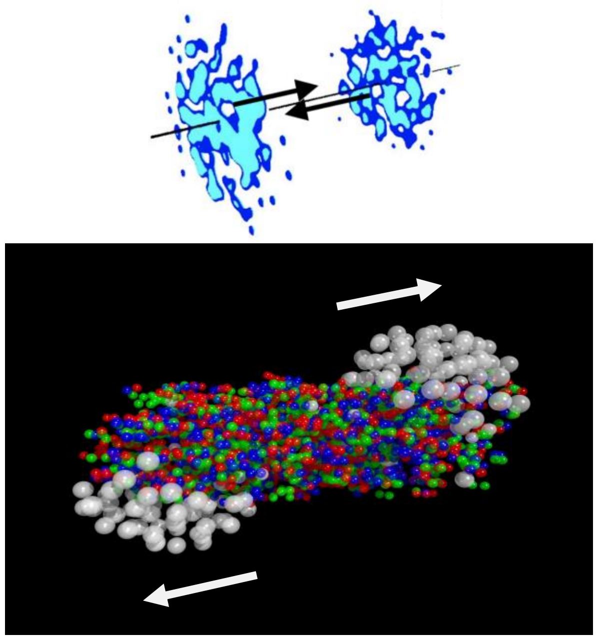


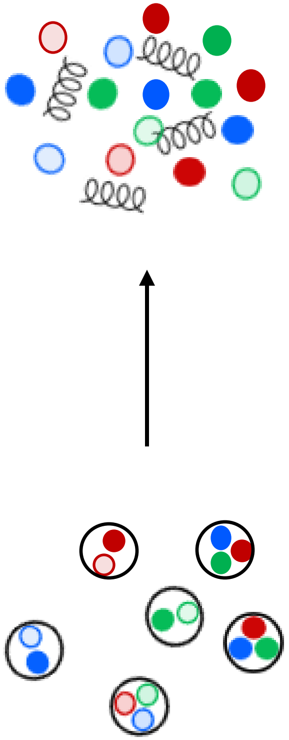


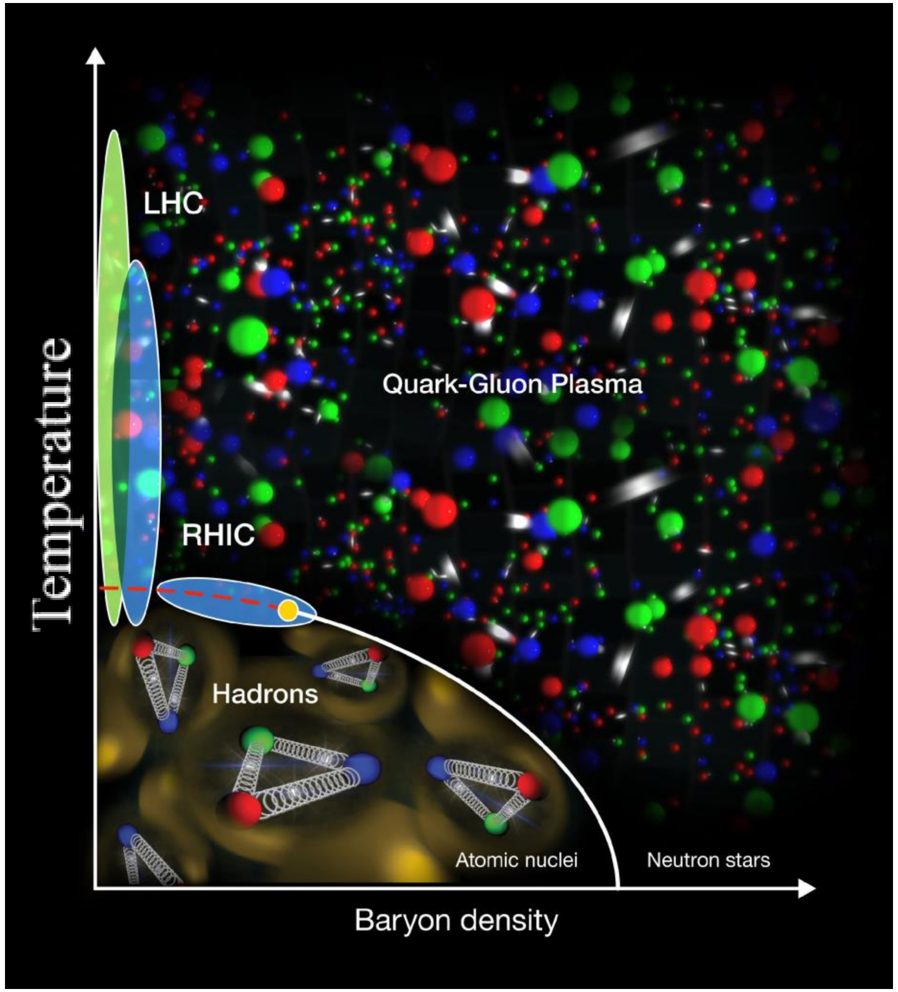


Understanding the fundamental interactions is just the beginning!

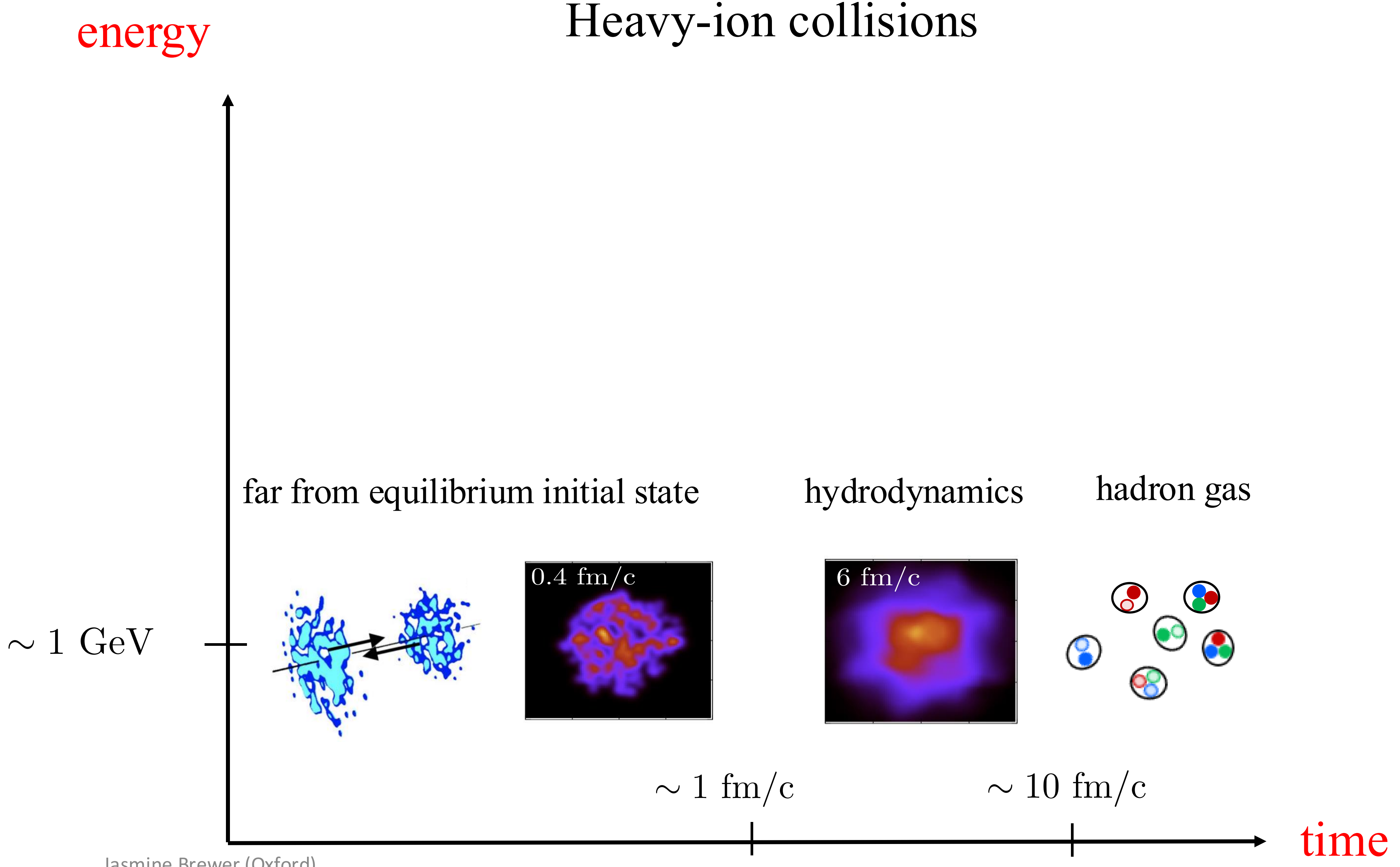
Heavy-ion collisions and quark-gluon plasma



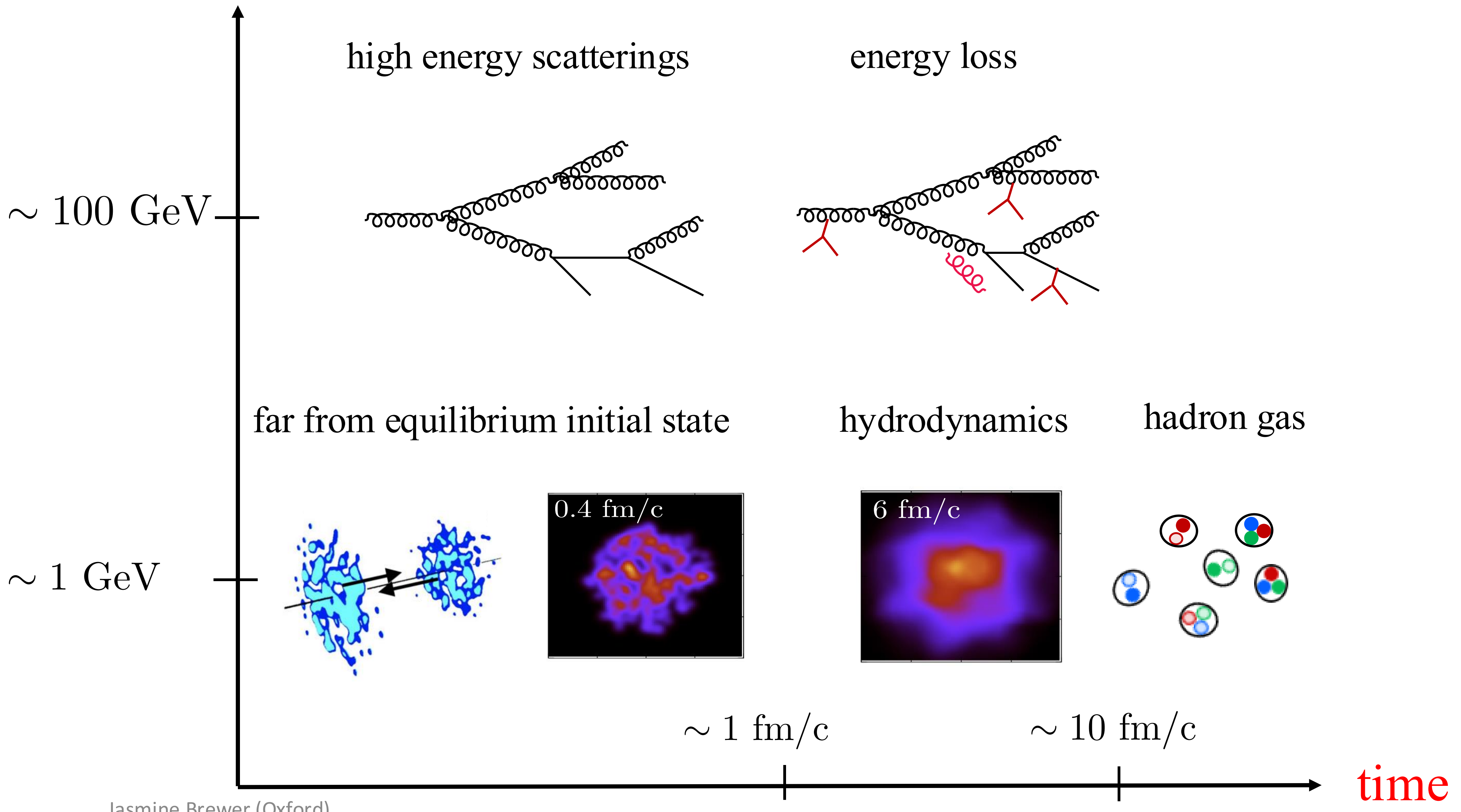




Heavy-ion collisions



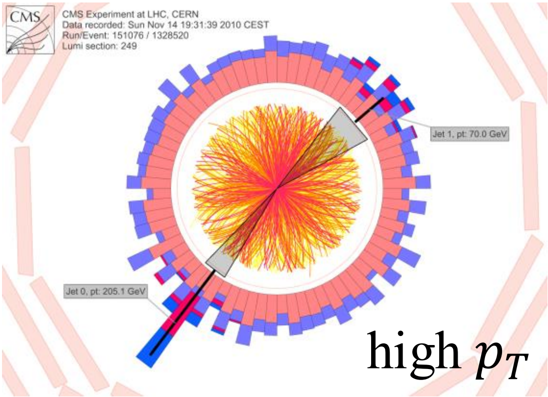
Heavy-ion collisions



Studying the dense QCD medium

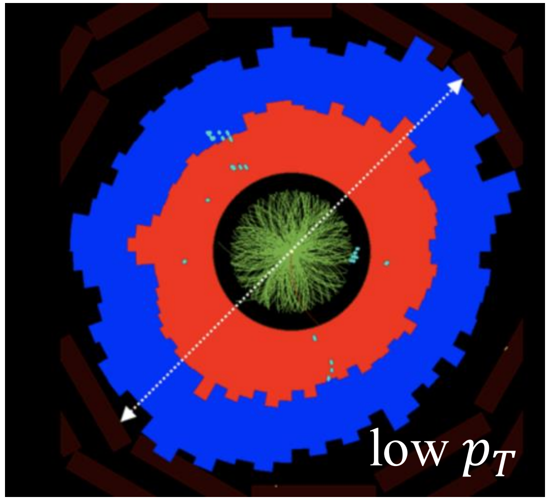
~ 100 GeV

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



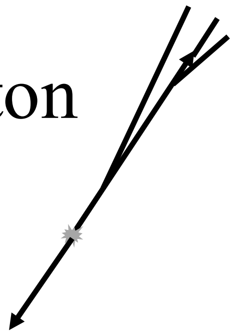
~ 1 GeV

Collective behavior of low-p_T particles

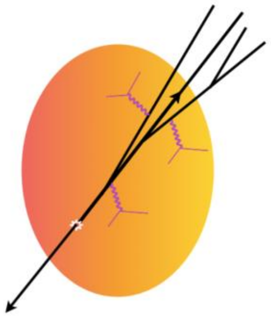


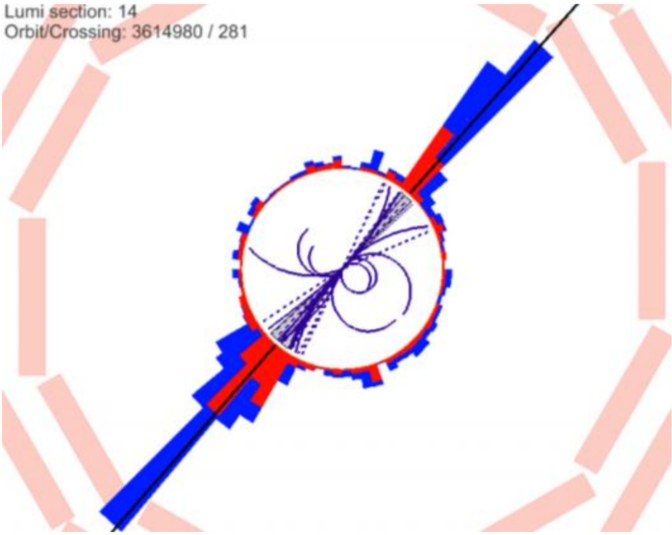
Modification of jets as a probe of quark-gluon plasma

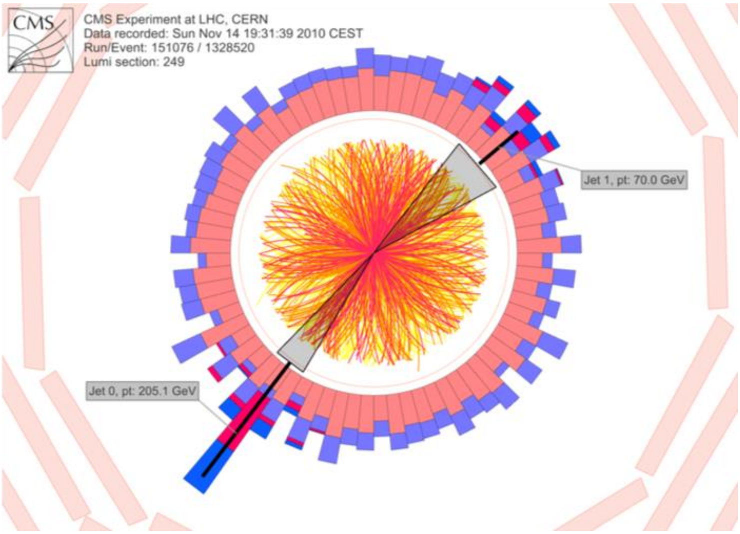
proton–proton



heavy-ion





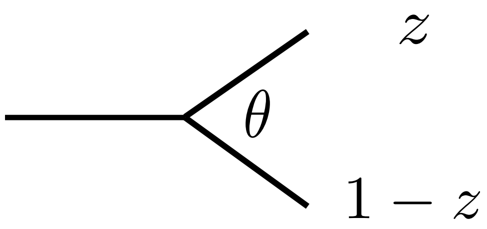


"baseline" jet properties

Large effect:

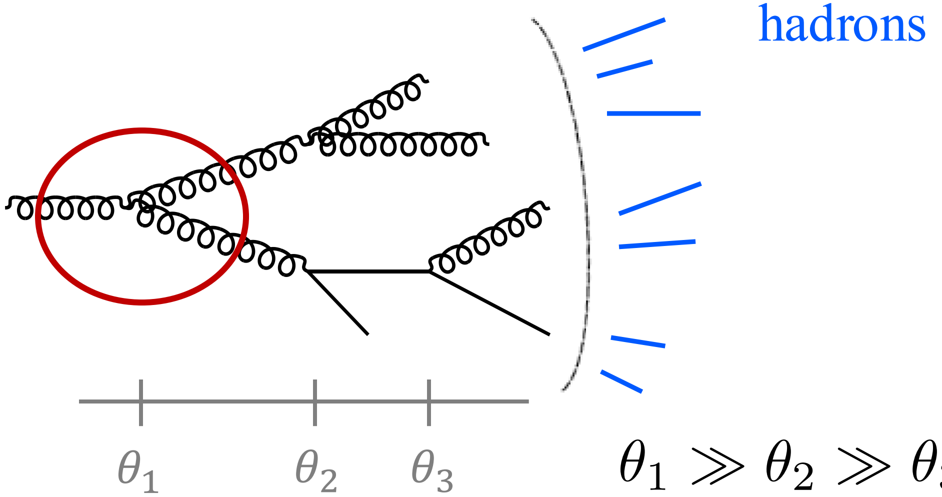
- Half as many jets per p_T in heavy-ion collisions
- Enhanced asymmetry of back-to-back jets
- …

Parton splittings in vacuum



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

Splitting functions



$\theta_1 \gg \theta_2 \gg \theta_3$

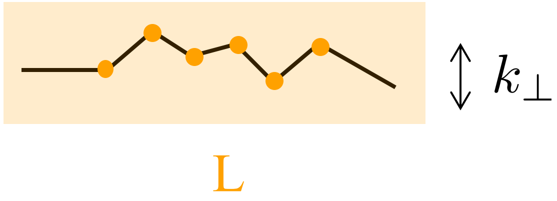
Iteratively apply splitting functions, descending in angle, virtuality

Parton showers connect perturbative QCD to hadronic world

Going to higher accuracy Parton showers $\longleftrightarrow$ ($\alpha_s \to 0$) Next-to-leading log calculations

A single high-energy parton in finite-temperature QCD

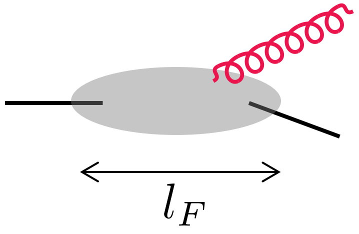
Parton undergoes transverse momentum diffusion



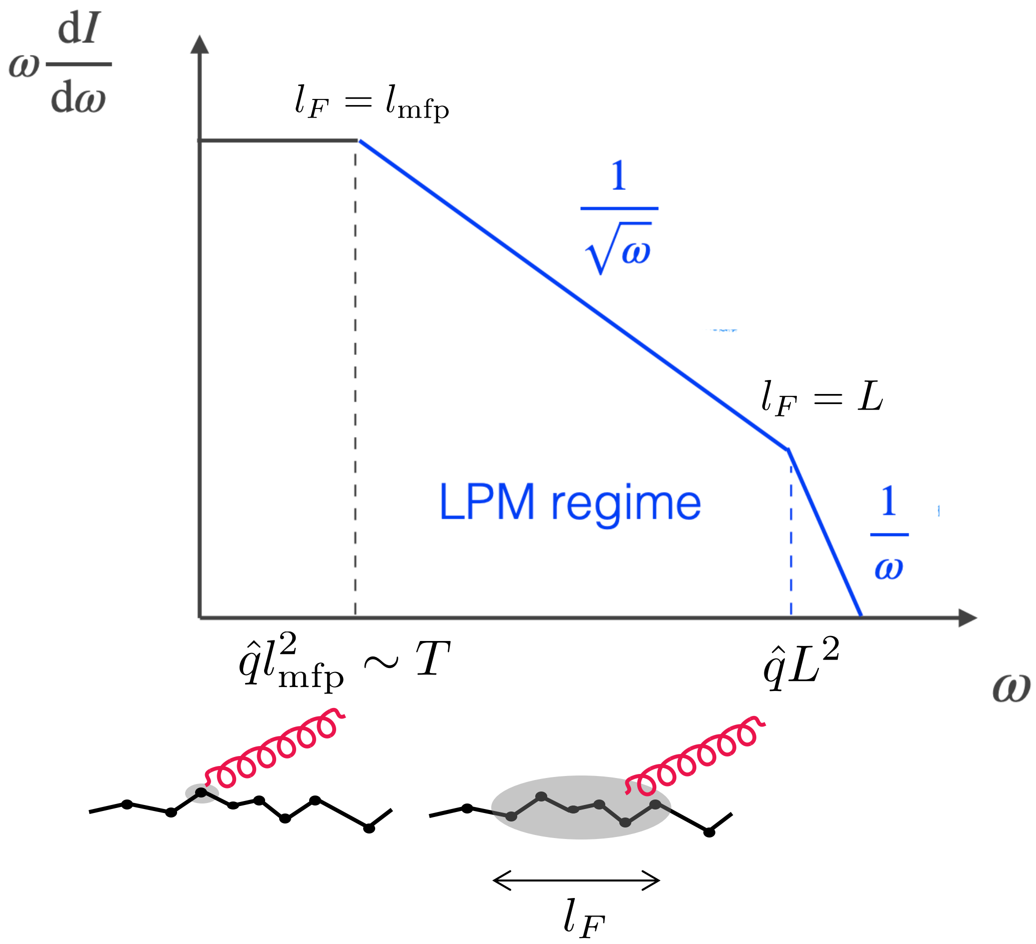
$$\hat{q} \equiv \frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t}$$

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

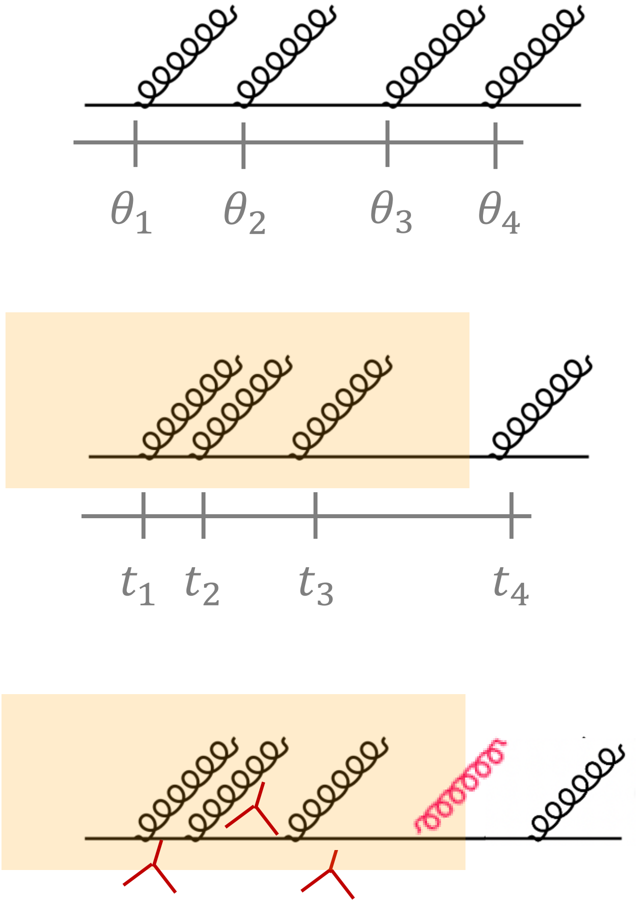
A high-energy parton fragments even in vacuum

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, …

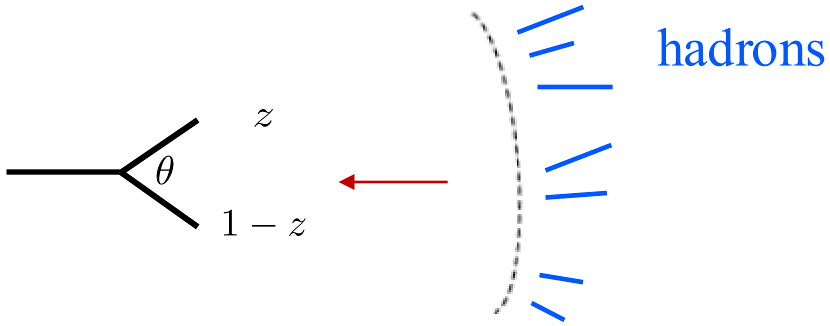
No current theories capture full complexity

Improved phenomenology

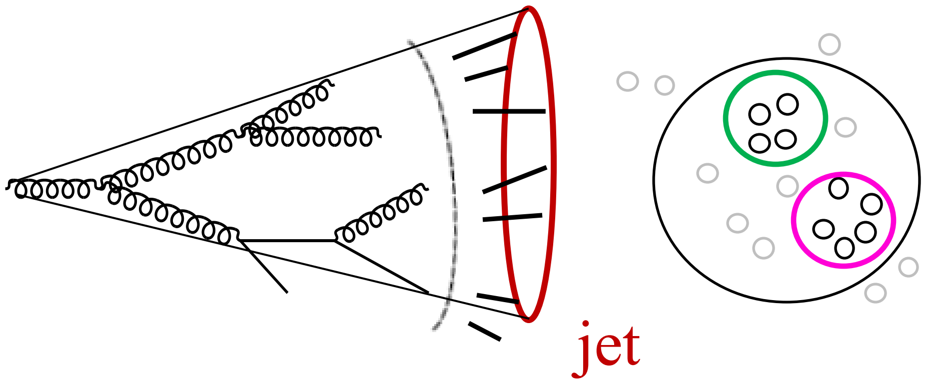
- Deconstructing a jet to access individual splittings

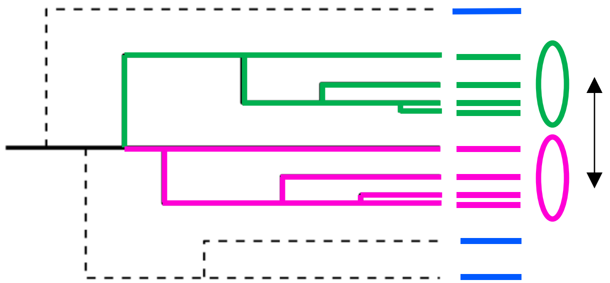
Building up a picture of a medium-modified jet from phenomenology

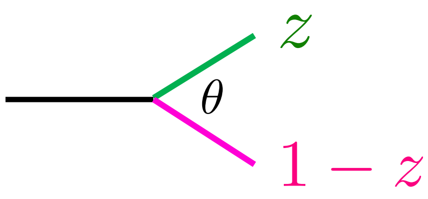
- Hadrons to splittings



Jet substructure: use (approximate) angular ordering of QCD to access kinematics of splittings in the shower







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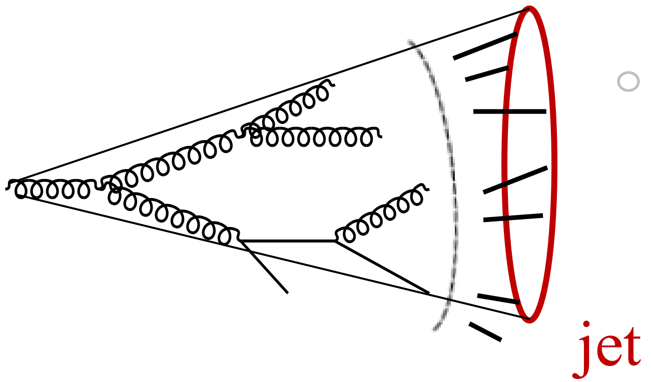
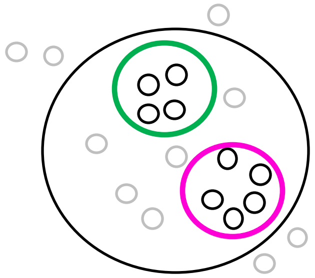
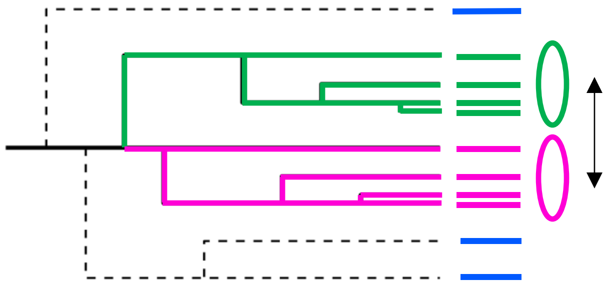
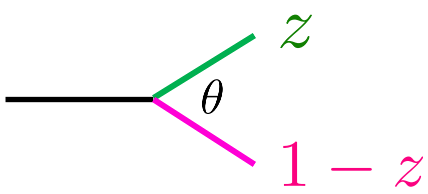
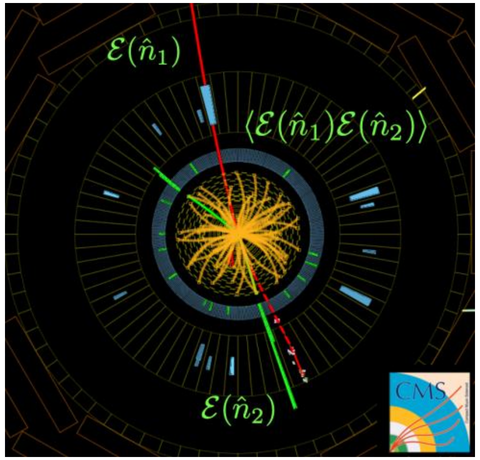








Energy correlators: re-organize event information in terms of correlation functions of energy flow, sorted by angle



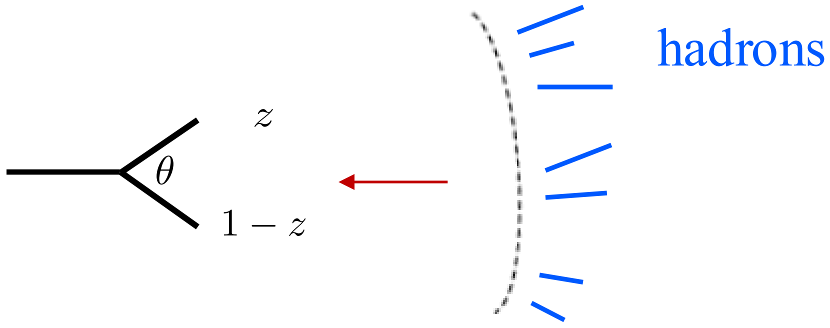
$$\mathcal{E}(\hat{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\hat{n})$$

$$\frac{d\sigma}{d\theta} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\theta - \theta_{ij}\right) \sim \langle \Psi \left| \mathcal{E}\left(\hat{n}_1\right) \mathcal{E}\left(\hat{n}_2\right) \right| \Psi \rangle$$

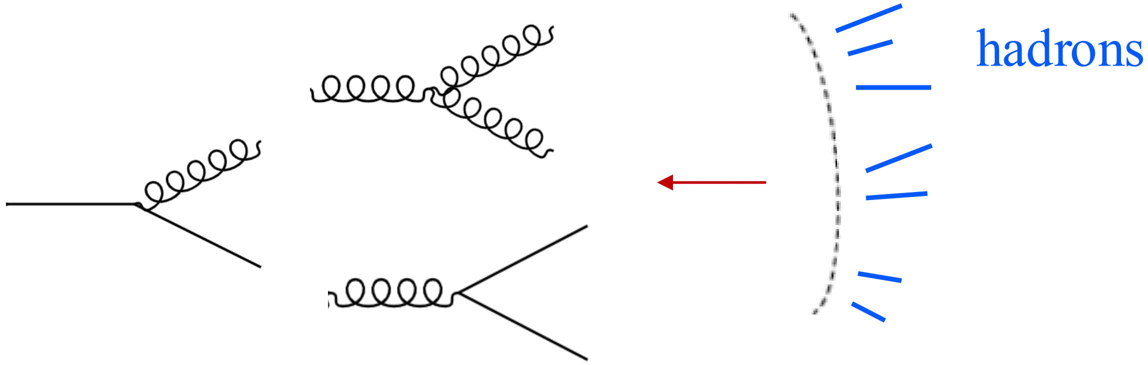
- Organize different physics effects into small/ large angle information

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

- Hadrons to splittings

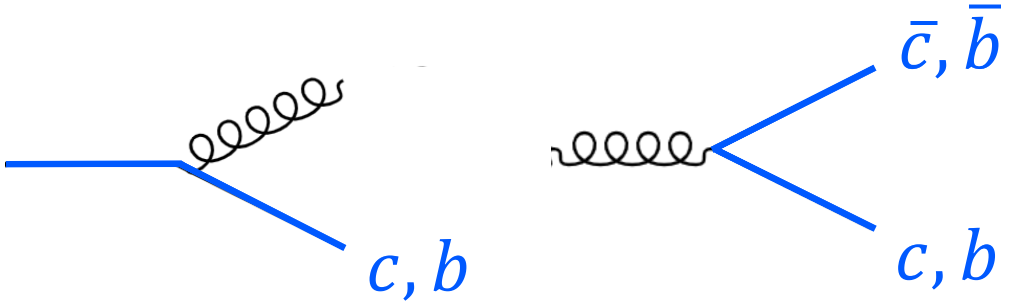


- Flavor-dependence of splittings



Accessing heavy flavor splitting functions

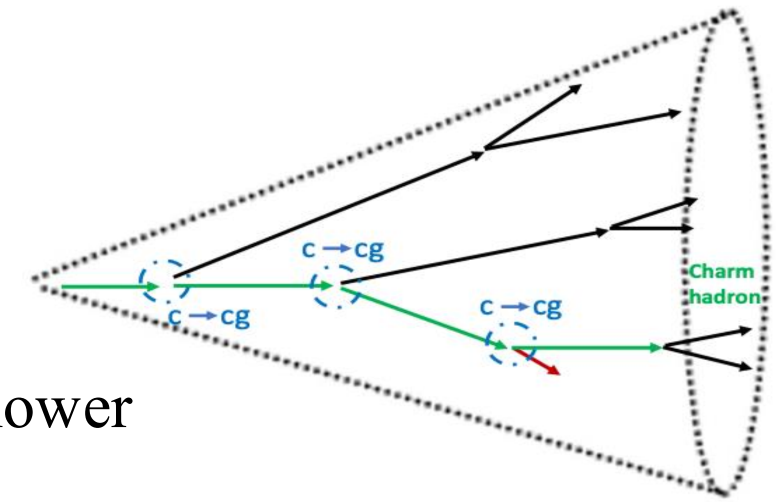
Heavy flavor splittings:



Advantages:

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

Used in ALICE [2106.05713]

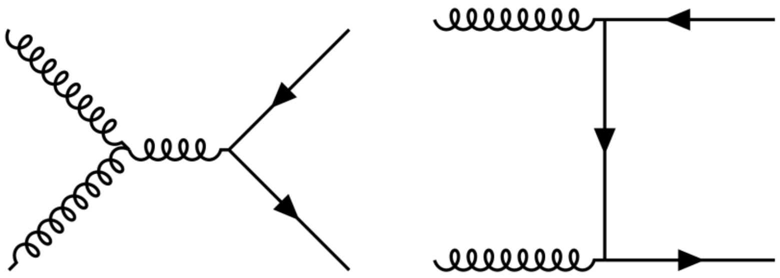


- Access later (more modified) splittings in the shower
- At high energies, access light flavor splittings

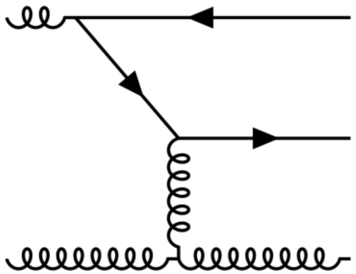
Focus of this talk: phenomenology of $g \to c\bar{c}$

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

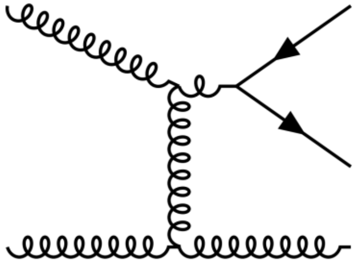
Leading processes for heavy quark production



Flavor creation

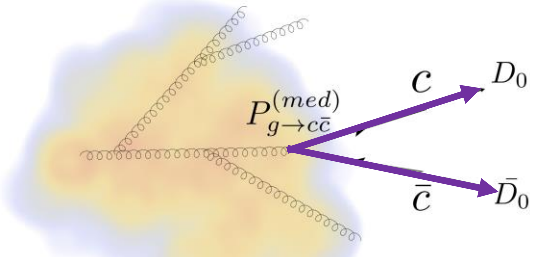


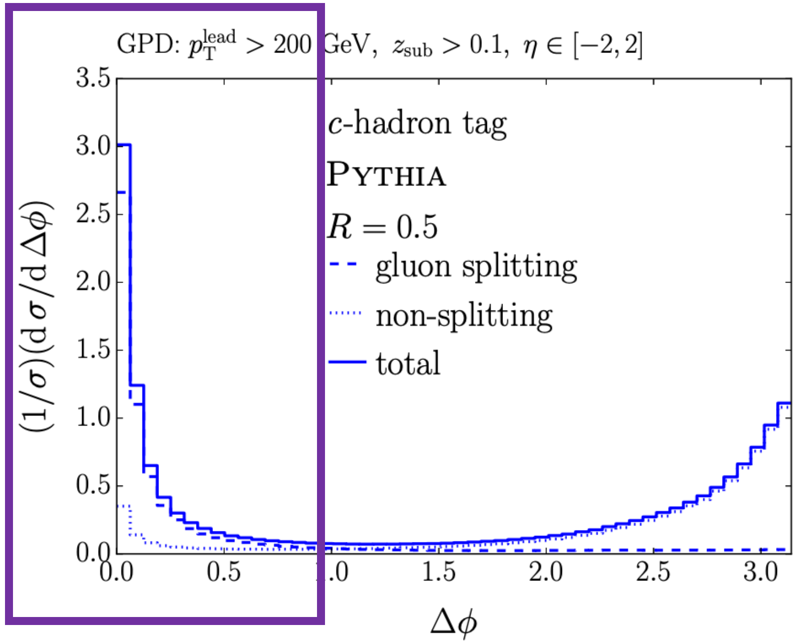
Flavor excitation



Gluon splitting

(approximately) collinear





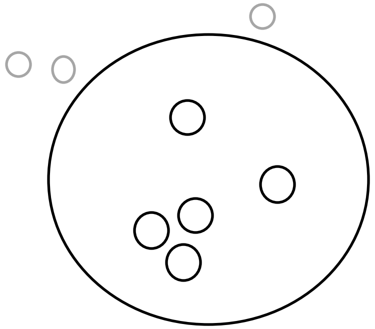
Gluon splitting

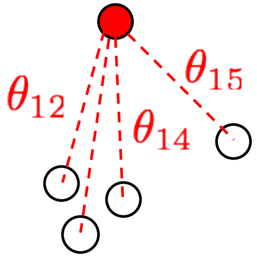
Non-gluon-splitting

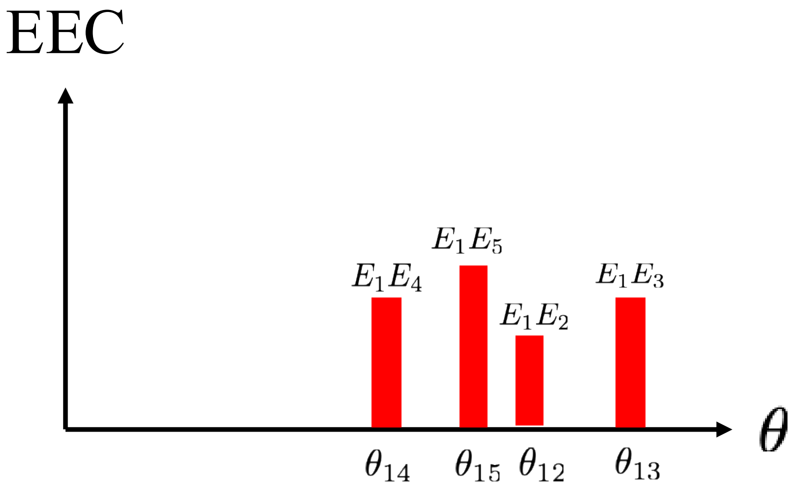
Ilten, Rodd, Thaler, Williams [1702.02947]

Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)

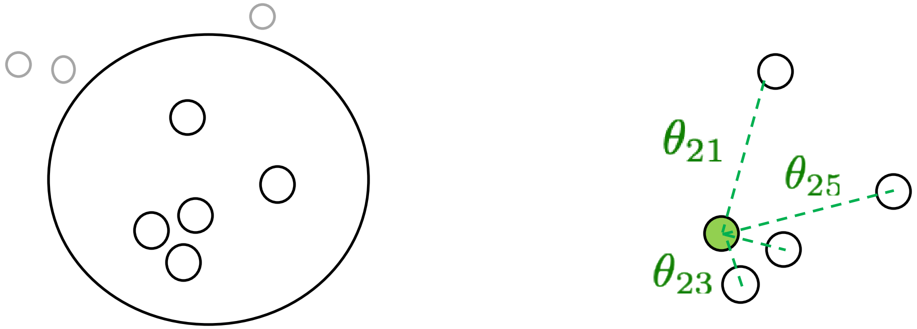




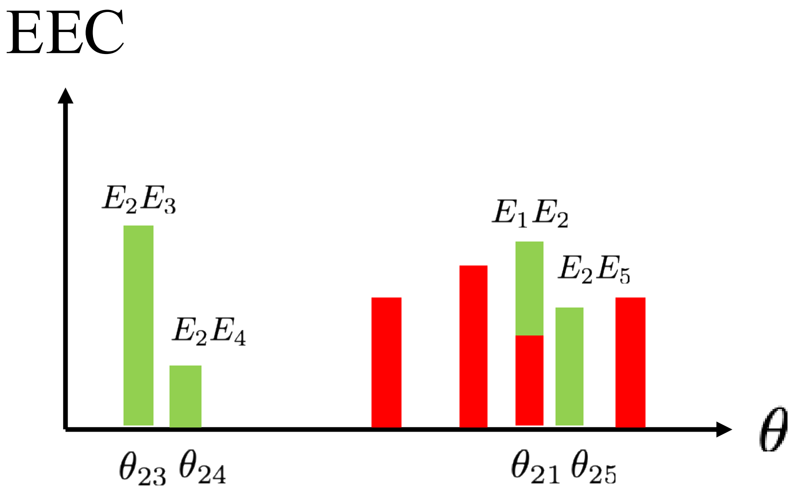


Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)

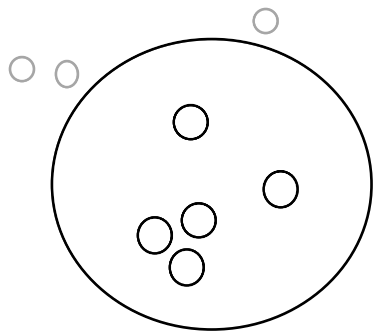


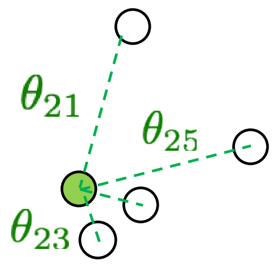
… etc for all particles and all events

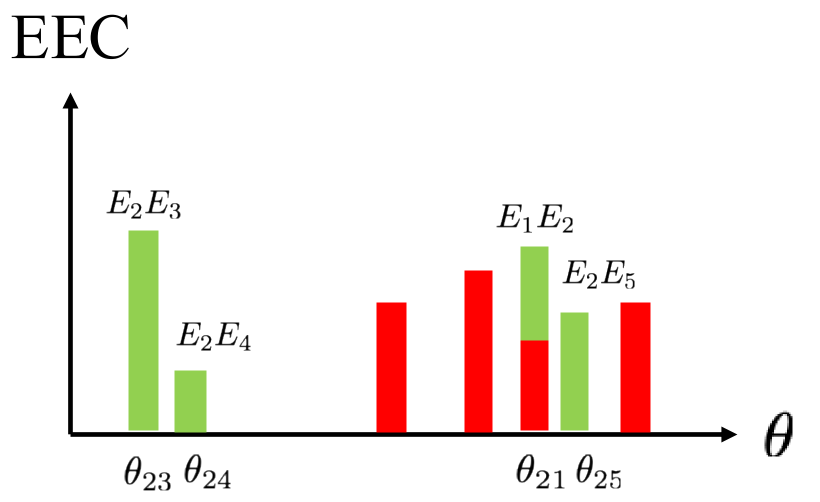


Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)

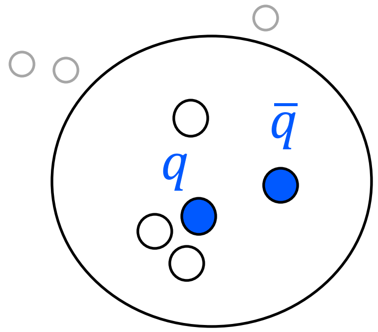


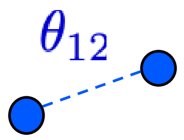


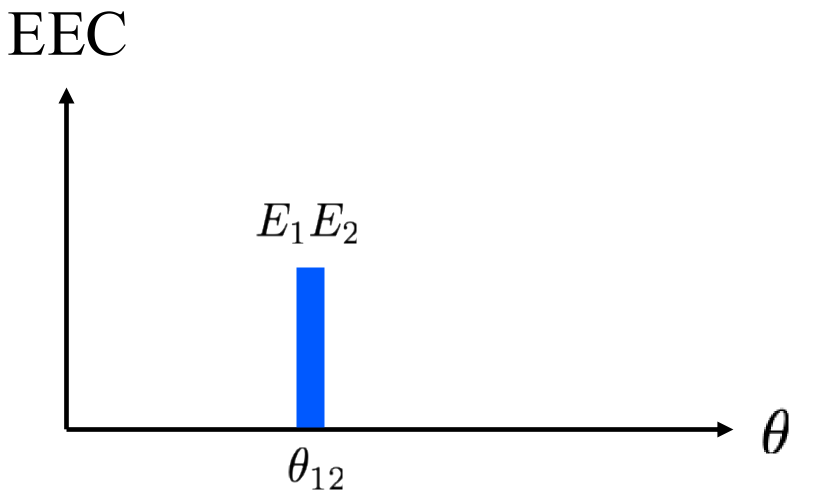


… etc for all particles and all events

EEC of heavy flavor jets



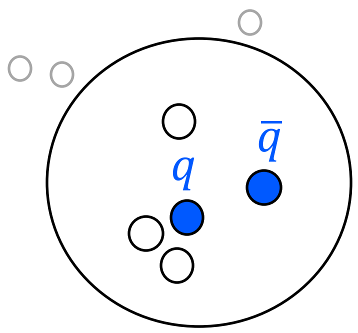


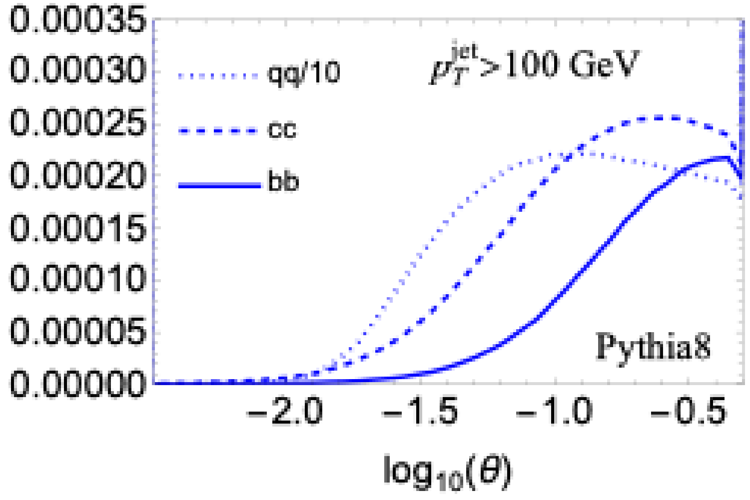


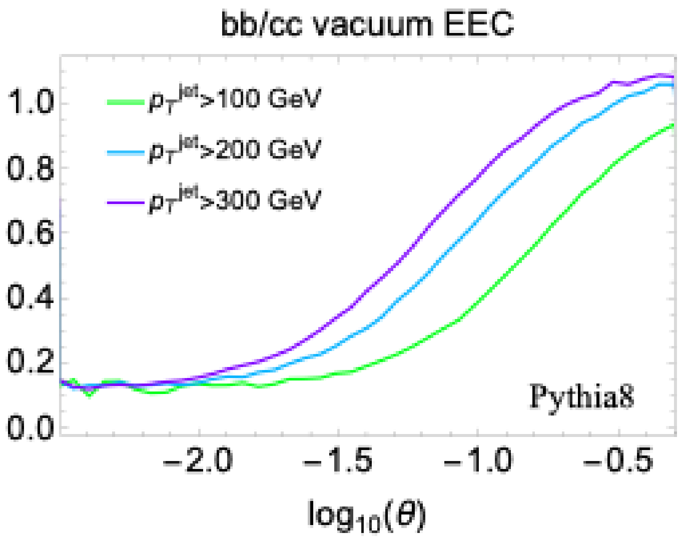
$$EEC(\theta) = \int dz \frac{P_{g\to q\bar{q}}(\theta, z)}{Q^2} z(1-z)$$

* throughout, normalize by total number of jets

In vacuum: quark mass effects in energy correlators







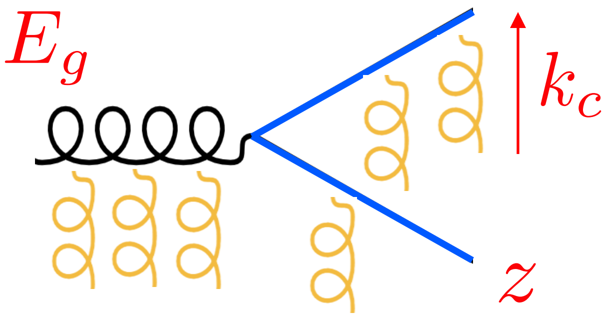
Heavier quarks tend to fragment earlier, at larger angles → Characteristic suppression of heavy/light EEC at small angles

See also Craft, Lee, Mecaj, Moult [2210.09311]

$$\theta_{\text{dead-cone}} \sim m_Q/E$$

Next step: understanding the medium modification of the $g \to q\bar{q}$ correlator

Medium effects: medium modification of the $g \to q\bar{q}$ 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 many soft gluon interactions with a medium of length L

Inspired by charm but the quark mass is just a parameter

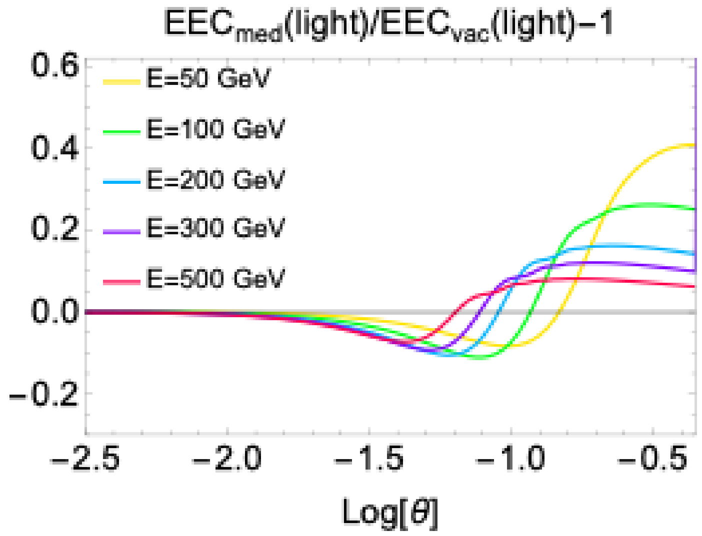
Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann *JHEP 01 (2023) 080* [2203.11241]

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 *Phys.Rev.Lett.* 132 (2024) 21 [2209.13600]

Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators



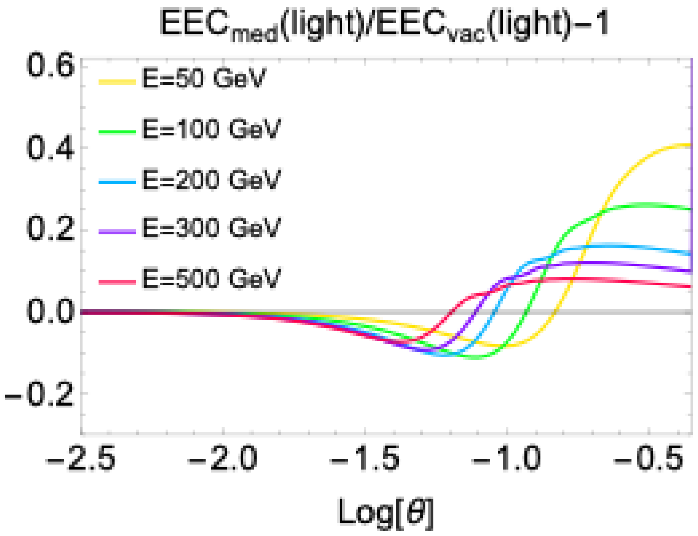
- Enhancement at large angles
- Depletion at intermediate angles

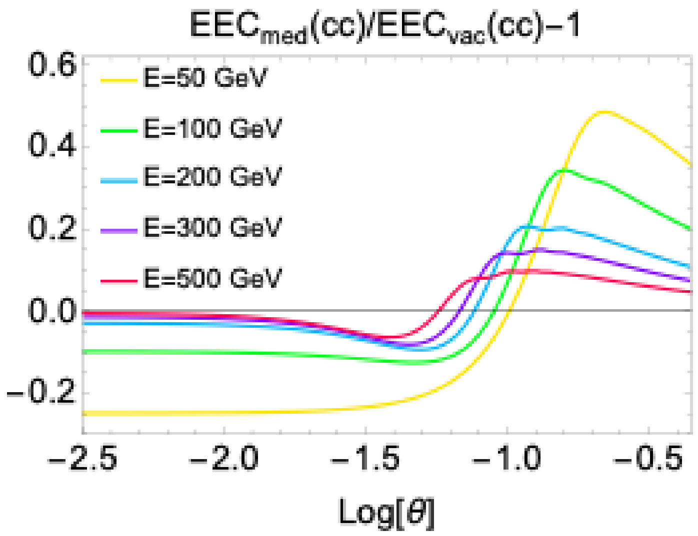
Momentum broadening effect

- No modification at very small angles

At small enough angles, massless splittings are always formed outside the medium

Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators





- Enhancement at large angles
- Depletion at intermediate angles

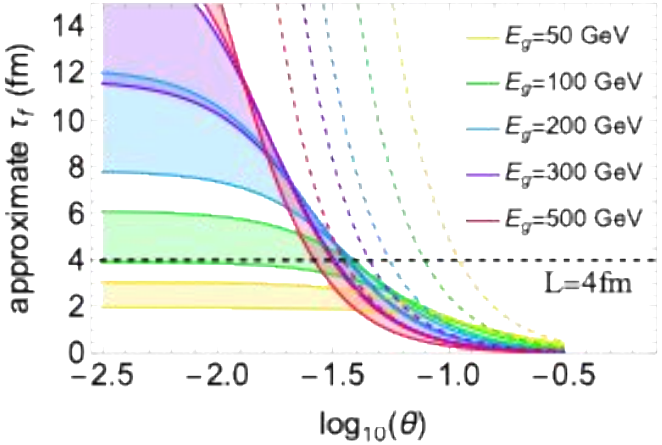
Momentum broadening effect

- No modification at very small angles

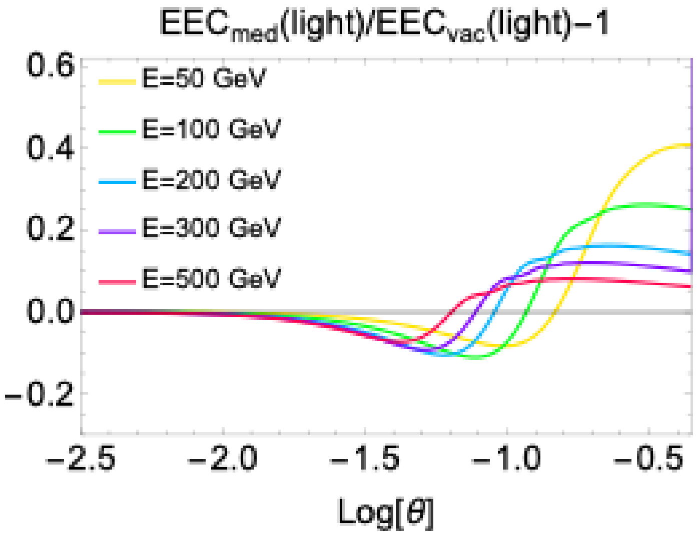
At small enough angles, massless splittings are always formed outside the medium

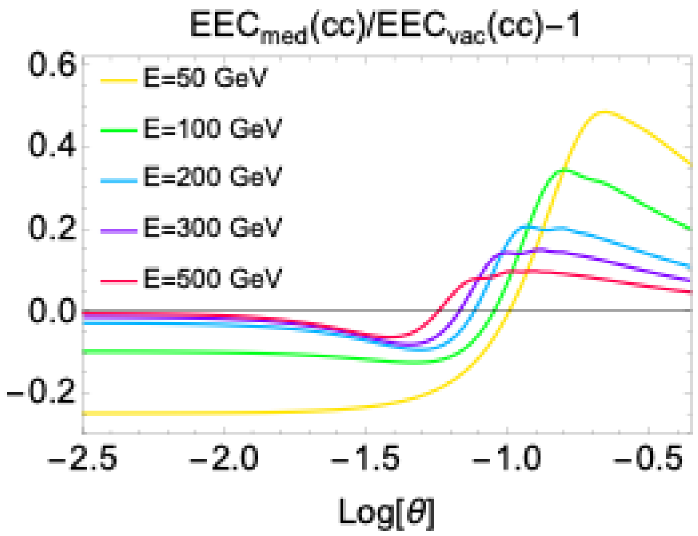
For massive quarks, splittings can be formed in the medium for all angles!

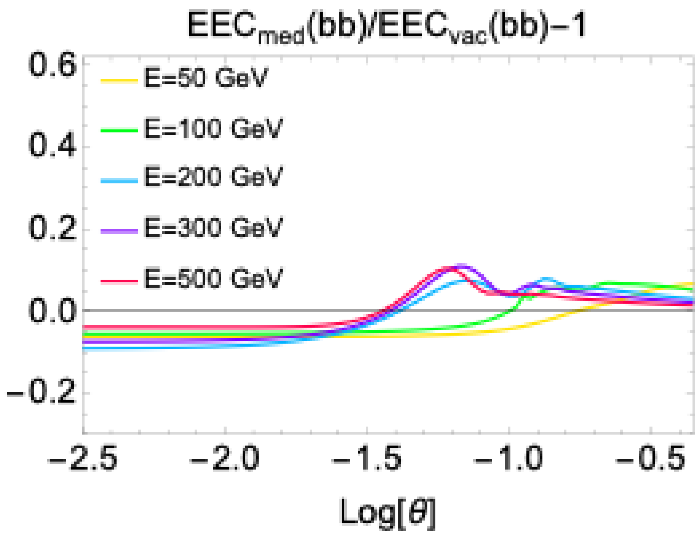
$$\tau_f \sim \frac{2E_g z(1-z)}{m^2 + E_g^2 z^2 (1-z)^2 \theta^2}$$



Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators







- Enhancement at large angles
- Depletion at intermediate angles

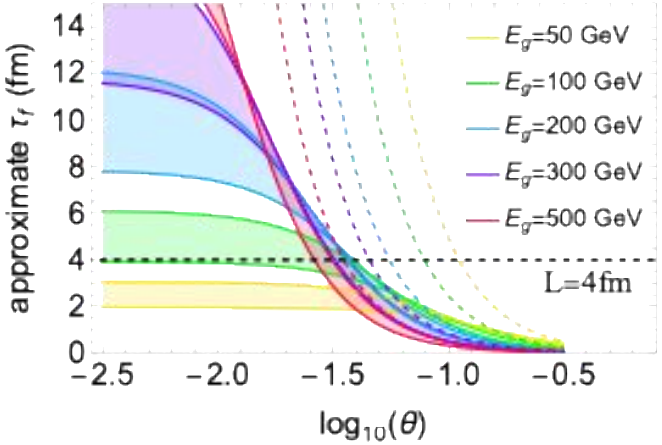
Momentum broadening effect

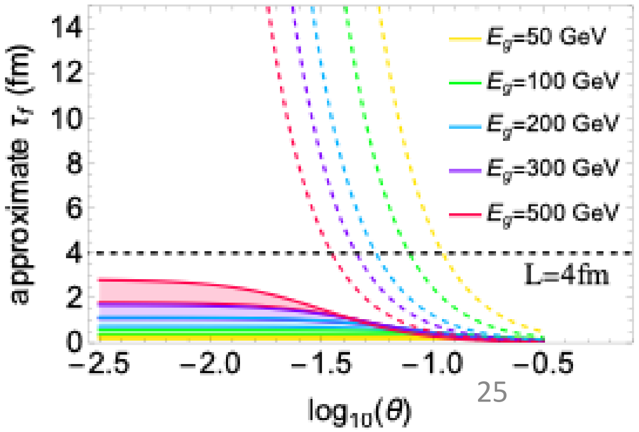
- No modification at very small angles

At small enough angles, massless splittings are always formed outside the medium

For massive quarks, splittings can be formed in the medium for all angles!

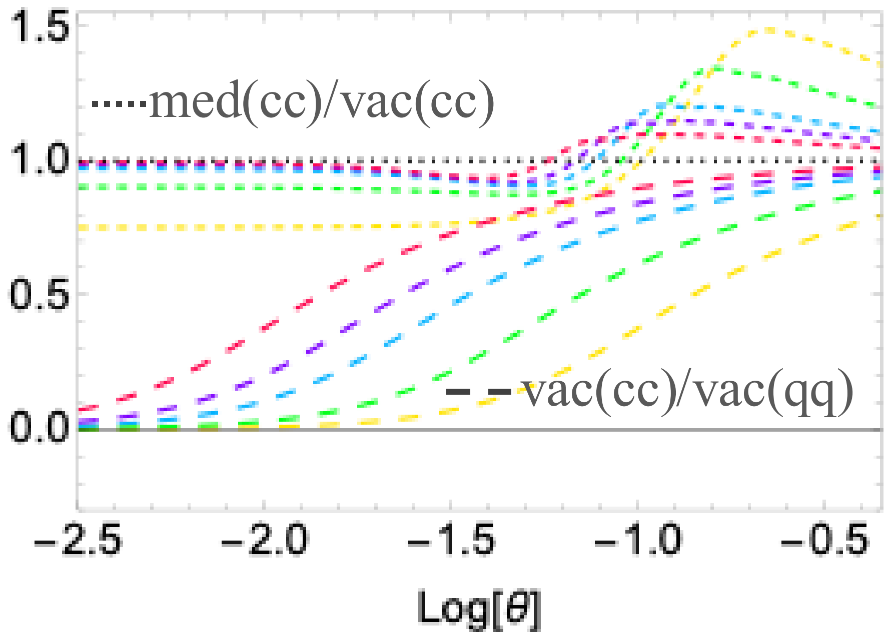
$$\tau_f \sim \frac{2E_g z(1-z)}{m^2 + E_g^2 z^2 (1-z)^2 \theta^2}$$

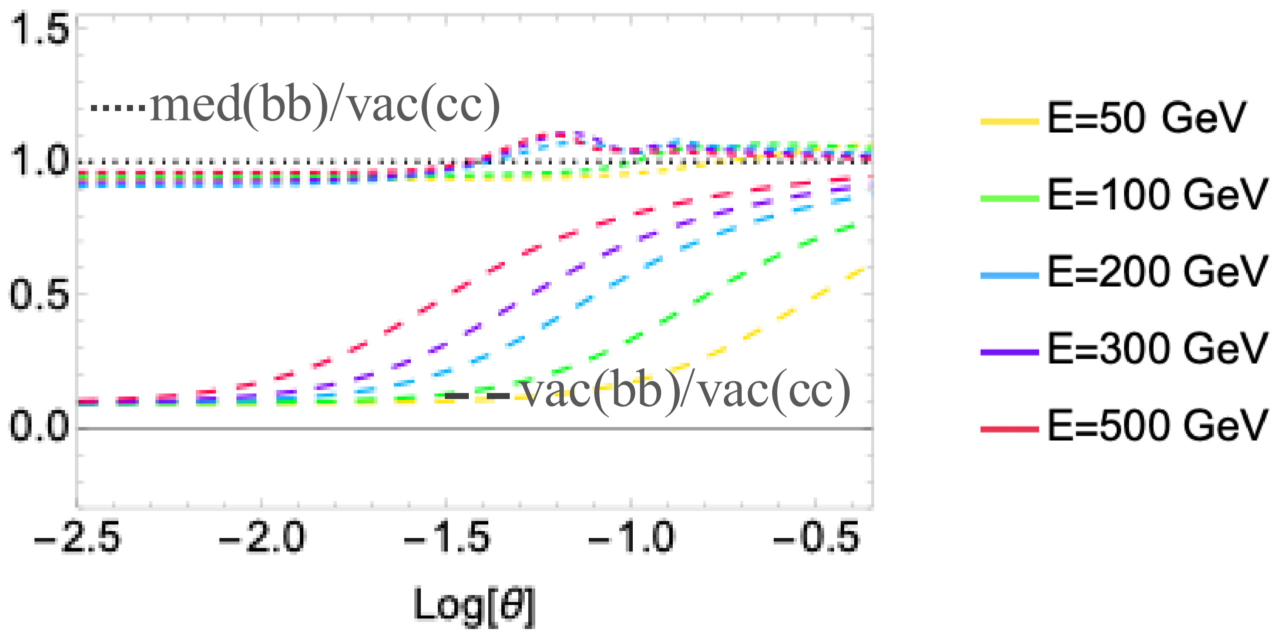




Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators

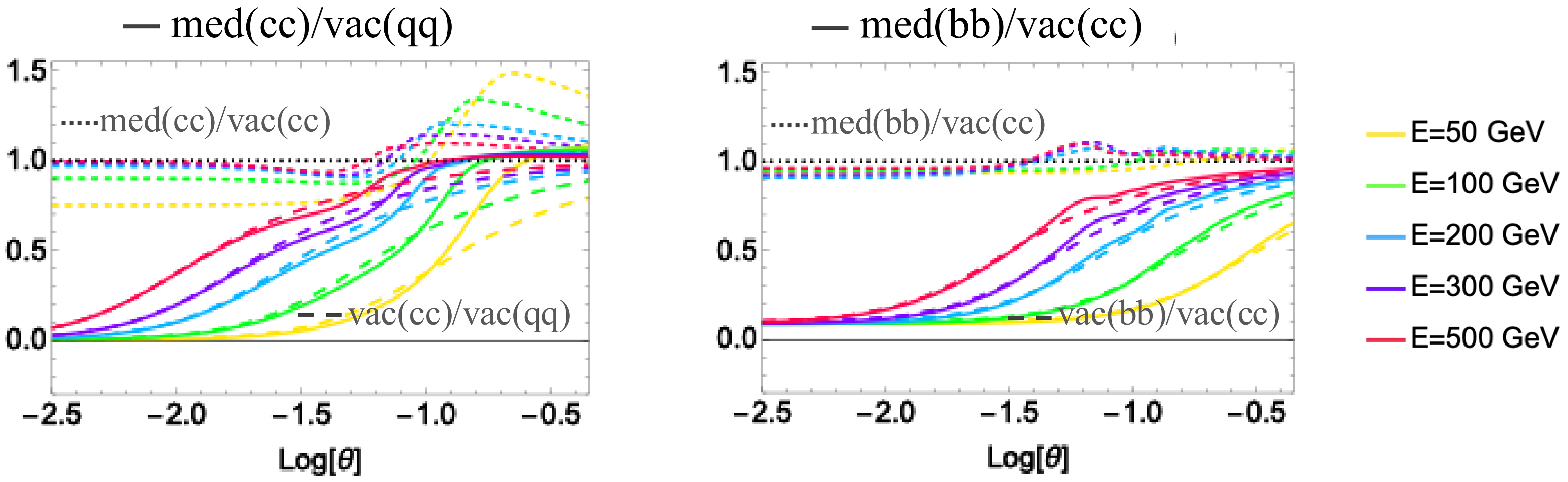
Dead cone effects and medium effects populate different angular regions in energy correlators





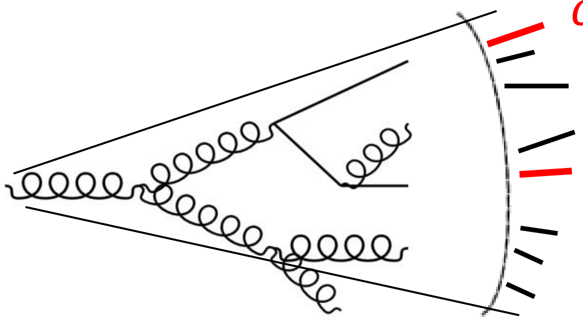
Medium modification of the $g \rightarrow q\bar{q}$ splitting function in energy correlators

Dead cone effects and medium effects populate different angular regions in energy correlators



Next step: understanding the impact of medium modification in phenomenology

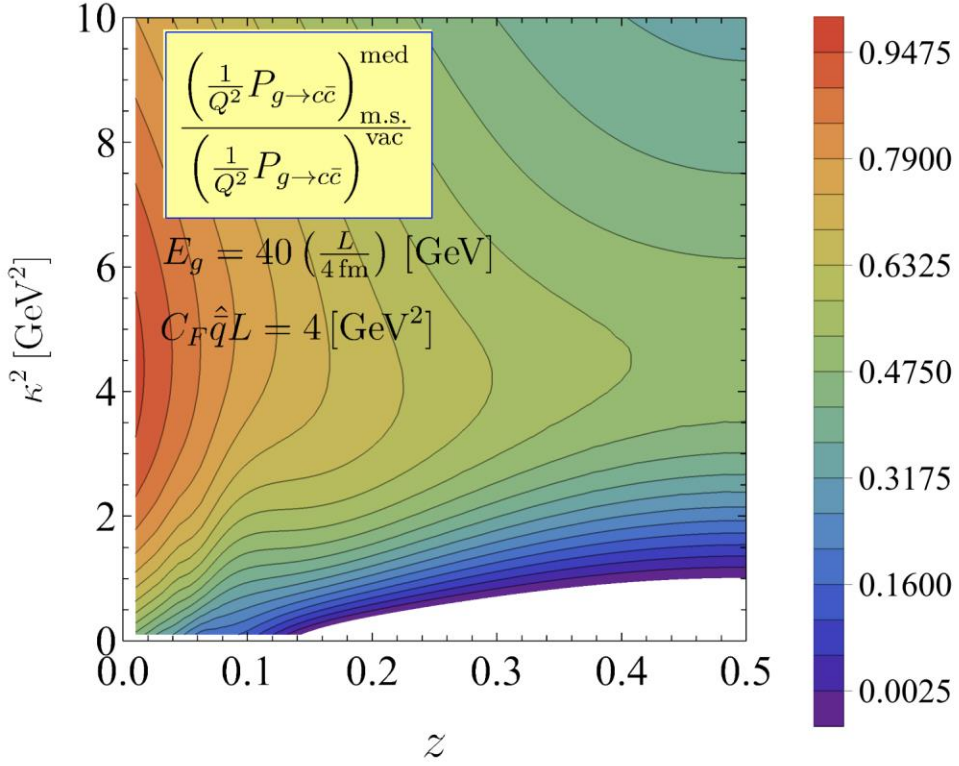
Medium modification of the $g \to q\bar{q}$ splitting function in a parton shower



- Find jets containing $c\bar{c}$ (or $D\bar{D}$) pairs in vacuum Monte Carlo simulations (Pythia)

- Use shower to reconstruct kinematics of the g $\to c\bar{c}$ splitting

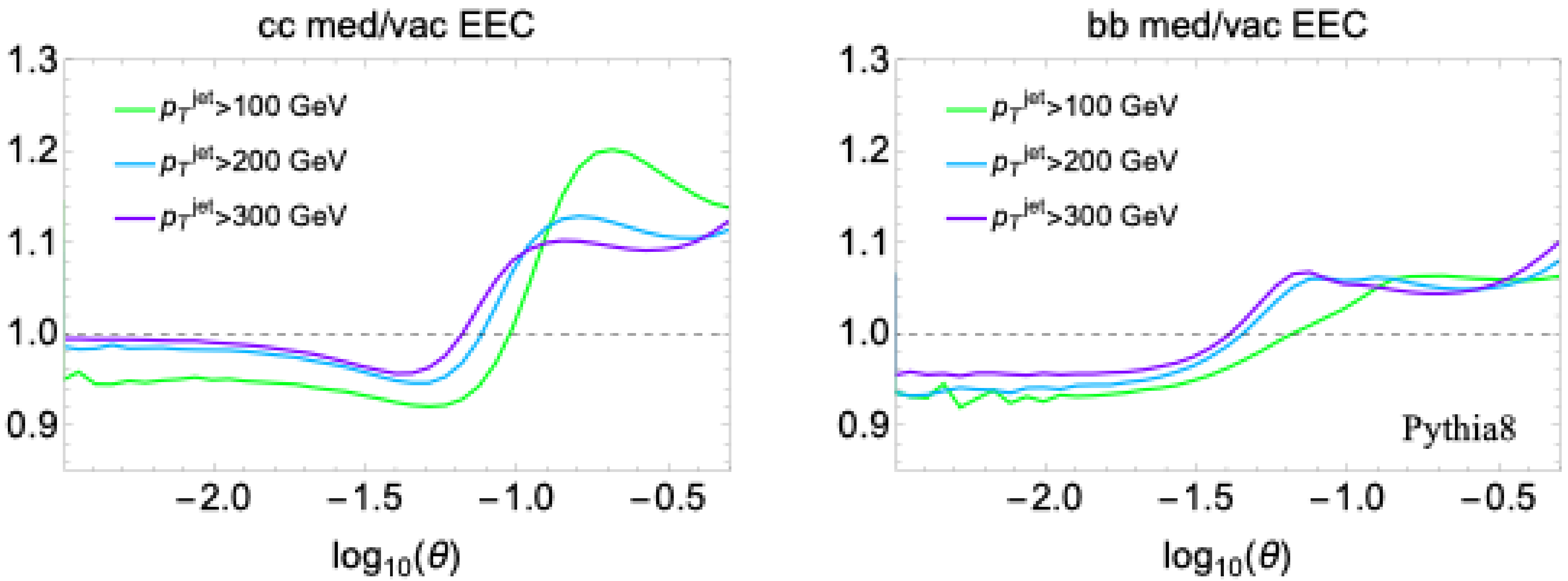
- Reweight events with $w^{\text{med}}_{g\to q\bar{q}} = 1 + \frac{\left(\frac{1}{Q^2}P_{g\to q\bar{q}}\right)^{\text{med}}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2}P_{g\to q\bar{q}}\right)^{\text{vac}}(E_g, k_c^2, z)}$



Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann *Phys.Rev.Lett.* 132 (2024) 21 [2209.13600]

Reproduces medium-modified splitting function, with realistic kinematics from vacuum shower

Medium modification of heavy flavor correlators



Qualitative signature of formation time effects at small angles

Estimating the effects of energy loss of the jet on heavy quark energy correlators

$$Q_i = \exp\left[-\int d\omega \int d^2\mathbf{k} \frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}})\right] = \exp\left[-\int_T^{\omega_s} d\omega \int d^2\mathbf{k} \frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}}) - \int_{\omega_s}^{\infty} d\omega \int d^2\mathbf{k} \frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}})\right]$$

Quenching weights

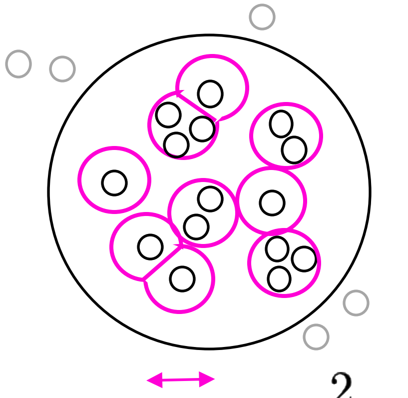
rapid turbulent thermalization; $\omega \ll \omega_c$

semi-hard perturbative gluon emission

Barata, Caucal, Soto-Ontoso, Szafron [2312.12527]

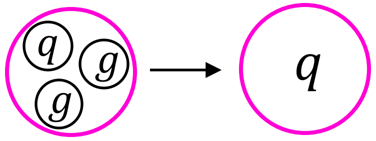
Energy loss of parton-level jets in Pythia assuming coherence within θ_c

- combine jet constituents into "clusters" of radius θ_c

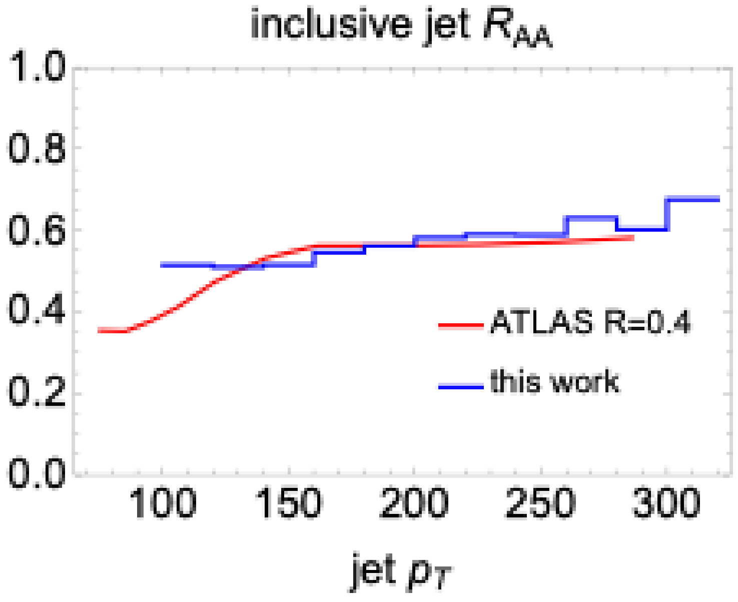


$$\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

- assign cluster flavor from parton content



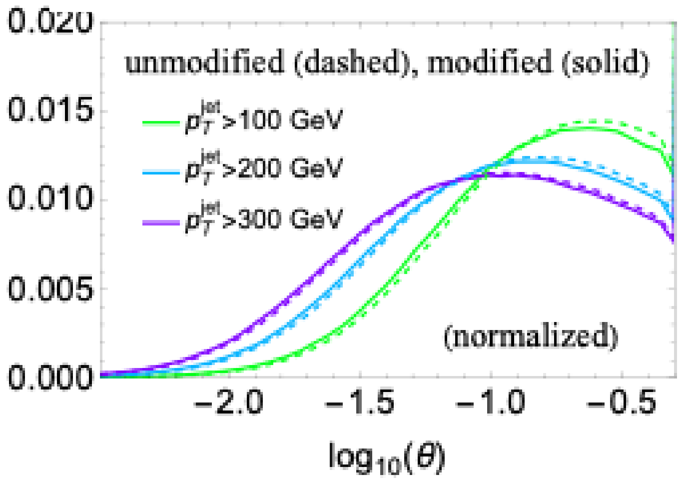
- jet energy loss is the sum of cluster energy loss



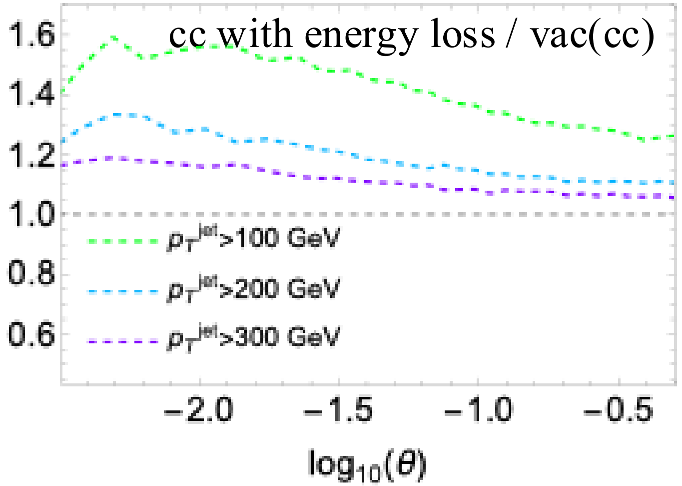
ATLAS [1411.2357]

Effects of energy loss on energy correlators of jets with two heavy quarks

Energy loss shifts the EEC toward smaller angles…

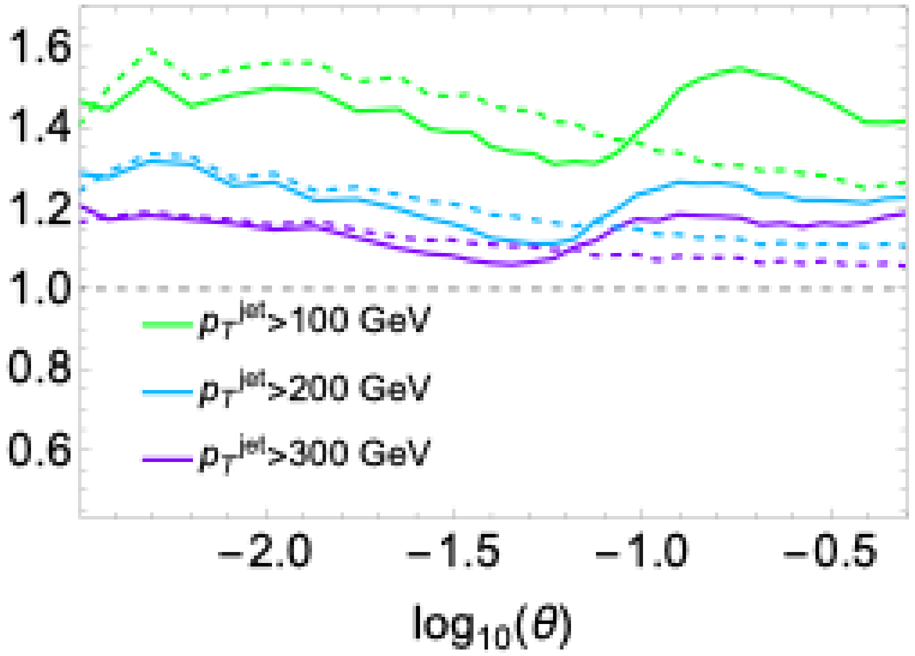


…and enhances the charm yield*



Putting it together: interplay of medium-modified $g \to c\bar{c}$ splitting with energy loss

med(cc) / vac(cc)

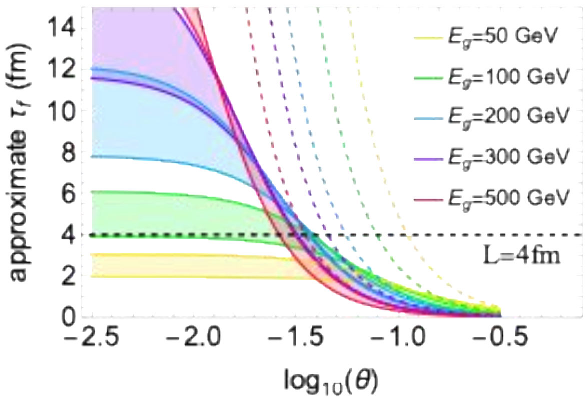


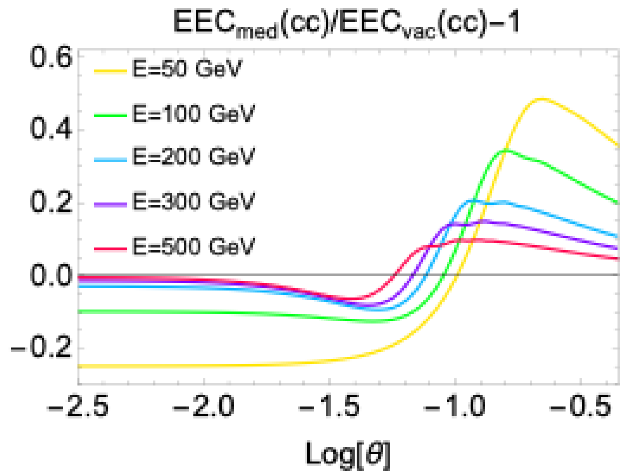
To dig out formation time effects, would like new ways to reduce energy loss effects

*(relative to the total number of jets)

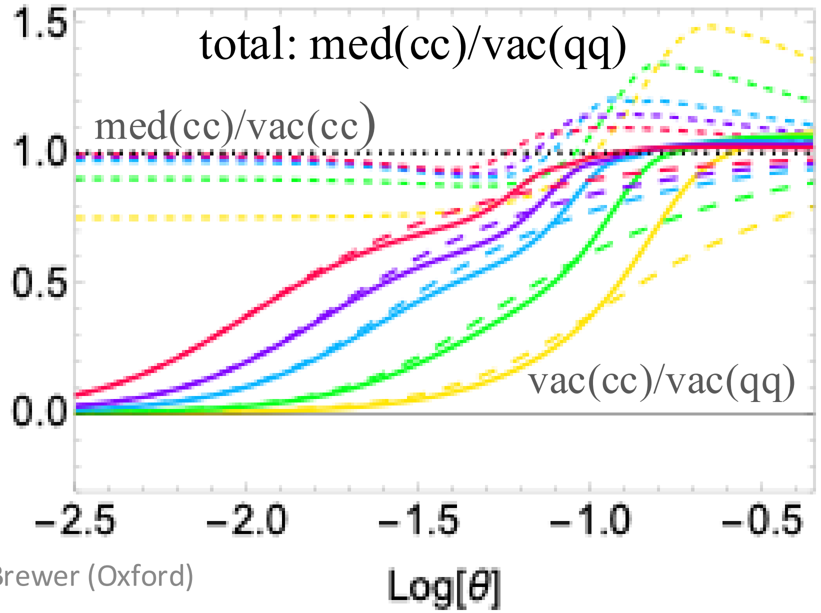
Conclusions

- Unique imprint of formation time in the medium modification of massive $g \to q\bar{q}$ energy correlators





- Interplay of mass effects and medium effects



- Medium effects persist in more realistic simulations with energy loss