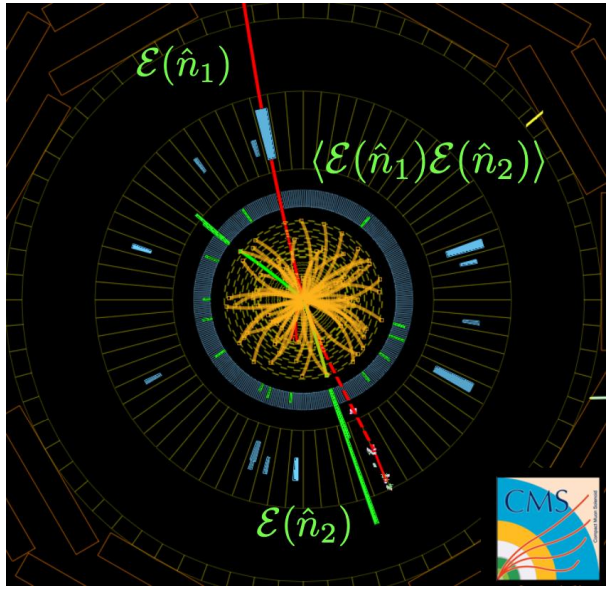
Energy correlators of the gluon splitting to heavy quarks

Jasmine Brewer

In collaboration with João Barata, Kyle Lee, and João Silva

Energy correlators for jets with two heavy quarks



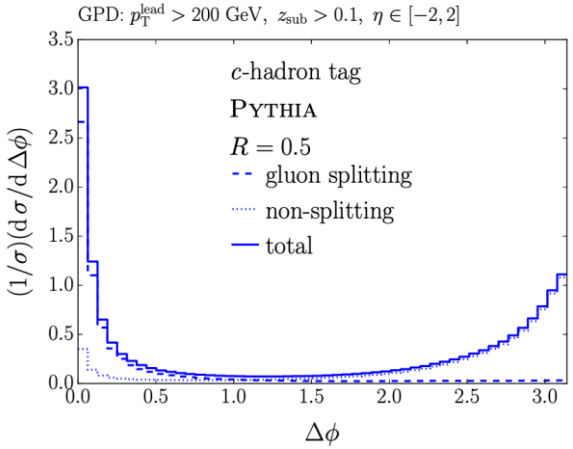
Energy correlators: re-organizing event information in terms of correlation functions of energy flow, sorted by angle

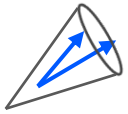
- Strong theoretical connection and perturbative control

  Hofman, Maldacena [0803.1467], Chen, Moult, Zhang, Zhu [2004.113811], etc

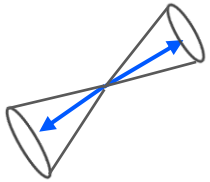
- Organize different physics effects into small/ large angle information

Andres, Dominguez, Holguin, Marquet, Moult [2202.11236, 2303.03413, 2307.15110]
Andres, Holguin, Kunnawalkam-Elayavalli, Viinikainen [2409.07514], Barata, Caucal, Soto-Ontoso, Szafron [2312.12527], Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal [2407.13818], Yan, He, Moult, Wang [2310.01500], etc





gluon splitting

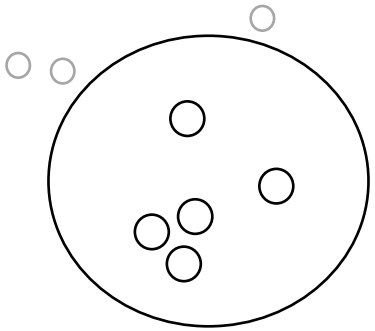


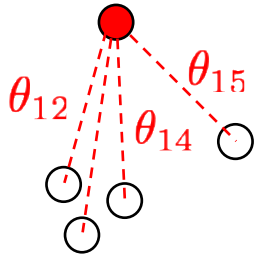
other processes

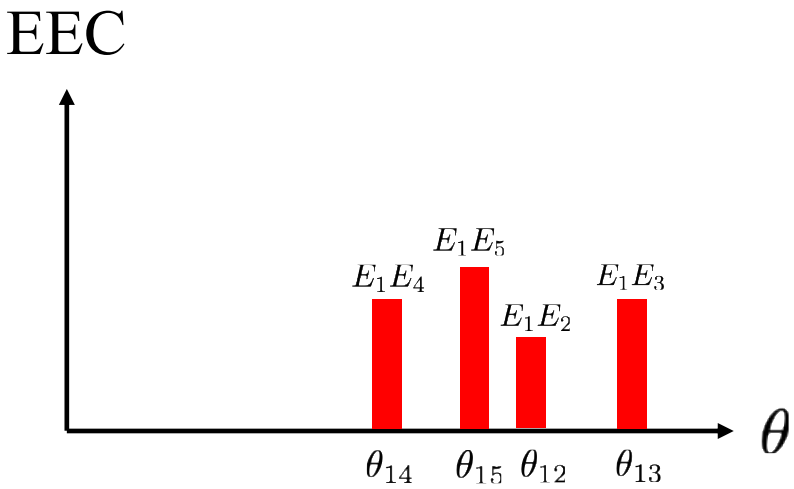
- Jets with two heavy hadrons provide opportunity to cleanly isolate only the $g \to Q\bar{Q}$ splitting

Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)

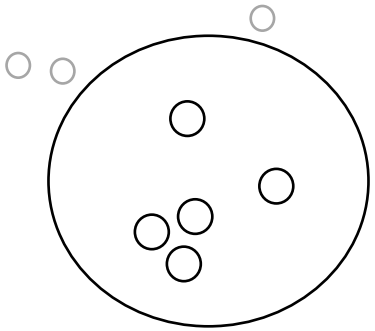


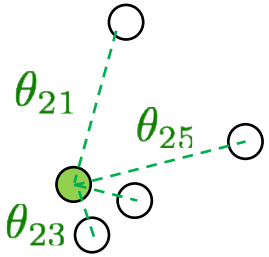




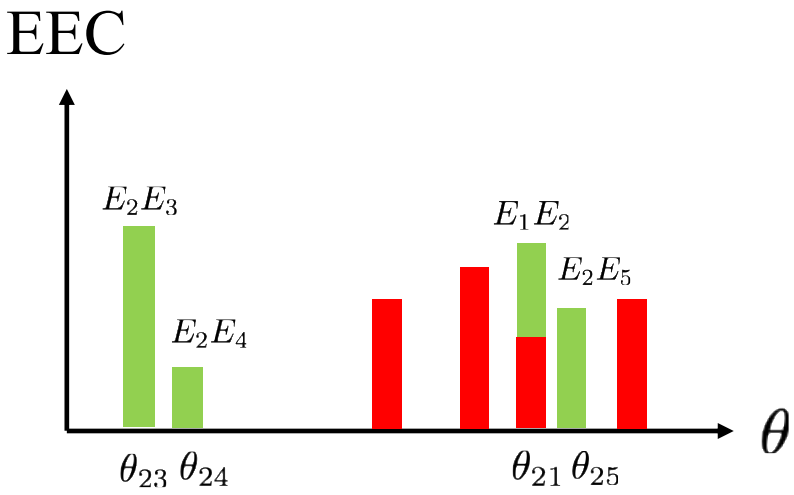
Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)



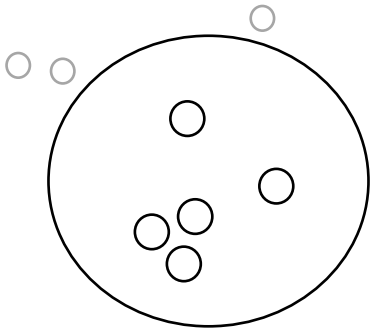


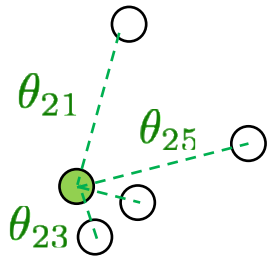
… etc for all particles and all events

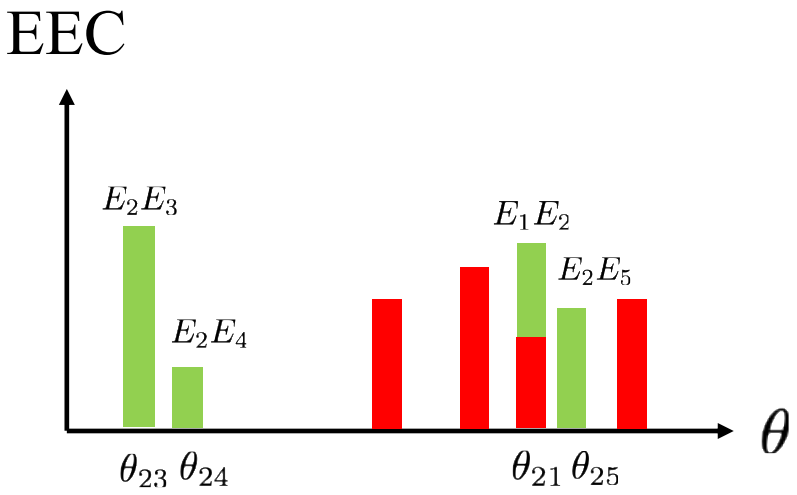


Energy correlators in jets with two heavy quarks

Normal EEC (without flavor tagging)

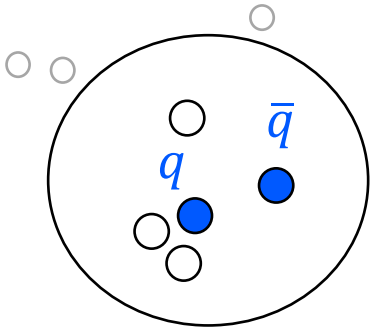


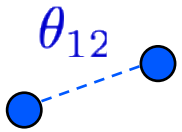


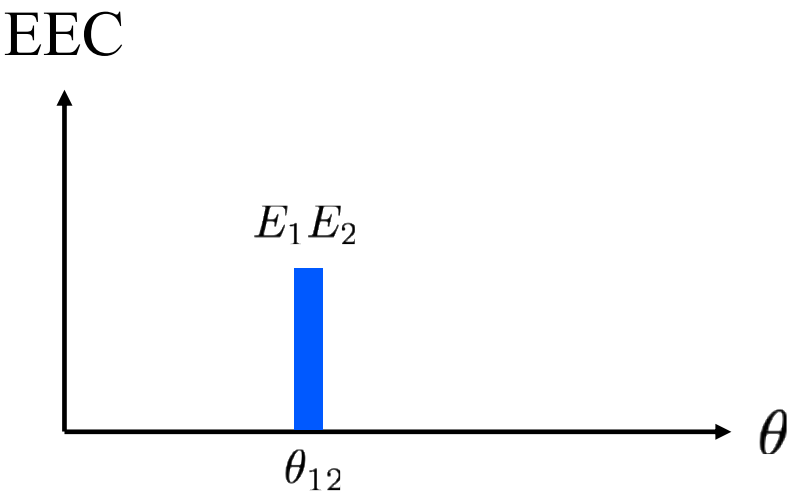


… etc for all particles and all events

EEC of heavy flavor jets



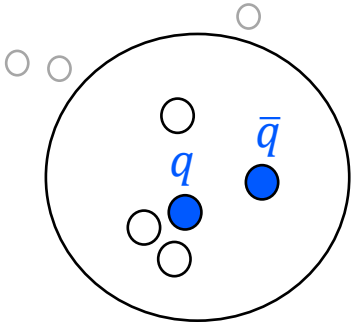


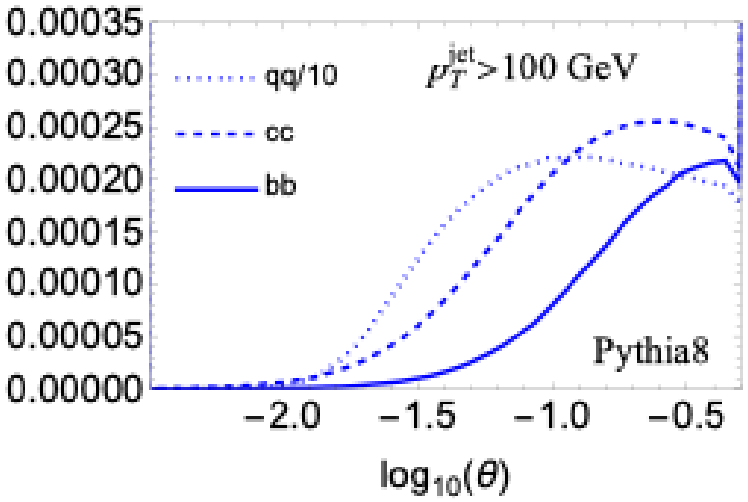


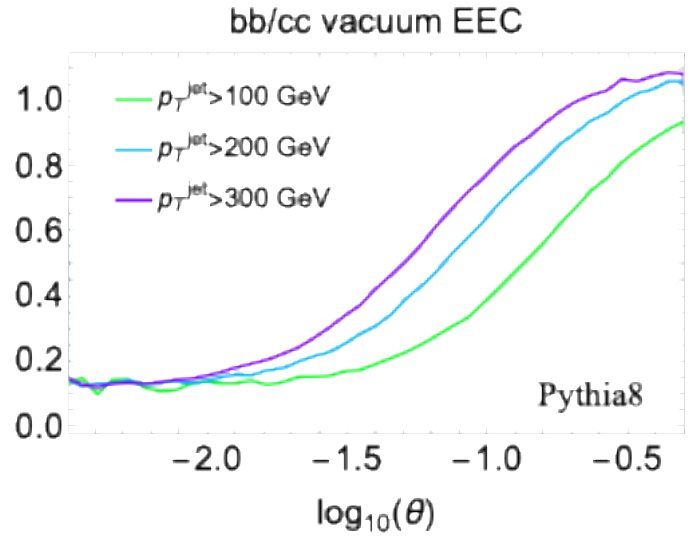
$$EEC(\theta) = \int dz \frac{P_{g\to q\bar{q}}(\theta, z)}{Q^2} z(1-z)$$

* throughout, normalize by total number of jets

In vacuum: quark mass effects in energy correlators







Heavier quarks tend to fragment earlier, at larger angles

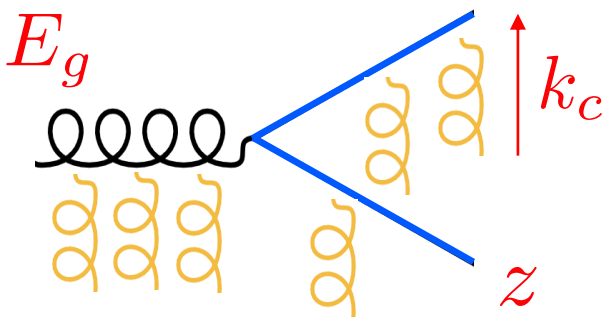
→ Characteristic suppression of heavy/light EEC at small angles

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]

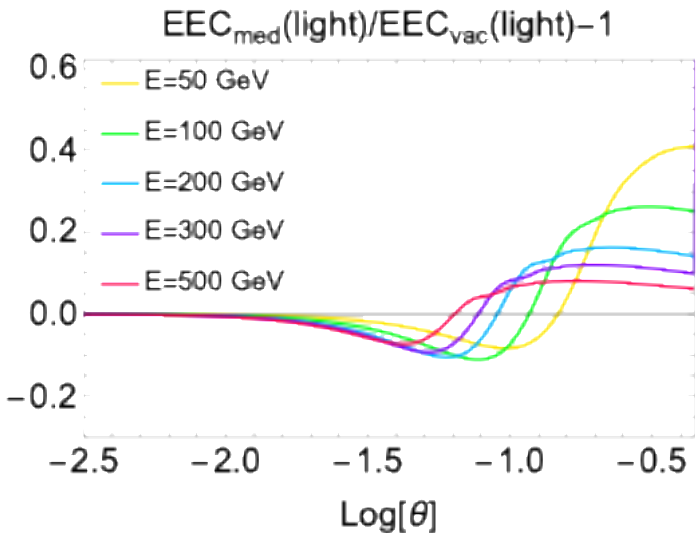
Results of the calculation:

- 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

See also talk by Urs Wiedemann

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



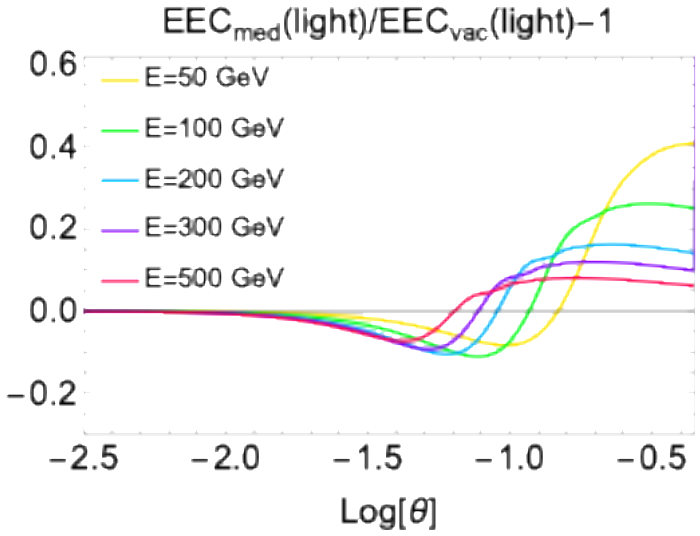
- Enhancement at large angles
- Depletion at intermediate angles

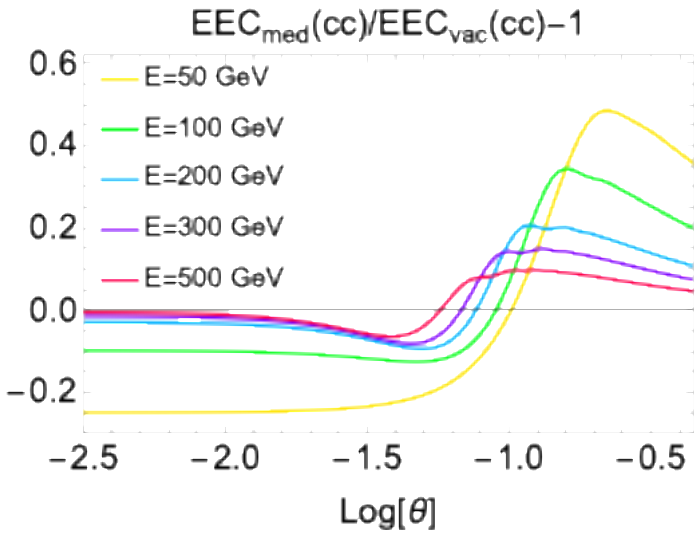
  Momentum broadening effect

- 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





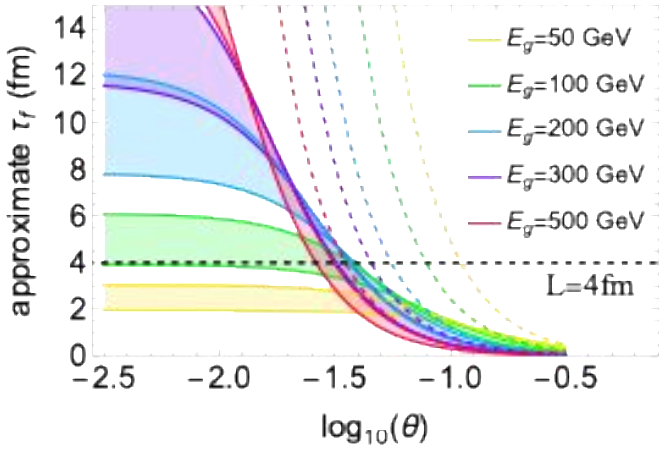
- Enhancement at large angles
- Depletion at intermediate angles

  Momentum broadening effect
- No modification at very small angles

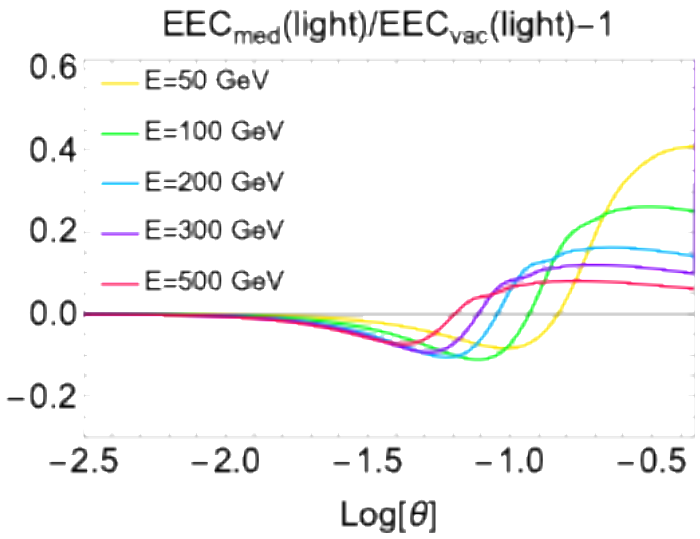
At small enough angles, massless splittings are always formed outside the medium

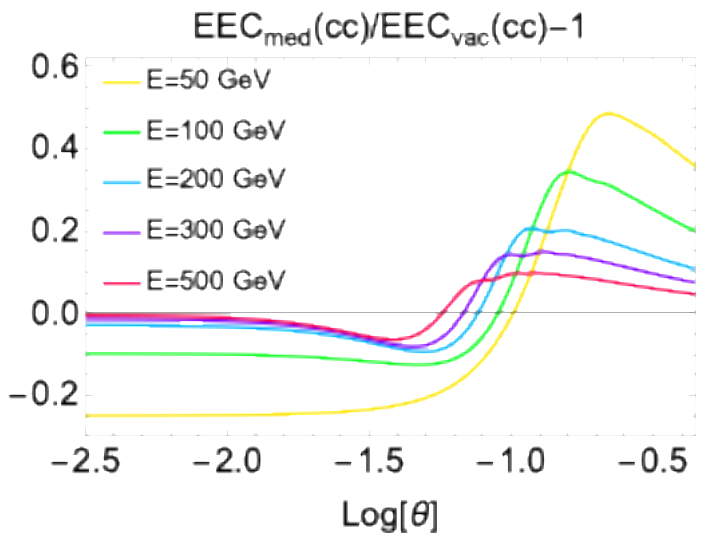
With quark masses, splittings can be formed in the medium for all angles!

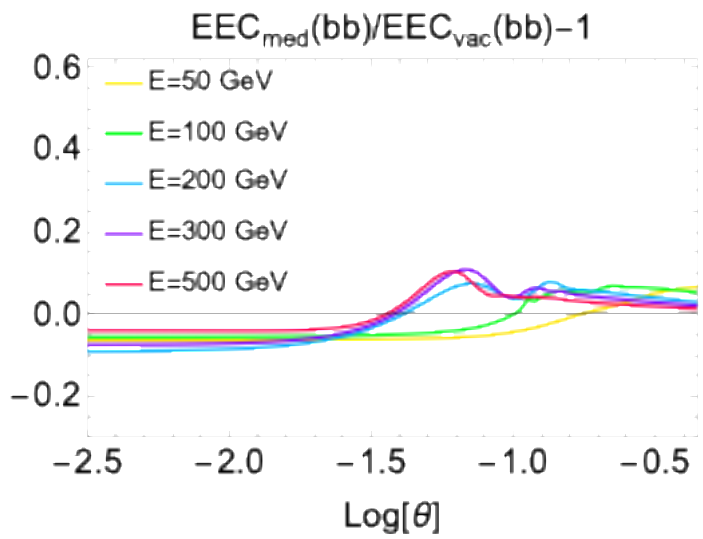
$$\tau_f \sim \frac{2E_g z(1-z)}{m^2 + E_g^2 z^2 (1-z)^2 \theta^2}$$



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







- Enhancement at large angles
- Depletion at intermediate angles

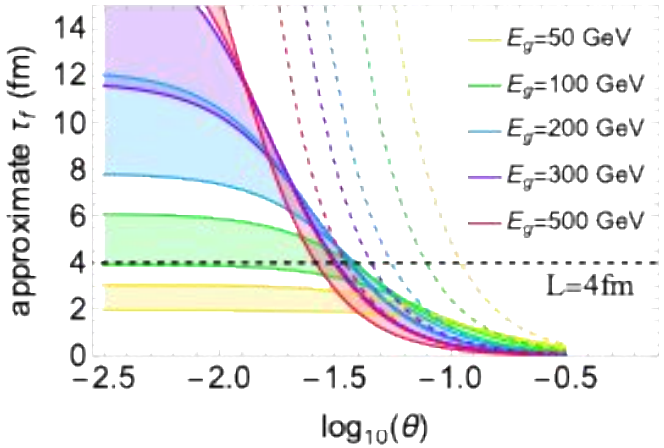
  Momentum broadening effect

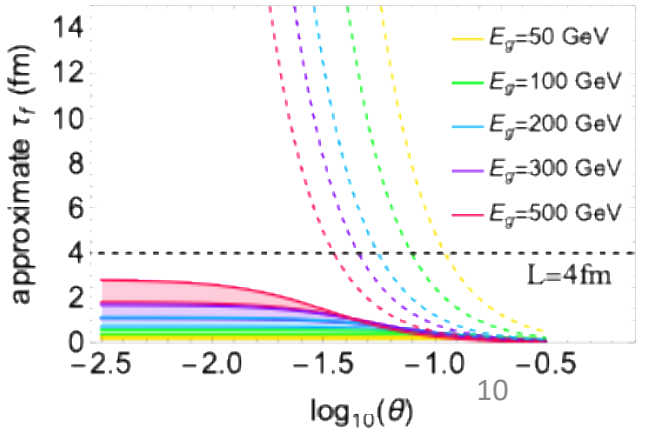
- No modification at very small angles

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!

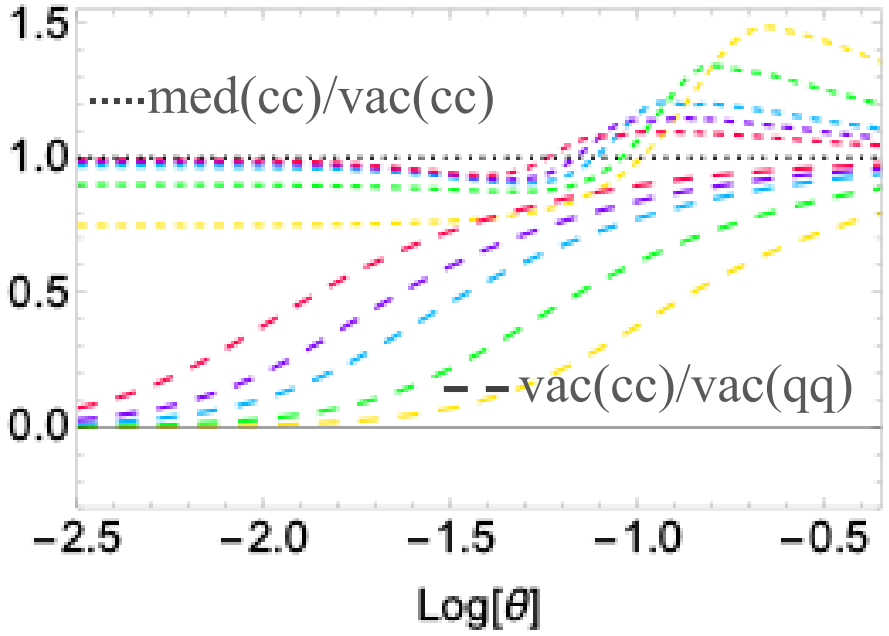
$$\tau_f \sim \frac{2E_g z(1-z)}{m^2 + E_g^2 z^2 (1-z)^2 \theta^2}$$

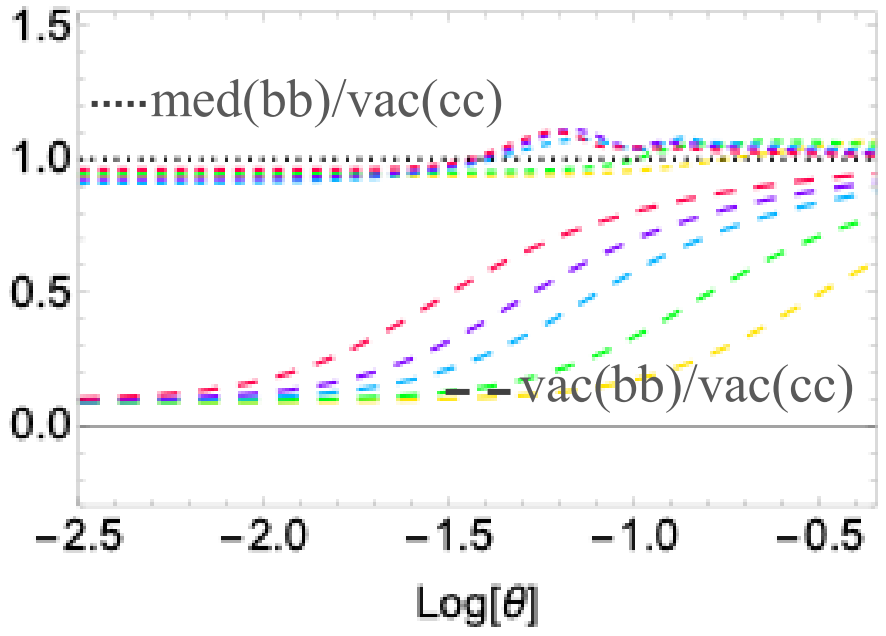


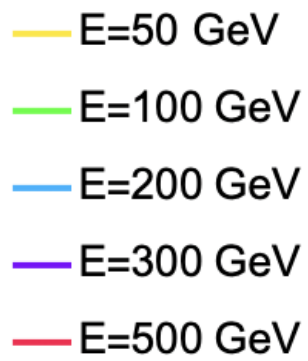


Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators

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



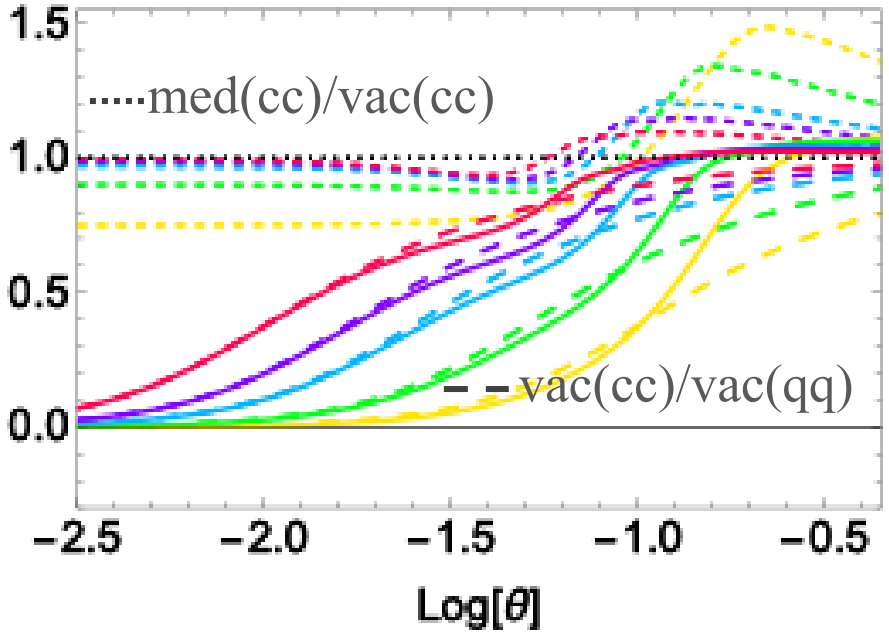




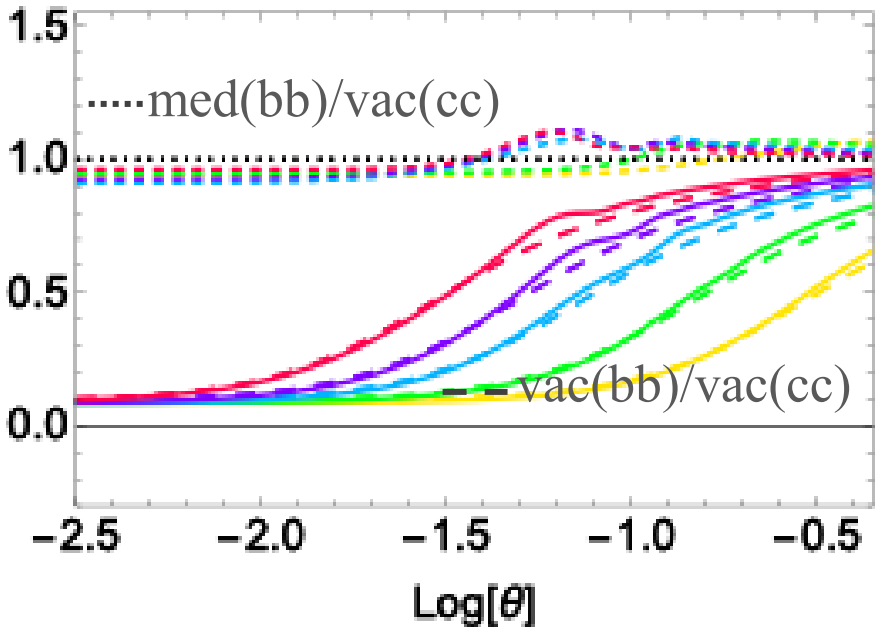
Medium modification of the $g \to q\bar{q}$ splitting function in energy correlators

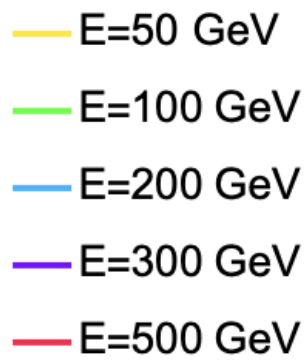
Dead cone effects and medium effects populate different angular regions in energy correlators

— med(cc)/vac(qq)



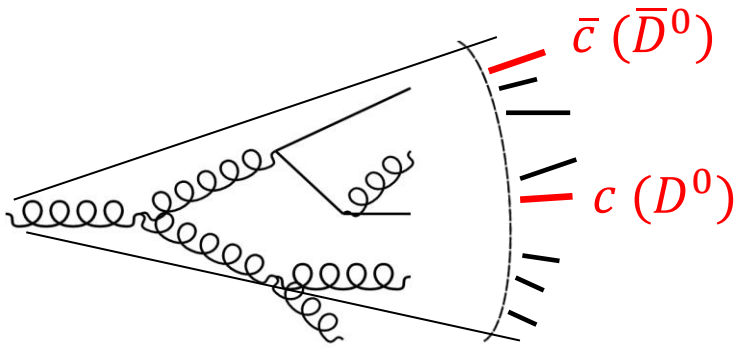
— med(bb)/vac(cc)



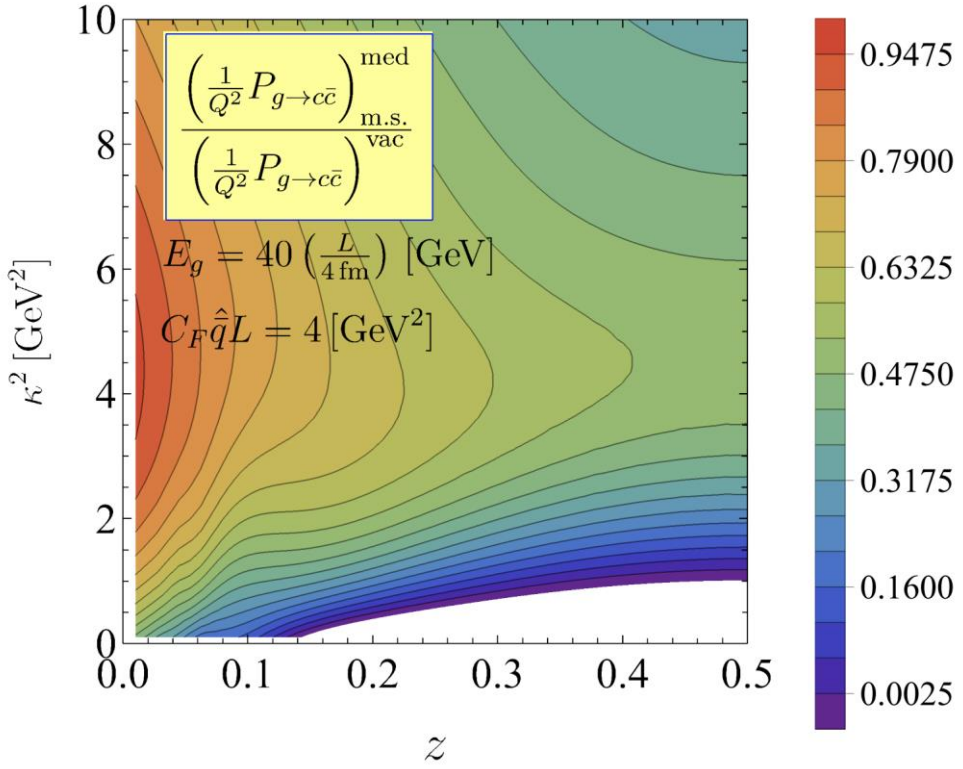


Next step: understanding the impact of medium modification in phenomenology

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



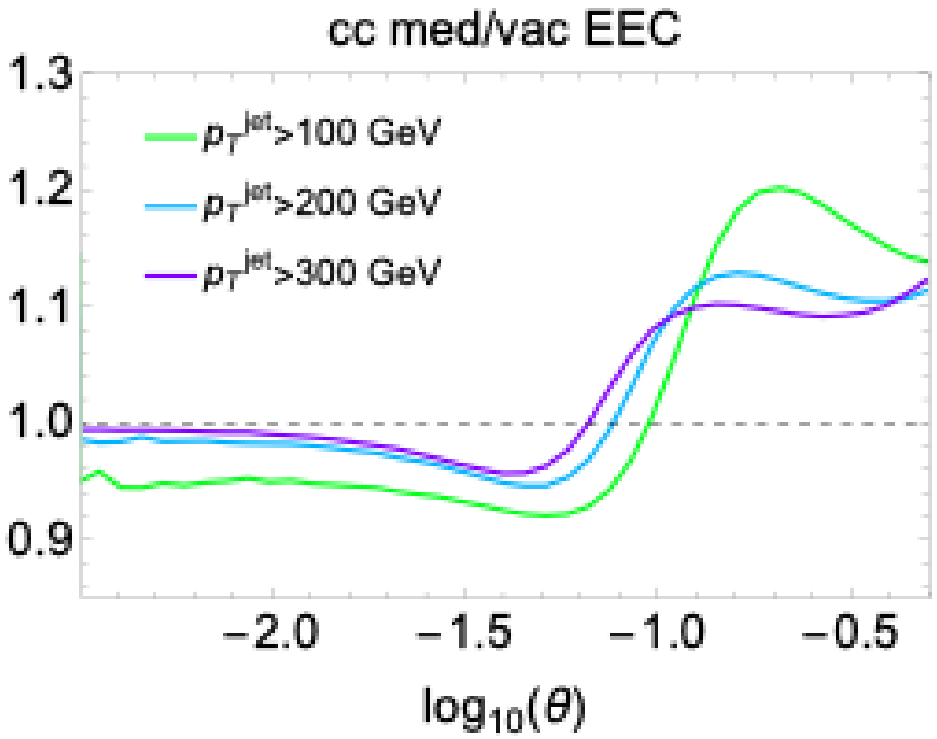
- Find jets containing $c\bar{c}$ (or $D\bar{D}$) pairs in vacuum Monte Carlo simulations (Pythia)
- Use shower to reconstruct kinematics of the $g \to c\bar{c}$ splitting
- Reweight events with $w^{\text{med}}_{g\to q\bar{q}} = 1 + \dfrac{\left(\frac{1}{Q^2}P_{g\to q\bar{q}}\right)^{\text{med}}(E_g, k_c^2, z)}{\left(\frac{1}{Q^2}P_{g\to q\bar{q}}\right)^{\text{vac}}(E_g, k_c^2, z)}$

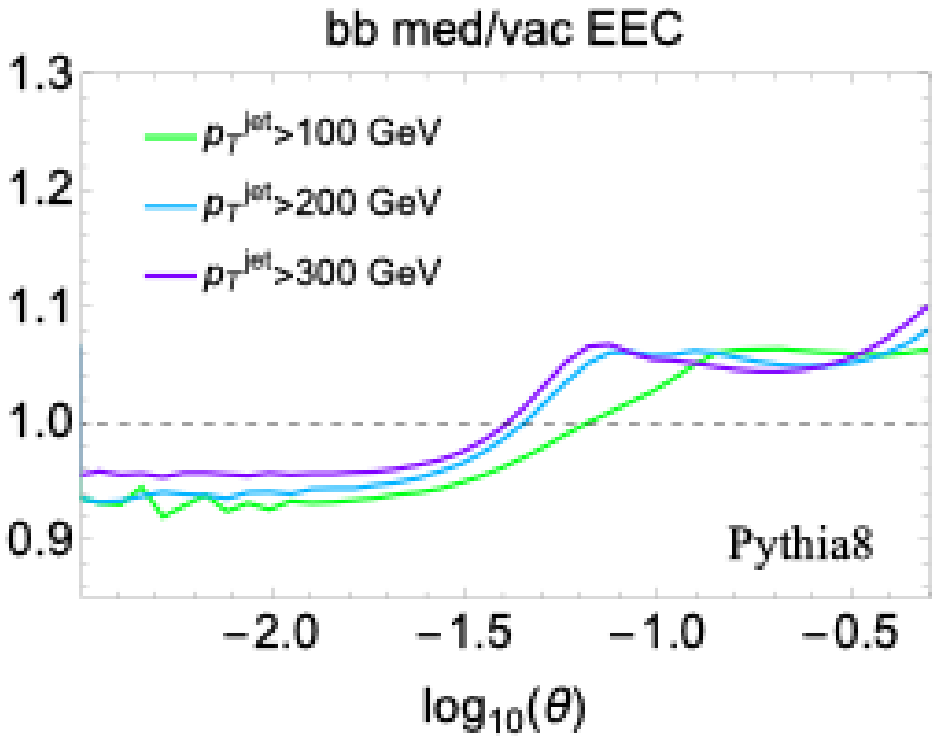


Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann *Phys.Rev.Lett.* 132 (2024) 21 [2209.13600]

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

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

Quenching weights

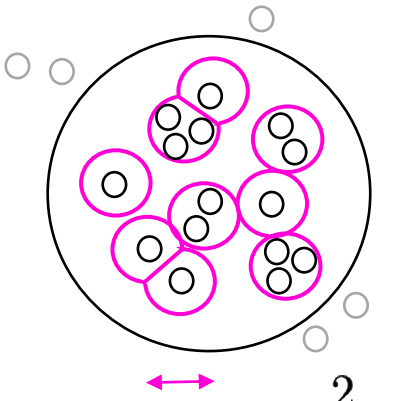
rapid turbulent thermalization; $\omega \ll \omega_c$

semi-hard perturbative gluon emission

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

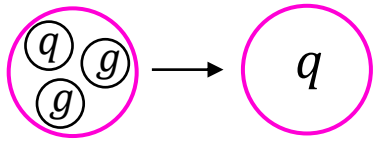
Energy loss of parton-level jets in Pythia assuming coherence within θ_c

- combine jet constituents into "clusters" of radius θ_c

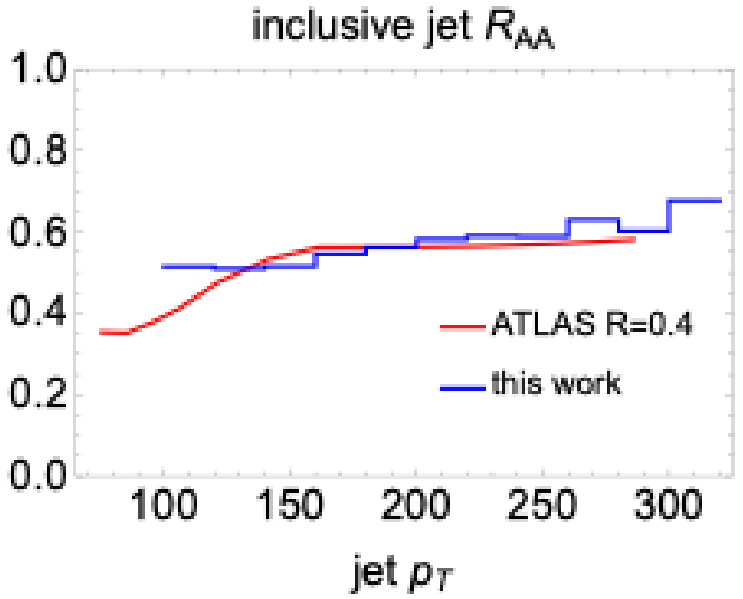


$$\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

- assign cluster flavor from parton content



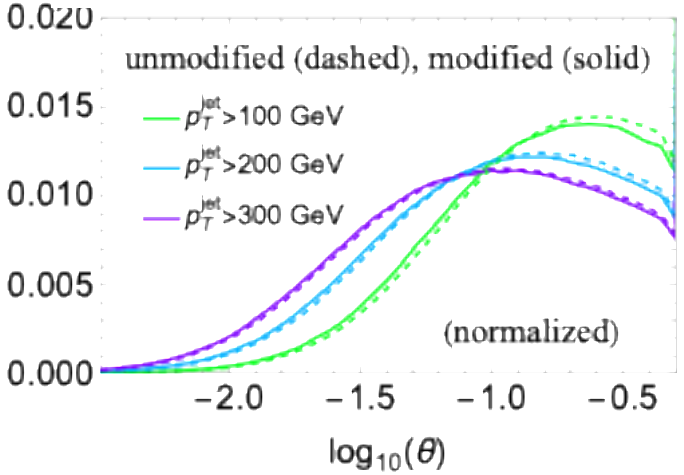
- jet energy loss is the sum of cluster energy loss



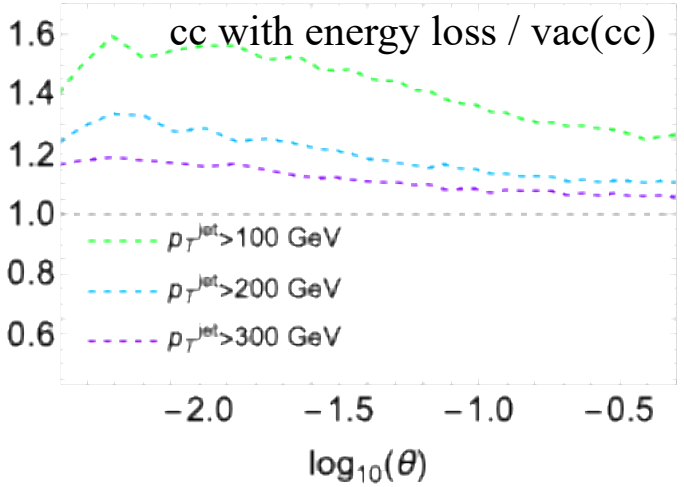
ATLAS [1411.2357]

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

Energy loss shifts the EEC toward smaller angles…



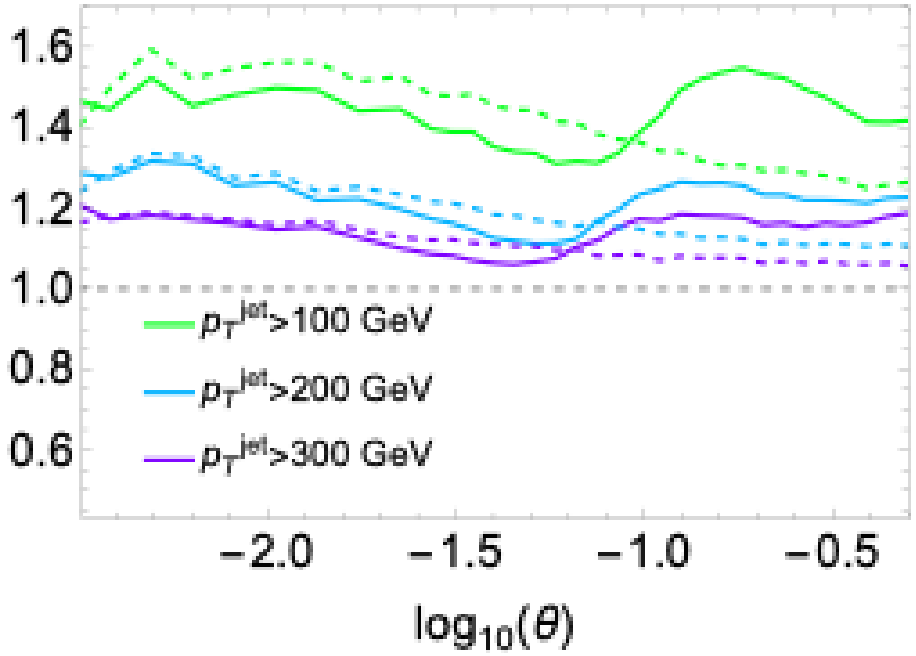
…and enhances the charm yield*



*(relative to the total number of jets)

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

med(cc) / vac(cc)



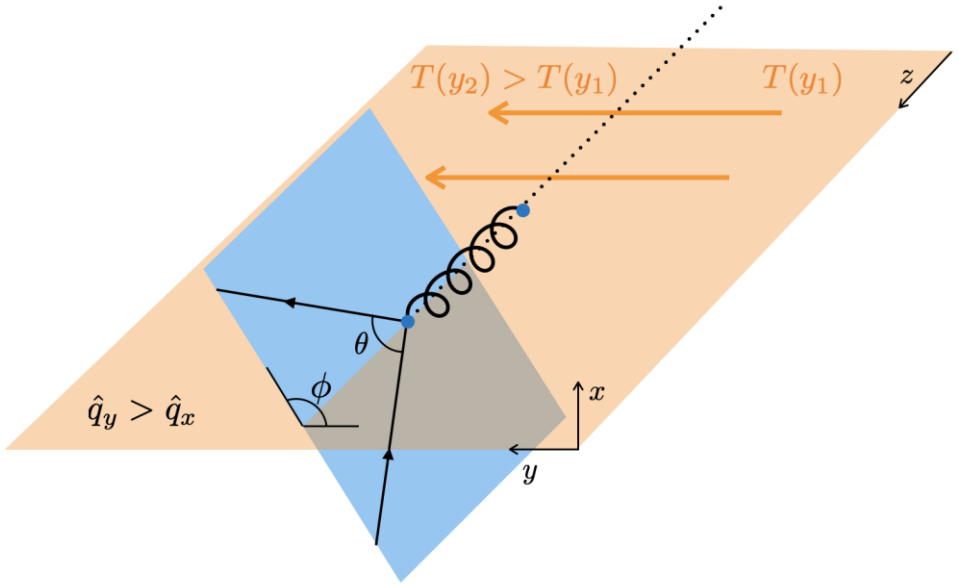
To dig out formation time effects, would like new ways to reduce energy loss effects

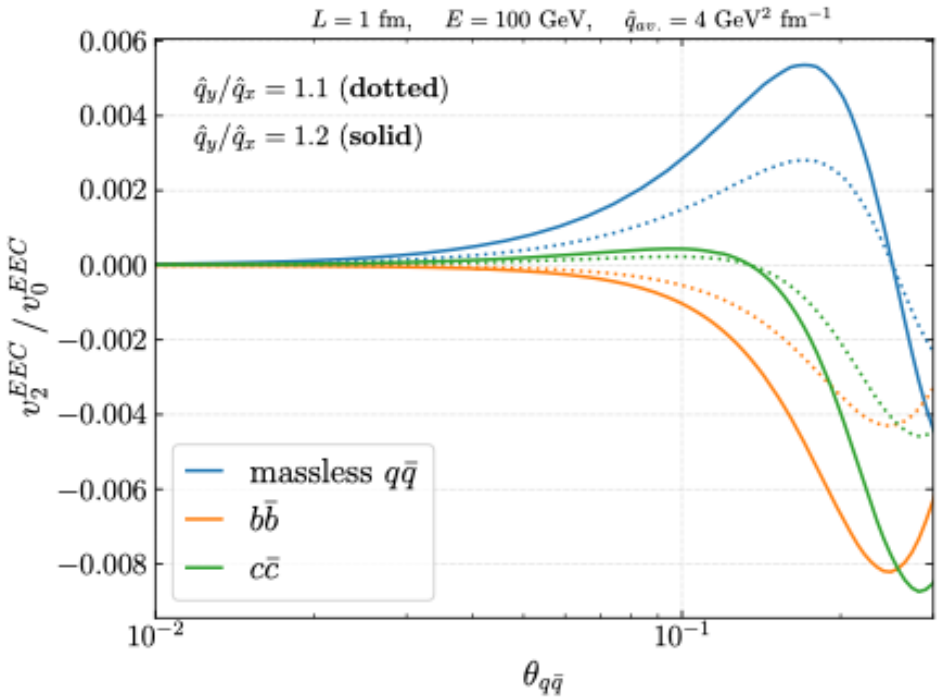
See talk by Carlota Andres

Advertisement: effects of medium anisotropies on heavy quark correlators

Talk by João Silva in 20 minutes in Parallel 30

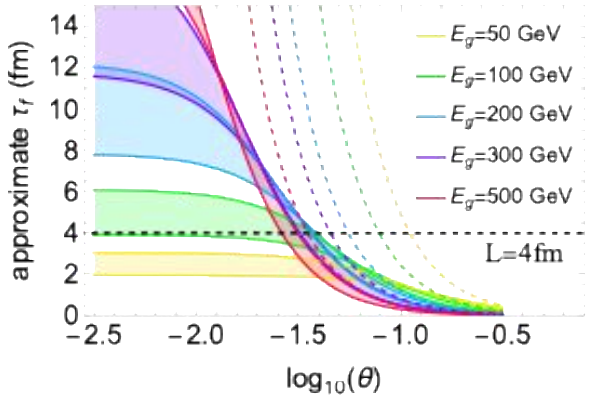
- opportunity to study strong, local medium anisotropies, as may be present at very early times
- ideal since heavy quarks are produced early

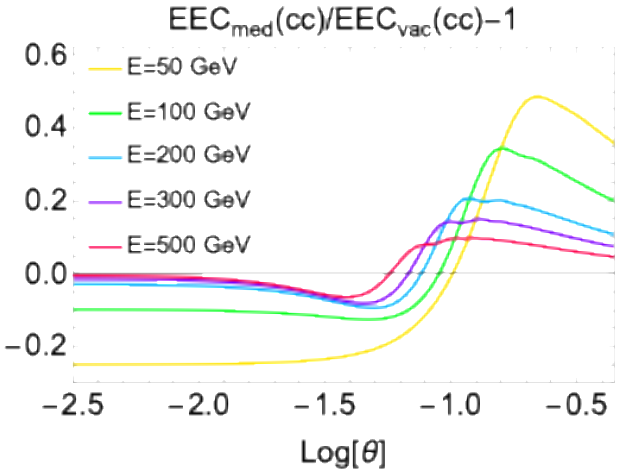




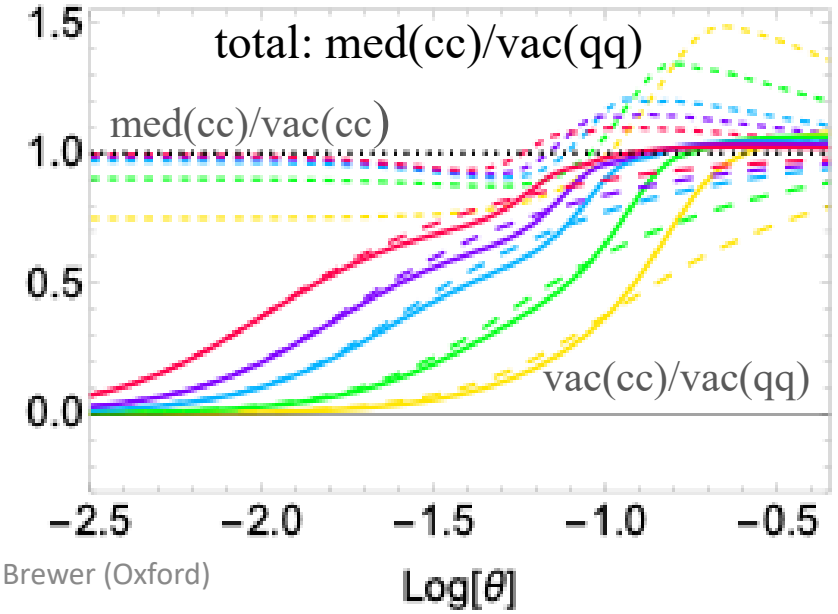
Conclusions

- 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