g → ccbar - ~~quenching~~ enhanced radiation, formation time, and all that …

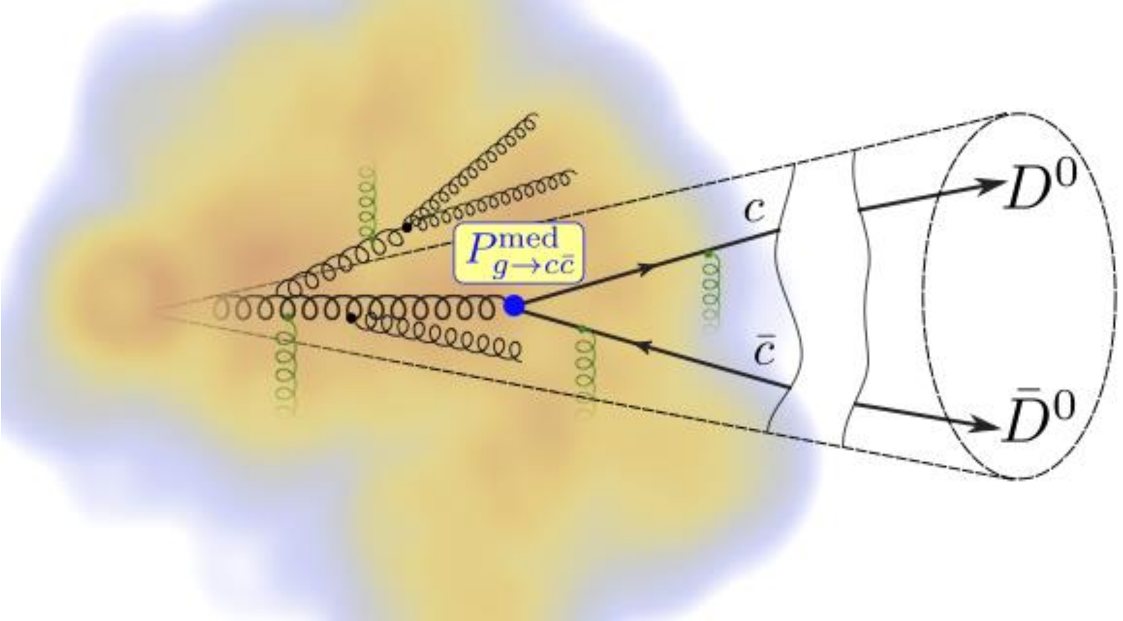
Hard Probes, Nagasaki, Japan

Urs Achim Wiedemann
24 Sept 2024

based on:
M. Attems, J. Brewer, G.M. Innocenti, A. Mazeliauskas, S. Park, W.v.d. Schee, U.A. Wiedemann, **JHEP 01 (2023) 080**

M. Attems, J. Brewer, G.M. Innocenti, A. Mazeliauskas, S. Park, W.v.d. Schee, G. Soyez, U.A. Wiedemann, **PRL 132 212301 (2024)**

J. Brewer, W.v.d. Schee, U.A. Wiedemann, **in preparation**



Heavy Flavor – unique opportunities

Exploited in this work

- ☐ **Calculable perturbatively**

  σ^{QQ}_{tot} and high-pT spectra

- ☐ **Conserved on QGP time scale**

- ☐ **Traceable experimentally**

  via displaced vertices or $c \to D^0 \to K^+\pi^-$

- ☐ **No soft singularity in $g \to c\bar{c}$**

  Advantage for reconstructing splitting via grooming

- ☐ **Exp Upgrades <=> TH Upgrades**

  HL-LHC, ALICE3, …

$$d\sigma = \text{pdf} \otimes \text{Hard} \otimes \text{Frag}$$

☐ Hard production is **short distance***,

$$\hat{s} \sim Q^2_{c\bar{c}} \gg 4m_c^2 \gg T\,, Q_s$$

yield **unaffected by QCD medium**

- ☐ Charmed hadron spectroscopy, hadronization, …
- ☐ …

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* M. Cacciari et al, JHEP 10 (2012) 137

Heavy flavor production as a **long distance** process

Collinear limit

$$\hat{\sigma}^{gg\to c\bar{c}X}\Big|_{Q^2_{c\bar{c}}\ll\hat{s}} \longrightarrow \hat{\sigma}^{gg\to gX}\,\frac{\alpha_s}{2\pi}\,\frac{1}{Q^2_{c\bar{c}}}\,P_{g\to c\bar{c}}$$

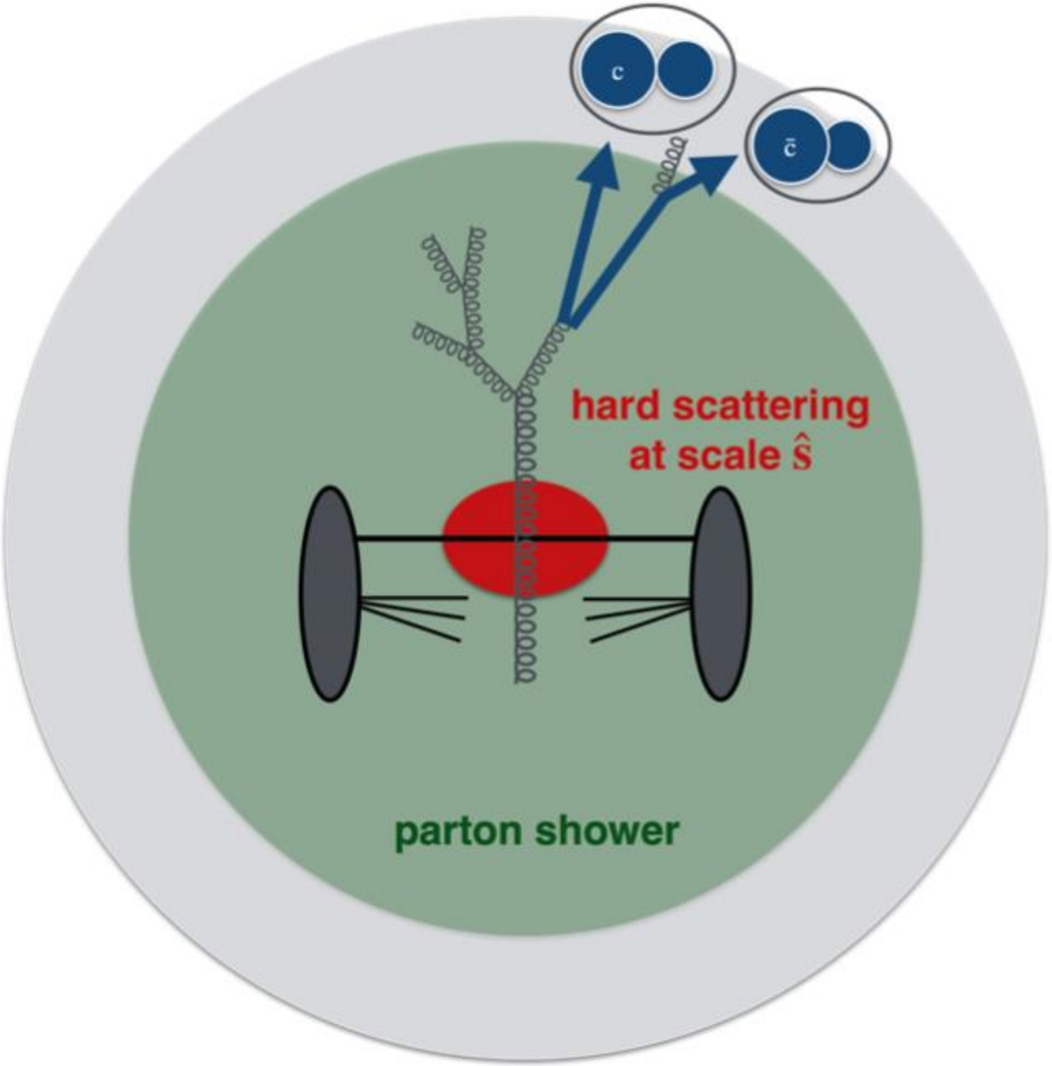
- ☐ g -> c cbar is long-distance.

  Formation time is **boosted**

$$\tau_{g\to c\bar{c}} \sim \frac{1}{Q_{c\bar{c}}}\,\frac{E_g}{Q_{c\bar{c}}}$$

- ☐ g-> c cbar medium-modified if boosted sufficiently

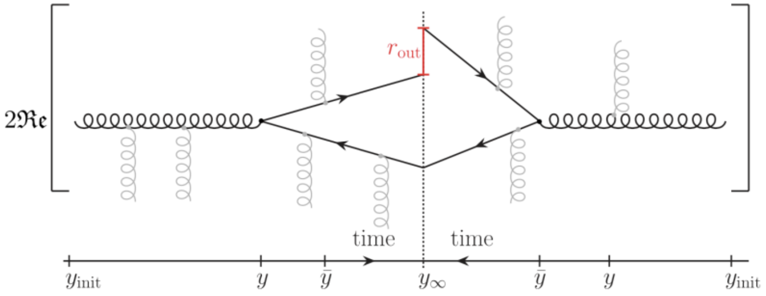
- ➢ **ccbar enhancement in jets**
- ➢ momentum broadening of c-cbar pair …



What we have calculated …

Medium-modified g-> c cbar splitting function* in Baier-Dokshitzer-Mueller-Peigné-Schiff / Zakharov formalism

(many other recent developments**)



$$\left(\frac{1}{Q^2}\,P_{g\to c\,\bar c}\right)^{\rm tot} \equiv \left(\frac{1}{Q^2}\,P_{g\to c\,\bar c}\right)^{\rm vac} + \left(\frac{1}{Q^2}\,P_{g\to c\,\bar c}\right)^{\rm med}$$

$$= 2\,\mathfrak{Re}\,\frac{1}{4\,E_g^2}\int_{t_{\rm init}}^{t_\infty} dt \int_t^{t_\infty} d\bar t\, \exp\left[i\frac{m_c^2}{2E_g z(1-z)}(t-\bar t) - \epsilon|t| - \epsilon|\bar t|\right]\int d\mathbf{r}_{\rm out}$$

$$\times \exp\left[-\frac{1}{2}\int_{\bar t}^{\infty} d\xi\, n(\xi)\,\sigma_3(\mathbf{r}_{\rm out}, z)\right]\exp\left[-i\,\boldsymbol{\kappa}\cdot\mathbf{r}_{\rm out}\right]$$

$$\times \left[\left(m_c^2 + \frac{\partial}{\partial \mathbf{r}_{\rm in}}\cdot\frac{\partial}{\partial \mathbf{r}_{\rm out}}\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right]\mathcal{K}\left[\mathbf{r}_{\rm in}=0, t; \mathbf{r}_{\rm out}, \bar t\right] .$$

$$\sigma_3(\mathbf{r}, z) \equiv -\frac{1}{2N_c}\sigma(\mathbf{r}) + \frac{N_c}{2}\sigma(z\mathbf{r}) + \frac{N_c}{2}\sigma((1-z)\mathbf{r})\,.$$

- ☐ Confirms **formation time** estimate

$$\tau_{g\to c\bar c} = \frac{2}{Q}\,\frac{E_g}{Q}$$

- ☐ Sensitive to **color field strength of medium**

$$\hat q \equiv \frac{\langle \mathbf{q}^2\rangle_{\rm med}}{\lambda_{\rm mfp}}$$

- ☐ Numerically sizeable for

$$\boxed{\langle \mathbf{q}^2\rangle_{\rm med} = \int_{\tau_i}^{\tau_f} d\tau\,\hat q(\tau) \sim \mathcal{O}(m_c^2)}$$

- ☐ Geometrically enhanced power-correction

$$P^{\rm med}_{g\to q\bar q} \sim \mathcal{O}\left(\frac{\langle \mathbf{q}^2\rangle_{\rm med}}{Q^2}\right)$$

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* ABIMSSW, **JHEP 01 (2023) 080** ** L. Apolinario et al, 1407.0599, F. Dominguez et al., 1907.03653, Isaksen et al., 2107.02542, 2206.02811 M. Sievert et al, 1903.06170, S. Caron-Huot&Gale, 1006.2379

g-> c-cbar: N=1 opacity:

Here, uniform QGP brick of length L and density n_0.

$$\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{med}}_{N=1} = \frac{1}{2}n_0\,L\int\frac{d\mathbf{q}}{(2\pi)^2}\underbrace{|a_3(\mathbf{q},z)|^2}_{\sigma_{\mathrm{elastic}}(\mathbf{q},z)}\underbrace{\left(1-\frac{1}{L/\tau_F}\sin\left[L/\tau_F\right]\right)}_{\text{formation time}}(\mathrm{BROAD}+\mathrm{RAD})$$

- characteristic **formation time dependence**, medium modification negligible for $\tau_F > L$, interpolation btw. coherent and incoherent limits.

$$\boxed{\frac{1}{\tau_F} = \frac{m_c^2+(\kappa+\mathbf{q})^2}{2E_g\,z(1-z)} = \frac{Q_1^2}{2E_g}}$$

- $g\to c\,\bar{c}$ that would occur in vacuum, undergo **momentum broadening**

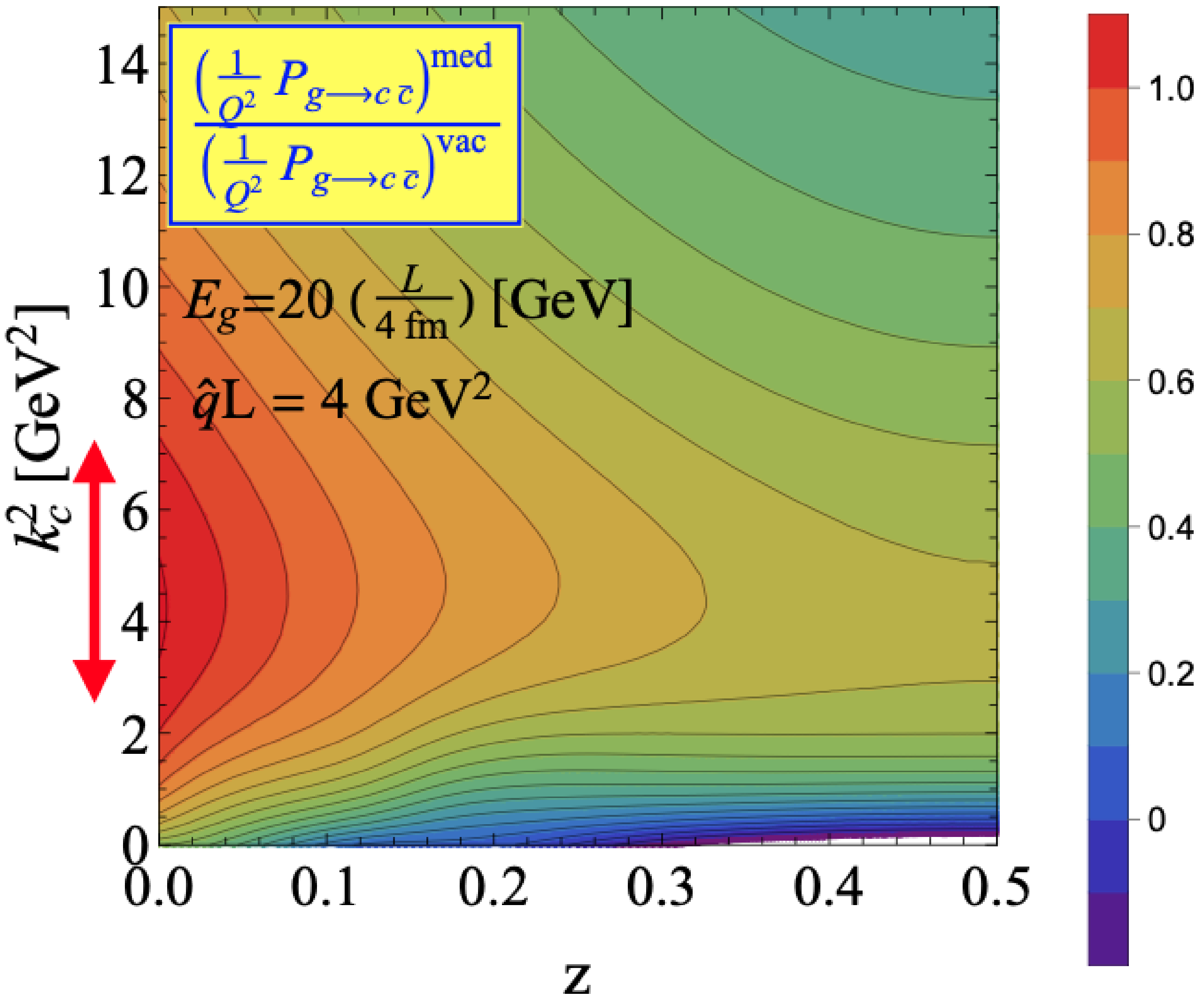
$$\mathrm{BROAD} = \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{vac}}_{\kappa\to\kappa+\mathbf{q}} - \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{vac}}$$

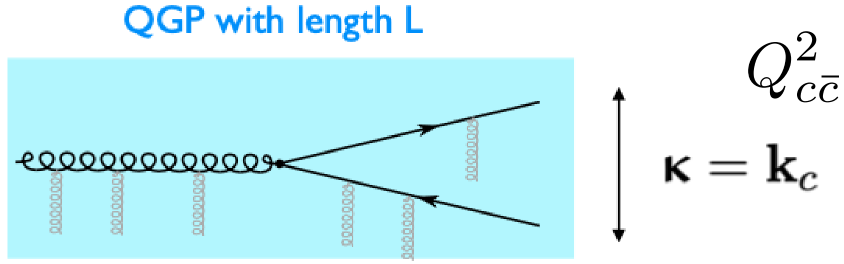
- In addition, we find stimulated medium-induced $g\to c\,\bar{c}$ radiation "RAD"

  We confirm this also in independent calculation in which "vacuum splitting is switched off".

* ABIMSSW, **JHEP 01 (2023) 080**

Medium-modified $g \to c\,\bar{c}$ splitting: numerical results





$$Q^2_{c\bar{c}} \simeq \frac{m_c^2 + k_c^2}{z(1-z)}$$

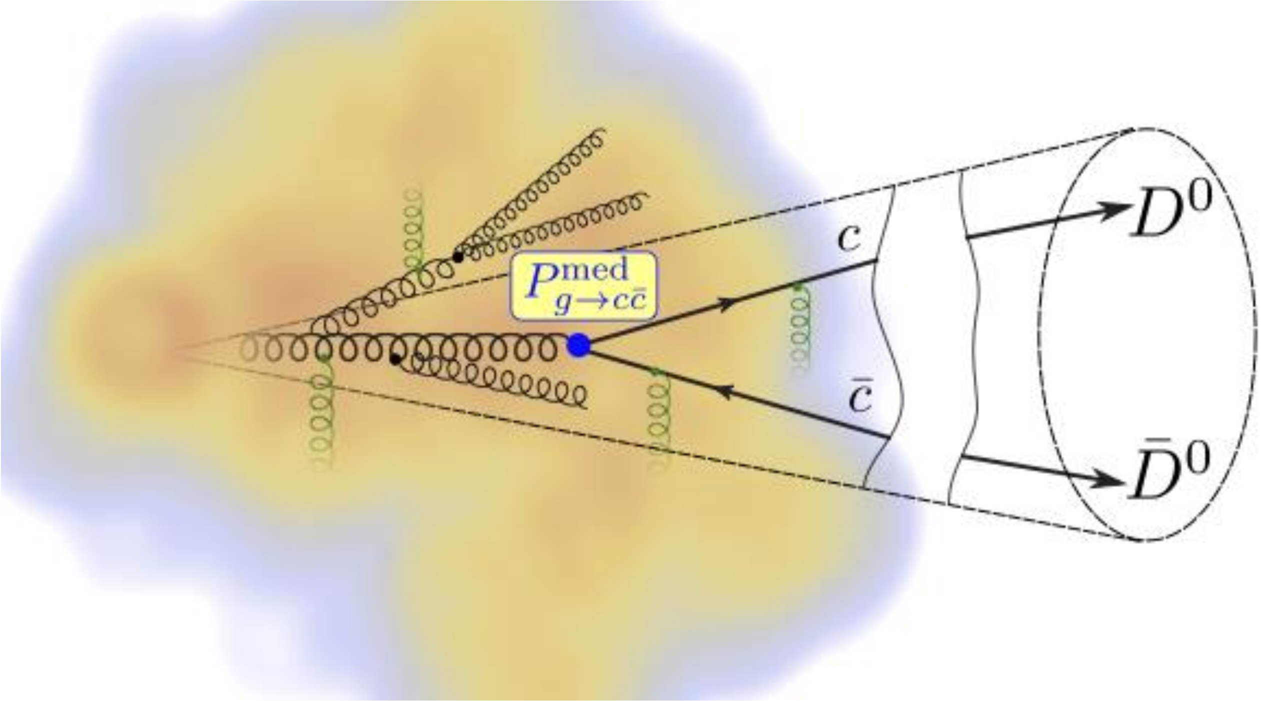
Numerically significant medium-stimulated c-cbar radiation.

Broadening depletes low transverse momentum.

* ABIMSSW, **JHEP 01 (2023) 080**

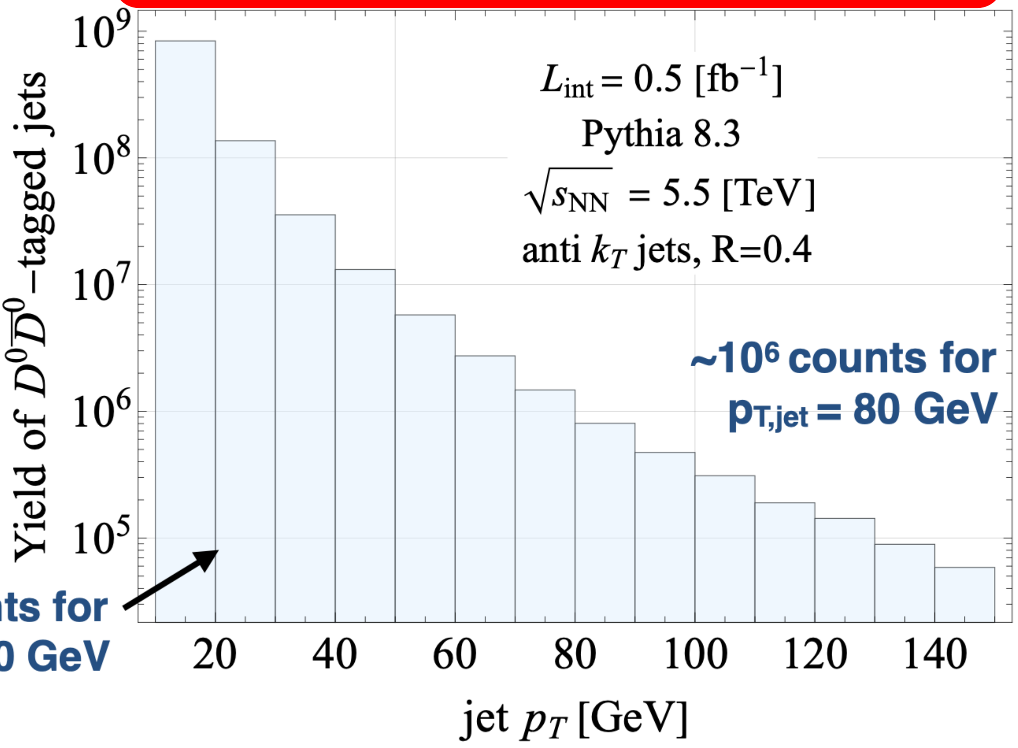
Integrated luminosity requirements

- To measure medium-enhanced c-cbar, one needs boosted gluons (i.e. jets) and identified charm



HL-LHC luminosity

L_{int} = 0.5 fb^{-1} pp ~ 10 nb^{-1} PbPb (no quenching)



~10^6 counts for $p_{T,\text{jet}}$ = 80 GeV

~10^8 counts for $p_{T,\text{jet}}$ = 20 GeV

- The two-body decay of D^0 can be reconstructed, but $BR(D^0 \to K^-\pi^+) \sim 4\%$
- The more abundant semi-leptonic decays of open charm remains to be explored.

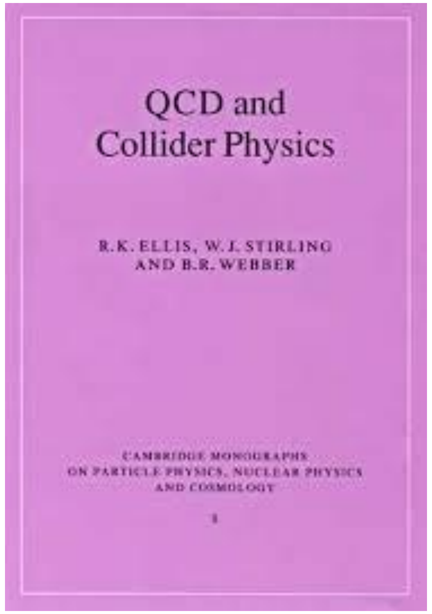
* ABIMSSSW, **PRL 132 212301 (2024)**

Heavy QQbar pairs in jets

- 1980’s: pQCD calculations of number of QQbar in jets as a function of jet energy E
    - MLLA calculation of number of gluons with off-shellness Q^2
    - Convoluted with g-> QQbar splitting function

A.H. Mueller and P. Nason, Heavy particle content in QCD jets, Phys. Lett. B 157 (1985) 226.

by now textbook physics



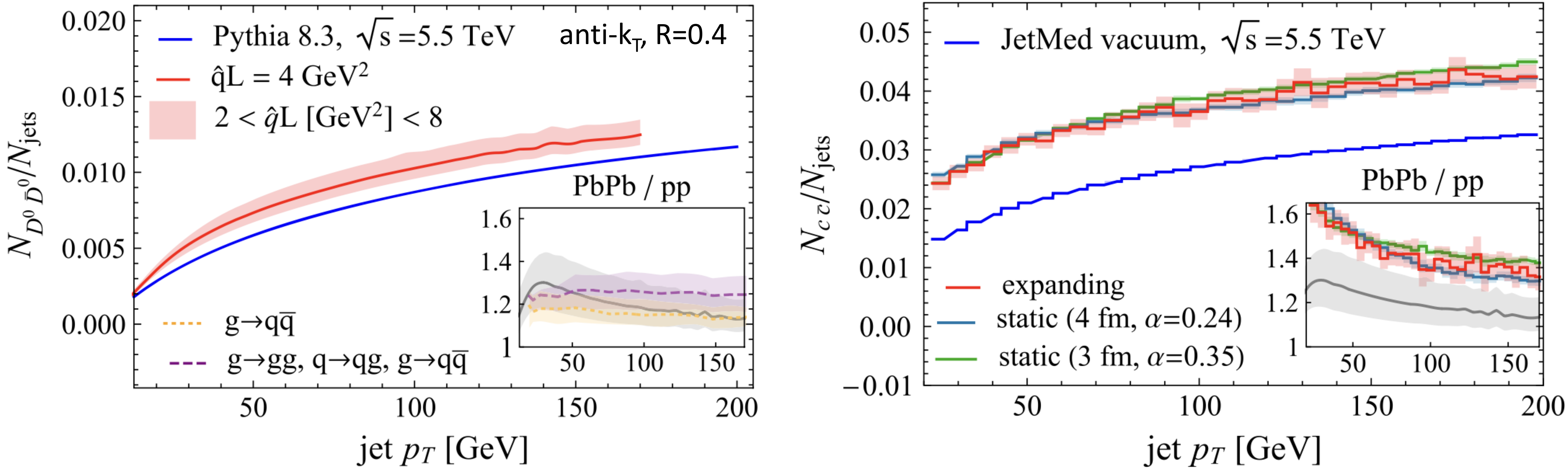
QCD and
Collider Physics

R.K. ELLIS, W.J. STIRLING
AND B.R. WEBBER

CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY

- Motivation at the time
    - Test running of strong coupling
    - Determine heavy quark mass
- Our work
    - **Calculate medium-modification on top of this pQCD baseline**

PHYSICAL REVIEW LETTERS **132,** 212301 (2024)



- Three independent model implementations:
  - Reweighting vacuum with P$^{\rm med}$
  - Parton shower with BDMPS splittings
  - ❑ JetMed supplemented by g-> c cbar

- **Observability of enhanced cc-bar radiation.**
- Control over confounding factors
  - Jet-pT is medium modified
  - Medium modifies also g-> gg

* ABIMSSSW, **PRL 132 212301 (2024)**

Can we measure directly τ_f -dependence of jet quenching?

- To measure the formation time

$$\tau_f = \frac{E_{\rm gluon}}{Q^2}\,, \qquad Q^2 = \frac{m_c^2 + k_c^2}{z\,(1-z)}$$

we need to determine
E_g, z and k_c

Strategy:

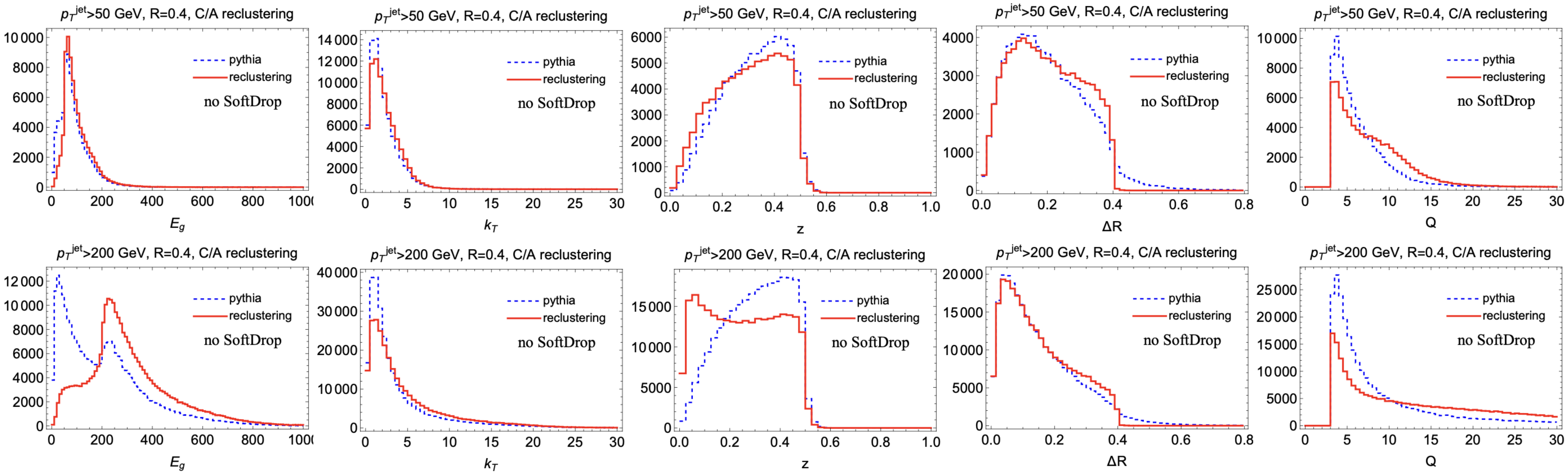
- reconstruct kinematic by tracing c and cbar to common vertex.
- compare kinematic τ_f -distribution in medium and vacuum.

Critical issues:

- High fidelity reconstruction of $g \to c\,\bar{c}$ from hadronic final state.
- Access to τ_f -range commensurate with in-medium path length.
- Size of medium-modification should vary significantly within reconstructable τ_f - range.

J. Brewer, W. v.d.Schee, U.A. Wiedemann, in preparation

Nothing is easy … Phythia MC truth vs C/A reclustering



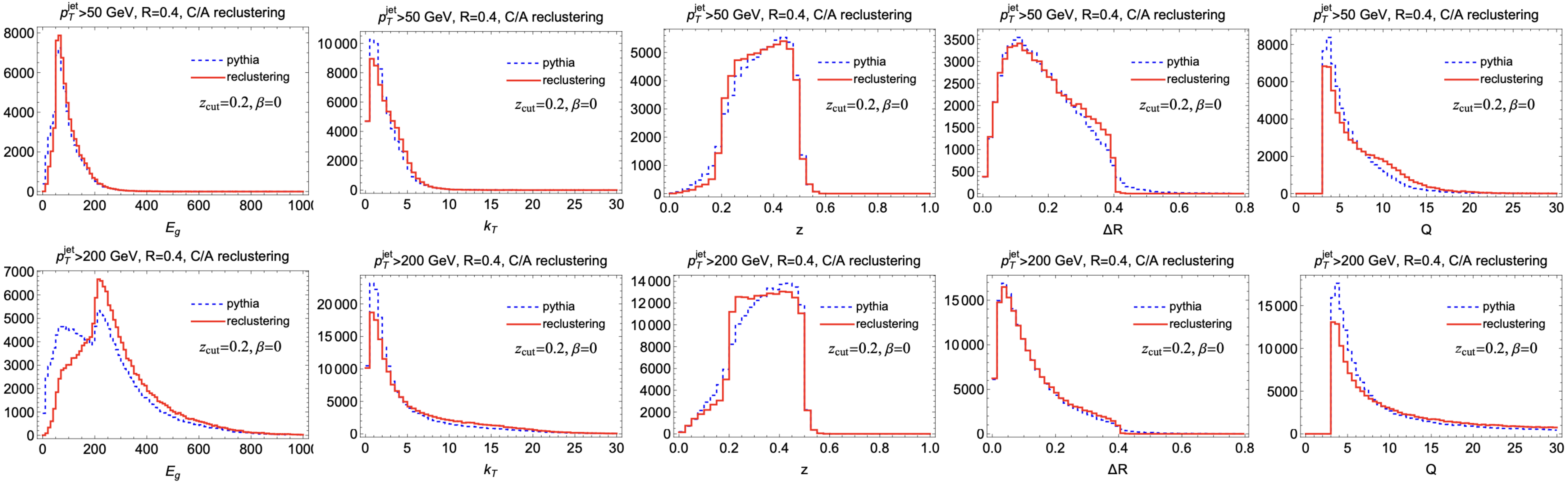
- ➢ This is parton level only.
- ➢ Relatively soft g-> ccbar splittings are reclustered with other jet fragments in high energy jets.

Improve on low fidelity with jet substructure techniques …

J. Brewer, W. v.d.Schee, U.A. Wiedemann, in preparation

Grooming away softer emissions

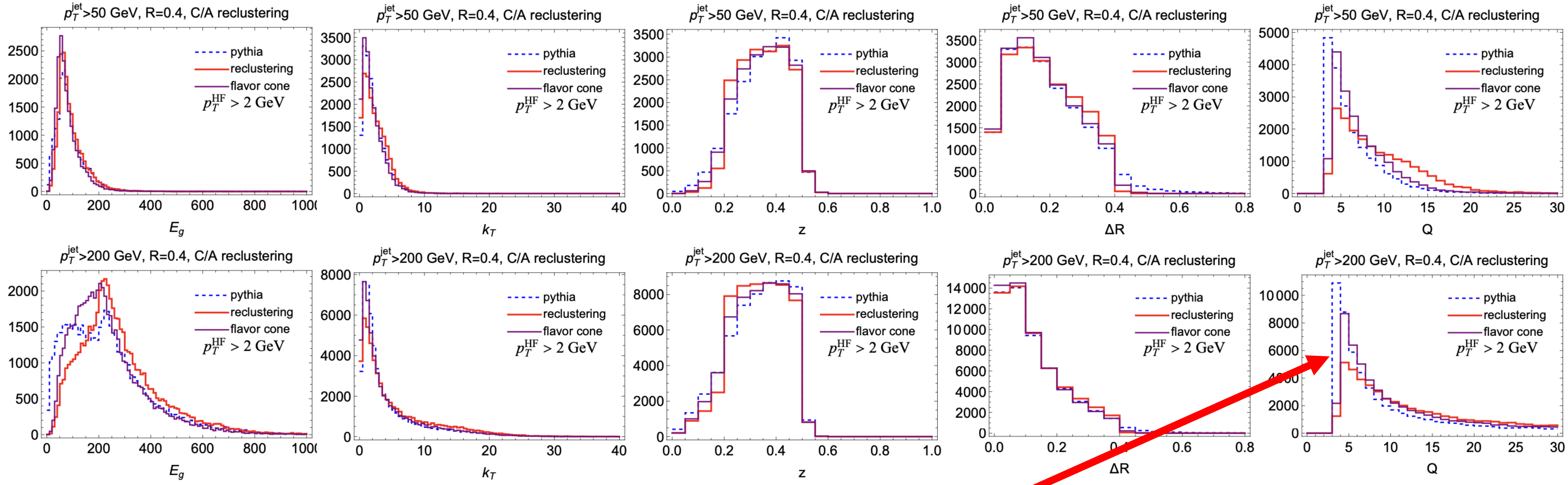
Leads to notable improvements (parton level only).



J. Brewer, W. v.d.Schee, U.A. Wiedemann, in preparation

SoftDrop + (modified) FlavorCone

Reconstruction at hadron level.

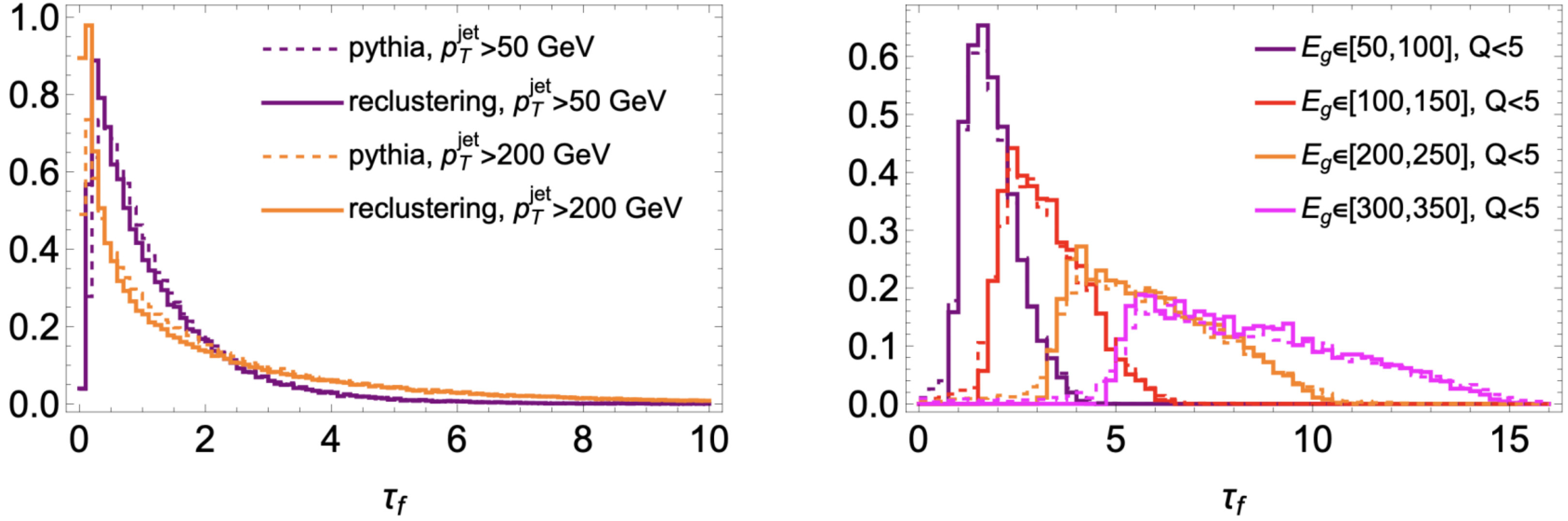


Reconstruction of pairs close to threshold is particularly challenging.

J. Brewer, W. v.d.Schee, U.A. Wiedemann, in preparation

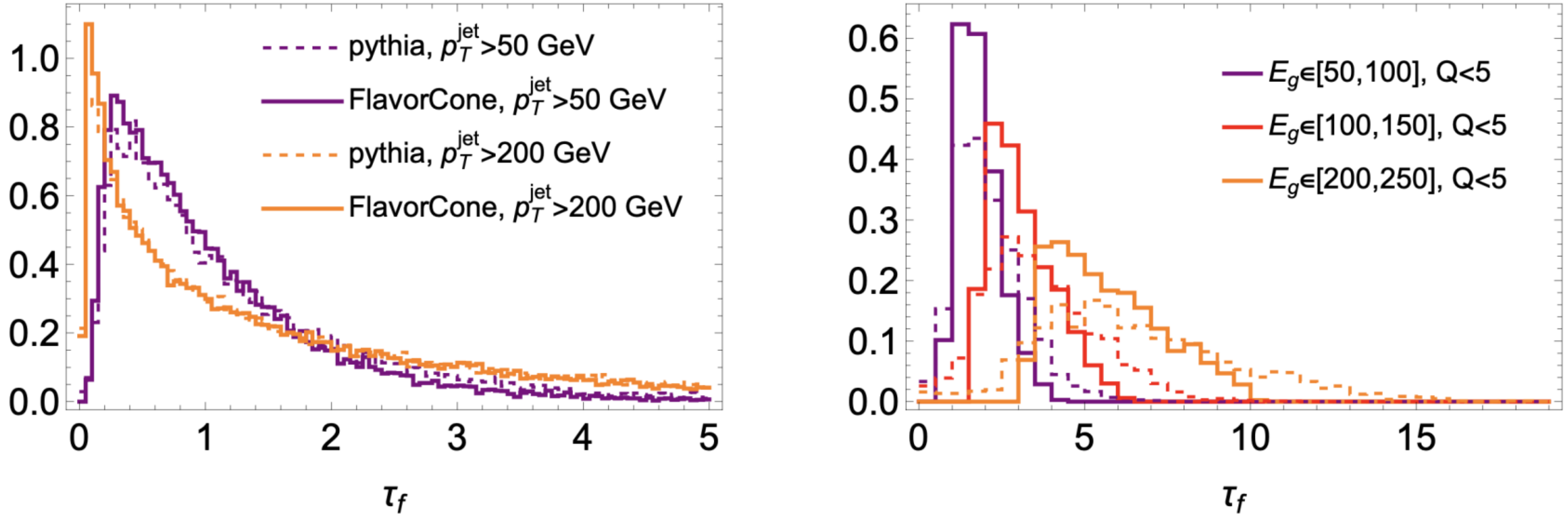
Accessible range of formation time scans the in-medium L

On parton level



Cutting on Q enhances τ_f -range

On hadron level



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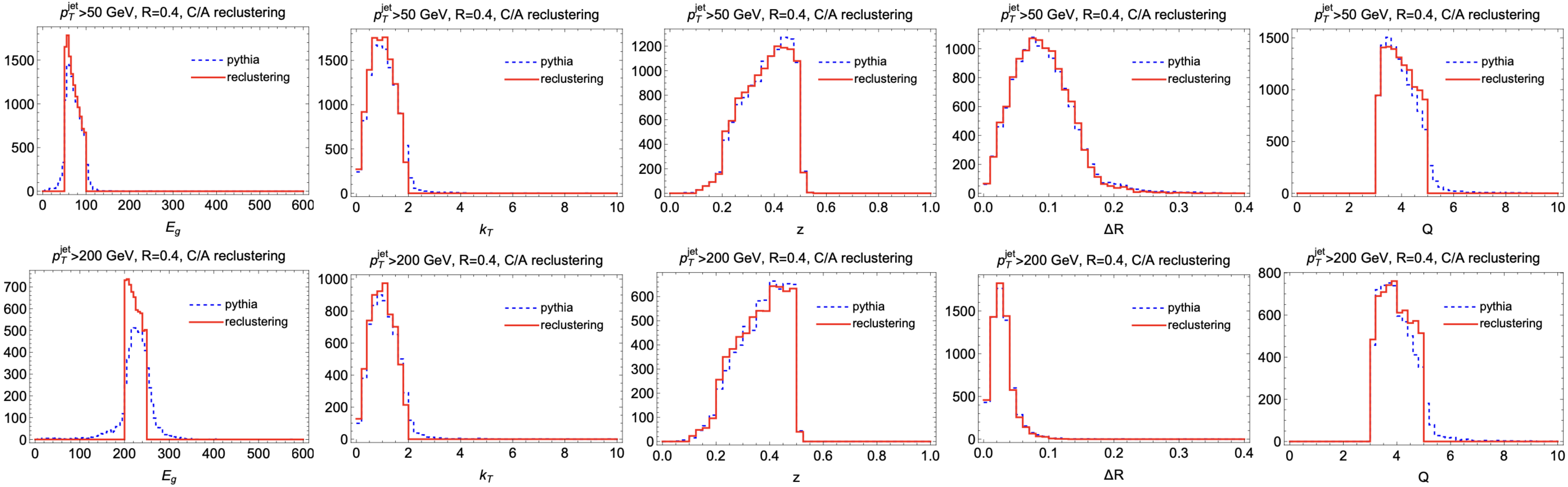
Sharp Q-cut does not spoil fidelity of reconstruction MC truth.



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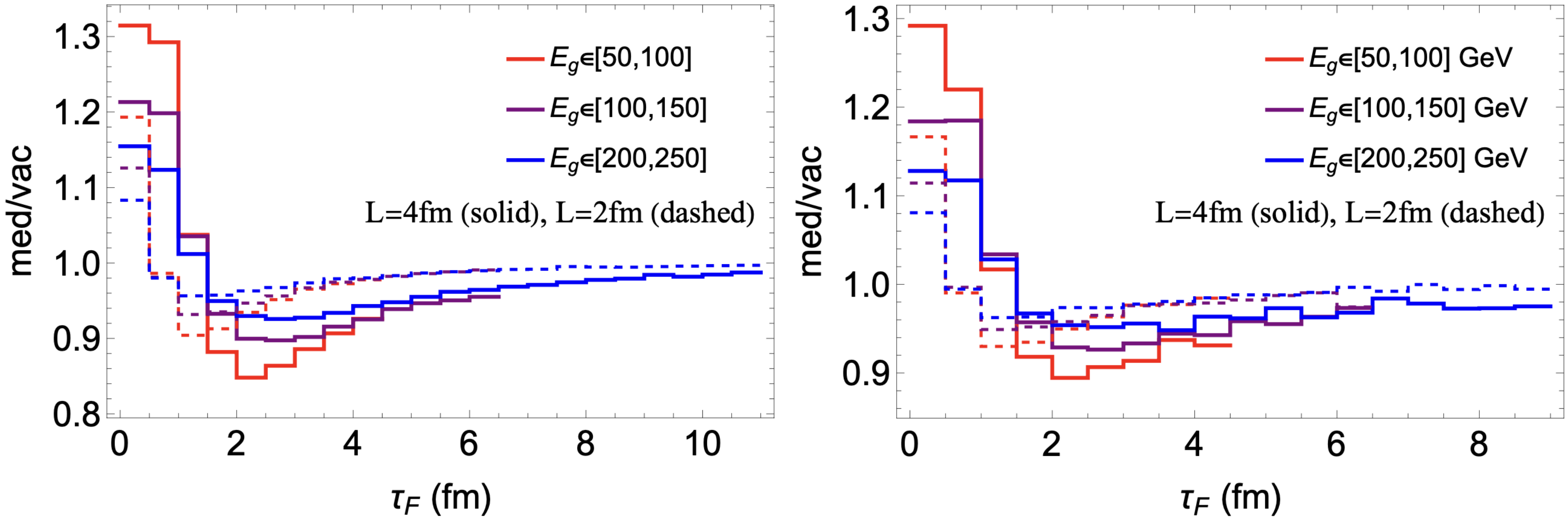
A measurable characterists of τ_f–dependent jet quenching

This is the ratio of normalized τ_f-distributions constructed in medium and in vacuum and plotted as a function of τ_f.



parton level

hadron level (FlavorCone)

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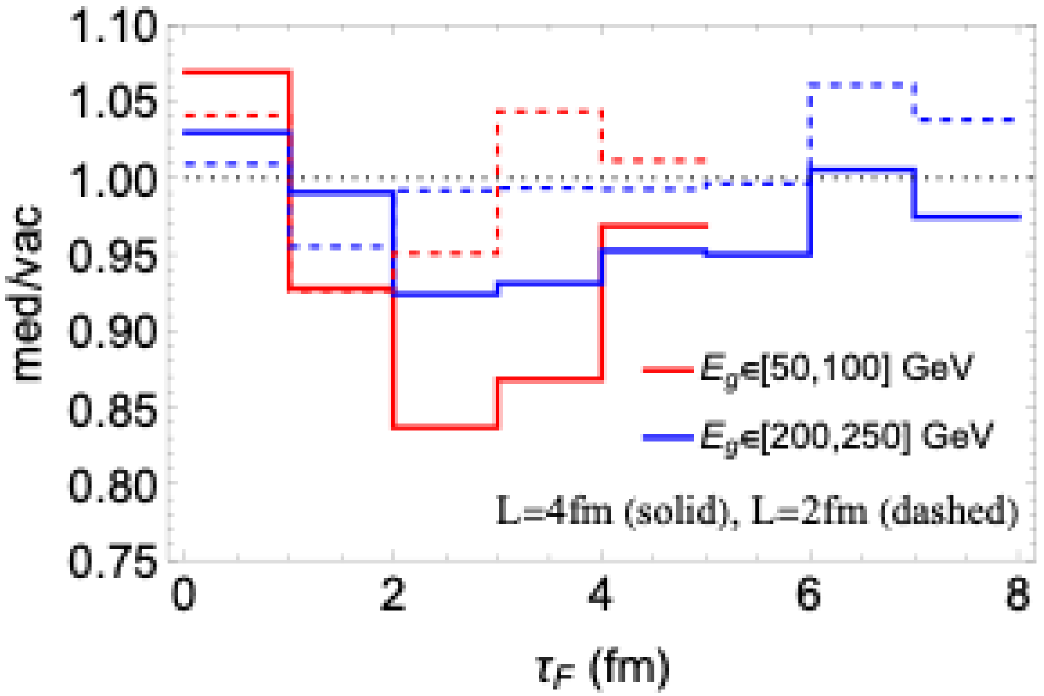
A measurable characterists of τ_f–dependent jet quenching

In presence of parton energy loss*, signal persists.



- For model details, see **Jasmine Brewer**'s talk **in parallel 29** on Wednesday, 11:10

J. Brewer, W. v.d.Schee, U.A. Wiedemann, in preparation

Conclusions

- **In theory**, $g \to c\,\bar{c}$ shows characteristic tell-tale signs of radiative parton energy loss in a clean and qualitatively novel way
  1. Enhanced ccbar-radiation
  2. Momentum broadening
  3. Formation time dependence

- **In experiment**, we expect that
  1. **testing enhanced ccbar-radiation** is accessible in a traditional counting experiment.
  2. **direct access to formation time dependence** of quenching requires modern jet substructure techniques but is feasible.

- **HL-LHC capabilities (luminosity & detector upgrades) are needed to exploit these physics opportunities.**

Back-up

Estimating the effects of energy loss on energy correlators

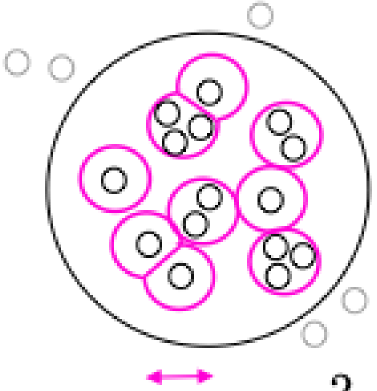
$$Q_i = \exp\left[-\int d\omega \int d^2\mathbf{k}\frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}})\right] = \exp\left[-\underbrace{\int_T^{\omega_s} d\omega \int d^2\mathbf{k}\frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}})}_{\text{rapid turbulent thermalization; }\omega \ll \omega_c} - \underbrace{\int_{\omega_s}^{\infty} d\omega \int d^2\mathbf{k}\frac{d\mathcal{P}_i^{\rm med}}{d\omega d^2\mathbf{k}}(1-e^{-\frac{n\omega}{p_t}})}_{\text{semi-hard perturbative gluon emission}}\right]$$

Quenching weights

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

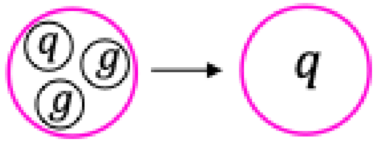
Energy loss of parton-level jets in Pythia assuming coherence within θ_c

- combine jet constituents into “clusters” of radius θ_c

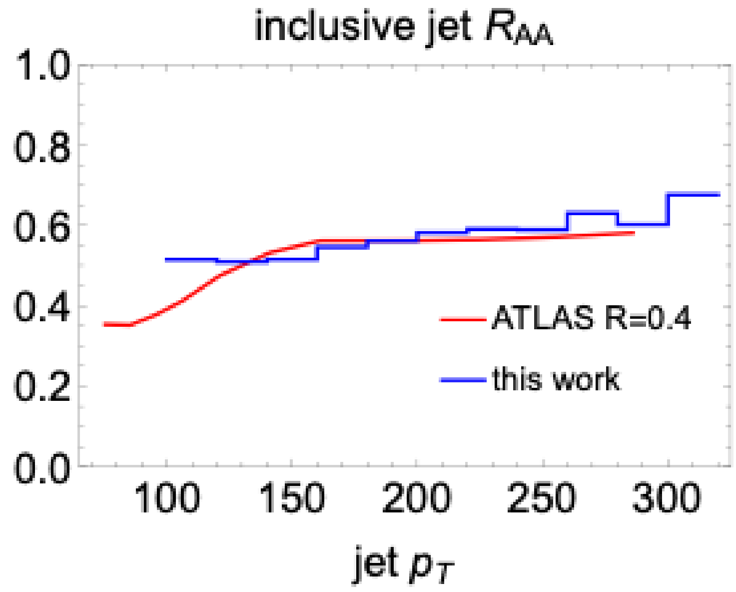


$$\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

- assign cluster flavor from parton content



- jet energy loss is the sum of cluster energy loss



ATLAS [1411.2357]