The medium enhanced $g \to c\bar{c}$ production

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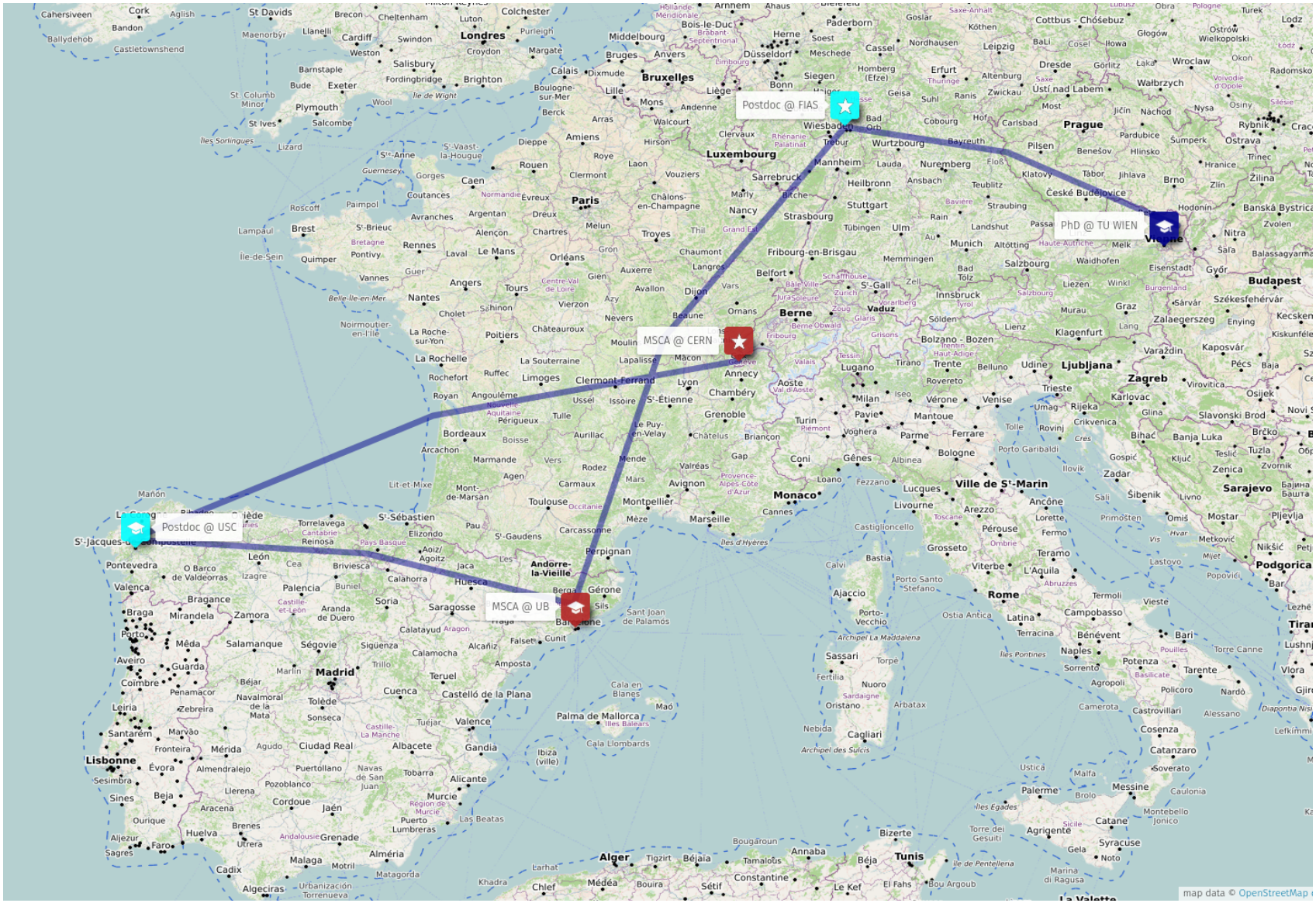
arXiv:2203.11241, arXiv:2209.13600

HI Group - Les Houches TH Retreat 2022

Introduction: Maximilian Attems CV mapview



CERN - Large Hadron Collider

Discovery and precisision machine at large scales to understand the most fundamental particles and laws of the universe:

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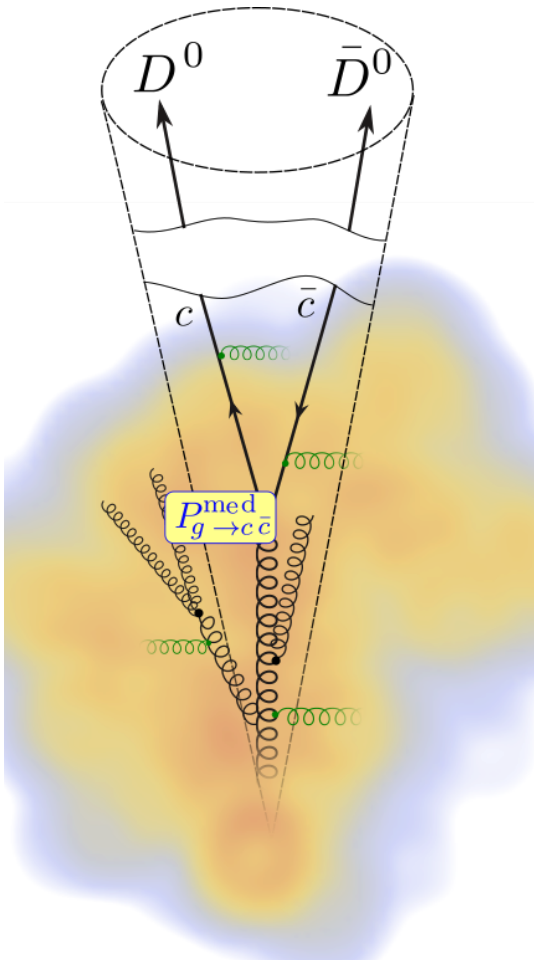
"Dass ich erkenne, was die Welt im Innersten zusammenhält" — J. W. von Goethe

Dominant medium-modification of HQ in the QGP



$m_b \sim 4.18\,GeV$
$m_c \sim 1.27\,GeV$
$T_{QGP} \sim 300\,MeV$
$\Lambda_{QCD} \sim 200\,MeV$

- short-distance high-momentum transferred
- mass threshold removes many non-perturbative effects
- pQCD can predict the total heavy-flavour (HF) production

"Perturbative" cross-sections in elementary collisions:

- set the yields for heavy-flavour production in heavy-ions
- Quark Gluon Plasma only modifies the p_T distribution of heavy-quarks.

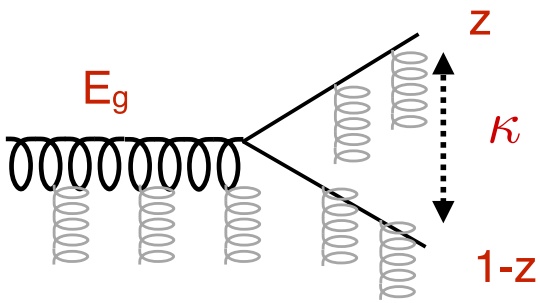
  M. Cacciari et al., JHEP 10 (2012) 137

$\rightarrow$ Observed experimentally via modification of high-p_T spectra of heavy-flavour hadrons

BDMPS, Nucl.Phys., B484:265–282, 199
B.G. Zakharov, JETP Lett., 63:952–957, 1996.

Y.L. Dokshitzer, D.E Kharzeev, Phys.Lett. B 519, 199-206, 2001

In-medium $g \to c\bar{c}$ splitting function in the BDMPS-Z formalism



In-vacuum splitting function to leading order in α_s

$$\left(\frac{1}{Q^2}\,P_{g\to c\,\bar{c}}\right)^{\rm vac} = \frac{1}{Q^4}\left[(m_c^2+\boldsymbol{\kappa}^2)\,\frac{z^2+(1-z)^2}{z(1-z)}+2m_c^2\right].$$

Medium-modification of the splitting function in time-ordered perturbation theory in the close-to-eikonal limit

Corrected 2203.11241 v2, thanks to F. Dominguez, C. Salgado

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

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

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

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

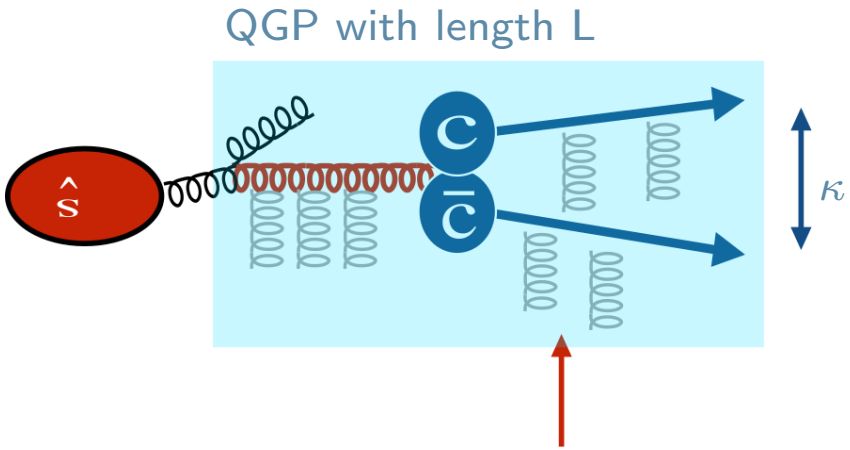
$\sigma(r)$: elastic cross section of a medium scattering center interacting with a projectile parton:

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

transverse rest frame of $c\bar{c}$ pair ($k_c + k_{\bar{c}} = 0$)

$$\kappa = \frac{1}{2}(k_c - k_{\bar{c}})$$

Related BDMPS-Z works include: 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



$\kappa \rightarrow$ relative transverse momentum of the pair

increases of κ^2 due to transverse momentum broadening on the individual quarks:
$\rightarrow$ conserves splitting probability

Enhancement of $g \rightarrow c\bar{c}$ splittings

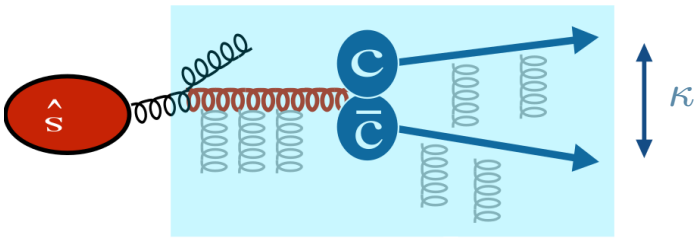
$\rightarrow$ Gluons which would not split in vacuum can split if in-medium scatters occurs

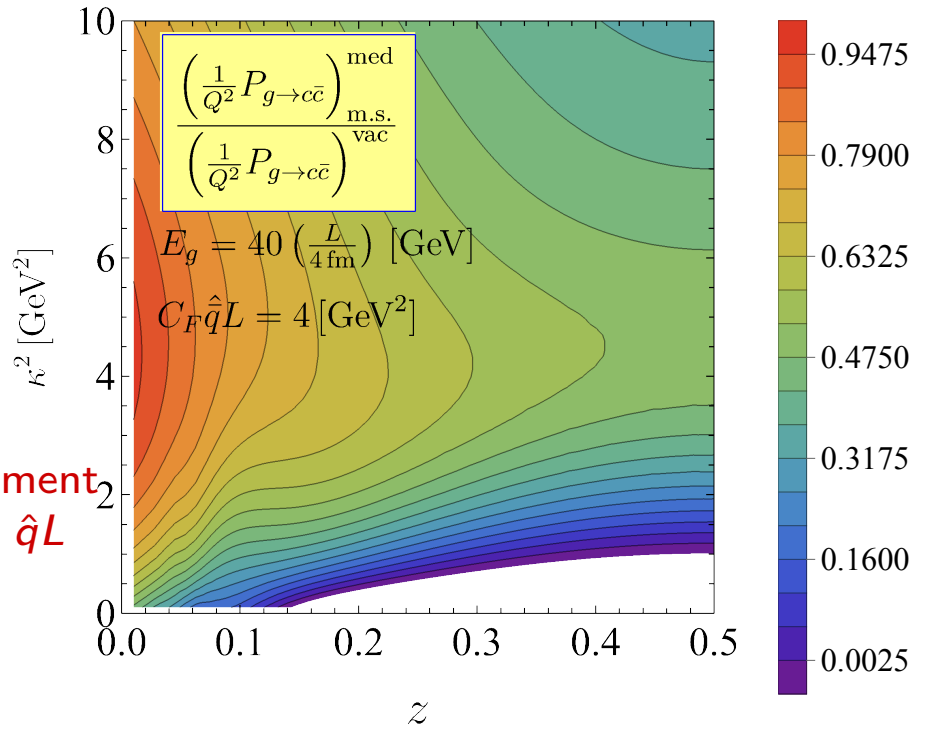
$\rightarrow$ increase of a "conserved" and "traceable" quantity via interaction with the medium

Numerical results for $P^{med}_{g\to c\bar{c}}$ / $P^{vac}_{g\to c\bar{c}}$

→ Multiple soft-scattering approximation
→ QGP brick with $\hat{q}L = 4GeV^2$

QGP with length L





Enhancement for $\kappa^2 \sim \hat{q}L$

→ magnitude of in-medium modification
$P^{med}_{g\to c\bar{c}} \sim P^{vac}_{g\to c\bar{c}}$

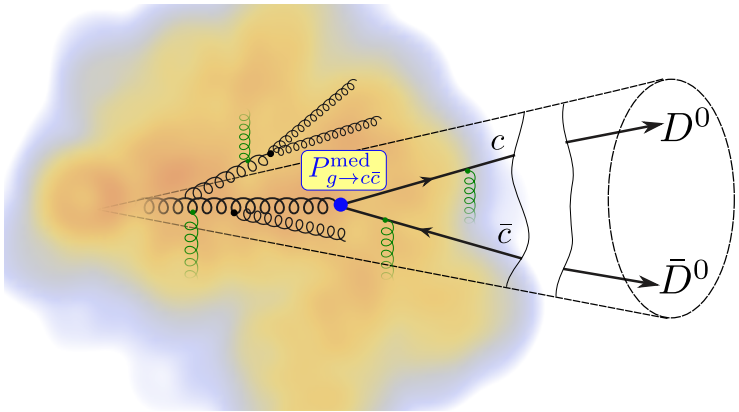
Depletion of low κ^2 splittings due to the in-medium broadening

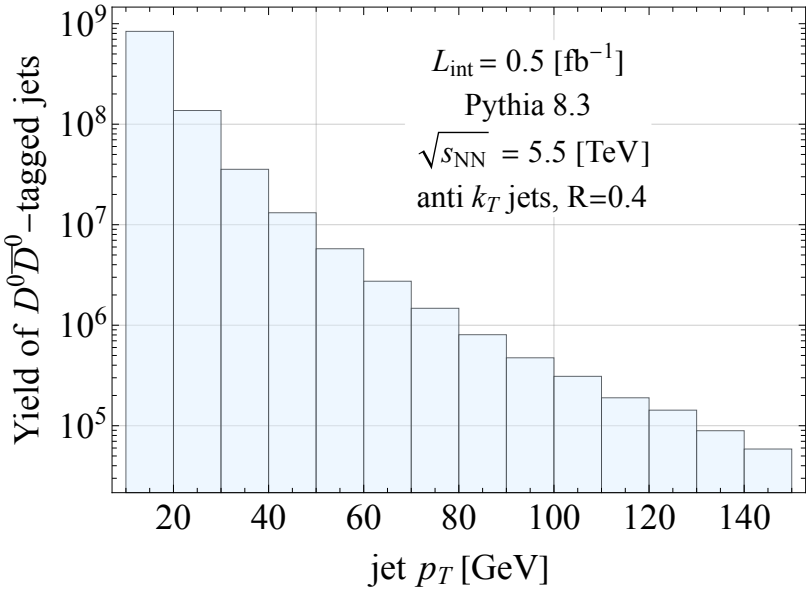
→ the formalism that describes enhanced gluon radiation in the QGP also predicts a sizeable enhancement of the $c\bar{c}$ radiation

Monte Carlo study with Pythia

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

- Anti-kT "full" jets with FastJet ($R = 0.4$)
- one $D^0\bar{D}^0$ pair per jet
- only prompt D^0 contribution considered ($c \rightarrow D^0$)

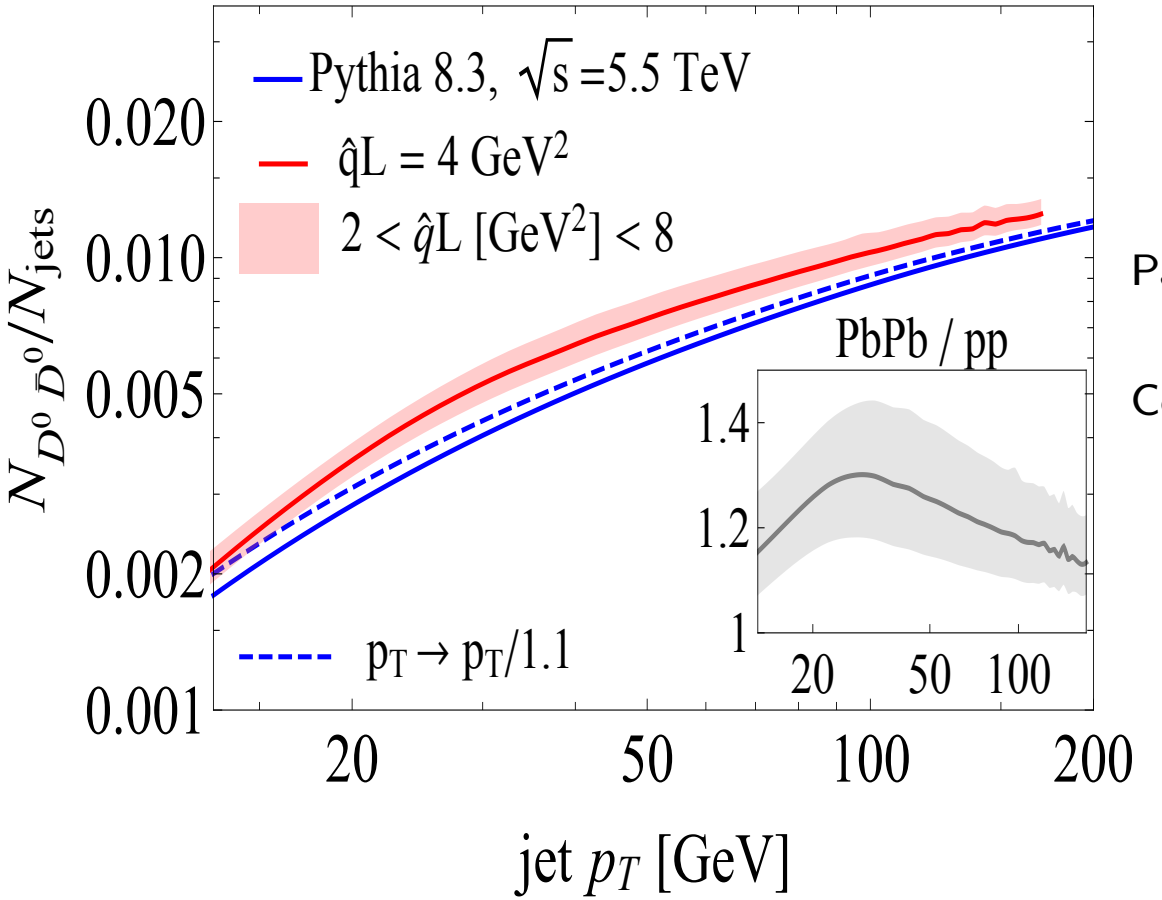




Fully reconstructed hadronic decays
But also $c\bar{c}$-tagging techniques high-p_T jets or tagging of semi-leptonic charm decays
→ sample ∼ entire $c\bar{c}$ statistics

Challenging measurement:
→ Based on expected yields, the measurement could be within reach with HL-LHC

"reweigh" each splitting to accounts for modified $g \to c\bar{c}$ probability This simplified strategy relies on few realistic assumptions/approximations (arXiv:2203.11241)
$\to$ captures the qualitative features of the in-medium modifications (arXiv:2209.13600)



Parton shower in vacuum (Pythia pp)

Corrected for jet quenching:

- 10% p_T shift for both $D^0\bar{D}^0$-tagged and inclusive jets
  - baseline to establish the effect of $P^{med}_{g\to c\bar{c}}$

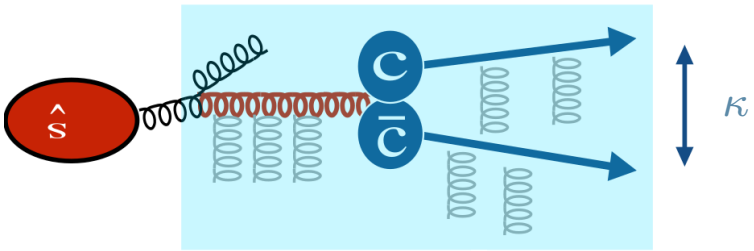
New observable sensitive to enhanced $g \rightarrow c\bar{c}$ in jets

$\rightarrow g \rightarrow c\bar{c}$ for "in-medium" production of heavy quarks

$g \rightarrow c\bar{c}$ splitting function with BDMPS-Z:

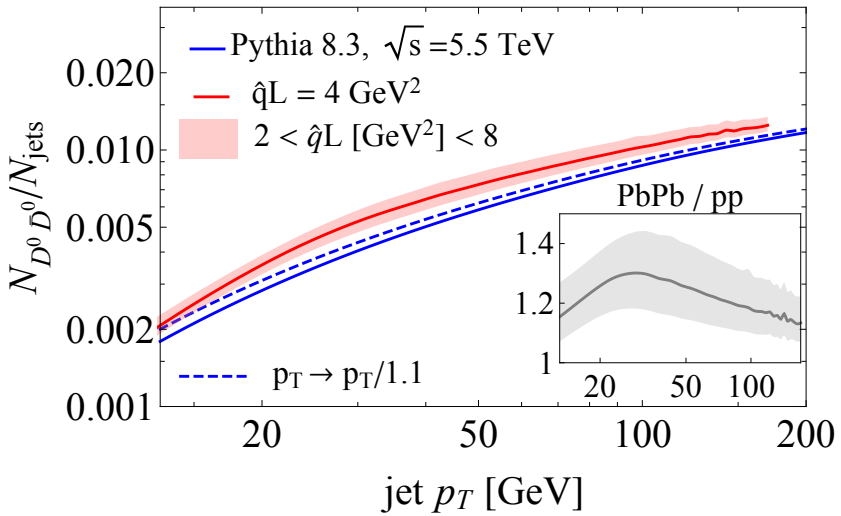
- broadening of $c\bar{c}$ pairs and enhancement of $c\bar{c}$ radiation

QGP with length L



Experimental strategy for $g \rightarrow c\bar{c}$ enhancement:

- challenging but potentially measurable signal

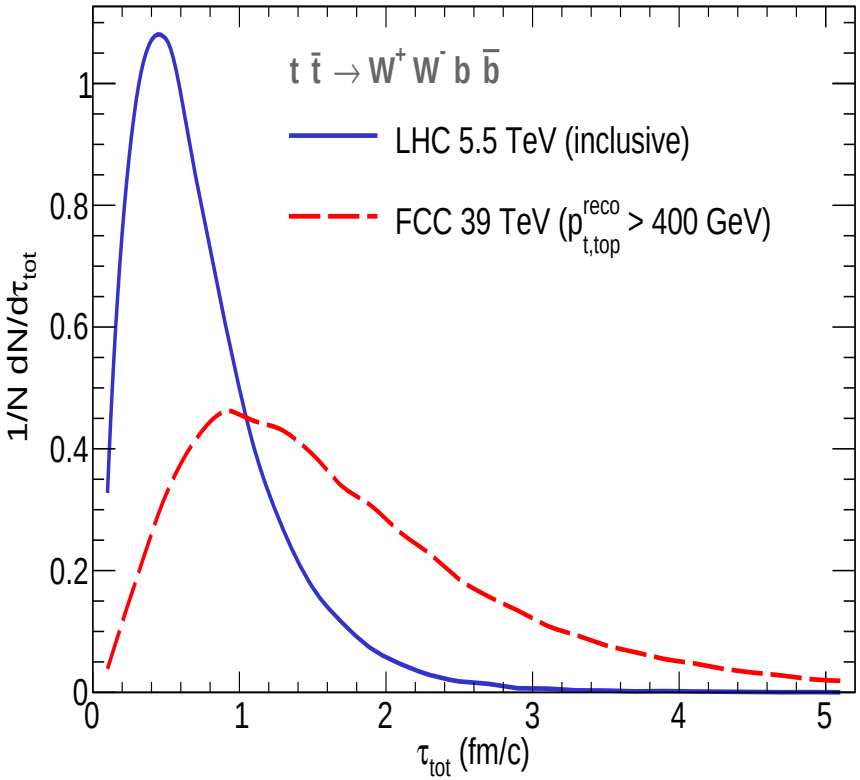


Push for new theoretical and experimental developments:

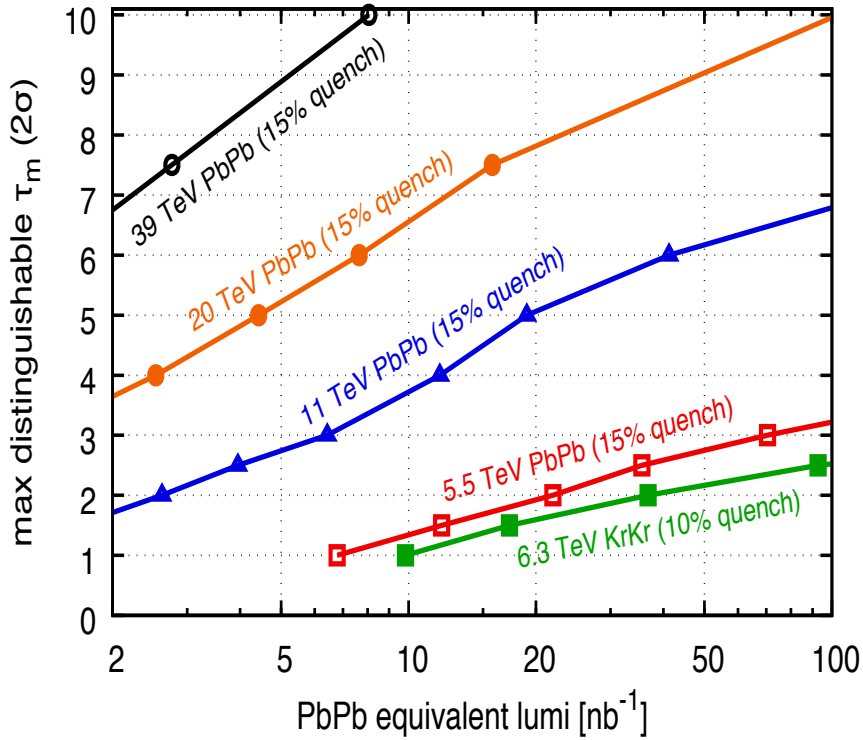
- parton showers including the in-medium modi cations of all splitting functions $\rightarrow$ more differential observables
- high-luminosity heavy-ion runs, improved detector capabilities and new analysis techniques

Yocotosecond chronometer - formation time

Probing the time structure of the QGP with top quarks:



Distribution of formation time τ_{tot} with a top-quark

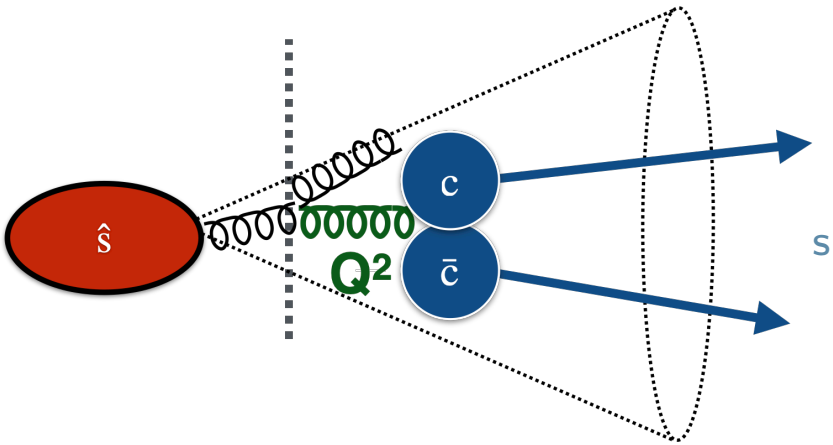


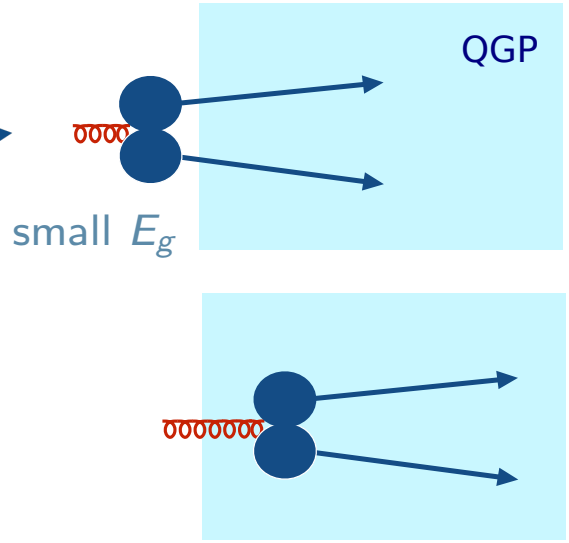
Maximum medium quenching end-time τ_m for different colliders

By controlling boost of top quark, you can control time when jets interact with the medium. Gives information in range $0.5 fm/c$–$5 fm/c$ with $p_T < 1 TeV$ for FCC. Some info maybe even accessible at HL-LHC with $p_T < 200 GeV$.

L. Apolinário, J. Guilherme, G. Salam, C. Salgado PRL. 120, 232301 (2018)

$c\bar{c}$ pairs in high-p_T gluon jets

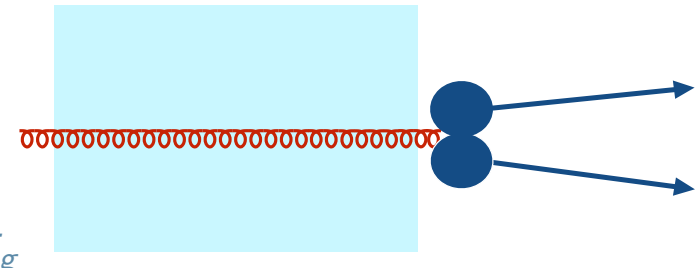




$$\tau^{rest}_{g\to c\bar{c}} \sim \frac{1}{Q}$$
$$\tau^{lab}_{g\to c\bar{c}} \sim \frac{1}{Q}\frac{E_g}{Q} = \frac{E_g}{Q^2}$$

$\hat{s}$ = center of mass energy of partonic scattering $Q^2 \ll \hat{s}$

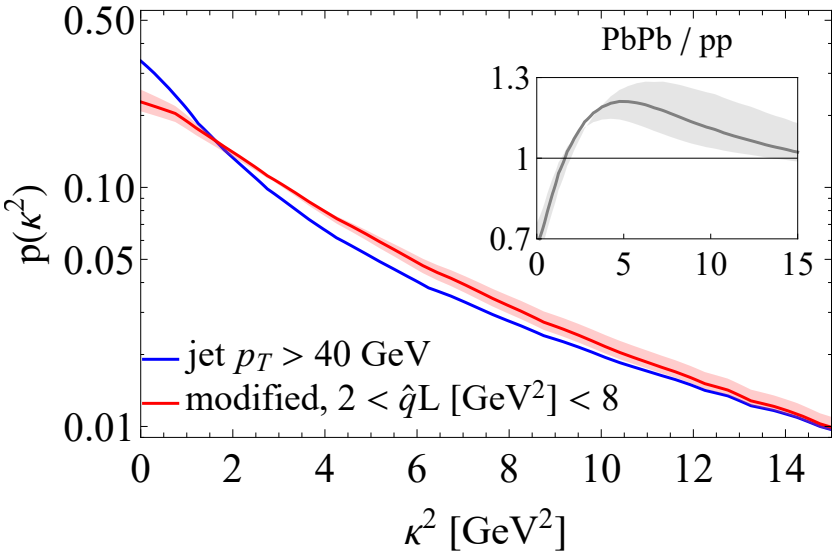
- preferentially select $g \to c\bar{c}$ splittings
- collinear limit of QCD

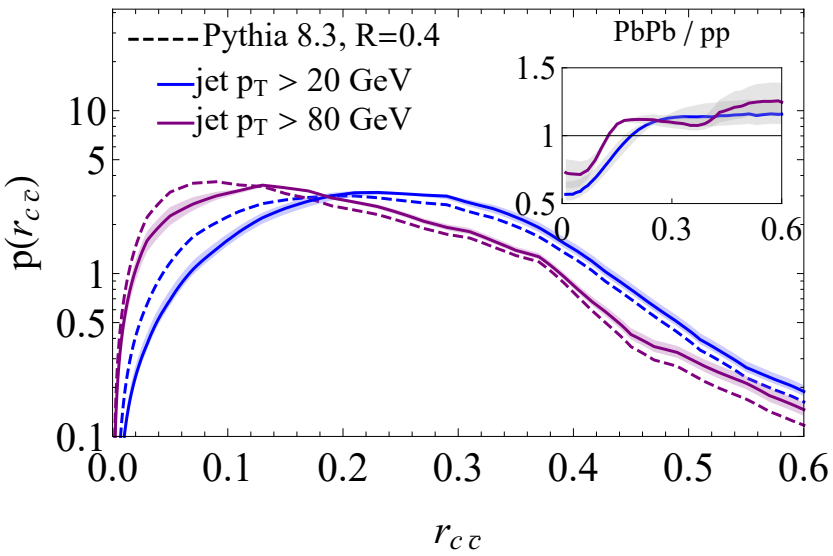


$$\hat{\sigma}^{gg\to c\bar{c}X} \xrightarrow{Q^2 \ll \hat{s}} \hat{\sigma}^{gg\to gX} \otimes \frac{\alpha_s}{2\pi}\frac{1}{Q^2} P_{g\to c\bar{c}}(z) \qquad t = 0 \xrightarrow{\tau_{QGP}} time[fm/c]$$

Formation time-dependence

Probability distribution in $c\bar{c}$ jet sample of relative momentum and angular separation:





larger broadening + larger formation time

CERN heavy-ion collaboration

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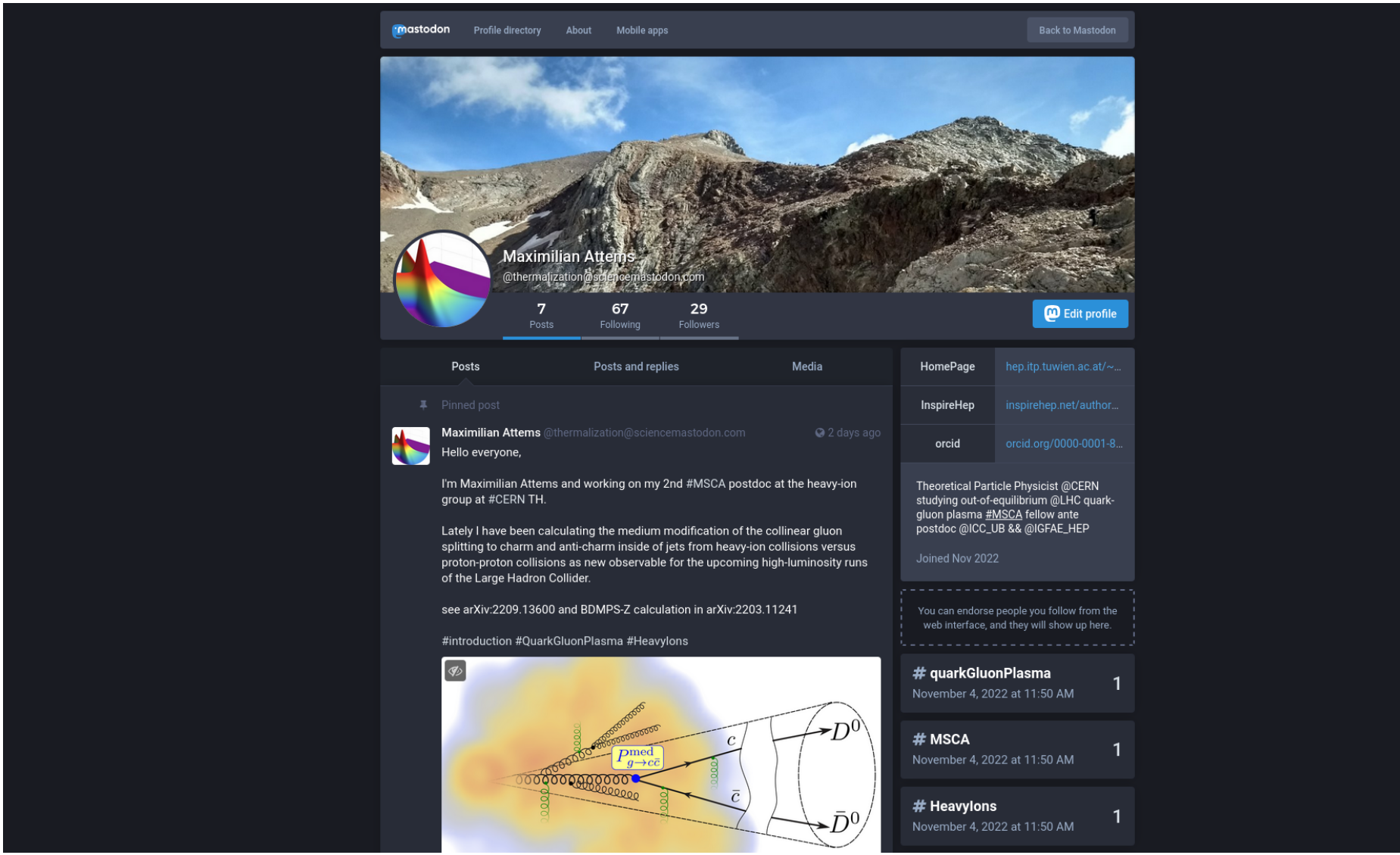
Jasmine Brewer
Gian Michele Innocenti
Aleksas Mazeliauskas
Sohyun Park
Wilke van der Schee
Urs Wiedemann

Outreach: science communication via mastodon

profile on sciencemastodon.com:



Outdoor activities 9/2022

Breithorn summit:

Col du Grand Colombier:

Thank you for your attention!