



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

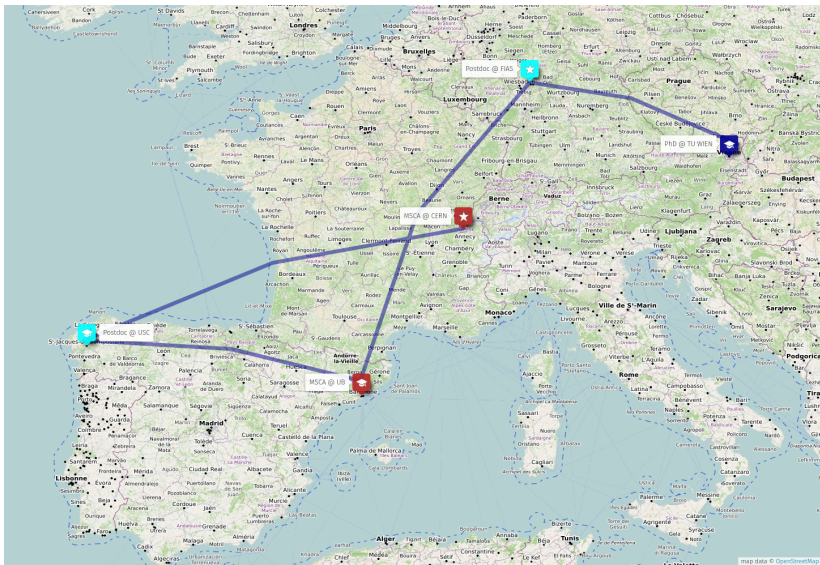
Maximilian Attems

Jasmine Brewer, Gian-Michele Innocenti, Aleksas Mazeliauskas,
Sohyun Park, Wilke van der Schee, Urs Wiedemann (CERN)

[arXiv:2203.11241](#), [arXiv:2209.13600](#)

HI Group - Les Houches TH Retreat 2022

Introduction: Maximilian Attems CV mapview



Discovery and precision 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

$$m_b \sim 4.18 \text{ GeV}$$

$$m_c \sim 1.27 \text{ GeV}$$

$$T_{QGP} \sim 300 \text{ MeV}$$

$$\Lambda_{QCD} \sim 200 \text{ MeV}$$

- **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.

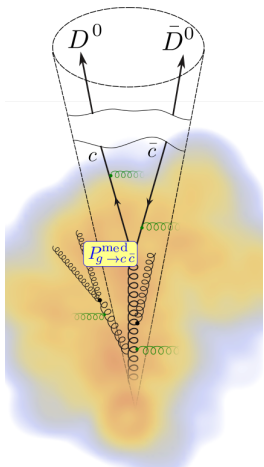
M. Cacciari et al., JHEP 10 (2012) 137

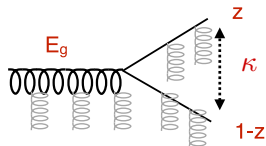
→ Observed experimentally via modification of high- p_T spectra of heavy-flavour hadrons

BDMPS, Nucl.Phys., B484:265–282, 1999

B.G. Zakharov, JETP Lett., 63:952–957, 1996.

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





In-vacuum splitting function to leading order in α_s

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

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

$$\begin{aligned} \left(\frac{1}{Q^2} P_{g \rightarrow c\bar{c}} \right)^{\text{tot}} &\equiv \left(\frac{1}{Q^2} P_{g \rightarrow c\bar{c}} \right)^{\text{vac}} + \left(\frac{1}{Q^2} P_{g \rightarrow c\bar{c}} \right)^{\text{med}} \\ &= 2 \Re \text{e} \frac{1}{4 E_g^2} \int_{t_{\text{init}}}^{t_{\infty}} dt \int_t^{t_{\infty}} d\bar{t} \exp \left[i \frac{m_c^2}{2 E_g z (1-z)} (t - \bar{t}) \right] \\ &\quad \times \int d\mathbf{r}_{\text{out}} \exp \left[-\frac{1}{2} \int_{\bar{t}}^{\infty} d\xi n(\xi) \sigma_3(\mathbf{r}_{\text{out}}, z) \right] \exp [-i \boldsymbol{\kappa} \cdot \mathbf{r}_{\text{out}}] \\ &\quad \times \left[\left(m_c^2 + \frac{\partial}{\partial \mathbf{r}_{\text{in}}} \cdot \frac{\partial}{\partial \mathbf{r}_{\text{out}}} \right) \frac{z^2 + (1-z)^2}{z(1-z)} + 2m_c^2 \right] \mathcal{K} [\mathbf{r}_{\text{in}} = 0, t; \mathbf{r}_{\text{out}}, \bar{t}] \end{aligned}$$

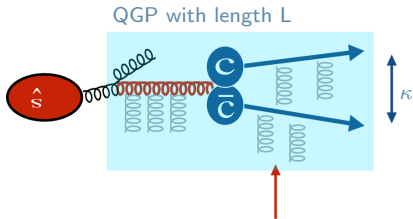
$\sigma(r)$: elastic cross section of a medium scattering center interacting with a projectile parton:

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

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

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

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:

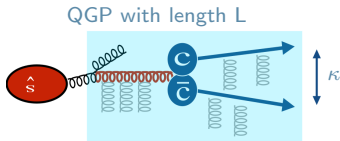
\rightarrow conserves splitting probability

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

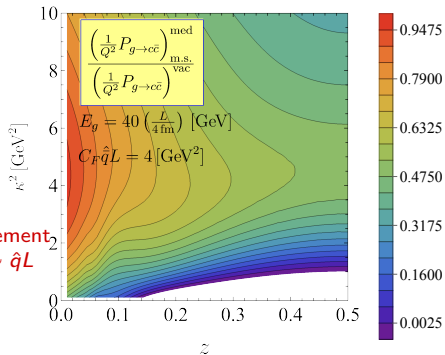
- Multiple soft-scattering approximation
- QGP brick with $\hat{q}L = 4 \text{ GeV}^2$



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

- magnitude of in-medium modification

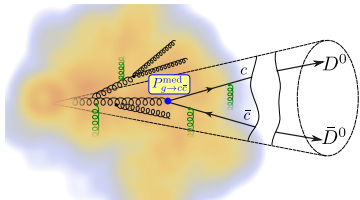
$$P_{g \rightarrow c\bar{c}}^{med} \sim P_{g \rightarrow c\bar{c}}^{vac}$$



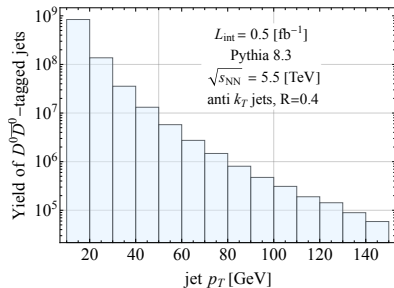
Depletion of low κ^2 splittings due to the in-medium broadening

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

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



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



Fully reconstructed hadronic decays

But also $c\bar{c}$ -tagging techniques high- p_T jets or tagging of semi-leptonic charm decays

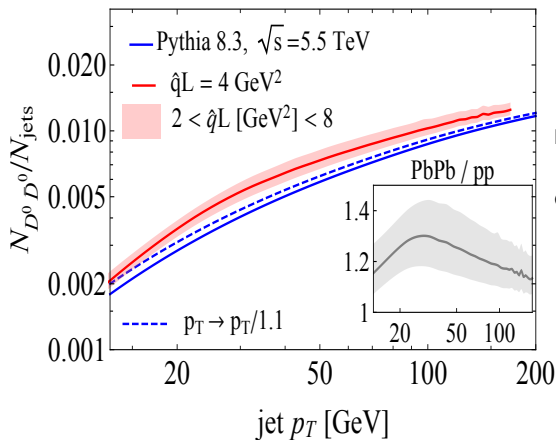
→ **sample** \sim **entire** $c\bar{c}$ **statistics**

Challenging measurement:

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

“reweigh” each splitting to account for modified $g \rightarrow c\bar{c}$ probability This simplified strategy relies on few realistic assumptions/approximations (arXiv:2203.11241)

→ captures the qualitative features of the in-medium modifications (arXiv:2209.13600)



Parton shower in vacuum (Pythia pp)

Corrected for jet quenching:

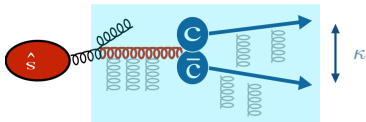
- 10% p_T shift for both $D^0 \bar{D}^0$ -tagged and inclusive jets
- baseline to establish the effect of $P_{g \rightarrow c\bar{c}}^{med}$

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

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

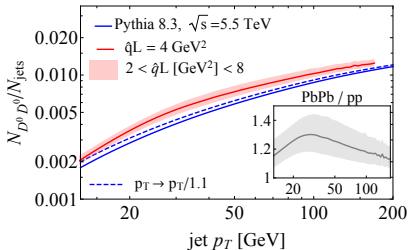
- broadening of $c\bar{c}$ pairs and enhancement of $c\bar{c}$ radiation

QGP with length L



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

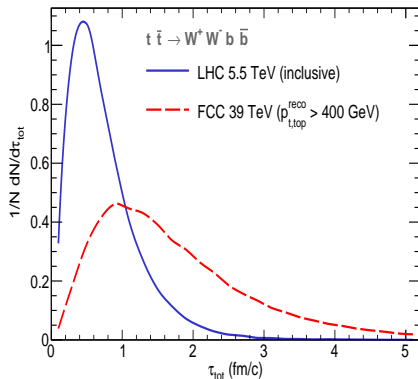
- challenging but potentially measurable signal



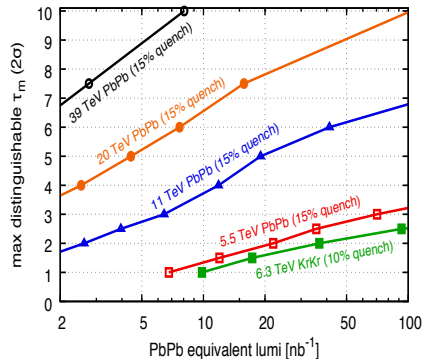
Push for new theoretical and experimental developments:

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

Probing the time structure of the QGP with top quarks:



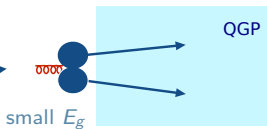
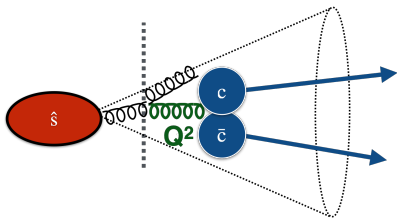
Distribution of formation time τ_{tot} with a top-quark



Maximum medium quenching end-time τ_m for different colliders

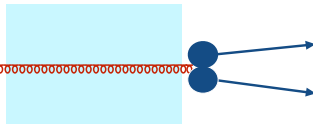
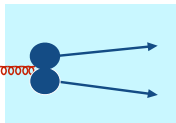
By controlling boost of top quark, you can control time when jets interact with the medium. Gives information in range $0.5 \text{ fm}/c$ – $5 \text{ fm}/c$ with $p_T < 1 \text{ TeV}$ for FCC. Some info maybe even accessible at HL-LHC with $p_T < 200 \text{ GeV}$.

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



$$\tau_{g \rightarrow c\bar{c}}^{\text{rest}} \sim \frac{1}{Q}$$

$$\tau_{g \rightarrow c\bar{c}}^{\text{lab}} \sim \frac{1}{Q} \frac{E_g}{Q} = \frac{E_g}{Q^2}$$

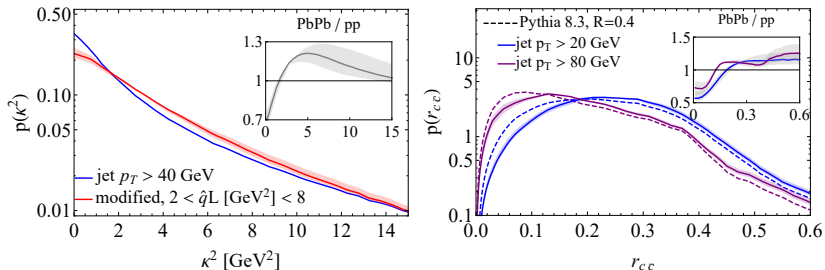


\hat{s} = center of mass energy of partonic scattering $Q^2 \ll \hat{s}$

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

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

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



larger broadening + larger formation time

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



profile on sciencemastodon.com:

The screenshot shows a Mastodon profile for Maximilian Attems (@thermalization@sciencemastodon.com). The profile header features a background image of a mountain range and a circular profile picture with a rainbow gradient. The name 'Maximilian Attems' and the handle '@thermalization@sciencemastodon.com' are displayed. Below the header, there are statistics: 7 Posts, 67 Following, and 29 Followers. A blue 'Edit profile' button is visible on the right.

The main content area shows a 'Planned post' from Maximilian Attems, dated 2 days ago. The text of the post reads: 'Hello everyone, I'm Maximilian Attems and working on my 2nd #MSCA postdoc at the heavy-ion group at #CERN TH. Lately I have been calculating the medium modification of the collinear gluon splitting to charm and anti-charm inside of jets from heavy-ion collisions versus proton-proton collisions as new observable for the upcoming high-luminosity runs of the Large Hadron Collider. see arXiv:2209.13600 and BDMP5-Z calculation in arXiv:2203.11241 #introduction #QuarkGluonPlasma #HeavyIons'.

Below the text is a diagram illustrating the production of a charm quark (c) and an anti-charm quark (\bar{c}) from a gluon splitting process. The diagram shows a gluon jet splitting into a charm quark and an anti-charm quark, with labels for D^0 and \bar{D}^0 mesons. A yellow box highlights the 'medium' modification of the gluon splitting process.

On the right side of the profile, there is a 'HomePage' section with links to 'hep.itp.tuwien.ac.at/~...', 'inspirehep.net/author...', and 'orcid.org/0000-0001-8...'. Below this is a bio: 'Theoretical Particle Physicist @CERN studying out-of-equilibrium @LHC quark-gluon plasma #MSCA fellow and postdoc @ICCC_LIB & @IGFAE_HEP'. It also mentions 'Joined Nov 2022' and a note: 'You can endorse people you follow from the web interface, and they will show up here.'

At the bottom right, there are three hashtag recommendations: '# quarkGluonPlasma' (1 post, Nov 4, 2022 at 11:50 AM), '# MSCA' (1 post, Nov 4, 2022 at 11:50 AM), and '# HeavyIons' (1 post, Nov 4, 2022 at 11:50 AM).

Breithorn summit:



Col du Grand Colombier:



Thank you for your attention!