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

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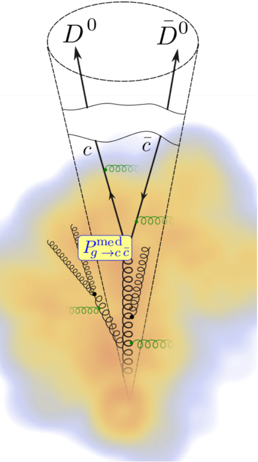
arXiv:2203.11241, arXiv:2206.XXXXX

SEWM 2022

CERN - Large Hadron Collider

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

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



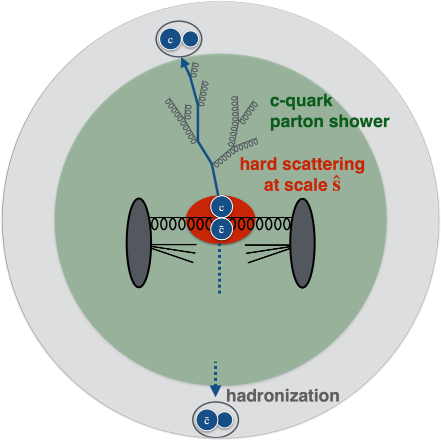
$m_b \sim 4.18 GeV$
$m_c \sim 1.27 GeV$
$\Lambda_{QCD} \sim 200 MeV$

- 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

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



$\rightarrow$ How?
heavy quarks rescatter inside the QGP

Modification of the parton shower:

- splitting function $g \rightarrow c\bar{c}$ can be modified by the QGP

$\tau_{hard} \ll \tau^{med}_{g \rightarrow c\bar{c}} \ll \tau_{hadr}$

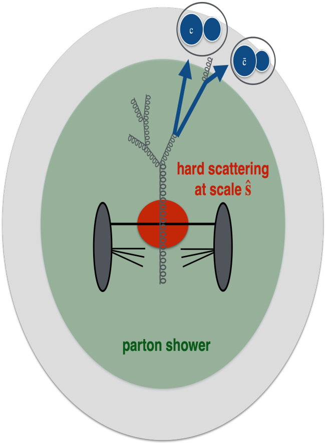
$\rightarrow$ enhanced gluon radiation from c and b quarks

$\rightarrow$ 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

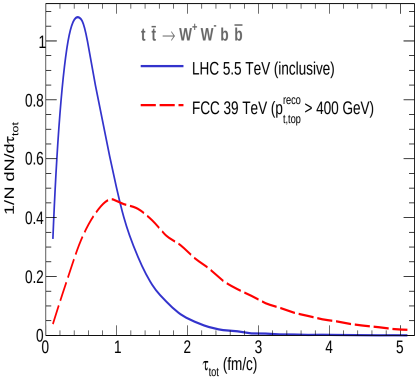
Heavy-quark production from collinear $g \to c\bar{c}$



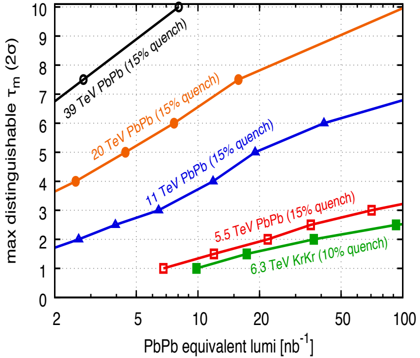
- **g → c$\bar{\text{c}}$ splittings** originated in the parton shower of high-p_T gluon jets:
    - long-distance process $\tau_{g\to c\bar{c}} \gg \tau_{hard}$
    - $g \to c\bar{c}$ splitting modified by the medium!
- features of the in-medium calculation of splitting function with BDMPS-Z
- One **experimental** signature for modifications: production in high-p_T jets

See arXiv:2203.11241

Probing the time structure of the QGP with top quarks:



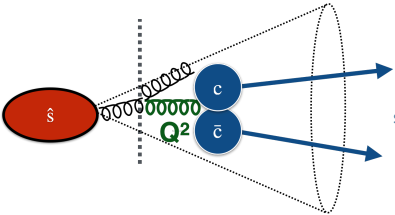
Distribution of formation time τ_{tot} with a top-quark

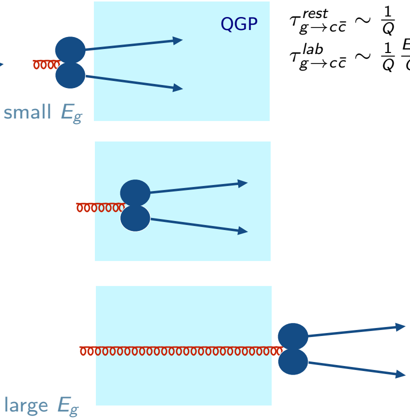


Maximum medium quenching end-time τ_m for different colliders

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)





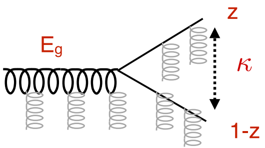
$$\tau^{rest}_{g\to c\bar{c}} \sim \frac{1}{Q}$$

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

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

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

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



In-vacuum splitting function to leading order in α_s

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

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

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

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

$\sigma(r)$: 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

$P^{med}_{g\to c\bar{c}}$: "magnitude" of the in-medium modification

From the calculation:

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

From model extraction in central PbPb data:

$1\ GeV^2 < \langle q^2 \rangle_{med} = \hat{q}L < 8\ GeV^2$ (conservative range)

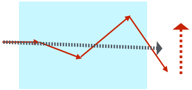
$$\Rightarrow \qquad \langle q^2 \rangle_{med} \sim O\left(m_c{}^2\right)$$

$$\Rightarrow \qquad P^{med}_{g\to c\bar{c}} \sim \mathcal{O}\left(\frac{m_c{}^2}{Q^2}\right) \qquad P^{vac}_{g\to c\bar{c}}(z) = z^2 + (1-z)^2 + 2\frac{m_c{}^2}{Q^2}$$

Medium properties and $g \to c\bar{c}$ kinematics:

- $\hat{q}$ average squared transverse momentum
- L medium length

$\langle q^2 \rangle_{med} \sim \hat{q}L$ average squared transverse momentum that a parton acquire in a medium of length L:



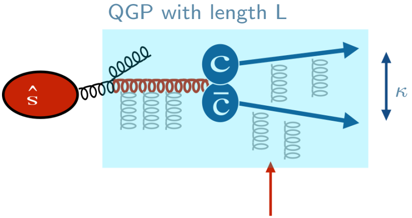
length L

$< \hat{q} >_{med} \sim \hat{q}L$

$P^{med}_{g\to c\bar{c}}$ has same "magnitude" of the mass term $P^{vac}_{g\to c\bar{c}}$ known to give origin to sizeable effects

$\to$ effect of $P^{med}_{g\to c\bar{c}}$ likely to be relevant

$P^{med}_{g\to c\bar{c}}$: $c\bar{c}$ broadening and $c\bar{c}$ enhancement



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

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

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

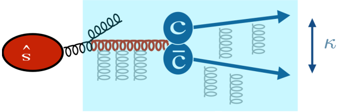
$\longrightarrow$ Gluons which would not split in vacuum can split if in-medium scatters occurs

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

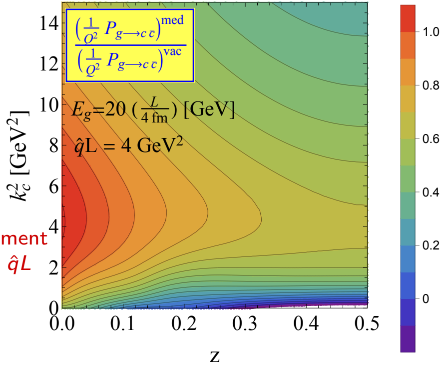
Numerical results for $P^{med}_{g\to c\bar{c}}$ / $P^{vac}_{g\to c\bar{c}}$

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

QGP with length L



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

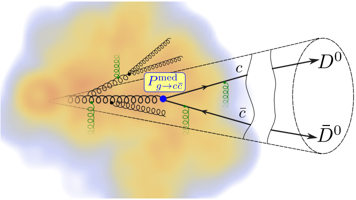


→ magnitude of in-medium modification
$P^{med}_{g\to c\bar{c}} \sim P^{vac}_{g\to c\bar{c}}$

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

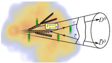
Experimental strategy for $g \to c\bar{c}$ enhancement

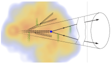


High-p_T jets with a pair inside the jet code:

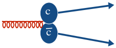
- D-meson reconstruction
  - constraints on the charm-quarks kinematics
  - accessible down to low p_T in heavy-ions

$$\frac{N^{D^0\bar{D}^0}_{jets}}{N_{jets}} =$$





$\rightarrow$



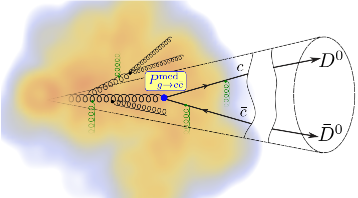
Due to $g \to c\bar{c}$ enhancement, a larger fraction of $D^0\bar{D}^0$-tagged jets expected in heavy-ions

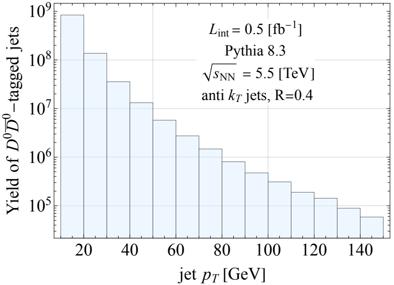
$\rightarrow$ dedicated MC study to provide a first assessment of the feasibility of such measurement

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 $D^0 \bar{D}^0$ per jet
- only prompt D^0 contribution considered ($c \to D^0$)

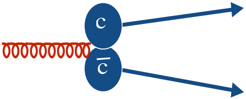




Fully reconstructed hadronic decays
But also $c\bar{c}$-tagging techniques high-p_T jets or tagging of semi-leptonic charm decays
$\to$ sample $\sim$ entire $c\bar{c}$ statistics

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

→ ideal strategy: include all modified splitting functions in the parton shower (currently not available)



$p_g = p_c + p_{\bar{c}}$

A simplified procedure:

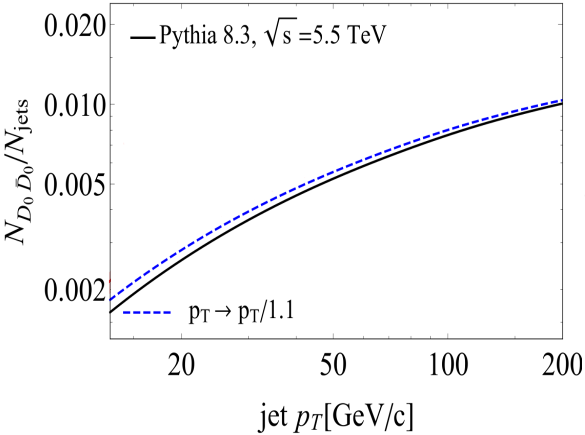
- identify and reconstruct the $g \to c\bar{c}$ kinematics in Pythia
- "reweigh" each splitting to accounts for modified $g \to c\bar{c}$ probability

$$w^{med}_{g\to c\bar{c}}\left(E_g, \kappa^2, z\right) = 1 + \frac{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{med}\left(E_g, \kappa^2, z\right)}{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{vac}\left(\kappa^2, z\right)}$$

This simplified strategy relies on few realistic assumptions/approximations (arXiv:2203.11241)

→ captures the qualitative features of the in-medium modifications

Letter in preparation



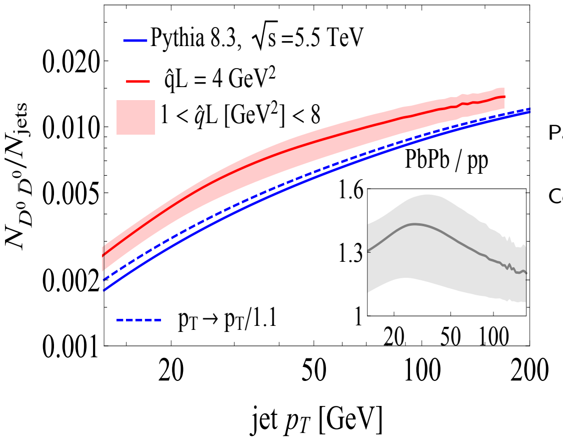
Parton shower in vacuum (Pythia pp)

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 $P^{med}_{g\to c\bar{c}}$

$N_{jets}^{D^0\bar{D}^0}/N_{jets}$ as a function of jet p_T

Letter in preparation



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Reweighed to account for modified $g \to c\bar{c}$ splitting function:
$\to$magnitude of the effect likely to increase with more differential observables

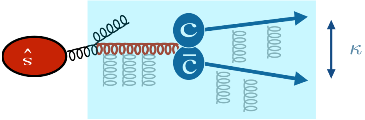
Conclusions - observable sensitive to enhanced $g \to c\bar{c}$ in jets

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

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

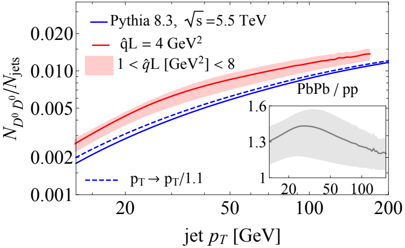
- broadening of $c\bar{c}$ pairs and enhancement of $c\bar{c}$ radiation

QGP with length L



Experimental strategy for $g \to c\bar{c}$ 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 $\to$ more differential observables
- high-luminosity heavy-ion runs, improved detector capabilities and new analysis techniques

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

Thank you for your attention!