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

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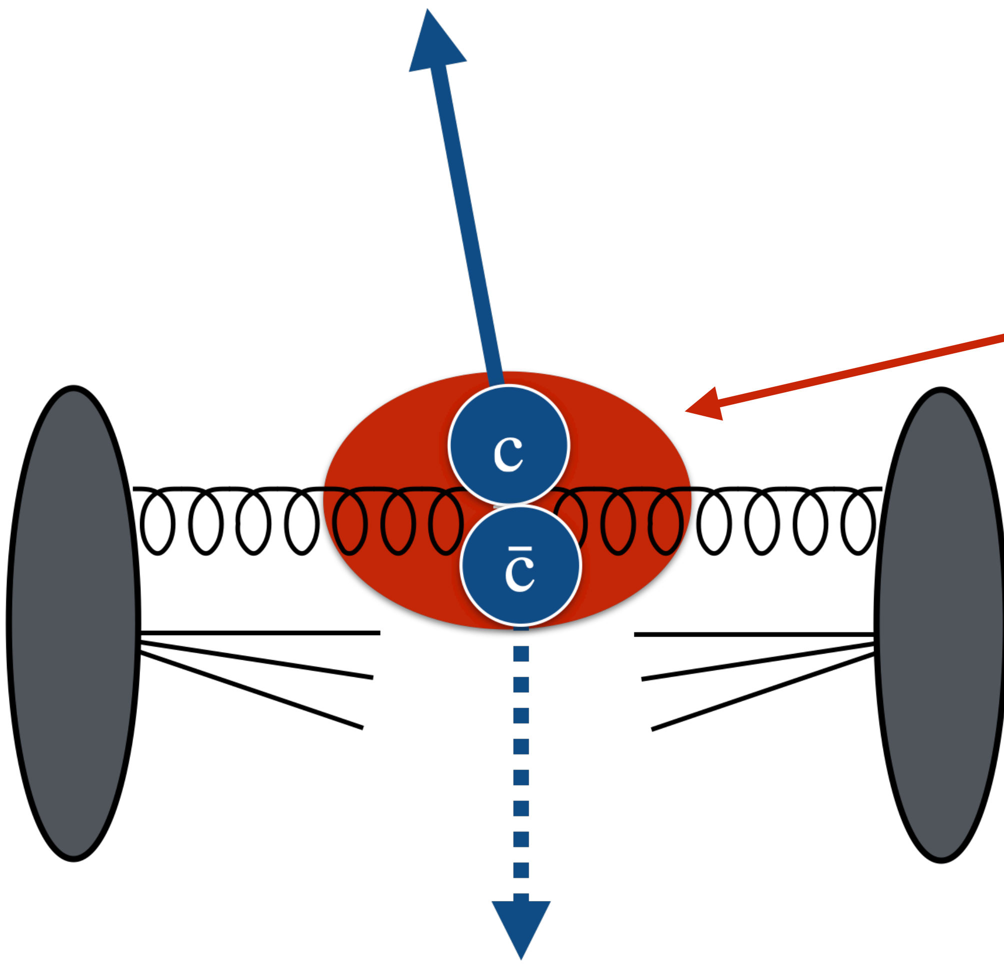
Based on arXiv:2203.11241

Heavy quark production in pp collisions

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

$\hat{s}$: partonic center of mass energy^2



$\hat{s} > m^2_{c,b}$

short-distance high-momentum transfer process

$m_{c,b} \gg \Lambda_{QCD}$

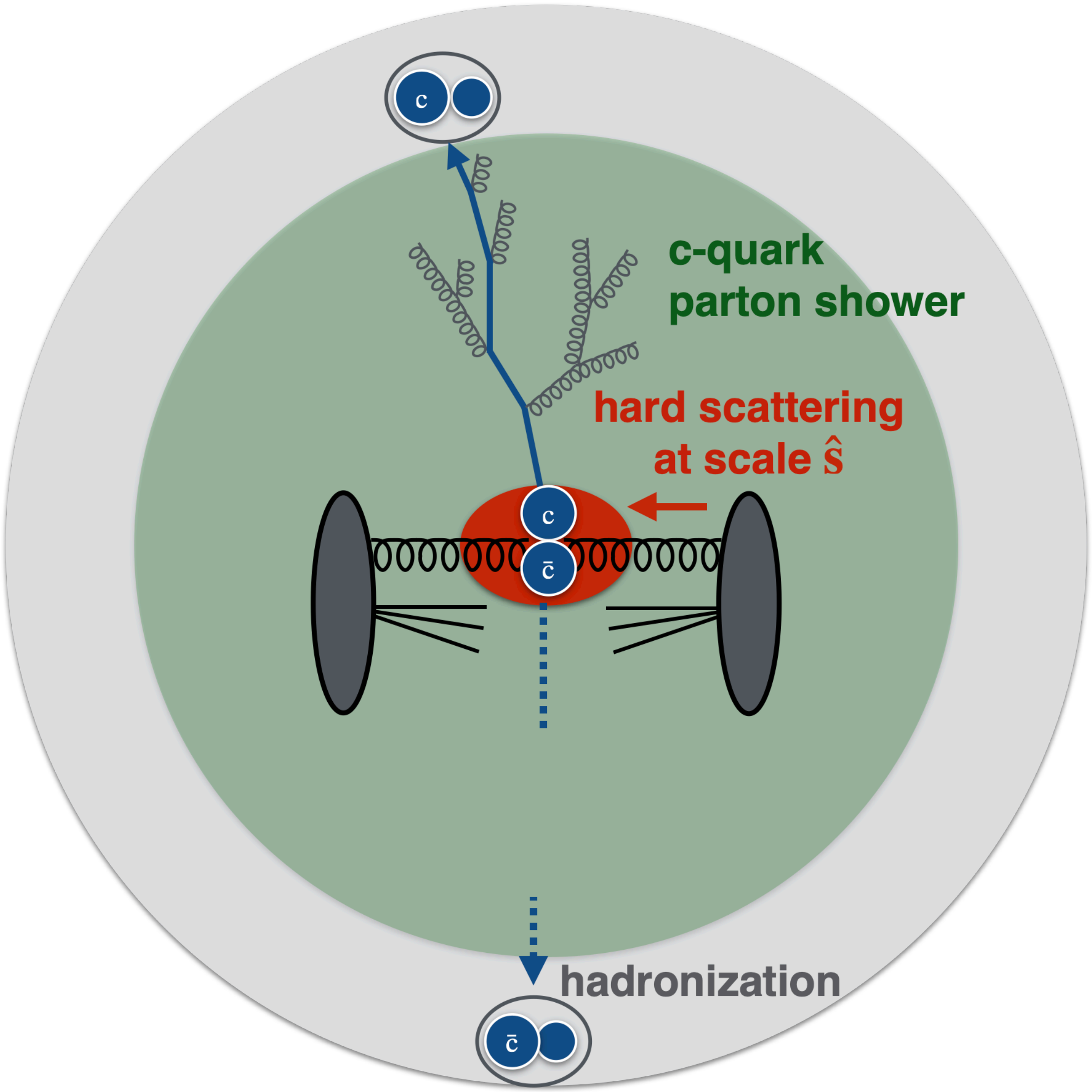
calculable in pQCD

- The total charm production cross section is dominated by $c\bar{c}$ pairs emerge back-to-back
  c.f. $g \rightarrow c\bar{c}$ is collinear
- The QGP forms later than this short-distance process & it only modifies the pT distribution of the cross section

→ set the reference for the total charm yield in heavy-ion collisions

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

Dominant medium-modification of charm in the QGP



As a charm traverses in QGP it re-scatters.

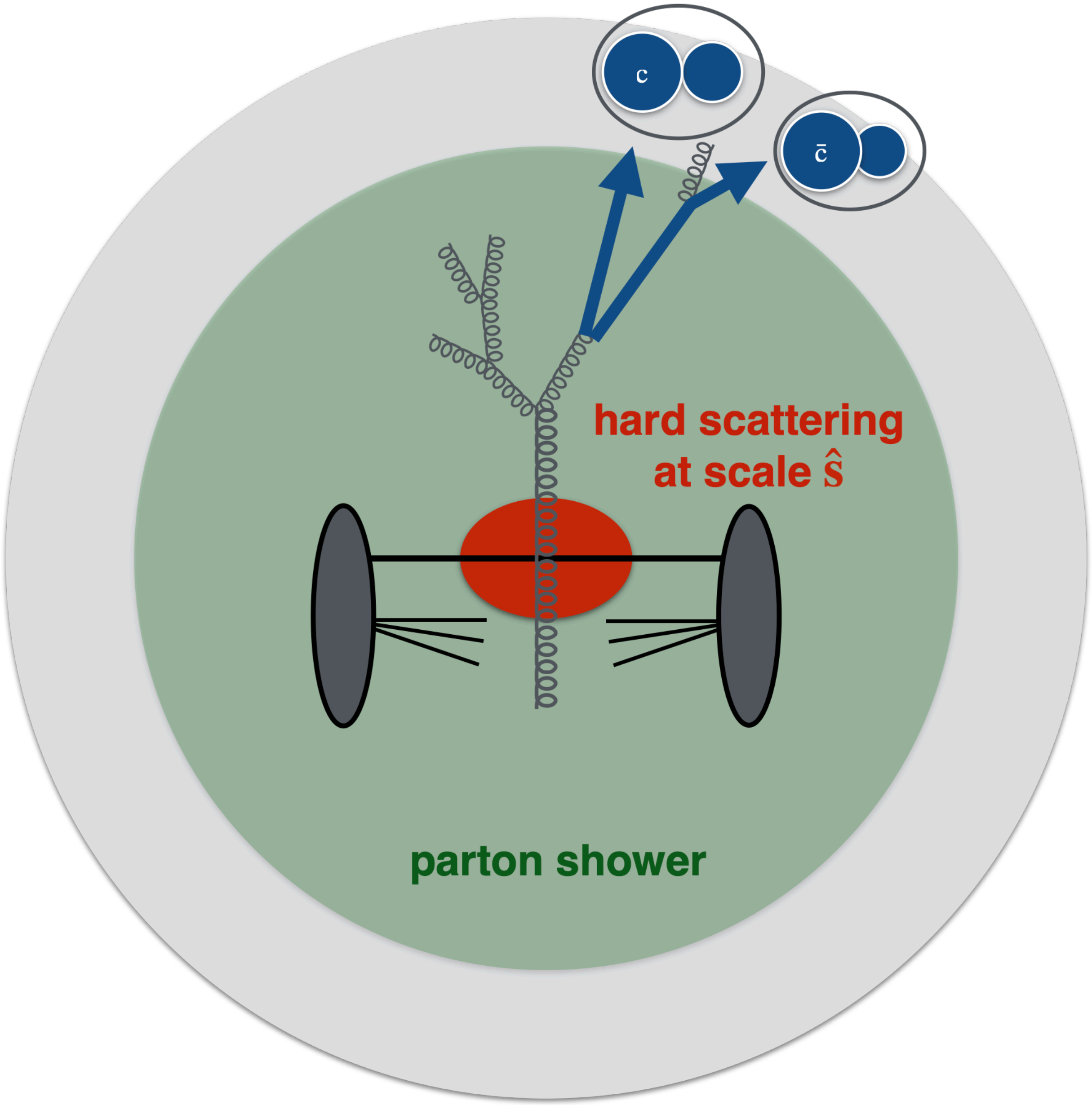
The dominant process is $\mathbf{c} \to \mathbf{cg}$,

described by the $\mathbf{c} \to \mathbf{cg}$ splitting function.

- BDMPS-Z calculation shows the enhancement of gluon radiation from charm in the QCD medium
- Experimentally observed via the modification of high-pT spectra of charmed hadrons due to radiative energy loss

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

Charm production from $g \to c\bar{c}$ splitting in the QGP



We applied the BDMPS-Z formalism to calculate the medium-modification of $g \to c\bar{c}$ splitting function

Why is this interesting?

- medium-induced production in the long distance (not dominant $c\bar{c}$ production in the short distance but dominant production in the medium)

  → a way to access medium properties

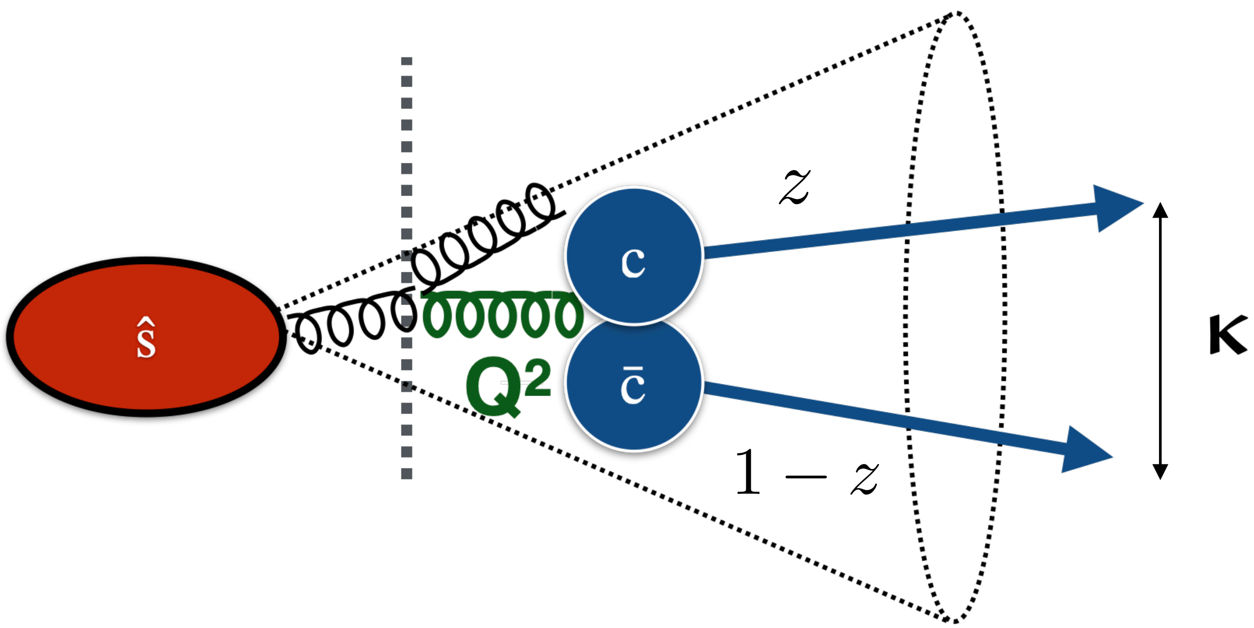
- collinear to the gluon direction (not back-to-back), so $c\bar{c}$ pairs likely to remain inside the gluon jet

  → traceable with gluon jets

arXiv:2203.11241 &
Letter in preparation

Plan:
- in-medium calculation of $g \to c\bar{c}$ splitting function in the BDMPS-Z formalism
- one experimental observable for medium-modification of $g \to c\bar{c}$ splitting function: $D^0\bar{D}^0$ production in high pT gluon jets

Factorization of partonic cross section in the collinear limit



In the collinear limit $Q^2 \ll \hat{s}$ a partonic cross section factorizes.

$$\hat{\sigma}^{gg\to c\bar{c}X} \xrightarrow{Q^2 \ll \hat{s}} \hat{\sigma}^{gg\to gX} \otimes \frac{\alpha_s}{2\pi}\frac{1}{Q^2} \boxed{P_{g\to c\bar{c}}}$$

splitting function: probability for a gluon to split to a $c\,\bar{c}$ pair

$\hat{s}$: partonic center of mass energy²

Q : virtuality of the gluon

$$Q^2 = \frac{m_c^2 + \kappa^2}{z(1-z)}$$

$$\kappa = \frac{1}{2}(\mathbf{k}_c - \mathbf{k}_{\bar{c}})$$

: relative transverse momentum of $c\,\bar{c}$ pair

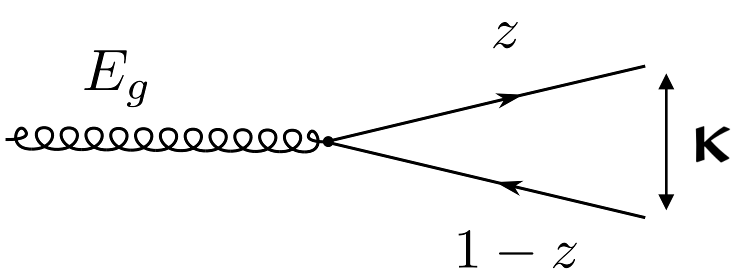
m_c : mass of charm

$\mathbf{k}_c$: transverse momentum of charm

z : longitudinal momentum fraction carried by charm

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

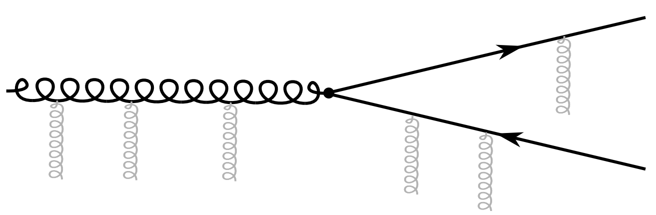
In-vacuum splitting function to leading order in α_s



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

kinematic factor

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



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

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

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

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

path-integral

E_g : gluon energy

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

$n(\xi)$: a longitudinal density of colored scattering centers

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

characterize medium

Features of the medium-modified $g \to c\bar{c}$ splitting function

- In the absence of medium $n(\xi) = 0$, it reduces to the vacuum splitting function

$$\left(\frac{1}{Q^2} P_{g\to c\,\bar{c}}\right)^{\text{tot}} \xrightarrow{n(\xi)=0} \left(\frac{1}{Q^2} P_{g\to c\,\bar{c}}\right)^{\text{vac}} = \frac{1}{Q^4}\left[\left(m_c^2 + \boldsymbol{\kappa}^2\right)\frac{z^2+(1-z)^2}{z(1-z)} + 2m_c^2\right]$$

- For multiple soft scattering (small $\mathbf{r}$), take saddle point approximation

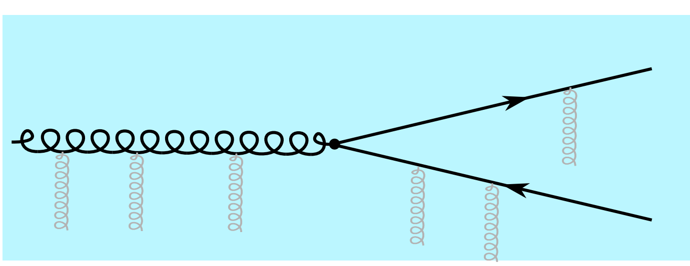
$$n(\xi)\,\sigma_3(\mathbf{r},z) \simeq \frac{1}{2}\boxed{\hat{q}(\xi)}\,(C_F - N_c z(1-z))\,\mathbf{r}^2$$

→ $\mathcal{K}$ becomes the path-integral of an harmonic oscillator

quenching parameter

color factors

QGP with length L



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

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

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

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

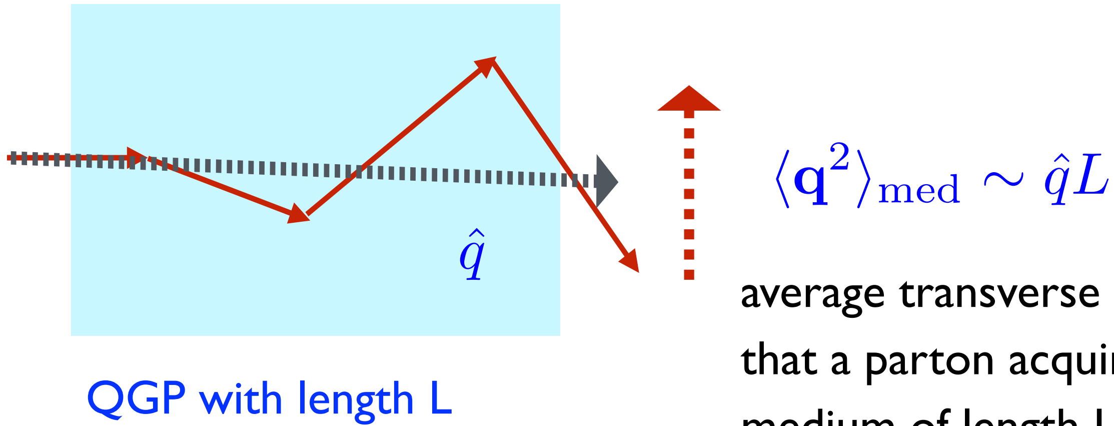
$$= \left(\frac{1}{Q^2} P_{g\to c\,\bar{c}}\right)^{\text{tot}} (E_g, \boldsymbol{\kappa}, z, \hat{q}, L)$$

parameterized to medium properties

Features of the medium-modified $g \to c\bar{c}$ splitting function

- From the calculation

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



average transverse momentum^2 that a parton acquires in a medium of length L

- From model extraction in central PbPb data

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

→ in heavy-ion collisions $\langle \mathbf{q}^2\rangle_{\text{med}} \sim \mathcal{O}(m_c^2)$

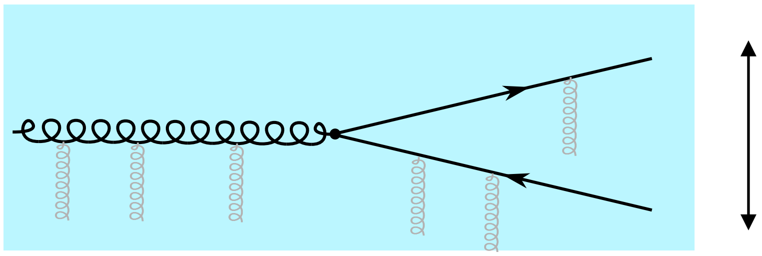
recall $P^{\text{vac}}_{g\to c\,\bar{c}} = z^2 + (1-z)^2 + 2\frac{m_c^2}{Q^2}$

→ Medium-modification $P^{\text{med}}_{g\to c\,\bar{c}} \sim \mathcal{O}\left(\frac{\langle \mathbf{q}^2\rangle_{\text{med}}}{Q^2}\right)$ becomes sizeable at the charm mass scale,

which is phenomenologically accessible!

Features of the medium-modified $g \to c\bar{c}$ splitting function

QGP with length L



K relative transverse momentum of the $c\,\bar{c}$ pair

Broadening

K increases due to transverse momentum broadening of the individual quarks

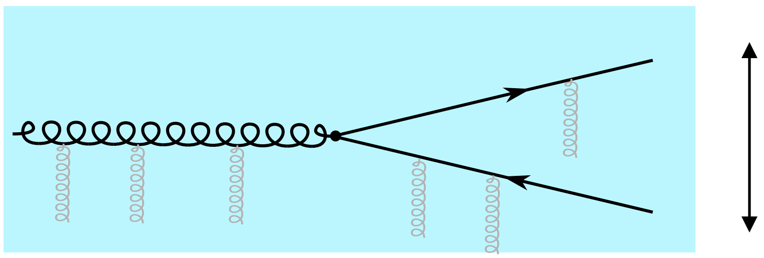
Enhancement

Gluons that would not split in vacuum can split if in-medium scatterings occur

→ medium-induced production of $c\,\bar{c}$ pairs!

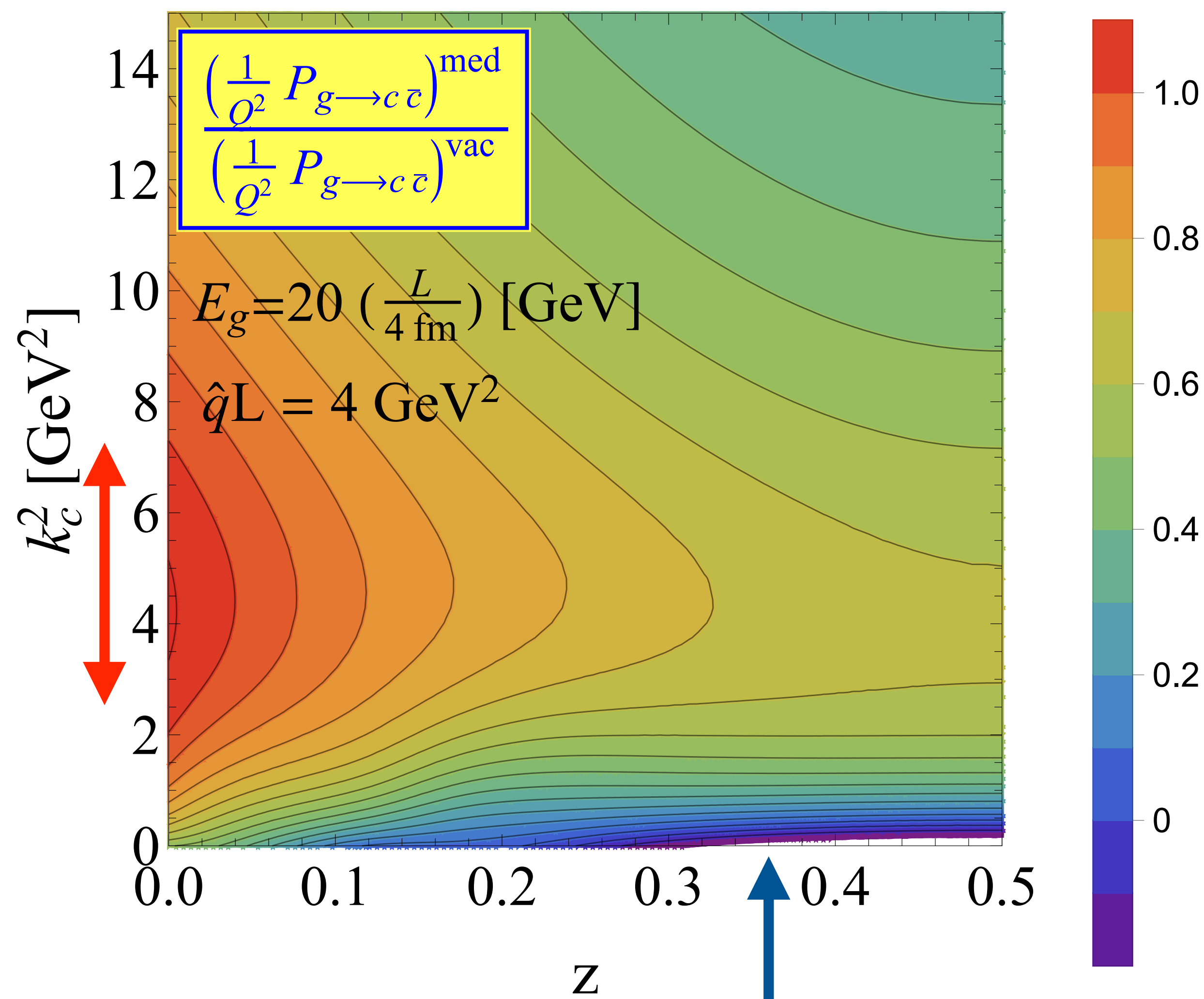
Numerical results of the medium-modified $g \to c\bar{c}$ splitting function

QGP with length L



$\boldsymbol{\kappa} = \mathbf{k}_c$ in the transverse pair rest frame

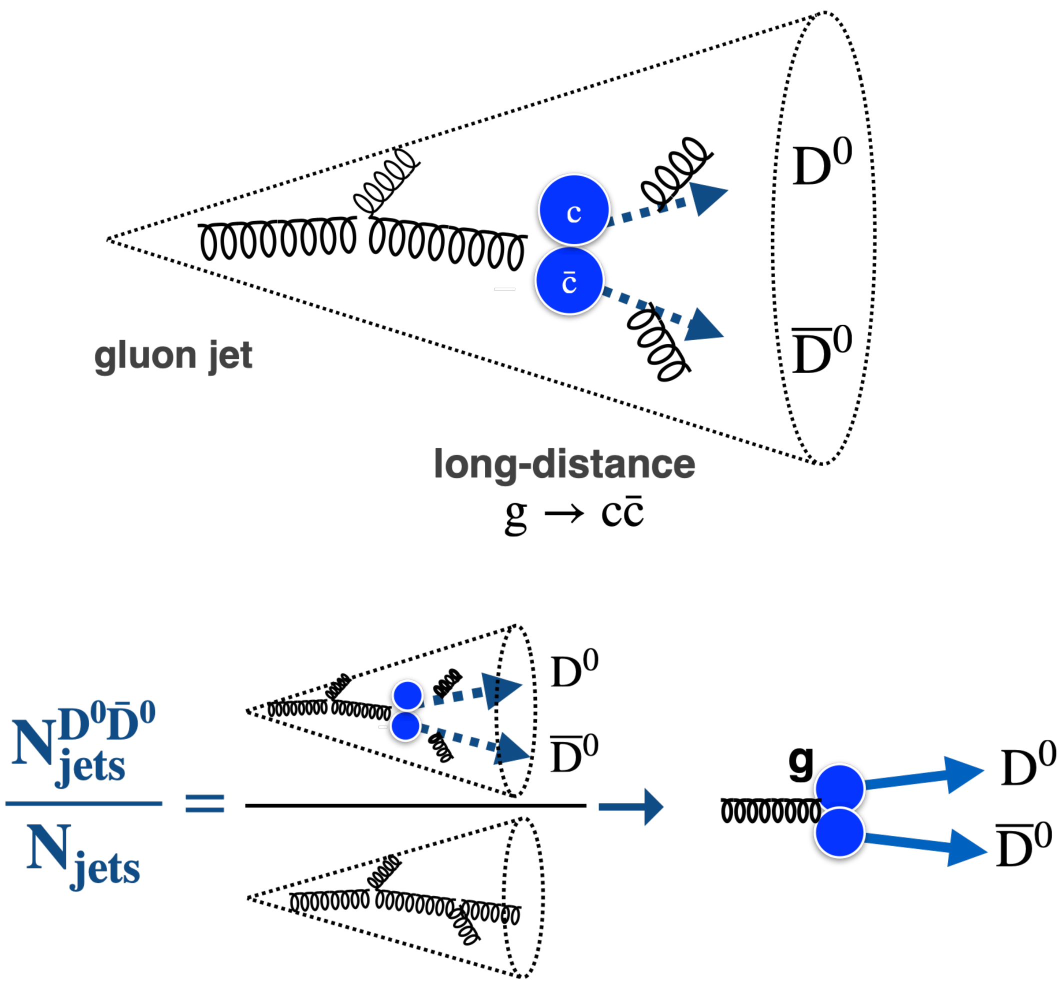
Enhancement for $\mathbf{k}_c^2 \sim \hat{q}L$



Depletion of low $\mathbf{k}_c^2$ splittings due to the in-medium broadening

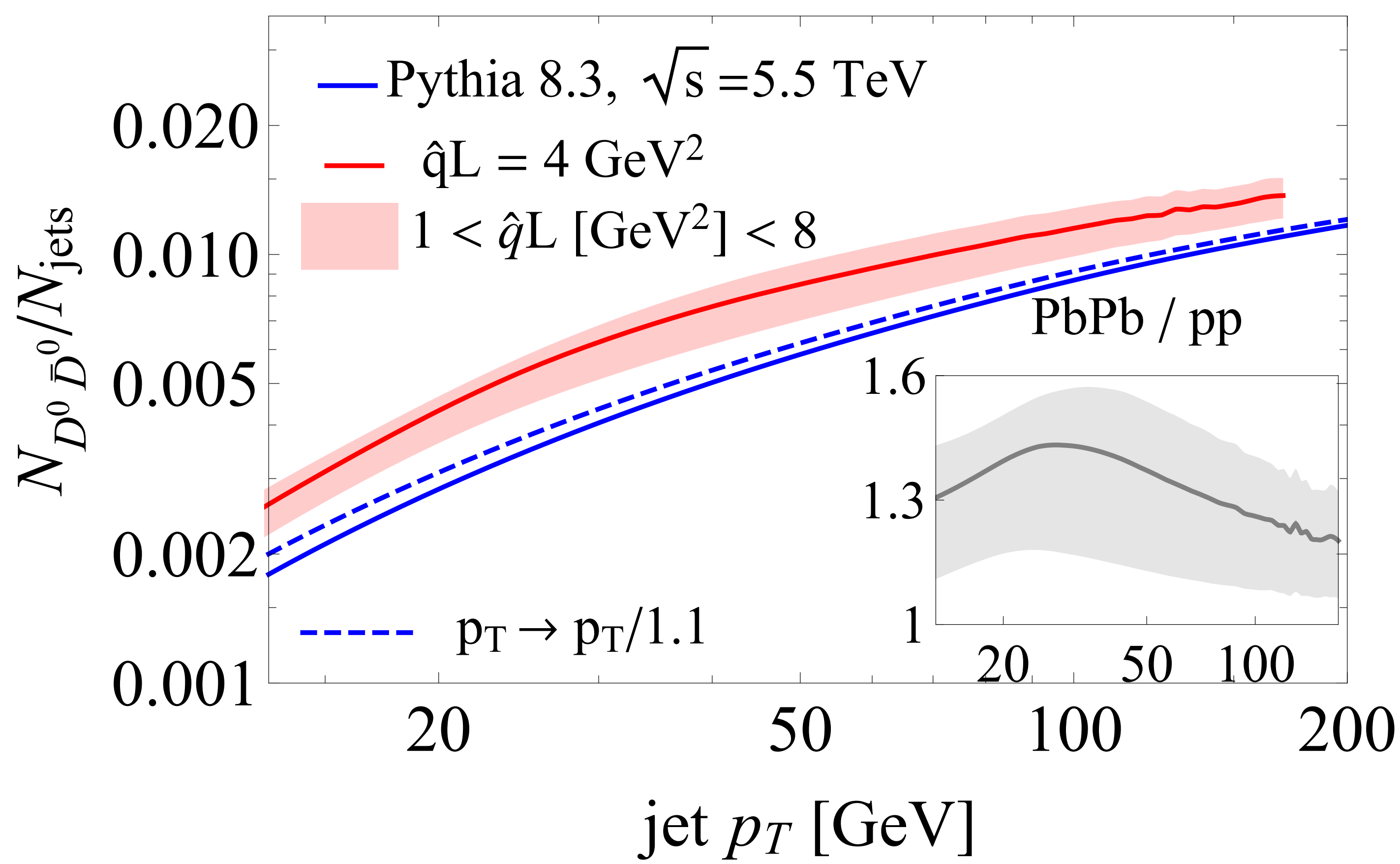
An observable sensitive to enhanced $g \to c\bar{c}$ splittings in jets

Experimental strategy



Monte Carlo study with Pythia

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



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

Dedicated MC study to provide a first assessment of the feasibility of such measurements

See poster by Aleksas Mazeliauskas, Tue 17:10

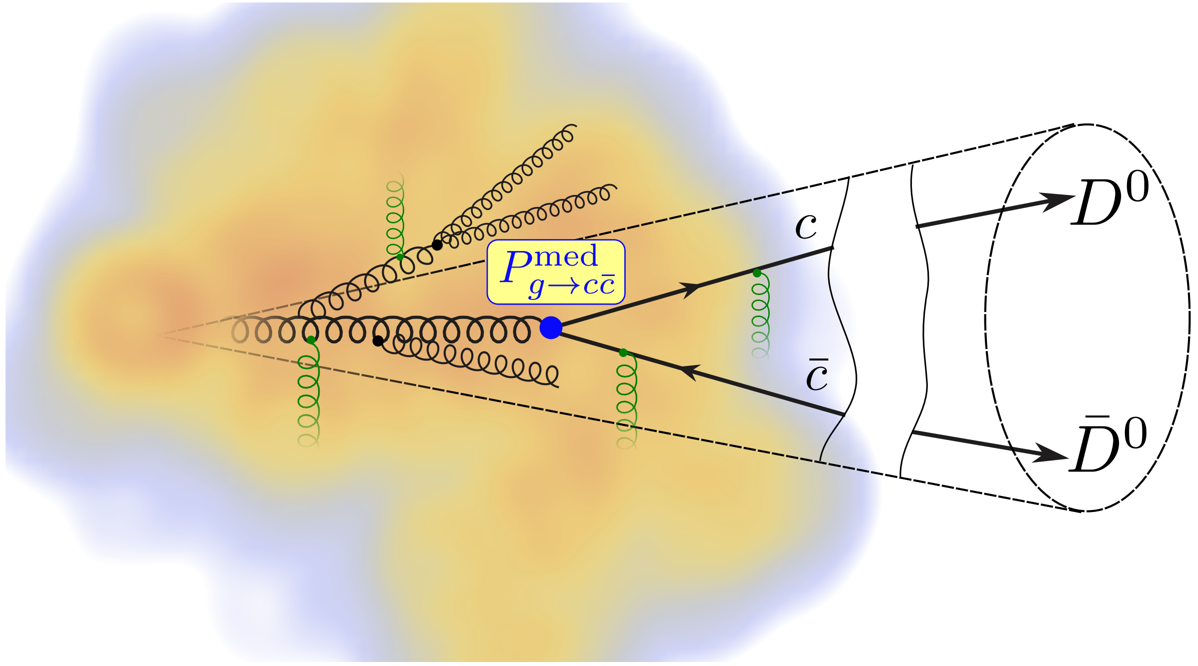
Conclusions

• We have calculated the medium-modification of the QCD leading order gluon splitting function into a charm and anti-charm pair in the BDMPS-Z formalism.

• The result of $P^{\mathrm{med}}_{g\to c\,\bar{c}}$ shows broadening of the relative momentum of a $c\,\bar{c}$ pair and enhancement of $c\,\bar{c}$ productions in the QCD medium, which is sizeable at the charm mass scale.

• As an experimental strategy we made a MC study for the fraction of $D^0\,\bar{D}^0$-tagged jets w/out, which shows over 10% enhancement of $D^0\,\bar{D}^0$-tagged jets.

Great opportunity for new theoretical and experimental developments to study this novel medium-induced effect!



Thank you!