Medium-Enhanced $c\bar{c}$ Radiation

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We show that the same QCD formalism that accounts for the suppression of high-p_T hadron and jet spectra in heavy-ion collisions predicts medium-enhanced production of $c\bar{c}$ pairs in jets. We demonstrate that this phenomenon, which cannot be accessed by traditional jet-quenching observables, can be directly observed using $D^0\bar{D}^0$-tagged jets in nuclear collisions.

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Introduction.—In ultrarelativistic heavy-ion collisions, heavy flavor quarks (charm and beauty) are produced in high-momentum transfer processes, which are calculable in perturbative QCD [1]. As these heavy quarks traverse the quark gluon plasma (QGP) created in the collision, they probe its properties. Over the lifetime of the QGP, charm and beauty quarks are stable and can be tagged experimentally. This makes them ideally suited for studying quark propagation in the QCD plasma [2].

Theory predicts that energetic quarks and gluons (partons) lose energy while traversing the QGP. This jet-quenching phenomenon is observed in heavy-ion collisions as a generic suppression of high-p_T single inclusive hadron and jet spectra [3]. The suppression is understood as a combination of elastic energy loss and radiative energy loss from medium-induced gluon radiation [4–6]. This theory framework explains the generic suppression of high-p_T hadron and jet spectra, and also predicts the enhancement of $q\bar{q}$ pairs in the phase space region in which medium-induced radiation occurs. However, in contrast to the suppression patterns that gave "jet quenching" its name, such a characteristic enhancement has not been tested experimentally so far. Here, we show that heavy quarks provide a unique avenue to measure this effect because gluon splittings into charm quarks can be tagged experimentally in jets containing a pair of heavy-flavor mesons; see Fig. 1.

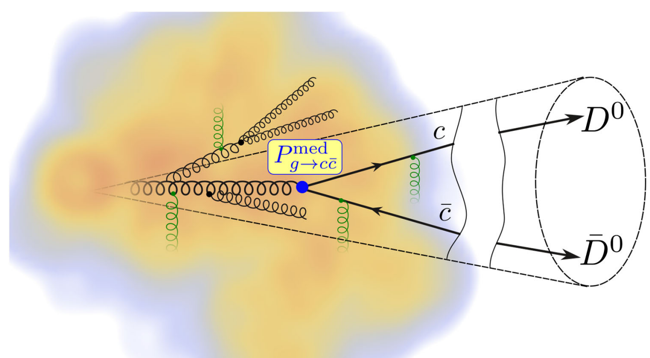

FIG. 1. Illustration of a parton shower containing a $g \to c\bar{c}$ splitting. This $c\bar{c}$ radiation is enhanced due to the QGP, which can be tested by measuring $D^0\bar{D}^0$ pairs inside jets.

In hadronic collisions, charm is produced in $c\bar{c}$ pairs of squared invariant mass $Q^2 = (p_c + p_{\bar{c}})^\mu (p_c + p_{\bar{c}})_\mu$ bounded by the charm quark mass m_c and the partonic center-of-mass energy $\hat{s}$, $4m_c^2 \le Q^2 \le \hat{s}$. Pairs can be produced at high Q^2 (typically through hard scattering or initial-state radiation) or at low Q^2 (often from gluon splitting); see, e.g., [1,7]. Up to now, most studies have focused on the gluon radiation $c \to cg$ that can reduce the charm momentum but leaves its yield unaffected [6]. In the present Letter, we emphasize that radiative parton energy loss predicts a qualitatively different phenomenon: For small Q^2, the $g \to c\bar{c}$ splitting receives significant medium modifications that increase the yield of $c\bar{c}$ pairs within high-p_T jets.

In the collinear limit $Q^2 \ll \hat{s}$, partonic cross sections for $c\bar{c}$ production factorize. For instance, the cross section for $gg \to c\bar{c}X$ can be written as

$$\hat{\sigma}^{gg\to c\bar{c}X} \overset{Q^2 \ll \hat{s}}{\longrightarrow} \hat{\sigma}^{gg\to gX} \frac{\alpha_s}{2\pi} \frac{1}{Q^2} P_{g\to c\bar{c}}(z). \tag{1}$$

The $g \to c\bar{c}$ splitting function depends on the momentum fraction z carried by the charm quark and the virtuality Q of the gluon,

$$P^{\mathrm{vac}}_{g\to c\bar{c}} = \frac{1}{2}\left(z^2 + (1-z)^2 + \frac{2m_c^2}{Q^2}\right). \tag{2}$$

We use E_g to denote the gluon energy and $2\boldsymbol{\kappa}$ the relative $c\bar{c}$ pair momentum transverse to the direction of the gluon. For collinear splittings $\boldsymbol{\kappa} \ll zE_g$, $(1-z)E_g$, the squared gluon virtuality is $Q^2 = [(m_c^2 + \boldsymbol{\kappa}^2)/z(1-z)]$.

For sufficiently high gluon energy, the gluon is boosted with respect to the QGP by a Lorentz factor $\gamma = E_g/Q$, and the formation time $\sim 1/Q$ of the $c\bar{c}$ pair is time delayed by γ and becomes $\sim E_g/Q^2$ in the rest frame of the QGP. For pairs within a jet, we are restricted to small Q^2, and the formation time can be comparable to the medium size. For instance, for $E_g = 100$ GeV and $Q^2 = 4m_c^2$, one finds $E_g/Q^2 = 3.1$ fm/c. We hence expect a characteristic enhancement of $c\bar{c}$ pairs within the same jet depending on the energy and the virtuality of the pair.

Medium-modified $g \to c\bar{c}$ splitting function.—For the $q \to qg$ and $g \to gg$ leading-order splitting functions, medium modifications have been calculated in the Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov (BDMPSZ) formalism [4,5,8] and in several related setups [9,10]. These calculations resum the effects of multiple interactions between the QCD plasma and the splitting process in a close-to-eikonal formulation, where the energy of the parent parton is much larger than any transverse momentum or mass scale. For the $g \to c\bar{c}$ splitting function, medium modifications have been calculated to first order in opacity [11,12] as well as in the BDMPSZ path-integral formalism where they read [12]

$$\begin{aligned}
\left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{tot}} &= \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{vac}} + \left(\frac{1}{Q^2}P_{g\to c\bar{c}}\right)^{\mathrm{med}} \\
&= 2\mathfrak{Re}\frac{1}{8E_g^2}\int_0^\infty dt \int_t^\infty d\bar{t} \int d\mathbf{r} \\
&\quad \times e^{i\frac{m_c^2}{2E_g z(1-z)}(t-\bar{t}) - \epsilon|t| - \epsilon|\bar{t}|} e^{-\frac{1}{4}\int_{\bar{t}}^\infty d\xi\, \hat{q}(\xi,z)\mathbf{r}^2} e^{-i\boldsymbol{\kappa}\cdot\mathbf{r}} \\
&\quad \times \left[\frac{m_c^2}{z(1-z)} + \frac{z^2+(1-z)^2}{z(1-z)} \frac{\partial}{\partial \mathbf{x}} \cdot \frac{\partial}{\partial \mathbf{r}}\right] \\
&\quad \times \mathcal{K}[\mathbf{x}=0, t; \mathbf{r}, \bar{t}].
\end{aligned} \tag{3}$$

This expression is written in the limit of a large number of colors. It has the space-time interpretation of a gluon that splits into a $c\bar{c}$ pair at longitudinal positions t ($\bar{t}$) in amplitude (complex conjugate amplitude). In the multiple soft scattering approximation, $\mathcal{K}[\mathbf{x}, t; \mathbf{r}, \bar{t}]$ is the path integral of a harmonic oscillator with imaginary potential

$$\mathcal{K}[\mathbf{x}, t; \mathbf{r}, \bar{t}] = \int_{\boldsymbol{\rho}(t)=\mathbf{x}}^{\boldsymbol{\rho}(\bar{t})=\mathbf{r}} \mathcal{D}\boldsymbol{\rho}\, e^{i\int_t^{\bar{t}} d\xi \left(\frac{E_g z(1-z)}{2}\dot{\boldsymbol{\rho}}^2 - \frac{\hat{q}(\xi,z)\boldsymbol{\rho}^2}{4i}\right)}.$$

It describes how the $c\bar{c}$ dipole grows from transverse size $\mathbf{x} = 0$ at t to size $\mathbf{r}$ at $\bar{t}$. Equation (3) depends on the kinematics of the splitting and on a single medium property, the quenching parameter $\hat{q}(\xi, z)$ along the parton trajectory in the medium.

Both adjoint and fundamental color configurations contribute in a z-dependent way to the interaction of the $g \to c\bar{c}$ splitting with the QGP [12]. This dependence can be factorized from the quenching parameter, $\hat{q}(\xi, z) \equiv [C_F - C_A z(1-z)]\hat{\hat{q}}$. For small z, the quenching parameter is hence, $\hat{q} = C_F\hat{\hat{q}}$, in contrast to $\hat{q}_A \equiv C_A\hat{\hat{q}}$ for $q \to qg$ and $g \to gg$, for which the leading medium modification is from the scattering of the emitted gluon [4,5,8].

To estimate $\hat{\hat{q}}$, we considered recent constraints [13–17] on $\hat{q}_A$ from heavy-ion data to determine the momentum transferred from the medium

$$\langle q^2 \rangle_{\mathrm{med}} = C_F \int_{\tau_i}^{\tau_f} d\xi\, \hat{\hat{q}}(\xi). \tag{4}$$

Here, $\tau_{i/f}$ denote the initial and final time within which jet-medium interactions occur. Explicit calculation of the line integrals for the jet-quenching models in [16] yields consistently $4\ \mathrm{GeV}^2 < \langle q^2 \rangle_{\mathrm{med}} < 8\ \mathrm{GeV}^2$ for the 0%–5% most central PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 2 shows the numerical results of the medium modification of Eq. (3) for a momentum transfer $\hat{q}L = 4\ \mathrm{GeV}^2$ [18]. Medium-induced transverse momentum broadening leads to a characteristic enhancement at the scale $\boldsymbol{\kappa}^2 \sim \hat{q}L$ while depleting the vacuum distribution of $c\bar{c}$ pairs at very small relative momenta $\boldsymbol{\kappa}^2$. This can be understood in terms of transverse Brownian motion of the charm

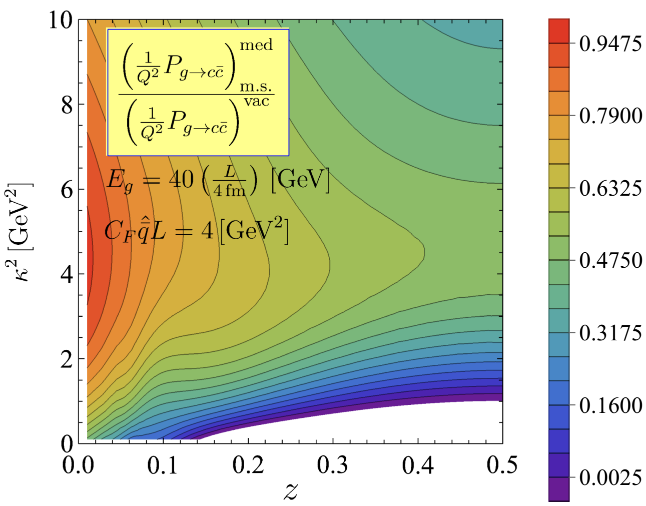

FIG. 2. The ratio of medium modification over vacuum splitting $P^{\mathrm{med}}_{g\to c\bar{c}}/P^{\mathrm{vac}}_{g\to c\bar{c}} \equiv P^{\mathrm{tot}}_{g\to c\bar{c}}/P^{\mathrm{vac}}_{g\to c\bar{c}} - 1$ shows an enhancement of nearly 100% over the vacuum baseline in a significant phase space region [see Eq. (5)].

quarks in the medium, which pushes the collinear pairs to larger $\boldsymbol{\kappa}^2$. Compared to the vacuum splitting function, the medium-modified splitting can be almost 100% larger in a range of intermediate $\boldsymbol{\kappa}^2$ for $\hat{q}L = 4\ \mathrm{GeV}^2$.

Tracing $g \to c\bar{c}$ via $D^0\bar{D}^0$ pairs in jets.—We now discuss one strategy for testing the enhanced $g \to c\bar{c}$ radiation experimentally. To this end, we simulate pp collisions at $\sqrt{s_{NN}} = 5.5$ TeV in PYTHIA8.3 (Monash tune) [19] with initial-state radiation (ISR) off and use FastJet [20] to reconstruct anti-k_t [21] jets with jet radius $R = 0.4$. We select jets with exactly one $D^0\bar{D}^0$ pair, which leads to a high-purity sample of jets in which the $D^0\bar{D}^0$ pair came from one $g \to c\bar{c}$ splitting. Including ISR increases the total jet yield but does not impact the ratio of $D^0\bar{D}^0$-tagged and inclusive jets on which our argument is based. The probability of having more than one $g \to c\bar{c}$ splitting in a $D^0\bar{D}^0$-tagged jet is below 1% for $p_T^{\mathrm{jet}} < 100$ GeV.

Figure 3 shows the yield of jets containing a single $D^0\bar{D}^0$ pair at midrapidity ($|\eta_{\mathrm{jet}}| < 1.6$) expected for the projected luminosity ($\mathcal{L}_{\mathrm{int}}^{\mathrm{PbPb}} = 10\ \mathrm{nb}^{-1}$) of the High-Luminosity Heavy-Ion LHC (HL HI LHC) [22]. Nonprompt contributions arising from b-quark fragmentation can be removed experimentally and are not considered in the following. The two-body decay $D^0 \to K^-\pi^+$ can be reconstructed in ultrarelativistic heavy-ion collisions, but it has a branching ratio of 3.96% [23], so only 1.6×10^{-3} of all $D^0\bar{D}^0$ pairs decay via this channel. Figure 3 therefore indicates that $\mathcal{O}(10^6)$ [$\mathcal{O}(10^3)$] counts are produced in this particular channel for $10\ \mathrm{GeV} < p_T^{\mathrm{jet}} < 20\ \mathrm{GeV}$ ($80\ \mathrm{GeV} < p_T^{\mathrm{jet}} < 90\ \mathrm{GeV}$), respectively. While we are not in a position to provide an experimental feasibility study for one particular detector, we conclude that there is sufficient yield to make such an effect measurable with a suitably optimized detector at the HL HI LHC.

Implementation of $g \to c\bar{c}$ medium modification in parton showers.—To identify the $g \to c\bar{c}$ splitting in Eq. (1), one requires $Q^2 \ll \hat{s}$. It is a generic feature of QCD

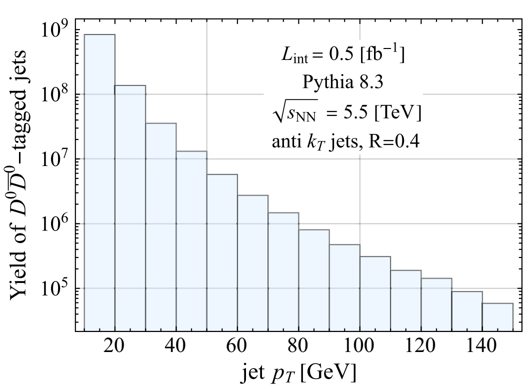

FIG. 3. Expected yield of $D^0\bar{D}^0$-tagged anti-k_t jets [21] with jet radius $R = 0.4$ in $10\ \mathrm{nb}^{-1}$ PbPb data, calculated without medium effects for an equivalent $\mathcal{L}_{\mathrm{int}}^{\mathrm{pp}} = 208^2 \mathcal{L}_{\mathrm{int}}^{\mathrm{PbPb}} \approx 0.5\ \mathrm{fb}^{-1}$ pp collisions.

that this scale difference $Q^2 \ll \hat{s}$ leads to a large logarithm that requires resummation. The right-hand side of Eq. (1) is therefore written in terms of the cross section $\hat{\sigma}^{gg\to gX}$ for a gluon jet, and the $c\bar{c}$ pair can arise at any stage in the branching history of that gluon. This resummation is accounted for in a parton shower. Parton showers are simulated by evaluating branching probabilities defined in terms of parton splitting functions.

In order to assess the medium modifications of the $c\bar{c}$ yield in a parton shower, we study three complementary implementations:

First, we take the PYTHIA events with a $D^0\bar{D}^0$-tagged jet described above, identify the $g \to c\bar{c}$ splitting, and reweight those events according to [12]

$$1 + \frac{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{med}} (E_g, \kappa^2, z)}{\left(\frac{1}{Q^2} P_{g\to c\bar{c}}\right)^{\mathrm{vac}} (\kappa^2, z)}. \tag{5}$$

The validity of this reweighting relies on the $g \to c\bar{c}$ splitting being sufficiently rare [12]. We evaluate Eq. (3) for an expanding medium by relating it to an equivalent static medium with adjusted $L = \tau_f - \tau_i = 4$ fm and $C_F \hat{\hat{q}} L = \hat{q} L = \langle q^2 \rangle_{\mathrm{med}}$ (see Ref. [12] for details). To account for uncertainties of this procedure and for possible model dependencies of medium parameters [13–15,17,24], we allow for a wide range $2\ \mathrm{GeV}^2 < \langle q^2 \rangle_{\mathrm{med}} < 8\ \mathrm{GeV}^2$. The resulting enhancement is shown in Fig. 4(a) (red) as compared to the vacuum baseline (blue).

The advantage of this approach is that one simulates hadronic distributions and implements directly the $\boldsymbol{\kappa}$-differential information from Eq. (3). Its limitation is that the reweighting does not account for the modification of other splittings (especially $g \to gg$), which could open phase space for extra gluon splittings and lead to energy loss of the jets studied. Our assumption in this approach is hence that the extra phase space is suppressed for small medium modifications and that energy loss similarly affects inclusive and $D^0\bar{D}^0$-tagged jets.

Second, we use the state-of-the-art jet-quenching Monte Carlo code JetMed [24]. It is based on a systematic factorization of (angular-ordered) vacuumlike and medium emissions. The in-medium evolution is based on a Markovian iteration [33] of the BDMPSZ rate with flavor-dependent kernels as derived in [34,35]. This implements the enhancement of the $\boldsymbol{\kappa}$-integrated $c\bar{c}$ rate consistent with Eq. (3). The distribution of this rate in transverse phase space is chosen according to Brownian motion, thus modeling the main feature of the $\boldsymbol{\kappa}$-differential distribution Eq. (3). To include heavy quark production in JetMed, we enforce that $g \to c\bar{c}$ satisfies the mass threshold $\boldsymbol{\kappa}^2 \geq 4m_c^2$ (see also Supplemental Material for details [25]). The advantage of JetMed is that it simulates the complete parton shower, including medium modifications of all parton splittings. We show results for a Bjorken-expanding

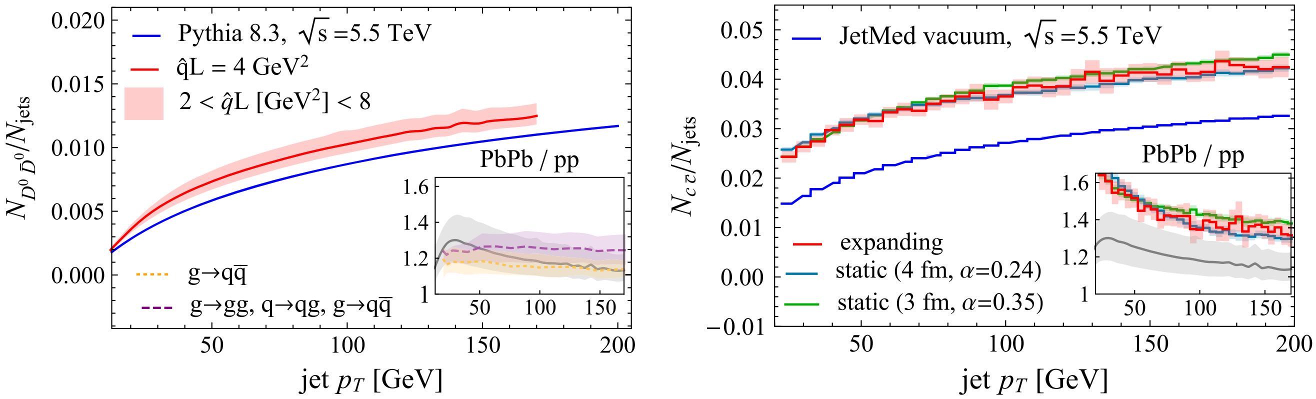

FIG. 4. (a) The fraction of jets of $R = 0.4$ that carry a $D^0\bar{D}^0$ tag in $\sqrt{s} = 5.5$ TeV midcentral ($|\eta_{\rm jet}| < 1.6$) collisions. The PYTHIA simulation for pp collisions (blue line) is compared to medium modifications using reweighting [Eq. (5)]. (b) JetMed results for the fraction of jets of $R = 0.4$ that carry a $c\bar{c}$ pair in $\sqrt{s} = 5.5$ TeV midcentral ($|\eta_{\rm jet}| < 1.6$) collisions. Results from pp collisions (blue line) are compared to results for in-medium propagation in static and expanding scenarios that describe the measured jet nuclear modification factors. Both insets show in gray the relative medium enhancement found in this simulation. As seen in the inset of Fig. 4(b), JetMed predicts a larger enhancement. The inset of Fig. 4(a) compares to results from a simple massless dipole shower with modification of $g \to q\bar{q}$ splittings only (orange band) and with modification to $g \to gg$, $q \to qg$, $g \to q\bar{q}$ splittings (purple band) (see Supplemental Material [25] for details).

medium (red) and for two static media with $L = 3$ fm and $L = 4$ fm (green and teal, respectively) in Fig. 4, with other parameters fixed to reproduce the jet nuclear modification in central PbPb collisions [24].

Third, we take a simple massless vacuum dipole shower and replace all splitting functions with medium-modified versions [36] with the same range of $\hat{q}L$ as in the first approach (see Supplemental Material [25] for details). This implements modifications to all parton splittings with the same parameters as the first approach. However, this does not implement hadronization or charm mass effects. Also, in contrast to JetMed, it is not tuned to jet spectra and their medium modifications. Its main use in the present study is to test the interplay between the modifications of different splittings. In the inset of Fig. 4(a), we show the results of this parton shower with only $g \to q\bar{q}$ enhancement (orange dotted) as well as with all splittings enhanced (purple dashed). This comparison shows that the dominant effect in the enhanced $D^0\bar{D}^0$-tagged jet yield is indeed due to the $g \to c\bar{c}$ splitting function.

Enhancement of $g \to c\bar{c}$ in medium-modified jets.—All three medium-modified parton showers in Fig. 4 indicate an enhancement of $g \to c\bar{c}$ splittings compared to the vacuum baseline (blue).

Figure 4(a) shows the enhancement of $N_{D^0\bar{D}^0}/N_{\rm jets}$ calculated via reweighting of PYTHIA. We find a sizeable increase of $N_{D^0\bar{D}^0}/N_{\rm jets}$ due to the medium modification of $g \to c\bar{c}$. In our (simpler) third approach, also $g \to gg$ and $q \to qg$ are medium modified and affect $N_{D^0\bar{D}^0}/N_{\rm jets}$. As seen in the inset of Fig. 4(a), the increase in the ratio $N_{D^0\bar{D}^0}/N_{\rm jets}$ is dominated by $g \to q\bar{q}$. The medium modification of $g \to gg$ and $q \to qg$ has a smaller but non-negligible effect in this simulation.

For the JetMed results in Fig. 4(b), the values of the medium parameters of all scenarios are fixed to reproduce the jet nuclear modification factor. We find an enhancement of $N_{c\bar{c}}/N_{\rm jets}$ that ranges from 60% to 40% as a function of p_T. $N_{D_0\bar{D}_0}$ can be obtained from $N_{c\bar{c}}$ by multiplying with the square of the $c \to D^0$ branching ratio $\approx$0.4–0.6 [37].

In JetMed, we have an independent test that the medium-induced $g \to gg$ splitting makes a negligible contribution to the enhanced $c\bar{c}$ yield. Namely, we can artificially prevent gluons produced by medium-induced radiation from splitting into $c\bar{c}$ pairs. This fixes the number of gluons available to split so that it is not enhanced by medium-induced radiation. We find that the $c\bar{c}$ enhancement in this case is not modified within the linewidth. This is consistent with the picture that medium-induced gluon emissions are soft and do not have sufficient virtuality to split into $c\bar{c}$ pairs.

Model-dependent differences in the three approaches are clearly visible. In particular, JetMed predicts an enhancement that is a factor $\approx$2 larger than the first and third approaches (see insets of Fig. 4). This is unsurprising, as the three approaches have different model parameters and rely on somewhat different assumptions. The fact that the enhancement of $N_{c\bar{c}}/N_{\rm jets}$ and $N_{D^0\bar{D}^0}/N_{\rm jets}$ is seen in all three cases allows us to conclude that it is a firm prediction of radiative parton energy loss.

Experimental feasibility is detector specific and needs to be assessed within experimental collaborations. However, several general remarks can be made: First, Fig. 4 includes jets that contain a D^0 and a $\bar{D}^0$ meson of any p_T. Experimentally, such a measurement amounts to accessing the $D^0\bar{D}^0$ yield down to arbitrarily soft momenta where reconstruction efficiency degrades and backgrounds are high. This, however, may not be critical since the D^0 and $\bar{D}^0$ mesons entering Figs. 3 and 4 typically carry a rather large fraction of the jet p_T (data not shown) due to the hard fragmentation of gluons into heavy quarks. In addition, jet substructure techniques tailored to $g \to c\bar{c}$ [38] could be used in the future to access the detailed kinematics of the $g \to c\bar{c}$ splitting from the hadron level. Finally, the measurement of $N_{D^0\bar{D}^0}/N_{\rm jets}$ is likely to remain statistics limited at the HL HI LHC due to the small branching ratio of $D_0 \to K\pi$. However, advances in tagging jets with a $c\bar{c}$ pair [39] may make it possible to sample the entire $c\bar{c}$ statistics for the study of boosted $g \to c\bar{c}$ topologies.

In summary, we have demonstrated that the standard paradigm of radiative parton energy loss implies an enhanced $g \to c\bar{c}$ splitting. We have shown that $N_{D^0\bar{D}^0}/N_{\rm jets}$ is an observable that is sensitive to this as yet unexplored, but qualitatively novel, feature of this parton energy loss paradigm. Both the magnitude of the enhancement and the abundance of the signal make this measurement a target for the future HL HI LHC, where novel detector technologies will allow for the highest rates and for extreme signal purities in Runs 5 and 6 [40].

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