Jets as a probe of the quark-gluon plasma

Jasmine Brewer

In collaboration with Maximilian Attems, Gian Michele Innocenti, Aleksas Mazeliauskas, Sohyun Park, Wilke van der Schee, and Urs Wiedemann

[2203.11241] and [2209.13600]
QED

Magic angle graphene
Cao et. al. *Nature* 556, 43–50 (2018)
Understanding the fundamental interactions is just the beginning!
Heavy-ion collisions and quark-gluon plasma
Heavy-ion collisions

- far from equilibrium initial state
- hydrodynamics
- hadron gas

energy

$\sim 1$ GeV

$0.4 \text{ fm/c}$

$6 \text{ fm/c}$

$\sim 1 \text{ fm/c}$

$\sim 10 \text{ fm/c}$

time
Heavy-ion collisions

- High energy scatterings
- Energy loss
- Far from equilibrium initial state
- Hydrodynamics
- Hadron gas

Energy:
- ~ 100 GeV
- ~ 1 GeV

Time:
- ~ 1 fm/c
- ~ 10 fm/c
Studying the dense QCD medium

Modification of high-energy probes (hadrons, jets, heavy flavor, ..)

Collective behavior of low-$p_T$ particles

Jasmine Brewer (CERN)
Modification of jets as a probe of quark-gluon plasma

proton–proton

heavy-ion

Large effect:

- Half as many jets per $p_T$ in heavy-ion collisions
- Enhanced asymmetry of back-to-back jets
- ...

“baseline” jet properties
Parton splittings in vacuum

\[ dP_{i\rightarrow jk} = \frac{d\theta}{\theta} dz P_{i\rightarrow jk}(z) \]

Splitting functions

Iteratively apply splitting functions, descending in angle, virtuality

Parton showers connect perturbative QCD to hadronic world

Going to higher accuracy

Parton showers \( \alpha_s \rightarrow 0 \) Next-to-leading log calculations
A single high-energy parton in finite-temperature QCD

Parton undergoes transverse momentum diffusion

\[ \hat{q} \equiv \frac{d \langle k^2_{\perp} \rangle}{dt} \]

Kicks occasionally induce gluon radiation

Radiation can’t be resolved instantaneously

\[ l_F \propto \sqrt{\omega} \]

Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1996), Arnold, Moore, Yaffe (2003)

Fig: adapted from Yacine Mehtar-Tani QM’19
A high-energy parton fragments even in vacuum

Detailed interplay of vacuum physics and medium modification

- Improved theory
  - Improved parton radiation spectrum
    - Mehtar-Tani, Tywoniuk, Andres, Dominguez, Salgado, …
  - Parton showers in medium
    - Caucał, Iancu, Mueller, Soyez, Wiedemann, Zapp, …

No current theories capture full complexity

- Improved phenomenology
  - Deconstructing a jet to access individual splittings
Building up a picture of a medium-modified jet from phenomenology

- Hadrons to splittings

- Flavor-dependence of splittings
Accessing splitting functions from jet substructure

Access kinematics of gluon that initiated the shower ($p_T, Q^2, \ldots$)
Accessing splitting functions from jet substructure

Access kinematics of gluon that initiated the shower \((p_T, Q^2, \ldots)\)

Use angular ordering of QCD to reconstruct emission history of shower from hadron level
Accessing splitting functions from jet substructure

- Adapted for heavy ions: splittings with shortest formation time, highest $k_t$, …

Mehtar-Tani, Soto-Ontoso, Tywoniuk [1911.00375]; Cauca! Soto-Ontoso, Takacs [2111.14768]
(see also Apolinario, Cordeiro, Zapp [2012.02199])

Larkoski, Marzani, Thaler [1502.01719]
Larkoski, Marzani, Thaler, Tripathee, Xue [1704.05066]
Accessing light flavor splitting functions

• In vacuum

  “gluon jet”

  “quark jet”

• In medium

  Flavor-dependent modification

Observable-based, machine learning approaches

Thaler, Metodiev, Komiske, Schwartz, Dreyer, Soyez, Takacs, Larkoski, many others…

Modified q,g splitting functions

Data-driven quark, gluon

Monte Carlo quark, gluon
Accessing heavy flavor splitting functions

Heavy flavor splittings:

Advantages:

• Heavy flavor is preserved in the shower and not produced at hadronization

• Access later (more modified) splittings in the shower

• At high energies, access light flavor splittings

Focus of this talk: phenomenology of $g \rightarrow c\bar{c}$
Unique features of the modification of $g \rightarrow c\bar{c}$

Signature of momentum broadening of $c\bar{c}$ pair
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Signature of momentum broadening of $c\bar{c}$ pair

Gluons have a “lifetime” $\tau_f \sim \frac{2E_g}{Q^2}$ depending on their energy
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Gluons have a “lifetime” $\tau_f \sim \frac{2E_g}{Q^2}$ depending on their energy

- Access modification of $c\bar{c}$ pair at later times in the QGP

Increasing gluon energy
Unique features of the modification of $g \rightarrow c\bar{c}$

Signature of momentum broadening of $c\bar{c}$ pair

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- Access modification of $c\bar{c}$ pair at later times in the QGP

$\sim 1 - 6$ fm delay for $20 - 100$ GeV gluons

Increasing gluon energy

Another time-delayed probe: Apolinario, Milhano, Salam, Salgado [1711.03105]
Modification of the $g \rightarrow c\bar{c}$ splitting function

$$P_{g\rightarrow c\bar{c}}(E_g, k_c^2, z) = P_{g\rightarrow c\bar{c}}^{\text{vac}}(k_c^2, z) + P_{g\rightarrow c\bar{c}}^{\text{med}}(E_g, k_c^2, z)$$

Resum arbitrarily-many soft gluon interactions with a medium of length L
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Results of the calculation:

• Depletion at small $k_c^2$
Modification of the $g \to c\bar{c}$ splitting function

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Resum arbitrarily-many soft gluon interactions with a medium of length L

Results of the calculation:

- Depletion at small $k_c^2$
- Less modification with increasing $E_g$
- Medium-enhanced rate of $c\bar{c}$ production!
Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets

Leading processes for heavy quark production

- **Flavor creation**
- **Flavor excitation**
- **Gluon splitting**

(approximately) collinear

GPD: $p_T^{had} > 200$ GeV, $x_{sub} > 0.1$, $\eta \in [-2,2]$

- c-hadron tag
- **PYTHIA**
- $R = 0.5$
- gluon splitting
- non-splitting
- total

Gluon splitting

Non-gluon-splitting
Phenomenologically accessing the $g \rightarrow c\bar{c}$ splitting in jets

High-purity sample of showers including $g \rightarrow c\bar{c}$ splitting

Expected experimental sensitivity in Run 3/4
Observing $g \to c\bar{c}$ enhancement in jets

Get kinematics of $g \to c\bar{c}$

Reweight each splitting by

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

Attems, JB, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann [2209.13600]
Observing $g \rightarrow c\bar{c}$ enhancement in jets

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Can use jet substructure to access broadening at hadron-level
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Ongoing: how to quantify modification differential in $E_g$?

- Access delayed probe of QGP
A process with many exciting future avenues!

So far..

• Medium-enhanced rate of $c\bar{c}$ production

Outlook

• Broadening of $c\bar{c}$ pair from hadron level
• Formation time dependence of modification

Clean process with a lot of exciting physics opportunities!
Outlook

Phenomenology of heavy-flavor tagged jets

Constructing a picture of modified jets from phenomenology