Probing the quark-gluon plasma using jets

Jasmine Brewer

Current

Future

Hard Probes
June 3, 2020
Jets in proton-proton collisions….

\[ q, g \]
Jets in heavy-ion collisions….

What’s in the box?
“Standard model” of jet modification

Shower evolution
Analytic methods; SCET
Monte Carlo
“Standard model” of jet modification

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Analytic methods; SCET
Monte Carlo

Medium evolution
Constant T; Bjorken flow
e-by-e viscous hydro

Fig: Schenke, Jeon, Gale [1009.3244]
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Analytic methods; SCET
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Shower modification
Medium-induced radiation
Drag; collisional energy loss

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**Medium response**
Energy deposited from jet sources medium evolution

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Physics of the quark-gluon plasma suited to jets

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- Monte Carlo

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Medium response
Energy deposited from jet sources medium evolution

Microscopic structure of the QGP on different energy scales
Yang-Ting Chien: 8:20

Far-from-equilibrium response of the QGP
Yasuki Tachibana: 9:00
Jets as a probe of the quark-gluon plasma

• Models have more physics than the physics we are after

• Models all have some physics deficiencies (no first-principles solution)

• Models with very different physics of jet-medium interaction and medium response can agree with a variety of measurements

Crucial to have a way towards highlighting the physics we care about without requiring that models be perfect
Things are (very often) not as they seem
- Many effects obfuscate the interpretation of measurements

Opening the box
- Using models effectively as a tool to understand the physics behind data

Toward interpreting data without models

Jasmine Brewer (MIT)
Toward jets as a calibrated probe of the QGP

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How can jet modification be quantified?

Ideally…

How do jets from an identical hard process differ in vacuum and in medium?
For inclusive jets, features of hard process cannot be observed.

Reality…
“Jet modification” observables: part modification and part bias

\[
\frac{d\sigma}{dp_T^{\text{jet}}} \quad (\text{log-log})
\]

\[
p-p
\]

A-A

Jasmine Brewer (MIT)
“Jet modification” observables: part modification and part bias

What are the A-A jets in this bin?
“Jet modification” observables: part modification and part bias

What are the A-A jets in this bin?

- Produced with higher $p_T$ in vacuum
“Jet modification” observables: part modification and part bias

- Produced with higher $p_T$ in vacuum
- Production cross-section falls by factor of $\sim 10$ between 100 and 150 GeV!

Most are relatively unmodified since those are produced in highest numbers!

What are the A-A jets in this bin?

$\Delta p_T \sim 50$ GeV

$\Delta \sigma \sim 10x$
Interpretation of modification depends crucially on jet selection

In hybrid model can look at the *same jet* before and after quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal [1405.3864]

Where did A-A jets come from?
Probed in inclusive jet

What do p-p jets become?
Probed in boson+jet

These questions have qualitatively different answers!

Brewer, Brodsky, Rajagopal; *in preparation*
Where did A-A jets come from?

What do p-p jets become?

Fractional energy loss

quenched jets > 80 GeV
unquenched jets > 80 GeV

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Sample of jets that lost little energy

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quenched jets > 80 GeV
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Brewer, Brodsky, Rajagopal; in preparation

Jasmine Brewer (MIT)
Interpretation of modification depends crucially on jet selection

What do p-p jets become?

Where did A-A jets come from?

Sample of jets that lost little energy
Larger energy loss probed with $\gamma/Z+$jet

Fractional energy loss

Brewer, Brodsky, Rajagopal; in preparation
Hybrid model study: interpretation depends crucially on jet selection

Where did A-A jets come from?

What do p-p jets become?

Lost less energy

Lost more energy

Little \( \Delta R \) modification

Casalderrey-Solana, Milhano, Pablos, Rajagopal [2002.09193]

Dramatic \( \Delta R \) modification

Brewer, Brodsky, Rajagopal; in preparation

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Toward jets as a calibrated probe of the QGP
What generates the higher energy asymmetry of dijets in A-A?

**Standard intuition: path-length difference**

\[ A_J = \frac{p_{T,j} - p_{T,j}}{p_{T,j} + p_{T,j}} \]

CMS [1202.5022] (also measured by STAR and ATLAS)

Models as a tool to understand data

Jasmine Brewer (MIT)

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Models as a tool to understand data

What generates the higher energy asymmetry of dijets in A-A?

In several very different models, this intuition does not appear to be correct.

Standard intuition: path-length difference

Symmetric

Asymmetric

CMSt [1202.5022]
(also measured by STAR and ATLAS)
Another effect: fluctuations in jet structure cause asymmetric energy loss.

Jets with same path length can lose different amounts of energy from their different structure.
Dijet asymmetry can be generated with no path-length difference

**BDMPS-Z**  
large energy loss fluctuations generate asymmetry for jets with same path length

Escobedo, Iancu [1601.03629]

**JEWEL**  
Centrally-produced All

Milhano, Zapp [1512.08107]

**holographic model**  
Changing path-length difference

Brewer, Sadofyev, van der Schee [1809.10695]

**In several models, path length difference not crucial for dijet asymmetry**
Models as a tool to understand data

Does quenching cause jets to narrow?

\[ \frac{\rho(r)_{\text{PbPb}}}{\rho(r)_{\text{pp}}} \]

CMS [1310.0878]
Models as a tool to understand data

Does quenching cause jets to narrow?  

Holographic model where *every* jet widens

CMS [1310.0878]

Rajagopal, Sadofyev, van der Schee [1602.04187]

Brewer, Rajagopal, Sadofyev, van der Schee [1710.03237]
Models as a tool to understand data

Does quenching cause jets to narrow? Holographic model where every jet widens

Not necessarily; average jet width can narrow because selection favors (typically narrow) jets that lose least energy (increased quark jet fraction) also may impact fragmentation functions

CMS [1310.0878]

Rajagopal, Sadofyev, van der Schee [1602.04187]
Brewer, Rajagopal, Sadofyev, van der Schee [1710.03237]

Chien, Vitev [1509.07257]

Caucal, Iancu, Mueller, Soyez [2005.05852]

Paul Caucal M 11:40
Models as a tool to understand data

Does quenching cause jets to narrow?

Narrowing is not apparent in $\gamma$-tagged jets where selection bias is removed.

Exciting opportunities of boson-tagged jet measurements!
Toward jets as a calibrated probe of the QGP

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Toward interpreting data without models

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Reducing the effect of $p_T$ migration on jet observables

Comparing jets horizontally corrects for biases due to average energy loss

For hadrons: PHENIX [0611007, 1208.2254, 1509.06735]  
Brewer, Milhano, Thaler [1812.05111]
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Toward measuring average fractional energy loss

\[ Q_{AA} = \frac{p_T^H}{p_T^{vac}} |_{\Sigma} \]

Average \( p_T \) loss per jet

Brewer, Milhano, Thaler [1812.05111]
Toward measuring average fractional energy loss

\[ Q_{AA} = \frac{p_T^{Hi}}{p_T^{vac}} \]

- is much less sensitive to vacuum spectra (crucial for RHIC ↔ LHC)
- tends to zero at high \( p_T \) even though \( R_{AA} \) is flat

Average # of jets lost per \( p_T \)

Average \( p_T \) loss per jet

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Sample-dependence: are quark and gluon jets quenched differently?

On what scale does the QGP resolve the color (sub)structure of a jet?

Quantitatively: difficult because inclusive jets have large quark fraction, and maybe also different quark fraction in A-A and p-p.
Quark- and gluon-dependence of jet quenching

CMS measurement of gluon fraction modification using jet charge found no modification

Relies on template fitting with (assumed unmodified) PYTHIA jet charge distributions

Hangal (CMS) [2004.14600]
Dhanush Hangal Th 13:10
Ivan Vitev W 12:25
Going beyond templates

Two samples with different q/g fraction (e.g. dijet, $\gamma$+jet) can be used to extract q/g fractions and separate q/g distributions from data, without templates.

Done in p-p: Metodiev, Thaler [1802.00008]
Komiske, Metodiev, Thaler [1809.01140]

A-A

$\gamma$+jet statistics available in Run 4!

Possibility for data-driven measurement of quark and gluon jet modification and fraction modification

Brewer, Thaler, Turner; in preparation
Inclusive samples have a lot of jets that lost little energy

Jet modification observables must be interpreted with care
  • Models can help!

Toward interpreting data without models
  • Enhancing sensitivity to more modified jets
  • Separating modification of quark and gluon jets
Many thanks to

Quinn Brodsky, Yang-Ting Chien, Eliane Epple, Raghav Kunnawalkam Elayavalli, Gian Michele Innocenti, Vit Kucera, Yen-Jie Lee, Aleksas Mazeliauskas, Guilherme Milhano, Lina Necib, Krishna Rajagopal, Jesse Thaler, Urs Wiedemann, Xiaojun Yao, Yi Yin, and Nima Zardoshti

for valuable feedback and discussions!
Backup
Distribution (un)modification does not imply jet (un)modification!

Apparent lack of modification of charged jet mass compared to PYTHIA expectation

ALICE data

0-10% PbPb $\sqrt{s} = 2.76$ TeV

PYTHIA Perugia 2011

ALICE [1702.00804]

(figure modified)
Comparing jets horizontally corrects for biases due to average energy loss

Ratio

compare p-p and A-A jets at same $p_T$

Fig: ALICE [1702.00804] (figure modified)
Comparing jets horizontally corrects for biases due to average energy loss.

Ratio
compare p-p and A-A jets at same $p_T$

Quantile
compare p-p and A-A jets with the same average $p_T$ before quenching

Quantile procedure gives rigorous definition for what $p_T$ ranges to compare between p-p and A-A.

Jasmine Brewer (MIT)

Fig: ALICE [1702.00804] (figure modified)
Going forward: centrality dependence of dijet asymmetry

\[ \text{ATLAS Preliminary} \]
\[ \text{anti-}\kappa_t, R = 0.4 \]
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ \text{Pb+Pb 1.72 nb}^{-1} \]
\[ \text{pp 260 pb}^{-1} \]
\[ 158 < p_{T,1} < 178 \text{ GeV} \]

Virginia Bailey M 11:00
Using models to propose more sensitive measurements

Jet cone size dependence of energy loss

Energy loss = transport of energy out of jet cone

When is all energy recovered?

Sensitive to inclusion of medium response in many models

Going forward: want to discriminate between the different physics of medium response

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$R_{AA}$ is very sensitive to vacuum spectra

Ex: temperature-dependence of jet quenching between 2.76 and 5.02 TeV

LBT

Measured by ATLAS [1805.05635]

Much more dramatic difference in spectra between RHIC and LHC!

$Q_{AA}$ crucial for quantitative comparisons