Sorting out energy loss for medium-modified jets

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Jets: a multi-scale probe of the QGP
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- How is a jet modified by the quark-gluon plasma?
Jets: a multi-scale probe of the QGP

• How is a jet modified by the quark-gluon plasma?
• What can we learn about the medium on different length scales?
How can jet modification be quantified?

Ideally…
How can jet modification be quantified?

Ideally…
How can jet modification be quantified?

Ideally…

p-p

A-A

jet

modified jet
How can jet modification be quantified?

Ideally…

How do jets from an identical hard process differ in vacuum and in medium?
Features of hard process can generally not be observed.

Reality…

- p-p
- A-A

jet

modified jet
Features of hard process can generally not be observed

Reality…

(Except: rare processes where boson recoils a jet)
Features of hard process can generally not be observed

Reality…

Without knowing the properties of the initial hard process, standard is to compare p-p and A-A jets of the same final jet $p_T$. 
“Jet modification” observables: part modification and part bias
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Compare features of p-p and A-A jets

modified jet

jet
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Compare features of p-p and A-A jets

• Significant biases from migration of jets to lower energy
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• Significant biases from migration of jets to lower energy
• Strongly emphasizes jets which are modified least
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- Significant biases from migration of jets to lower energy
- Strongly emphasizes jets which are modified least

Often requires significant theory input to interpret measurements
Goal: data-driven approach to interpreting jet modification
Roadmap
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• Demonstrate new strategy for matching p-p and A-A jets
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- Discuss impact for interpretation of jet modification observables
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• Demonstrate in Monte Carlo that it does a reasonable job of comparing p-p and A-A jets with the same hard process
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• Discuss impact for interpretation of jet modification observables
• Demonstrate in Monte Carlo that it does a reasonable job of comparing p-p and A-A jets with the same hard process
• Advertisement: relevance for finding features that control jet quenching
Key question: compare A-A jets to which p-p jets?
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- Standard answer: match final (reconstructed) $p_T$
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Is $m/p_T$ modified or not?
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A-A jets were higher $p_T$ when they were produced.
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Jet quenching

$p_T^\text{vac}$ [GeV]

$p_T^\text{HI}$ [GeV]
Is $m/p_T$ modified or not?

A-A jets were higher $p_T$ when they were produced

- How to isolate jet samples with the same initial parton $p_T$?
Key question: compare A-A jets to which p-p jets?

• Another answer: match in (effective) cumulative jet cross-section

\[ \sigma_{\text{eff}} = \sigma_{\text{pp}}, \sigma_{\text{HI}} / \langle T_{\text{AA}} \rangle \]

\[ \Sigma_{\text{eff}}(p_T) = \int_{p_T}^{\infty} dp_T \frac{d\sigma_{\text{eff}}}{dp_T} \]

• “Quantile” matching
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- “Quantile” matching

\[ Q_{\text{AA}} = \frac{p_{T}^{\text{HI}}}{p_{T}^{\text{vac}}} \mid \Sigma \]
Interpretation of $R_{AA}$ and $Q_{AA}$ is significantly different…

Average jet loss per $p_T$

Average $p_T$ loss per jet
Sorting out energy loss: quantile matching
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Quenched and initial $p_T$ have same ordering
Sorting out energy loss: quantile matching

Quenched and initial $p_T$ have same ordering \^ may
Sorting out energy loss: quantile matching

Energy loss is...

on average monotonic in $p_T$
Sorting out energy loss: quantile matching

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- monotonic in $p_T$
Sorting out energy loss: quantile matching

Energy loss is...

In this limit, quantile matching gives equivalent jets in p-p and A-A

on average monotonic in $p_T$

monotonic in $p_T$
Sorting out energy loss: quantile matching

Energy loss is...

on average monotonic in $p_T$

monotonic in $p_T$

How does quantile matching work in the more realistic case?
How to quantify that?
How to quantify that?

$Z + \text{jet}$
How to quantify that?

$Z + \text{jet} \quad p_T^Z \quad p_T^{\text{jet}}$
How to quantify that?

\[ Z + \text{jet} \]

\[ p_T^Z \sim p_T^{\text{jet}} \]
How to quantify that?

Probe of $p_T^\text{jet}$ in data
How to quantify that?

Probe of $p_T^{\text{jet}}$ in data

$Z+\text{jet}$

$\sim p_T^{Z}$

$\sim p_T^{\text{jet}}$

Di-jets

$p_T^{\text{MC,1}}$

$p_T^{\text{MC,2}}$
How to quantify that?

Probe of $p_T^{\text{jet}}$ in data
How to quantify that?

Probe of $p_T$ in data

Unphysical $p_{T,MC} \sim p_T$
How to quantify that?

**Z+jet**

- $p_T^Z \sim p_T^{jet}$
- Probe of $p_T^{jet}$ in data

**Di-jets**

- Unphysical $p_T^{MC} \sim p_T^{jet}$
- Probe of $p_T^{jet}$ in Monte Carlo
Quantile matching approximates initial $p_T$ of A-A jets

$Z$+jet
Quantile matching approximates initial $p_T$ of A-A jets

**Z+jet**

![Graph showing $\langle \frac{p_T^{jet}}{p_T^{Z}} \rangle$ for Z+jet events.]

**Di-jets**

![Graph showing $\langle \frac{p_T^{jet}}{p_T^{MC}} \rangle$ for Di-jet events.]

- **Z+Jet Events**
  - JEWEL 2.1.0
  - $\sqrt{s} = 2.76$ TeV, $R = 0.4$

- **Dijet Events**
  - JEWEL 2.1.0
  - $\sqrt{s} = 2.76$ TeV, $R = 0.4$
Quantile matching approximates initial $p_T$ of A-A jets

Compared to reconstructed $p_T$ in A-A…
Quantile procedure does not undo energy loss fluctuations
Is \( m/p_T \) modified or not?
Is $m/p_T$ modified or not?

- Sensitivity to matching indicates significant jet $p_T$ migration effects
Ongoing work
What features $F$ control fractional energy loss of a jet?
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all jets; $p(p_T^{\text{fin}}|p_T^{\text{in}})$
What features $F$ control fractional energy loss of a jet?

all jets: $p(p_T^{\text{fin}} | p_T^{\text{in}})$

averaging over other features $F$ gives wide range of fractional energy loss for jets with the same initial $p_T$
What features $F$ control fractional energy loss of a jet?

all jets: $p(p_T^{\text{fin}} | p_T^{\text{in}})$

subset of jets with same features $F$:

$p(p_T^{\text{fin}} | p_T^{\text{in}}, \{F_i\})$
What features $F$ control fractional energy loss of a jet?

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subset of jets with same features $F$ $p(p_T^{\text{fin}}|p_T^{\text{in}}, \{F_i\})$

By definition, have same fractional energy loss
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$p(p_T^{\text{fin}} | p_T^{\text{in}}, \{F_i\})$

By definition, have same fractional energy loss

Quantile procedure gives exact result in this case
What features $F$ control fractional energy loss of a jet?

all jets: $p(p_T^{\text{fin}} | p_T^{\text{in}})$

subset of jets with same features $F$ $p(p_T^{\text{fin}} | p_T^{\text{in}}, \{F_i\})$

By definition, have same fractional energy loss

- HOWEVER: features in $F$ may be unobservable (e.g. path length)
What *observable* features (if any) control jet quenching?
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What *observable* features (if any) control jet quenching?

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What **observable** features (if any) control jet quenching?

subset of jets with same features \( F \);  
\[ p(p_{T}^{\text{fin}} | p_{T}^{\text{in}}, \{F_i\}) \]

Expectation: performance of the quantile procedure provides quantitative test of extent to which a feature controls jet energy loss
Summary

Going beyond matching p-p and A-A jets in reconstructed $p_T$
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- New “quantile matching” inspired by (approximate) monotonicity of energy loss in $p_T$
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Going beyond matching p-p and A-A jets in reconstructed $p_T$

- New “quantile matching” inspired by (approximate) monotonicity of energy loss in $p_T$
- New interpretation of jet modification observables
- Resulting $p_T^{\text{quant}}$ gives a reasonable handle on the initial energy of an A-A jet in di-jet events
- Minimizes effect of $p_T$ migration in jet modification observables

Going forward: finding jet features that control quenching?
For more on all that…
Comments on the definition of the quantile matching

To match the *cumulative* jet cross-section, the formal definition of $p_T^{\text{quant}}$ is

$$
\int_{p_T^{\text{HI}}}^{\infty} dp_T \left( \frac{d\sigma_{\text{HI}}^{\text{eff}}}{dp_T} \right) = \int_{p_T^{\text{quant}}}^{\infty} dp_T \left( \frac{d\sigma_{\text{pp}}^{\text{eff}}}{dp_T} \right)
$$

However, for steeply-falling spectra this is identical (to ~1\% level corrections) to simply matching jets in the same cross-section

$$
\sigma_{\text{HI}}^{\text{eff}} (p_T^{\text{HI}}) = \sigma_{\text{pp}}^{\text{eff}} (p_T^{\text{quant}})
$$
mean more similar

standard deviation larger

Compared to reconstructed $p_T$ in A-A…
$m/p_T$ for Z+jet and di-jet events