Data-driven quark and gluon jet modification in heavy-ion collisions

Jasmine Brewer

In collaboration with Jesse Thaler and Andrew Patrick Turner

Based on arXiv:2008.08596
Modification of jets a probe of quark-gluon plasma

proton–proton

heavy-ion

“baseline” jet properties
At leading order, jets are initiated by a quark or gluon from the hard process

\(q, g\)

\(C_q = 4/3\)

\(C_g = 3\)
Differences in quark and gluon jet energy loss in quark-gluon plasma

Quarks and gluons interact with the plasma proportional to their color factor

\[ \frac{dE}{dx}(q) = \frac{C_q}{C_g} \frac{dE}{dx}(g) \]

Quark and gluon jets are extended objects whose energy loss may depend on their structure

\[ \frac{dE}{dx}(q) = \text{???} \frac{dE}{dx}(g) \]
Separating quark and gluon jets is challenging because jet measurements are mixture of contributions from both
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Outline

• A data-driven method for q/g separation (in cartoons)

• Monte Carlo studies in pp and AA
Disentangling mixture distributions into “quark” and “gluon”

\[ p_1 = f_1 b_1 + (1 - f_1) b_2 \]

\[ p_2 = (1 - f_2) b_1 + f_2 b_2 \]

Disentangling mixture distributions into “quark” and “gluon”

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Solve for base distributions \( b_1, b_2 \) in terms of mixture distributions and fractions

Disentangling mixture distributions into “quark” and “gluon”

Requires…

Sample independence:

example

dijets

Jet Observable

\( b_1 \)

\( b_2 \)

\( \gamma + \text{jet} \)

Jet Observable

\( b_1 \)

\( b_2 \)
Disentangling mixture distributions into “quark” and “gluon”

Requires…

Sample independence:

Mutual Irreducibility: samples are pure quark and pure gluon in some limits

Above: base distributions are completely separated at \( \pm \infty \)

Quantified by

\[
\lim_{\mathcal{O} \to \infty} \frac{b_1(\mathcal{O})}{b_2(\mathcal{O})} = 0 \quad \lim_{\mathcal{O} \to -\infty} \frac{b_2(\mathcal{O})}{b_1(\mathcal{O})} = 0
\]
Mutual irreducibility of counting observables

Poisson distributions are mutually irreducible for large $\Delta \lambda$

\[
\lim_{\mathcal{O} \to \infty} \frac{b_1(\mathcal{O})}{b_2(\mathcal{O})} = 0
\]

\[
\lim_{\mathcal{O} \to 0} \frac{b_2(\mathcal{O})}{b_1(\mathcal{O})} = \exp(\lambda_1 - \lambda_2)
\]

Quark and gluon constituent multiplicity distributions are mutually irreducible in the high-energy limit

Frye et al [1704.06266]
How are quark- and gluon-initiated jets modified by the quark–gluon plasma?

**proton–proton**

Proton-Proton (PYTHIA 6.4.25)  
$p_T \in [100, 120] \text{ GeV}, |\eta| < 1$

**heavy-ion**

Heavy-Ion (JEWEL 2.1.0)  
$p_T \in [100, 120] \text{ GeV}, |\eta| < 1$
Fractions are sensitive to tails of the distribution where statistics are low.

proton–proton

\[ \frac{1 - f_1}{1 - f_2} \]

\[ \frac{f_2}{f_1} \]
Fractions are sensitive to tails of the distribution where statistics are low

proton–proton

\[
\frac{1 - f_1}{1 - f_2} \quad \frac{f_2}{f_1}
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heavy-ion

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Fractions are sensitive to tails of the distribution where statistics are low.

How to robustly extract fractions with statistical uncertainties?

proton–proton

\[ \frac{1 - f_1}{1 - f_2} \]

heavy-ion

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A solution: use fitting to constrain the tails using the interior of the distribution

proton–proton

heavy-ion

Each distribution is a distinct sum of 4 skew-normal distributions (18 fit parameters)

Fit using MCMC with Poisson likelihood function
A solution: use fitting to constrain the tails using the interior of the distribution

proton–proton

\[
\frac{1 - f_1}{1 - f_2}
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heavy-ion

\[
\frac{1 - f_1}{1 - f_2}
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Extracting quark/gluon contributions to constituent multiplicity

proton–proton

Proton–Proton (PYTHIA 6.4.25) $p_T \in [100, 120]$ GeV, $|\eta| < 1$

Constituent Multiplicity

Probability

Proton–Proton (PYTHIA 6.4.25) $p_T \in [100, 120]$ GeV, $|\eta| < 1$

Constituent Multiplicity

Gluon-like Fraction

Proton–Proton (PYTHIA 6.4.25)
Extracting quark/gluon contributions to constituent multiplicity

Jasmine Brewer (CERN)
Data-driven quark and gluon jet modification from dijet and $\gamma$+jet

**proton–proton**

Proton–Proton (Pythia 6.4.25)
$p_T \in [100, 120]$ GeV, $|y| < 1$

- "q" Topic
- "g" Topic
- $\gamma$+q
- $\gamma$+g

**heavy-ion**

Heavy-Ion (Jewel 2.1.0)
$p_T \in [100, 120]$ GeV, $|y| < 1$

- "q" Topic
- "g" Topic
- $\gamma$+q
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Data-driven quark and gluon jet modification from dijet and $\gamma$+jet

**proton–proton**

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![Proton–Proton (PYTHIA 6.4.25) $p_T \in [100, 120]$ GeV, $|\eta| < 1$](image)

![Heavy-Ion (JEWEL 2.1.0) $p_T \in [100, 120]$ GeV, $|\eta| < 1$](image)

![Proton–Proton (PYTHIA 6.4.25) $p_T \in [100, 120]$ GeV, $|\eta| < 1$](image)

![Heavy-Ion (JEWEL 2.1.0) $p_T \in [100, 120]$ GeV, $|\eta| < 1$](image)
Outlook

Toward measuring quark- and gluon-like jet modification and energy loss

• This type of method has been used in p—p by ATLAS [1906.09254]

• Method of posterior estimation substantially improves robustness of the method to statistical uncertainties

  How to deal with systematic uncertainties?

• What observables are robust to background subtraction?
  charged particle multiplicity? constituent multiplicity of soft-dropped jets?

  Work in progress with Kylie Ying, Yi Chen, Yen-Jie Lee (MIT)

Applications to other category problems in heavy-ions?
What do differences between topic and MC fractions mean?
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- Deviations from quark/ gluon mutual irreducibility in constituent multiplicity

- “Quark-initiated” jets become more gluon-like