Probing Heavy Ion Collisions Using Quark and Gluon Jet Substructure with Machine Learning

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Outline

- Jet substructure: hard and soft probes at all energy scales
- Quark and gluon jets as two different probes
- Jet representation and analysis
  - physics-motivated multivariate analysis: constructive
  - unbiased machine-learning features: comprehensive
- Telescoping deconstruction: a complete jet observable basis
  - subjet, soft-drop and collinear-drop
- Conclusion and outlook
The era of precision jet substructure studies

SCET Chien-Vitev JHEP05(2016)023

Relate precise jet modifications to medium properties

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
\[ R = 0.4, |\eta| < 2 \]

\[ R_{AA} \]

**ATLAS**

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

**CMS**

\[ p_T > 100 \text{ GeV} \]

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Quark jets and gluon jets

- All the jets are a mixture of quark jets and gluon jets
- Quark and gluon jets have different color charges and substructure
- Quark/gluon jet fraction affects jet substructure
  - 40% quark 60% gluon → 60% quark 40% gluon: jets become more quark-jet like
- Substructure of each jet is modified
  - Quark jets and gluon jets are modified differently
Use quark jets and gluon jets as independent probes

- Classify quark jets and gluon jets in pp and AA
- Distinguish pp jets from AA jets
  - identify all jet features which encode all jet modifications
- Closely related to quark/gluon discrimination
  - highlight quark and gluon jet differences
Jet representations

- Different multivariate techniques suit different jet representations
  - list of physics-motivated observables
  - unbiased and raw input
  - complete basis and expansion
- Modern computation power and deep learning tools help benchmark jet feature identification

- Illustrate using supervised learning in classification task
- Quark and gluon enriched jet samples are generated from Monte Carlo simulations
  - e.g. using JEWEL \( q + \gamma \) and \( g + \gamma \) channels (Zapp et al)
  - methods applicable to all simulations and experimentally quark/gluon-enriched data

Kaya and Dennis’s talks on inclusive and \( \gamma \)-tagged jets
Physics-motivated multivariate analysis

- Representative variables capturing quark and gluon jet features
- Exploiting observable correlations in high-dimensional space
- jet mass and radial moments $\sum_i p^i_T \Delta \theta^{\kappa}_{ijet,i}/p^i_T$ with $\kappa = 0.5, 1$
- $p^D_T = \sqrt{\sum_i p^i_T^2}/p^i_T$ and pixel multiplicity

**Graphs**

- JEWEL+PYTHIA [2.76 TeV]
- Quark and gluon jet substructure

**Plots**

- Frequency vs. Jet Mass [GeV/c²]
- Pixel Multiplicity
- First Radial Moment (girth)
Jet image

**Quark gluon jet substructure**

Jet image

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Quark and gluon jet substructure

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Image recognition using convolutional neural network

- A convolutional neural network is trained on GPU using quark and gluon jet images
- New jet features are learned with significantly improved tagging performance
- In this work we use grey scale jet images encoding jet energy distribution

Schwartz et al, Deep learning in color, JHEP01(2017)110
Telescoping Deconstruction: a complete subjet fragmentation basis

- A fixed-order $N$ subjet expansion with subjet kinematics
  - identify dominant energy flow directions using $N$ soft recoil-free axes
  - reconstruct subjets around the axes with multiple subjet radii $R$
  - TD observables represent *subjet topology* and *subjet substructure*
- Closely related to perturbative expansion and parton shower picture

Subjet distribution, soft drop, and Lund diagram

Soft drop, Thaler et al, JHEP05(2014)146

- C/A tree-based procedure to drop soft radiation
- Soft-drop condition
  \[ z < z_{\text{cut}} \theta^\beta, \quad z = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \]
- Lund diagram encodes branching kinematics along hard branches

\[ \log \frac{z\theta}{R} \quad \frac{dz d\theta}{z} \propto d\log \theta \, d\log z\theta \]

Lund diagram

Wide angle

\[ \frac{1}{\sigma} \frac{dz_{g}}{dzg} \]

Groomed Momentum Fraction

Hervig ++, 13 TeV LHC
\[ R_0 = 0.5, \quad \beta = 0 \]
- \[ p_T > 50 \text{ GeV} \]
- \[ p_T > 100 \text{ GeV} \]
- \[ p_T > 500 \text{ GeV} \]
- \[ p_T > 2000 \text{ GeV} \]
- \[ F_{g}^{q} \]
Modification of $z_g$

Telescoping subjet topology

- Enhancement of soft, wide angle radiation

\[ z \]

\[ \theta \]

\[
\begin{align*}
\gamma &+ \text{Jet Events, anti-} k \ R=0.4 \ \text{Jets} \\
p_t^j > 100 \ \text{GeV/c}, \ p_T^{V^*} > 50 \ \text{GeV/c} \\
\Delta\phi > 2\pi/3, |\eta^{V^*}| < 1.5 \\
\text{w/ Recoils Grid-Sub} & \ (\Delta\eta,\Delta\phi = 0.08)
\end{align*}
\]
Telescoping subjet substructure

- Reveal subjet flavor dependence in first splitting $q \rightarrow qg$ and $g \rightarrow gg$ using $m^{\text{sub}}/p_T^{\text{sub}}$

**Hard Subjet**

**Soft Subjet**

**JEWEL+PYTHIA pp 2.76 TeV**

| Event Type | $p_T > 100 \text{ GeV}/c$, $p_T^{\text{jet}} > 50 \text{ GeV}/c$ | $\Delta \phi > 2\pi/3$, $|\eta| < 1.5$ |
|------------|------------------------------------------------|----------------------------------|
| Jets       | $\gamma+\text{Jet}$, anti-$k$, $R=0.4$            | Gluon-Jet T3 Quark-Jet T3        |

**JEWEL+PYTHIA PbPb 0-20% 2.76 TeV**

| Event Type | $p_T > 100 \text{ GeV}/c$, $p_T^{\text{jet}} > 50 \text{ GeV}/c$ | $\Delta \phi > 2\pi/3$, $|\eta| < 1.5$ | w/ Recoils Grid-Sub ($\Delta \eta, \Delta \phi = 0.08$) |
|------------|------------------------------------------------|----------------------------------|---------------------------------|
| Jets       | $\gamma+\text{Jet}$, anti-$k$, $R=0.4$            | Gluon-Jet T3 Quark-Jet T3        | Gluon-Jet T3 Quark-Jet T3      |
Collinear-drop: probing soft-dropped radiation

- Variation of $m^2$ between ungroomed and groomed jets: $\delta m = \sqrt{m_{\text{ungroomed}}^2 - m_{\text{groomed}}^2}$
- Quark/gluon jet difference disappearing in AA collisions
Lund diagram

- Significant increase of wide angle, soft radiation in AA

![Lund diagram](Lund_diagram.png)

**JEWE+PYTHIA pp, Quark-Jets**

- γ+Jet Events, anti-k, R=0.4 Jets
- $p_T > 100$ GeV/c, $p_T > 50$ GeV/c
- $\Delta \phi > 2\pi/3, |Y^{q,MJ}| < 1.5$

**JEWE+PYTHIA pp, Gluon-Jets**

- Grid-Jet ($\Delta \eta, \Delta \phi = 0.08$)

**JEWE+PYTHIA PbPb (0-20%), Quark-Jets**

**JEWE+PYTHIA PbPb (0-20%), Gluon-Jets**

- w/ Recoils Grid-Sub ($\Delta \eta, \Delta \phi = 0.08$)
Much wide angle, soft radiation is removed (soft-drop $\beta = 0$, $z_{\text{cut}} = 0.1$)
Lund diagram, hard branch

- Significant soft radiation still remains within the hard branch (soft-drop $\beta = 0$, $z_{\text{cut}} = 0.1$)
Quark gluon jet classification

- ROC curves: the lower the curve, the better the performance
- Performance drops in heavy ion collisions
- Information contained in subleading subjets is washed out in JEWEL
pp and AA jet classification

- Gluon jets are modified more than quark jets
- Pixel multiplicity is the dominant feature distinguishing pp and AA jets in JEWEL

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Conclusion and outlook

▶ Quark and gluon jet classification provides a new method of studying jet modification
▶ Modifications of collective jet substructure observables provide qualitatively new insights
▶ Machine-learning techniques are powerful tools in jet modification studies
▶ Quark/gluon classification performance drops in JEWEL-simulated AA collisions
▶ Telescoping deconstruction provides a complete and systematic jet substructure framework
▶ Jet modification inverse problem: complete jet substructure studies will teach us the inner working of QGP