HARD PROBES 2018

Probing Heavy Ion Collisions Using Quark and Gluon Jet Substructure

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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
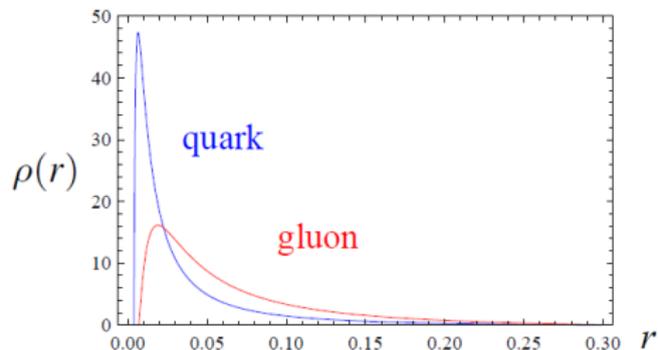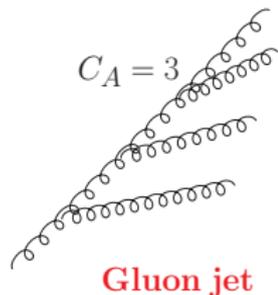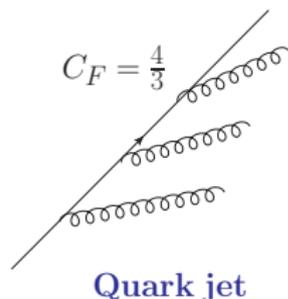- Conclusion

The era of precision jet substructure studies

SCET Chien-Vitev JHEP05(2016)023
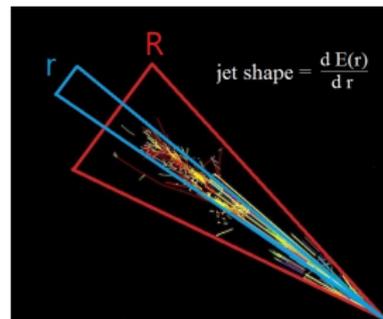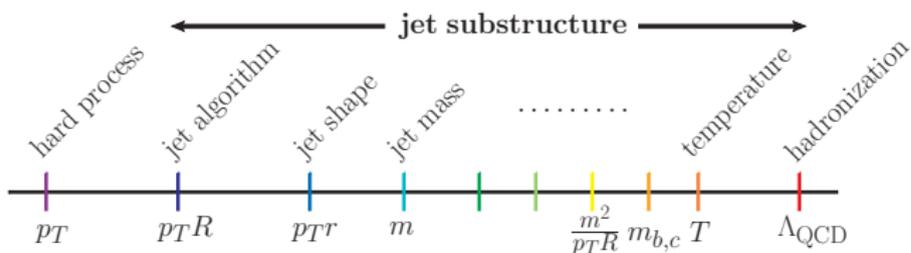
Relate precise jet modifications to medium properties

Quark jets and gluon jets


$C_F = \frac{4}{3}$

Quark jet

$C_A = 3$
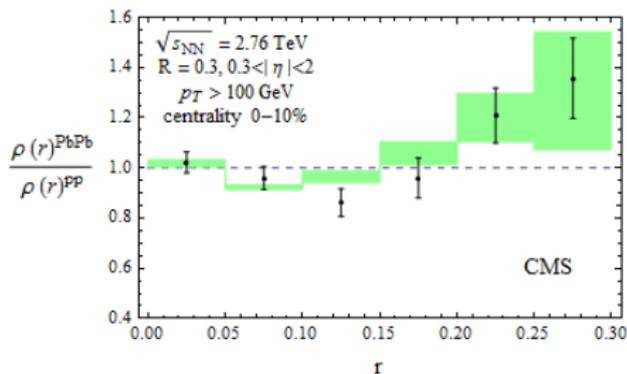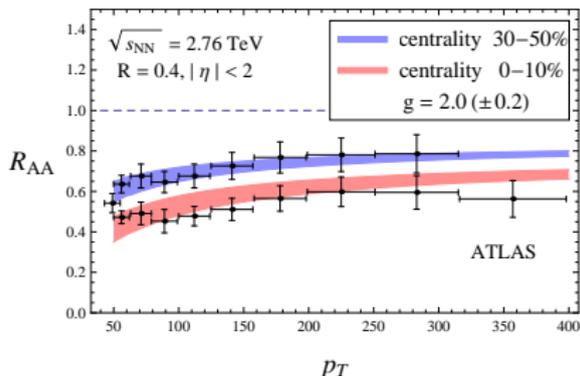
Gluon jet

$\rho(r)$ quark gluon r

- 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 $\rightarrow 60\%$ 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
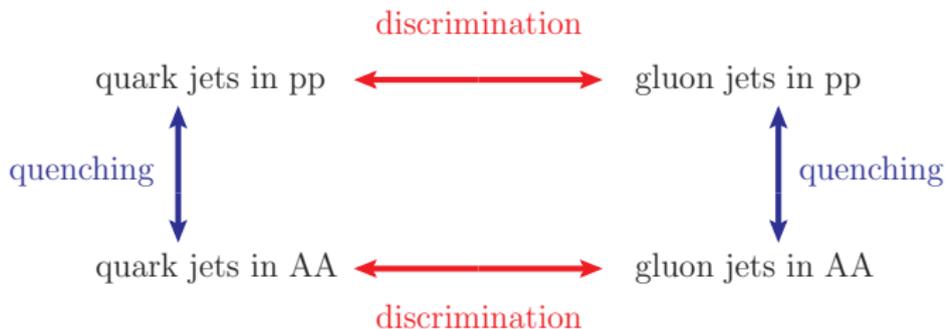
- ▶ Classify quark jets and gluon jets in pp and AA
- ▶ Distinguish pp jets from AA jets
    - ▶ identify **all** jet features which encode **all** jet modifications
- ▶ Closely related to quark/gluon discrimination
   - ▶ highlight quark and gluon jet differences

Jet representations

Jet
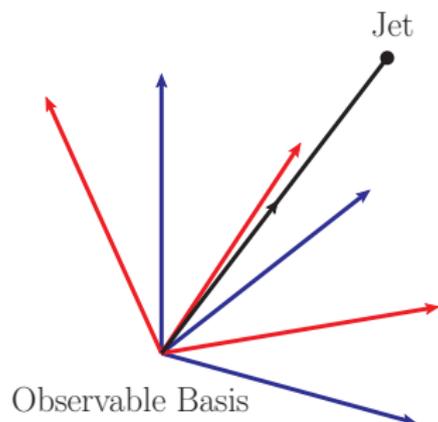
Observable Basis

▶ 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

Physics-motivated multivariate analysis

- Representative variables capturing quark and gluon jet features

- Exploiting observable correlations in high-dimensional space

- jet mass and radial moments $\sum_i p_T^i \Delta\theta_{\text{jet},i}^\kappa / p_T^{\text{jet}}$ with $\kappa = 0.5,\ 1$

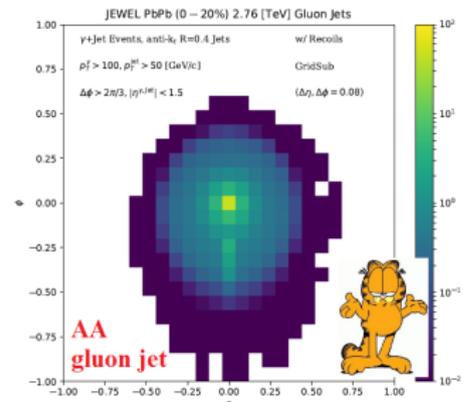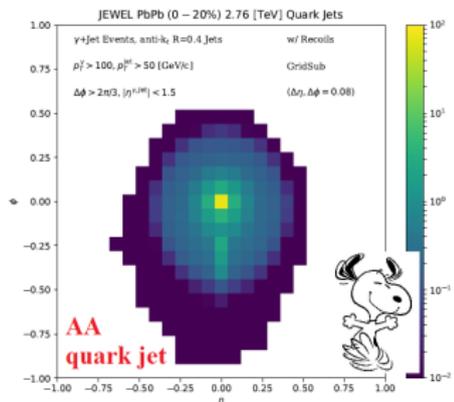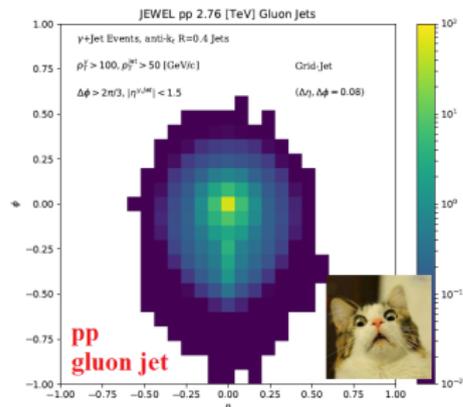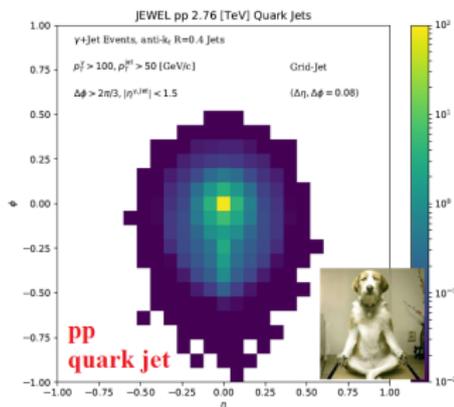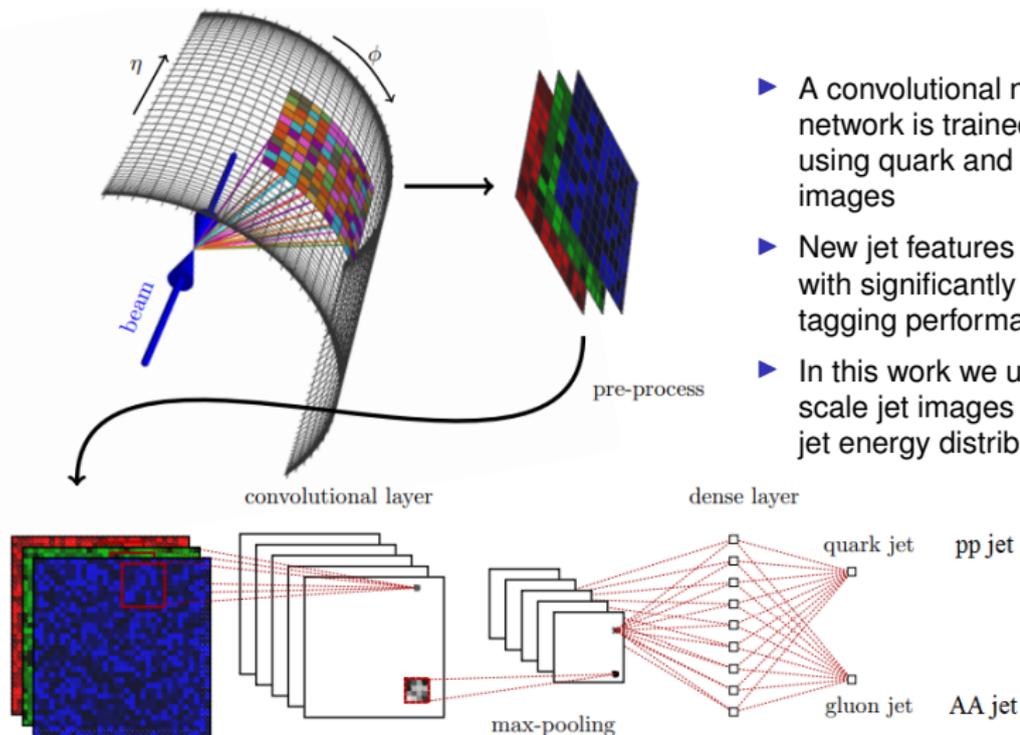- $p_T^D = \sqrt{\sum_i p_T^{i\,2}} / p_T^{\text{jet}}$ and pixel multiplicity
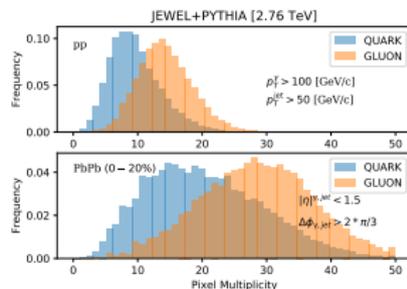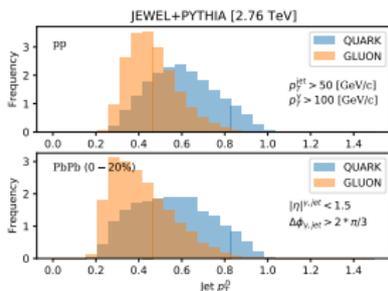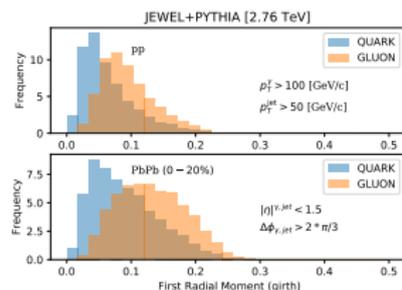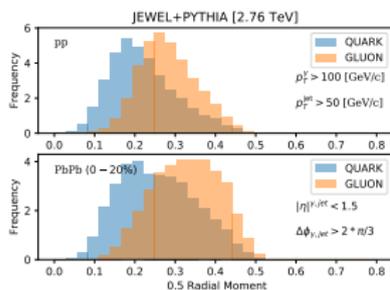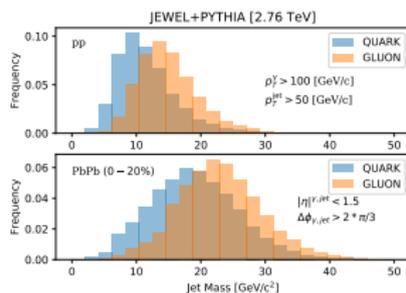
Jet image

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 obervables represent *subjet topology* and *subjet substructure*
▶ Closely related to perturbative expansion and parton shower picture
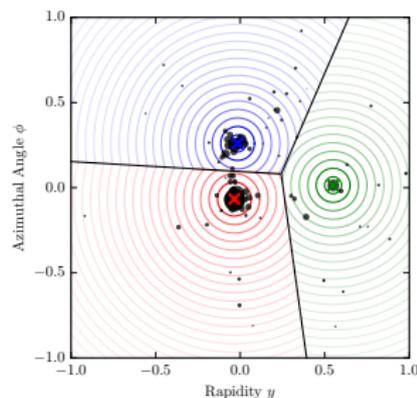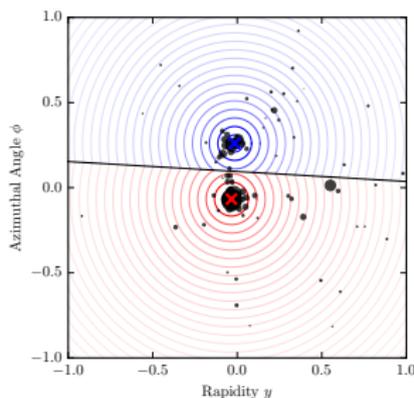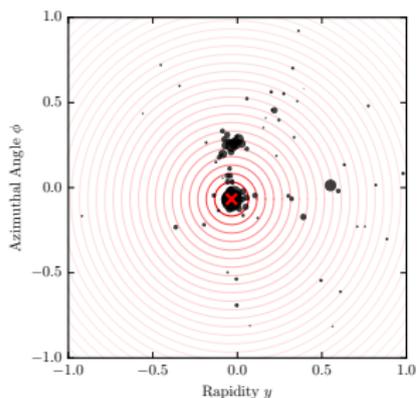
Chien et al, arXiv:1711.11041

Telescoping subjet topology
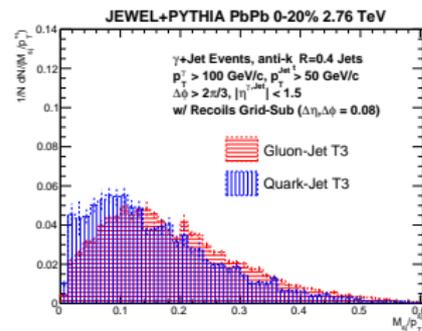
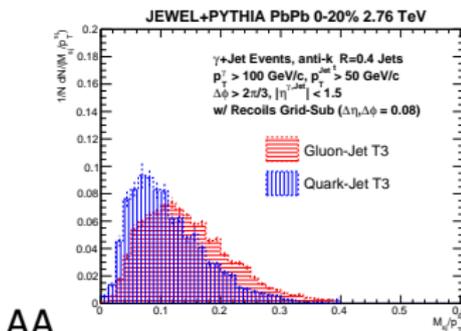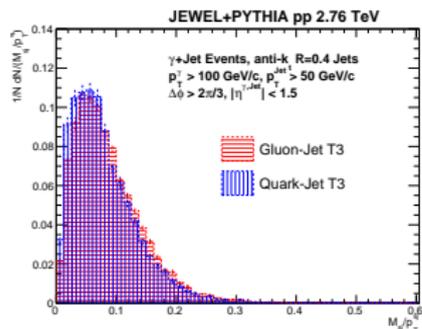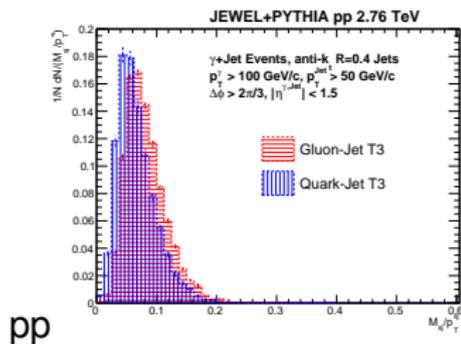▶ Enhancement of soft, wide angle radiation
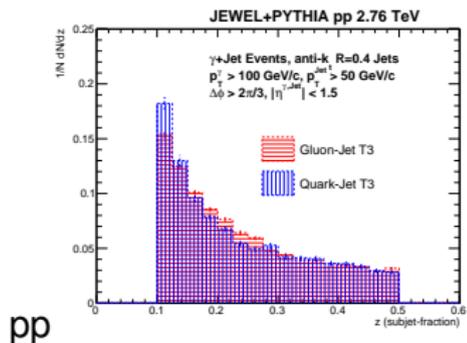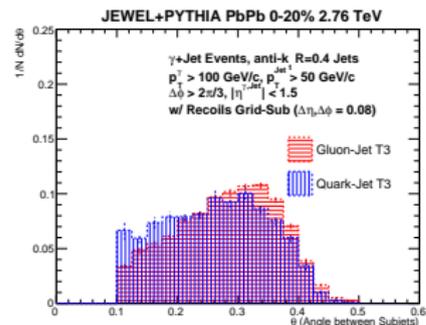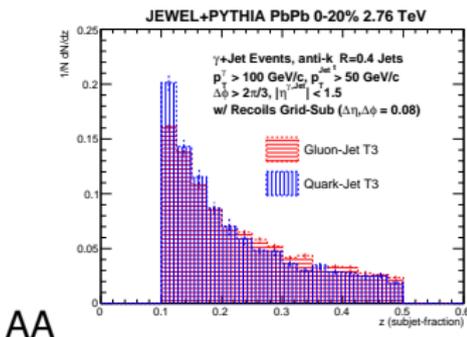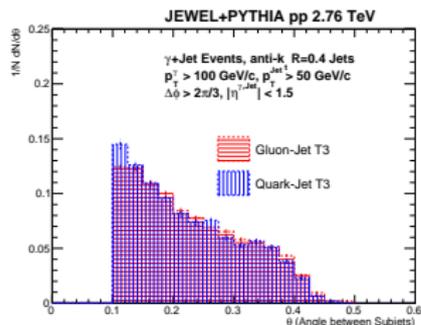
Telescoping subjet substructure

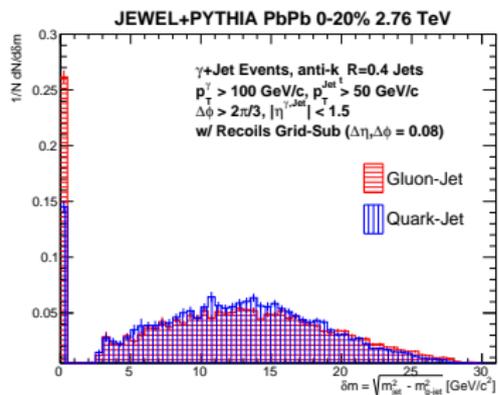▶ Reveal subjet flavor dependence in first splitting $q \to qg$ and $g \to gg$ using $m^{\mathrm{sub}}/p_T^{\mathrm{sub}}$
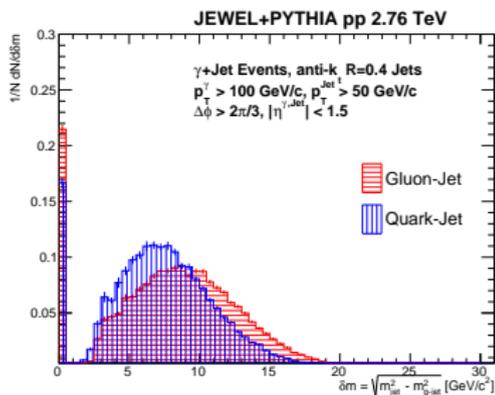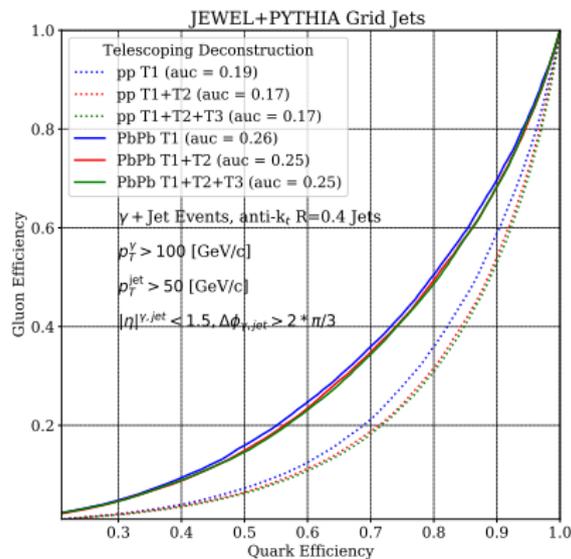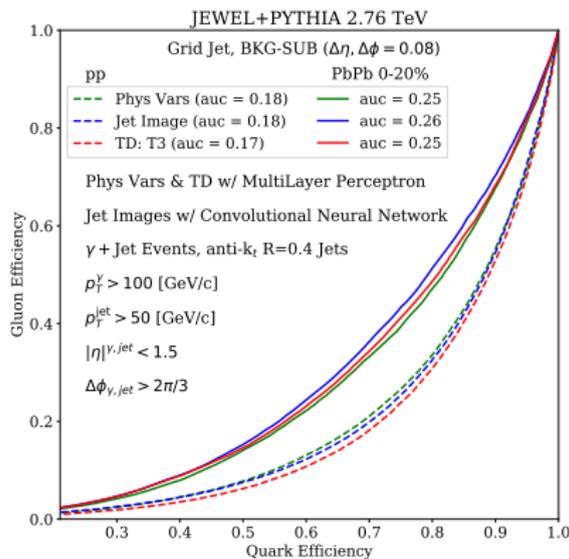
Hard Subjet   Soft Subjet

Collinear-drop: probing soft-dropped radiation

▶ Variation of m^2 between ungroomed and groomed jets: $\delta m = \sqrt{m_{\text{ungroomed}}^2 - m_{\text{groomed}}^2}$

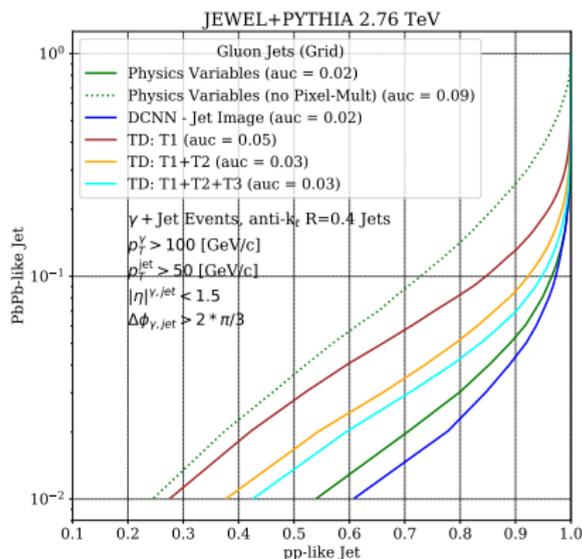▶ Quark/gluon jet difference disappearing in AA collisions
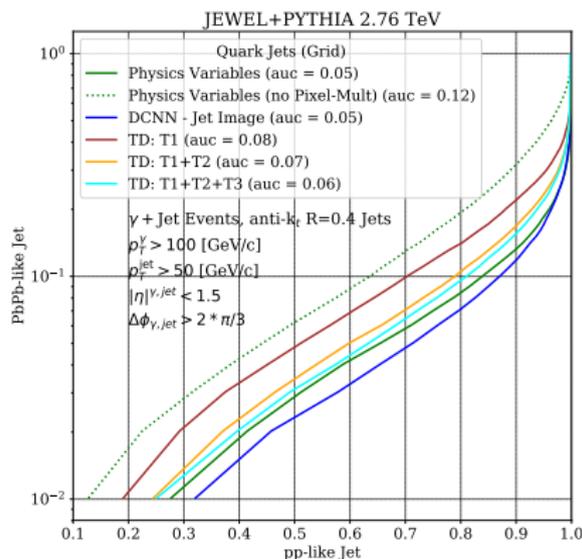
Quark gluon jet classification

- ▶ 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

Conclusion

- ▶ 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