



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

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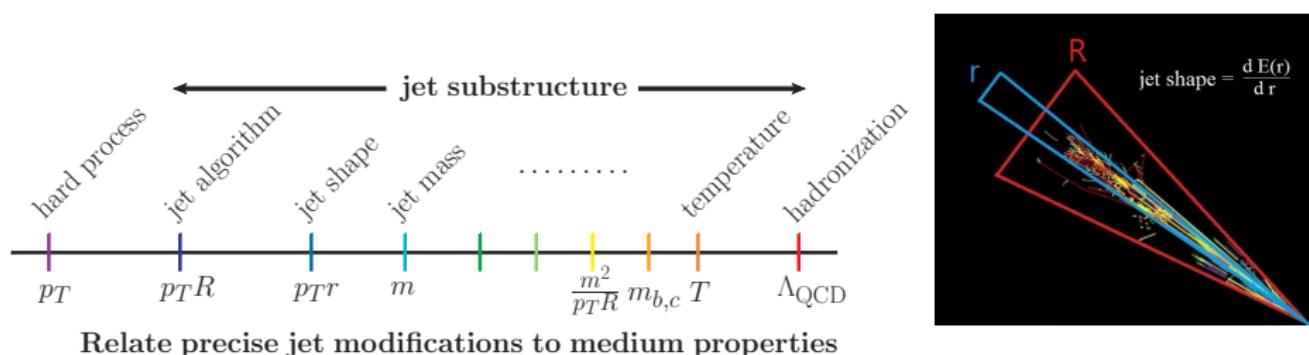


Outline

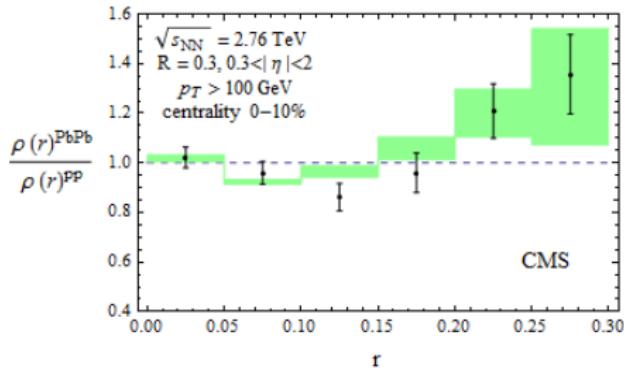
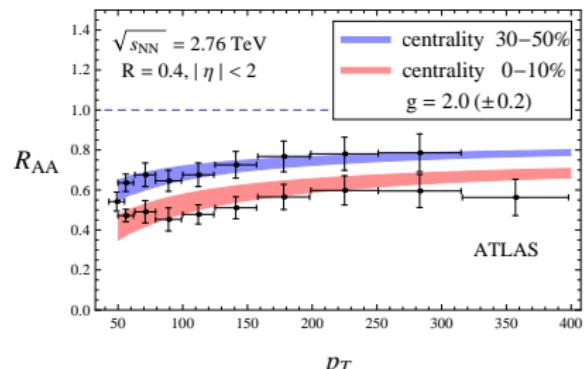
- ▶ Jet substructure: hard and soft probes at all energy scales
- ▶ Quark and gluon jets as two different probes
- ▶ Jet representation and analysis
 - ▶ physics-motivated multivariate analysis: constructive
 - ▶ unbiased machine-learning features: comprehensive
- ▶ Telescoping deconstruction: a complete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

The era of precision jet substructure studies

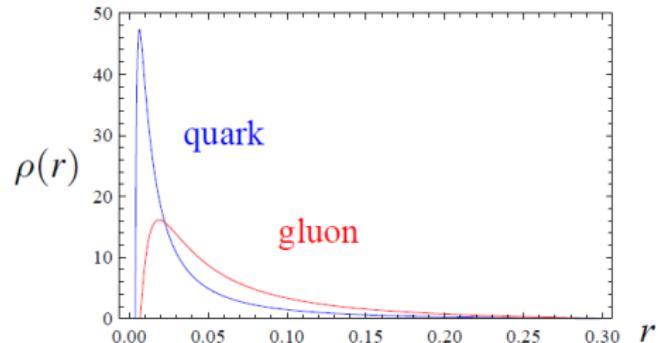
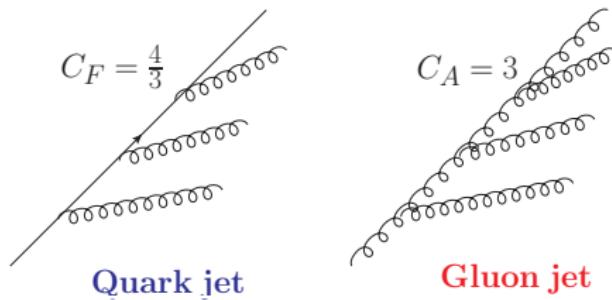
SCET Chien-Vitev JHEP05(2016)023



Relate precise jet modifications to medium properties



Quark jets and gluon jets



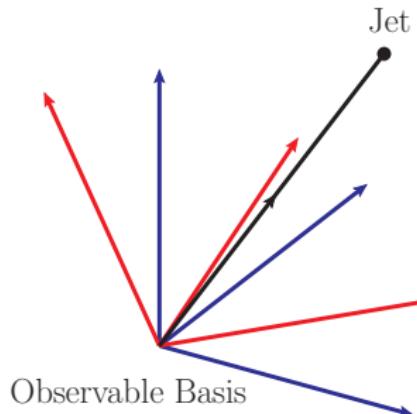
- ▶ All the jets are a mixture of quark jets and gluon jets
- ▶ Quark and gluon jets have different color charges and substructure
- ▶ Quark/gluon jet fraction affects jet substructure
 - ▶ 40% quark 60% gluon → 60% quark 40% gluon: jets become more quark-jet like
- ▶ Substructure of each jet is modified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



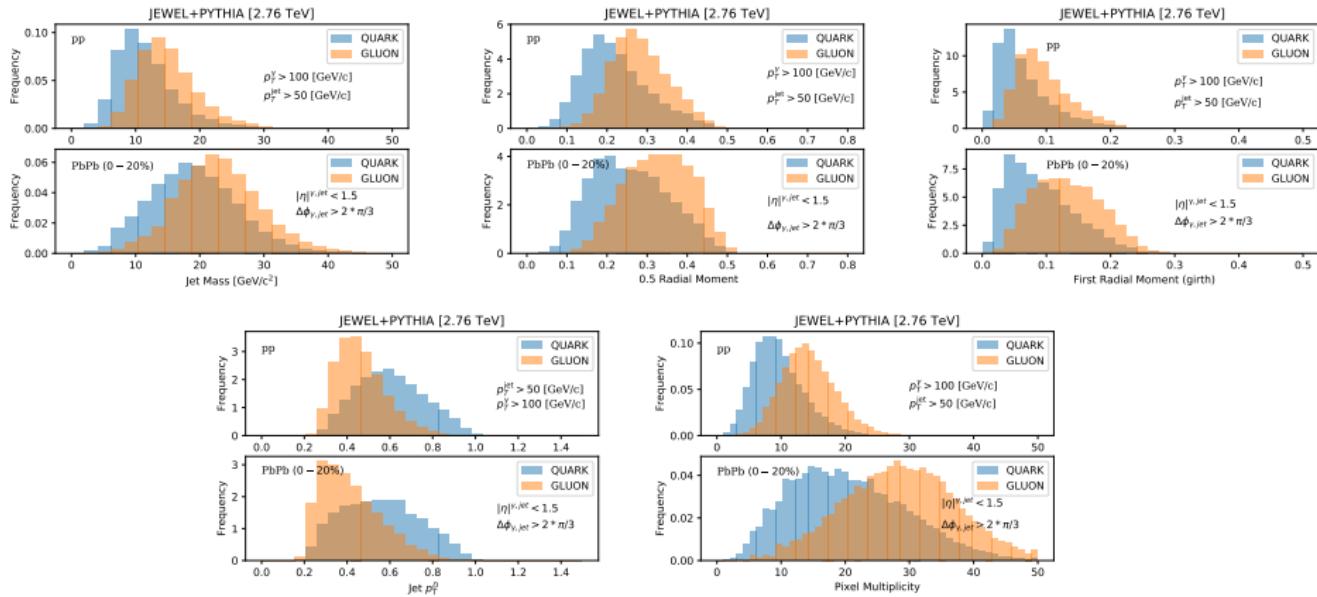
- ▶ Different multivariate techniques suit different jet representations
 - ▶ list of physics-motivated observables
 - ▶ unbiased and raw input
 - ▶ complete basis and expansion
- ▶ Modern computation power and deep learning tools help benchmark jet feature identification

- ▶ 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 γ -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 $\sum_i p_T^i \Delta\theta_{jet,i}^\kappa / p_T^{\text{jet}}$ with $\kappa = 0.5, 1$
- ▶ $p_T^D = \sqrt{\sum_i p_T^i} / p_T^{\text{jet}}$ and pixel multiplicity



Jet image

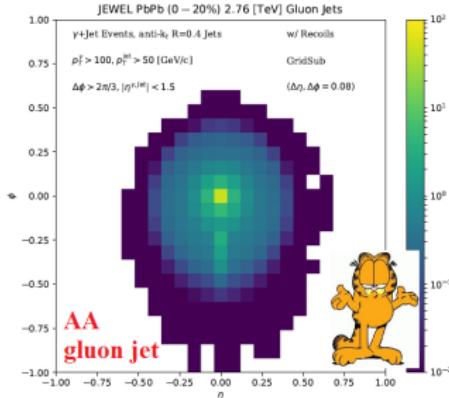
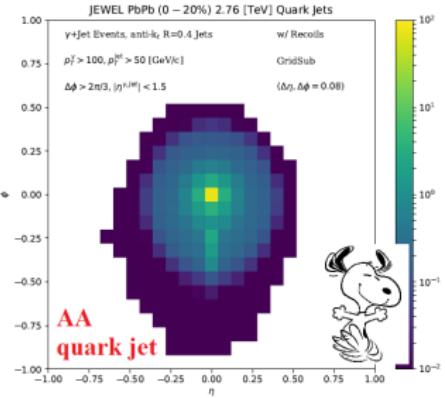
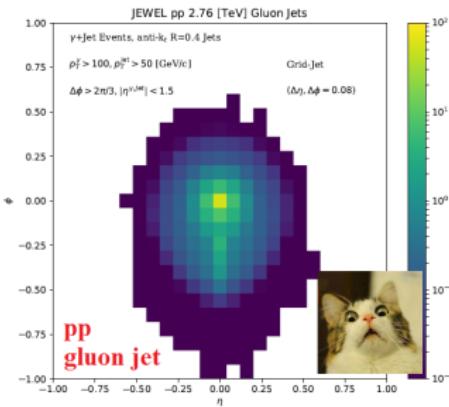
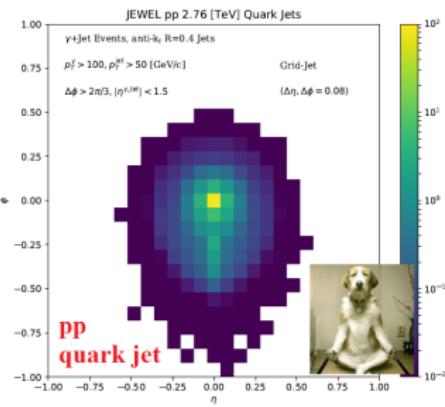
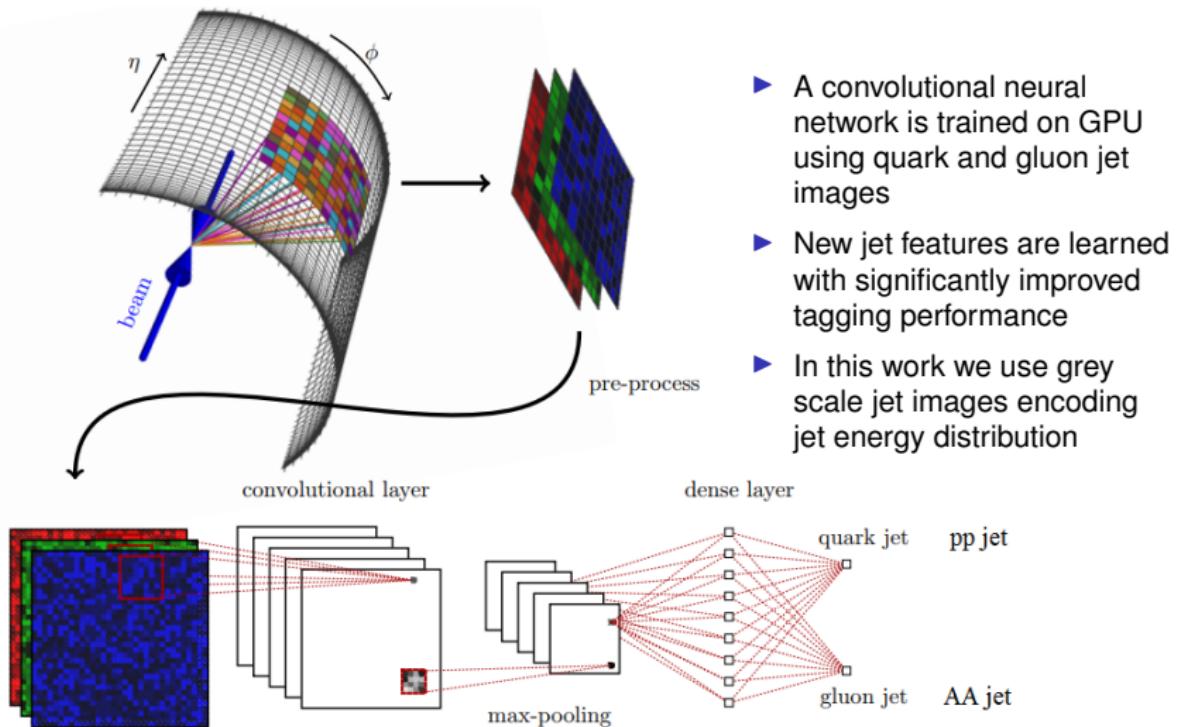


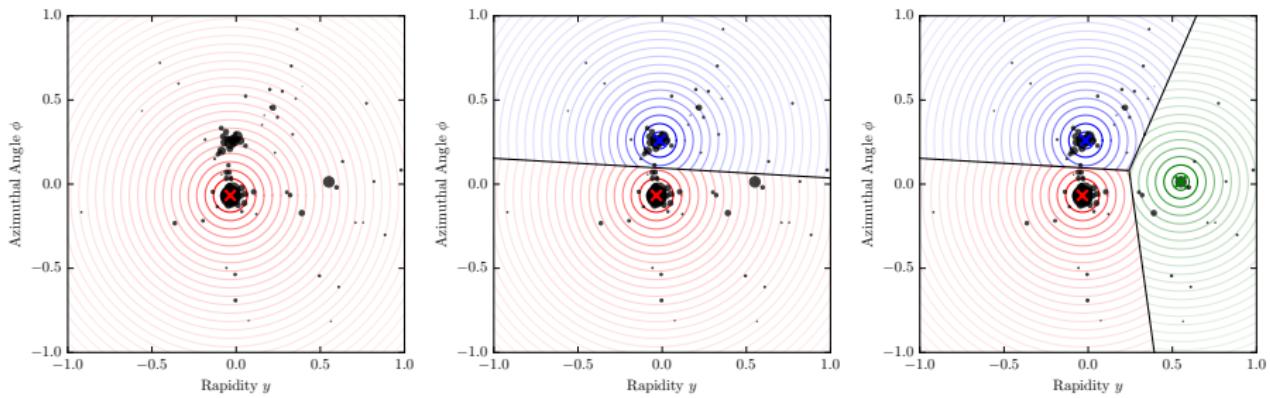
Image recognition using convolutional neural network



Schwartz et al, Deep learning in color, JHEP01(2017)110

Telescoping Deconstruction: a complete subjet fragmentation basis

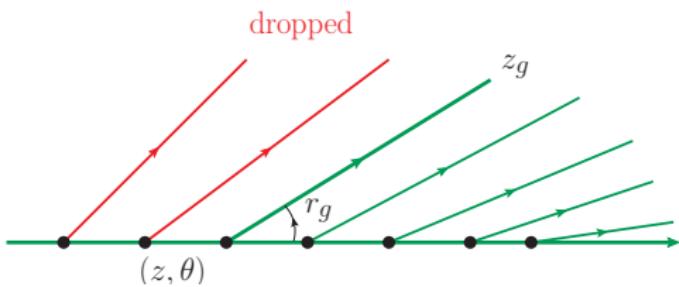
- ▶ A fixed-order N subjet expansion with subjet kinematics
 - ▶ identify dominant energy flow directions using N soft recoil-free axes
 - ▶ reconstruct subjets around the axes with multiple subjet radii R
 - ▶ TD observables represent *subjet topology* and *subjet substructure*
- ▶ Closely related to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



Chien et al, arXiv:1711.11041, submitted to PRL

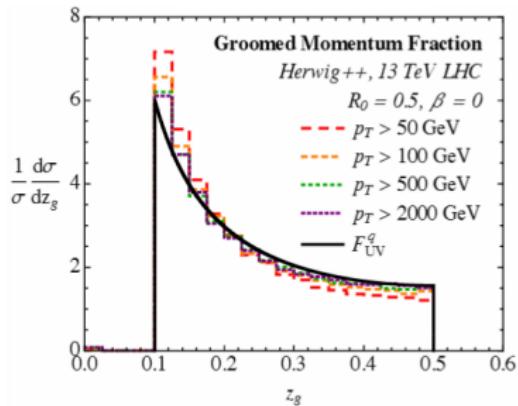
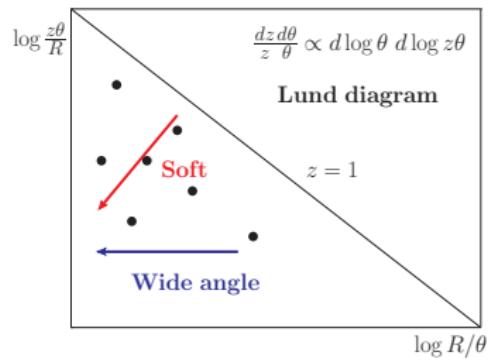
Subjet distribution, soft drop, and Lund diagram

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



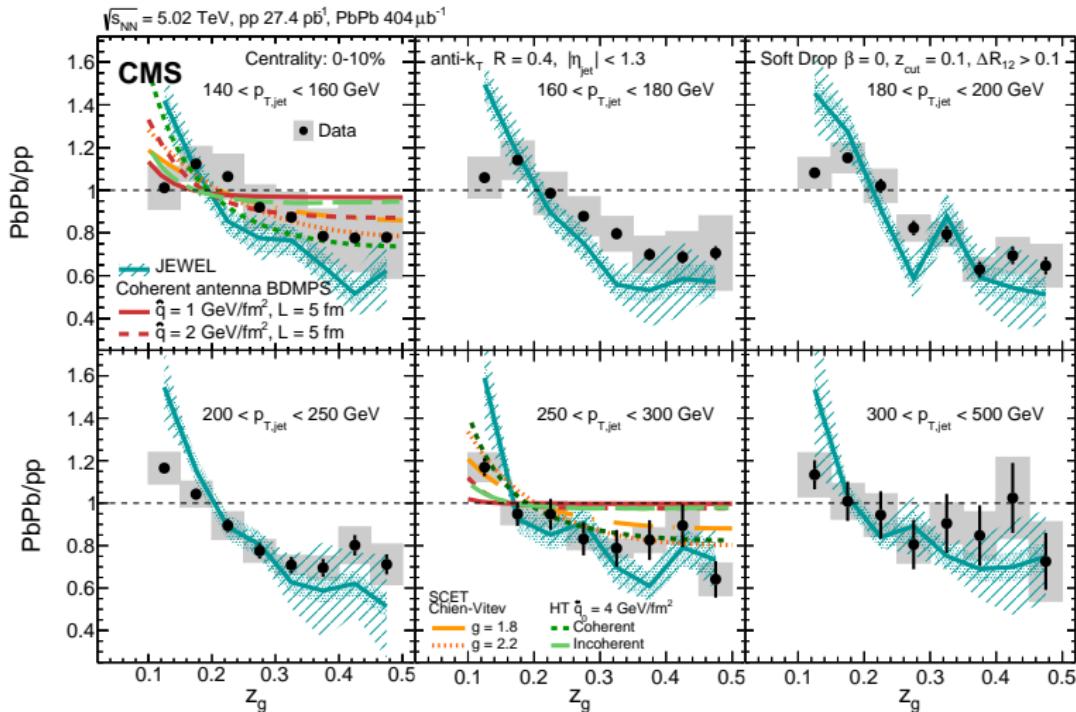
- ▶ C/A tree-based procedure to drop soft radiation
- ▶ Soft-drop condition

$$z < z_{\text{cut}} \theta^{\beta}, z = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$
- ▶ Lund diagram encodes branching kinematics along hard branches



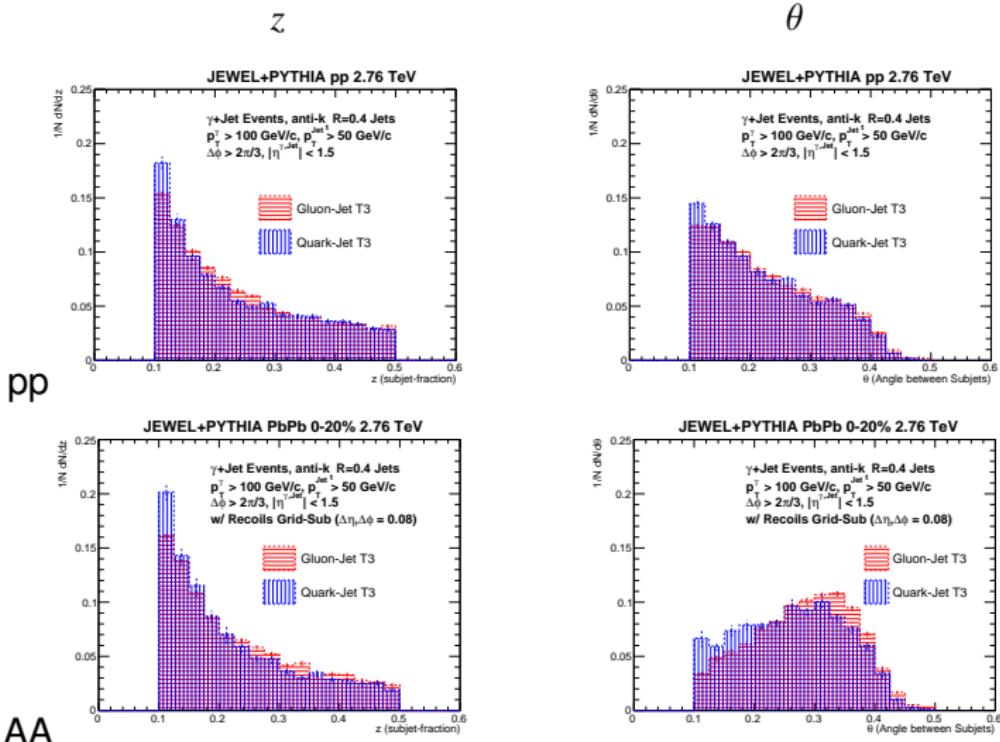
Modification of z_g

SCET Chien-Vitev PRL 119 (2017) 112301, CMS PRL 120 (2018) 142302



Telescoping subjet topology

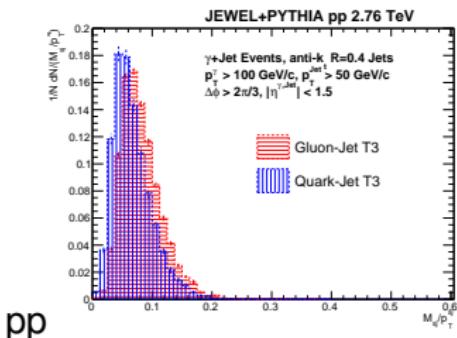
- Enhancement of soft, wide angle radiation



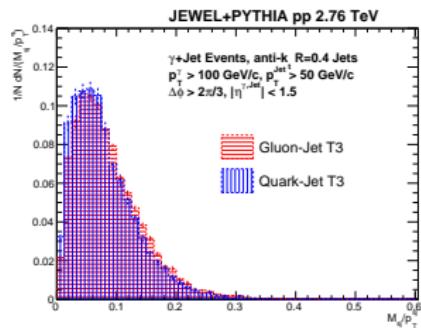
Telescoping subjet substructure

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

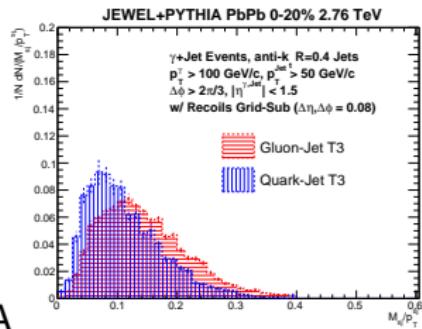
Hard Subjet



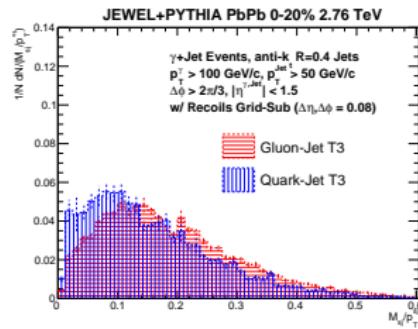
Soft Subjet



pp

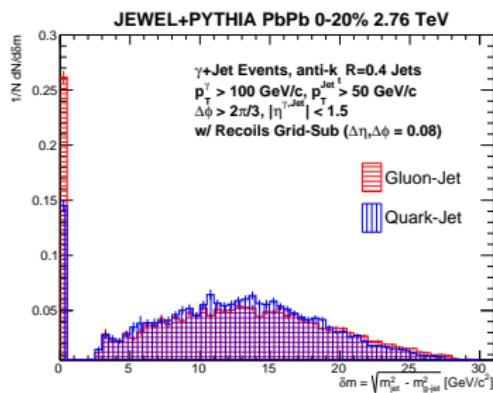
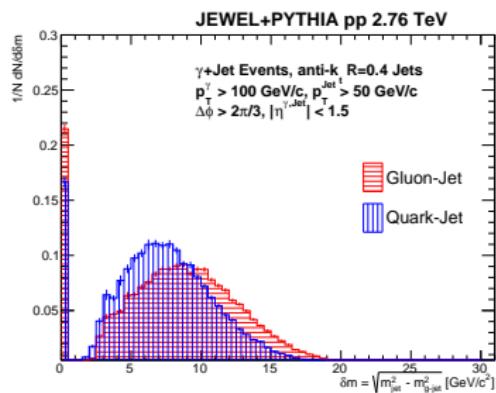


AA



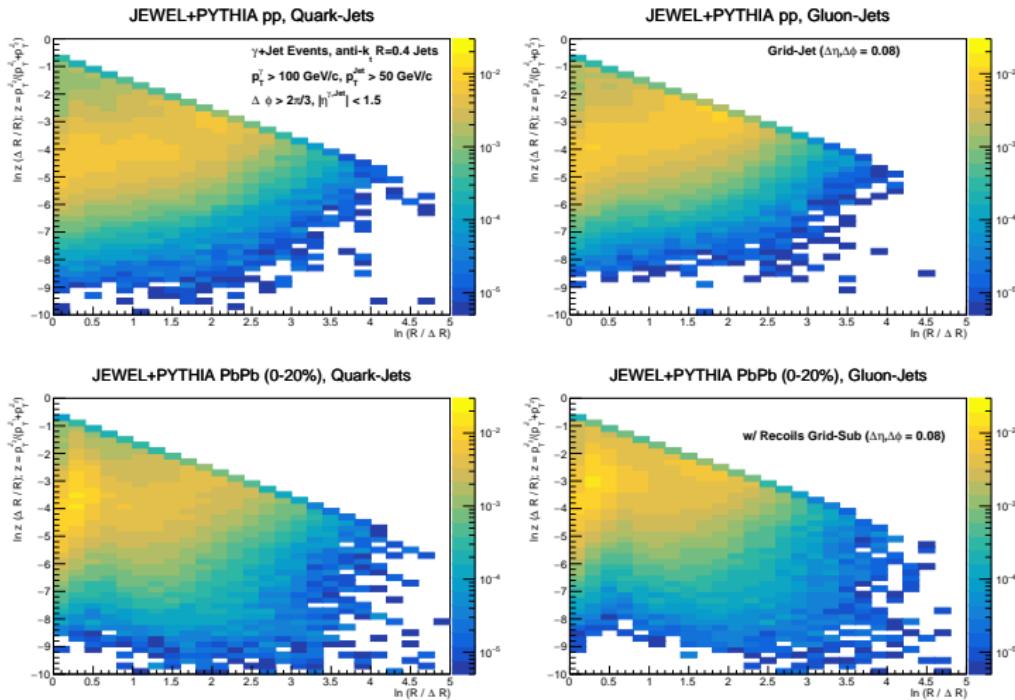
Collinear-drop: probing soft-dropped radiation

- ▶ 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



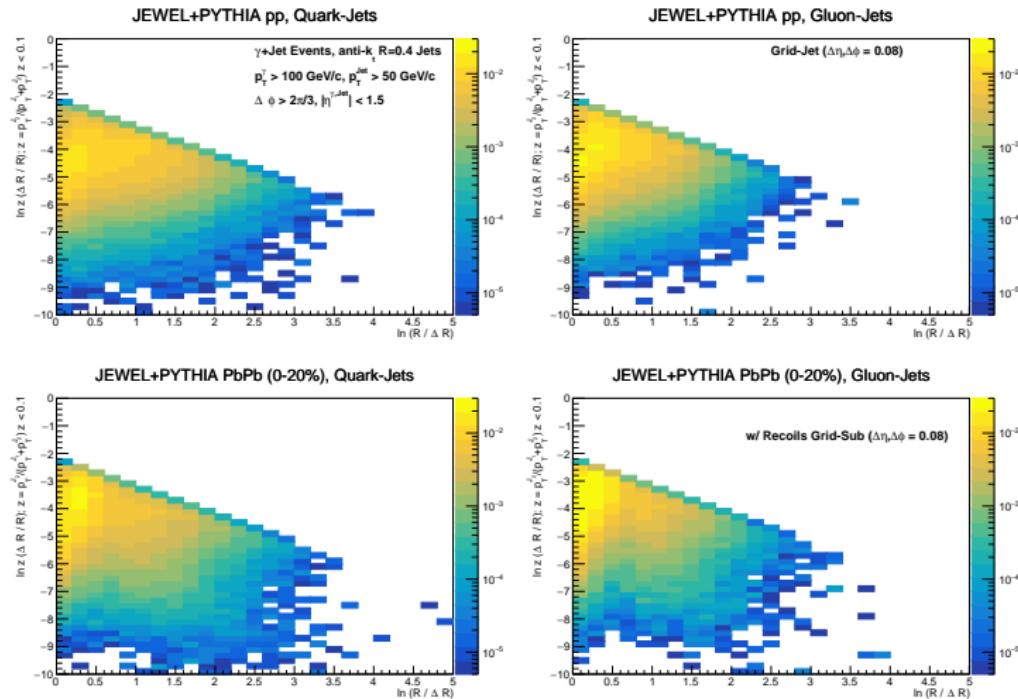
Lund diagram

- Significant increase of wide angle, soft radiation in AA



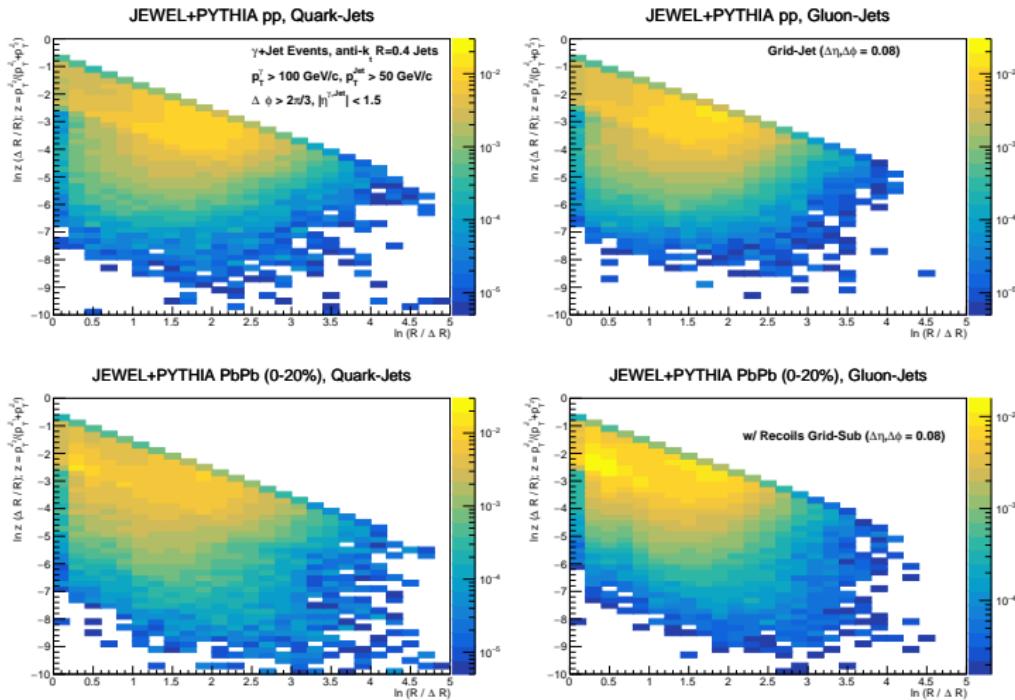
Lund diagram, soft-dropped radiation

- Much wide angle, soft radiation is removed (soft-drop $\beta = 0$, $z_{\text{cut}} = 0.1$)

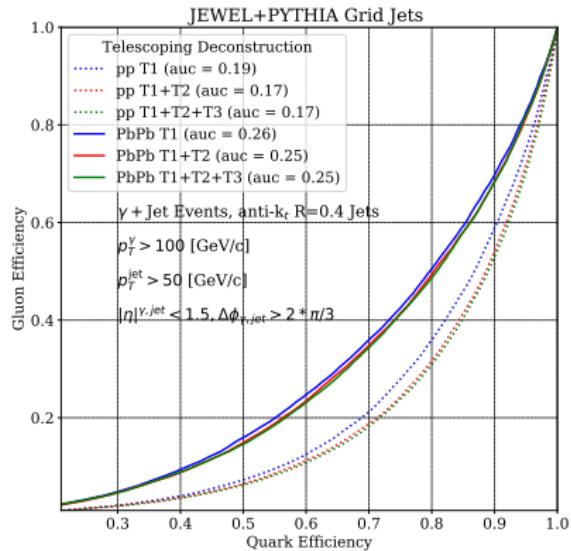
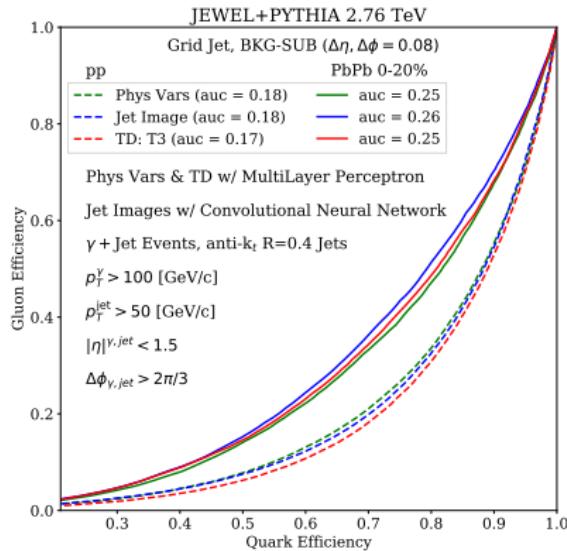


Lund diagram, hard branch

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

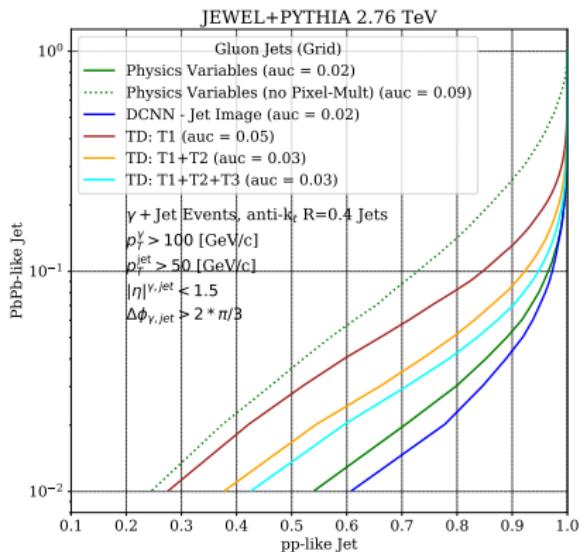
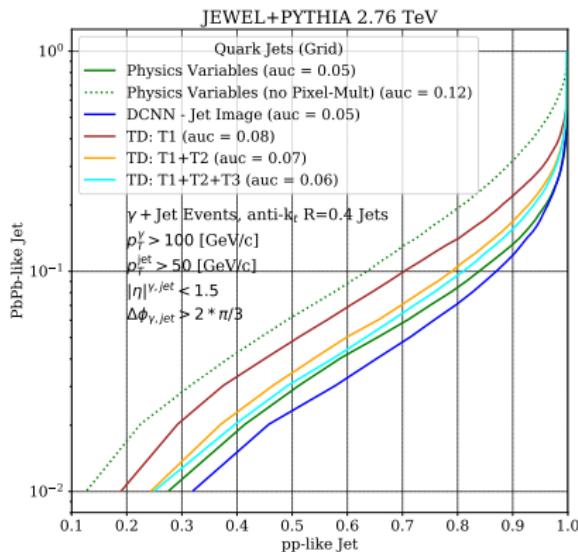


Quark gluon jet classification



- ▶ 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

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

