

Jet Spectroscopy Method using Telescoping Subjets

Yang-Ting Chien

LHC Theory Initiative Fellow, MIT Center for Theoretical Physics

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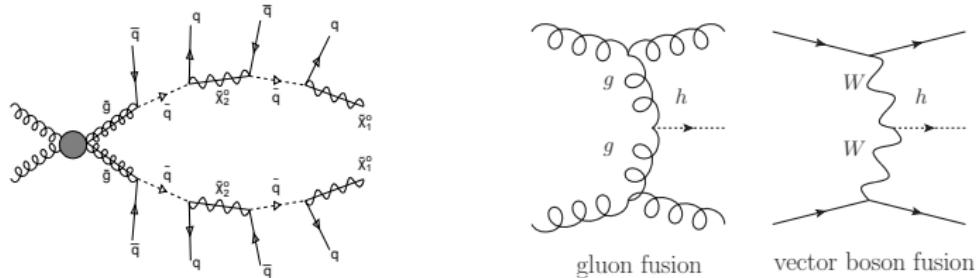
in collaboration with A. Emerman, S.-C. Hsu, S. Meehan, Z. Montague,
E. Metodiev, P. Komiske and R. Elayavalli, 1711.11041 and 1802.xxxxx

Outline

- ▶ Jet substructure
- ▶ Telescoping jet deconstruction
- ▶ Applications
 - ▶ quark gluon discrimination
 - ▶ boosted W and top tagging
 - ▶ heavy ion jet modification
- ▶ Conclusions and outlook

Quark-gluon discrimination

- ▶ Many SM and BSM signals have quark-heavy final states
- ▶ QCD backgrounds are gluon-heavy
- ▶ Quark and gluon jets have different jet substructures

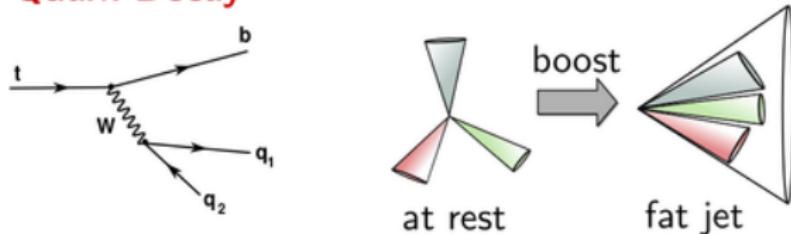


(Left) Gluino decay chain with a quark-heavy final state. (right) Different higgs production mechanisms with quark or gluon jets in the final state

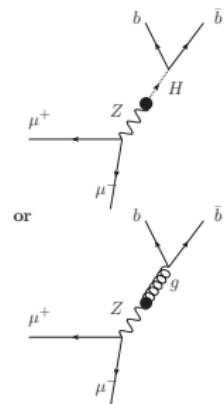
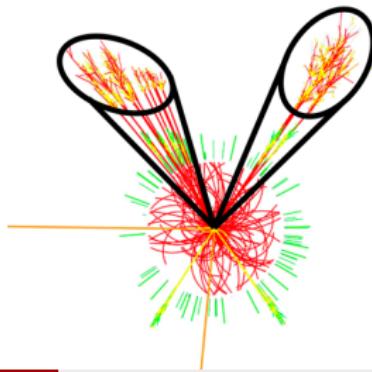
Boosted heavy particle tagging

- Hadronic decays of boosted heavy particles form fat jets with substructures

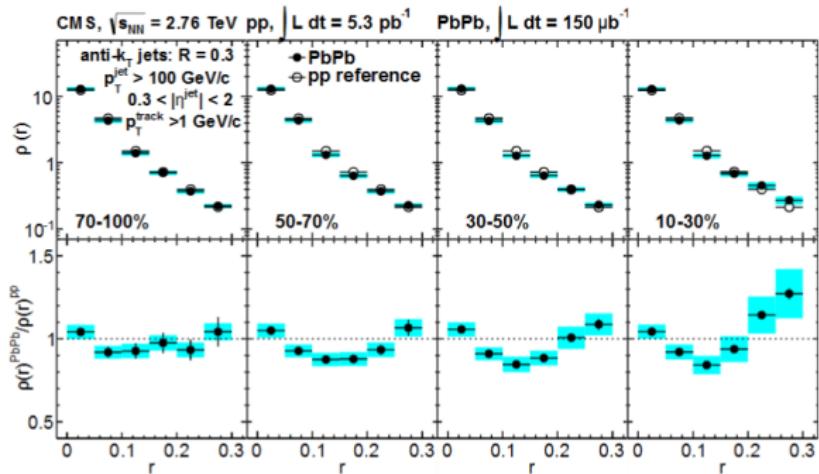
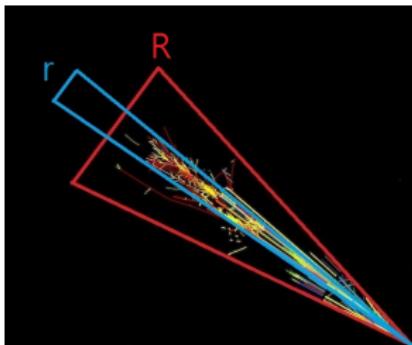
Top Quark Decay



- Improve background discrimination using substructure features



Jet spectroscopy of the QGP



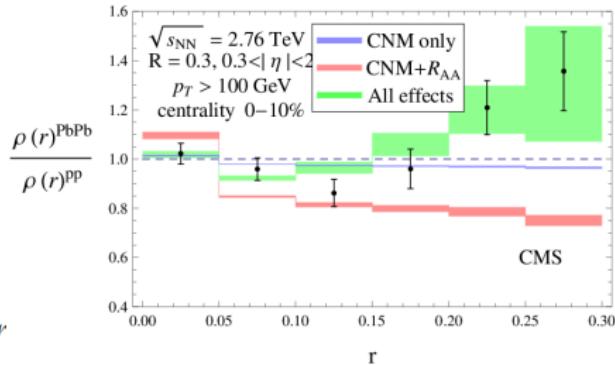
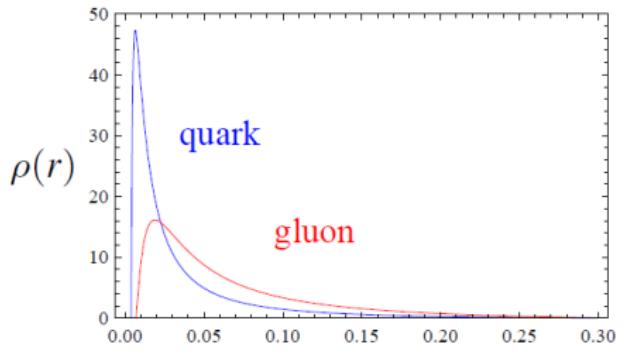
$$\Psi_J(r) = \frac{\sum_{r_i < r} E_{Ti}}{\sum_{r_i < R} E_{Ti}}$$

$$\langle \Psi \rangle = \frac{1}{N_J} \sum_J \Psi_J(r, R)$$

$$\rho(r) = \frac{d\langle \Psi \rangle}{dr}$$

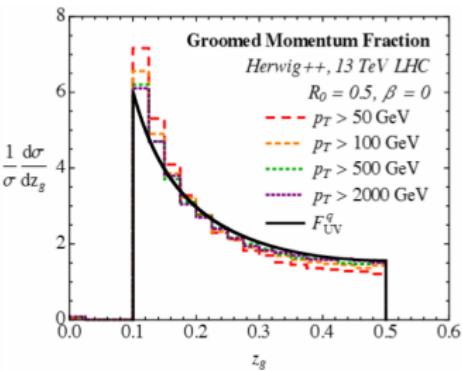
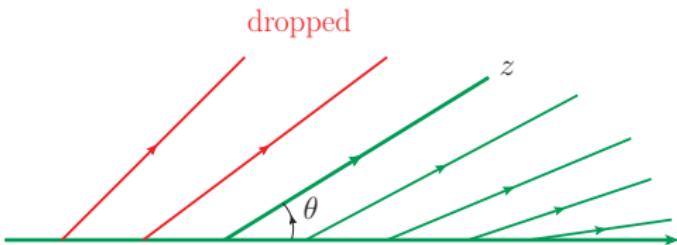
- ▶ Jets have become essential tools to probe the quark-gluon plasma produced in heavy ion collisions
- ▶ One typically evaluates the observable modification by the ratio of the curves in AA and pp collisions $\frac{\mathcal{O}_{AA}}{\mathcal{O}_{pp}}$
- ▶ With detailed understanding of jets and their structures we can relate their modifications to the medium properties: precise jet substructure studies

Flavor dependence in jet modification



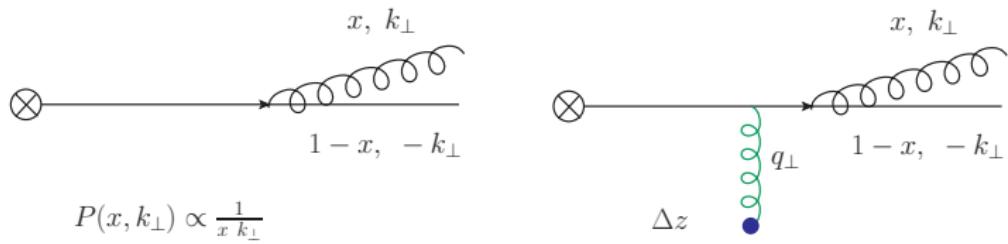
- ▶ Jet shapes probe the averaged energy distribution inside a jet
- ▶ Sensitive to the partonic origin of jets and the quark/gluon jet fraction
 - ▶ Jet quenching increases the quark jet fraction
 - ▶ Jet-by-jet the shape is broadened
- ▶ Quark jets and gluon jets can be independent probes

Subjet distribution



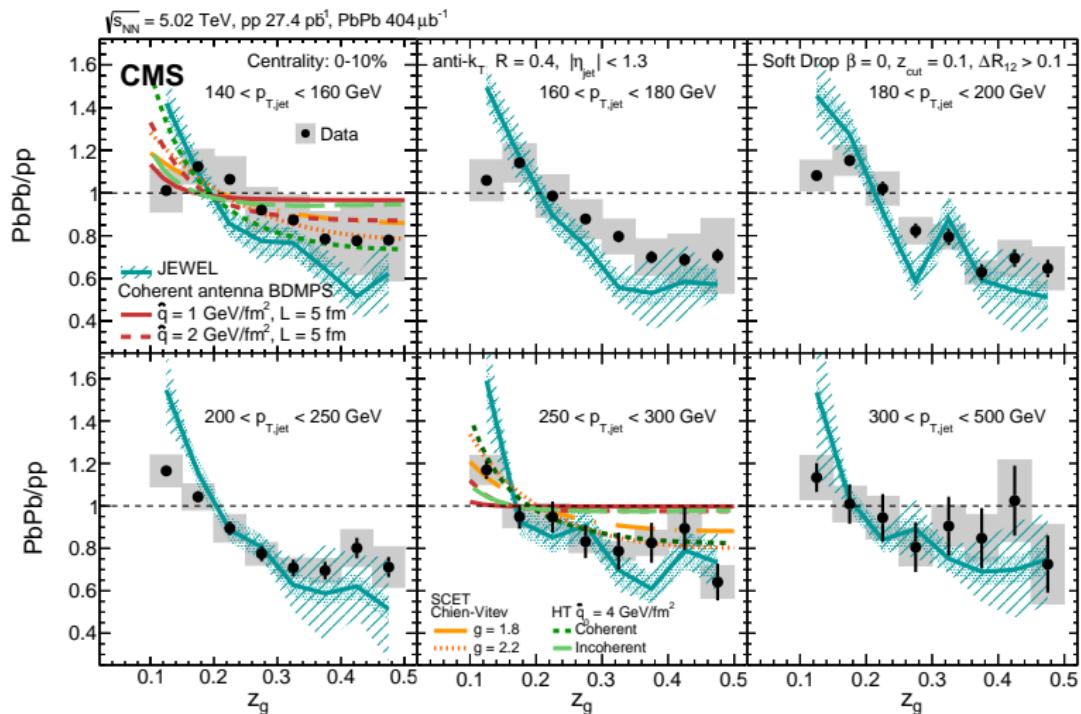
- ▶ Soft Drop: a tree-based procedure to drop soft radiation
 - ▶ Recluster a jet using C/A algorithm: angular ordered
 - ▶ For each branching, consider the p_T of each branch and the angle θ
 - ▶ Drop the soft branch if $z < z_{cut} \theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$
 - ▶ CMS used $\beta = 0$, $z_{cut} = 0.1$, $R = 0.4$, $\Delta R_{12} > \Delta = 0.1$ and measured z_g
- ▶ z_g : the momentum fraction of the soft branch. r_g : the angle between the branches

Splitting and bremsstrahlung



- ▶ In vacuum, the soft branch kinematics is closely related to the Altarelli-Parisi splitting function
- ▶ In the medium, the bremsstrahlung component modifies the soft branch kinematics

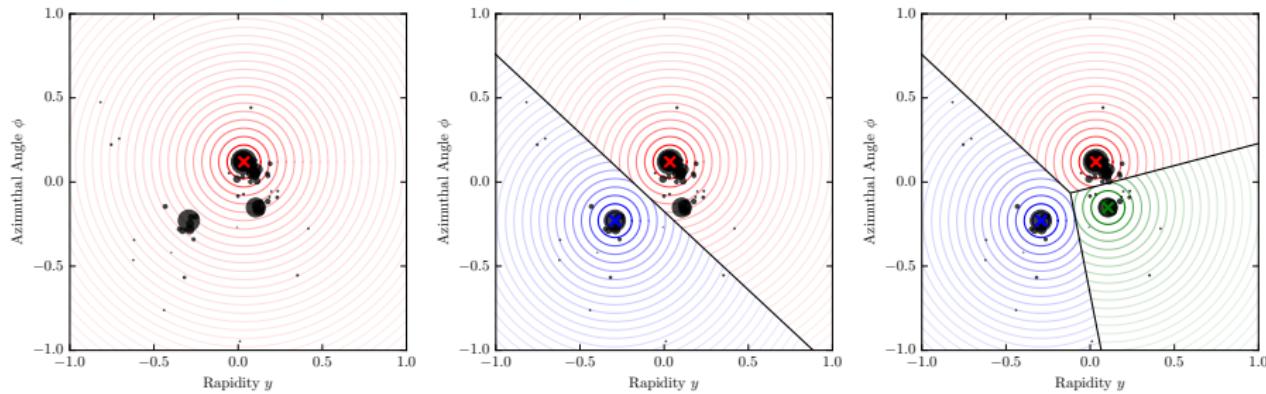
Modification of the hardest branching



- Parton shower can be modified throughout the whole jet formation

Telescoping deconstruction: subjet expansion

- ▶ We develop a systematic framework for studying all aspects of jet formation
- ▶ The $\sum_N N$ -subjett (TN) expansion is ordered by the number N of exclusively reconstructed subjets
- ▶ Procedures
 - ▶ Identifying dominant energy flow directions using N soft recoil-free axes
 - ▶ Reconstruct subjets around the axes with multiple subjet radii R_T
 - ▶ The transverse momenta and masses of the subjets together with the positions of the axes form the telescoping deconstruction observables: subjet kinematics



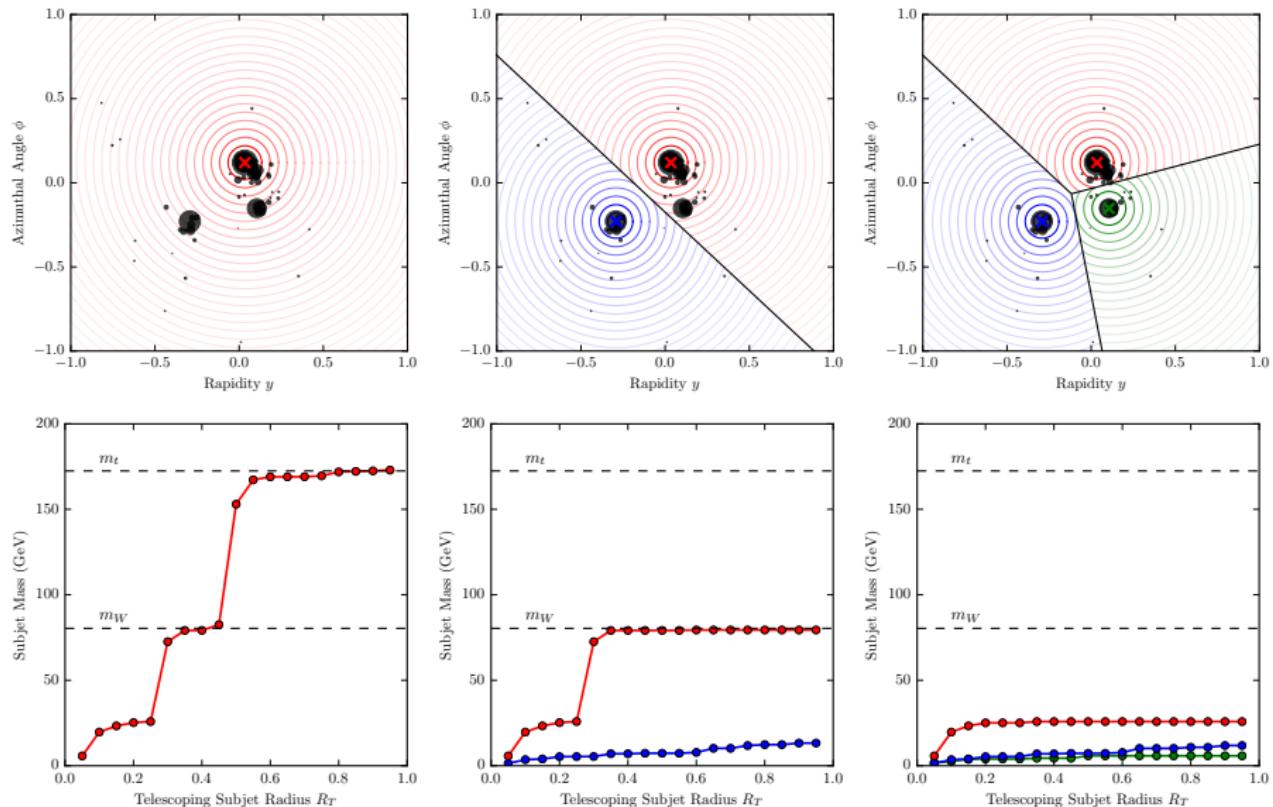
The physics of telescoping deconstruction observables

- ▶ The observables fall into two categories
 - ▶ subjet topology: energy flow directions and subjet transverse momenta
 - ▶ subjet substructure: subjet mass
- ▶ Features
 - ▶ Completeness: capture relevant physics information
 - ▶ Simplicity: using simple, physically-meaningful observables
 - ▶ Analyticity: as close to perturbative expansion and parton shower as possible

Examples

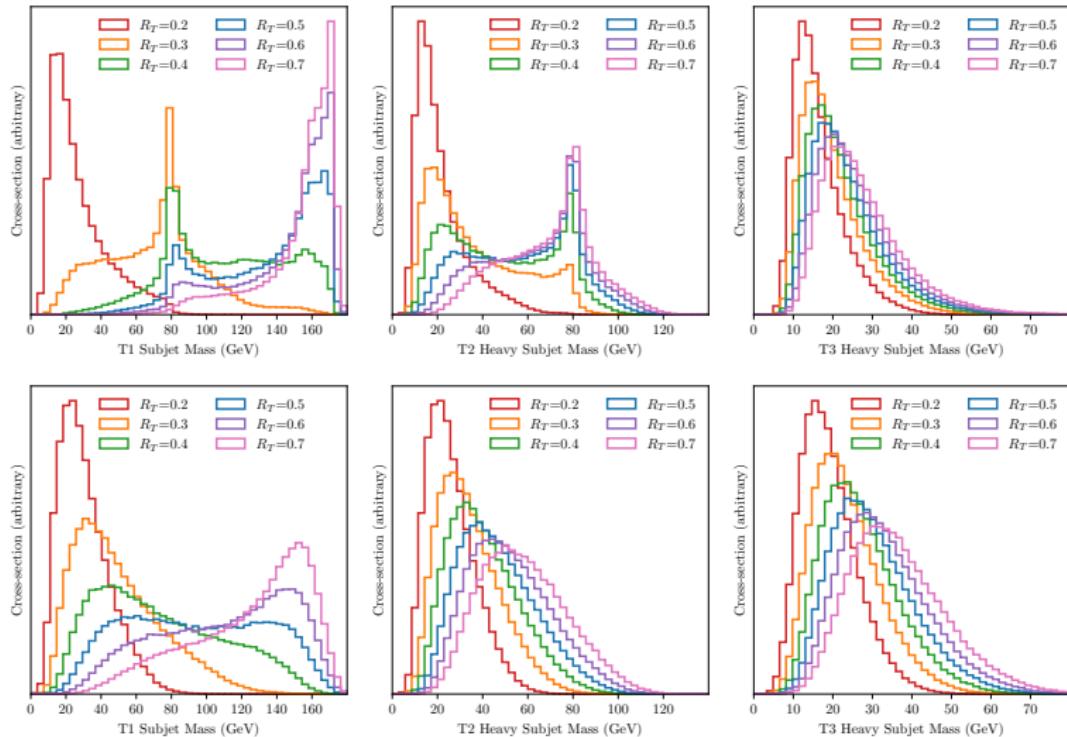
- ▶ We discuss applications to quark gluon discrimination, boosted W and top tagging, and jet modification studies
- ▶ Event samples generated from Monte Carlo simulations using Pythia 8
 - ▶ anti- k_T $R = 0.4$ (q/g) and 1.0 (W/top) jets
 - ▶ $800 \text{ GeV} < p_T^{\text{jet}} < 900 \text{ GeV}$ and $|\gamma^{\text{jet}}| < 1.5$
 - ▶ $75 \text{ GeV} < m^{\text{jet}} < 85 \text{ GeV}$ (W) and $160 \text{ GeV} < m^{\text{jet}} < 180 \text{ GeV}$ (top)
- ▶ JEWEL+PYTHIA simulation (Zapp et al) of heavy ion collisions
 - ▶ quark and gluon jets are generated from the $q + \gamma$ and $g + \gamma$ channels
 - ▶ pp and PbPb collisions at $\sqrt{s} = 2.76 \text{ TeV}$
 - ▶ $p_T^\gamma > 100 \text{ GeV}$, $p_T^{\text{jet}} > 50 \text{ GeV}$, $|\eta| < 2$, $\Delta\phi_{\gamma j} > 2\pi/3$
 - ▶ with medium recoil model and background subtraction
- ▶ Can be applied to other simulations and data

Subjet masses of a top jet



Heavy subjet mass distribution

- Top (top row) v.s. QCD (bottom row)

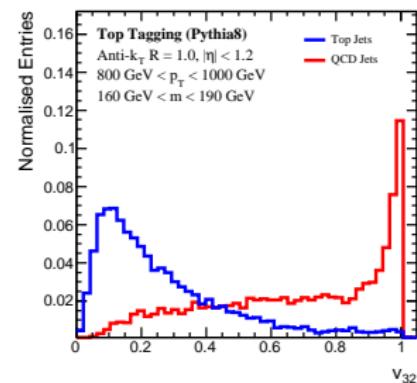
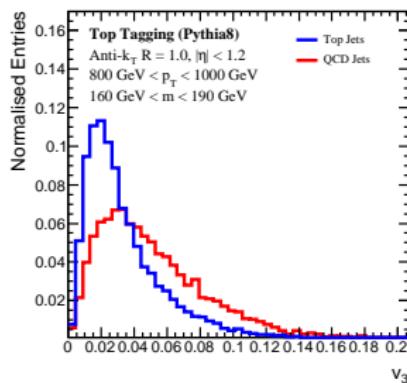
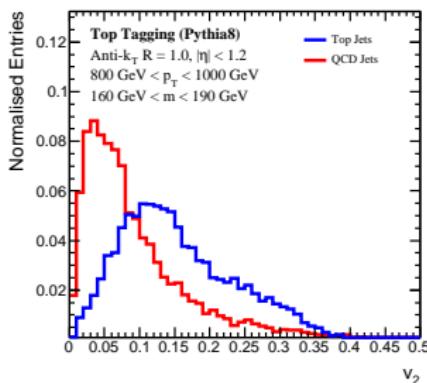


Variability

- The variation of the invariant masses $m_N(R_T)$ of the sum of N subjets can be quantified by the *variability*

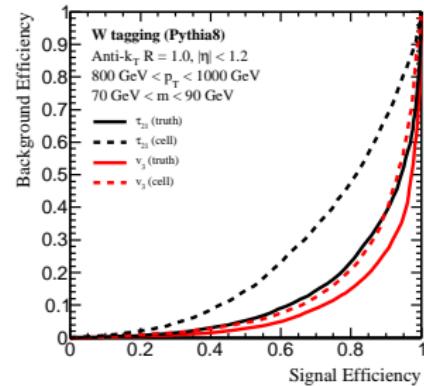
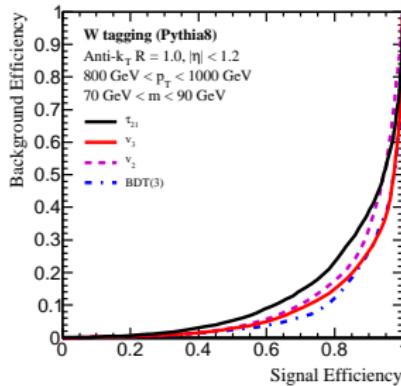
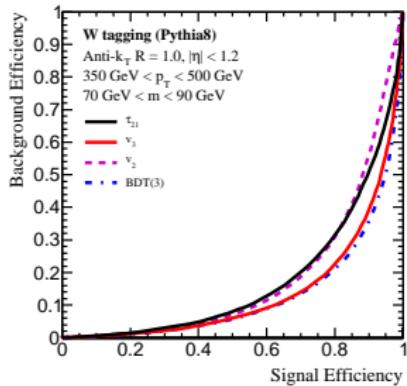
$$v_N = \frac{\sigma(\{m_N(R_T)\})}{\langle \{m_N(R_T)\} \rangle}$$

- In the case of top tagging, we also consider $v_{N2} = v_N/v_2$ for $N = 3, 4$ to optimize the variability performance



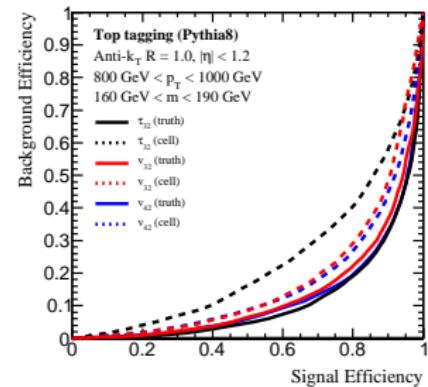
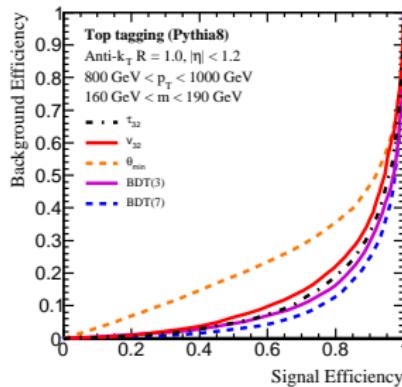
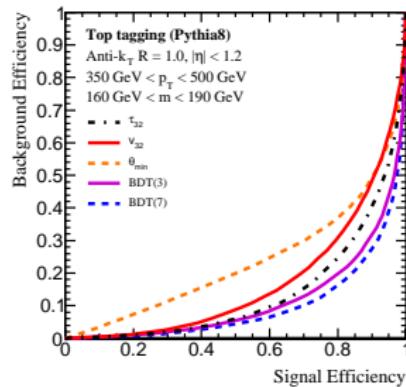
Variability in W tagging

- ▶ We compare with a standard N -prong tagger: N -subjettiness ratios
 - ▶ τ_{21} for W tagging
- ▶ v_3 outperforms τ_{21} and is robust against detector smearing
 - ▶ The lower the ROC curve the better the performance
- ▶ It is the manifestation of the isolation of W jets due to its color-singlet nature
 - ▶ A dominant feature over the two-prong structure

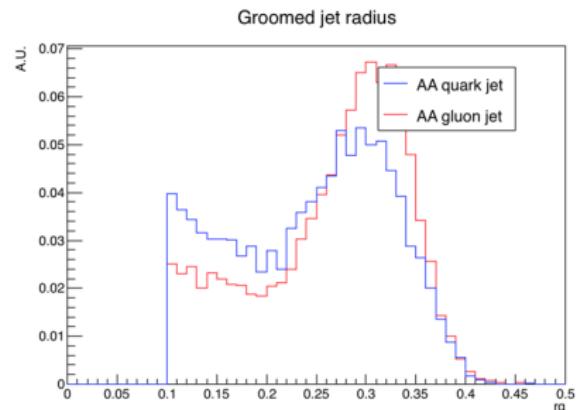
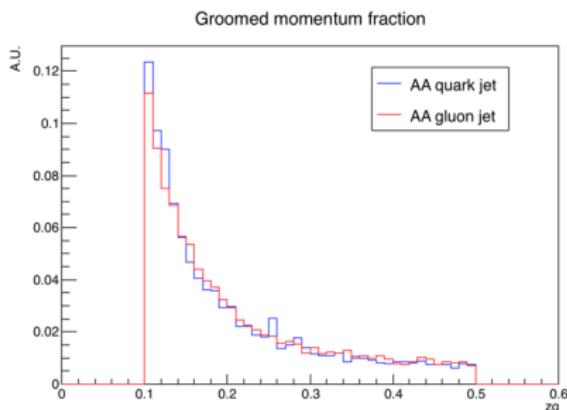
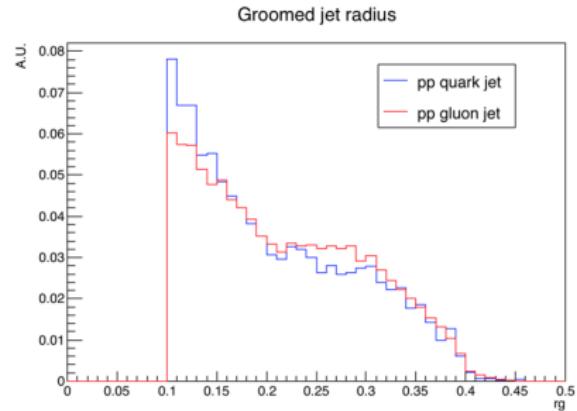
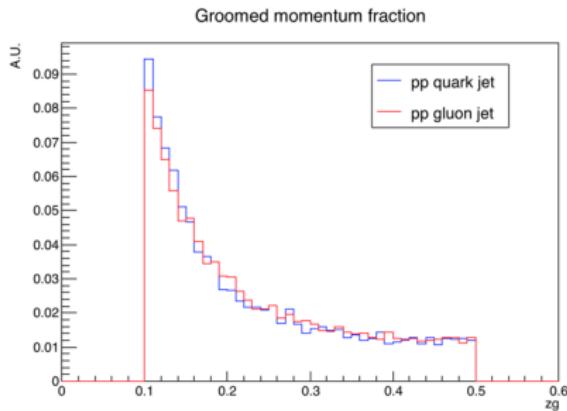


Variability in top tagging

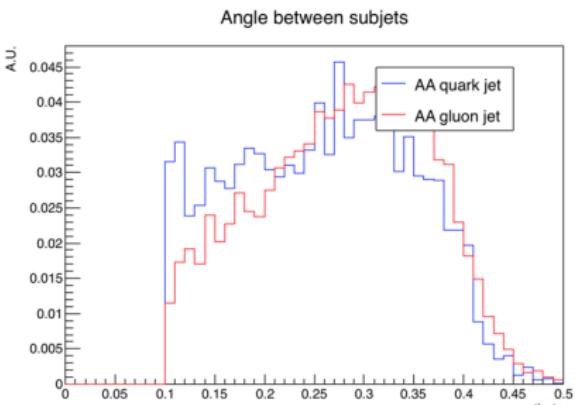
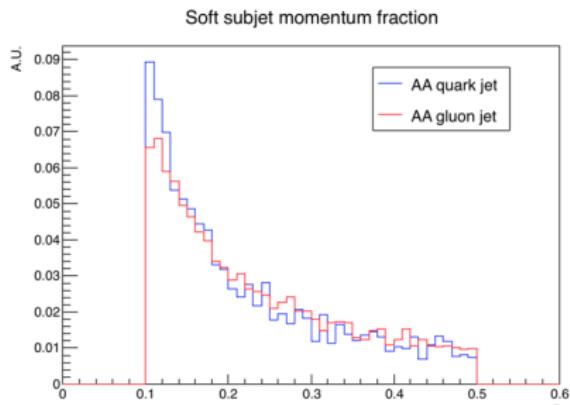
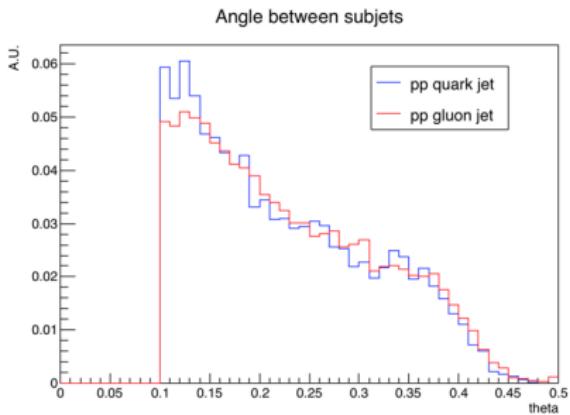
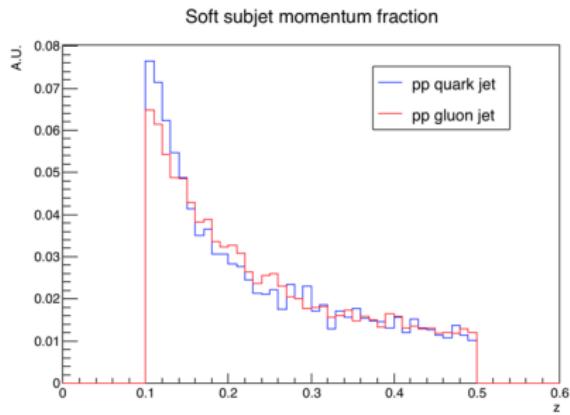
- ▶ We compare with τ_{32}
- ▶ v_{42} performs very well and is robust against detector smearing
- ▶ The presence and isolation of a W inside a top jet are important features



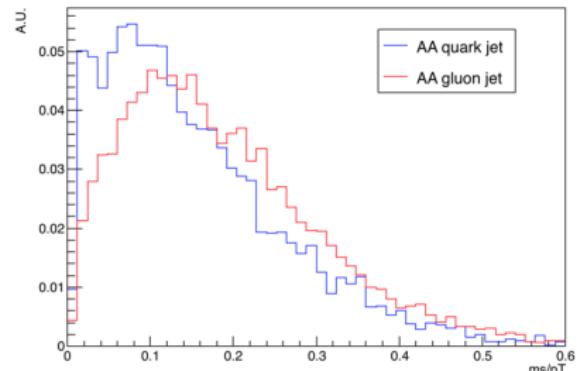
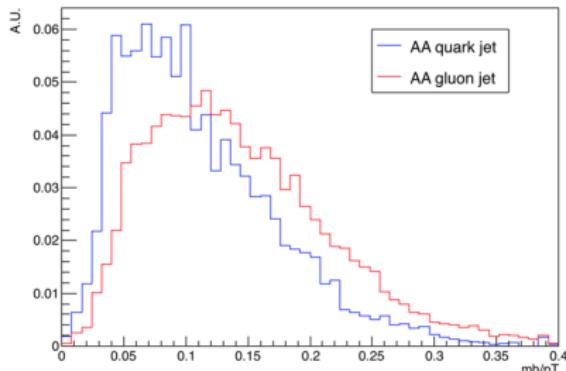
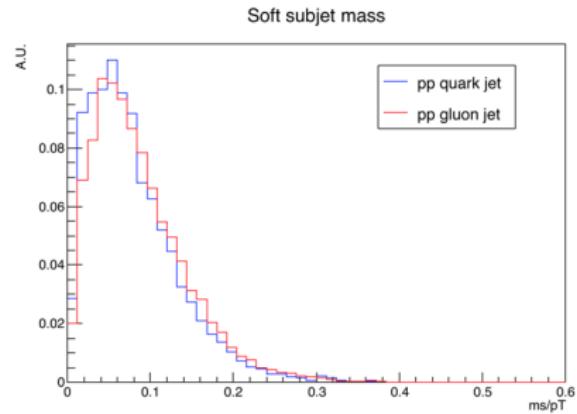
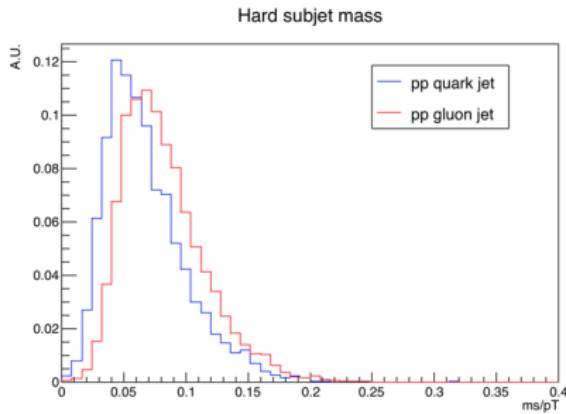
Quark and gluon soft drop z_g and r_g



Quark and gluon telescoping subjet topology



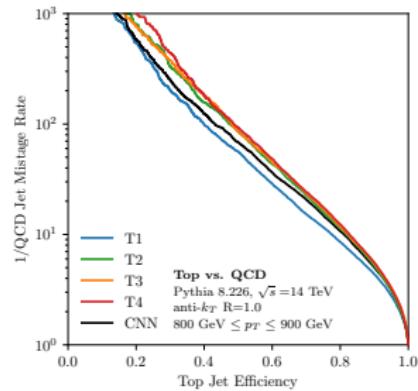
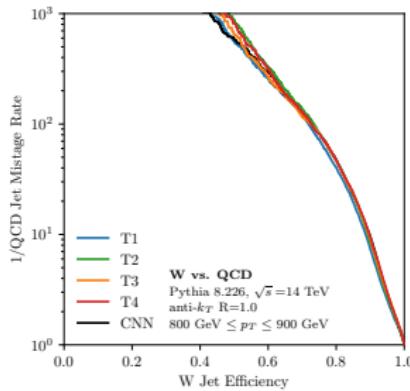
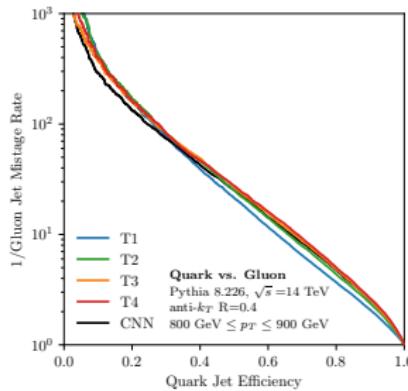
Quark and gluon telescoping subjet substructures



Telescoping deconstruction and machine learning

- ▶ Tagging is a classification problem
- ▶ Extract the complete information of jets from correlations among subject 4-momenta
 - ▶ Machine learning techniques can be easily combined
 - ▶ Deep learning is in fact a giant classifier fitting
- ▶ Deep neural network architecture implemented with Keras library and Theano backend
 - ▶ 3-layer (100,100,100) dense nets
 - ▶ Rectified linear unit (ReLU) activation function
 - ▶ He-uniform model weight initialization
 - ▶ network trained using the Adam algorithm for 50 epochs
 - ▶ can be trained on a laptop CPU in 5 minutes
- ▶ Compared to convolutional neural network (CNN) used in jet image recognition
 - ▶ jet images are size 33×33
 - ▶ 3 convolutional layers (48 filters each) + 1 dense layer (128)
 - ▶ training on GPU is needed

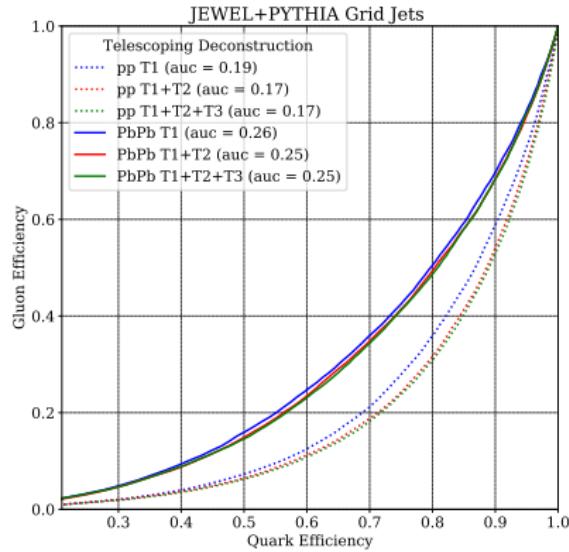
Performances I



- ▶ The performance can be captured in a Receiver Operating Characteristic (ROC) curve plotting the inverse of the background mistag rate at different signal efficiencies
- ▶ TN performances converge quickly to the jet image performance
- ▶ The subjet expansion converges efficiently and telescoping deconstruction faithfully represents the jet information

Performances II

- ▶ In the medium, the performance drops and T2 provides little additional information
- ▶ Information contained in subleading subjets seems washed out



Conclusions and outlook

- ▶ Subjet kinematic information is a complete representation of jets
- ▶ There are useful features beyond the N -prong structure
- ▶ Color singlet jet isolation is observed and quantified by variability
- ▶ Telescoping deconstruction is a systematic framework for jet studies