Jet Substructure: Theory

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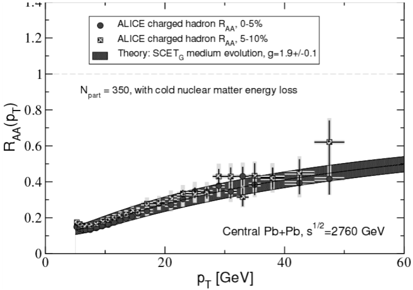
January 6, 2018
JETSCAPE workshop, LBL

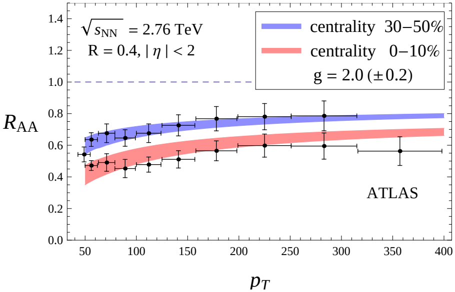
Outline

- From jet quenching to jet modification
  - precision jet substructure study
  - multi-scale effective field theory
  - hadron and heavy flavor not covered in this talk
- Engineering jet substructure
  - jet grooming as artificial jet quenching
  - quark and gluon jets as independent probes
  - jet deconstruction and multivariate analysis
- Improving Monte Carlo
  - stress-testing jet quenching models with designed jet observables
  - sensitivity studies and theory boundaries
- Conclusion and outlook

Jet quenching: hadron and jet cross section suppression

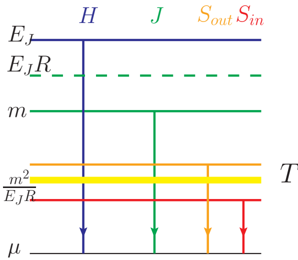
- Decade-long jet energy loss paradigm
- Going beyond moving the R_{AA} curves up and down: precision jet R_{AA} and the jet reconstruction dependence



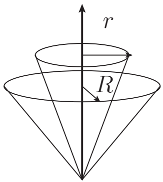


QCD radiation and jet observables

- Jets are manifestation of the infrared structure of QCD at high energy: enhancement of soft/collinear radiation
- They are multi-scaled objects with rich information about the physics across the **entire** energy spectrum
  - E_J is the hard scale which is the energy of the jet
  - $E_J\lambda$ is the jet scale and λ is the angular spread of particles ($\lambda \approx p_\perp/p_\parallel \ll 1$)
  - Relevant soft modes depend on the observables, e.g. for jet mass, a lower soft, seesaw scale emerges ($E_s \approx m^2/E_J R$)
  - Medium modes interact with and respond to jets
  - Don't forget about Λ_{QCD} at the bottom!



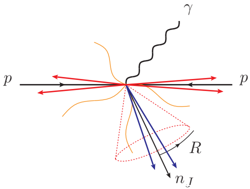
Sensitivity of jet observables to QCD radiation



$$\Psi_J(r,R) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

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

$$\psi(r,R) = \frac{d\langle\Psi\rangle}{dr}$$



$$m^2 = \Big(\sum_{i\in J} p_i\Big)^2$$
$$= \big(p_c + p_s\big)^2$$
$$\approx p_c^2 + 2p_c\cdot p_s$$
$$\approx p_c^2 + 2E_J n_J\cdot p_s$$

- Jet shape has dominant contributions from energetic collinear radiation

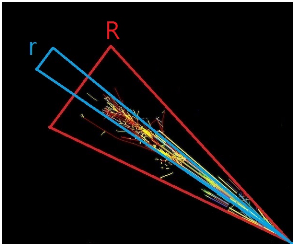
$$\Psi(r) = \frac{E_c^{<r}+E_s^{<r}}{E_c^{<R}+E_s^{<R}} = \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}\Big(\frac{E_s}{E_c}\Big)$$

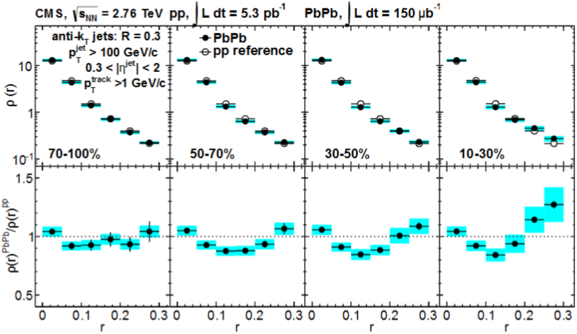
- Jet mass is sensitive to soft radiation

$$m^2 \approx p_c^2 + 2E_J n_J\cdot p_s\,, \quad \Delta m \approx E_s\frac{E_J}{m}$$

- Jet observables have different sensitivities to physics at different energy scales simply because of **kinematics**. In principle, through a series of jet measurements we will be able to map out the whole jet formation history

Jet spectroscopy of the QGP: the devil is in the detail





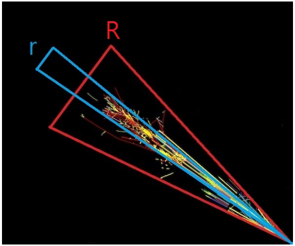
$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

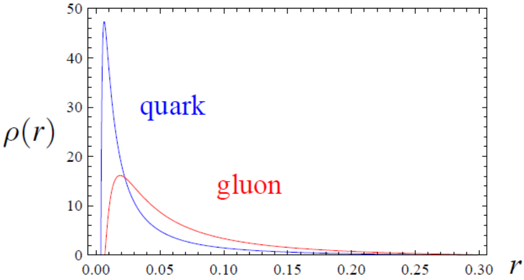
$$\langle \Psi \rangle = \frac{1}{N_J} \sum_{J}^{N_J} \Psi_J(r,R)$$

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

- Jets have become essential tools to probe the medium dynamics
- We evaluate the observable modification by the ratio $\frac{\mathcal{O}^{AA}}{\mathcal{O}^{pp}}$
- With detailed understanding of jets and their structures we can relate their modifications to the medium properties: **the need of precise jet substructure studies**

Jet substructure calculation and resummation (see Ian's nice talk)





- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n), \ n = 1, ..., \infty$ need to be resummed
- Sensitive to the partonic origin of jets and the quark/gluon jet fraction

Resummation and effective field theory

THE BASIC IDEA

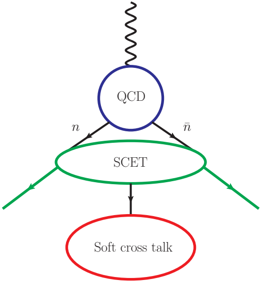
- Logarithms of *scale ratios* appear in perturbative calculations
  - Logarithms become large when scales become hierarchical

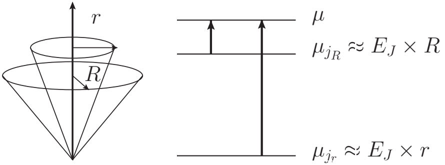
$$\log \frac{r}{R} = \log \frac{\text{scale 1}}{\text{scale 2}}$$

- In effective field theories, logarithms are resummed using renormalization group evolution between characteristic scales
  - To resum *all* the logarithms we need to identify *all* the relevant scales in EFT

Soft-Collinear Effective Theory (SCET)

- Effective field theory techniques are most useful when there is hierarchy between characteristic energy scales
- SCET factorizes physical degrees of freedom in QCD by a systematic expansion in power counting
  - Match SCET with QCD at the hard scale by integrating out the hard modes
  - Integrating out the off-shell modes gives collinear Wilson lines which describe the collinear radiation
  - The soft sector is described by soft Wilson lines along the jet directions



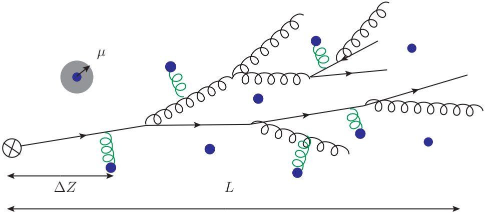


Renormalization group evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

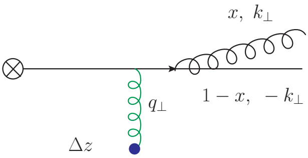
(Chien et al 1405.4293)

Multiple scattering in a medium and QCD bremsstrahlung

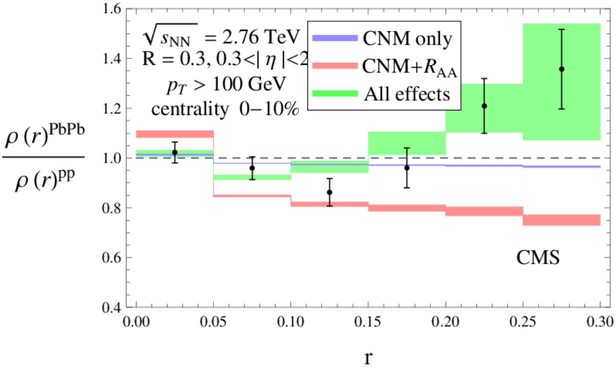
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ



- Jet-medium interaction using SCET with background Glauber gluon fields $\mathrm{SCET_G}$ (Glauber-collinear: Majumder et al, Vitev et al. Glauber-soft: work in progress)
- Leading-order medium induced splitting functions $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ were calculated using $\mathrm{SCET_G}$ (Vitev et al)



First quantitative understanding of jet shape modification



- Cold nuclear matter effect is negligible
- Jet quenching increases the quark jet fraction
- Jet-by-jet the shape is broadened
- Chien et al 1509.07257 and CMS data 1310.0878

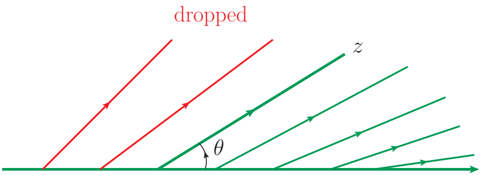
How do we isolate physics and distinguish jet quenching models?

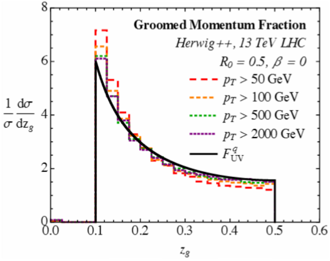
- Whether the model relies on the low scale physics corresponds to two rough pictures of jet quenching
  - Yes. Parton showers are not affected much until the later stages. The medium depletes the partons out of the jet
  - No. The medium effects open up more channels in the jet formation process, all the way from the hard process through hadronization
- Can we test the two pictures and the role of medium response?
  - We are able to dissect radiations and pick out the components of interest
  - The idea: come up with an observable as insensitive to low scale physics as possible
  - The tool: jet grooming

Jet grooming is actually an artificial jet quenching

- It is a controlled way to remove soft radiation
  - A way to design sensitivity to soft physics
  - The original motivation is to mitigate radiation contaminations
- How does a jet quenching model confront with jet grooming?
  - Do they add up or interfere?
  - How are groomed jets quenched?
  - How are quenched jets groomed?

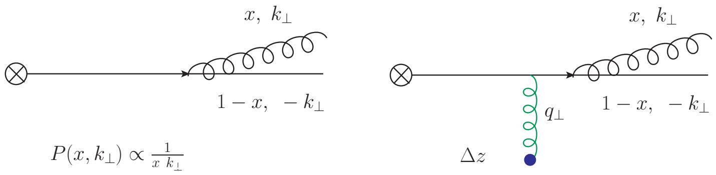
Subjet distribution





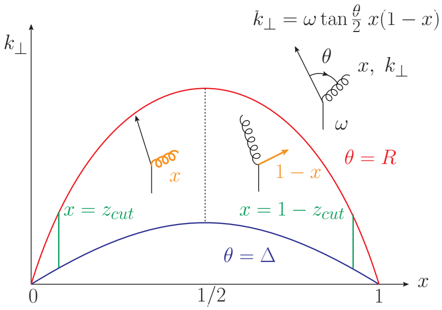
- Soft Drop: a tree-based procedure to drop soft radiation (Larkoski et al 1402.2657)
  - Recluster a jet using C/A algorithm: capturing collinear/soft splitting
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - CMS used $\beta = 0$, $z_{cut} = 0.1$, $R = 0.4$, $\Delta R_{12} > \Delta = 0.1$ and measured z_g
  - STAR does without the ΔR_{12} cut
- 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

Analysis of z_g (Chien and Vitev, PRL)



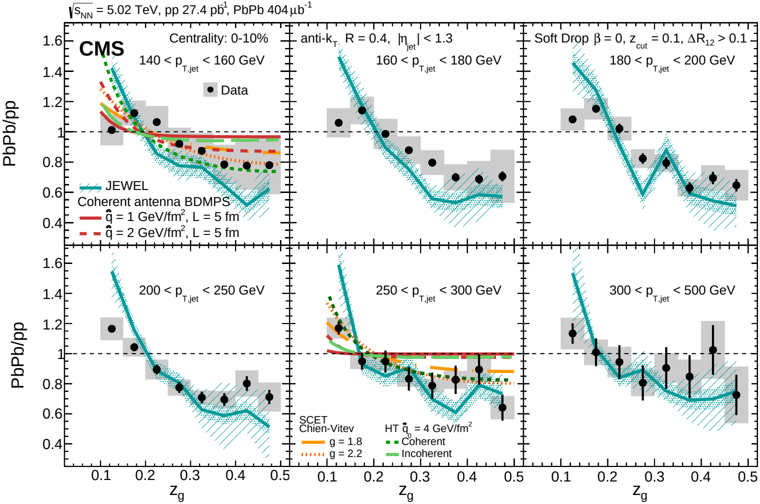
- The partonic phase space is constrained by R (jet algorithm), Δ (jet selection) and z_{cut} (jet grooming)
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

$$\mathcal{P}_{i\to jl}(x,k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x,k_\perp) + \mathcal{P}^{med}_{i\to jl}(x,k_\perp)$$

- The distributions of z_g and r_g are calculated ($\overline{\mathcal{P}}(x) = \mathcal{P}(x) + \mathcal{P}(1-x)$)

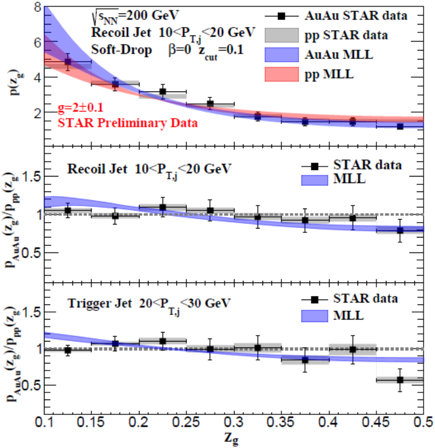
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g,k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x,k_\perp)}\,, \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x)\overline{\mathcal{P}}_i(x,k_\perp(r_g,x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x,k_\perp)}$$

Modification of the hardest branching



- Parton shower can be modified throughout the whole jet formation

Consistent with STAR preliminary data (Vitev 1801.00008)



Quark jets and gluon jets can be independent probes

- Conventionally, one studies the modification of individual jet observables
- However, correlations among jet observables contain a huge amount of information which can be exploited
- Can we study the collective modifications of *all* the features of jets?

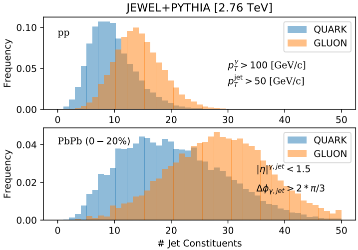
Classification of quark and gluon jets (Chien and Elayavalli, to appear soon)

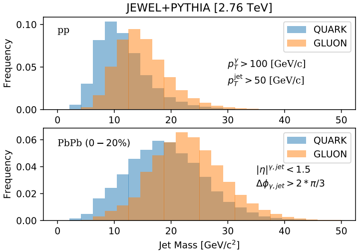
- We are able to select jets with different quark and gluon jet fractions
- One needs **all** jet features to optimize the classification of quark and gluon jets
- The idea: study how q/g discrimination changes from pp to AA
- We use the JEWEL+PYTHIA simulation (Zapp et al) as an example
- It can be applied to **all other Monte Carlo simulations (including JETSCAPE) and data**

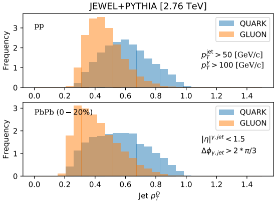
Study the modification of the comparisons between quark and gluon jets

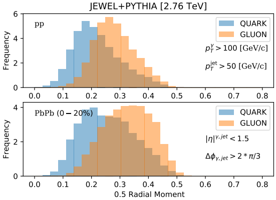
Multivariate analysis of a list of useful variables

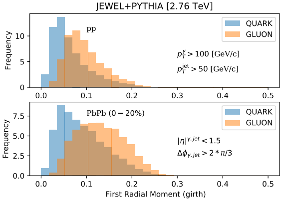
- Empirically, the following five variables together provide good discrimination power
  - subjet multiplicity, jet mass, $p_T^D = \sqrt{\sum_i {p_T^i}^2}/p_T^{\rm jet}$, radial moments $\sum_i p_T^i \Delta\theta^\kappa_{{\rm jet},i}/p_T^{\rm jet}$





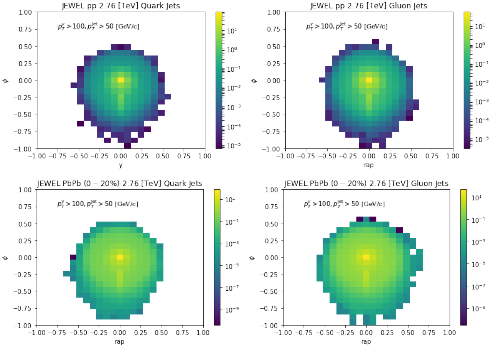


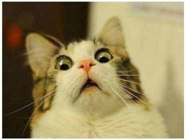


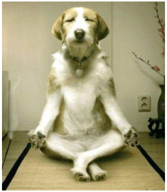


Jet image and convolutional neural network

- A fixed-dimensional representation of the energy distribution in the $y-\phi$ plane

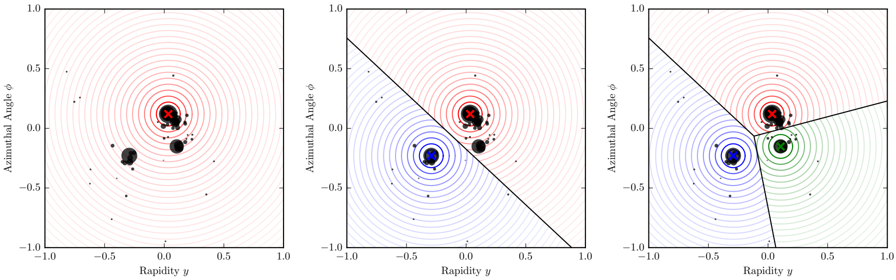






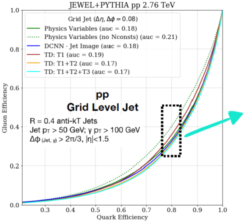
Telescoping deconstruction: subjet expansion (Chien et al 1711.11041)

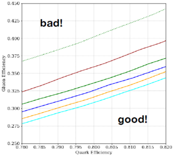
- Telescoping: probing around dominate energy flows with multiple angular resolutions R
- Extract the complete information of jets from correlations among subjet 4-momenta using deep neural network
- Procedures
  - Identifying dominant energy flow directions using N soft recoil-free axes
  - Reconstruct subjets around the axes with multiple subjet radii R
  - The transverse momenta and masses of the subjets together with the positions of the axes form the telescoping deconstruction obervables



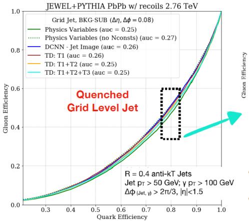
Receiver Operating Characteristic (ROC) curves (preliminary)

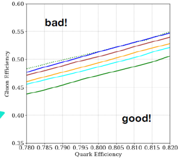
- In the medium, the performance drops and T2 provides little additional information
- Information contained in subleading subjets seems washed out



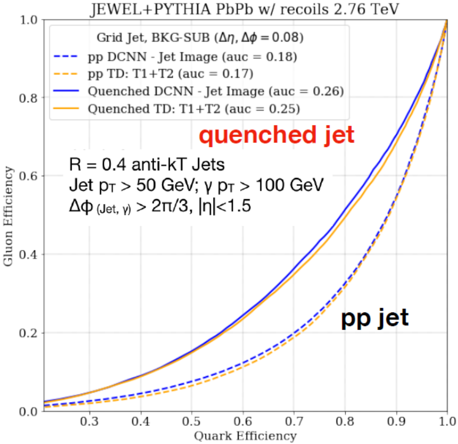


- # Jet Constituents powerful in discrimination
- Reasonably safe in pp,
- Major challenge in heavy ions

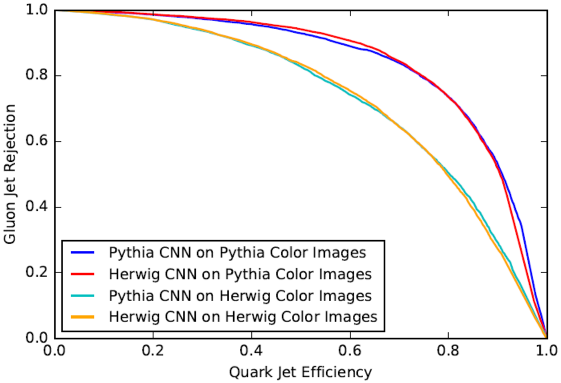




- Jet Image and (useful) Physics Vars Similar
- TD saturates with T2 providing little more on top of T1



A story about Pythia and Herwig



- Jet substructures **are** being used to constrain and tune parton shower Monte Carlos
- Quark and gluon jets are different beats
- Are you tuning parton shower or hadronization model?
- Is the combination of perturbative and non-perturbative physics solid, or arbitrary?
- How to compare with data with all realistic complications?

How to train your model?

- "provide guidance about how best to utilize substructure measurements to test and improve Monte Carlos"
- Goal: fit all current and future jet substructure data
- Caution: since all jet quenching models manage to fit R_{AA} very well, to combine them one must limit the regions of validity of each sector to avoid double-counting: need rigorous and fundamental theory (QCD)
- One should develop perturbative tools which is systematically improvable
- Design jet substructure observable sensitive to different sectors: need a jet representation which suits heavy ion jet physics
- This is like a "new-QCD physics search"
- Once Monte Carlo fits data, one may want to do sensitivity studies and simplify the models
- Can one train Monte Carlo using machine learning techniques?

Conclusion and outlook

- Importance of flavor dependence and the role of quark/gluon jet fraction in jet substructures
- Subjet distribution provides an opportunity to test the modification of hard splitting within jets
- Although not covered in this talk, heavy flavors and hadrons continue to be important probes of the QGP
- Quark gluon discrimination provides a new method of studying jet modification
- Modifications of collective jet features provides qualitatively new insights
- The classification performance drops in heavy ion collisions simulated by JEWEL+PYTHIA
- Telescoping deconstruction is a complete and systematic framework for jet quenching studies